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WATER RESOURCES RESEARCH PROGRAM

**MEASUREMENTS OF PHYSICAL PHENOMENA
RELATED TO POWER PLANT WASTE HEAT DISCHARGES:
LAKE MICHIGAN, 1973 AND 1974**

GREAT LAKES PROJECT

MASTER

**ENERGY AND ENVIRONMENTAL
SYSTEMS DIVISION**

ENVIRONMENTAL STATEMENT PROJECT

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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LAKE MICHIGAN, 1973 AND 1974

by

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March 1975

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WATER RESOURCES RESEARCH PROGRAM
VOLUME I. MEASUREMENTS OF PHYSICAL PHENOMENA
RELATED TO POWER PLANT WASTE HEAT DISCHARGES:
LAKE MICHIGAN, 1973 AND 1974

by

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ABSTRACT

Maps are presented of the areas of surface thermal plumes from single or dual (identical) discharges at the Point Beach nuclear plant near Two Rivers, Wisconsin. The dual discharge situation produces far field plume areas more than double those of the single discharge situation. Such behavior is consistent with simple two- or three-dimensional plume model predictions. Simultaneous mappings of the Point Beach plumes, using remote aerial infrared scanning by the University of Wisconsin and EES's boat profiling method, were conducted to contrast the two measurement techniques. The methods were found to compare reasonably well except when lake surface conditions were very calm, at which time there was very little agreement between the two techniques. The dynamic character of the thermal plume jet regimes at the Point Beach, Waukegan, and Campbell power plants were monitored using in situ temperature and current measurements. Significant temperature oscillations on the order of 3-5°C (peak-to-peak) with a 140-sec period were observed at the Point Beach plant on several occasions. Oscillations with a 1200-sec period were also observed. The measurements at the Waukegan and Campbell plants show less evidence of systematic oscillatory behavior. The mechanism(s) causing such oscillations are speculated upon; however, they still remain an enigma.

The thermal plume from the Zion Nuclear Power Station (the first operational power plant on the Great Lakes using a high velocity, submerged offshore outfall) was mapped five times to characterize the effectiveness of submerged diffusers for promoting high initial dilutions with the ambient receiving water. Preliminary analyses of the data indicate that the Zion diffuser design is more efficient in reducing surface plume areas and temperatures per Mw of waste heat discharged than the conventional shoreline outfalls presently existing on the Great Lakes.

Measurements of vertical and horizontal eddy diffusivities were made at several nearshore areas in the vicinity of the Cook, Point Beach, and Campbell plant sites. Horizontal diffusivities were found to be unperturbed by plume stratification and interfaces within the far field. The values seem to be consistent with open lake values reported in the literature, when correlated as a function of a characteristic length scale. Moreover, the diffusivity values vary to the 1.1 or possibly the $4/3$ power of the characteristic length scale. Vertical diffusivities ($1-3 \text{ cm}^2/\text{sec}$) within the plumes and in the far field were found to be several orders of magnitude smaller than the horizontal values. These vertical values, however, cannot be considered insignificant with regard to far field plume dispersion, considering the large aerial size of the far field.

Lake current velocities measured near the Point Beach plant site show that near the surface (down to 3 m) transport is closely correlated to the local wind field. The time response of the currents is typically on the order of a few hours or less. Such currents are predominantly shore parallel; however, flow normal to the shoreline does occur. The near-surface current speed was found to be between 1-3% of the wind speed.

1.0 INTRODUCTION

This report summarizes most of the primary field activities of the Energy and Environmental Systems Division (EES) during the 1973 and 1974 field years on Lake Michigan as part of the Argonne National Laboratory Great Lakes Research Program sponsored by the U.S. Energy Research and Development Administration. The overall objectives, goals, and philosophy of the EES program have already been elaborated upon in earlier reports (ANL/ES-16, -25, and -32), and for that reason will not be repeated here to any significant extent. In brief, the EES portion of the Great Lakes Program has been to work toward a better understanding and a predictive capability of the physical impacts of discharging power-plant waste heat to any of the Great Lakes or any other large temperate lake. Biological aspects of the Great Lakes Program are being studied by the Radiological and Environmental Research Division of the Laboratory.

The activities discussed in this report span several topical areas, all of which, however, have relevance to developing a methodology for the a priori prediction of the temporal and spatial extent of thermal plumes resulting from heated discharges as a function of environmental and power plant design and operating conditions. Section 3 discusses plume temperature measurements acquired from the Point Beach and Zion Nuclear Power Plants, both located on Lake Michigan. The plume measurements at the Point Beach plant represent a continuation of similar studies already performed there for the past several years. The 1973 measurements show the effects of two-unit operation at the plant site; the second unit became operative in August 1972. However, not until 1973 did the opportunity to measure the combined plumes from both Point Beach units, each operating at nominally full power, first become possible.

The Zion plant, in contrast to the shoreline surface discharge of the Point Beach station, has offshore submerged outfalls. This generic, rather than specific, outfall design is being increasingly used by utilities for more recent power plant outfalls, since designs of this variety more readily meet restrictive state and federal thermal water quality standards. Little is known concerning the performance of submerged discharges in relation to surface designs. Therefore, in the next several years, EES is planning to devote a considerable amount of effort to mapping prototype plumes from such outfalls and to comparing the findings with the hydraulic model study investigations used to develop and predict the performance of such designs. An effort of this kind should provide the biologists with needed information concerning the behavior of submerged discharges and further furnish to the outfall design engineer some indication of the viability of hydraulic or analytical model predictions.

Section 4 discusses fluorescent dye studies performed at the D. C. Cook, Point Beach, and J. H. Campbell power plant sites in order to acquire knowledge of the magnitude of the lateral and vertical turbulent transport coefficients, which are important parameters in plume dispersal. Several field techniques were used; however, one of the most fundamentally useful, simple, and truly inexpensive methods for measuring lateral diffusivity was to take a series of aerial photographs of dye plume dispersal over a period of time and densitometrically analyze the film negatives to determine the

lateral coefficients. Knowledge gleaned from experimentation of this kind is essential for analytical model evaluations of plume dispersal, since the classic difficulty with most analytical (predictive) plume models is the inability to specify the turbulent transport parameters. Basically, the 1973 dye studies revealed that the range of diffusivities determined from the various measurement locations were within the range of values reported in the literature; however, this finding is not entirely satisfying since diffusivities in the literature range over three to four orders of magnitude. Secondly, the diffusivities measured internally, within the far field of a thermal plume, were found to be essentially similar to simultaneous diffusivity determinations outside the plume in the ambient water. This finding implies that preoperational site determinations of transport coefficients might be sufficiently suitable for use in predictive modeling. However, the suitability of using ambiently determined parameters is likely only for calculations in the far-field reaches of a plume where buoyant spreading probably plays only a minor role in plume dispersal. Lastly, it was found that the vertical diffusivities in the far-field plume were roughly comparable to those found within the ambient waters, the ambient values, expectedly and generally, being somewhat larger. The vertical diffusivities also were found generally to be two to three orders of magnitude lower in magnitude than the lateral values on the order of $1-3 \text{ cm}^2/\text{sec}$. This finding questions the foundations of many classical analytical modeling approaches treating the far-field plume as a two-dimensional horizontal problem. Considering the physically large size of the far-field portions of a thermal plume, even a small vertical diffusivity suggests a possibly significant vertical dispersal mechanism.

Section 5 outlines the results of a combined study with the University of Wisconsin, Marine Studies Center, in comparing near simultaneous thermal plume mappings, using the University's remote aerial infrared scanning system and EES's in situ boat measurement methods at the Point Beach Power Plant on five different occasions. Both techniques have several inherent advantages and disadvantages, such that the techniques complement each other. Thermal infrared scanning detects only surface temperatures; however, the data are acquired rapidly, requiring about a minute to scan an entire plume area. On the other hand, in situ boat methods are capable of measuring temperatures with depth, but the method requires about one hour to sufficiently define a plume. Other less obvious contrasts between the two methods are

presented within the section. There is good agreement, with only one anomalous exception, between the two methods with respect to plume features such as contour configurations, areas, centerline temperature decays, upwelling definitions, and other factors.

The results of two years of nearshore ambient current studies performed at the Point Beach plant are discussed in Sec. 6. The current measurements were made using in situ meters modified by EES for shallow water use. Typically, the nearshore currents were found to be shore parallel, flowing in either direction most of the time. Current speed was not normally constant for periods greater than several hours, and unidirectional flow periods lasted from one day to several weeks. Power spectrum analyses have been performed on the data, and the results are discussed within this section. One of the most pertinent findings to date of the nearshore current study has been the observation that the nearshore current velocities show a marked coupling to the wind velocities with a response time measured in the order of hours or less.

It is intended that the nearshore current studies will be continued and expanded in the forthcoming field years to gain an improved understanding of important phenomena governing currents, along with the turbulence associated with them. The goal of this program will be to produce a method for forecasting nearshore transport processes, which is not only important for understanding the behavior of thermal plumes but also for understanding the longer term and larger scale transport of chemical effluents.

Section 7 discusses the results of an initial effort to examine the possible dynamical character of heated discharges. Several investigators have noted the presence of hydrodynamic and thermal oscillations of measurable amplitude within thermal plumes. If present, such oscillations could cause ramifications in presently used boat techniques for measuring thermal plumes and in regulatory criteria governing heated discharges, which treat such discharges as a steady-state phenomenon.

To explore the possible existence of oscillatory temperature and velocity phenomena in heated discharges, temperature and current profiling instrumentation was positioned at fixed stations within the jet regime of several power plant discharges, and near-continuous recordings of current and temperature were made. The data were recorded in digital form on magnetic

tape, and a spectral analysis was run on the data. The results indeed sometimes showed significant temperature and current oscillations; however, their cause can only be speculated upon at present. Considerably more work needs to be done before the implications of such dynamical characteristics can be fully assessed in relation to boat-oriented thermal plume temperature measurements and certain federal and state thermal regulatory criteria.

It should be indicated at this point that Secs. 4, 5, and 7 were actually written for outside publication and, as such, each is basically autonomous. A bibliography of the EES program reports and presentations under the Great Lakes Research Program is presented in Appendix A.

2.0 FIELD SITE DESCRIPTIONS

Essentially all of the 1973 and 1974 field investigations were conducted at the Point Beach, Zion, and D. C. Cook nuclear power plant sites, all situated on Lake Michigan. A brief description of these plants is provided.

2.1 POINT BEACH NUCLEAR POWER PLANT

The Point Beach plant is located in the town of Two Creeks, Wisconsin, on the western shore of Lake Michigan. Figure 2.1 shows an aerial view of the plant. The plant is a two-unit station using pressurized water reactors. Each unit has a gross capacity of 523 MWe and a net capacity of 505 MWe. Lake water is brought from the intake into the forebay through two 4.3-m-dia pipes buried beneath the lakebed. The intake structure (see Fig. 2.2) is located 533 m offshore, where the lake is about 6.7 m deep. The structure is in the form of a hollow upright cylinder standing on the bottom. It has a steel piling superstructure having its annulus filled with limestone blocks. It has an outside diameter of 33.5 m and an inside chamber with a diameter of 18.3 m. The top protrudes about 1.9 m above the high-water level of the lake. Water enters the chamber through void spaces around the limestone blocks and through 0.8-m-dia pipes that penetrate the blocks in a ring at an elevation of 1.5 m above the lakebed. The outer ends of the pipes are covered with 0.03 x 0.05-m bar grating to prevent large fish or debris from entering the intake system. Horizontal water velocities entering the intake are not expected to exceed 61 cm/sec at full-flow conditions. The condenser cooling water flow rate is 25.1 m³/sec for full-power operation of each individual unit.

The water is returned to the lake about 50 m offshore through two 10.7-m wide discharge flumes (one flume per unit). Water depth in the flumes is about 4.2 m. The flumes extend in opposite directions at a 30° angle from the plant centerline that passes through the intake. Exit flow velocity varies across the flume as reported in ANL/ES-16 and -32, with average velocity of about 55 cm/sec. Temperature rise across the condensers is about 10.7°C. Unit 2 is geographically the northernmost unit, its outfall discharging in a northeasterly direction, and Unit 1's outfall consequently discharging in a southeasterly direction.

2.2 ZION NUCLEAR POWER STATION

The Zion station is located in northeastern Illinois on the western shore of Lake Michigan about 5.1 km south of the Illinois-Wisconsin line. An aerial view of the power station is shown in Fig. 2.3. The Zion facility consists of two pressurized water reactors, each capable of a net generating capacity of 1100 MWe. In the fall of 1973, only Unit 1 (the southernmost system) was operational.

Cooling water for the station's once-through cooling system is taken from Lake Michigan through a submerged intake crib located 792 m offshore in about 6.4 m of water (see Fig. 2.4). At maximum power the station's condenser cooling water flow requirement is $48.5 \text{ m}^3/\text{sec}$ per unit. Water enters vertically downward through two large diameter pipes near the center of the intake structure and through 45 small diameter ports spaced around the periphery of the structure. A "cap" is located above the large inlet pipes to prevent vortex formations in the inlet water. At full circulating flow, the maximum waterflow velocity into the offshore intake structure during nonwinter operation is about 75 cm/sec.

The cooling water leaves each unit through separate piping and is discharged to the lake via two submerged, high-velocity discharge structures (see Fig. 2.5). Each discharge structure is located 231 m offshore, spaced 47 m on either side of the centerline of the intake pipes. The top of each structure is about 2.4 m below lake level in about 3.7 m of water. Each structure consists of a rectangular box, with outlet louvers, located on the offshore end and on the side away from the intake pipes. The outlet from the discharge structure consists of 14 ports roughly 2.1 m wide by 0.9 m high. The ports form a 45° angle with both the intake lines and the shore. At maximum power operation, the average velocity of the water at the face of the outlet ports is 290 cm/sec. The temperature rise of the cooling water is 11.1°C . For five of the surveys conducted at the Zion station in the fall of 1973, Unit 1 was operating at about 50% of full-load capacity. For the survey on October 9, 1973, Unit 1 was operating at 8% of capacity.

2.3 DONALD C. COOK NUCLEAR POWER PLANT

The Cook plant is located near Bridgman, Michigan, on the southeastern shore of Lake Michigan. It is located about 18 km south of Benton

Harbor, Michigan. An aerial view of the plant is shown in Fig. 2.6. The two D. C. Cook nuclear reactors are nearly identical pressurized water units capable of a gross generating capacity of 1090 MWe each and a net capacity of 1054 MWe each. At present, neither unit is operational. Operation is scheduled to begin late in 1975 for Unit 1.

The condenser cooling water flow rate requirement at full power is about $45 \text{ m}^3/\text{sec}$ for Unit 1 and $59 \text{ m}^3/\text{sec}$ for Unit 2. The cooling water is taken from three intake cribs located about 685 m offshore in about 7.3 m of water. The intake cribs consist of smoothly rounded intake elbows set in the lake bottom, surrounded by sacked concrete and riprap to prevent erosion. Each elbow is further surrounded by an octagonal-shaped heavy structural frame, provided with bar racks and $20 \times 20\text{-cm}$ grating on all eight sides. The top of each frame is covered with a solid steel roof. At full flow, the intake water velocity through the grating interstices is about 39 cm/sec . Figure 2.7 shows a vertical view of a typical intake structure. The cooling water is discharged to the lake via two discharge pipes. These pipes are completely buried under at least two feet of sand along the lake bottom.

The cooling water discharges are located in about 5.5 m of water, 365 m offshore. The two outfall structures are about 91 m apart. Each discharge pipe is connected to an engineered structure that discharges slot-type jets in a generally offshore direction with an exit velocity of 4.0 m/sec . The Unit 1 structure has two discharge slots, each 9.1 m wide $\times$ 0.61 m high and 0.46 m above the lake bottom (see Fig. 2.8). The Unit 2 structure has three discharge slots, each 6.1 m wide $\times$ 0.84 m high and 0.53 m above the lake bottom. At full power, the temperature rise for the condenser cooling water is expected to be 12.1°C for Unit 1 and 9.3°C for Unit 2.

Fig. 2.1 Aerial View of Point Beach Nuclear Power Plant

Fig. 2.2 Schematic of Water-Intake Structure at Point Beach Nuclear Power Plant

Fig. 2.3 Aerial View of Zion Nuclear Power Station

Fig. 2.4 Schematic of Water-Intake Structure at Zion Nuclear Power Plant

Fig. 2.5 Schematic of Unit 2 Discharge Structure at the Zion Nuclear Power Station

Fig. 2.6 Aerial View of the Donald C. Cook Nuclear Power Plant

Fig. 2.7 Intake Crib and Screen-house for the Donald C. Cook Nuclear Power Plant

Fig. 2.8 Schematic of the Two-slot Discharge Structure for the Donald C. Cook Nuclear Power Plant

3.0 THERMAL PLUME MAPPING

A. A. Frigo, L. S. Van Loon, and C. Tome

3.1 INSTRUMENTATION, DATA COLLECTION, AND DATA REDUCTION

To adequately define a thermal plume in three dimensions, it is necessary to develop procedures and instrumentation that allow a large area to be covered rapidly while sampling temperature as a function of depth. Techniques for measuring plumes in this manner have been developed by the Great Lakes Research Program. A significant part of the initial effort for the project was the development of a semiautomated system for collecting field data and processing it into the form of isotherm mappings.

The present instrumentation system, mounted on a survey boat (see Fig. 3.1), makes it possible to measure temperature as a function of depth from a moving boat at about 900 known locations in about 1 hr, typically covering 10-11 linear km. The block diagram in Fig. 3.2 shows the essential components of the system. Figure 3.3 is a photograph of the system. In essence, the plume measurement system employs submerged temperature-sensing thermistors, digitizing and recording electronics, and positioning and depth-sounding instrumentation. Analog information proportional to temperature from seven YSI Series 700 linearized thermistors, which are positioned 0.5 to 3 m apart on a submerged boom, is sampled at time intervals measured by a solid-state clock and selected by the operator. These thermistors were specially made with a 0.6-sec time constant. The signals from the thermistors are digitized and displayed on light-emitting diodes, printed on paper tape, and recorded on magnetic cassette tape. Each time the thermistors are sampled, information from the clock, the depthfinder, and the positioning equipment is also displayed and recorded.

The boat operator uses the visual display to determine the position of the plume. The printed paper tape is a backup for the cassette tape and a place to record observations while the plume is being measured. The cassette tape, after transcription to an IBM-compatible tape, allows the data to be read into the computer. The printer is an Anadex Type DP650 capable of printing up to two lines of 21 characters per second. The cassette tape unit is an incremental digital tape recorder, Model 201, made by Memodyne. A tape reader is part of the laboratory gear that converts this cassette tape into an IBM-compatible

tape for computer processing. The depth finder is a digital Datamarine unit, which has been modified to provide binary-coded-decimal (BCD) output for interfacing with the display, tape, and printer units. The positioning system is a Motorola Mini-Ranger which consists of two shore-based transponders and a receiver/transmitter unit and range console on board the boat. Range information from each transponder is actually updated many times per second; however, the readings are displayed and printed at a preselected interval along with the other data. This information is translated by trilateration into boat position during computer processing. The entire system is powered by storage batteries and requires 6 A at 24 V dc. A high-efficiency commercial inverter (Flite-Tronics PC16 Aircraft Static Inverter) supplies the Mini-Ranger with 117 V ac.

The plume data are read onto the magnetic tape transcribed from the original cassette and, with additional calibration data, are used in a program developed to plot the temperature and bathymetric data as a function of position. Seven horizontal plots, representing data taken at seven depths, are plotted by a Calcomp Digital Incremental Plotter. The isotherms and centerlines are drawn by hand on this output. Vertical cross sections of the plume are obtained by identifying, on the horizontal sections, the boat transects of interest. Index numbers associated with the data points are identified and used as input for another computer program, which plots the data in vertical sections.

The plume measurement system described has been highly reliable. We have used this system under all normal conditions without serious malfunction. Problems have arisen, however, when the air temperature was below 0°C, since the boat is essentially open and some of the solid-state-circuitry temperature specifications are between 0 and 40°C.

Ambient conditions are routinely measured in conjunction with plume temperature mapping. Ambient lake current is measured with a Bendix Q-15 geomagnetic ducted-impeller, current meter. Wind speed and direction are measured with a hand-held anemometer on the boat and by a shore-based Meteorology Research, Inc. (MRI), portable meteorological station. Air temperature, humidity, lake conditions, etc., are also measured with each plume. Table 3.1 lists the instrument specifications.

Dye dispersion studies of eddy diffusivity (see Sec. 4) were conducted during 1973. The instrumentation used included a Model III Turner Fluorometer. This instrument was interfaced with the data-acquisition system described above and with a Moseley Model 7101B strip-chart recorder. Used in this manner, both an analog and a digital record were produced.

For the 1973 field year, three Braincon Type 381 current meters, modified at Argonne and using an Argonne design, were used for the in situ lake current measurements. The modification consisted of changing the speed-sensing element from a Savonius rotor to a ducted impeller in order to null out the oscillatory wave motions likely to be present in the relatively shallow nearshore areas of interest to the program. The Braincon current meter produces records on 16-mm film, which are reduced by an image processing computer designed by Argonne's Applied Mathematics Division. The modified meters were calibrated using the Northwestern University tow tank.

3.2 INTRODUCTION TO THE THERMAL PLUME DATA

The results of the thermal plume measurements at the Point Beach Nuclear Power Plant and the Zion Nuclear Power Station follow. The data are presented in sequence according to date. The thermal plume drawings show the discharge and intake structures, the shoreline, and the lake bottom, where applicable. In general, for the Point Beach plant, each plume data set consists of a surface isotherm plot, which also contains in tabular form, pertinent plant and ambient meteorological and lake data; six additional temperature plots corresponding to the 0.5-, 1.0-, 1.5-, 2.0-, 2.5-, and 3.0-m depth levels; and vertical cross-sectional temperature plots, which are specified on the surface isotherm plot as A-A', B-B', etc. The presentation is similar for Zion, except that there is no surface drawing for the Zion studies (due to a faulty thermistor probe). All the operational and environmental information presented on the surface drawings for the Point Beach surveys is presented on the 0.5-m level drawing for the Zion studies.

Values of ambient water temperature range, as a function of depth, are contained in Table 3.2. The ambient temperature range reported was selected as being representative of the lowest temperatures peripheral to the plume. Generally the lake area immediately upcurrent from the plume was used for definition purposes; however, this was not always possible, particularly

under zero-current conditions. The selection of an ambient temperature or ambient temperature range remains as an enigma to our group, as we are sure it is to every field group. The time and location of current measurements are listed in Table 3.3, along with the respective measured values for the Point Beach and Zion locations. Where a thermistor malfunctioned, some plume data sets may be missing from the horizontal plot corresponding to that thermistor depth level. Also, in several vertical cross-sectional temperature plots, and in some horizontal plots, blocks of data appear to be missing. The reason for these gaps is that, in some situations, the level of the temperature boom had to be raised to avoid possibly catastrophic interaction with the lake bottom. In final explanation of the thermal plume plots, the barely legible dots in the figures represent actual temperature values at the location indicated and hence the boat path. The data are not legible because, for presentation purposes, the figures were substantially reduced from much larger working drawings. The bold dots with accompanying temperature values were placed on the figures to yield readable representative temperatures corresponding to particular locations.

Both the horizontal and vertical sections of the plume isotherms shown in the figures were drawn by hand; thus some degree of intuitive judgment and latitude in interpolation was exercised. In most cases, the individuals who participated in plume contouring attempted to interpolate linearly between points. Since it was not always possible to do so, some subjectivity is inherent in the data. A more detailed explanation of this method of plume drawing, along with several others that were tried, appears in ANL/ES-32. Subjective hand contouring was considered the best approach for plume isotherm construction. The top-layer isotherms were constructed first, the lower-depth isotherms followed in consecutive order. The personnel involved in temperature contouring always tried to factor into each succeeding depth level the insight and trends established in the previous levels so that a more consistent set of plume data could be obtained.

The vertical cross sections were drawn independently of the horizontal sections, and close inspection of the vertical and horizontal plots reveal some minor differences between the two sets in relationship to isotherm positions. Part of the problem is that the vertical sections were constructed by unfolding into a straight line the point-to-point distances. If there was some minor position error due to range-equipment noise

from one point to another, this error would then be incorporated into the vertical section plotting and would tend to increase the distances between locations designated by the cross-section markings. The cross sections for presentation were chosen to be closely representative of centerline normal sections proceeding away from the discharge.

The plume centerlines designated on the surface drawings for Point Beach and the 0.5-m level drawings for Zion are quite subjective. When the temperatures are not distributed symmetrically in the plume, the term "centerline" loses its meaning. In the near field (the jet regime), where the plume configuration is often tongue-shaped, the centerline is generally drawn to divide the plume symmetrically. Away from the immediate near field, the plume configuration can take an untold number of shapes, making it almost impossible to define a unique centerline. The location for the centerline in these reaches of each plume was generally chosen to be the locus of maximum temperatures. Where that was not practical, the centerline was drawn to bisect the area of the highest isotherms. The centerlines should therefore not be interpreted too literally within these somewhat remote plume regimes.

Several general comments seem appropriate regarding the ambient lake current and meteorological data presented in block form on the highest-level plume drawing. The meteorological data reported were acquired from the boat, using a portable Weather Measure three-cup anemometer held about 2 m above the water surface. Wet- and dry-bulb temperatures were measured using a conventional sling psychrometer. The important fact here is that these meteorological measurements were typically gathered over a 5-min period before and after a plume data run, which generally required an average of 60 to 80 min to complete. Therefore, the meteorological conditions recorded before and after each plume measurement period might not have been representative of the "mean" conditions during the actual plume measurement period. Readers interested in using more representative values for wind speed and direction at Point Beach should therefore refer to Sec. 6 dealing with nearshore current studies, which summarizes in greater detail prevailing wind speed and direction data collected during and after each plume measurement period. The wind data presented for Zion represent an "average" of data collected from the boat, as discussed above, along with data collected from a portable recording station.

Basically, the same general comments apply for the ambient current values reported for each surface plume. These current values were obtained either before or after, or occasionally both before and after, each plume measurement period. Table 3.3 lists the pertinent data regarding the location, date and time, and current conditions obtained for each plume data set. In most cases, the ambient current data were taken on the upcurrent side of the plume to avoid possible bias due to the discharge dynamics of the plant effluent itself. Because lake currents are both spatially and temporally variable, it is difficult to define an "ambient current" from a single measurement, as is demonstrated by the fact that some of the before-and-after ambient current values reported in Table 3.3 for the same data show significant differences. In such cases, the current values reported on the highest level plume drawings represent average values of before-and-after conditions or the particular reading thought to be more closely representative of the measurement period or more representative of the plume position. Where there was no clear choice between before-and-after conditions, a range is presented.

One final comment is made regarding the measurement technique. As discussed earlier, the temperature data were collected from a moving boat equipped with a thermistor boom that allowed temperature measurements to be made to a depth of 3 m. This system was found to be very good for collecting temperature data to define the Point Beach plume. Unfortunately, the plume from the submerged discharge at the Zion plant was usually deeper than 3 m. Hence, it was not possible to completely define the Zion plume in the vertical direction. Future studies at the Zion plant will use a redesigned method of temperature measurement so that the plume can be completely defined.

3.3 POINT BEACH THERMAL PLUMES

3.3.1 Point Beach Nuclear Power Plant: May 5, 1973

A temperature survey was conducted during the afternoon of May 5. During this survey, only Unit 1 was operational with a reported load of 366 MWe. The MRI portable meteorological station could not be installed until 1300 hr on the day of the survey; hence the data until this time are incomplete. However, the wind on the previous day was northerly at 8-9 m/sec (wave height, 1 m) with the wind diminishing and the lake calming by the evening hours. During the plume mapping, winds were from the south at

6-7 m/sec, skies were cloudy, and waves were running 0.3 m (see Fig. 3.4). Lake current near the surface was 14 cm/sec at 340°. (See Sec. 6 for meteorological data and Table 3.3 for lake current data.)

Results of the plume mapping are shown in Fig. 3.5(A-F). The isotherm maps for the 1.5- and 3.0-m levels are missing due to thermistor failure. The plume moved northward in response to the ambient current. Ambient current was relatively constant from the surface to the 2-m level. Below 2 m, the speed dropped with increasing depth. Ambient water temperature was constant to the 3-m depth, indicating well-mixed water.

Table 3.4 shows plume areas as a function of isotherm and depth. The areas were obtained from planimeter measurements taken on each horizontal section. The table is inclusive of all plumes measured at Point Beach and Zion during 1973.

3.3.2 Point Beach Nuclear Power Plant: May 10, 1973

On the morning of May 10, a temperature survey was conducted at Point Beach. Both units were operating; however, Unit 1 was at about 71% of full power; Unit 2, 95%. The difference in power levels is also noted as a 2°C difference in outfall temperature between Units 1 and 2. The MRI portable meteorological station had been in place on the intake structure since May 5, so that meteorological data were available for the 24 hr prior to the temperature survey. On the previous day, the wind was generally southeast at 4 m/sec. Through the night, however, the wind shifted through south to west and wind speed increased to about 10 m/sec. The air temperature also increased from about 9°C on May 9 to about 15°C during the time of the temperature survey. (See Sec. 6 for more complete wind records.) The lake surface conditions during the time of the survey were calm with 0- to 0.25-m waves (see Fig. 3.6). Lake current near the surface (to 2 m) was about 12 cm/sec at 010 degrees (see Table 3.3).

Figure 3.7(A-H) shows the results of the temperature survey. The double plumes are pushed north by the ambient current, and after merging they drift straight offshore as if the offshore current was not as strong as that nearer the shoreline. The south edge of the plume has a well defined interface with ambient water. There is some puddling south of the plant of water 1-2° above ambient that does not appear to be associated with the plume. This may be an indication of some surface heating.

3.3.3 Point Beach Nuclear Power Plant: June 5, 1973

For the June 5 temperature survey, both units of the Point Beach plant were very near full power output. This temperature survey was preceded by light southerly winds on June 4. The winds increased through the night to moderate on the morning of the survey and remained southerly. Air temperature was steady on June 4 at about 15°C, then rose on June 5 reaching about 23°C during the temperature survey (see Sec. 6). Sky conditions were overcast and the lake was calm with a northerly current of about 5-6 cm/sec. See Table 3.3 for lake current measurements and Fig. 3.8 for an indication of the ambient lake surface conditions.

Results of this temperature survey are shown in Fig. 3.9(A-H). The plume is influenced by a northward current and drifts to the north. There is a possible slight upwelling as indicated by cooler water in some areas near-shore. The ambient water temperature appears to be almost constant with depth (see Table 3.3). There is no well defined interface between the plume and ambient water. The plume areas for this survey appear to be generally larger than previous plumes, which should be expected, as this is the first survey conducted with the plant running at full output during calm lake conditions.

3.3.4 Point Beach Nuclear Power Plant: June 6, 1973

Both units were running at full power during the temperature survey conducted on June 6, allowing another double plume to be mapped. The winds diminished during the evening of June 5 and continued light and variable through the night and all day June 6. At the time of the survey, winds were 1-3 m/sec from the west-northwest. The skies were clear and lake conditions were calm with no waves (see Fig. 3.10). A check on lake current near the plant at the 1-, 2-, and 3-m depths indicated no measurable current (see Table 3.3). The results of this survey are shown in Fig. 3.11(A-H). This survey indicates a very large floating plume on the surface due to the stable lake conditions. Isotherm areas decrease rapidly with depth. Ambient temperatures decrease from about 10°C on the surface to about 8°C at the 2.5-m level. The plume drifts toward the north; there is no well defined interface with ambient water. Due to a thermistor malfunction, the 3.0-m isotherm level is missing.

An infrared survey was conducted at the same time that this survey was being run. Results of the two survey methods are analyzed in Sec. 5.

3.3.5 Point Beach Nuclear Power Plant: June 7, 1973

The survey on this date was done while both units were once again near full capacity. Infrared overflights were also conducted simultaneously on this date, and the results are discussed in Sec. 5.

Local winds began increasing during the evening of June 6, changing from light to moderately strong and switching from southerly to westerly by late morning on June 7. The air temperature on June 6 reached 28°C, and then dropped to 15°C through the night and climbed to 26°C by the time of the temperature survey. The lake conditions were choppy with 0.3-m waves (see Fig. 3.12) under cloudy skies.

The results of this survey are shown in Fig. 3.13(A-H). Some near-field data are missing for the 0.5-m map due to a data reduction and plotting problem. The plume on this date is similar to the plume mapped on the previous day, except for a slight southerly drift. Lake currents are not similar, however (see Table 3.3). The currents on this day are interesting in that the direction of flow is east-southeast at the surface (to 1 m) and is west-southwest below that depth to 5 m. (See Sec. 6 for wind and current correlations.)

3.3.6 Point Beach Nuclear Power Plant, June 12, 1973

The June 12 temperature survey was preceded by nearshore current profiling at four stations with bottom depths of about 3, 7, 9, and 12 m (see Table 3.3).

The temperature survey was done while both units of the plant were at full power. The wind on the preceding day was moderate from the south and switched to southwest and remained moderate on the morning of the survey. The wind switched to north at the time of the temperature survey and continued moderate with an air temperature of about 15-20°C. The lake currents (see Table 3.3) were southerly and were higher at the surface than at depths below 1 m. Lake conditions are listed as calm with waves less than 0.3 m.

The results of this survey are shown in Fig. 3.14(A-H). The plume is pushed along shore to the south of the plant and remains nearshore until

it disperses with the ambient water. Ambient water at the surface is hard to define, apparently due to the onshore drift of the plume water. Although the currents at the surface are stronger than at several meters below the surface, the isotherm maps at the lower levels generally have the same shape as the surface plot.

3.3.7 Point Beach Nuclear Power Plant: August 10, 1973

The temperature survey on this day preceded an eddy diffusivity study which is discussed in Sec. 4. There was also an infrared overflight conducted during the afternoon hours (see Sec. 5). Both units were at full power during these studies.

The weather conditions preceding this plume were steady, with winds light to moderate from the west. Air temperature during the afternoon hours approached 30°C; skies were partly sunny, and seas were choppy with 0.3-m waves. Ambient lake current was not obtained for this survey; however, continuous current records for this period are presented in Sec. 6. Lake conditions are shown in Fig. 3.15.

The results of the survey are not as complete in the far field as others presented here since the intent of this survey was to determine the direction of plume drift before beginning the dye dispersal studies.

Results of the survey are shown in Fig. 3.16(A-G). The plume is nearly stagnant with some indication of upwelling present. Some 11°C water is present offshore, which is not included in areas calculated for that isotherm. Due to lack of data and upwelling conditions, ambient temperatures specified may be misleading. The 2.5-m isotherm map is missing as that data channel of the acquisition system was interfaced to the fluorometer used during the dye dispersal studies.

3.3.8 Point Beach Nuclear Power Plant: August 23, 1973

This survey was run prior to a dye dispersal study conducted in the afternoon of August 23 (see Sec. 4). Once again, both reactors were at full power.

The winds in the preceding 24 hr were moderately strong from the south, but slackened and switched to the west at the time of the survey.

Due to a current meter malfunction, lake current was not measured. However, current information obtained from in situ instrumentation (see Sec. 6 and Table 3.3) shows a shore-parallel, northerly current at about 3 cm/sec. Lake conditions are shown in Fig. 3.17. Boat observations list the sky condition as 100% overcast and the lake calm with less than 0.3-m waves.

Isotherm maps of this survey are presented in Fig. 3.18(A-H). The plume has a noticeable interface on the upcurrent side and exhibits a northward drift. This survey is not as thorough as others done during this field year because it was done hastily as an indicator of plume behavior prior to conducting dye studies as was the August 10 plume mapping.

3.4 ZION THERMAL PLUMES

Before presenting the results of the Zion temperature surveys, a few words of explanation concerning the plant and meteorological data are necessary. The plant load, intake temperature, and discharge flow rate data were obtained from Commonwealth Edison Co. personnel. The discharge flow rate is expressed in terms of the number of circulating water pumps in use, 3 per unit. These pumps are nominally rated at 15.5 m³/sec. Actual flow could not be calculated since discharge valve position and pump head were not available. The listed outfall temperature value represents the highest temperature measured by EES while the survey boat was in the vicinity of the submerged discharge. The wind data represent a combination of measurements made on board the survey boat and data gathered near the plant using an MRI meteorological station. All other data were gathered from the survey boat.

3.4.1 Zion Nuclear Power Station: September 19, 1973

The first two temperature surveys at the Zion station were conducted on September 19. The morning survey provided synoptic temperature data to construct isotherms to within 0.5°C of the ambient temperature for the entire plume; the afternoon survey concentrated on collecting temperature data in the near-field region of the plume. Although the Zion plant employs a submerged discharge structure, it was easy to locate the plume visually, particularly in the near-field region because of the turbulence generated at the lake surface near the discharge. In the discharge area for all the

surveys at the Zion station discussed in this report, lake conditions were rough, making it an exciting experience to collect data near the discharge with a small boat.

For both surveys, the lake was slightly choppy, with waves increasing from 0.5 m for the morning survey to 1.0 m for the afternoon survey. Wind direction was out of the west-southwest and was constant from the previous afternoon and night, averaging 3.8 m/sec. Wind speeds began to increase at around 0600 hr on September 19 reaching the values reported for the temperature surveys. The air temperature remained fairly stable from the previous day with no abrupt changes occurring.

The results of these two surveys are shown in Figs. 3.19(A-H) and 3.20(A-H). The plume was driven north by a northward shore-parallel current. The current was measured before and after the surveys at various depths to the bottom (see Table 3.3). Current speed increased slightly during the day; current direction remained relatively constant. For both surveys, as seen in Table 3.2, the ambient water temperature was well defined. Constancy with depth prevailed not only in the ambient water temperature but also in plume temperature, as noted by the almost vertical isotherms in the vertical cross sections and in plume areas contained within the lower depth temperature isotherms (see Table 3.4).

3.4.2 Zion Nuclear Power Station: October 9, 1973

A temperature survey was conducted during the early afternoon of October 9. Unfortunately, not much information concerning the thermal plume could be gleaned from the data since the power level was being brought back up after being reduced to zero during the early morning hours. During the survey, the plant load was only up to 88 MWe. Results of the survey, which are provided for completeness, are given in Fig. 3.21. For this survey, the wind was out of the southeast at 2.8 m/sec. Lake conditions were marked by a slight swell of 0.3 m. The ambient lake current was measured as a function of depth after the survey. The results given in Table 3.3 indicated a fairly strong northward flowing current in the top 2 m, with the current speed dropping to a very low value below the 2-m level. The ambient temperature listed in Table 3.2 was well defined and constant with depth.

3.4.3 Zion Nuclear Power Station: October 10, 1973

The thermal plume was mapped twice on October 10 -- once in the late morning and early afternoon and again later in the afternoon. Lake conditions were calm for the first survey, but choppy for the second. Lake conditions continued to roughen during the day. At about 1400 hr, the lake surface looked as shown in Figs. 3.21 and 3.22. Winds were light the previous night and out of the south-southwest. Wind direction shifted during the first temperature survey to south-southeast with an increase in wind speed. This south-southeast wind caused the lake conditions to become rougher as the afternoon progressed and increased the height of the waves, which were running toward the northwest. Ambient lake current was measured before the first survey, but current could not be measured later in the day due to the worsening lake conditions. A strong northerly shore-parallel current was measured. Results of the current measurements as a function of depth are given in Table 3.3. The submerged discharge, which was in operation on October 10, directs the discharge water in a southeasterly direction. The high velocity discharge combined with the northerly current and northwesterly heading waves caused lake surface conditions to be extremely rough in the near-field region of the Zion thermal plume. Figure 3.23 is a photograph of the discharge as taken from the survey boat while in calmer lake water, and Fig. 3.24 is a picture taken from the boat while in the near-field region of the plume. Ambient air temperature remained fairly constant from the previous day.

Results of the plume mappings are shown in Figs. 3.25(A-H) and 3.26(A-G). The plume was driven north by the northward current. A pronounced temperature interface was apparent on the upcurrent side of the plume. Plume areas in general decreased slightly with depth and were similar for the two surveys. The result of the temperature survey conducted later in the afternoon is interesting because the plume bifurcates. As seen in Fig. 3.26A, the strong northward current with the wave action (directly opposing the discharge flow) apparently split the plume into two warmer regions with a cooler region between them. The double centerline indicates the center of the two higher temperature regions. Ambient water temperature was constant with depth for both surveys, although the ambient temperature was slightly higher for the afternoon survey. A strong upwelling situation existed on this day with lake water temperature varying from 13.5 to 14.5°C at about

150 m from shore to 16.1°C at 1700 m from shore. This situation can be seen in Figs. 3.25A and 3.26A by the higher temperature offshore isotherms. Since the temperature measuring system used for collecting the plume data allowed temperature to be measured only to the 3.0-m level, temperature profiling was also conducted near the discharge using a probe that could be lowered over the side of the boat. Results of the profiling are presented in Table 3.5. The data are listed according to increasing distance from the submerged discharge. For measurements made closest to the discharge, variations in temperature occur with depth, the highest temperature occurring between the 2- and 3-m levels. The next two profiles indicated that the plume was fairly well mixed to the bottom. The last profile, which is the farthest from the discharge, indicates that the plume is beginning to float with temperatures ranging from 17.4°C at the 1.0-m level to 14.8°C at the 5.0-m level.

3.4.4 Zion Nuclear Power Station: October 11, 1973

The temperature survey was conducted during the morning of this day. Lake conditions were moderately rough before the survey and became rougher as the morning progressed. In the immediate area of the discharge, the lake conditions were extremely rough. Wind direction shifted from southerly during the previous night to south-southeasterly during the plume mapping. Wind speed began to increase in intensity at 0800 hr and continued to increase during the plume mapping. Ambient air temperature remained relatively constant from the previous night.

Results of the temperature survey are shown in Fig. 3.27(A-G). As on the previous day, the plume was driven north by a strong northward, shore-parallel current (see Table 3.3). A pronounced temperature interface occurred on the upcurrent side of the plume. An upwelling situation was present as on the previous day. Ambient temperature was once again well defined and constant with depth. The plume was similar in direction and areal extent to the plumes mapped on the previous day. Plume areas that decreased slightly with depth are listed in Table 3.4.

3.5 COMPARISON OF ISOTHERM AREAS OF SINGLE AND DUAL DISCHARGES AT THE POINT BEACH NUCLEAR POWER PLANT

During the 1973 field year, Point Beach Unit 2 came on line at full power and offered an opportunity for a comparison of "dual" thermal plumes with

single plumes. Such a comparison for identical ambient conditions was expected to reveal how adjacent thermal plumes interact, and it would help to evaluate model predictions for future plant capacity additions at other locations. Dual plumes were mapped for this purpose on four days in the summer of 1973.

In the close-in near field at Point Beach, where the separate jets of dual plumes have not grown to a size that they approach each other spatially, there would be no important mechanism for communication between jets, especially under stagnant lake conditions. Hence, for these conditions, one expects the higher temperature isotherm areas for dual plumes to be twice those of single plumes. On the other hand, in the distant far field, where the two plumes have combined, one expects to see no "imprint" of the discharge geometry (i.e., dimensions, exit Froude No., dual or single discharge) on the nature of the thermal plume. Hence, a dual plume consists of twice the effluent volume of a single plume, and this alone should determine any differences in rates of dispersal and cooling. In this regime, heat transfer to the atmosphere is typically a small portion of the plume cooling as compared with mixing with the ambient water. When the mixing is modeled as a two-dimensional diffusion process with a constant diffusivity, one finds that isotherm areas increase as the cube of the heat source strength or effluent rate.¹ This would indicate dual plume isotherm areas eight times those of single plumes. If three-dimensional diffusion with a constant diffusivity is appropriate, Edinger and Polk¹ show isotherm areas varying as the $3/2$ power of source strength, making the dual plume areas 2.8 times the single plume areas. The eddy diffusivity is not expected to be constant over the entire plume, and is certainly not the same for horizontal and vertical directions. Hence, these two theoretical relationships are cited primarily to set the experimental measurements into a frame of reference. The Asbury-Frigo empirical correlation² would indicate an approximately linear proportionality between source strength and isotherm area, giving a factor of two between the areas of single and dual plumes. Hence, far-field area changes anywhere from 2 to 8 are suggested by the several forecasting means at hand for identical ambient conditions.

Thermal plume isotherm areas measured with both Point Beach units operating in 1973 (dual plume operation) are compared with 1971 and 1972

measurements when only one unit of the plant was operating (single plume operation), in Figs. 3.28, 3.29, and 3.30. Only four dual plume cases are available. These are matched with 1971 and/or 1972 single plume cases on the basis of similarity of the more salient parameters:

- a. Current speed and direction.
- b. Wind speed and direction.
- c. Ambient wave heights.

Ambient conditions could not be matched perfectly within these few parameters. A number of other parameters such as ambient eddy diffusivity, ambient water and air temperatures, and variability of conditions during the measurements are also important effects. These could not be included in the matching because either they were not measured (e.g., eddy diffusivity), or they were difficult to quantify (e.g., variability of conditions), or there were no days during which these parameters were identical for dual plume and single plume measurements (e.g., ambient air and water temperatures).

In Figs. 3.28, 3.29, and 3.30, error bars on the data points indicate the measured range of ambient water temperatures at the time of the plume measurement when reflected in the θ values. The lowest observed value was arbitrarily selected for calculating the excess temperature θ (isotherm temperature excess over ambient water temperatures) and the excess temperature ratio θ/θ_0 . If the highest observed ambient temperature rather than the lowest had been used to determine θ and θ_0 , the curves in Figs. 3.28, 3.29, and 3.30 would pass through the lower extremes of the error bars. In Fig. 3.28 the error bars are relatively small; whereas in Figs. 3.29 and 3.30, they are large by comparison with the differences between the curves.

In Fig. 3.28, where the ambient conditions are low northward currents, moderate northward winds (winds out of the south), and calm lake surface, the dual plume areas, for a given excess temperature ratio, are consistently larger than the single plume areas. There is a factor of two between them in the near field $\theta/\theta_0 > 0.75$, and a factor of four to ten in the far field $\theta/\theta_0 < 0.40$. For $0.5 < \theta/\theta_0 < 0.7$, the dual and single plume areas are not much different in this comparison, a fact that might be attributed to plume variability during the measurements or the influence of unaccounted-for differences in the ambient conditions. No mechanism is recognized for producing equal areas in this intermediate region.

In Fig. 3.29, the comparison is for cases in which there was virtually no ambient current, little or no wind, and a very calm lake surface. Large variability existed in the measured ambient water temperature as evidenced by the large error flags on all but the May 18, 1972 single plume data. In this figure, the area of the dual plume case actually drops below the areas of each of the four single plume cases selected. This is believed to be the result of the above-mentioned unaccounted-for variables.

Figure 3.30 compares a dual plume curve with three single plume cases for conditions of moderate southward currents and winds (winds out of the north) and moderately calm lake. Uncertainty in the ambient water temperature is large for the dual plume case. The dual plume isotherm areas exceed the single plume areas in the near field and far field, but are surpassed in the intermediate field for the October 28, 1971 and May 20, 1971 cases. Again, this must be due to imperfect matching of conditions or other unaccounted-for variables.

In Fig. 3.31, the data for all three cases are plotted on one graph. The single plume data exhibit much more scatter than the dual plume data. The single plume data were collected in every case when only the south outfall was operating. Discharge water from this plume enters the lake at about a 60° angle to the shoreline south of the plant. Hence, the ambient lake current will affect the plume differently, depending on whether its direction is north shore-parallel or south shore-parallel. For example, a south flowing current would drive the plume from the south discharge more easily against the shoreline than a north flowing current. Hence, entrainment on the shore side of the plume is more easily cut off with a south current than a north current. Areas may vary because of this. On the other hand, when both units are operating, the discharge is symmetrical with respect to the lake. Hence, the plume should behave the same when subjected to either north or south shore-parallel currents of similar magnitude. The results of plume measurements indicate that this is true. Thus, there is less scatter in the data displayed in Fig. 3.31 for dual plumes than for single plumes.

In summary, comparisons have been made between a limited number of dual plumes and single plumes where the more salient ambient conditions are matched approximately. The dual plume had isotherm areas about double those of single plumes in the jet regime, where the two jets of the dual discharge

have not yet interacted, and therefore, behave as two isolated jets. In this regime, the behavior of the plume is only weakly dependent on ambient conditions. In two of the three comparisons, the far field isotherm areas of the dual discharge plumes are considerably more than double the areas of the corresponding single discharges. In all comparisons, the areas in the intermediate field isotherms are about the same for the dual and single discharges, a finding that is surprising. This last observation is tentatively attributed to the unaccounted-for variabilities in the measurements. The authors recognize no mechanism that would cause the intermediate region of a dual plume to systematically equal that of the corresponding single plume.

TABLE 3.1. Instrument Specifications

Instrument	Sensor	Accuracy	Threshold	Range	Resolution	Time Constant	Remarks
Bendix Q-15 Current Meter	Speed; Impeller	±4% of full scale	0.04 knot	0-1.0 knot; low scale 0-5.0 knots; high scale	0.02 knot; low scale 0.01 knot; high scale		
	Direction; vane	±12°	-	0-360°	5°	2-30 sec; selectable	Vane has adjustable length; 0.3-3.0 m
Temperature Measurement System	Thermistor	±0.2°C	-	0-50°C	0.1°C	0.6 sec	Thermistor YSI Series 700 specially made with 0.6 sec + mc constant
Motorola Mini-Ranger	-	±3 m	-	0.1-35 km	1 m	-	Accuracy applied to each range measurement. System accuracy varies with position of transponders rela- tive to boat. For most measurements, ±3 m applies
Data-Marine Depth-Sounder	Model 2301 (Transom Mounted)	± ft; low range	2 ft; low range	2-99 ft; low range	1 ft	-	
		± fathom; high range	2 fathoms; high range	2-99 fathoms; high range	1 fathom	-	
MRI Meteorolo- gical Station	Speed; 3 cup anemometer	±2%	0.75 mph	0.75 - 100 mph	0.2 mph	18 ft (response distance)	
	Direction; vane	±5°	0.75 mph	0.75 - 100 mph	5°	8 ft (response distance)	
	Temperature; Bi- metallic coil	±3°F	-	-30° + +120°F	1°F	unknown	
	Clock	±60 sec/24 hrs	-	32 days	-	-	Clock specifications are open to question
Turner Fluorometer	-	-	-	0-100 arbitrary units	.25 unit	-	Comparison type instrument must be calibrated with known standards. Sensitivity changed by neutral density filters in the light path
Braincon Current Meter Type 381	Speed; ducted impeller	±3% fs	.04 kts	0-5 kts	.01 unit	-	
	Direction; mag- netic compass	±1%	-	0-360°	2°	-	

Conversion factors:

1 knot = 0.514 m/sec; 1 mph = 0.447 m/sec; 1 ft = 0.305 m; 1 fathom = 1.829 m; °C = (°F - 32) 5/9

TABLE 3.2. Ambient Water Temperature Data

Location	Date of Survey (1973)	Time of Survey	Ambient Water Temperature (°C)						
			Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
Point Beach	May 5	1445-1604	7.2-8.2	6.7-7.4	6.7-7.4	NA	6.6-7.4	6.4-7.3	NA
Point Beach	May 10	0925-1139	6.4-7.8	6.4-7.8	6.4-7.8	6.3-7.7	6.3-7.7	6.4-7.5	NA
Point Beach	June 5	1150-1400	7.4-7.9	7.3-7.9	7.2-7.9	7.2-7.9	7.2-7.9	6.8-7.9	6.8-7.9
Point Beach	June 6	1120-1255	9.6-11.2	9.5-11.2	9.4-11.0	8.4-10.3	7.9-9.2	7.8-8.3	NA
Point Beach	June 7	1102-1230	7.7-8.4	7.0-8.0	7.0-8.0	7.0-8.0	7.0-8.0	7.0-7.9	6.8-7.8
Point Beach	June 12	1515-1647	10.1-11.6	9.6-10.6	9.4-10.3	9.2-10.1	9.2-10.0	9.1-9.6	9.1-9.6
Point Beach	Aug 10	1416-1500	7.5-7.8	7.4-7.8	7.2-7.8	7.0-7.8	7.0-7.8	NA	6.3-7.3
Point Beach	Aug 23	1156-1304	17.6-17.9	17.7-17.9	17.7-18.0	17.7-17.9	17.7-17.9	17.7-17.9	17.6-17.9
Zion	Sept 19	1041-1212	NA	16.5-16.9	16.5-16.9	16.5-16.9	16.4-16.9	16.4-16.9	16.4-16.9
Zion	Sept 19	1320-1357	NA	16.8-16.9	16.9	16.9	16.8-16.9	16.8-16.9	16.7
Zion	Oct 9	1227-1303	NA	14.9-15.5	14.9-15.5	14.9-15.5	14.8-15.4	14.7-15.4	14.7-15.3
Zion	Oct 10	1020-1237	NA	13.5-14.5	13.5-14.5	13.5-14.5	13.5-14.5	13.6-14.5	13.5-14.5
Zion	Oct 10	1528-1632	NA	14.5-15.3	14.5-15.3	14.5-15.3	14.5-15.3	14.4-15.2	14.4-15.2
Zion	Oct 11	1020-1115	NA	13.2-14.0	13.2-14.0	13.3-14.0	13.2-14.0	13.2-14.0	13.1-14.0

TABLE 3.3. Ambient Lake Current Data

Location	Date (1973)	Time	Lake Location ^a		Bottom Depth (meters)	Measurement Depth (meters)	Current	
			x (meters)	y (meters)			(cm/sec)	Direction (degrees)
Point Beach	May 5	1640	+1318	+ 423	6.5	0.5	13.9	340
		"	"	"	"	1.0	17.8	345
		"	"	"	"	2.0	16.1	350
		"	"	"	"	3.0	12.2	345
		"	"	"	"	4.0	9.4	335
		"	"	"	"	5.0	8.9	330
Point Beach	May 10	0855	+1668	+ 560	7.0	0.5	11.4	010
		"	"	"	"	1.0	12.5	350
		"	"	"	"	1.5	9.2	015
		"	"	"	"	2.0	4.7	020
		"	"	"	"	2.5	8.1	360
		"	"	"	"	3.0	3.1	360
		"	"	"	"	4.0	3.1	345
		"	"	"	"	5.0	2.5	345
Point Beach	June 5	1050	+ 941	+ 580	7.6	0.0	5.6	353
		1723	+ 259	+ 618	8.2	0.5	11.1	110
Point Beach	June 5	"	"	"	"	1.0	8.3	130
		"	"	"	"	1.5	10.0	150
		"	"	"	"	2.0	5.6	165
		"	"	"	"	2.5	2.8	180
		"	"	"	"	3.0	2.8	180
		"	"	"	"	4.0	0	-
		"	"	"	"	6.0	5.6	333
		"	"	"	"	7.5	0	-
Point Beach	June 6	0935	+ 850	+ 63	3.5	1.0	0	-
		"	"	"	"	2.0	0	-
		"	"	"	"	2.8	0	-
Point Beach	June 7	1000	+1436	+ 355	5.8	0.5	6.1	115
		"	"	"	"	1.0	2.8	120
		"	"	"	"	1.5	0.6	230
		"	"	"	"	2.0	1.7	235
		"	"	"	"	2.5	3.9	250
		"	"	"	"	3.0	6.7	260
		"	"	"	"	4.0	3.3	270
		"	"	"	"	5.0	2.2	270
Point Beach	June 12	1055	+ 878	+ 70	3.0	1.0	0	-
		"	"	"	"	2.0	0.8	035
Point Beach	June 12	1130	+ 960	+ 445	7.0	1.0	7.8	180
		"	"	"	"	2.0	3.9	190
		"	"	"	"	3.0	1.7	190
		"	"	"	"	4.0	0	-
		"	"	"	"	5.0	1.1	180
		"	"	"	"	6.0	0.6	210
Point Beach	June 12	1215	+1193	+ 893	9.4	1.0	6.7	170
		"	"	"	"	2.0	3.3	200
		"	"	"	"	3.0	0	-
		"	"	"	"	4.0	0	-
		"	"	"	"	5.0	1.1	170
		"	"	"	"	6.0	0	-
		"	"	"	"	7.0	1.1	190
		"	"	"	"	8.0	0.6	220
Point Beach	June 12	1255	+1419	+1838	12.5	1.0	9.4	150
		"	"	"	"	2.0	0.6	130
		"	"	"	"	3.0	2.2	130
		"	"	"	"	4.0	0.6	130
		"	"	"	"	5.0	0	-
		"	"	"	"	6.0	0	-
		"	"	"	"	7.0	0	-
		"	"	"	"	8.0	1.1	020

^aCoordinate system shown in Fig. III-32a.

TABLE 3.3 (Contd.)

Location	Date (1973)	Time	Lake Location ^b		Bottom Depth (meters)	Measurement Depth (meters)	Current	
			x (meters)	y (meters)			(cm/sec)	Direction (degrees)
Point Beach	Aug 10	1400	+ 991	+1071	10.4	3.0	3.0	360
Point Beach	Aug 23	1200	+1390	+ 334	5.8	3.0	6.0	330
Zion	Sept 19	0950	-1112	+ 465	6.4	0.5	6.7	360
		"	"	"	"	1.0	5.6	360
		"	"	"	"	1.5	6.7	360
		"	"	"	"	2.0	7.2	360
		"	"	"	"	2.5	7.8	010
		"	"	"	"	3.0	5.6	360
		"	"	"	"	4.0	5.0	350
		"	"	"	"	5.0	5.6	350
Zion	Sept 19	1430	-1049	+ 490	6.4	0.5	9.4	030
		"	"	"	"	1.0	8.9	020
		"	"	"	"	1.5	8.3	010
		"	"	"	"	2.0	6.7	360
		"	"	"	"	2.5	5.6	360
		"	"	"	"	3.0	6.1	360
		"	"	"	"	4.0	6.1	340
		"	"	"	"	5.0	11.1	300
Zion	Oct 9	1510	-1934	+ 352	4.9	0.5	17.2	005
		"	"	"	"	1.0	17.2	350
		"	"	"	"	1.5	14.4	010
		"	"	"	"	2.0	13.3	005
		"	"	"	"	3.0	3.3	360
		"	"	"	"	4.0	0	-
Zion	Oct 10	0930	+1640	+ 412	4.6	0.5	17.8	010
		"	"	"	"	1.0	16.1	010
		"	"	"	"	1.5	15.6	010
		"	"	"	"	2.0	11.1	360
		"	"	"	"	2.5	9.4	360
		"	"	"	"	3.0	8.3	360
		"	"	"	"	4.0	6.7	345
Zion	Oct 11	0950	+1165	+ 461	4.9	0.5	16.1	010
		"	"	"	"	1.0	17.2	010
		"	"	"	"	1.5	18.9	010
		"	"	"	"	2.0	16.7	010
		"	"	"	"	3.0	13.9	010
		"	"	"	"	4.0	8.3	025

^bCoordinate system shown in Fig. III-32a.

TABLE 3.4. Plume Areas as a Function of Isotherm and Depth

Power plant: Point Beach Nuclear Power Plant
Date and time of survey: May 5, 1973 (1445-1604)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
16.0	3.33×10^2	-	-	Malfunctioned	-	-	Malfunctioned
15.0	1.07×10^3	2.00×10^2	-		-	-	
14.0	6.06×10^3	4.66×10^2	5.99×10^2		-	-	
13.0	1.90×10^4	2.06×10^3	2.20×10^3		-	-	
12.0	3.84×10^4	4.53×10^3	3.66×10^3		-	-	
11.0	1.24×10^5	3.20×10^4	2.08×10^4		-	-	
10.0	-	1.17×10^5	1.08×10^5		6.37×10^4	2.96×10^4	

Power plant: Point Beach Nuclear Power Plant
Date and time of survey: May 10, 1973 (0925-1139)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
15.0	3.26×10^3	2.46×10^3	1.93×10^3	-	-	-	Malfunctioned
14.0	6.06×10^3	5.19×10^3	4.93×10^3	-	-	-	
13.0	1.41×10^4	1.26×10^4	1.11×10^4	-	-	-	
12.0	3.42×10^4	2.69×10^4	2.31×10^4	-	-	-	
11.0	9.53×10^4	9.21×10^4	6.62×10^4	3.81×10^4	3.38×10^4	1.37×10^4	
10.0	2.03×10^5	1.81×10^5	1.69×10^5	1.16×10^5	9.71×10^4	6.94×10^4	
9.0	6.76×10^5	3.85×10^5	3.45×10^5	2.61×10^5	2.39×10^5	1.11×10^5	
8.0	1.11×10^6	9.61×10^5	9.27×10^5	6.97×10^5	8.89×10^5	5.01×10^5	

Power plant: Point Beach Nuclear Power Plant
Date and time of survey: June 5, 1973 (1150-1400)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
17.0	1.13×10^2	5.33×10^2	7.32×10^2	6.66×10^2	-	-	-
16.0	1.73×10^3	1.53×10^3	1.13×10^3	9.32×10^2	-	-	-
15.0	2.93×10^3	2.20×10^3	1.93×10^3	1.47×10^3	-	-	-
14.0	5.33×10^3	3.26×10^3	3.13×10^3	2.66×10^3	-	-	-
13.0	1.14×10^4	1.03×10^4	7.39×10^3	4.86×10^3	-	-	-
12.0	4.25×10^4	2.90×10^4	1.66×10^4	1.39×10^4	-	-	-
11.0	5.16×10^5	1.22×10^5	5.25×10^4	2.76×10^4	2.08×10^4	1.49×10^4	8.99×10^3
10.0	1.90×10^6	7.51×10^5	5.36×10^5	4.51×10^5	6.49×10^4	2.98×10^4	1.68×10^4
9.0	-	-	-	-	3.38×10^4	6.93×10^4	3.26×10^4

Power plant: Point Beach Nuclear Power Plant
Date and time of survey: June 6, 1973 (1120-1255)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
17.0	1.80×10^3	1.86×10^3	1.53×10^3	1.73×10^3	-	-	Malfunctioned
16.0	4.00×10^3	4.06×10^3	3.13×10^3	3.26×10^3	-	-	
15.0	6.86×10^3	7.59×10^3	5.79×10^3	4.73×10^3	-	-	
14.0	1.35×10^4	1.19×10^4	-	6.86×10^3	-	-	
13.0	6.43×10^4	3.35×10^4	-	1.08×10^4	-	-	
12.0	-	-	-	2.40×10^4	1.30×10^4	1.19×10^4	

TABLE 3.4 (Contd.)

Power plant: Point Beach Nuclear Power Plant
Date and time of survey: June 7, 1973 (1102-1230)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
17.0	1.47 x 10 ³	-	5.99 x 10 ²	7.99 x 10 ²	-	-	-
16.0	2.60 x 10 ³	-	1.60 x 10 ³	1.60 x 10 ³	-	-	-
15.0	4.93 x 10 ³	-	3.06 x 10 ³	2.80 x 10 ³	-	-	-
14.0	8.32 x 10 ³	-	6.26 x 10 ³	4.46 x 10 ³	-	-	-
13.0	2.43 x 10 ⁴	-	1.45 x 10 ⁴	9.12 x 10 ³	-	-	-
12.0	9.25 x 10 ⁴	7.09 x 10 ⁴	4.77 x 10 ⁴	2.14 x 10 ⁴	-	-	-
11.0	-	3.41 x 10 ⁵	3.95 x 10 ⁵	1.43 x 10 ⁵	-	-	-

Power plant: Point Beach Nuclear Power Plant
Date and time of survey: June 12, 1973 (1515-1647)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
18.0	1.07×10^3	1.20×10^3	1.13×10^3	9.32×10^2	-	-	-
17.0	2.26×10^3	2.20×10^3	1.53×10^3	1.80×10^3	-	-	-
16.0	4.13×10^3	3.20×10^3	2.93×10^3	3.00×10^3	-	-	-
15.0	1.46×10^4	7.39×10^3	6.59×10^3	5.73×10^3	-	-	-
14.0	3.15×10^4	2.36×10^4	1.73×10^4	9.72×10^3	-	-	-
13.0	9.68×10^4	1.06×10^5	5.13×10^4	2.01×10^4	-	-	-
12.0	-	1.05×10^6	1.70×10^5	6.42×10^4	3.34×10^4	-	-
11.0	-	-	-	-	9.97×10^5	1.41×10^5	9.82×10^4

Power plant: Point Beach Nuclear Power Plant
Date and time of survey: August 10, 1973 (1416-1500)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
16.0	-	2.26 x 10 ³	-	-	-	No Data	-
15.0	2.60 x 10 ³	3.93 x 10 ³	2.66 x 10 ³	2.13 x 10 ³	-		-
14.0	5.59 x 10 ³	6.19 x 10 ³	4.99 x 10 ³	4.26 x 10 ³	-		-
13.0	1.71 x 10 ⁴	1.62 x 10 ⁴	1.33 x 10 ⁴	7.92 x 10 ³	-		-
12.0	3.96 x 10 ⁴	3.28 x 10 ⁴	2.92 x 10 ⁴	1.60 x 10 ⁴	-		-
11.0	1.40 x 10 ⁵	1.17 x 10 ⁵	8.78 x 10 ⁴	4.48 x 10 ⁴	-		-
10.0	-	-	3.14 x 10 ⁵	1.00 x 10 ⁵	-		-

Power plant: Point Beach Nuclear Power Plant
Date and time of survey: August 23, 1973 (1156-1304)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
24.0	1.02 × 10 ⁴	6.86 × 10 ³	-	-	-	-	-
23.0	5.15 × 10 ⁴	2.34 × 10 ⁴	1.42 × 10 ⁴	7.19 × 10 ³	-	-	-
22.0	1.56 × 10 ⁵	8.66 × 10 ⁴	3.38 × 10 ⁴	2.90 × 10 ⁴	-	-	-
21.0	3.34 × 10 ⁵	2.67 × 10 ⁵	7.84 × 10 ⁴	4.04 × 10 ⁴	-	-	-
20.0	-	-	4.85 × 10 ⁵	6.77 × 10 ⁴	-	-	-
19.0	-	-	-	5.31 × 10 ⁵	-	-	-

Power plant: Zion Nuclear Power Station
Date and time of survey: September 19, 1973 (1041-1212)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
21.0	Malfunctioned	-	-	-	-	-	8.59 × 10 ¹
20.0		1.16 × 10 ³	1.42 × 10 ³	8.59 × 10 ²	9.45 × 10 ²	7.73 × 10 ²	8.16 × 10 ²
19.0		1.19 × 10 ⁴	1.06 × 10 ⁴	7.69 × 10 ³	6.27 × 10 ³	4.04 × 10 ³	5.03 × 10 ³
18.0		1.64 × 10 ⁵	1.81 × 10 ⁵	1.72 × 10 ⁵	1.35 × 10 ⁵	1.79 × 10 ⁵	1.10 × 10 ⁵

TABLE 3.4 (Contd.)

Power plant: Zion Nuclear Power Station
Date and time of survey: September 19, 1973 (1320-1357)

Plume Area within Isotherm, (m ²)							
Isotherm, °C	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
21.0	Malfunctioned	2.68×10^2	1.63×10^3	1.89×10^3	9.45×10^2	8.59×10^2	7.73×10^2
20.0		3.49×10^3	1.24×10^4	8.85×10^3	8.03×10^3	8.21×10^3	5.76×10^3
19.0		2.06×10^4	8.06×10^4	6.33×10^4	4.60×10^4	3.97×10^4	3.66×10^4

Power plant: Zion Nuclear Power Station
Date and time of survey: October 9, 1973 (1227-1303)

Plume Area within Isotherm, (m ²)							
Isotherm, °C	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
16.0	Malfunctioned	4.51×10^3	4.47×10^3	5.07×10^3	3.44×10^3	3.91×10^3	2.92×10^3

Power plant: Zion Nuclear Power Station
Date and time of survey: October 10, 1973 (1020-1237)

Plume Area within Isotherm, (m ²)							
Isotherm, °C	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
20.0	Malfunctioned	-	3.62×10^2	2.15×10^2	-	-	-
19.0		9.45×10^2	8.16×10^2	5.58×10^2	3.62×10^2	2.15×10^2	2.14×10^2
18.0		2.84×10^3	2.36×10^3	1.33×10^3	1.37×10^3	1.12×10^3	6.87×10^2
17.0		8.98×10^3	5.93×10^3	7.47×10^3	6.36×10^3	3.44×10^3	2.23×10^3
16.0		2.00×10^4	5.32×10^4	4.20×10^4	3.60×10^4	2.58×10^4	1.28×10^4
15.0		6.57×10^5	6.69×10^5	4.78×10^5	4.02×10^5	3.26×10^5	2.31×10^5

Power plant: Zion Nuclear Power Station
Date and time of survey: October 10, 1973 (1528-1632)

Plume Area within Isotherm, (m ²)							
Isotherm, °C	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
19.0	Malfunctioned	1.63×10^3	2.06×10^3	7.30×10^2	6.44×10^2	4.29×10^2	3.44×10^2
18.0		5.97×10^3	5.80×10^3	4.73×10^3	2.45×10^3	1.29×10^3	1.42×10^3
17.0		3.90×10^4	2.81×10^4	1.98×10^4	1.56×10^4	8.21×10^3	7.39×10^3
17.0		2.51×10^5	2.24×10^5	1.84×10^5	1.60×10^5	1.12×10^5	1.01×10^5

Power plant: Zion Nuclear Power Station
Date and time of survey: October 11, 1973 (1020-1115)

Plume Area within Isotherm, (m ²)							
Isotherm, °C	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
18.0	Malfunctioned	1.14×10^3	-	-	-	-	3.22×10^2
17.0		8.46×10^3	6.83×10^3	2.53×10^3	9.02×10^2	8.59×10^2	1.29×10^3
16.0		5.64×10^4	3.77×10^4	1.92×10^4	6.23×10^3	7.99×10^3	5.20×10^3
15.0		4.41×10^5	4.06×10^5	3.60×10^5	2.04×10^5	1.77×10^5	1.12×10^5

TABLE 3.5. Temperature Profiling Near the Zion Unit 1 Discharge
on October 10, 1973 at 1700 Hr

Lake Location ^a		Bottom Depth (meters)	Measurement Depth (meters)	Temperature (°C)
x (meters)	y (meters)			
+ 60	+258	5.0	1.0	19.1
			2.0	21.0
			3.0	21.0
			4.0	20.5
			5.0	20.1
+146	+290	4.0	1.0	19.0
			2.0	19.3
			3.0	19.0
			4.0	18.3
+147	+344	5.0	1.0	17.0
			2.0	17.0
			3.0	17.1
			4.0	17.1
			5.0	17.1
+210	+422	6.0	1.0	17.4
			2.0	16.7
			3.0	16.0
			4.0	15.1
			5.0	14.8

^aCoordinate system shown in Fig. III-32b.

Fig. 3.1 Survey Boat and Instrumentation

Fig. 3.2 Schematic of Data-Acquisition System

Fig. 3.3 Photograph of Data-Acquisition System

Fig. 3.4 Lake-Surface Conditions at Point Beach: May 5, 1973

Fig. 3.5A Thermal Plume at Surface for Point Beach:
May 5, 1973, 1445-1604 Hr

Fig. 3.5B Thermal Plume at 0.5-m Depth for Point Beach:
May 5, 1973, 1445-1604 Hr

Fig. 3.5C Thermal Plume at 1.0-m Depth for Point Beach:
May 5, 1973, 1445-1604 Hr

Fig. 3.5D Thermal Plume at 2.0-m Depth for Point Beach:
May 5, 1973, 1445-1604 Hr

Fig. 3.5E Thermal Plume at 2.5-m Depth for Point Beach:
May 5, 1973, 1445-1604 Hr

Fig. 3.5F Vertical Cross Sections for Point Beach: May 5, 1973, 1445-1604 Hr

Fig. 3.6 Lake-Surface Conditions at Point Beach; May 10, 1973

Fig. 3.7A Thermal Plume at Surface for Point Beach:
May 10, 1973, 0925-1139 Hr

Fig. 3.7B Thermal Plume at 0.5-m Depth for Point Beach:
May 10, 1973, 0925-1139 Hr

Fig. 3.7C Thermal Plume at 1.0-m Depth for Point Beach:
May 10, 1973, 0925-1139 Hr

Fig. 3.7D Thermal Plume at 1.5-m Depth for Point Beach:
 May 10, 1973, 0925-1139 Hr

Fig. 3.7E Thermal Plume at 2.0-m Depth for Point Beach:
May 10, 1973, 0925-1139 Hr

Fig. 3.7F Thermal Plume at 2.5-m Depth for Point Beach:
May 10, 1973, 0925-1139 Hr

Fig. 3.7G Vertical Cross Sections for Point Beach:
May 10, 1973, 0925-1139 Hr

Fig. 3.7H Vertical Cross Sections (continued) for Point Beach:
May 10, 1973, 0925-1139 Hr

Fig. 3.8 Lake-Surface Conditions at Point Beach: June 5, 1973

Fig. 3.9A Thermal Plume at Surface for Point Beach:
June 5, 1973, 1150-1400 Hr

Fig. 3.9B Thermal Plume at 0.5-m Depth for Point Beach:
June 5, 1973, 1150-1400 Hr

Fig. 3.9C Thermal Plume at 1.0-m Depth for Point Beach:
June 5, 1973, 1150-1400 Hr

Fig. 3.9D Thermal Plume at 1.5-m Depth for Point Beach:
June 5, 1973, 1150-1400 Hr

Fig. 3.9E Thermal Plume at 2.0-m Depth for Point Beach:
June 5, 1973, 1150-1400 Hr

Fig. 3.9F Thermal Plume at 2.5-m Depth for Point Beach:
June 5, 1973, 1150-1400 Hr

Fig. 3.9G Thermal Plume at 3.0-m Depth for Point Beach:
June 5, 1973, 1150-1400 Hr

Fig. 3.9H Vertical Cross Sections for Point Beach: June 5, 1973, 1150-1400 Hr

Fig. 3.10 Lake-Surface Conditions at Point Beach: June 6, 1973

Fig. 3.11A Thermal Plume at Surface for Point Beach:
June 6, 1973, 1120-1255 Hr

Fig. 3.11B Thermal Plume at 0.5-m Depth for Point Beach:
June 6, 1973, 1120-1255 Hr

Fig. 3.11C Thermal Plume at 1.0-m Depth for Point Beach:
June 6, 1973, 1120-1255 Hr

Fig. 3.11D Thermal Plume at 1.5-m Depth for Point Beach:
June 6, 1973, 1120-1255 Hr

Fig. 3.11E Thermal Plume at 2.0-m Depth for Point Beach:
June 6, 1973, 1120-1255 Hr

Fig. 3.11F Thermal Plume at 2.5-m Depth for Point Beach:
June 6, 1973, 1120-1255 Hr

Fig. 3.11G Thermal Plume at 3.0-m Depth for Point Beach:
June 6, 1973, 1120-1255 Hr

Fig. 3.11H Vertical Cross Sections for Point Beach: June 6, 1973, 1120-1255 Hr

Fig. 3.12 Lake-Surface Conditions at Point Beach: June 7, 1973

Fig. 3.13A Thermal Plume at Surface for Point Beach:
 June 7, 1973, 1102-1230 Hr

Fig. 3.13B Thermal Plume at 0.5-m Depth for Point Beach:
June 7, 1973, 1102-1230 Hr

Fig. 3.13C Thermal Plume at 1.0-m Depth for Point Beach:
June 7, 1973, 1102-1230 Hr

Fig. 3.13D. Thermal Plume at 1.5-m Depth for Point Beach:
June 7, 1973, 1102-1230 Hr

Fig. 3.13E Thermal Plume at 2.0-m Depth for Point Beach:
June 7, 1973, 1102-1230 Hr

Fig. 3.13F Thermal Plume at 2.5-m Depth for Point Beach:
June 7, 1973, 1102-1230 Hr

Fig. 3.13G Thermal Plume at 3.0-m Depth for Point Beach:
June 7, 1973, 1102-1230 Hr

Fig. 3.13H Vertical Cross Sections for Point Beach:
June 7, 1973, 1102-1230 Hr

Fig. 3.13I Vertical Cross Sections (continued) for Point Beach: June 7, 1973, 1102-1230 Hr

Fig. 3.14A Thermal Plume at Surface for Point Beach:
June 12, 1973, 1515-1647 Hr.

Fig. 3.14B Thermal Plume at 0.5-m Depth for Point Beach:
June 12, 1973, 1515-1647 Hr

Fig. 3.14C Thermal Plume at 1.0-m Depth for Point Beach:
June 12, 1973, 1515-1647 Hr

Fig. 3.14D Thermal Plume at 1.5-m Depth for Point Beach:
June 12, 1973, 1515-1647 Hr

Fig. 3.14E Thermal Plume at 2.0-m Depth for Point Beach:
June 12, 1973, 1515-1647 Hr

Fig. 3.14F Thermal Plume at 2.5-m Depth for Point Beach:
June 12, 1973, 1515-1647 Hr

Fig. 3.14G Thermal Plume at 3.0-m Depth for Point Beach:
June 12, 1973, 1515-1647 Hr

Fig. 3.14H Vertical Cross Sections for Point Beach: June 12, 1973, 1515-1647 Hr

Fig. 3.15 Lake-Surface Conditions for Point Beach: August 10, 1973

Fig. 3.16A Thermal Plume at Surface for Point Beach:
August 10, 1973, 1416-1500 Hr

0.5 METER DEPTH CONTOUR

Fig. 3.16C Thermal Plume at 1.0-m Depth for Point Beach:
August 10, 1973, 1416-1500 Hr

Fig. 3.16D Thermal Plume at 1.5-m Depth for Point Beach:
August 10, 1973, 1416-1500 Hr

Fig. 3.16E Thermal Plume at 2.0-m Depth for Point Beach:
August 10, 1973, 1416-1500 Hr

Fig. 3.16F Thermal Plume at 3.0-m Depth for Point Beach:
August 10, 1973, 1416-1500 Hr

Fig. 3.16G Vertical Cross Sections for Point Beach: August 10, 1973, 1416-1500 Hr

Fig. 3.17 Lake-Surface Conditions for Point Beach: August 23, 1973

Fig. 3.18A Thermal Plume at Surface for Point Beach:
 August 23, 1973, 1156-1304 Hr

Fig. 3.18B Thermal Plume at 0.5-m Depth for Point Beach:
August 23, 1973, 1156-1304 Hr

Fig. 3.18D Thermal Plume at 1.5-m Depth for Point Beach:
August 23, 1973, 1156-1304 Hr

Fig. 3.18E Thermal Plume at 2.0-m Depth for Point Beach:
August 23, 1973, 1156-1304 Hr

Fig. 3.18F Thermal Plume at 2.5-m Depth for Point Beach:
August 23, 1973, 1156-1304 Hr

Fig. 3.18G Thermal Plume at 3.0-m Depth for Point Beach:
August 23, 1973, 1156-1304 Hr

Fig. 3.18H Vertical Cross Sections for Point Beach: August 23, 1973, 1156-1304 Hr

Fig. 3.19A Thermal Plume at 0.5-m Depth for Zion:
 September 19, 1973, 1041-1212 Hr

Fig. 3.19B Thermal Plume at 1.0-m Depth for Zion:
September 19, 1973, 1041-1212 Hr

Fig. 3.19C Thermal Plume at 1.5-m Depth for Zion:
September 19, 1973, 1041-1212 Hr

Fig. 3.19D Thermal Plume at 2.0-m Depth for Zion:
September 19, 1973, 1041-1212 Hr

Fig. 3.19E Thermal Plume at 2.5-m Depth for Zion:
September 19, 1973, 1041-1212 Hr

Fig. 3.19F Thermal Plume at 3.0-m Depth for Zion:
September 19, 1973, 1041-1212 Hr

Fig. 3.19G Vertical Cross Sections for Zion: September 19, 1973, 1041-1212 Hr

Fig. 3.19H Vertical Cross Sections (continued) for Zion:
September 19, 1973, 1041-1212 Hr

Fig. 3.20A Thermal Plume at 0.5-m Depth for Zion:
 September 19, 1973, 1320-1357 Hr

Fig. 3.20B Thermal Plume at 1.0-m Depth for Zion:
September 19, 1973, 1320-1357 Hr

Fig. 3.20C Thermal Plume at 1.5-m Depth for Zion:
September 19, 1973, 1320-1357 Hr

Fig. 3.20D Thermal Plume at 2.0-m Depth for Zion:
September 19, 1973, 1320-1357 Hr

Fig. 3.20E Thermal Plume at 2.5-m Depth for Zion:
September 19, 1973, 1320-1357 Hr

Fig. 3.20F Thermal Plume at 3.0-m Depth for Zion:
September 19, 1973, 1320-1357 Hr

Fig. 3.20G Vertical Cross Sections for Zion: September 19, 1973, 1320-1357 Hr

Fig. 3.20H Vertical Cross Sections (continued) for Zion:
September 19, 1973, 1320-1357 Hr

Fig. 3.21 Thermal Plume at All Depths for Zion: October 9, 1973, 1227-1303 Hr

Fig. 3.22 Lake-Surface Conditions for Zion: October 10, 1973,
1400 Hr

Fig. 3.23 Lake-Surface Conditions Near Zion Submerged Discharge:
October 10, 1973, 1400 Hr

Fig. 3.24 Lake-Surface Conditions as Viewed Within Near Field
of the Zion Plume: October 10, 1973, 1400 Hr

Fig. 3.25A Thermal Plume at 0.5-m Depth for Zion:
 October 10, 1973, 1020-1237 Hr

Fig. 3.25B Thermal Plume at 1.0-m Depth for Zion:
October 10, 1973, 1020-1237 Hr

Fig. 3.25C Thermal Plume at 1.5-m Depth for Zion:
October 10, 1973, 1020-1237 Hr

Fig. 3.25D Thermal Plume at 2.0-m Depth for Zion:
October 10, 1973, 1020-1237 Hr

Fig. 3.25E Thermal Plume at 2.5-m Depth for Zion:
October 10, 1973, 1020-1237 Hr

Fig. 3.25F Thermal Plume at 3.0-m Depth for Zion:
October 10, 1973, 1020-1237 Hr

Fig. 3.25G Vertical Cross Sections for Zion:
October 10, 1973, 1020-1237 Hr

Fig. 3.25H Vertical Cross Sections (continued) for Zion:
October 10, 1973, 1020-1237 Hr

PLANT LOAD (MWe): 432 - 435
DISCHARGE FLOW RATE (m³/sec): 2 PUMPS
OUTFALL TEMPERATURE (°C): 19.6
INTAKE TEMPERATURE (°C): 14.8 - 15.1
AMBIENT WATER TEMPERATURE (°C): 14.5 - 15.3
DRY BULB TEMPERATURE (°C): 18.5
RELATIVE HUMIDITY (%): 95
WIND SPEED & DIRECTION (m/sec ± Deg): 5.5, 155
AMBIENT CURRENT SPEED & DIRECTION (cm/sec ± Deg): 16.5, 010
LAKE SURFACE CONDITIONS: CHOPPY ; 0.5 - 1m WAVES
SKY CONDITIONS: PARTLY SUNNY WITH HAZE
ALL TEMPERATURES IN DEGREES CENTIGRADE

Fig. 3.26A Thermal Plume at 0.5-m Depth for Zion:
October 10, 1973, 1528-1632 Hr

Fig. 3.26B Thermal Plume at 1.0-m Depth for Zion:
October 10, 1973, 1528-1632 Hr

Fig. 3.26C Thermal Plume at 1.5-m Depth for Zion:
October 10, 1973, 1528-1632 Hr

Fig. 3.26D Thermal Plume at 2.0-m Depth for Zion:
October 10, 1973, 1528-1632 Hr

Fig. 3.26E Thermal Plume at 2.5-m Depth for Zion:
October 10, 1973, 1528-1632 Hr

Fig. 3.26F Thermal Plume at 3.0-m Depth for Zion:
October 10, 1973, 1528-1632 Hr

Fig. 3.26G Vertical Cross Sections for Zion:
October 10, 1973, 1528-1632 Hr

PLANT & METEOROLOGICAL DATA

PLANT LOAD (MWe): 342 - 439
 DISCHARGE FLOW RATE (m^3/sec): 2 PUMPS
 OUTFALL TEMPERATURE ($^{\circ}C$): 18.6
 INTAKE TEMPERATURE ($^{\circ}C$): 14.1 - 14.3
 AMBIENT WATER TEMPERATURE ($^{\circ}C$): 13.2 - 14.0
 DRY BULB TEMPERATURE ($^{\circ}C$): 17.8
 RELATIVE HUMIDITY (%): 93
 WIND SPEED & DIRECTION (m/sec & Deg): 5.2, 190 - 150
 AMBIENT CURRENT SPEED & DIRECTION (cm/sec & Deg): 14.9, 010
 LAKE SURFACE CONDITIONS: ROUGH; 1m WAVES
 SKY CONDITIONS: CLEAR WITH HAZE
 ALL TEMPERATURES IN DEGREES CENTIGRADE

LAKE MICHIGAN

Fig. 3.27A Thermal Plume at 0.5-m Depth for Zion:
 October 11, 1973, 1020-1115 Hr

Fig. 3.27B Thermal Plume at 1.0-m Depth for Zion:
October 11, 1973, 1020-1115 Hr

Fig. 3.27C Thermal Plume at 1.5-m Depth for Zion:
October 11, 1973, 1020-1115 Hr

Fig. 3.27D Thermal Plume at 2.0-m Depth for Zion:
October 11, 1973, 1020-1115 Hr

Fig. 3.27E Thermal Plume at 2.5-m Depth for Zion:
October 11, 1973, 1020-1115 Hr

Fig. 3.27F Thermal Plume at 3.0-m Depth for Zion:
October 11, 1973, 1020-1115 Hr

Fig. 3.27G Vertical Cross Sections for Zion:
October 11, 1973, 1020-1115 Hr

Fig. 3.28 Fractional Excess Temperature vs. Plume Surface Area for Conditions of Low Northward Currents, Calm Lake Surface and Winds Out of the South

Fig. 3.29 Fractional Excess Temperature vs. Plume Surface Area for Conditions of No Ambient Current, Very Calm Lake Surface and Little or No Wind

Fig. 3.30 Fractional Excess Temperature vs. Plume Surface Area for Conditions of Moderate Southward Currents, Calm Lake Surface and Winds Out of the North

Fig. 3.31 Fractional Excess Temperature vs. Plume Surface Area for All Data Shown in Figs. 28, 29, and 30

a. Point Beach

b. Zion

Fig. 3.32 Definition Sketch for Point Beach and Zion Plant Coordinate Systems

SECTION 3.0

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4.0 MEASUREMENTS OF EDDY DIFFUSIVITIES IN NEARSHORE REGIONS OF LAKE MICHIGAN

S. M. Zivi, D. E. Frye, R. E. Buell, and L. S. Van Loon

4.1 INTRODUCTION

4.1.1 Purpose of Study

The dispersal of warm water effluents in large lakes is governed largely by processes of mixing with the ambient water. In the far field region of the thermal plume, the mixing process is usually treated analytically as a diffusion phenomenon (Fick's law), the eddy diffusivity being treated as the diffusion coefficient. Most of the available analytical or numerical models of far field thermal plumes require the input of the eddy diffusivity often considered a constant in the calculation. The eddy diffusion process describes the convective transport of heated water by turbulent eddies, a process that is usually overwhelmingly more important than molecular thermal diffusion, in the behavior of thermal plumes. The molecular thermal diffusivity of water is about 10^{-3} cm²/sec, whereas eddy diffusivities are generally three to eight orders of magnitude greater. Fick's law of diffusion is not a true description of a turbulent dispersal process, but for thermal plume forecasts, there is presently no satisfactory alternative. Therefore, it is important to be able to select realistic values for the eddy diffusivity in computations of thermal plumes and to obtain as good an understanding as possible of the way the eddy diffusivity varies with ambient conditions and site-dependent factors.

Only limited data are available on eddy diffusivities in large lakes, and the scarcity is partly attributable to some of the complications in the experimental measurement. These complications include the sensitivity of the eddy diffusivity to variations of the wind and to other natural phenomena. Even under stationary atmospheric and limnological conditions, the turbulent nature of the fluid makes it laborious to obtain valid field measurements. Furthermore, there is no theory or first-principle method for forecasting eddy diffusivities, so that generalizing the data has not been possible.

With the needs for additional data and understanding, there was adequate justification for the measurements described in the following. The objectives were:

a. To obtain measurements of the horizontal and vertical eddy diffusivities in Lake Michigan at several nearshore sites that might be somewhat representative of power plant sites. These measurements would augment the limited data already in the literature for Lake Michigan and the other Great Lakes.

b. To determine if the eddy diffusivities observed in the far field of existing thermal plumes from power plants are comparable with the eddy diffusivities in the nearby ambient waters, or whether the stratification of the far field plumes is sufficient to affect the diffusivities.

c. To make simultaneous measurements of the eddy diffusivity and the far field thermal plume from a power plant at the same location, which would enable a far field analytical model to be compared with a measured temperature field for a measured eddy diffusivity.

d. To develop a field methodology that would facilitate the measurement of eddy diffusivities so that future measurements might be undertaken more readily, thereby making it easier to obtain additional data under a variety of ambient conditions.

4.1.2 Relationship to Prior Work of Others

The turbulent diffusion of heat is analogous to that of dissolved chemical substances (Hinze¹). Therefore, an accepted method for determining the eddy diffusivity for heat dispersal is to use a readily measurable dissolved chemical substance and to observe its rate of dispersal. Fluorescent dyes are frequently used because of the facility with which precision quantitative measurements can be made using a fluorometer.²⁻⁴ The scale of turbulence of importance to the processes of thermal plume dispersal in the far field is less than or perhaps equal to the width of the plume. Therefore, eddies up to several hundred meters in scale are of interest. Large scale eddies would be responsible for the meandering of a thermal plume having a width much smaller than the large scale eddies and would be relatively unimportant in dispersing the heat and lowering the temperature in the plume.

Huang² obtained measurements of the horizontal eddy diffusivity at several locations in Lake Michigan during the spring and summer of 1968.

Murthy^{4,13} and Murthy and Csanady³ have published eddy diffusivity data for Lakes Huron and Ontario, and these data are relevant to thermal plume calculations on the Great Lakes.

The results of some of the previous work are shown in Fig. 4.20, along with the eddy diffusivities measured in the present study. The present results are consistent with the earlier work within the scatter that is to be expected from the diverse conditions extant.

Our interest in developing a method of measurement that would be more amenable to rapid execution in response to the occurrence of selected lake conditions led us to adopt a photodensimetric method described by Ichiye and Plutchak.⁶ This uses aerial photography of dye patches with subsequent analysis in the laboratory using a densitometer. Horizontal diffusivities may be determined by this method. This proved to be a most useful and economical technique, with quantitative results apparently as precise as those obtained by the more conventional fluorometer method.

4.1.3 Overall Description of Eddy Diffusivity Measurement Program

During the summer of 1973, horizontal and vertical eddy diffusivities were measured at three sites on Lake Michigan. At the site of the Point Beach Nuclear Power Plant at Two Rivers, Wisconsin, fluorescent dye was injected simultaneously into the thermal plume from the power plant and into the nearby ambient water. Measurement of the dispersal of these two simultaneous dye injections produced data on the degree of difference that might be attributable to the thermal stratification in the far field of the thermal plume. Results of the several sets of measurements indicated no clear tendency of the thermal plume to diminish either the vertical or horizontal eddy diffusivities, although buoyancy did distort the dye pattern in the thermal plume. For these measurements, transects were made of the dye plume or dye patch while the fluorometer system on the 5.5-m boat drew a sample stream from a selected depth. Also, numerous sets of bottle samples were drawn from various depths from which the vertical distribution of dye was later determined.

At a second location at the J. H. Campbell coal-fired power plant, the photodensimetric method was applied. In this case, no measurements were made of the vertical diffusivity. At a third location, that of the Donald C.

Cook Power Plant at Bridgman, Michigan, both the continuous dye-plume fluorometer method and the photodensimetric methods were used.

Values of horizontal eddy diffusivity varied from about 50 to 10^4 cm^2/sec over the entire set of measurements. Vertical eddy diffusivities ranged from 0.3 to 3.0 cm^2/sec in a set of three pairs of measurements (in thermal plume and ambient waters). At present, the data do not suggest any quantitative correlation of eddy diffusivity with current, wind, or other parameters. However, there were several days in which there was virtually no wind but strong current (50 cm/sec) in a region where the bottom depth was about 10 m. There was strong natural stratification in the ambient water. The diffusivity was too low to permit a meaningful measurement because the dye traveled in a sheet only about 15 cm thick, showing that current per se is not a major parameter in causing turbulence.

As mentioned earlier, the photodensimetric method is to be commended for the synoptic scope that it provides and for the relative simplicity of the operation that leads to a capability for acquiring greater amounts of data. Although it would have been desirable to apply both methods simultaneously to the same dye injection so as to verify the consistency of the results, problems of weather and airplane availability interfered. The work of Ichiye and Plutchak,⁶ however, did verify the equivalence of the two methods.

In most of the measurements, approximately Gaussian distributions of dye concentrations were observed; however, in several cases strongly skewed distributions occurred. In the latter instances, meaningful eddy diffusivity cannot be determined by an available technique. In the several cases in which vertical diffusivities were determined by sets of bottle samples taken from various depths, nearly Gaussian distributions were observed with good statistical reproducibility. The magnitudes observed for the vertical eddy diffusivity are sufficient to be of some assistance in attenuating a thermal plume having a large width in the far field.

4.2 DESCRIPTION OF METHODS

4.2.1 Fluorescent Dyes

Fluorescent dyes have been used in a variety of environmental studies and research, such as for tracing water flows, measuring currents,

measuring the rate of mixing in estuaries, and measuring eddy diffusivities in lakes. The fact that very small concentrations (down to 10^{-10} gm/cm³) of certain fluorescent dyes are detectable by field portable instruments makes these substances exceedingly valuable. In recent years, Rhodamine B and Rhodamine WT have emerged as two of the most popular dyes for experimental research because their price is moderate, their resistance to degradation by sunlight is excellent, they have low toxicity, and they fluoresce in a wavelength region in which competition from naturally occurring matter is negligible. Rhodamine WT has the further advantage of only moderate susceptibility to adsorption onto suspended particulate matter in water.

Initially, Rhodamine WT was selected for the eddy diffusivity measurements; however, the U.S. Environmental Protection Agency⁷ suggested that Rhodamine WT was considered an unacceptable contaminant in waters from which drinking water is drawn and suggested sodium fluorescein instead.

Fluorescein, an early water-tracing compound, had been largely displaced by Rhodamine because of two major problems. First, fluorescein decomposes in sunlight much more rapidly than does Rhodamine. This property would preclude the use of fluorescein for tests lasting more than a few hours. Secondly, the wavelength of fluorescence (0.49-0.54 micron) coincides with the spectral region in which some prevalent species of phytoplankton also fluoresce. Consequently, an instrument adjusted to detect the presence of fluorescein would experience a high background reading from the naturally occurring phytoplankton. In spite of these recognized difficulties, there was little choice but to proceed with the measurements using fluorescein.

To deal with the sunlight fading problem, most of the measurements were made in late afternoon. Experience soon showed that the problem was not severe over time intervals of only a few hours. On the question of background fluorescence by phytoplankton, exploratory measurements in Lake Michigan indicated background readings that corresponded to about 2-5 ppb (parts per billion) of fluorescein, being relatively constant at a given location. Background readings of up to five times this amount were observed in rivers, but the sites where the fluorometer method was used were not complicated by the contribution of rivers. In addition, rather high concentrations of fluorescein were used so as to minimize the importance of background fluorescence.

4.2.2 Fluorometer Transect Method

When measurements were carried out by the fluorometer transect method, a pump (12 V, 1/12 hp, rated at 4.6 gpm at 10-ft head, 3.7 gpm at 20-ft head) on the 18-ft boat would draw a continuous flow of water from the desired depth and would pump this through a fluorometer (G. K. Turner Associates, Model 111) in the boat. Sampling tubes were attached to the 3-m deep boom used for temperature measurements. The fluorometer output was recorded simultaneously on a strip-chart recorder and on the main data-acquisition system of the boat, along with boat position, bottom depth, and water temperatures (when appropriate). The boat would travel at an essentially constant speed across the dye plume or dye patch while the data were being recorded.

For those measurements in which a continuous point source of dye was used to produce a continuous dye plume, the dye solution was pumped from a 15-gallon drum (or two such drums) on a moored raft. The pump(s) was a positive displacement (peristaltic), Masterflex Model 70 16-20, having a pumping rate of about 5 cm³/sec. The pump would discharge the dye through an injector tube that extended the selected distance below the water surface, normally 1.5 m. The depth of the dye plume would soon depart from the injection depth as the dye rose or fell to the level corresponding to its density. This movement was present despite the fact that the density of the dye solution was adjusted with ethyl alcohol to correspond to the ambient water density as closely as possible at the beginning of the experiment. Temporal and spatial variations in water density and insufficient precision in dye solution density adjustment resulted in some density mismatch, and the plume then compensated by a vertical displacement from the depth at which it was injected. Typical proportions of sodium fluorescein and ethyl alcohol in the dye solution were 0.9 pound of sodium fluorescein and 0.46 gallon of ethyl alcohol per gallon of solution.

4.2.3 Vertical Dye Profiles by Bottle Sampling

Following a suggestion by Kilpatrick⁸, we decided to combine the fluorometer-transect technique with the practice of obtaining numerous bottle samples of the dye plume for later fluorometric analysis in the laboratory. The bottle samples provide an absolute measure of the dye concentration as

compared with the relative distributions provided by the fluorometer transect. The bottle sample technique provided what turned out to be an excellent means of obtaining data on the vertical eddy diffusivity. Figure 4.1 shows the system for obtaining syringe samples from a manifold that draws a stream of water from each of the six depths simultaneously. Each of the six streams was delayed by an appropriate length of delay tubing, so that six streams entered the manifold with the same transport delay time. A 15-cc sample was drawn from each of the six streams virtually simultaneously by an array of six syringes. The contents of the syringes were then simultaneously discharged into six bottles, and the syringes were then replaced on the manifold for the next sample. This sampling cycle required about 1 min, so that in about 5 min, samples from the six depths could be repeated five times producing a total of 30 bottle samples (six depths replicated five times). This technique produced excellent results.

4.2.4 Aerial Photography and Photodensimetric Method

The basic method, attributed to Ichiye and Plutchak⁶, was found to be especially convenient and quite inexpensive to carry out. In this method, a boat lays out the desired pattern of fluorescent dye on the surface of the waters to be studied. Soon after the dye pattern is deployed (allowing time for boat-induced turbulence to dissipate), aerial photography starts and continues as the dye drifts and disperses. The film, after development, is scanned with a densitometer that produces the quantitative distribution of optical density of the film. The relationship between optical density of the film and image brightness on the film is determined experimentally from calibrated exposures of the film. Hence, the distribution of image brightness determined by the densitometer scan is quantitatively related to the distribution of fluorescent emission of the dye. Changes in this distribution, from one photograph to the next in sequence, are used to deduce the eddy diffusivity.

Elliason, et al.⁹ describes a somewhat more modern and automated system in which the airplane is equipped with a multispectral scanner instead of a photographic camera. The multispectral scanner produces an electronic image of a number of wavelength bands, each amenable to computer analysis. This technique was tried on several occasions with the assistance of the American Electric Power Co. and through a contract with the Environmental

Research Institute of Michigan, who carried out the multispectral scanning. For the specific and limited objectives of this study (concerning only the spectral band of fluorescein emission), the ordinary photographic method produced results that were at least as useful and considerably less expensive than the more sophisticated methods.

In the measurements reported here, a large T-shaped patch of dye solution was layed out, each line of the T being about 1000 ft long and containing about 0.5 gallon of a 5 or 10% (both were used) fluorescein solution. The airplane hired for these observations was a Cessna 170 equipped with a Zeitz Camera, Model RMK 15/2323, having a f5.6 lens, 90° angle, 6-in. focal length, and 9-in. x 9-in. film size. The camera was loaded with standard Eastman Kodak Tri-X aerographic film, No. 2403. We installed a Wratten No. 61 filter in the filter frame external to the camera in order to enhance the contrast of the dye pattern in the image. Figure 4.2 is the transmission spectrum of the Wratten 61 filter, along with the fluorescent emission band of sodium fluorescein. The filter passes much of the emission band and attenuates most of the other wavelengths. The effect is to enhance the relative brightness of the dye image as compared with the background. This is an important detail when seeking precise quantitative measurements from the film.

Flight altitudes from 4000 to 5500 ft were used, and known landmarks were included in each photograph of the dye pattern, so that the scale of distances could be determined during analysis of the photographs. As mentioned, it was necessary to account for the nonlinear relationship between the optical density of the developed negative and the light intensity in the image. This relationship was computed by exposing the film leader at each end of the roll to a calibrated stepwedge. The steps of the wedge were graded in optical-density steps of 0.15 and the film was then developed. By comparison of the dye image with the density of the step-wedge pattern, the relative brightness of each portion of the dye image could be determined.

The large photograph size (9 in. x 9 in.) makes precision analysis by densitometer convenient. A Leeds and Northrup Model 6700 P1 densitometer (vintage 1948) was used to scan the image. The aperture in the densitometer corresponded to a 0.5 x 5-m window at the surface of the water in the location determined by the scanning aperture. The aperture was scanned across the

image so that the 5-m dimension was parallel to the axis of the dye line being traversed, and the 0.5-m slit width was parallel to the direction of scanning. In this way, each scan across the dye line produced a signal that was the average of a 5-m-long sample of that line. This minimized the noise in the measurements. Figure 4.3 illustrates the densitometer system systematically.

4.2.5 Data Reduction and Diffusivity Calculations

4.2.5.1 Mathematical Basis for Analysis

In diffusion by a Fick's law process from a point source in a uniform flow field with constant diffusivity K , the diffusing substance forms a plume having a Gaussian concentration distribution at a sufficiently great distance from the source¹⁰. The horizontal distribution of concentration, relative to the centerline concentration, is given by

$$\frac{C(x,y)}{C(x,0)} = \exp(-Uy^2/4K_yx), \quad (1)$$

where

$C(x,y)$ = concentration at (x,y) ,

x = distance from point source,

y = transverse distance from dye plume centerline to the point of interest,

$C(x,0)$ = centerline concentration at x distance from source,

U = velocity of flow field (ambient current),

and

K_y = eddy diffusivity in the y direction.

Equation 1 is a Gaussian-shaped curve in y with a standard deviation of $\sqrt{2K_yx/U}$. If experimental measurements of dye concentration distribution are made and are found to be described by a Gaussian having standard deviation σ , the eddy diffusivity is then deduced by setting

$$\sqrt{2K_yx/U} = \sigma \quad (2)$$

or

$$K_y = \frac{\sigma^2 U}{2x} \quad (3)$$

or

$$K_y = \frac{\sigma^2}{2t}, \quad (4)$$

where

t = diffusion time

= U/x for a continuous source in a constant and uniform flow.

In the measurements reported here, σ was determined from the fluorescent emission measurements across the dye plume or patch, U was measured with a current meter, and x by position measurements of the dye source and transect location. When dye patches, instead of continuous dye plumes, were injected, t was measured directly, obviating the need for using independent x and U values. Being able to measure the diffusing time directly was a convenience that favored the use of a patch rather than a continuous plume. When a continuous plume was used, variations in current speed and direction during the measurement introduced error and uncertainty into the diffusion time determination.

In the above, it was tacitly assumed that the diffusion occurred in an infinite isotropic medium. Where horizontal diffusion and vertical diffusion are governed by different diffusivities, K_y and K_z , respectively, and where the vertical field is of infinite extent below the plume but is bounded by a reflecting surface above the plume, the horizontal distribution is still given by Eq. 1, while the vertical distribution is given by¹¹

$$\frac{C(x,z)}{C(x,0)} = \frac{1}{2} \exp\left(-\frac{z^2}{2\sigma^2}\right) \left[\exp\left(\frac{Hz}{\sigma^2}\right) + \exp\left(-\frac{Hz}{\sigma^2}\right) \right], \quad (5)$$

where

z = vertical distance from the plume axis,

$$\sigma = \sqrt{2K_z x/U} \quad (6)$$

or

$$\sigma = \sqrt{2K_z t}, \quad (7)$$

and

H = depth of plume axis beneath the reflecting surface.

The reflecting surface is the water free surface. Equation 5 satisfies the boundary condition of zero-rate-of-mass transfer at the free surface. Measurements of vertical distribution of dye concentration were matched with Eq. 5 by finding a combination of H and σ that caused Eq. 5 to fit the data. Equation 6 or 7 was then used to determine the vertical eddy diffusivity, K_z .

4.2.5.2 Data Reduction Procedures

a. Horizontal Distributions

In each measurement of horizontal distribution of dye (whether by fluorometer transect or photodensimetric method), some number of N scans or traverses were made across the dye plume or patch. These were averaged by the following procedure:

The center of gravity of each individual scan or traverse was determined, such that

$$\int_{-Y_{\max}}^{+Y_{\max}} C_n(y) [y - \bar{y}_n] dy = 0, \quad (8)$$

where

$C_n(y)$ = measured distribution of concentration on nth scan,

and

$\bar{y}_n$ = center of gravity of the nth scan,

$Y_{\max}$ = half-width of scan from an arbitrary origin.

The N distributions $C_n(y)$ of a given set of measurements were then shifted along the y coordinate so that their centers of gravity were superimposed, and these new distributions $C_n(y')$ were averaged to obtain the average dye distribution for that transect (continuous plume) or for that time (for the drifting patch method). This averaging was done by first applying a multiplier to each individual scan to correct for apparent differences in the total amount of dye from scan to scan in a given set. The multiplier was of the order of unity and was used to eliminate a possible introduction of bias to the shape of the average distribution, as might have been introduced by, say, one scan with a spurious large or small total amount of dye. In the traversing of a drifting patch of dye, such variation in total quantity of dye traversed would occur as a result of the transect being somewhat off-center in the patch. Since the shape of each distribution rather than the integrated concentration of each scan is sought, the adjustment was made as follows:

$$C'_n(y') = C_n(y') \frac{\bar{A}}{A_n}, \quad (9)$$

where

$C'_n(y')$ = adjusted distribution, nth scan,

$C_n(y')$ = raw distribution, nth scan,

y' = coordinate relative to center of gravity, nth scan,

$$A_n = \int_{-\infty}^{\infty} C_n(y') dy',$$

and

$$\bar{A} = \frac{1}{N} \sum_{n=1}^N A_n.$$

Then the average distribution for the set of N scans was determined as the arithmetic average of the $C'_n(y')$ distributions:

$$\bar{C}(y') = \frac{1}{N} \sum_{n=1}^N C'_n(y') \quad (10)$$

The shape of $\bar{C}(y')$ was then compared with a Gaussian having the same variance, where the variance of $\bar{C}(y')$ was calculated from

$$\sigma^2 = \frac{\int (y')^2 \bar{C}(y') dy'}{\int \bar{C}(y') dy'}, \quad (11)$$

where

σ^2 = variance,

σ = standard deviation.

To provide a measure of the scan-to-scan scatter in the distributions, another parameter was calculated for the set of N scans. This is the variance from the mean distribution, defined as follows:

$$S^2(y') = \frac{1}{N} \sum_{n=1}^N [C'_n(y') - \bar{C}(y')]^2. \quad (12)$$

At each value of y' , $S(y')$ is an index of the scatter of the N scans. In the plots of the experimental distributions presented later, "flags" consisting of $\pm S(y')$ are shown to indicate the scatter in the measurement.

b. Vertical Distributions

Vertical distributions were obtained from N sets of bottle samples having concentrations (after subtraction of the measured background) denoted $C_n(z)$. In the present measurements, N was usually 5.

The average vertical distribution for the set was determined according to

$$\bar{C}(z) = \frac{1}{N} \sum_{n=1}^N C_n(z). \quad (13)$$

Error bars were obtained by

$$S^2(z) = \frac{1}{N} \sum_{n=1}^N [C_n(z) - \bar{C}(z)]^2, \quad (14)$$

where

$S(z)$ = standard deviation of set of N measurements at a given depth.

The Gaussian-shape factors (standard deviation σ and depth H in Eq. 5) were determined by fitting $\bar{C}(z)$ to templates corresponding to the solution of Eq. 5, shown in Fig. 4.4.

4.3 RESULTS AND DISCUSSIONS

4.3.1 Locations and Ambient Conditions

The three locations at which eddy diffusivity measurements were made in this study are shown in Figs. 4.5, 4.6, and 4.7. Measurements were carried out in 7 to 10 m of water at offshore distances of about 500 m at Point Beach and about 1000 m at the Donald C. Cook and J. H. Campbell sites. Measurements using the fluorometer transect method were conducted at the Point Beach, Wisconsin, location during August. At the Donald C. Cook location, the fluorometer transect method was used in July 1973 (data not included here) and the photodensimetric method in October. The photodensimetric method was also used at the J. H. Campbell plant in Michigan during September 1973. The measurements at the Point Beach plant were dual sets with simultaneous measures from the power plant in the thermal plume and in the nearby ambient water. All other measurements reported here are single sets in ambient waters. The eddy diffusivity measurements of August 23, 1973,

at the Point Beach plant followed (by several hours) the mapping of thermal plume presented in Sec. 3 of this report. Table 4.1 summarizes the meteorological and limnological data observed for each measurement of eddy diffusivity.

4.3.2 Eddy Diffusivity Measurements in Thermal Plumes and in Nearby Ambient Water at the Point Beach Plant

The measurements at Point Beach were the most difficult of the program because an attempt was made to make almost simultaneous measurements of the temperature field in the thermal plume and the dispersal of dye in two continuous plumes (or two sets of batches) using the more difficult fluorometric technique, while at the same time attempting to synchronize aerial overflights carrying multispectral scanning equipment. The limitations of available personnel and equipment, coupled with changeable weather, prevented the completion of some of these tasks at Point Beach. The major failing was the synchronization of aerial measurements with valid fluorometric measurements. Also, on August 23 a delay of about 4 hr intervened between the mapping of the thermal plume and the measurement of eddy diffusivity. Conditions in this interval changed sufficiently so that the objective of simultaneous measurements was thwarted.

All the measurements at the Point Beach Nuclear Power Plant were addressed to the question of possible influences of the thermal plume on eddy diffusivity. The results are summarized in Table 4.2. Figures 4.8 through 4.13 illustrate various aspects of the distribution of the fluorescein. The temperature profiles in Table 4.2, which are plotted in Fig. 4.15, indicate varying degrees of stratification on the three days of measurement. On August 9, 1973, the temperature profile in the ambient water suggests a well-mixed layer down to about 2-m depth. The profile in the far field thermal plume looks similar, except that the temperature gradient between the 2- and 3-m depths is about twice as great as in the ambient water. The vertical distribution of dye concentration in the continuous dye plumes of August 9, 1973 are shown in Fig. 4.8, along with several interpretations. For the dye plume in the ambient water, a good fit is obtained with a Gaussian curve having $H = 0$ (suggesting that the dye plume rose to the surface). The Gaussian shape leads to a straightforward calculation of vertical eddy diffusivity, but is somewhat inconsistent with the idea of a 2-m deep, well

mixed layer, since diffusion extends smoothly to 3 m, at least. Evidently, the stratification in the ambient water was weak enough not to impose a significant barrier to vertical diffusion. A vertical diffusivity K_z of $2.7 \text{ cm}^2/\text{sec}$ is consistent with the observed vertical dye profile in the ambient water on this date.

The dye stream in the thermal plume of August 9, 1973 seems to be amenable to two interpretations. The data are fit fairly well by a Gaussian having $H = 1.2 \text{ m}$ and a K_z of $0.5 \text{ cm}^2/\text{sec}$, but is also consistent with a 2-m, well-mixed layer above a thermocline, which is suggested by the temperature profile in Fig. 4.15. If the 2-m deep, well-mixed layer interpretation is assumed and a Reynolds number (u^*h/K_m) of 20 is taken, as was observed by Csanady in Ref. 15, one is led to an estimate of K_m , the coefficient for the vertical turbulent diffusion of momentum.[†] Although K_m is not identical to K_z , the coefficient for vertical turbulent diffusion of mass, it is expected to be of the same order of magnitude. Csanady⁵ observes that the August 9, 1973 air temperature was about 13°C above the water temperature, suggesting low air turbulence and low wind stress. Under neutral air stability, the measured wind of 4.7 m/sec would produce a wind stress of about 0.5 dyne/cm^2 , but Csanady estimates that the very stable conditions would produce a wind stress of 0.1 dyne/cm^2 or less. A wind stress of 0.1 dyne/cm^2 , with a depth of mixed-surface layer of 200 cm and a Reynolds number $u^*h/K_m = 20$, yields a value of $3 \text{ cm}^2/\text{sec}$ for the eddy viscosity, K_m . Then K_z would probably be of this order. The value of K_z in the far field thermal plume would seem to be comparable with that in the ambient water on August 9, 1973 by the order-of-magnitude estimate based on the well-mixed layer hypothesis. On the other hand, if the submerged dye plume interpretation ($H = 1.2 \text{ m}$) is assumed in the thermal plume, as suggested by the Gaussian curve in Fig. 4.8, a much lower value of K_z ($0.5 \text{ cm}^2/\text{sec}$) is obtained. It is difficult to conclude an effect by comparing a submerged dye distribution in the thermal plume with a more nearly surface plume in the ambient water. This is because K_z would be expected to diminish with increasing depth. It is concluded that

[†]We are indebted to Dr. G. T. Csanady⁵ for suggesting the well-mixed layer interpretation and for his calculation of eddy viscosity. In the above calculation, u^* is the friction velocity ($\sqrt{\tau/\rho}$, where τ is wind stress and ρ , water density), h is depth of the well-mixed layer, and K_m is eddy viscosity.

the data of August 9, 1973 indicate a different behavior of the dye in the ambient water as compared with the dye in the thermal plume far field, but to the degree that K_z may be calculated and compared, no clear difference in K_z is ascribed for the two cases. In fact, if a Gaussian having $H = 0$ is fit to the thermal plume dye distribution, as is done in Fig. 4.8, an eddy diffusivity $K_z = 2.7 \text{ cm}^2/\text{sec}$ is obtained. This is the same value as obtained for the ambient water.

On August 23, 1973, the temperature profile in the ambient water is nearly flat, and even in the far field thermal plume there is much less stratification than on August 9. The wind was quite variable during the measurements of August 23, leading to highly nonstationary processes and impairing the determination of diffusivities. Figure 4.9A shows two sets of vertical dye distribution measurements in the ambient water on August 23, and Fig. 4.9B shows two sets in the thermal plume. In each location, K_z values range from 0.4 to about $2 \text{ cm}^2/\text{sec}$, depending on which set of measurements are used and on whether the submerged or surface level dye stream is assumed. About all that can be said is that K_z was of the order of $1 \text{ cm}^2/\text{sec}$ in both the ambient water and the thermal plume.

Regarding the measurements on August 24, 1973, Fig. 4.15 indicates a distinctly different temperature profile in the thermal plume than in the ambient water, with substantial stratification of the upper 1.5 m. The vertical profiles of dye concentration (Fig. 4.10) are again subject to the several interpretations of August 9. Vertical diffusivities ranging from 0.3 to $1 \text{ cm}^2/\text{sec}$ are estimated for both dye patches. (A drifting patch in each location was used in this experiment; the dye was initially injected at a depth of 1.5 m.) Again, there seems to be no significant difference in vertical mixing in the far field thermal plume as compared with the nearby ambient water on August 24, 1973.

The depth of the dye plume was determined from the bottle-sample data such as that shown in Figs. 4.8, 4.9, and 4.10 by the method described earlier. In every case, the dye was injected 1.5 m below the surface. These figures indicate that nearly Gaussian shapes were obtained. They also document the absolute concentrations of dye observed at the sampling location. The dye plume (or patch) depth shown in Table 4.2 is the depth (H) for which a good match was obtained in comparison with the mathematical Gaussian. The apparent

depths in Table 4.2 were rounded off to the nearest meter, consistent with the accuracy of the curve-fitting procedure. Figures 4.8, 4.9, and 4.10 also show dashed Gaussian curves for $H = 0$ for reference. The "zero-H" Gaussians were selected to give best zero-H fit to the data by the visual curve-matching technique using Fig. 4.4. They are shown along with the best-fit Gaussians ($H \neq 0$) to illustrate the persuasiveness of the evidence for a varying depth of submergence of the dye. The magnitudes of vertical diffusivity indicate that, in a time interval of several hours, vertical mixing would occur over a depth increment of about 1 m. The significance of this will be discussed shortly.

Some of the data supporting the horizontal diffusivity values in Table 4.2 are presented in Figs. 4.11, 4.12, and 4.13. In Fig. 4.11, the average dye distribution is plotted against horizontal distance for each of the two dye plumes studied on August 9, 1973. Each graph represents $\bar{C}(y')$, defined in Eq. 10. The bars are $\pm S$, where S is defined in Eq. 12. On August 9, there appeared to be significant buoyant spreading of the thermal plume, giving an advective transverse growth of the dye pattern. This is understandable from the temperature profile for the water in the far field thermal plume as compared with the ambient water on August 9. The increase in width due to buoyant spreading is postulated to be responsible for the apparently higher diffusivity obtained in the thermal plume on this date. Figure 4.12 is a similar plot for the measurements of August 24, 1973. Both Figs. 4.11 and 4.12 show a reasonably good Gaussian distribution. Figures 4.13A and 13B are tracings of the fluorometer records from two single transverse of the dye plumes on August 23, 1973: one in the thermal plume of the Point Beach plant and one in the nearby ambient waters. The exceedingly asymmetrical shape of both of these dye plumes is apparent and precludes the determination of diffusivity values by the present technique. Rapid changes in wind direction occurred during the measurements; these would be expected to introduce directional changes in surface currents and the departure from Gaussian diffusion as indicated in Fig. 4.13. Figure 4.14 shows hourly sampled wind vectors during the measurements of August 9, 23, and 24, 1973. The measurements of August 9 and 24 (Table 4.2 and Figs. 4.11 and 4.12) indicate larger horizontal eddy diffusivities in the thermal plume than in the ambient water. However, this is probably attributable to buoyant spreading of the dye plumes or patches. Based on these limited statistics,

it is concluded that the far field thermal plume does not diminish the horizontal eddy diffusivity and that it is appropriate to use values of ambient horizontal diffusivity in calculations of far field thermal plumes.

The data of Table 4.2 indicate a ratio of horizontal-to-vertical eddy diffusivity of about 100, which is consistent with expectations based on previous work of others. In Fick's law, the distance over which a given relative concentration will advance in a given time is proportional to the square root of the diffusivity. The 100:1 ratio of horizontal-to-vertical eddy diffusivity would imply that if the aspect ratio of a thermal plume (ratio of plume half-width to depth) were about 10:1, the contributions of horizontal and vertical diffusion would be about equal. In far field thermal plumes where the half-width is greater than 10 times the depth of the plume and under conditions in which the vertical-to-horizontal diffusivity ratio is about 1:100, vertical diffusion would become more important than horizontal diffusion for mixing with ambient water. Of course, as the plume depth approaches the bottom depth, the opportunity for vertical mixing would vanish.

4.3.3 Eddy Diffusivity Measurements at the Site of the Donald C. Cook Plant, Bridgman, Michigan

Measurements of horizontal eddy diffusivity were made about 1000 m offshore at the site of the Donald C. Cook Plant on October 23, 1973, using the photodensimetric method operating on the width of the dye lines. Figure 4.16 shows a sequence of three aerial photographs of the T-shaped drifting dye patch. Figure 4.17 combines these three photographs to show the dimensions of the T and the transport and deformation of the T during the measurement. The results of the photodensimetric measurements by the method described earlier are presented in Figs. 4.18 and 4.19 covering the three observations shown in Fig. 4.16. The quantity plotted is $C(y')$, defined in Eq. 10, and the error flags are S, as defined by Eq. 12. The eddy diffusivity was determined as

$$K = \frac{\sigma_2^2 - \sigma_1^2}{2(t_2 - t_1)}, \quad (15)$$

where

K = horizontal eddy diffusivity in the transverse direction (K_y) or the longitudinal direction (K_x),

σ_1 = standard deviation determined from the first pair of photographs,

σ_2 = standard deviation determined from the second pair of photographs,

and

t_1, t_2 = the times of the two photographs.

The standard deviations σ_1 and σ_2 were determined by the calculation described by Eq. 11. A sequence of three photographs taken at 1345, 1410, and 1500 CDT on October 23, 1973 was used to obtain the eddy diffusivity over the time intervals between the first and second and second and third photographs. These results are given in Table 4.3.

The width of the drifting line of dye ranged from about 10 m in the first photograph to about 150 m in the last one. The eddy diffusivity does appear to be increasing with time according to Table 4.3. An increasing diffusivity would signify the participation of larger eddies as time progresses. A plot of eddy diffusivity versus linear scale (taken as three standard deviations) shows approximately the same relationship ($K_y \propto S^{1.1}$) as do other measurements in this effort (see Fig. 4.20). This distortion of the T indicates that a gross shearing was present, with respect to distance from shore. The conditions are therefore more complicated than the initial assumption anticipated.

The diffusivity magnitudes of a few hundred to about 1000 cm^2/sec measured on October 23, 1973 are within the range reported by previous workers, although somewhat larger than observed earlier at the Point Beach location. As stated previously, there is great variation in the eddy diffusivity. For example, on July 19, 1973 at the D. C. Cook location, the natural thermal stratification was so great (thermocline at 6.5-m depth; 21.3°C at 2 m, 18.7°C at 6 m, 12.9°C at 7 m, and 7.7°C at 9 m depth) that the vertical eddy diffusivity was virtually zero. The dye was carried by the current (25 cm/sec) as a thin lamina (15 cm thick) at the 1-m depth. The dye layer was so thin that the sampling tube of the fluorometer could not be maintained within the dye layer. Observations of the thickness of the layer were made by divers. The lamina flow persisted for several hours (until after the dye supply was exhausted) and at least 1000 m from the injection point.

4.3.4 Eddy Diffusivity Measurements at the J. H. Campbell Plant, Holland, Michigan

The J. H. Campbell plant is a coal-burning plant with once-through cooling using a surface discharge on Lake Michigan. Several experiments were carried out there in 1973 including the photodensimetric measurements of horizontal eddy diffusivity presented here. These measurements were made on September 12, 1973 between 1356 and 1444 CDT. The results given in Table 4.3 show that horizontal transverse eddy diffusivity values increased from about 300 to about 1000 cm^2/sec during the 48 min of observation. During this time, the width of the line of dye in the T grew from several meters to about 20 m.

4.3.5 Summary

The various horizontal diffusivity measurements on Lake Michigan during 1973 are summarized in Fig. 4.20. It appears from Fig. 4.20 that these measurements can be correlated by a relationship between diffusivity and scale of turbulence (i.e., scale of dye plume or patch) such that K_y varies approximately as scale to the 1.1 or possibly the 4/3 power. Furthermore, previous measurements of Murthy and Huang on the Great Lakes are seen to be roughly consistent with the present data. Also, measurements of horizontal eddy diffusivities in the surface layer of the sea, as reported by Okubo¹⁴, are similar to those observed in the Great Lakes as shown in Fig. 4.20. In accordance with the first objective of this study, these measurements provide a range of values for use in theoretical models of thermal plume dispersal where eddy diffusivity is a required input parameter. There was no evidence of a significant turbulence-damping effect due to stratification in the far field thermal plume, answering the second objective. The third objective was to obtain virtually simultaneous measurements of eddy diffusivity and temperature in a thermal plume so that far field models might be evaluated with realistic eddy diffusivities. This objective was not accomplished because experimental difficulties introduced a delay of several hours between the mapping of a thermal plume and the measurement of eddy diffusivity on August 23, 1973 at Point Beach. The occurrence of rapidly shifting winds and currents during the diffusivity measurements--but not during the thermal plume measurements--thwarted the comparison of data. The fourth objective of developing a field technique and methodology for more rapidly measuring

eddy diffusivities has been largely accomplished by the refinement of the photodensimetric method and the bottle sampling technique.

TABLE 4.1. Ambient Conditions During or Near the Time of Diffusivity Measurements

Date, Location, Time	Wind Speed (m/sec), Direction	Air Dry Bulb/ Wet Bulb °C	Current			Water Temp		Water Visibility (Secchi disc) (m)	Water Surface	
			Depth (m or hrs)	Speed (cm/sec)	Direction (degrees)	Depth (m)	°C			
August 9, 1973, Point Beach, Wisconsin, 1130 hrs except where noted otherwise	4.7, SW	24.4/20.0	1500 hrs			See Table II		3	Calm, 0-1 ft waves in NNW direction	
			1 m	14	350					
			2	7.7	330					
			3	5.2	280					
			4	5.2	240					
			5	4.1	250					
			1 m Deep							
			1600 hrs	10.8	350					
			1710	10.3	005					
			1730	11.3	010					
			1750	9.8	040					
			1815	11.3	030					
			1845	8.2	025					
			1915	11.8	035					
			1945	11.8	035					
August 23, 1973, Point Beach, Wisconsin, 1015 hrs except where noted	5.0, 175°	15.6/15.0	1600 hrs			See Table II		2.5	Calm, waves less than 1 ft, 350°	
August 24, 1973, Point Beach, Wisconsin, 1300 hrs	2.8, 120°	20.0/18.9	0.5 m	5-10	15	See Table II		1	Choppy, 1-2 ft waves, 300°	
				1	8	20				
				2	~ 0	20				
				3	~ 0	350				
				5	~ 0	240				
September 12, 1973, J. H. Campbell Plant, Port Sheldon, Michigan, 0855 EDT ^a	2-4, 195°	14.4/11.7	0.5	14.4	190	0-.2	13.7	2	Slight chop, 0-1 ft waves, 20°	
			1.0	18.0	190	0.5	13.2			
			1.5	19.0	185	1.0	13.0			
			2	15.4	185	1.5	12.2			
			3	12.9	200	2.0	11.8			
			4	5-10	215	3.0	11.1			
			5	5-10	215	4.0	8.9			
						5.0	7.6			
October 23, 1973, D. C. Cook site, Bridgman, Michigan, 1400 EDT	0.3, 200°	18.3/16.1	1.5	5	200	0	15.8	2	Calm	
			3.0	5	200	1	14.8			
			5.0	~ 0	200	2	14.6			
			7.0	~ 0	200	3	14.4			
						4	14.4			
						5	14.3			
						6	14.3			
						7	14.3			
						8	14.3			
						9	14.2			
						10	14.2			
						11	14.2			
						12	14.2			

^aOther wind data provided by Consumers Power Co. are:

Time	Wind
0600	7, NE
0800	7, S
1000	7, SW
1500	7, N
2100	3, N

TABLE 4.2A. Horizontal Eddy Diffusivity Measurements at the Point Beach Nuclear Power Plant in Ambient Water and in Thermal Plumes

Date, Time (1973)	Remarks on Conditions	Method	Horizontal Eddy Diffusivity			Apparent Depth of Dye Plume		Temperature Profiles at Dye Injection Point and at Measurement Location				
			In Ambient Water (cm ² /sec)	In Thermal Plume (cm ² /sec)	Remarks	Ambient	Thermal Plume	Depth m	Ambient Water		Thermal Plume	
									Inject.	Meas.	Inject.	Meas.
Aug. 9, 1700-2000 CDT	Strong upwelling Bottom depth 7-10 m	Fluorometer transects and bottle samples, continuous injection of 10% fluorescein solution at depth of 1.5 m from 2 moored dye rafts	75	390	6 traverses of dye in thermal plume at a transect location corresponding to 6000 ± 2000 sec transport time from source 5 traverses of dye in ambient water at a transect location corresponding to 5000 ± 1600 sec transport time from source	0	1 m	0	-	-	-	-
								0.5	-	10.8	16.0	12.8
								1.0	-	10.7	16.2	12.8
								1.5	-	10.7	16.2	12.8
								2.0	-	10.9	16.7	12.8
								3.0	-	9.9	17.0	10.8
Aug. 23, 1430-1700 CDT	Bottom depth 7-10 m	Fluorometer transects and bottle samples, continuous injection of 5% fluorescein solution at depth of 1.5 m from 2 moored dye rafts	(12,000)	3,500 & 2,900	4 traverses at one transect and 5 at another in the thermal plume at locations corresponding to transport times of 2500 and 4600 sec from the source 4 traverses at one transect in the ambient water at 3100 sec from the source	1 m	1 m	0	17.8	-	20.0	18.6
						1 m	1 m	0.5	17.9	-	20.4	19.3
								1.0	17.9	-	19.2	19.3
								1.5	17.8	-	18.4	19.2
								2.0	17.7	-	18.3	18.9
								3.0	17.4	-	18.2	17.7
Aug. 24, 1000-1200 CDT	Bottom depth 7-10 m	Fluorometer transects and bottle samples, batch in- jection 1 gallon 5% solu- tion at depth of 1.5 m two locations	65	130	7 traverses at one transect in the thermal plume, 4300 sec from the dye source 8 traverses at one transect in the ambient water, 5200 sec from the dye source	1 m	1 m	0	-	-	-	-
								0.5	19.9	-	20.8 ^a	21.2 ^b
								1.0	20.0	-	20.8 ^a	21.0 ^b
								1.5	19.8	-	20.6 ^a	19.7 ^b
								2.0	19.4	-	19.6 ^a	18.8 ^b
								3.0	17.8	-	18.3 ^a	18.1 ^b

^aObserved at the dye-patch 290 m down-current from injection 53 min after injection.

^bObserved 110 m down-current from location of previous measurements, 385 m from injection.

TABLE 4.2B. Vertical Eddy Diffusivity Measurements at the Point Beach Nuclear Power Plant in Ambient Water and in Thermal Plumes

Date, Time (1973)	Remarks on Conditions	Method	Vertical Eddy Diffusivity		Remarks	Apparent Depth of Dye Plume		Temperature Profiles at Dye Injection Point and at Measurement Location				
			In Ambient Water (cm ² /sec)	In Thermal Plume (cm ² /sec)		Ambient	Thermal Plume	Depth m	Ambient Water		Thermal Plume	
									Inject.	Meas.	Inject.	Meas.
Aug. 9, 1700-2000 CDT	Strong upwelling Bottom depth 7-10 m	Fluorometer transects and bottle samples, continuous injection of 10% fluorescein solution at depth of 1.5 m from 2 moored dye rafts	3.0	0.5	Bottle samples, 5 replications at location of horizontal transects	0	1 m	0	-	-	-	-
								0.5	-	10.8	16.0	12.8
								1.0	-	10.7	16.2	12.8
								1.5	-	10.7	16.2	12.8
								2.0	-	10.9	16.7	12.8
							3.0	-	9.9	17.0	10.8	
Aug. 23, 1430-1700 CDT	Bottom depth 7-10 m	Fluorometer transects and bottle samples, continuous injection of 5% fluorescein solution at depth of 1.5 m from 2 moored dye rafts	0.4	1.4	Bottle samples, 5 replications for each of the measurements	1 m	1 m	0	17.8	-	20.0	18.6
			1.4	0.4		1 m	1 m	0.5	17.9	-	20.4	19.3
			The vertical distribu- tion was approximately Gaussian	1.0		17.9	-	19.2	19.3			
				1.5		17.8	-	18.4	19.2			
				2.0		17.7	-	18.3	18.9			
				3.0		17.4	-	18.2	17.7			
Aug. 24, 1000-1200 CDT	Bottom depth 7-10 m	Fluorometer transects and bottle samples, batch in- jection 1 gallon 5% solu- tion at depth of 1.5 m two locations	0.3	0.3	Bottle samples, 5 replications at each horizontal transect	1 m	1 m	0	-	-	-	-
			Measured at a sin- gle location, at times 20 min apart	Measured at two stations, diffusing times 2500 and 4600 sec (upper and lower entries, respec- tively)		0.5	19.9	-	20.8 ^a	21.2 ^b		
						1.0	20.0	-	20.8 ^a	21.0 ^b		
						1.5	19.8	-	20.6 ^a	19.7 ^b		
						2.0	19.4	-	19.6 ^a	18.8 ^b		
						3.0	17.8	-	18.3 ^a	18.1 ^b		

^aObserved at the dye-patch 290 m down-current from injection 53 min after injection.

^bObserved 110 m down-current from location of previous measurements, 385 m from injection.

TABLE 4.3. Diffusivities Calculated for the
J. H. Campbell Site: September 12, 1973

Time, hr	Diffusivity Between Consecutive Observations, cm^2/sec
	N-S Plume K_y
1355	290 $\pm$ 29
1417	480 $\pm$ 48
1434	1130 $\pm$ 113
1444	
Avg. diffusivity (over 48 min)	525 $\pm$ 52

Diffusivities Calculated for the D. C. Cook Site: October 23, 1973

Time, hr	Diffusivity Between Consecutive Observations, cm^2/sec	
	N-S Plume K_y	E-W Plume K_x
1345	600 $\pm$ 60	470 $\pm$ 47
1410	2160 $\pm$ 216	1260 $\pm$ 500
1500	5000 $\pm$ 500	2600 $\pm$ 900
1520		
Avg. diffusivity (over 95 min)	2400 $\pm$ 500	1350 $\pm$ 700

Fig. 4.1 Schematic Diagram of System for Obtaining Dye Samples from Various Depths.

Fig. 4.2 Filter Transmission Characteristic and Fluorescein Emission Band

Fig. 4.3 Schematic Diagram of Densitometer-Scanner

Fig. 4.4 Gaussian Reference Curves for Diffusion with a Reflecting Boundary at $y = H$

$$\frac{\bar{C}(y/\sigma)}{\bar{C}(0)} = \frac{1}{2} \exp \left(-\frac{1}{2} \frac{y^2}{\sigma^2} \right) \exp \left[\left(\frac{Hy}{\sigma} \right) + \exp \left(-\frac{Hy}{\sigma} \right) \right]$$

Fig. 4.5 Locations of Eddy Diffusivity Measurements, 1973

Fig. 4.6 Locations of Dye Sources and Approximate Directions of Dye Plumes or Dye Patches at the Point Beach (Wisconsin) Site

Fig. 4.7. Locations of Eddy Diffusivity Measurements at the J. H. Campbell (Holland, Michigan) Site

Fig. 4.8 Vertical Distribution of Dye, Point Beach, August 9, 1973.
Error Bars $\pm 1\sigma$, 5 replications

Fig. 4.9A Vertical Distribution of Dye, Point Beach, August 23, 1973, Ambient Water, Two Sets of Measurements. Error Bars $\pm 1\sigma$

Fig. 4.9B Vertical Distribution of Dye, Point Beach, August 23, 1973, In Thermal Plume, Two Sets of Measurements. Error Bars $\pm 1 \sigma$

Fig. 4.10 Vertical Distribution of Dye in Drifting Patch, Point Beach, August 24, 1973, in Ambient Water and Thermal Plume. Error Bars $\pm 1\sigma$

Fig. 4.11 Relative Horizontal Distributions of Dye, 1-m Depth,
at Point Beach, Wisconsin, August 9, 1973

a) IN THERMAL PLUME

b) IN AMBIENT WATER

Fig. 4.12 Relative Horizontal Distributions of Dye, 0.5-m Depth, Point Beach, Wisconsin, August 24, 1973

(a) IN FAR-FIELD THERMAL PLUME

DYE PLUME TRAVELING
APPROXIMATELY EASTWARD
(OFF-SHORE)

(b) IN AMBIENT WATER

DYE PLUME TRAVELING
APPROXIMATELY NORTHEAST

Fig. 4.13 Relative Horizontal Distributions of Dye from a Single Fluorometer Traverse of Each Dye Plume, 0.5-m Depth, Point Beach, Wisconsin, August 23, 1973

Fig. 4.14 Wind and current data for days of Eddy-Diffusivity Measurements at Point Beach. Current measurements at 3-m depth in 6 m of water. Wind measurements at water intake crib, about 2 m above periphery of crib, and about 4 m above water. Current vectors are in direction of water flow, wind vectors are in opposition to direction of air flow.

Fig. 4.15 Vertical Profiles of Water Temperature Corresponding to the Point Beach Diffusivity Measurements

Fig. 4.16 Aerial Photographs (from about 4500 ft altitude) of T-Shaped Dye Patch, Donald C. Cook Site, Bridgman, Michigan, October 23, 1973

Fig. 4.17 Drift of T-Shaped Dye Patch, Donald C. Cook, October 23, 1973

Fig. 4.18 Relative Horizontal Distribution of Dye, as Determined by the Photodensitometer Method, for T-shaped Patch shown in Figs. 4.16 and 4.17, Donald C. Cook site, October 23, 1973, approximately 1500 sec between observations.

Fig. 4.19 Relative Horizontal Distribution of Dye, as Determined by the Photodensitometer Method, for T-shaped patch shown in Figs. 4.16 and 4.17, Donald C. Cook site, October 23, 1973, approximately 1200 sec after the later observation in Fig. 4.18.

Fig. 4.20 Horizontal Eddy Diffusivities from the Present Study and from Previous Measurements, as a Function of Linear Scale

Section 4.0

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5.0 A COMPARISON OF AERIAL INFRARED AND BOAT ORIENTED THERMAL PLUME MEASUREMENT TECHNIQUES¹

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5.1 INTRODUCTION

Condenser waste heat release from steam electric power plants is a critical aspect of power plant siting and licensing within the U.S. According to federal law, waste heat discharged to any body of water should be considered a pollutant and as such must be regulated. In fact, in accordance with the mandates of the Federal Water Pollution Control Act Amendments of 1972 in eliminating all pollutant discharges into navigable waters by 1985, the United States Environmental Protection Agency (EPA) has recommended essentially the total abolishment of open-cycle (once-through) condenser cooling in favor of closed-cycle methods. The proposed EPA guidelines, which presently are only recommendations subject to revision, are shown in Table 5.1. Note that the suggested thermal guidelines allow for variances. The 1972 Water Quality Act specifies that variances will be permitted if it can be shown that the proposed thermal regulations are more stringent than necessary to ensure the propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on the body of the water into which the heated discharge is to be made; the onus of proof is on the utility either using or proposing to discharge condenser waste heat.

Clearly, as part of any variance request, some evidence of thermal plume behavior, both temporally and spatially, must be provided. For a newly proposed plant or one under construction, the only recourse available is to use theoretical or hydraulic model studies to provide such information. For operating power plants, field measurements can be made on actual plumes.

Historically, plume field measurements have been made with possibly one or more of the following objectives in mind.

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- a. To assess and therefore minimize plume water recirculation between intake and discharge points that could reduce plant efficiency.
- b. To help predict possible ecological effects associated with heated discharges.
- c. To develop better intake and outfall designs to satisfy water quality standards, or conversely, to demonstrate the viability of such designs for compliance with such standards.

For some time the classical technique for measuring plume temperatures has been to use a boat with in situ temperature-sensing instrumentation; for spatial resolution, the boat merely negotiates through the plume area. More recently (in the later 1960s), aerial infrared scanning became commercially available after having been originally developed for remote surveillance by the military. Both methods are in common usage today for thermal plume measurements; however, except for the obvious advantages and disadvantages of the methods, little effort has been extended to systematically contrast the two methods for the purpose of determining other possible significant weaknesses or strengths. Since the occurrence of transient phenomena in natural water bodies is able to continuously distort plume configurations, it is impossible to assess the adequacy of each method individually because there is no standard by which this can be done. However, by comparing the data of both methods, acquired essentially simultaneously on a particular plume, it might at least be possible to demonstrate reasonable agreement—between the methods and thus, in a quantitative way, indicate something about their viability. Should there be significant disparities between the methods, it would be difficult to point to the more or less accurate method since many mitigating factors affecting each method could cast doubts on any positive conclusions one might be tempted to make. In any event, because of the wide use of both methods for determining plume configurations, it was felt that a systematic program to contrast the techniques should offer valuable information to those contemplating future efforts involving these methods. To this end, Argonne National Laboratory and the University of Wisconsin undertook a joint investigative effort, each capitalizing on its respective experience with boat or infrared acquisition methods. In all, five different thermal plumes were measured nearly simultaneously on four different dates.

The studies were performed at the Point Beach Nuclear Power Plant located on the shoreline of Lake Michigan in Wisconsin. The Point Beach plant has two 523-MWe pressurized light-water-moderated and -cooled reactors. At full power operation, each unit has a $25.1 \text{ m}^3/\text{sec}$ cooling water flow rate with a corresponding 10.7°C temperature rise across the condenser. The cooling water is returned to the lake about 50 m offshore through two (one per unit) 10.7-m wide, 4.2-m deep surface canals. The outfalls extend into the water in opposite directions at a 60° angle with the shoreline. The cooling water intake for both units is located 533 m offshore.

5.2 EQUIPMENT, DATA ACQUISITION, AND DATA REDUCTION

5.2.1 Boat (In Situ)

The boat temperature measurements for this study were taken from a 5.5-m cathedral-hull fiberglass boat powered by twin 50-hp (37.31 kW) outboard motors. The measurements were acquired from a submerged boom affixed to the side of the boat having six attached thermistors spaced at 0.5-m intervals from 0.5 to 3 m from the surface. A seventh thermistor was attached to a 0.75-m long piece of spring strap steel, which was held about 3 m away from the side of the boat. This thermistor was used for surface temperature measurements. While the boat is moving, the spring steel allows the thermistor probe to follow the water surface in the presence of waves. The surface probe is typically located several centimeters below the water surface. Figure 5.1 schematically shows the survey boat with the temperature boom and outrigger surface probe in addition to other equipment described below.

When underway, the boat travels up to 3 m/sec, and in a 1-hr time interval (a period typically devoted to plume measurement), the boat travels 10-11 linear km. Yellow Springs Instrument Series 700 linearized thermistors were used for this work; the thermistors have a 0.6-sec time constant. Analog information proportional to the temperature from the seven probes was digitized and then visually displayed and recorded on paper tape and on magnetic cassette tape. System measurement accuracy is estimated to be $\pm 0.2^\circ\text{C}$. Each time the thermistors are sampled, time, water depth, and range location are also displayed and recorded. The data sampling and recording interval is selectable by an operator; however, a 4-sec period was used for this study. Thus, 900 known locations will be sampled per hour.

The visual display is used by the boat operator to locate the position of the plume. The printed paper tape is used as a place to record possible observations while a plume is being measured and as a backup for the cassette tape. The data from the cassette are then transcribed to a magnetic tape in a format suitable for computer processing. The paper printer (Anadex Type DP650) is capable of writing up to two lines of 21 characters per second. The cassette tape recorder is an incremental unit Memodyne Model 201. Depth readings are taken from a Datamarine unit, modified to provide binary-coded-decimal output for interfacing with the boat's data acquisition system. The location system is a Motorola Mini-Ranger microwave system, which consists of two shore-based transponders positioned at known shore locations in addition to a receiver/transmitter unit and a range console located on board the boat. Range information from each transponder is updated about five times per second; however, the range information is recorded at the system acquisition rate preselected by the instrumentation operator for recording all boat data. The range information is translated by trilateration into boat position during computer processing. The entire instrumentation system is powered by two 12-V lead-acid storage batteries; the system requires nominally 6 A at 24 V. In addition to the above measurements, the boat crew routinely makes ambient water and atmospheric measurements such as wind speed and direction and water current speed and direction. These measurements are normally taken immediately before and after each boat temperature survey.

The boat crew normally consists of three members. One specifically handles the boat (the pilot), another operates the instrumentation, and the third manually depresses the boom to maintain it in a selected position within the water. This is done by means of a depressor bar shown in Fig. 5.1.

All the data as transcribed from the original cassette tape are fed into a computer back at the laboratory along with necessary calibration data and suitable programming to prepare temperature-position plots. Isotherm contouring to this data has been done by hand. Figure 5.2 shows an example of a hand contoured plume with actual temperature values appearing as barely legible dots within the figure. The temperature data are not legible because the figure was substantially reduced in size for presentation purposes. The lines formed by the dots represent the boat path.

It was stated that the boat-acquired isotherms were contoured by hand. Obviously, some degree of intuitive judgment and latitude in data interpolation must be exercised in drawing the isotherms. Therefore, subjectivity and error are inherent in the presented contours. Numerous two-dimensional computer data interpolation and contouring codes are available. Some of the most promising codes were previously tested with similar data taken using the present Argonne boat method. These codes invariably mis-interpolated the temperature values between two somewhat separated data transects, but did reasonably well in fitting the data close to the transects themselves. This is to be expected since the codes do not contain the necessary physics describing turbulent heat transport, but, rather generally use a nearest-neighbor algorithm. Such algorithms are more suitable for uniformly or randomly distributed data.

Observations on thermal plumes show them to meander and undergo distortions with time. This kind of plume behavior is the result of ever-changing wind stresses on the water surface and turbulent motions within the water body. Therefore, to gain a reasonably accurate picture of a plume using boat-acquired data, one has the dilemma of gathering the data over a reasonably short period of time, but yet obtaining sufficient data for isotherm-contouring purposes. Experience with the present technique has shown a one-hour data acquisition period to be nearly optimum if the boat pilot initially concentrates his data transects in the near field region of the plume (near the discharge), where the temperature gradients are largest, and then progressively works the boat outward from the discharge with increasing separation between transects. A serpentine course through the plume should be taken, terminating each individual transect when possible, in ambient temperature water. Although this is a rather straightforward plan, it is often difficult to follow in the field since there are too few reference points in the water or on the land by which a pilot can conveniently gauge his turns and course for differing sets of plume configurations. The Mini-Ranger readings are difficult for the pilot to use in the field because they yield range, not coordinate, information. Significant portions of the plume can therefore be missed entirely by the boat survey method. This fact can be discovered in the laboratory only after the data have been processed by the computer. Furthermore, a pilot will occasionally spend a great deal of time on a misdirected course, particularly when a plume has a complicated

structure. These are significant factors that occasionally lead to poor quality or unacceptable plume data. Incorporating a small desk-top computer and an x-y plotter aboard the boat makes it possible to minimize such problems. The range information can be converted immediately to a real-time position indication on the plotter. If the instrumentation operator marks off on the position plotter selected temperature information, such as when ambient temperatures are reached along a given transect, the pilot can better select a course since everything is in real time. This capability is being designed into the present Argonne instrumentation package.

5.2.2 Infrared

The heart of the University of Wisconsin thermal scanning system is a Texas Instruments (TI) RS-18A thermal scanner employing a liquid-nitrogen-cooled HgCdTe detector. Operated as a single-channel system, the RS-18A detects 8-14 μm wavelength radiation emitted from the first few tens of microns of the water's surface. The field of view of the scanner is 100° (50° on either side of nadir); its instantaneous field of view (resolution) is 2.5 milliradians (mrad) based on 30% modulation. For real temperature measurement, 100% modulation is necessary, so the effective resolution of the RS-18A becomes about 10 mrad.¹ The scanner is electronically roll-stabilized resulting in a lightweight, easily mountable system.

The output of the RS-18A is fed in parallel to an oscilloscope, a film maker (Honeywell 1856 Oscillograph), and an FM tape recorder (Sangamo SABRE III). The video and sync signals are monitored with the oscilloscope both before and after being recorded. The film maker delivers a real-time output on Visicorder recording paper enabling the operator to quickly ascertain the nature and scope of the thermal plume. Flight lines can thus be adjusted to spatially and temporally encompass the most interesting thermal features.

In addition to the nonpermanent Visicorder imagery, the film maker produces a permanent high quality film image from the tape recorded data. The tangential image distortion caused by linearly sweeping scans generated at a uniform angular speed is removed by applying an external tangential sweep signal to the film maker. Since the variation in spot size (resolution) with scan angle is left uncorrected, the image intensity variation with scan

angle precludes any serious quantitative densitometric efforts. (TI manufactures a film maker for about three times the price of the Honeywell, which is designed to compensate for these variations.) The film imagery is a guide to further data analysis and helps to evaluate and categorize general types of thermal plumes.²

Obtaining accurate thermal maps from the analog tape data requires high quality ground truth. Although the RS-18A has a blackbody calibration capability, atmospheric attenuation effects necessitate surface temperature measurements. The limiting factor in most thermal scanning efforts has been the quality of the ground support. For a scanner resolution of 10 mrad (100% modulation), one must have isothermal regions as large as 144 m² for a typical flying height of 1200 m. At least two calibration points are necessary, preferably one at either end of the plume temperature range. These criteria are difficult to attain with shore-based ground truth measurements.

To make a thermal map, the analog data are digitized to 256-level resolution. Terrain features on a digital printout are compared to aerial photographs and maps. A scaled rectilinear map is then produced. Resulting spatial coordinates are accurate to better than 5%. The ground truth locations are identified and temperatures assigned to the digital voltage levels. Since the scanner responds only to radiant energy in the 8-14 μ m region, the usual assumption of radiant energy proportional to T^4 is not completely correct.¹ However, assuming

$$V = A + BT^4 \quad (1)$$

introduces errors less than 0.04°C over a 30°C temperature range. (V is the digital voltage level, T is the Kelvin temperature, and A and B are constants.)

At this point, one can produce either a digital temperature map or call upon a contouring program to draw isotherms. Each technique has inherent advantages. The contoured isotherm display is much easier to view and is thus more suitable for all except the most detailed analysis.

Digital tape data of about 650 points per scan line and about 400 scan lines per plume are transferred into a 100 x 200 array using linear interpolation. The contouring subroutine then locates the intersections of the isotherms with the grid lines associated with the array. These points are passed back to the main program as plotter coordinates. The coordinates are adjusted to correct for aircraft crab (the angle between the aircraft

centerline and the direction of flight caused by crosswinds). These crab corrected coordinates are sent back to the contouring subroutine. Smoothing is achieved by using a running average to generate intermediate plotter coordinates every 0.5 mm. Figure 5.3 is an example of a contour map with the intake and outfall structures drawn in by hand for clarity.

A Douglas DC-3, owned and operated by the Wisconsin Department of Natural Resources, was used as a platform for the thermal scanning. Adequate electric power is available and is separate from that used for flight instruments. Two belly holes allow aerial photographs and thermal scanning to be done simultaneously. A vertical television monitoring system, adjacent to the scanner and camera wells, allows the pilot to see most of the scanner and camera fields of view. This greatly increases the accuracy of the flight lines, which is necessary for low altitude work. An area navigation system allows precise and reproducible flight lines to be flown.

5.3 COMPARISON OF BOAT AND INFRARED DATA

5.3.1 Introduction

Three convenient and widely recognized ways of describing a thermal plume are:

- a. Isothermal configurations.
- b. Areas contained within isotherms.
- c. Centerline temperature decay.

With these as a common denominator, the two methods are critically compared. In addition, point-by-point checks of temperature were made for a number of locations for two dates.

5.3.2 Plume Configurations

On May 15, 1974 an intensive study was made whereby four infrared and four boat plume measurements were obtained. Two sets of data were taken, the first in the early afternoon and the other in the late afternoon. Because of flight scheduling reasons, each comprised two thermal scans sandwiched between two boat runs.

Just before the first boat plume measurement, the along-shore wind speed changed from 8.5 to 5 m/sec. In addition, the along-shore component

steadily decreased throughout the day, then shifted dramatically by 180° within 15 min of completion of the final boat measurement (1635). Air temperature was 8.3°C , and lake surface conditions were slightly choppy with 0.3- to 0.6-m waves. The ambient current at noon (1200) was 7 cm/sec along shore in a southerly direction.

Figures 5.4 through 5.7 compare the four boat plumes with two representative thermal scans. All the boat and thermal scanner data for this date indicate that the plume moved northward as the day progressed, exhibiting a strong correlation with the wind changes. All plumes display a fairly sharp temperature gradient on their upcurrent edge. In addition, there is good agreement between gross plume curvatures on each figure except for Fig. 5.4. In this case, the boat plume exhibits a greater gross southward curvature. Ascribing this shift to the 44-min delay between the boat and IR data is consistent with the northward-progressing plume.

In view of the differences in measuring techniques and the temporal variability of the ambient lake and atmospheric environment, which has a pronounced effect on plume behavior, the general plume configurations agree well. This evaluation is admittedly somewhat subjective.

Figure 5.8 compares plumes on August 10, 1973. The weather conditions preceding these plumes were steady with 4.5-m/sec offshore winds. Air temperature during the afternoon hours approached 30°C , and the lake was choppy with 0.3-m waves. The ambient current was northward at 3 cm/sec. Although the IR data were taken 1.5 hr after the completion of the boat run, the general configuration between the two plumes is good. Both measurements show the presence of strong upwelling; the IR technique, due to its more intensive coverage, indicates this more pronouncedly.

Figure 5.9 compares the plumes taken on the morning of June 7, 1973. There was a 7-m/sec offshore wind. The air temperature was 28°C and the lake was choppy with 0.3-m waves. Once again, gross plume features agree well.

Figure 5.10 compares the plumes measured on June 6, 1973. The winds were 1-3 m/sec from the west-northwest. The skies were clear, and lake conditions were calm with no waves. Temperature measurements at five depths indicated a very large floating plume on the surface due to the quiescent lake conditions. The isotherms greater than 13°C agree fairly well. However, away

from the outfalls, agreement was poor. The IR contour show large disconnected isothermal regions. This amorphous character of the plume made contouring the boat measurements extremely difficult.

Several conclusions can be drawn from the above comparisons.

a. At those times when the driving forces (e.g., wind, lake currents, and discharge velocities) remain constant for the duration of both measuring techniques, general plume shapes and characteristics can be expected to agree. When driving forces vary with time in a known manner (e.g., the wind variation on May 15, 1974), observed differences can be explained.

b. A general feature of contour mapping should be pointed out. In regions of strong gradients, spatial separation of contour lines is small. Thus, differences in contour lines between the two techniques due to experimental uncertainties (e.g. calibration) will be minimized. This can be seen near the outfall, the upcurrent edge, and other regions where strong gradients occur.

c. Thermal scanner data exhibit considerably more surface detail than boat data. On days such as June 6, 1973, when the plume is not well defined, considerably more boat data would be required before agreement could be expected. Also, on such calm days there exists the possibility of solar heating and evaporative cooling establishing strong temperature gradients through the first few millimeters below the surface. This would preclude agreement ever being attained, since the scanner would respond to this effect much more strongly than the boat measurement.

5.3.3 Point-by-Point Comparisons

Two dates (May 15, 1974 and June 6, 1973) were selected for point-by-point comparisons of the thermal scanner data with the boat data. A rectilinear digital map of scanner output voltages was produced as discussed in Sec. 5.2.2. Several boat locations were then mapped onto the display. Due to the inherent time differences in data acquisition, most points were chosen well outside the central plume region. Most points were also selected in isothermal areas away from regions of large temperature gradients as indicated by the digital map. The main exceptions were the plume outfall

locations. As long as power plant conditions remained constant, these regions exhibited constant temperatures over several hours.

Least-squares fits using Eq. 1 were performed for both dates. The results are shown in Tables 5.2 and 5.3. In both instances the constraint of choosing points outside the plume caused the data to be packed near the low temperature end, except for the one or two outfall temperatures.

There is excellent agreement in the May 15, 1974 comparison, except for one point that shows a 0.7°C deviation. This point was taken intentionally within the plume to indicate the problems one faces. On the other hand, the June 6, 1973 comparison showed fairly large deviations, although all points were well outside the central plume region. As discussed in the preceding section, these differences could be ascribed to either

- a. Solar heating and thermal boundary layer effects,
- b. Time variability of the far field region, or
- c. A combination of both.

Insufficient experimental data were obtained to separate these effects. Both, however, are caused by quiescent lake conditions.

5.3.4 Areas Contained Within Isotherms and Centerline Temperature Decay

Figure 5.11 is a plot of the areas within given isotherms for the early afternoon runs, May 15, 1974. Figure 5.12 is a similar plot for the late afternoon runs. The agreement among all four sets of data is very good. The primary cause for deviations in the boat plumes is the subjective interpolation required when drawing the plumes.

Even though the plumes were shifting with time throughout the day and changing shape, the area within a given isotherm remained relatively constant.

Figures 5.13 and 5.14 represent the centerline temperature decay of the plumes. Again, the agreement is good, not only between the two methods but also with time.

Figure 5.15 shows the area contained within isotherms for August 10, 1973. Both nuclear units were operating, producing two distinct plumes (except for the isotherms near ambient, which result from interference between the two individual plumes). The lower IR data set in this figure

(circles and squares) resulted from calibration with the University of Wisconsin ground truth. This consisted of a measurement at the edge of the south discharge structure and one near the shore south of the outfall. Calibrating with ground truth obtained from the boat shifted the data set (triangles and hexagons) to agree much better with the data obtained from the boat.

The centerline temperature decay of the two plumes for August 10, 1973 agree well (see Fig. 5.16). The plume areas as measured by both methods agree well for the higher temperature isotherms (see Fig. 5.17), but larger deviations are seen for the lower temperature isotherms. The same is true of the centerline temperature decay, although deviations at the low end are not as great (see Fig. 5.18).

No attempt was made to ascertain the areal extent or centerline temperature decay for the June 6, 1973 data since agreement between the boat and IR plumes was so grossly different, except for the higher temperature isotherms near the outfalls, as mentioned previously.

5.4 DISCUSSION

Thermal scanning measures temperatures within only few tens of microns of the surface, whereas the boat method has the option of measuring at a number of different depths. Surface conditions are usually rough enough so the infrared measurements are representative of the surface temperature. Occasionally, however, calm conditions can cause surface skin effects that mask the infrared detection of the representative surface temperatures. This phenomenon has apparently also been observed by another university group.³ Near an outfall, the mechanical turbulence generated by the discharge momentum causes sufficient mixing to destroy this effect, and the scanning is therefore expected to be accurate.

Thermal scanning offers the capability of generating two orders of magnitude more data in about 1/100th the time required for boat measurements. The aerial infrared monitoring offers a truly synoptic detailed picture of the surface temperature, whereas the boat technique offers a time-distorted picture of the plume. The distortion is a function of the sampling course chosen by the boat pilot and the environmental conditions influencing the plume.

Furthermore, the limited amount of data generated by the boat technique necessitates exercising interpolative judgment to generate isotherms. On days when a thermal plume displays an unusually amorphous character, contouring boat data become extremely difficult (e.g. June 6, 1973). It is speculated this would occur on very quiescent days, which can also cause problems for the infrared technique.

The results of this and other work have shown that atmospheric attenuation effects demand ground truth for good thermal scanner calibration.¹ Some proponents of thermal scanning claim sufficient accuracy can be obtained using internal scanner calibration; we do not feel this to be true.

In view of all the problems inherent to each technique, the results of this report indicate good agreement between the two methods for all but one of the dates considered. This includes comparison of general plume configuration, centerline temperature decay, areas contained within isotherms, and point-by-point comparisons.

For routine monitoring of surface plumes, both the infrared and boat techniques are viable. However, with respect to the speed of acquisition and extent of coverage, the infrared method is superior. For situations in which three-dimensional temperature data are required or when simultaneous in situ measurements of other physical, chemical, and biological parameters with temperature are needed, the in situ method is clearly the only feasible one to use at present. Judiciously combining the two methods can provide a better total picture of thermal plumes.

TABLE 5.1. Summary of Effluent Limitations Guidelines and Standards for Heat

Type of Unit	Best Practicable Control Technology Currently Available to be met no later than July 1, 1977	Best Available Technology Economically Achievable to be met no later than (date)
Large Base-Load		
Construction completed after July 1, 1977	No discharge	No discharge (July 1, 1980)
Construction completed before July 1, 1977		
• 500 MWe and larger	No limitation	No discharge (July 1, 1978)
• 300-499 MWe	No limitation	No discharge (July 1, 1979)
• all other	No limitation	No discharge (July 1, 1980)
Small Base-Load	No limitation	No discharge (July 1, 1983)
Cyclic	No limitation	No discharge (July 1, 1983)
Peaking	No limitation	No discharge (July 1, 1983)
<p>Large means units in plants over 25 MWe and in systems over 150 MWe. No limitation for any unit with a remaining service life of six years or less. No limitation on once-through house service water for nuclear units. No discharge excludes blowdown, which is limited to a temperature not exceeding the temperature of water returned to the condenser. Variations can be granted on a case-by-case basis where sufficient land is not available and (for best practicable control technology currently available, only) where neighboring land uses would be impacted by saltwater drift, provided (for both land availability and saltwater drift) alternative technologies are not practicable.</p>		
<p>Standard of performance for new sources is no discharge of heat (except for blowdown) for all units, without exception.</p>		

TABLE 5.2 . Least-Squares Results for Point-by-Point Comparison:
May 15, 1974, Late Afternoon

Scanner Level	Boat Temperature °C	Calculated Temperature °C	Temperature Deviation °C
3.9	7.2	7.1	-0.1
4.3	7.7	7.4	-0.3
5.5	8.2	8.3	0.1
5.5	8.4	8.3	-0.1
5.8	8.5	8.5	0.0
6.4	8.8	8.9	0.1
6.3	9.0	8.8	-0.2
6.5	9.0	9.0	0.0
9.8	10.5	11.2	0.7
19.0	17.4	17.2	-0.2

TABLE 5.3. Least-Squares Results for Point-by-Point Comparison:
June 6, 1973

Scanner Level	Boat Temperature, °C	Calculated Temperature, °C	Temperature Deviation °C
12.5	17.7	17.7	0.0
12.0	17.4	17.3	-0.1
4.5	11.7	11.9	0.2
4.9	11.6	12.2	0.6
2.7	10.9	10.5	-0.4
2.7	10.6	10.5	-0.1
4.6	12.3	12.0	-0.3
4.9	11.8	12.2	0.4
4.5	11.8	11.9	0.1
3.2	11.3	10.9	-0.4

Fig. 5.1 Survey Boat Equipped with Temperature Measuring and Range/Range Equipment

Fig. 5.2 Boat Thermal Contour Mapping

Fig. 5.3 Infrared Thermal Contour Mapping

Fig. 5.4 Comparison of Boat (1045-1150) and Infrared (1234) Thermal Mappings on May 15, 1974

Fig. 5.5 Comparison of Boat (1245-1345) and Infrared (1234)
Thermal Mappings on May 15, 1974

Fig. 5.6 Comparison of Boat (1450-1545) and Infrared (1600) Thermal Mappings on May 15, 1974

Fig. 5.7 Comparison of Boat (1555-1650) and Infrared (1600) Thermal Mappings on May 15, 1974

Fig. 5.8 Comparison of Boat (1416-1500) and Infrared (1630) Thermal Mappings on August 10, 1973

Fig. 5.9 Comparison of Boat (1102-1230) and Infrared (1048) Thermal Mappings on June 7, 1973

Fig. 5.10 Comparison of Boat (1120-1255) and Infrared (1300) Thermal Mappings on June 7, 1973

Fig. 5.11 Comparison of Areas Within Isotherms on May 15, 1974, Early Afternoon

Fig. 5.12 Comparison of Areas Within Isotherms on May 15, 1974, Late Afternoon

Fig. 5.13 Comparison of Centerline Temperature Decay on May 15, 1974, Early Afternoon

Fig. 5.14 Comparison of Centerline Temperature Decay on May 15, 1974, Late Afternoon

Fig. 5.15 Comparison of Areas Within Isotherms on August 10, 1973

Fig. 5.16 Comparison of Centerline Temperature Decay on August 10, 1973

Fig. 5.17 Comparison of Areas Within Isotherms on June 7, 1973

Fig. 5.18 Comparison of Centerline Temperature Decay on June 7, 1973

SECTION 5.0

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6.0 NEAR SHORE LAKE CURRENT INVESTIGATIONS

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6.1 INTRODUCTION

Three in situ recording current meters were used during the 1973 field year to obtain continuous records of the lake currents near the Point Beach Plant. From these three meters (only two of which have yielded data thus far), six data records were gathered over the time period from May 11 through October 9, 1973. All the records were taken at a depth of about 3 m; three records were taken in about 6 m of water, and three in about 10 m of water. Figure 6.1 shows the location of the meters in relation to the Point Beach plant, and Table 6.1 gives the time of each record.

Meteorological data (wind speed, direction, and air temperature) were gathered on a continuous basis throughout the measurement period. However, for several periods during the months of interest the portable weather station used throughout most of the program was inoperable. Data gathered at the Point Beach site by the Limnetrics Corporation of Milwaukee, Wisconsin were therefore substituted where appropriate (see Table 6.2).

The current data were reduced by computer and are plotted in several ways. Some spectral analysis techniques were used in examining the current data and the relation of the data to the wind. This analysis is continuing on the 1973 data as well as on data being collected under the ongoing effort.

6.2 INSTRUMENTATION

The current meters used for this study were in-house modified Braincon Type 381 histogram recording current meters. The modification consisted of replacing the Savonius rotor speed sensor with a ducted impeller assembly.¹ The meters were set up to record the total number of turns of the impeller during a 20-min interval (adding turns in one direction and subtracting turns in the other direction). Current direction was also recorded as a 20-min average. The meter data are recorded on 16-mm film by exposing a film frame for 20 min using small radioactive luminescent markers, which are coupled to the speed and direction sensors.

The purchased meters were modified for use near the water surface in the zone where surface wave action is important. The Savonius rotor supplied

with the instrument is an omnidirectional device, and oscillatory motion such as that produced by the orbital particle motion beneath a wind wave is rectified and included in the indicated average current. The modified meters integrate this oscillatory motion and retain just the nonoscillatory component of the flow. The directional vane on the Type 381 meter is large ($\sim 0.35 \text{ m}^2$) and does not respond rapidly to wave-induced direction changes. On the modified meters, this vane orients the duct into the mean flow, and its slow response to wave action was therefore an asset for the purposes of this study.

The Braincon meters (both before and after modification) were calibrated in the tow tanks at the University of Chicago and at Northwestern University, respectively. The results indicate that the modified meters are suitable for use near the surface (several meters below the surface). In the laboratory tests, the ducted impeller successfully nulled out oscillatory wave motion and recorded the true mean flow. The threshold of the impeller was less than 2 cm/sec, and the sensor was found to be linear from 3 to more than 100 cm/sec, which compares favorably with commercial ducted impeller meters. To a first approximation, the response of the ducted impeller assembly to flow at an angle to the duct axis is a cosine response. The major fault of the meters in this configuration (besides maintenance, about which more will be said) is that the vane does not respond to low flow as readily as the impeller. The vane could not be tested in a completely submerged position in the laboratory tests; in a semisubmerged position, it required a current of at least 7 cm/sec to completely orient the duct. In a taut line monitoring system in a completely submerged position, this figure would be much reduced.

The calibration data obtained using the Savonius rotor in the presence of waves indicated that the rotor does a good job of rectifying and integrating the total flow of both the oscillatory and steady components. When the mean flow is greater than the maximum orbital velocity associated with a wave group at a given sensor depth, then flow sensed by the Savonius rotor is about the same as the mean flow. This would only be true when both the mean flow and orbital velocity are in the same direction, as in the tank studies. Then the orbital flow is at some angle with the mean flow, the current speed sensed by the Savonius rotor is actually greater than the mean flow. The effects of rotor inertial response were not considered in these conclusions. When the mean flow is less than the maximum orbital motion,

the speed sensed by the rotor is always greater than the mean flow. Using first order wave theory, the speed data obtained in the presence of waves in the University of Chicago tow tank is consistent with what one would expect. Figure 6.2 shows an example of the tow tank data with the actual towing speed, the speed sensed by the Savonius rotor, and the speed that is calculated for rectifying the orbital wave motion. Also, using first-order theory, it is apparent that waves on Lake Michigan at some times produce strong horizontal motion to depths greater than some of the bottom depths in this study. Because the wave orbital motion is a function of wave height, wave period, and depth of the sensor, no specific numbers can be given in defining the zone of significant wave pulsing, but one example is shown in Table 6.3. These numbers were calculated using the deep water approximation. If intermediate water equations were used, the dropoff with depth would be slightly less. Thus, use of a Savonius rotor in the nearshore region may lead to uncertainties in the data.

The meteorological data were gathered using an MRI mechanical weather station described in Sec. 3. Where necessary, these data were supplemented by data gathered by Limmetics Corporation from an Aerovane type wind velocity sensor, also mounted on the Point Beach plant intake crib 7.5 m above water. In general, the overlapping data from the two stations agreed quite well.

6.3 DATA COLLECTION

The current meters were deployed about 1.5 km south of the Point Beach plant. One meter was located in about 6 m of water with the speed sensor at about a 3-m depth. Two instruments were located in 10 m of water with the speed sensor of the top meter at a depth of about 3 m. Data from the lower meter are not yet available. The shoreline direction and the bottom contours are approximately parallel with a direction of 335-155°. The location is slightly sheltered by Rawley Point about 8 km to the south and by Kewaunee Point about 8 km to the north.

The current data were gathered in the form of 20-min averages. The meters were set up to run for a maximum of 50 days but were normally serviced at monthly intervals. The mooring configuration for the offshore station is shown in Fig. 6.3. The nearshore station had a similar mooring but had only a single instrument at a depth of 3 m. Divers normally serviced the meters;

and all installation, service, and retrieval of the meters were carried out from the project's 5.5-m boat or a 4.6-m inflatable Zodiac boat. The meters required frequent maintenance due mainly to problems with bearing adjustment and initially with impeller clearance and durability. For these reasons, the ducted impeller assemblies manufactured at Argonne were replaced by commercial replacements (Endeco) for the 1974 field year as soon as Endeco design became available.

The meteorological data were collected in the form of strip-chart records of approximately one-month duration. The MRI meteorological station required little maintenance.

6.4 DATA REDUCTION

The current meter records (on 16-mm film) were reduced using an optical pattern recognition computer, "Alice," designed and built at Argonne.² Software was developed to handle the film from the Braincon meters, and all the records but one were reduced in this way. The one record not reduced by Alice was sent to the Braincon Company for manual reduction because a malfunction in the camera made machine reduction difficult. From this point, with the raw data on magnetic tape, several programs were developed to calibrate the data, to weed out bad data, and to plot the data in several ways. Plots of current speed and direction versus time, current histograms, current and wind velocity as a function of time, and progressive vector displays were generated.

The wind data were read manually and transcribed onto punched cards in the form of hourly averages of the wind speed, wind direction, and air temperature. The data from the Limetics meteorological tower was handled in a similar way and incorporated into the routines used for the MRI data.

6.5 DATA ANALYSIS

Data analysis of the current and wind data consisted of a visual examination of the reduced data in the form of the figures discussed above. Analysis of the data using spectral techniques in an attempt to gain insight into the relation between wind and current and the relation between the current fields at two points has begun, but the only results presently available are power spectra of each current record.

Figures 6.4 through 6.7 are plots of the current speed and direction as a function of time. Each vertical line on the direction plot shows the movement of the direction vane over a 20-min period. Each dot on the speed plot is the result of a 20-min average of the current speed. Those records that were taken simultaneously are shown on the same figure when simultaneous data exist. Not all the current speed data are plotted on the same scale; care must therefore be taken when comparing two records.

In general, these figures show that currents flow predominantly in two directions (shore-parallel north and shore-parallel south) and that when two meters were recording at the same time, they saw similar events. The currents typically remain in one direction from 1-10 days (72 points = 24 hr) except when current speeds are very low, and then some highly variable directions are apparent. Current speed on the other hand is unsteady, typically increasing to a peak and then decreasing to near zero on about a daily basis. Rarely is the current speed even nearly constant, except when it is very low. The plots for the nearshore and offshore meters indicate that they are coupled closely with respect to direction and direction changes. Current speeds are slightly less well correlated, but still show a high degree of coherence between the two locations.

Examination of individual plots indicates that significant shifts in the current may be either gradual or abrupt. The current direction may change completely in one 20-min period or it may change gradually over a period of hours. An example of both of these occurrences is shown in Fig. 6.4, where a gradual current change begins at about noon on May 14. The current speed drops to zero over a period of several hours, and the direction swings from south to north over a period of about 2 hr. At about 0300 on May 16, however, a much more abrupt change in the current is apparent where the direction shifts 180° in 20 min and the speed changes from about 15 cm/sec to 0 and back to 15 cm/sec in about 2 hr. These abrupt changes are often coupled with rapid changes in the wind direction. Due to an impeller failure, the speed data shown after May 24 are not available.

Figure 6.5 shows a plot of speed and direction from record (1-97-73); this record was reduced manually by the Braincon Corporation. Braincon did not supply information on the total movement of the direction reading; they just reported an average value. For this reason, a constant spread of 10° was assumed for plotting purposes in the figure. Note also that the speed

scales for the plot are different than in the previous figure. Also, the record did not begin until the afternoon of June 7. Figure 6.6 shows current speed and direction from records (2-96-73) and (2-97-73), which were taken simultaneously. Again, the speed scales are not the same. Although a comparison of the records shows that both current meters were responding to a generally similar current field, it is clear that, at any moment, the currents sensed by the meters may vary substantially. Major directional shifts are normally seen in both records, but the exact time and direction are not necessarily the same. The speed data are more variable and not as easy to compare by examining these figures. However, the records are roughly similar at both stations with the offshore station seeing higher values.

Figure 6.7 is a plot of the current velocity from records (3-96-73) and (3-97-73), which were taken simultaneously in the late summer and early fall. Again, these records are plotted with different speed scales. The records show basic similarity, but are not similar in all detail. A problem exists with the data from record (3-96-73). At some point in the recording period (which may have been about October 5 from some indications), the meter broke free from its anchor and floated to the surface where an auxiliary anchor kept it from drifting away. This in effect moved the speed sensor from a depth of 3 m to a depth of 1 m and resulted in a mooring that was not taut. This slack mooring would result in the meter seeing decreased value of speed due to instrument tilt, and there is a definite indication of this about October 5. Also, high frequency variations in the current velocity would undergo some filtering due to the slack mooring. This is better seen in the wind and current time plots that follow.

Some of the information contained in the current velocity histories is summarized in the histograms plotted in Figs. 6.8 through 6.14. The histograms show the percent of time the current direction was in each of the four quadrants, the average speed in a quadrant (the number inside the direction bar), and the percent of time the current speed was in each speed interval. The direction quadrants are those centered about the shore-parallel and shore-perpendicular directions. These figures show that the current direction is usually in a quadrant centered about the shore-parallel direction, that the average speed in these quadrants is considerably higher than in the shore-perpendicular quadrants, and that the current is typically fairly low and only rarely greater than 20 cm/sec.

Specifically, records taken at the nearshore station [(2-96-73), Fig. 6.10; and (3-96-73), Fig. 6.12] exhibit lower current speeds in all quadrants, and currents between 0 and 5 cm/sec a large portion of the time. Figure 6.14 shows the average histograms comparing the nearshore station with the farshore station for records taken over the same time period. The percent of time in each quadrant is about the same, but the nearshore station sees speeds only equal to about one-half of those at the offshore station. In the shore-perpendicular quadrants, the difference in the average speed is even greater. The percent speed histograms show a shift from lower speeds to higher speeds as a function of distance offshore (or bottom depth).

Progressive vector diagrams of the lake currents are shown in Figs. 6.15 through 6.20. The small dots on the current track indicate the distance a "particle" passing through the current meter moved during a 20-min period. The asterisks are separated by 24 hr, and the record begins at the large circle. These plots further support the insight gained by examining the previous plots. The predominant direction is approximately parallel to the shoreline and the bottom contours ($335-155^\circ$), and flow is about equal in both directions. Since a progressive vector display is not a representation of the track of a water parcel, but a measurement made continuously in one position, it is interesting to note the onshore-offshore components that occur in the nearshore currents. At the inshore station, the currents in these records have a net onshore component, while the offshore station has a net offshore component. These perpendicular motions are perhaps an order of magnitude smaller than those motions along the shore. However, they may still be of importance in terms of the mixing between nearshore and offshore waters. In this regard, temperature measurements made simultaneously with the current measurements would be of interest in order to determine upwelling, downwelling, or oscillations in the thermocline. Unfortunately, the temperature data that were recorded simultaneously with the current data (on the Braincon film) have proved to be of insufficient clarity for machine reduction.

Another dissimilarity between the inshore and offshore stations apparent from the progressive vector plots is that the offshore station is apparently constrained less forcefully by the shoreline direction than the inshore station. This is illustrated by larger excursions in directions other than those parallel to shore by the offshore meter. Also, the scales of the motions in all directions are larger at the offshore station. (This

is, of course, a result of higher current speeds.) Typically, a directional event (one in which the current flows in a specific direction for a number of hours or days) has a distance associated with it of tens of kilometers, with the inshore station seeing excursions about half the size of the offshore station.

Looking at individual plots, Fig. 6.15 shows the track calculated from record (1-96-73) (an offshore record). This record is particularly strongly parallel to shore. (The shoreline direction is 25° to the left of the north arrow.) The scale of each individual vector plot is not the same (making machine plotting easier), but the scale is shown in the figure. The total motion represented from the start of the record to the end is about 60 km over about 13 days or about 5 km/day. One particularly interesting event occurs at about tract 325 where the current reverses quite rapidly. This occurs simultaneously with a strong shift in the wind as will be seen in other plots.

Figure 6.16, also an offshore station, looks considerably different from the previous figure. The motion appears much less constrained by the shoreline direction and a number of circular, gradual current shifts appear. The total motion represented in these figures is about 300 km over about 52 days or about 6 km/day, which is about the same as record (1-96-73) (see Fig. 6.15). Both records show flow in the onshore/offshore direction to be about 3 to 1 km/day, which may be of significance in terms of mixing shoreline effluent with offshore water.

Figures 6.17 and 6.18 are progressive vector plots of records (2-96-73) and (2-97-73), which were taken simultaneously. The onshore record (2-96-73) shows little variability in direction with a net flow onshore of about 0.25 km/day; the offshore station is not so limited to shore-parallel motion and shows a net offshore flow of 0.8 km/day. Total movement recorded was about 3.5 km/day for the onshore meter and 4 km/day for the offshore meter.

Figures 6.19 and 6.20 are plots of the tracks for records (3-96-73) and (3-97-73), respectively. Once again, the onshore record (3-96-73) is strongly constrained to shore-parallel directions, while the offshore meter is much less so constrained. Total motion at the onshore station was about 3 km/day with about 0.3 km/day in a shore-perpendicular direction and zero net perpendicular motion. At the offshore station, total motion was about

5.5 km/day with offshore motion of about 0.75 km/day. There are a number of current reversals in all the records (more noticeable in the offshore records) with periods from about one day to several days. As far as can be determined at present, most of these are related to changes in the local winds, although there are a number of examples for which this explanation is not appropriate.

In addition to the information gained on the occurrence of the nearshore currents, work is in progress to define the causative factors involved in the establishment of these currents. In light of this goal, perhaps the most interesting results are shown in Figs. 6.21 through 6.24. In each figure, time is represented on the horizontal axis where 24 hr is shown on each line. Wind and current vectors are drawn on the time axis. Current vectors have the direction of current flow, and wind vectors have the direction from which the air is moving. Therefore, when wind and current vectors are directly opposite one another, both fluids are moving in the same direction. As can be seen from the figures, at both the inshore and offshore stations the relation between the wind vector and current vector is quite striking (the shoreline direction is $335-155^\circ$). The current typically behaves as a bidirectional current whose direction is a function of the wind direction over the previous few hours. In most cases, if the wind is from a direction between 45 and 65° , then the current flows south, shore parallel. If the wind is from the opposite direction, the current flows north, shore parallel. There are, of course, numerous cases for which this simple idea does not hold true, but for about 75% of the time the local wind appears to be the dominant forcing function.

The current speed is not so clearly related to wind speed, although it is clear from the plots that current speed is generally 1-3% of wind speed. The speed (and direction) is a function of the sensor depth and water depth so that these results are not applicable to all points in the water column. However, at a depth of 3 m (above which the far field thermal plume typically floats), the above numbers are representative.

It is also apparent from these plots that a change in the wind direction is felt rapidly by the current meters. In fact, a steady current is often reversed over a period of several hours. It has not been possible to establish a quantitative relationship between the current vector and the wind vector, but efforts are continuing toward this goal. Other parameters

besides the local wind are influencing the current, and the precision of prediction will depend upon how many and how accurately these parameters are included. From an examination of the wind and current plots, however, a solution using local winds as the primary forcing function looks promising.

Figure 6.21 shows the wind and current vectors for record (1-96-73). This record indicates that the wind direction plays a dominant role in setting up the current direction in an alongshore mode. The wind speed, however, does not appear to be directly linked with the current speed. In numerous instances throughout these records, fluctuations in the current speed are not easily traceable to fluctuations in the wind speed. However, this is not surprising in light of the limitations of the wind measurements, that is, hourly averages at a single level. What is surprising is the obvious coupling between these gross measurements. Particularly striking examples of this rapid coupling in this record are on May 14 and 15 when abrupt changes in wind direction caused almost equally abrupt changes in current direction. On other occasions (May 17) a similar change in the wind caused the current to undergo a much slower response.

Figure 6.22 contains plots of wind and current for record (1-97-73). (The current record does not begin until June 7, and data are not available between June 15 and 26.) This figure also shows a pronounced coupling between wind and current, particularly when winds are high and from the north or south. July 2 is an example of a high current that is slowed and reversed by several hours of opposing winds; July 16 and 17 are examples where moderate winds gradually slowed the current and eventually completely reversed it over about a day.

In Fig. 6.23 showing records (2-96-73) and (2-97-73) that were taken simultaneously, the wind coupling is again apparent, but the currents set up at the nearshore station are not so pronounced as those at the offshore station. This makes them appear less dramatic, but they are coupled to the wind just as closely. There are times, however, when forces other than local winds have a profound influence on the near-surface currents. In some cases a change in current direction leads a change in wind direction. Although this may be due to nonsimultaneous wind and current records, it may also be due to wind fields acting outside the local area. An example of the current shifting before the wind is shown on August 3 in both records. Examples of currents

opposing the local winds are not infrequent, although records (1-96-73) (shown in Fig. 6.21) and (1-97-73) (shown in Fig. 6.22) do not have any clear-cut examples. On August 6, in both records (2-96-73) and (2-97-73) (shown in Fig. 6.23), the current reverses, while the wind (moderately strong) remains from the same directions. Again, on August 8 and 15 similar events are occurring in both records with the August 15 event indicating a significant current opposing the wind. Although these kinds of events are interesting, they are infrequent enough that a clearer understanding of why they occur may not be crucial to the main task, which is predicting the local currents in general so as to gain an understanding of the transport of pollutants in the nearshore region.

Figure 6.24 is a plot of wind and current versus time for records (3-96-73) inshore and (3-97-73) offshore. In essence, these plots also show a remarkable coupling of currents with local wind and further support the idea that a simple theory will make the currents predictable to a reasonable degree. There are a number of cases in which currents appear to be experiencing excursions unrelated to the winds (i.e. August 23, 25, and 30); and numerous examples of direct response of currents to winds (i.e. September 3, 5, 11, 14-16, 19; October 1, 3, and 4; etc.)

Energy density spectra have been computed for the shore-parallel components of the current velocity and plotted in Figs. 6.25 through 6.28. The plots were generated using a Fast Fourier Transform technique through application of a program written at UCLA.³ The number of data points in each record varied, but the plots were generated such that each spectral estimate had 14-27 degrees of freedom depending upon the record. To make plotting easier and avoid losing all detail at low frequency, a band averaging scheme of the following description was used on the data. Starting with the lowest frequency, frequency estimates 1-8 were plotted as single estimates, estimates 9-24 were plotted as an average over two frequency bands, estimates 25-56 were plotted as an average over four frequency bands, estimates 57-128 were plotted as an average over eight frequency bands. Where more or less than 128 estimates were generated, a similar scheme was used. Error bars in the figures represent 80% confidence limits. These were estimated from the equivalent degrees of freedom at each location.⁴

The figures in general appear similar, especially at low frequency. In Figs. 6.27 and 6.28, both the onshore and offshore records for the same periods are plotted together. As expected, the energy levels at the offshore station are considerably higher than those present at the nearshore station. This is probably a consequence of the frictional damping of the current due to the bottom. This difference in energy level is particularly noticeable at the high-frequency end of the spectrum. Figures 6.25 and 6.26, however, also have quite low energy at the high-frequency end of the spectrum, and both of these records are from the offshore station. In Fig. 6.27, a significant peak at about 24 hr occurs in both spectra. This is probably a function of the wind, a land sea breeze effect perhaps, but this peak is not apparent in the other spectra. Unfortunately, a spectrum of the wind has not yet been computed for these periods; such a spectrum may shed light on this question. Further analysis using spectral techniques is in progress utilizing this data as well as new data now being collected.

6.6 DISCUSSION OF DATA RELIABILITY

6.6.1 Current Meters

The use of the Argonne modified Braincon meters has not been totally successful. Although the meters do a good job of measuring currents near the surface, there are a number of uncertainties in their operation due to the ability of the vane to orient the duct and the chance that the gears or magnetic coupling will become uncoupled because of bearing misalignment. The bearings were made adjustable, and on several occasions their adjustment changed during operation. This sometimes resulted in loss of contact between the impeller and the inside housing and sometimes in the impeller seizing. Both of these possibilities result in a recording with zero current speed, so they are recognizable, but the lost data cannot be tolerated. However, most of the unusable data have resulted from a malfunctioning motor drive running the film cartridge.

6.6.2 MRI Meteorological Station

Although the MRI Met Station only rarely needs maintenance, it has a severe fault in the reliability of its timing mechanism. It has been difficult to trust the timing indications completely. The data reported here

have been cross-referenced with the data reported by Limmetics Corporation, as was indicated earlier, and the timing was adjusted where necessary. This problem is easy to remedy once it is recognized, and tying the time down by an independent method is in process. In a study of this kind, timing is critical. For this reason, the Accutron timers supplied with the Braincon current meters were replaced with crystal-controlled clocks before the season began.

6.6.3 Data Reduction

The computer reduction of the Braincon film is an excellent method for fast, efficient data reduction. However, care must be taken not to let erroneous information into the data record. This is particularly troublesome when the Braincon film has not been pretensioned properly and some overlapping of the data frames occurs. The meteorological station data were reduced by hand and were not nearly so voluminous as the current data. Problems with errors were also much less troublesome. However, because the data are recorded on a small strip chart, precision of the measurements was not as high as would be feasible with a more sophisticated system. The time period over which averages may be taken is also limited by the chart reduction. These limitations, however, are probably outweighed by the station's reliability.

6.7 CONCLUSIONS

The following general conclusions are supported by the data shown in this section.

a. The local wind field is coupled closely to the currents present in the nearshore region, at least to depths of 3 or more meters. The current speed was found to be generally 1-3% of wind speed. The time response of these currents is typically on the order of a few hours or less.

b. Forces other than the local winds play a role in establishing the current field in nearshore waters, but these forces are often overshadowed by the action of the wind. It may be possible to obtain a reasonable forecasting ability from a knowledge of the wind field only, but this is yet to be demonstrated.

c. The currents in the nearshore regions are predominantly in the alongshore directions. Flow perpendicular to shore does occur and may be

significant in terms of mixing a shoreline discharged effluent with offshore water. Flow alongshore is about one order of magnitude greater than flow perpendicular to shore. Typical alongshore flows are about 5 km/day; shore perpendicular flow is about 0.5 km/day.

d. Assuming that a bidirectional current describes the nearshore current regime, the direction of the flow can be predicted more than 80% of the time from the local wind direction. When high winds are present, this figure is conservative.

e. Bottom friction plays an important role in the inhibition of currents in the nearshore waters. In cases for which relatively steady conditions prevailed, the inshore meter (6-m depth) experienced only 70% of the current speed that the offshore meter (10-m depth) recorded.

f. A knowledge of the current profile in the vertical as well as horizontal directions and a temperature record taken concurrently would lead to greatly increased understanding of the phenomena described here (in particular, the effects of bottom friction as a function of bottom depth). The decay of the wind induced currents with depth, the coupling of the waters above and below the thermocline, the time lag involved in forcing current at different depths, and the changes in the current vector with depth would all contribute to an improved understanding.

TABLE 6.1. Current Meter Location and Data-Acquisition Period

Record No.	Time	Location	Comments
1-96-73	5/11 - 6/ 6/73	10-73	Speed recorded for about 1/2 of record
1-97-73	6/ 7 - 7/24/73	10-73	
2-96-73	7/25 - 8/22/73	6-73	
2-97-73	7/26 - 8/20/73	10-73	
3-96-73	8/23 - 10/10/73	6-73	Meter broke loose from taut mooring during this period
3-97-73	8/22 - 10/ 9/73	10-73	

TABLE 6.2. Meteorological Instrumentation and Sampling Period

Recording Period	Instrument	Location
5/10 - 6/15/73	ANL - MRI	Point Beach intake - 4 m above water surface
6/16 - 6/25/73	No data	
6/26 - 8/ 6/73	Limmetrics Aerovane	Point Beach intake - 7.3 m above water surface
8/ 7 - 10/18/73	ANL - MRI	Point Beach intake - 4 m above water surface

TABLE 6.3. Maximum Orbital Wave Motion Associated with a Specified Wave

Sensor Depth (m)	Maximum Horizontal Orbital Motion (cm/sec)
1	75
5	28
10	8
25	~0

Fig. 6.1 Point Beach Current Meter Locations

Fig. 6.2 Savonius Rotor Behavior in the Presence of Laboratory Waves

MOORING CONFIGURATION FOR IN SITU CURRENT METERS
(OFFSHORE STATION)

Fig. 6.3 Typical Mooring Configuration for In Situ Current Meters

Fig. 6.4 Direction vs. Time: Record (1-96-73), 5/25 - 6/6/73.

Fig. 6.4 (Contd.) Direction vs. Time: Record (1-96-73), 5/25 - 6/6/73

Fig. 6.5 Direction vs. Time: Record (1-97-73), 6/6 - 7/24/73

Fig. 6.5 (Contd.) Direction vs. Time: Record (1-97-73), 6/6 - 7/24/73

Fig. 6.5 (Contd.) Direction vs. Time: Record (1-97-73), 6/6 - 7/24/73

Fig. 6.5 (Contd.) Direction vs. Time: Record (1-97-73), 6/6 - 7/24/73

Fig. 6.6 Direction vs. Time: Record (2-96-73), 7/26 - 8/22/73

Fig. 6.6 (Contd.) Direction vs. Time: Record (2-96-73), 7/26 - 8/22/73

Fig. 6.6 (Contd.) Direction vs. Time: Record (2-96-73), 7/26 - 8/22/73

Fig. 6.6 (Contd.) Direction vs. Time: Record (2-96-73), 7/26 - 8/22/73

Fig. 6.7 Direction vs. Time: Records (3-96-73) and (3-97-73),
8/23 - 10/10/73

Fig. 6.7 Direction vs. Time: Records (3-96-73) and (3-97-73),
(Contd.) 8/23 - 10/10/73

Fig. 6.7 Direction vs. Time: Records (3-96-73) and (3-97-73),
(Contd.) 8/23 - 10/10/73

Fig. 6.7 Direction vs. Time: Records (3-96-73) and (3-97-73),
(Contd.) 8/23 - 10/10/73

Fig. 6.7 Direction vs. Time: Records (3-96-73) and (3-97-73),
(Contd.) 8/23 - 10/10/73

Fig. 6.7 Direction vs. Time: Records (3-96-73) and (3-97-73),
(Contd.) 8/23 - 10/10/73

Fig. 6.7 Direction vs. Time: Records (3-96-73) and (3-97-73),
(Contd.) 8/23 - 10/10/73

Fig. 6.8 Histogram of Current Direction and Speed, Record (1-96-73)

Fig. 6.9 Histogram of Current Direction and Speed, Record (1-97-73)

Fig. 6.10 Histogram of Current Direction and Speed, Record (2-96-73)

Fig. 6.11 Histogram of Current Direction and Speed, Record (2-97-73)

Fig. 6.12 Histogram of Current Direction and Speed, Record (3-96-73)

Fig. 6.13 Histogram of Current Direction and Speed, Record (3-97-73)

Fig. 6.14 Average Histogram of All Current Records Which Were Simultaneous of Both Stations

Fig. 6.15 Progressive Vector Plot, Record (1-96-73)

Fig. 6.18 Progressive Vector Plot, Record (2-97-73)

Fig. 6.20 Progressive Vector Plot, Record (3-97-73)

Fig. 6.21 Wind and Current Direction vs. Time for Record (1-96-73)

Fig. 6.21 (Contd.) Wind and Current Direction vs. Time for Record (1-96-73)

Fig. 6.22 Wind and Current Direction vs. Time for Record (1-97-73)

Fig. 6.22 (Contd.) Wind and Current Direction vs. Time for Record (1-97-73)

Fig. 6.22 (Contd.) Wind and Current Direction vs. Time for Record (1-97-73)

Fig. 6.22 (Contd.) Wind and Current Direction vs. Time for Record (1-97-73)

Fig. 6.22 (Contd.) Wind and Current Direction vs. Time for Record (1-97-73)

Fig. 6.22 (Contd.) Wind and Current Direction vs. Time for Record (1-97-73)

Fig. 6.23 Wind and Current Direction vs. Time for Records (2-96-73) and (2-97-73)

Fig. 6.23 Wind and Current Direction vs. Time for
(Contd.) Records (2-96-73) and (2-97-73)

Fig. 6.23 Wind and Current Direction vs. Time for
(Contd.) Records (2-96-73) and (2-97-73)

Fig. 6.23 Wind and Current Direction vs. Time for
(Contd.) Records (2-96-73) and (2-97-73)

Fig. 6.23 Wind and Current Direction vs. Time for
(Contd.) Records (2-96-73) and (2-97-73)

Fig. 6.23 Wind and Current Direction vs. Time for
(Contd.) Records (2-96-73) and (2-97-73)

Fig. 6.23 Wind and Current Direction vs. Time for
(Contd.) Records (2-96-73) and (2-97-73)

TAPE 2-96-73 RUN 29.07.74 0900
 SCALE: WIND 5 M/S CURRENT 10 CM/S

21 AUG 73

DAY 73.233
 CURRENT PLOTTED FROM TRACKS:
 1889 TO 1960

22 AUG 73

DAY 73.234

0000 0100 0200 0300 0400 0500 0600 0700 0800 0900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400

Fig. 6.23 Wind and Current Direction vs. Time for
 (Contd.) Records (2-96-73) and (2-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73).

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

TAPE 3-96-73 WIND, CURRENT VS TIME

SCALE: WIND $\text{---} \text{---} \text{---}$ 5 M/S CURRENT $\text{---} \text{---} \text{---}$ 10 CM/S

9 OCT 73

DRY 73.282

CURRENT PLOTTED FROM TRACKS:
3381 TO 3452

10 OCT 73

DRY 73.283

11 OCT 73

DRY 73.284

12 OCT 73

DRY 73.285

0000 0100 0200 0300 0400 0500 0600 0700 0800 0900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400

TAPE 3-97-73 WIND, CURRENT VS TIME

SCALE: WIND $\text{---} \text{---} \text{---}$ 5 M/S CURRENT $\text{---} \text{---} \text{---}$ 10 CM/S

9 OCT 73

DRY 73.282

10 OCT 73

DRY 73.283

11 OCT 73

DRY 73.284

12 OCT 73

DRY 73.285

0000 0100 0200 0300 0400 0500 0600 0700 0800 0900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400

Fig. 6.24 Wind and Current Direction vs. Time for
(Contd.) Records (3-96-73) and (3-97-73)

Fig. 6.25 Shore-Parallel Energy Density Spectrum, Record (1-96-73)

Fig. 6.26 Shore-Parallel Energy Density Spectrum, Record (1-97-73)

Fig. 6.27 Shore-Parallel Energy Density Spectrum, Records (2-96-73) and (2-97-73)

Fig. 6.28 Shore-Parallel Energy Density Spectrum, Records (3-96-73) and (3-97-73)

SECTION 6.0

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7.0 FIELD OBSERVATIONS OF THE DYNAMICS OF HEATED DISCHARGE JETS

A. A. Frigo, S. M. Zivi, R. F. King, and E. D. Levinson

7.1 INTRODUCTION

In estimating the environmental effects of heated effluents from power plants and other industrial sources, one must forecast the behavior and extent of the thermal plume. Analytical models exist for such calculations, but in general they assume steady-state temperature and flow fields in the plume. This section addresses that assumption and reports observations of thermal plumes in which significant periodic fluctuations of water temperature and velocity are observed. The dynamics of thermal plumes may be important for several reasons.

a. The dynamical character of a discharge probably determines or influences the mixing coefficients that are input parameters in thermal plume models.

b. In measuring or mapping a thermal plume as part of a monitoring program of an operating plant, one must consider the periodic fluctuations of the measured temperatures in planning the measurement and interpreting the results.

c. Regulatory criteria usually deal with temperature distributions that are considered steady. To the degree that measurements in a monitoring program indicate large fluctuations, the regulatory criteria will be difficult or impossible to implement.

Evidence of dynamic phenomena in thermal plumes has been reported by earlier workers in the field. Wavelike temperature variations have been inferred from aerial infrared scans of cooling water discharges at power plants¹ and hydraulic model studies have indicated temperature and flow fluctuations near the simulated outfall.² The studies reported here were initiated to further explore these phenomena and to attempt to understand some of the mechanisms involved.

7.2 DESCRIPTION OF EXPERIMENTS

Measurements were made in the near field or jet regime of three power plant discharges: the Point Beach Nuclear Power Plant at Two Rivers,

Wisconsin; the Waukegan Generating Station at Waukegan, Illinois; and the J. H. Campbell Plant at Port Sheldon, Michigan. Greatest emphasis was put on the Point Beach plant. The experimental procedure consisted of mooring a 5.5-m instrumented boat (by means of a two-point anchor system) at the desired position in the thermal plume and recording temperature and velocity data for up to several hours at that location. Temperature measurements were made at seven depths (half-meter intervals), ranging from the water surface down to 3 m. At the Point Beach plant, the lowermost measurement was virtually at the lake bottom. The temperature measurements were made by means of thermistors mounted on a boom which extended below the boat. Each thermistor output was recorded simultaneously on a data-acquisition system described in Sec. 3. Time intervals between temperature recordings were selected for the time scale of interest, usually about 2 sec between readings. The time constant of the thermistors was about 0.6 sec. Water velocities were measured by means of a Bendix Q-15 current meter modified to introduce a 2-sec time constant.

Most of the data were recorded on magnetic tape in digital form. Records of temperature and current were often sufficiently revealing that the oscillatory character of the plume could be observed directly on plots of these variables versus time. In addition, spectra of temperatures and current were calculated using the Fast Fourier Transform technique embodied in computer program BMDX92 of the Health Sciences Computing Facilities, University of California at Los Angeles.

7.3 EXPERIMENTAL RESULTS

7.3.1 The Point Beach Nuclear Power Plant

Studies were made at Point Beach on four dates: May 10, June 6, June 7, and August 22, 1973. The results observed on these dates showed strong similarities indicating that the phenomena reported here are probably the result of some systematic oscillation related to the discharge rather than an occasional natural event in the ambient water.

On May 10, the boat was anchored at about 76 m from the lakeside end of the northern discharge canal (flume). Figure 7.1 illustrates the arrangement of the discharge flumes and the location of the measurements.

Each discharge canal is about 68 m long, 10.7 m wide, and 4.2 m deep. The mean velocity in the canal is about 55 cm/sec and the discharge densimetric Froude number $(U/\sqrt{gH\Delta\rho/\rho})$ is about 3.

The temperature-time record of each of the seven thermistor outputs shows an oscillatory character. The most informative method of presentation was found to be a plot of all seven temperature histories superimposed. Figure 7.2 is such a record for May 10. Several aspects are immediately obvious in Fig. 7.2. First, there is a relatively high-frequency nonlinear oscillation manifested by the sawtooth-shaped record having a period of about 140 sec. During these oscillations, the temperature at all seven thermistors drop 3-5°C in about 60 sec and then recover independently over the ensuing 80 sec or so to complete one cycle. Second, a longer period variation is visible in the figure as the scalloped lower boundary of the data points having a period of about 1200 sec. In the study shown in Fig. 7.2, this longer period oscillation is less apparent than will be seen in later measurements because the duration of the record in this case was only 2500 sec. The May 10 study was an exploratory investigation that led to the further measurements described below. Table 7.1 lists some of the important plant and lake data for all the studies.

Study No. 2 was conducted on June 6 by a different experimental technique. One-point temperature recorders were deployed at two locations in the thermal plume. Each instrument package contained one thermistor at a single depth and a strip-chart recorder. Although there is definite evidence of periodic fluctuations, as can be seen in Fig. 7.3, the measurements lack the clarity of those conducted with the boat and with seven thermistors.

Study No. 3 on June 7 is illustrated in Fig. 7.4, which shows the record of the seven thermistor readings and the simultaneous current speed. The high-frequency sawtooth oscillation having a period of about 140 sec is again obvious, and the longer period (1200-sec) oscillation is quite evident. There is an apparent correlation between the current speed oscillations and the temperature oscillations so that an increase in current speed corresponds to an increase in the temperatures in the 1200-sec oscillation. There are episodes in which fluctuations in the current speed in the 140-sec oscillation also seem to be coherent with the higher frequency temperature oscillations, and cross-correlation computations confirm this as will be discussed.

The average current speed at this location is about 25 cm/sec. If thermal waves were to propagate at about this speed, a wavelength of about 30 m would correspond to the 140-sec oscillations. The longer period fluctuations would correspond to about 300-m wavelengths. The infrared images of Scarpace and Green¹ indicate wavelengths of the major thermal fronts as being about 200 m. Thus, there is some indication that the longer period oscillations observed in this study may correspond to the thermal fronts reported by Scarpace and Green. This would bear further analysis.

Figure 7.5 is the power spectrum calculated by the Fast Fourier Transform technique for the seven thermistor records of Fig. 7.4. Seven individual power spectra were calculated, one for each thermistor. These seven spectra were then averaged at each frequency to obtain the spectrum plotted, and the standard deviation of each ensemble was used to determine the error bars in Fig. 7.5. The peak at about 140 sec is strong and was clearly evident in all seven individual spectra. This confirms the direct observation of periodicity from inspection of the time records. The record length is sufficient for only four periods of the 1200-sec oscillation, and the 1200-sec oscillation is therefore not discernible in the calculated spectrum. Figure 7.6 shows the power spectrum for the current speed. There is evidence of a peak between about 100 and 160 sec in this spectrum.

To investigate the degree to which fluctuations of the velocities and temperatures in the discharge canal might have contributed to the above observations, measurements were made at the mouth of the southern discharge flume on August 22. The temperature records indicate constant temperatures with no perceptible fluctuations. However, significant current variations were observed as shown in Fig. 7.7. No evidence is seen of the 1200-sec period oscillations in Fig. 7.7, but both the current speed and direction show fluctuations with about the frequency of the 140-sec oscillations observed in the thermal plume on May 10 and June 7. The fundamental longitudinal natural oscillation of the canal is calculated to have a period of about 50 sec. The observed 140-sec oscillations are evident in both the time records and in the spectrum (not shown here). Since both current speed and direction show coherent oscillations, the velocity surges in the canal would seem to be not simply the longitudinal mode of the canal, but would also include a transverse component. It appears that 140-sec flow disturbances

do exist in the discharge canals and may well be involved in the high-frequency temperature oscillations observed several hundred feet off the mouth of the canal.

To summarize the observations in the thermal plume at Point Beach, the following facts seem to have a significant bearing on the dynamics of thermal plumes at that plant.

a. Coherent temperature oscillations of 3-5°C peak-to-peak amplitudes were observed 50-90 m off the discharge at all depths down to the bottom with about a 140-sec period on May 10 and June 7; a single thermistor record on June 6 showed similar oscillations; that is to say, each time the measurement was attempted, oscillations were found at about 140 sec.

b. On June 6 and 7 (primarily the latter date), about 1200-sec temperature oscillations were observed to be superimposed on the shorter period oscillations; there is some evidence of the long-period oscillations on May 10, but the length of record is too short to allow confidence in that observation.

c. Significant current speed oscillations were observed having strong coherence with the 1200-sec temperature oscillations and essentially in phase with those oscillations; a cross spectrum also indicates correlation between current and temperature oscillations at about a 180-sec period.

d. Measurements of the discharge velocity at the mouth of one of the discharge canals give strong evidence of velocity oscillations in the canal with about 140-sec period; there is no evidence of slower oscillations corresponding to the 1200-sec period seen in the temperatures 50-90 m off the discharge.

The mechanisms that cause the observed oscillations have not been identified. The measured temperature gradient of about 1.4°C/m leads to a Brunt-Vaisala period of about 140 sec, the same as the dominant period observed in the temperature oscillations and the discharge velocity fluctuations. The coincidence is too remarkable to be dismissed, although we do not presently have a model that can relate the field observations to this parameter for internal waves. Simple two-dimensional internal waves would seem to be excluded by several factors. First, the situation is obviously three-dimensional since the cold water involved in the temperature oscillations

must reach the plume centerline from the sides of the plume, and not from the bottom, inasmuch as the thermal plume extends to the lake bottom for much of the time. Second, the temperature oscillations near the surface and near the bottom have the same amplitudes as in the intermediate regions; this would be inconsistent with simple two-dimensional internal waves.

Thermal plume measurements at Point Beach have shown that the "zone of flow establishment" extends about 30 m from the mouth of the flume. In this zone, velocity and temperature profiles gradually change from uniform at the flume mouth to approximately Gaussian at the edge of the zone. It is hypothesized that the observations of 140-sec periods, occurring as they do shortly beyond the "zone of flow establishment," are revealing the periodicity and scale of the eddies that are responsible for lateral mixing of the plume in the jet region. The period of these eddies may result from an as yet unspecified interaction between the discharge canal and a gravity-dominated phenomenon in the plume, an interaction that produces the observed coherent velocity fluctuations at the mouth of the canal. The longer period oscillations (1200 sec) would be consistent with a systematic lateral meandering of the plume such that it crosses the boat position every 1200 sec. The mechanisms causing such a periodic meandering can only be conjectured. The long period oscillations remain even less understood than the short period ones.

7.3.2 Measurements at Other Locations

One set of observations was made at each of the two other sites of the study: Campbell and Waukegan. Figure 7.8 shows the boat location for measurements at the J. H. Campbell plant on September 14, and Fig. 7.9 shows the extensive record of temperatures, current speed, and current direction for that date. These measurements show much less evidence of systematic oscillatory behavior than the Point Beach observations. The upper two thermistors were at a depth of 0.5 m, the next thermistor at 1 m, and the next two at 2 and 3 m, respectively. The current meter sensor was at 0.5 m. In this case, the plume is floating and the 1-m depth seems to be just beneath the thermal plume; the thermistor at 1 m indicates quasi-periodic fluctuations that are evidently the result of internal waves. The bottom two thermistors are below the influence of the thermal plume and show the essentially constant temperature of the near-bottom waters. There is some evidence of a long period oscillation of temperature and current at the 0.5-m depth.

Figure 7.10 shows the boat location for the October 8 observations at the Waukegan site, and Fig. 7.11 shows the data record. Thermistors 1, 3, and 7 were suspended from the boat at depths of 1, 1, and 3 m, respectively. Thermistors 2 and 5 were suspended from buoys at 25 m on either side of the boat (arranged in a line perpendicular to the plume axis) and at depths of 0.8 and 1.4 m, respectively. The purpose of this deployment was to detect meandering if it occurred. The current meter sensor was at a 1.3-m depth.

Thermistors 1 and 3 (at the 1-m depth) show episodes of temperature oscillations with about 8-min periods coherent with current speed oscillations. Thermistor 2, at 0.8 m, shows similar oscillations but roughly out of phase with respect to thermistors 1 and 3, indicating that the observed oscillations can indeed be explained by a systematic meandering of the plume. Thermistor 5 seems below the main part of the plume and therefore does not contribute much information.

The measurements at Campbell and Waukegan serve primarily to demonstrate that the systematic oscillations studied at Point Beach are not peculiar to one plant, but rather probably exist to some degree at most surface discharges.

7.4 CONCLUDING REMARKS

There appear to be at least several types of hydrodynamic oscillations associated with thermal plumes. Significant oscillations have been reported here for two plants, and minor oscillations at the third (Campbell). This study has dealt with fluctuations in the jet regime of surface discharges, whereas Scarpace and Green¹ observed large scale thermal structure in the far field region of thermal plumes at some of the same plants. The relationship between the present findings and those of Scarpace and Green remains to be established, but it seems possible that the longer period waves reported here might develop into the "thermal fronts" of Scarpace and Green.

The higher frequency oscillations discussed here for the Point Beach plant are postulated to be a manifestation of the eddy phenomenon that is active in initiating the lateral dispersal of the plume. Further study of this aspect would appear to be worthwhile toward a better understanding of the near field mixing process and a better plume modeling capability. Present modeling techniques fail to include the nonsteady state temperature and flow fields addressed in this study. Hence at present, most analytical models are not altogether strictly representative.

TABLE 7.1. Plant and Lake Data

Study	Date 1973	Plant	Plant Operating Data			Ambient Current		Ambient Water Conditions		Bottom Depth of Study Location
			Load (MWe)	Discharge Flow Rate (m ³ /sec)	Outfall Temp. (°C)	Speed (cm/sec)	Direction	Temp. (°C)	Surface	
1	5/10	Point Beach Unit 2	478	24.3	18.6	11	010°	6.4-7.8	Calm	3.0
2	6/6	Point Beach Unit 2	470- 485	24.3	17.5	0	-	9.6-11.2	Calm 0.3 m Waves	A-3.5 B-2.0
3	6/7	Point Beach Unit 2	471	24.3	16.5	6	115°	7.7-8.4	Calm 0.3 m Waves	2.7
4	8/22	Point Beach Unit 1	440- 480	24.3	27.5	Not Available	335°	18.2	Very rough, 1.0-1.5 m Waves	4.4
5	9/14	J. H. Campbell	595	15.1	21.7	Not Available	360°	12.8	Calm	4.6
6	10/8	Waukegan	← Not Available →					16.3	Calm 0-0.3 m Waves	3.4

Fig. 7.1 Station Locations for the Studies Conducted at the Point Beach Nuclear Power Plant

POINT BEACH: MAY 10, 1973 (1410-1514)

Fig. 7.2 Temperatures at 0.0-, 0.5-, 1.0-, 1.5-, 2.0-, 2.5-, and 3.0-m Depths at 76 m from the Point Beach Nuclear Power Plant Unit 2 Outfall: May 10, 1973, 1410-1514 Hr

Fig. 7.3 Temperatures Near the Surface at 52- and 88-m from the Point Beach
Nuclear Power Plant Unit 2 Outfall: June 6, 1973, 1523-1720 Hr

POINT BEACH : JUNE 7, 1973 (1529-1645)

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Fig. 7.4 Temperatures at 0.0-, 0.5-, 1.0-, 1.5-, 2.0-, 2.5-, and 2.7-m Depths and Current Speed at Depths of 2.5 m (between triangle marks) and 1.5 m at 67 m from the Point Beach Nuclear Power Plant Unit 2 Outfall: June 7, 1973, 1529-1645 Hr

Fig. 7.5 Power Spectrum of Plume Water Temperatures, Point Beach Unit 2, June 7, 1973. Data points are average of spectral estimates for the 7 simultaneous measurements in the previous figure. Error bars are one standard deviation of the 7 estimates. Each of the 7 estimates was computed with 7 degrees of freedom

Fig. 7.6 Power Spectrum of Current Speed in the Plume, Point Beach Unit 2, June 7, 1973. 11 degrees of freedom

POINT BEACH: AUGUST 22, 1973 (0910-1130)

Fig. 7.7 Current Speed and Direction at the 1.5-m Depth at the Center of the Mouth of the Point Beach Nuclear Power Plant Unit 1 Outfall: August 22, 1973, 0910-1130 Hr

Fig. 7.8 Station Location for the Study Conducted at the J. H. Campbell Power Plant

J.H. CAMPBELL: SEPTEMBER 14, 1973 (1055-1315)

Fig. 7.9 Temperatures at 0.5-, 0.5-, 1.0-, 2.0-, and 3.0-m Depths and Current Speed and Direction at the 0.5-m Depth at 177 m from the J. H. Campbell Power Plant Outfall: September 14, 1973, 1055-1315 Hr.

Fig. 7.10 Station Location for the Study Conducted at the Waukegan Generating Station

WAUKEGAN: OCTOBER 8, 1973 (1423-1659)

Fig. 7.11 Temperatures at 1.0-, 1.0-, and 3.0-m Depths at the Boat Position, 0.8-m Depth at 25 m South of the Boat, 1.4-m Depth at 25 m North of the Boat Position, and Current Speed and Direction at 1.3-m Depth at 154 m from the Waukegan Generating Station Outfall: October 8, 1973: 1423-1659 Hrs

WAUKEGAN: OCTOBER 8, 1973 (1423-1659) (CONTINUED)

Fig. 7.11 Temperatures at 1.0-, 1.0-, and 3.0-m Depths at the Boat Position, 0.8-m Depth at 25 m South of the Boat, 1.4-m Depth at 25 m North of the Boat Position, and Current Speed and Direction at 1.3-m Depth at 154 m from the Waukegan Generating Station Outfall: October 8, 1973: 1423-1659 Hrs

SECTION 7.0

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