PHYSICAL MEASUREMENTS OF THERMAL DISCHARGES
INTO LAKE MICHIGAN: 1971

by

A. A. Frigo and D. E. Frye

ARGONNE NATIONAL LABORATORY

CENTER FOR ENVIRONMENTAL STUDIES

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.95

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Center for Environmental Studies

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October 1972

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ABSTRACT

This report represents a compilation of field data collected on Lake Michigan during the 1971 field year by Argonne National Laboratory under the auspices of the Great Lakes Research Program. The data presented were collected for the purpose of studying the physical structure of thermal plumes existing at power-plant outfalls. The power plants studied included the Point Beach Nuclear Power Plant located in Two Creeks, Wisconsin, the Waukegan Generating Station located in Waukegan, Illinois, and the State Line Generating Station located in Hammond, Indiana.

I. INTRODUCTION

Waste-heat discharges from steam electric power plants, particularly nuclear plants employing once-through cooling, have become a topic of much concern. In these plants, cooling water is typically heated 5-17°C above intake water temperature and then, in the case of a once-through cooling system, returned directly to its source. The impact this heated water may have on the body of water from which it was drawn and later returned is referred to as thermal effects.

Nuclear plants currently being marketed operate at a lower efficiency and reject more heat to the environment than most fossil fuel plants of the same generating capacity. Also, some heat rejected by a fossil plant is discharged through a stack to the atmosphere. For this reason, present-generation nuclear plants typically require 30-50% more cooling water than a fossil plant of similar size.

Effects of the thermal discharges can be separated somewhat arbitrarily into physical, chemical, and biological effects. The data presented here are concerned with the physical effects of the cooling-water discharges from several power plants operating on Lake Michigan using once-through cooling. Information concerning water temperatures, currents, meteorological conditions, and other physical parameters is needed for the following reasons:

1. To test various proposed analytic and hydraulic models.
2. To provide data for determining temperature and current patterns resulting from heated-water discharges.
3. To provide biologists with physical data for assessment of thermal effects.
4. To provide data so that systems can be designed to minimize thermal effects.
5. To provide data so that systems can be designed to avoid recirculation of heated discharges.
6. To ensure compliance with standards.

The field program this report describes was designed with particular emphasis on the acquisition of data to be used as input to analytical models of thermal plumes. Numerous models have been proposed, but suitable field data have been difficult to obtain and, therefore, little has been done to validate these models.^{7,11} We have attempted to make the necessary far-field measurements and have begun measurements in the near-field for the testing of models. Work at Argonne using the data in this report as input for model testing is in progress.

II. EQUIPMENT DESCRIPTION

The data described in this report were gathered from two boats owned by Argonne National Laboratory. The data collected early in the field year (before August 15, 1971) were obtained using an 18-ft cathedral hull fiberglass boat. After August 15, 1971, a second boat, a 24-ft deep V cabin cruiser with a 165-hp inboard-outboard drive, was used. Both boats are trailerable so that they can be used at any site within driving distance of the laboratory.

The plume data recorded here were obtained with two separate data-acquisition systems. Both will be described. The original system (used before August 15, 1971) consisted of an inverter, which changed a 12-V dc signal (from an automobile battery) to a 110-V ac signal, a two-channel digital thermometer (Digitec Model 8500-1) with a five-position switch, and a 12-ft aluminum bar attached to the boat's gunwhale with four YSI No. 409 two-lead thermistors connected at the 1-, 3-, 6-, and 9-ft levels (see Fig. 1). A surface float with a similar thermistor attached was used to measure surface temperature. These thermistors were found to be adequate for use underwater after being epoxied to eliminate leakage and were calibrated before and after use. The recording technique used involved manually switching from one probe to another and transcribing by hand the temperature displayed on the digital thermometer. A constant speed was maintained by the boat, and a constant time interval between interrogations of each probe was assumed.

Fig. 1. Survey Boat Equipped with Thermistors for Measuring Surface and Subsurface Temperatures. ANL Neg. No. 190-567.

A second-generation plume-measuring system, which eliminated the manual interrogation and recording of the temperature information, was used from August 16, 1971, until the end of the field year. An inverter supplied 110-V ac power to a digital thermometer, which consisted of a Digitec Digital Main Frame 251A with Thermistor Plug-In Module Model 551-2 interfaced with a scanner and digital clock built at Argonne. The channels of temperature information were transmitted to an IBM Selectric typewriter for recording (see Fig. 2). Elapsed time in seconds from the digital clock and periodic calibration checks were also printed. The temperature transducers were YSI No. 709 three-lead linearized thermistors located on an aluminum bar at $1/2$ -m intervals to 3 m (see Fig. 1). Surface temperature was measured using the same kind of thermistor attached to a piece of spring steel, which enabled the probe to follow the surface very closely (see Fig. 3). The thermistors were calibrated before and after use.

Current measurements were made with several types of current meters during the field year. An Ekman-Merz current meter (Fig. 4) made by Tsurumi-Suki Kosakusho Co. Ltd. was used for measuring outfall plume velocities and ambient currents. This ducted current meter has an eight-bladed impeller with a vane about $2\frac{1}{2}$ ft long, which orients the impeller.

Fig. 2. Second-generation Data-acquisition System. ANL Neg. No. 190-568-12.

Fig. 3. Surface-temperature Probe. ANL Neg. No. 190-569-21.

Fig. 4. Ekman-Merz Current Meter. ANL Neg. No. 190-568-4.

The meter is actuated and deactuated by messenger weights on the supporting line. The total revolutions of the impeller over a known time allow an average current speed to be obtained. Direction is found by averaging the locations in which small metal pellets are found in the vane-oriented directional compartment. Although of unsophisticated design, this meter has been calibrated in the laboratory and found to be quite reliable even at very low speeds (less than 0.2 fps). Wave motion is effectively nulled out by the impeller, which rotates freely in both directions.

Fig. 5. Braincon Model 381 Histogram Recording Current Meter. ANL Neg. No. 190-570-8.

Several Braincon Model 381 Histogram recording current meters (Fig. 5) were used in situ at the Point Beach Nuclear Power Plant to record ambient current velocity for extended periods. These meters consist of a Savonius rotor, which is connected by a magnetic coupling to an inside housing, which is rotated by the rotor after a 3456:1 gear reduction. Luminescent spots on the inside housing are recorded on film for 10 min intervals. Thus the arc through which the inside housing rotates is related to the number of turns of the rotor and, therefore, to current speed. Direction is obtained from a photographic record of the vane's position. These meters were rigged to record ambient temperature on film using a thermometer with a radioluminescent background. The film record is made on Kodak Tri-X reversal, 16-mm film in 50-ft cartridges, which are good for 25 days. Time is measured by a battery-powered Accutron timer. Because of mechanical problems, these meters recorded very little information on current speeds, and what was recorded had to be viewed with skepticism due to the effects of wave motion on the Savonius rotors. Information on current direction was recorded and is of some interest. Data reduction was done by hand and was quite tedious.

A third type of meter, the Bendix Q-15 geomagnetic ducted current meter (Fig. 6), was acquired late in the field year and used for a study of the near-field regime. The Q-15 has a five-bladed impeller, which rotates freely in both directions and is enclosed in a duct. The ducted assembly is aligned with the current by a vane of adjustable length. The effects of wave motion and boat motion are nulled out by electronic averaging (over about 25 sec) of the number of turns of the impeller and by the presence of the

Fig. 6. Bendix Q-15 Geomagnetic Ducted Current Meter. ANL Neg. No. 190-568-11.

duct. Current speed and direction are displayed on deck by means of a readout unit, Model No. S-232, which is connected to the current meter through a four-conductor cable. The current meter, powered by six 9-V batteries, was found to be very useful for measuring ambient lake velocities and velocities in plant discharges. The meter weighs about 36 lb in air (19 lb in water) and is thus easy to use over the side of the boat, although a lead weight must be attached in areas of high currents (greater than 3 fps) to keep the meter vertically oriented.

Current information was also obtained by following the path of drogues. Surveyors' transits were used to obtain drogue position as a function of time. Each drogue (Fig. 7) was made of aluminum with a styrofoam surface float. A drogue can be set at a predetermined level by adjusting a line between the drogue and the surface float. The surface float was made

as small as possible to reduce the effect of wind on the drogue while still enabling transit sightings to be made.

Ambient wind conditions were monitored with a Weather-Measure three-cup anemometer with direction vane and a meter readout. Wet- and dry-bulb temperatures were measured with a sling psychrometer.

In situ recording Geodyne Model A-119-4 thermographs (Fig. 8) were used in the sinking-plume experiment to monitor bottom-water temperature at fixed locations for an extended period of time. Temperature is sensed by a precision Bourdon-tube assembly, which in turn causes a stylus to move. Inside a water-tight housing, pressure-sensitive paper moves past the stylus at 10-min intervals, thereby recording an instantaneous temperature every 10 min. Power for two months' operation is supplied by a 6-V battery.

Infrared images of the thermal plume were obtained on several occasions by Bendix Aerospace Systems Division. Ground-truth data were collected concurrently with these flights using the instrumentation previously described.

Fig. 7. Drogue. ANL Neg. No. 190-568-20A.

Fig. 8. Geodyne Model A-119-4 Temperature Recorder. ANL Neg. No. 201-9576-20.

III. POWER-PLANT DESCRIPTIONS

During the 1971 field year, surveys of the thermal plumes were conducted at three power plants located on Lake Michigan. The power plants studied included the Point Beach Nuclear Power Plant, operated by the Wisconsin Electric Power Company and the Wisconsin Michigan Power Company, and the Waukegan and Stateline Generating Stations, operated by the Commonwealth Edison Company. Brief descriptions of these plants follow.

A. Point Beach Nuclear Power Plant

Most of our 1971 field work was concentrated at the Point Beach Nuclear Power Plant. This power plant is located in the town of Two Creeks in east-central Wisconsin, on the western shore of Lake Michigan, about 30 miles southeast of Green Bay and about 90 miles north-northeast of Milwaukee. Figure 9 is an aerial view of the plant and intake crib. The plant is a two-unit steam-generating station. The two units are adjacent to each other near the shoreline of Lake Michigan. The Point Beach nuclear reactors for each unit are pressurized light-water-moderated and -cooled systems. Each unit has a gross capacity of about 523 MWe. For the 1971 field year, only Unit 1 (which began operation in December 1970) was operational. The water intake for the power plant consists of a circular intake crib about 1750 ft from the shore. Cooling water for the operation of the power plant is drawn from Lake Michigan and passes through the cooling condensers at a maximum rate of 885 cfs for full-power operation of one unit of the plant. (See addendum for a discussion of discharge flow rate.) The water is returned to the lake, about 150 ft offshore, through two discharge flumes (one flume per unit). The flumes are 35 ft wide, and the water in the flume is 13.5 ft deep (IGLD 579.6 ft). The maximum temperature rise in the cooling water at the cooling condenser is about 10.6°C above the intake temperature at a flow rate of 885 cfs.¹²

B. Waukegan Generating Station

The Waukegan Generating Station is located in the city of Waukegan in northeastern Illinois, on the western shore of Lake Michigan, north of the city of Chicago. An aerial view of the plant is shown in Fig. 10. This plant is a seven-unit, fossil-fueled steam-generating station. The gross capacity of the plant is about 1100 MWe. The cooling water for the plant is removed from the lake and transported through an open canal to the plant intake, where it passes through the cooling condensers at about 1950 cfs for full plant operation. The water is returned to the lake in an open canal, which is parallel to the intake canal. The water intake and discharge canals are separated by a breakwater. The normal temperature rise of the cooling water at full plant generation is 7.1°C , with a water flow of 1950 cfs.³

Fig. 9. Aerial View of Point Beach Nuclear Power Plant. ANL Neg. No. 190-492.

Fig. 10. Aerial View of Waukegan Generating Station. ANL Neg. No. 190-490.

C. State Line Generating Station

The State Line Generating Station is located in the city of Hammond in northwestern Indiana, on the southwest shore of Lake Michigan, adjacent to the city of Chicago. Figure 11 is an aerial view of this power plant. The State Line plant is a four-unit, fossil-fueled steam-generating station. The combined design output of this steam plant is about 992 MWe. The cooling water for operation of the power plant is drawn from Lake Michigan and passed through the cooling condensers at about 1854 cfs for full-power operation of the station. It is returned to the lake at very low velocity through a rock-filled opening in a discharge flume that is parallel to the shore (see Fig. 12). The normal temperature rise of the cooling water at full plant generation from intake to discharge is about 5.8°C with a water flow of 1854 cfs.³

Fig. 11. Aerial View of State Line Generating Station. ANL Neg. No. 190-491B.

Fig. 12. Plan View of State Line Generating Station. ANL Neg. No. 190-571.

IV. RESULTS OF THE FIELD WORK

A. Discussion of Data

The drawings included here are the results of measurements at the three power plants studied. The thermal-plume drawings show the power plant, the discharge flume, the intake crib or canal, the shoreline, and the lake bottom, where applicable. The circled numbers or letters in the drawings represent reference buoy locations. The dots represent points at which temperatures were measured. Uncircled numbers are representative temperatures. Isotherms were hand-drawn, and linear interpolation between points was used where necessary. The isotherms are shown by the heavy, dark lines, which are labeled in degrees Centigrade. The dashed portions of the isotherms represent an assumed location, unsupported by data. The areal extent of the plume within a given isotherm was measured using a planimeter on the original large-scale drawings. Plant, meteorological, and ambient lake data are summarized in the table on each drawing. (See addendum.)

Temperature measurements were made simultaneously at a number of depths, and the appropriate depth is indicated on each plume drawing. Vertical cross sections were also constructed from the data. Sections perpendicular to an assumed plume centerline were chosen to be displayed along with the cross section following the assumed plume centerline. Circled numbers or letters above the cross sections indicate buoy locations, which are shown on the corresponding surface thermal plume drawing. A cross section along the assumed plume centerline is designated ϕ . As on the plume drawings, dots represent points at which temperatures were measured, and the heavy dark lines are isotherms. Approximate lake depth is indicated below each section.

Several drogue studies were conducted. The paths of the drogues are indicated on the drogue-study drawings included with the plumes measured on the same day.

The units used in the drawings in reference to probe depth depend upon the acquisition system. The equipment used at the beginning of the field year was calibrated in engineering units, and the drawings were made using these units. The second-generation acquisition system measured depth in metric units. Degrees Centigrade were used throughout.

B. Thermal-plume Measurements

Both data-acquisition systems used basically the same technique for measuring the areal extent and location of the plume. In essence, the boat with probes attached at various levels was driven between known locations at a constant speed assuming a straight-line course while sampling

each probe at a constant time interval. At the Point Beach Nuclear Power Plant, moored buoy locations were established early in the field year with transits from shore. The buoy grid used at any one time was established by determining the approximate location of the plume before taking measurements. At the Waukegan and State Line Generating Stations, the buoy locations were established by sextant sightings taken on known locations in the area. This method of operation was previously used by Romberg et al.⁹

1. Point Beach Nuclear Power Plant: May 20, 1971

Two temperature surveys were conducted the afternoon of May 20, 1971. The results are shown in Figs. 13-24. During the surveys, weather conditions were relatively stable with winds out of the northwest shifting to the west at 10-15 mph. Ambient current was measured northeast of the plant in 20 ft of water at a depth of 6 ft using an Ekman-Merz current meter. The ambient current speed was found to be 0.3 fps with a direction heading of 123°. Current direction is measured clockwise from the north in the direction of flow. An ambient water-temperature measurement was conducted north of the plant from 1603 to 1609 Hours. The temperature of the ambient water was found to be 8.3-8.5°C. (Ambient temperature is defined as surface temperature of water outside the plume in the vicinity of the plant.)

Outfall temperature and velocity were measured. The outfall temperature was found to be 17.5°C and remained constant during both surveys. The outfall velocity was measured at two depths using the Ekman-Merz current meter at 1700 Hours. The velocity at a depth of 3 ft was 2.2 fps and at a depth of 6 ft was 1.9 fps.

As can be seen from the figures, the plume moved southeast, parallel to shore, and stayed near the shore. A sharp interface on the north side of the plume was noted. The plume shape and direction remained relatively constant over the two surveys. Variations in the drawings for the two surveys may be due in part to different data-collection points.

Plume areas within the isotherms at all depths were measured from the drawings and are tabulated in the appendix. Plume areas decreased as a function of depth, as would be expected for a buoyant effluent. Examination of the plume cross sections (Figs. 18 and 24) indicated that the major portion of the plume for both surveys was approximately 8 ft deep or less.

2. Waukegan Generating Station: June 2, 1971

On June 2, 1971, a joint field day was conducted to study the condenser-cooling-water discharge from Commonwealth Edison Company's Waukegan Generating Station. Organizations participating in the field day

Fig. 13. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
 May 20, 1971, 1438-1550 Hours. -ANL Neg. No. 190-320 Rev. 1.

Fig. 14. Thermal Plume at 1-ft Depth for Point Beach Power Plant (Unit 1):
 May 20, 1971, 1438-1550 Hours. ANL Neg. No. 190-321.

Fig. 15. Thermal Plume at 3-ft Depth for Point Beach Power Plant (Unit 1):
 May 20, 1971, 1438-1550 Hours. ANL Neg. No. 190-322.

Fig. 16. Thermal Plume at 6-ft Depth for Point Beach Power Plant (Unit 1):
 May 20, 1971, 1438-1550 Hours. ANL Neg. No. 190-323.

Fig. 17. Thermal Plume at 9-ft Depth for Point Beach Power Plant (Unit 1):
 May 20, 1971, 1438-1550 Hours. ANL Ncg. No. 190-324.

Fig. 18. Vertical Cross Sections at Point Beach Power Plant (Unit 1): May 20, 1971, 1438-1550 Hours. ANL Neg. No. 190-393.

ALL TEMPERATURES IN DEGREES CENTIGRADE

PLANT & METEOROLOGICAL DATA

PLANT NAME: POINT BEACH NUCLEAR PLANT (UNIT 1)
 DATE & TIME OF SURVEY: 20 MAY 71 (1740-1850)
 PLANT LOAD (MW_e): 474
 DISCHARGE FLOW RATE: 771 CFS
 OUTFALL TEMPERATURE: 17.5°C
 INTAKE TEMPERATURE: 8.9°C
 AMBIENT WATER TEMPERATURE: 8.2-8.6°C
 DRY-BULB TEMPERATURE: 12.2-13.9°C
 WET BULB TEMPERATURE: N. A.
 WIND SPEED & DIRECTION: 10-15 MPH - 270°
 AMBIENT CURRENT SPEED & DIRECTION: 0.3 FPS - 125°
 LAKE LEVEL: 579.6 FT. (IGLD)
 LAKE SURFACE CONDITIONS: 0-1 FT. WAVES

Fig. 19. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
 May 20, 1971, 1740-1850 Hours. ANL Neg. No. 190-325.

Fig. 20. Thermal Plume at 1-ft Depth for Point Beach Power Plant (Unit 1):
 May 20, 1971, 1740-1850 Hours. ANL Neg. No. 190-326.

Fig. 21. Thermal Plume at 3-ft Depth for Point Beach Power Plant (Unit 1):
 May 20, 1971, 1740-1850 Hours. ANL Neg. No. 190-327.

ALL TEMPERATURES IN DEGREES CENTIGRADE

PLANT & METEOROLOGICAL DATA

PLANT NAME: POINT BEACH NUCLEAR PLANT (UNIT 1)
 DATE & TIME OF SURVEY: 20 MAY 71 (1740-1850)
 PLANT LOAD (MW_e): 474
 DISCHARGE FLOW RATE: 771 CFS
 OUTFALL TEMPERATURE: 17.5°C
 INTAKE TEMPERATURE: 8.9°C
 AMBIENT WATER TEMPERATURE: 8.2-8.5°C
 DRY BULB TEMPERATURE: 12.2-13.9°C
 WET BULB TEMPERATURE: N. A.
 WIND SPEED & DIRECTION: 10-15 MPH - 270°
 AMBIENT CURRENT SPEED & DIRECTION: 0.3 FPS - 125°
 LAKE LEVEL: 579.5 FT. (IGLD)
 LAKE SURFACE CONDITIONS: 0-1 FT. WAVES

Fig. 22. Thermal Plume at 6-ft Depth for Point Beach Power Plant (Unit 1):
 May 20, 1971, 1740-1850 Hours. ANL Neg. No. 190-328.

ALL TEMPERATURES IN DEGREES CENTIGRADE

PLANT & METEOROLOGICAL DATA

PLANT NAME: POINT BEACH NUCLEAR PLANT (UNIT 1)
DATE & TIME OF SURVEY: 20 MAY 71 (1740-1850)
PLANT LOAD (MW): 474
DISCHARGE FLOW RATE: 771 GFS
OUTFALL TEMPERATURE: 17.5°C
INTAKE TEMPERATURE: 8.9°C
AMBIENT WATER TEMPERATURE: 8.2-8.5°C
DRY BULB TEMPERATURE: 12.2-13.9°C
WET BULB TEMPERATURE: N/A
WIND SPEED & DIRECTION: 10-15 MPH - 270°
AMBIENT CURRENT SPEED & DIRECTION: 0.3 FPS - 125°
LAKE LEVEL: 579.5 FT. (IGLD)
LAKE SURFACE CONDITIONS: 0-1 FT. WAVES

Fig. 23. Thermal Plume at 9-ft Depth for Point Beach Power Plant (Unit 1):
May 20, 1971, 1740-1850 Hours. ANL Neg. No. 190-329.

Fig. 24. Vertical Cross Sections at Point Beach Power Plant (Unit 1): May 20, 1971, 1740-1850 Hours. ANL Neg. No. 190-394.

were Argonne National Laboratory, the Metropolitan Sanitary District of Greater Chicago, Bio-Test Industrial Laboratories, Inc., the Environmental Parameters Research Organization, and Texas Instruments, Inc. One objective of this study was to compare the various measurement techniques.

Argonne's assignment was to map the thermal plume from the power plant at various depths and to sample the water near the condenser-cooling-water discharge using a Battelle Sampler. It is not within the scope of this report to discuss the results obtained using the Battelle Sampler. Results of the thermal plume mapping by Argonne are shown in Figs. 25-36. The plume was mapped twice, once from 1140 to 1320 Hours and once from 1443 to 1723 Hours. Wind speed was 7-14 mph for the first survey and 7-10 mph for the second survey, with wind out of the west for both surveys. Lake surface conditions were relatively calm with 0-1-ft waves. Outfall temperature was 18.8°C for the first survey and 18.3°C for the second survey. Ambient lake temperature was measured about 2 miles north of the plant on a transect perpendicular to the shoreline, beginning $1\frac{1}{2}$ miles offshore and proceeding almost to the beach. Ambient lake temperature varied from 10.2°C at the point farthest offshore to 11.3°C at the point nearest the shore. Ambient lake currents were not measured for these surveys.

The two plumes were similar in both centerline direction and shape. Plume areas (see appendix) decreased with depth for both surveys. Plume depth was estimated from the vertical cross sections for both surveys and found to be about 6 ft.

TABLE I. Plant Operating Data for Waukegan Generating Station for June 4, 1971

Hour	Plant Load, MWe	Discharge Flow Rate, cfs	Intake Temp, °C	Outfall Temp, °C
2400	540	1061	12.2	16.7
0100	340	1061	12.2	16.1
0200	335	1061	12.2	15.6
0300	335	1061	12.2	15.6
0400	335	1061	12.2	15.6
0500	335	1061	12.2	15.0
0600	335	1061	11.7	15.0
0700	390	1355	12.2	15.6
0800	825	1511	12.2	17.8
0900	895	1622	12.2	18.9
1000	890	1622	12.8	18.9
1100	895	1622	12.8	18.9
1200	895	1622	12.8	18.9
1300	890	1622	12.2	18.9
1400	895	1622	12.2	18.9
1500	880	1622	12.8	18.9
1600	855	1622	12.2	18.9
1700	825	1511	12.2	18.9
1800	835	1511	12.2	18.3

Fig. 25. Thermal Plume at Surface for Waukegan Generating Station: June 2, 1971, 1140-1320 Hours. ANL Neg. No. 190-330.

Fig. 26. Thermal Plume at 1-ft Depth for Waukegan Generating Station: June 2, 1971, 1140-1320 Hours. ANL Neg. No. 190-331.

Fig. 27. Thermal Plume at 3-ft Depth for Waukegan Generating Station: June 2, 1971, 1140-1320 Hours. ANL Neg. No. 190-332.

Fig. 28. Thermal Plume at 6-ft Depth for Waukegan Generating Station: June 2, 1971, 1140-1320 Hours. ANL Neg. No. 190-333.

Fig. 29. Thermal Plume at 9-ft Depth for Waukegan Generating Station: June 2, 1971, 1140-1320 Hours. ANL Neg. No. 190-334.

Fig. 30. Vertical Cross Sections at Waukegan Generating Station: June 2, 1971, 1140-1320 Hours. ANL Neg. No. 190-395.

Fig. 31. Thermal Plume at Surface for Waukegan Generating Station: June 2, 1971, 1443-1723 Hours. ANL Neg. No. 190-335.

Fig. 32. Thermal Plume at 1-ft Depth for Waukegan Generating Station: June 2, 1971. 1443-1723 Hours. ANL Neg. No. 190-336.

Fig. 33. Thermal Plume at 3-ft Depth for Waukegan Generating Station: June 2, 1971, 1443-1723 Hours. ANL Neg. No. 190-337.

Fig. 35. Thermal Plume at 9-ft Depth for Waukegan Generating Station: June 2, 1971, 1443-1723 Hours. ANL Neg. No. 190-339.

Fig. 36. Vertical Cross Sections at Waukegan Generating Station: June 2, 1971, 1443-1723 Hours. ANL Neg. No. 190-396.

Fig. 37. Thermal Plume at 1-ft Depth for Waukegan Generating Station: June 2, 1971, 0910-1300 Hours. Data collected by Bio-Test Industrial Laboratories, Inc. (courtesy of Commonwealth Edison Company). ANL Neg. No. 190-487.

Fig. 38. Thermal Plume at Surface for Waukegan Generating Station: June 2, 1971, 1500 Hours. Data collected by Texas Instruments, Inc., using Airborne Infrared Imagery (courtesy of Commonwealth Edison Company). ANL Neg. No. 190-488 Rev. 2.

Results of the thermal-plume mapping by Bio-Test and Texas Instruments are shown in Figs. 37 and 38. The Bio-Test data were obtained using a station-by-station technique; the Texas Instruments thermal plume map was compiled by airborne infrared imagery. The Argonne and Bio-Test contours are in reasonable agreement with respect to the shape of the plume. To the north of the discharge, the Texas Instruments contours are in fair agreement with the others, but south of the discharge, temperatures are somewhat higher than those measured by Argonne and Bio-Test. The Texas Instruments data show the plume to be spreading southeast; this phenomenon is not apparent from the Argonne or Bio-Test contours. Greater detail, due to the airborne infrared imagery technique used, is shown in the Texas Instruments thermal-plume map. Differences in contours as mapped by the three organizations may be in part attributed to difference in time of measurement. Time of measurement is particularly important for these surveys since the power-plant loading changed abruptly in the morning hours. (See Table I for plant operating data.)

3. Point Beach Nuclear Power Plant: June 25, 1971

On the morning of June 25, 1971, an initial survey of the waters near the outfall indicated that the plume was following the southeast shoreline. For this reason the technique of running between buoys was not feasible due to the shallow near-shore water. Therefore, the boat was allowed to drift with the wind toward the shore. Where temperatures were measured, two transits were used to determine boat position from shore. Temperatures were measured at 1-m intervals to the lake bottom. This technique allowed the measurement of temperature as a function of depth at 61 positions.

The data were plotted, and results are shown in Figs. 39-43. During the survey, meteorological and lake conditions remained constant with winds from the northeast at 15 mph and 2-3-ft waves with a south-westerly heading. Ambient water temperature was found to be 11.0°C. Unfortunately, due to the rough lake conditions, ambient current was not measured. In our opinion, from the shape of the plume, we would have expected to find a strong southeasterly, shore-parallel current in the near-shore region.

As can be seen from the figures, the plume followed the shoreline southeast of the plant and extended offshore about 700-800 ft. Water at least 2°C above ambient extended more than $1\frac{1}{2}$ miles southeastward along the shore. Beyond this point, the boat's position could not be determined and data were not collected.

Examination of the subsurface plume drawings showed that the plume changed very little with depth. This fact, along with the vertical cross sections of the plume (Fig. 43--sections are labeled on the surface drawing as A-A', etc.), indicates that this plume was not dominated by

Fig. 39. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
 June 25, 1971, 1000-1215 Hours. ANL Neg. No. 190-340.

Fig. 40. Thermal Plume at 1.0-m Depth for Point Beach Power Plant (Unit 1):
 June 25, 1971, 1000-1215 Hours. ANL Neg. No. 190-341.

Fig. 41. Thermal Plume at 2.0-m Depth for Point Beach Power Plant (Unit 1):
 June 25, 1971, 1000-1215 Hours. ANL Neg. No. 190-342.

Fig. 42. Thermal Plume at 3.0-m Depth for Point Beach Power Plant (Unit 1):
 June 25, 1971, 1000-1215 Hours. ANL Neg. No. 190-343.

Fig. 43. Vertical Cross Sections at Point Beach Power Plant (Unit 1): June 25, 1971, 1000-1215 Hours. ANL Neg. No. 190-397.

buoyant forces. In fact, the isotherms in the cross-section drawings are almost all vertical. Plume areas (see appendix) within the same isotherms decrease as a function of depth, but this is due mainly to the intrusion of the bottom.

4. Point Beach Nuclear Power Plant: July 20-21, 1971

One temperature survey was conducted on the afternoon of July 20, 1971. The results are shown in Figs. 44-49. For the survey, the lake was calm with 15-mph winds out of the southwest. Ambient current was measured with an Ekman-Merz current meter at two locations about 1 mile southeast of the power plant at 1900 Hours. Current velocity at Buoy 1 (see Fig. 50) was 0.3 fps (018°) at a depth of 2 ft and 0.2 fps (007°) at a depth of 9 ft. At Buoy 14 (see Fig. 50) a current of 0.4 fps (014°) was recorded at a depth of 2 ft and 0.2 fps (287°) at a depth of 9 ft. Ambient water temperature was 12.6-12.8°C, and outfall temperature was 21.5°C. Plume discharge speed was measured at several locations and depths across the flume (20 ft in from the lake end of the discharge). Results are given in Table II.

TABLE II. Discharge Velocity for Point Beach Nuclear Power Plant (Unit 1)

Ekman-Merz Current-meter Data for July 20, 1971			Drogue Data for July 21, 1971	
Location ^a	Depth, ft	Speed, fps	Depth, ft	Speed, fps
5 ft from north side of flume	1.0	2.59	Surface ^b (run 1)	2.6
5 ft from north side of flume	6.0	2.25	Surface ^b (run 2)	2.5
5 ft from north side of flume	11.0	1.38	4.0 ^b	2.5
Center of flume	1.0	2.51	8.0 ^b	1.7
Center of flume	6.0	1.47		
Center of flume	11.0	1.37		
5 ft from south side of flume	1.0	1.90		
5 ft from south side of flume	6.0	1.92		
5 ft from south side of flume	11.0	1.34		

^aEkman-Merz measurements made 20 ft in from lakeside end of flume.

^bDrogues placed in water from center of lakeside end of flume.

Fig. 44. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
July 20, 1971, 1632-1805 Hours. ANL Neg. No. 190-344.

Fig. 45. Thermal Plume at 1-ft Depth for Point Beach Power Plant (Unit 1):
 July 20, 1971, 1632-1805 Hours. ANL Neg. No. 190-345.

Fig. 46. Thermal Plume at 3-ft Depth for Point Beach Power Plant (Unit 1):
 July 20, 1971, 1632-1805 Hours. ANL Neg. No. 190-346.

Fig. 47. Thermal Plume at 6-ft Depth for Point Beach Power Plant (Unit 1):
 July 20, 1971, 1632-1805 Hours. ANL Neg. No. 190-347.

Fig. 48. Thermal Plume at 9-ft Depth for Point Beach Power Plant (Unit 1):
 July 20, 1971, 1632-1805 Hours. ANL Neg. No. 190-348.

Fig. 49. Vertical Cross Sections at Point Beach Power Plant (Unit 1): July 20, 1971, 1632-1805 Hours. ANL Neg. No. 190-398.

As can be seen from the figures, the plume is bending toward the north due to the ambient current. Plume areas within isotherms at all depths were measured from the drawings and are tabulated in the appendix. Plume areas decreased as a function of depth. From the plume cross sections (Fig. 49), plume thickness appears to be about 7 ft.

Two temperature surveys and one drogue study were conducted during the morning and afternoon of July 21, 1971. The results of the morning temperature survey are shown in Figs. 50-55. Winds were light (5-10 mph) for this survey and out of the southwest. The lake was moderately calm for both surveys with 1-2-ft waves. For the first survey ambient water temperature ranged from 11.5 to 11.9°C and outfall temperature was 20.5°C. Ambient current was not measured. The afternoon survey was conducted about 4 hr after the conclusion of the morning survey (see Figs. 57-62). Winds for this survey increased to 12-18 mph out of the southwest. Ambient water temperature varied from 11.1 to 11.5°C, and outfall temperature was 21.8°C. Ambient current was measured at Buoys 1 and 14 (see Fig. 50) at 1730 Hours. At depths of 2 and 9 ft at both stations, the current velocity was 0.6 fps at 335°.

A dramatic shift in the centerline direction of the plume occurred from one survey to the next (see Figs. 50 and 57). A sharp interface on the southeastern side of the afternoon plume is indicative of deflection by the ambient current. The morning plume appears not to be influenced by any ambient current as the centerline extends directly out from the discharge and no sharp interface is present. These two surveys clearly show the variability of a thermal plume over a time span of only a few hours.

During both surveys the plume, in general, was found to be 6-8 ft thick (see Figs. 55 and 62). Plume areas within isotherms (see appendix) were compared for the two plumes, and areas for the morning survey were found to be larger than those for the afternoon survey.

Drogue studies were conducted between the two plume mappings. Results are presented in Fig. 56. Four drogues (two surface, one at 4 ft and one at 8 ft) were dropped from the center of the 1-beam across the end of the discharge flume and tracked with transits. Surface drogue 2 moved off the discharge at an initial speed of 2.5 fps, but was caught in an eddy and moved out of the plume jet. Surface drogue 1 moved away from the discharge at an initial speed of 2.6 fps; at 240 ft from the discharge, the drogue speed had fallen to 1.1 fps. From this point to the end of the run (900 ft from the discharge), the speed remained constant at 1.1 fps. The 4-ft drogue left the discharge at 2.5 fps. The speed gradually decreased to 0.8 fps 600 ft from the discharge. The initial speed of the 8-ft drogue was 1.7 fps; it decreased to 0.6 fps 200 ft from the discharge. Its speed then remained constant at 0.6 fps until the end of the run (500 ft from discharge).

Fig. 50. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
 July 21, 1971, 1020-1117 Hours. ANL Neg. No. 190-349 Rev. 1.

Fig. 51. Thermal Plume at 1-ft Depth for Point Beach Power Plant (Unit 1):
 July 21, 1971, 1020-1117 Hours. ANL Neg. No. 190-350.

Fig. 52. Thermal Plume at 3-ft Depth for Point Beach Power Plant (Unit 1):
 July 21, 1971, 1020-1117 Hours. ANL Neg. No. 190-351.

Fig. 53. Thermal Plume at 6-ft Depth for Point Beach Power Plant (Unit 1):
 July 21, 1971, 1020-1117 Hours. ANL Neg. No. 190-352.

Fig. 54. Thermal Plume at 9-ft Depth for Point Beach Power Plant (Unit 1):
July 21, 1971, 1020-1117 Hours. ANL Neg. No. 190-353.

Fig. 55. Vertical Cross Sections at Point Beach Power Plant (Unit 1): July 21, 1971, 1020-1117 Hours. ANL Neg. No. 190-399.

Fig. 56. Drogue Studies at Point Beach Power Plant (Unit 1): July 21, 1971, 1238-1336 Hours. ANL Neg. No. 190-407.

Fig. 57. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
July 21, 1971, 1508-1639 Hours, ANL Neg. No. 190-354.

Fig. 58. Thermal Plume at 1-ft Depth for Point Beach Power Plant (Unit 1):
 July 21, 1971, 1508-1639 Hours. ANL Neg. No. 190-355.

Fig. 59. Thermal Plume at 3-ft Depth for Point Beach Power Plant (Unit 1):
July 21, 1971, 1508-1639 Hours. ANL Neg. No. 190-356.

Fig. 60. Thermal Plume at 6-ft Depth for Point Beach Power Plant (Unit 1):
July 21, 1971, 1508-1639 Hours. ANI, Neg. No. 190-357.

Fig. 61. Thermal Plume at 9-ft Depth for Point Beach Power Plant (Unit 1):
 July 21, 1971, 1508-1639 Hours. ANL Neg. No. 190-358.

Fig. 62. Vertical Cross Sections at Point Beach Power Plant (Unit 1): July 21, 1971, 1508-1639 Hours. ANL Neg. No. 190-400.

Table II compares the initial speeds of the drogues with the values measured with the Ekman-Merz current meter the previous day.

5. State Line Generating Station: August 4, 1971

The thermal plume from the State Line Generating Station was mapped by both Bio-Test Industrial Laboratories, Inc. (in the morning), and Argonne National Laboratory (in the afternoon) on August 4, 1971. The plume at a depth of 1 ft, as mapped by Bio-Test, is shown in Fig. 63 for comparative purposes. Figures 64-69 present results of the Argonne data. During the afternoon, wind speeds of 7-12 mph out of the northeast were recorded. Waves of 1-3 ft were observed. Ambient lake temperature was 17.5°C, and discharge temperature was 25.3°C. Ambient lake current was not measured, although not much current would be expected at this location, due to the breakwater to the north and the shore configuration to the southeast of the plant.

Comparison of the Argonne 1-ft-depth data (Fig. 65) with the Bio-Test data indicates that the plume increased in areal extent considerably from the morning to the afternoon. After the plumes were drawn and compared, plant operating data were obtained from the Commonwealth Edison Company. It is apparent from the data (Table III) that the increase in size in the Argonne plume over the Bio-Test plume is attributable to a gradual increase in plant load.

TABLE III. Plant Operating Data for
State Line Generating Station for August 4, 1971

Hour	Plant Load, MWe	Discharge Flow Rate, cfs	Intake Temp, °C	Outfall Temp, °C
0100	442	963	18.9	21.7
0200	354	963	18.9	21.7
0300	354	963	18.9	21.7
0400	356	963	18.3	21.1
0500	358	1631	18.3	20.6
0600	398	1854	18.3	21.1
0700	626	1854	18.3	22.8
0800	918	1854	18.9	24.4
0900	954	1854	20.0	25.0
1000	958	1854	20.0	25.0
1100	947	1854	20.0	25.0
1200	945	1854	20.0	25.0
1300	949	1854	20.0	25.0
1400	946	1854	20.0	25.0
1500	945	1854	20.0	25.0
1600	942	1854	20.0	25.0
1700	937	1854	21.7	27.2

Fig. 63. Thermal Plume at 1-ft Depth for State Line Generating Station: August 4, 1971, 0930-1230 Hours. Data Collected by Bio-Test Industrial Laboratories, Inc. (courtesy of Commonwealth Edison Company). ANL Neg. No. 190-572.

Fig. 64. Thermal Plume at Surface for State Line Generating Station:
August 4, 1971, 1227-1550 Hours. ANL Neg. No. 190-359.

Fig. 65. Thermal Plume at 1-ft Depth for State Line Generating Station:
 August 4, 1971, 1227-1550-Hours. ANL Neg. No. 190-360.

Fig. 66. Thermal Plume at 3-ft Depth for State Line Generating Station:
 August 4, 1971, 1227-1550 Hours. ANL Neg. No. 190-361.

Fig. 67. Thermal Plume at 6-ft Depth for State Line Generating Station:
 August 4, 1971, 1227-1550 Hours. ANL Neg. No. 190-362.

Fig. 68. Thermal Plume at 9-ft Depth for State Line Generating Station:
 August 4, 1971, 1227-1550 Hours. ANL Neg. No. 190-363.

ALL TEMPERATURES IN DEGREES CENTIGRADE

Fig. 69. Vertical Cross Sections at State Line Generating Station: August 4, 1971, 1227-1550 Hours. ANL Neg. No. 190-401.

The drawings of the plume at depth and the vertical cross sections (Fig. 69) indicate that this is a particularly well-defined buoyant plume. This occurrence is probably the result of the sheltered nature of the receiving body of water and the low-velocity discharge. The plume appears to be almost nonexistent at the 6-ft depth (see Fig. 67). Plume depth is estimated as 4-5 ft. As shown in the appendix, plume areas within the same isotherms decrease rapidly with depth.

6. Point Beach Nuclear Power Plant: August 31 and September 1, 1971

One temperature survey and one drogue study were conducted during the afternoon of August 31, 1971. The drogue study (Fig. 70) was conducted before the temperature survey. Two surface drogues were dropped in the discharge flume in succession and tracked with transits. Both drogues moved in a southeasterly direction, as shown in the figure. Initial speed of drogue 1 was 2.4 fps. This speed gradually decreased to 0.4 fps 350 ft from the discharge. From here to the end of the run, the speed remained relatively constant. Drogue 2, while following a very similar track, exhibited an initial speed of 3.0 fps. At 300 ft from the discharge, its speed had dropped to 0.9 fps, at which speed it remained until the run was completed.

The thermal plume was mapped immediately after the drogue studies; results are shown in Figs. 71-75. Ambient conditions were measured during the survey. Wind speed was 5-7 mph out of the northeast. Ambient water temperature was measured at 17.6°C, although there was evidence of near-shore heating (see Fig. 71). Discharge temperature was 26.2°C. Lake conditions were moderately rough with 2-3-ft waves. Ambient current speed was not available, but the current direction obtained from in situ Braincon meters was found to be northward.

Due to an equipment malfunction, plume temperatures were measured only at the surface, 1.5, 2.0, and 2.5 m. When compared to the other plumes mapped at the Point Beach Plant, this plume is by far the largest in areal extent. A sharp interface, marked by a rapid temperature change and an abrupt change in turbidity, was noted on the eastern side of the plume.

Plume depth was estimated at 1.5-2.0 m from the vertical cross sections (see Fig. 75). As previously found, plume areas within isotherms (see appendix) decreased with depth.

On September 1, 1971, an effort was made to study the changes in a plume over a short period of time. To this end, the plume was mapped twice using our standard technique. In the interval between these two plume mappings, Bendix Aerospace Systems Division made a number of overflights

Fig. 70. Drogue Studies at Point Beach Power Plant (Unit 1): August 31, 1971, 1430-1451 Hours. ANL Neg. No. 190-408.

Fig. 71. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
 August 31, 1971, 1530-1631 Hours. ANL Neg. No. 190-364.

Fig. 72. Thermal Plume at 1.5-m Depth for Point Beach Power Plant (Unit 1):
 August 31, 1971, 1530-1631 Hours. ANL Neg. No. 190-365.

Fig. 73. Thermal Plume at 2.0-m Depth for Point Beach Power Plant (Unit 1):
 August 31, 1971, 1530-1631 Hours. ANL Neg. No. 190-366.

Fig. 74. Thermal Plume at 2.5-m Depth for Point Beach Power Plant (Unit 1):
 August 31, 1971, 1530-1631 Hours. ANL Neg. No. 190-367.

Fig. 75. Vertical Cross Sections at Point Beach Power Plant (Unit 1): August 31, 1971, 1530-1631 Hours. ANL Neg. No. 190-402.

using both airborne infrared imagery and black and white photography. Several of the resultant photographs (Figs. 76-91) are included to show a complete surface plume at essentially one instant in time. The quality of the infrared images did not allow isotherms to be drawn. Thus, the images are presented as purely qualitative information.

Results of the thermal-plume measurements by our regular boat measurement technique are shown in Figs. 92-97 for the morning survey and Figs. 99-104 for the afternoon survey. For both surveys, wind speed was 8-14 mph out of the southeast, lake conditions were moderately calm with 1-2-ft waves, the ambient water temperature was 17.4-17.8°C, and the discharge temperature ranged from 27.1°C in the morning to 26.5°C in the afternoon. Ambient current speed was not measured. Current direction was northward. Due to an equipment malfunction, data are not available for plume temperatures at the 0.5- and 1.0-m depths.

Comparing the surface plumes for both surveys shows that the plume centerline direction changed somewhat over about 5 hr. This gives an example of the time span over which the plume can vary. The aerial photographs show the plume at intermediate times between these surveys and give a remarkably consistent picture of the plume when compared to the ground truth information. Even the slightly cooler water just northeast of the intake crib shows up on both the infrared images (Figs. 76-78) taken shortly after the morning survey and the drawing of the morning surface plume (Fig. 92). If the intake crib is used as a reference point, it can be seen that the plume's interface shifted from about 1000 ft south of the intake crib during the morning survey to just north of the crib during the afternoon survey. In Figs. 84-91, the plume's eastern interface is characterized by an abrupt change in the turbidity of the water, which is clearly shown as lighter-colored water. This interface was also observed from the boat during both surveys and was marked by a rapid temperature change. From the vertical cross sections (Figs. 97 and 104), plume depth for both surveys was estimated as 1.5-2.0 m. Plume areas are listed in the appendix.

During the overflights, four drogues were released from the outfall and tracked using transits. Results of these studies are shown in Fig. 98. Surface drogue 1 left the discharge flume at 3.2 fps. It was tracked until it was 600 ft from the discharge, where its speed was 1.2 fps. Surface drogue 2 had a speed of 3.0 fps at the discharge, which decreased to 0.6 fps, 500 ft from the end of discharge flume. The drogue at a depth of 4 ft left the discharge at 1.7 fps. At 200 ft from the discharge, the speed had dropped to 1.2 fps and remained constant to the end of the run (400 ft from the discharge). The drogue at a depth of 8 ft had an initial speed of 1.9 fps, which decreased to 0.3 fps, 180 ft from the discharge where the run was terminated.

Fig. 76. Infrared Image of the Thermal Plume from Point Beach Nuclear Power Plant: September 1, 1971, 1241 Hours. ANL Neg. No. 190-516.

Fig. 77. Infrared Image of the Thermal Plume from Point Beach Nuclear Power Plant: September 1, 1971, 1246 Hours. ANL Neg. No. 190-511.

Fig. 78. Infrared Image of the Thermal Plume from Point Beach Nuclear Power Plant: September 1, 1971, 1259 Hours. ANL Neg. No. 190-209A.

Fig. 79. Infrared Image of the Thermal Plume from Point Beach Nuclear Power Plant: September 1, 1971, 1314 Hours. ANL Neg. No. 190-514.

Fig. 80. Infrared Image of the Thermal Plume from Point Beach Nuclear Power Plant: September 1, 1971, 1327 Hours. ANL Neg. No. 190-512.

Fig. 81. Infrared Image of the Thermal Plume from Point Beach Nuclear Power Plant: September 1, 1971, 1347 Hours. ANL Neg. No. 190-517.

Fig. 82. Infrared Image of the Thermal Plume from Point Beach Nuclear Power Plant: September 1, 1971, 1357 Hours. ANL Neg. No. 190-513.

Fig. 83. Infrared Image of the Thermal Plume from Point Beach Nuclear Power Plant: September 1, 1971, 1414 Hours. ANL Neg. No. 190-515.

Fig. 84

Photograph of the Thermal Plume from Point Beach Nuclear Power Plant:
September 1, 1971, 1241 Hours. ANL Neg. No. 190-500.

Fig. 85

Photograph of the Thermal Plume from Point Beach Nuclear Power Plant:
September 1, 1971, 1246 Hours. ANL Neg. No. 190-501.

Fig. 86

Photograph of the Thermal Plume from Point Beach Nuclear Power Plant:
September 1, 1971, 1259 Hours. ANL Neg. No. 190-502.

Fig. 87

Photograph of the Thermal Plume from Point Beach Nuclear Power Plant:
September 1, 1971, 1314 Hours. ANL Neg. No. 190-503.

Fig. 88

Photograph of the Thermal Plume from Point Beach Nuclear Power Plant:
September 1, 1971, 1327 Hours. ANL Neg. No. 190-504.

Fig. 89

Photograph of the Thermal Plume from Point Beach Nuclear Power Plant:
September 1, 1971, 1347 Hours. ANL Neg. No. 190-505.

Fig. 90

Photograph of the Thermal Plume from Point Beach Nuclear Power Plant:
September 1, 1971, 1357 Hours. ANL Neg. No. 190-506.

Fig. 91

Photograph of the Thermal Plume from Point Beach Nuclear Power Plant:
September 1, 1971, 1414 Hours. ANL Neg. No. 190-507.

Fig. 92. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
 September 1, 1971, 0950-1130 Hours. ANL Neg. No. 190-368.

Fig. 93. Thermal Plume at 1.5-m Depth for Point Beach Power Plant (Unit 1):
 September 1, 1971, 0950-1130 Hours. ANL Neg. No. 190-369.

Fig. 94. Thermal Plume at 2.0-m Depth for Point Beach Power Plant (Unit 1):
September 1, 1971, 0950-1130 Hours. ANL Neg. No. 190-370.

Fig. 95. Thermal Plume at 2.5-m Depth for Point Beach Power Plant (Unit 1):
 September 1, 1971, 0950-1130 Hours. ANL Neg. No. 190-371.

Fig. 96. Thermal Plume at 3.0-m Depth for Point Beach Power Plant (Unit 1):
 September 1, 1971, 0950-1130 Hours. ANL Neg. No. 190-372.

Fig. 97. Vertical Cross Sections at Point Beach Power Plant (Unit 1): September 1, 1971, 0950-1130 Hours. ANL Neg. No. 190-403.

Fig. 98. Drogue Studies at Point Beach Power Plant (Unit 1): September 1, 1971, 1300-1337 Hours. ANL Neg. No. 190-409.

Fig. 99. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
 September 1, 1971, 1445-1727 Hours. ANL Neg. No. 190-373.

Fig. 100. Thermal Plume at 1.5-m Depth for Point Beach Power Plant (Unit 1):
 September 1, 1971, 1445-1727 Hours. ANL Neg. No. 190-374.

Fig. 101. Thermal Plume at 2.0-m Depth for Point Beach Power Plant (Unit 1):
 September 1, 1971, 1445-1727 Hours. ANL Neg. No. 190-375.

Fig. 102. Thermal Plume at 2.5-m Depth for Point Beach Power Plant (Unit 1);
 September 1, 1971, 1445-1727 Hours. ANL Neg. No. 190-376.

Fig. 103. Thermal Plume at 3.0-m Depth for Point Beach Power Plant (Unit 1):
 September 1, 1971, 1445-1727 Hours. ANL Neg. No. 190-377.

Fig. 104. Vertical Cross Sections at Point Beach Power Plant (Unit 1): September 1, 1971, 1445-1727 Hours. ANL Neg. No. 190-404.

7. Point Beach Nuclear Power Plant: October 28, 1971

The thermal plume was mapped twice on October 28, 1971. Simultaneous echo soundings, using a fish locator, provided information on the distribution of fish in the thermal plume. The relationship between temperature structure and fish distribution in the plume is discussed by Romberg and Spigarelli.¹⁰ Only the physical structure of this plume will be discussed here.

Figures 105-120 present the results of the temperature surveys. Figures 105-112 show the plume as it appeared during the afternoon (1402-1539 Hours), and Figs. 113-120 show the plume during darkness (2000-2100 Hours). The night plume is of particular interest, since few plumes have been measured after dark. However, no significant differences in the plumes were observed. Low wind speeds were recorded in the afternoon (4-5 mph) with direction variable (100-210°). These winds shifted in the evening to a steady northeast (50°) breeze at 7 mph. For the afternoon survey, slightly choppy conditions were noted (0-1-ft waves), and for the evening survey, the lake conditions were quite calm. Ambient current velocities were available from an in situ Braincon current meter located at a 6-ft depth at Buoy 1 (see Fig. 105). The current was steady for both surveys flowing shore parallel in a southeasterly direction. The speed was recorded as 0.4-0.5 fps for most of the day. We hesitate to base any conclusions on current speed, because these Savanious rotor-type meters were located in the region affected by wave motion. Ambient lake temperature was 12.6-12.9°C for the surveys, and discharge temperature was constant at 21.2°C for both surveys.

The two plumes were similar in both centerline direction and shape, although the evening plume appeared to orient itself closer to the shore. At Buoy 2 (see Fig. 105) in the afternoon survey, inconsistencies in the data occurred, and these are represented somewhat artificially in Figs. 105-110 by the dotted lines. Plume areas (see appendix) decreased with depth for both surveys in a way consistent with previous findings. Examination of the vertical cross sections (Figs. 112 and 120) for both surveys indicate plume depth to be about 2 m.

Fig. 105. Thermal Plume at Surface for Point Beach Power Plant (Unit 1):
 October 28, 1971, 1402-1539 Hours. ANL Neg. No. 190-378.

Fig. 106. Thermal Plume at 0.5-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 1402-1539 Hours. ANL Neg. No. 190-379.

Fig. 107. Thermal Plume at 1.0-m Depth for Point Beach Power Plant (Unit 1):
October 28, 1971, 1402-1539 Hours. ANL Neg. No. 190-380.

Fig. 108. Thermal Plume at 1.5-m Depth for Point Beach Power Plant (Unit 1): October 28, 1971, 1402-1539 Hours. ANL Neg. No. 190-381.

Fig. 109. Thermal Plume at 2.0-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 1402-1539 Hours, ANL Neg. No. 190-382.

Fig. 110. Thermal Plume at 2.5-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 1402-1539 Hours. ANL Neg. No. 190-383.

Fig. 111. Thermal Plume at 3.0-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 1402-1539 Hours. ANL Neg. No. 190-384.

Fig. 112. Vertical Cross Sections at Point Beach Power Plant (Unit 1): October 28, 1971, 1402-1539 Hours. ANL Neg. No. 190-405.

Fig. 113. Thermal Plume at Surface for Point Beach Power Plant (Unit 1);
 October 28, 1971, 2000-2100 Hours. ANL Neg. No. 190-385.

Fig. 114. Thermal Plume at 0.5-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 2000-2100 Hours. ANL Ncg. No. 190-386.

Fig. 115. Thermal Plume at 1.0-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 2000-2100 Hours. ANL Neg. No. 190-387.

Fig. 116. Thermal Plume at 1.5-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 2000-2100 Hours. ANL Neg. No. 190-388.

Fig. 117. Thermal Plume at 2.0-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 2000-2100 Hours. ANL Neg. No. 190-389.

Fig. 118. Thermal Plume at 2.5-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 2000-2100 Hours. ANL Neg. No. 190-390.

Fig. 119. Thermal Plume at 3.0-m Depth for Point Beach Power Plant (Unit 1):
 October 28, 1971, 2000-2100 Hours. ANL Neg. No. 190-391.

Fig. 120. Vertical Cross Sections at Point Beach Power Plant (Unit 1): October 28, 1971, 2000-2100 Hours. ANL Neg. No. 190-406.

C. Jet-regime Study

On November 3, 1971, a field study of the temperature and velocity profiles near the outfall of the Point Beach Nuclear Plant was made. Data on the temperature and velocity structure in the jet regime are needed to test various models that have been proposed to specify this region. Some of these models are discussed by Policastro and Tokar.⁸ The results of the survey are shown in Figs. 121-125.

A three-point mooring system was used to hold the boat steady while obtaining simultaneous temperature and velocity measurements in the near-field region (see Fig. 126). Anchors were located on either side of the plume and attached to the stern cleats of the boat, and a bow line was attached to the center of the outfall. Transects across the plume centerline were then made at about 25, 90, and 240 ft from the outfall by pulling the boat from one side anchor to the other. The boat's position was held relatively constant, and transits were used to obtain the location of each station. A Bendix Q-15 current meter with a YSI No. 409 thermistor attached was used to measure the current velocity and water temperature. The meter was lowered over the side and suspended at 2-ft intervals to a depth of 10 ft or to the bottom. The lake was $13\frac{1}{2}$ ft deep at the outfall and decreased in depth to 7 ft at a point 240 ft from the outfall. Water depth and surface temperature were measured at each station, and wind velocity was measured at several stations. Lake conditions for the survey were calm. Ambient lake current and temperature were measured out of the plume approximately $1/4$ mile north of the outfall, in a region outside the influence of the plume. Plant operating data were obtained from the Point Beach Power Plant personnel.

The data with the range of variability is plotted in Figs. 121-123 for three different depths. Drawings for the 8- and 10-ft depths were not made because data were not available at all stations. Depth profiles of current speed and temperature are shown in Figs. 124 and 125. The temperature at a given depth and location exhibited greater variability than expected, even when near the plume centerline. As a result, temperature ranges are presented in Figs. 121-123 with the lowest temperature in parentheses and in Fig. 125 as the dotted extensions. Each measurement was made over a period of about 1 min, which is indicative of the rapid variability of the temperature. Variations in the velocity were not as easily observed because of the current-meter time constant. The lengths of the arrows in the figures are proportional to current magnitude, and their directions indicate current directions. The directions presented have been corrected by adding 12° in a clockwise direction to the original data to offset a systematic error in the direction sensor. The ambient lake current was found to be flowing shore parallel in a southeasterly direction at a speed of 0.2 fps. Ambient water temperature was 7.8°C .

Fig. 122. Jet-regime Study at 4-ft Depth for Point Beach Power Plant (Unit 1): November 3, 1971, 1245-1605 Hours. ANL Neg. No. 190-411.

Fig. 123. Jet-regime Study at 6-ft Depth for Point Beach Power Plant (Unit 1): November 3, 1971, 1245-1605 Hours. ANL Neg. No. 190-412.

Fig. 124. Speed vs Depth for Jet-regime Study: November 3, 1971, 1245-1605 Hours. ANL Neg. No. 190-551 Rev. 1.

Fig. 125. Temperature vs Depth for Jet-regime Study: November 3, 1971, 1245-1605 Hours. ANL Neg. No. 190-550 Rev. 1.

Fig. 126. Jet-regime Study at Point Beach Nuclear Power Plant: November 3, 1971. ANL Neg. No. 190-243.

For each axial position, the velocity and temperature data were fitted to Gaussian distributions. At the second and third transects (90 and 240 ft from the outfall), a Gaussian is a good approximation to the data. At 25 ft, the data fit a tophat distribution better. A trial-and-error, least-squares fit was used to find the standard deviation assuming a centerline estimated from the figure. The width of the jet, as calculated separately from the temperature and velocity data, was assumed to be two standard deviations on either side of the jet axis.

The jet width estimated from the temperature data at 2 ft was found to be about 1.15 times as great as the width estimated from the velocity data at 2 ft, though the relatively small amount of data precludes any definite conclusions. This result implies that temperature diffuses more rapidly than momentum, which has been established experimentally for free turbulence.²

Figures 124 and 125 show the change of temperature and current speed with depth at each station (station locations are shown in Fig. 127).

Fig. 127. Station Locations for Jet-regime Study: November 3, 1971, 1245-1605 Hours. ANL Neg. No. 190-573.

Both show a steady decrease with depth, although some variability is evident. No essential differences were found between the rates of decay of temperature and current speed with depth or distance from the outfall. At 240 ft from the outfall, the average temperatures and current speeds measured were about 75% of the values recorded 25 ft from the discharge.

D. Sinking-thermal-plume Experiment

The purpose of the sinking-plume experiment was to make exploratory measurements of water temperature on the lake bottom to determine the degree to which this water might be heated as a result of a sinking thermal plume. The experiment is relevant to the behavior of waste-heat inputs during winter conditions. The Lake Michigan Enforcement Conference Technical Committee on Thermal Discharges has expressed concern⁵ that "Bottom layering of warm water might occur over relatively large areas, having its chief effects on bottom fauna and the disruption of fish reproduction." The premature hatching of fish eggs resulting from exposure to warmer than normal ambient water is an item of particular concern.

The phenomenon of a sinking plume occurs when the lake temperature is less than 4°C. The heated water discharged from the power plant entrains and mixes with the cold lake water. When the discharged and entrained water cools to 4°C, it achieves its maximum density, and gravitational forces cause it to sink through the colder, more buoyant lake water. This slightly denser mass of water should flow along the lake bottom until additional mixing further reduces the temperature.

The site chosen for the experiment was the Point Beach Nuclear Power Plant. The experiment consisted of placing 11 Geodyne, Model A 119-4, temperature recorders on the lake bottom in an area expected to be influenced by the thermal plume. (These instruments were obtained on loan from the U.S. Environmental Protection Agency, Great Lakes Region.) The instruments were bolted to 800-lb steel anchors so that the temperature sensor would be about 0.5 ft above the lake bottom (see Fig. 8). The instruments were placed in the lake on March 11 and 12, 1971. The lake temperature at that time was 0.5°C. Nine of the instruments were placed in a three-by-three grid slightly south of the plant, an area where the plume was observed to flow most often. Three instruments were placed in 16 ft of water, about 1000 ft offshore; three in 22 ft of water, about 2000 ft offshore; two in 32 ft of water, about 3700 ft offshore; and one in 36 ft of water, about 4800 ft offshore (see Fig. 128). Also, two instruments were placed 2 miles north of the plant at depths of 20 and 30 ft to provide measurements of ambient lake conditions.

The instruments were deployed by lowering them from a 90-ft vessel, the Telson Queen. A diver observed the placement of the instruments on the bottom to see that they were upright and not sitting on rocks. While on the

bottom, he described bottom conditions and reported seeing numerous crayfish, sculpins, and rocks covered with a dense growth of periphyton. The instruments were set to record water temperature every 10 min for about 2 months. The positions of the sensors were determined by transit sitings and marked with buoys.

Fig. 128. Temperature-recorder Locations for Sinking-plume Experiment:
March 13-April 30, 1971. ANL Neg. No. 190-574.

On May 13, 1971, the 11 temperature recorders were recovered. The buoys originally attached to the temperature-recorder anchors were still intact, although several of them were damaged. On May 14, 1971, the temperature recorder casings were opened and the strip charts for recording

temperatures were removed. An examination of the data indicated that only five of the recorders near the plant (No. 176, 182, 243, 297, and 368) functioned properly for the entire length of the experiment, one of the recorders, No. 248, functioned properly for part of the experiment, and four recorders failed to give any useful results. One of the recorders placed in ambient water 2 miles north of the plant also functioned properly.

An analysis of the data revealed that the plume did sink to the bottom as long as the ambient lake temperature was 4°C or less. When the ambient temperature exceeded 4°C, there was no evidence of temperature perturbations on the bottom produced by the thermal discharge. Figure 129 shows typical data obtained from three of the thermographs. For this data period reactor Unit No. 1 (southeast outfall) was operating at 480 MWe. Part of the cooling water was being recirculated, and this resulted in a condenser inlet temperature of 5.6°C and a discharge temperature of 13.9°C. During the period shown, the sky conditions changed from cloudy to foggy. Winds were from the southeast and varied from 3 to 12 mph. The air temperature was relatively constant at 1.0-2.8°C, and the lake had 1-2-ft waves. Table IV summarizes the results of the experiment in terms of the percentage of time

Fig. 129

Typical Data Obtained from
Temperature Recorders. ANI,
Neg. No. 190-206 Rev. 2.

TABLE IV. Effect of Sinking Thermal Plume by Location^a

Sensor No.:	248	297	176	182	243	368
Depth, ft	16	16	22	22	36	32
Distance from discharge, ft	1100	2300	2000	2700	4800	5000
Maximum ΔT , °C	5.2	4.6	4.5	3.0	2.4	2.6
Percentage of time	(March 13-April 3)					
$\Delta T > 1.5^\circ\text{C}$	32.8	45.5	29.8	23.2	6.8	9.6
$\Delta T > 2.6^\circ\text{C}$	14.4	28.6	16.4	4.6	1.4	0.3
$\Delta T > 4.0^\circ\text{C}$	3.0	0.5	0.1	0	0	0
Percentage of time	(April 17-30) ^b					
$\Delta T > 1.5^\circ\text{C}$	-	14.4	17.8	3.7	8.8	5.8
$\Delta T > 2.6^\circ\text{C}$	-	5.5	3.4	1.7	1.2	1.0

^aSee Fig. 128 for locations.

^bReactor shut down April 4-17.

a particular sensor was influenced by the sinking plume. Three percentages are given: One represents the fraction of time the sensor was influenced by water more than 1.5°C above ambient, the second represents an influence greater than 2.6°C above ambient, and the third represents an influence greater than 4.0°C . The lake temperature reached 4°C on approximately April 16.

The instruments nearest the discharge recorded the most influence and the sharpest temperature gradients. Instruments No. 243 and 368 indicated much less influence than the four closest instruments. It therefore appears that a fair degree of mixing occurs between the inner and outer instruments. The maximum change in temperature over ambient recorded by the various thermographs is also shown in Table IV. The discussion of the sinking-plume experiment in this report is merely an attempt to acquaint the reader with the experiment, since it was part of our 1971 field work. A more detailed discussion of the experiment and results is given in Ref. 6.

E. In Situ Current-meter Data

Current-direction data near the Point Beach site were obtained for several periods during the field year from three Braincon histogram recording current meters. No current-speed measurements are presented here because the meters were located in shallow water where wave action has a significant influence on the speed recorded. Three recording periods are presented, labeled A, B, and C as shown in Fig. 130, as are meter location and depth. Meters are arbitrarily numbered 1, 2, and 3. The directional data are shown in Figs. 131-135, where direction is shown on the ordinate and time on the abscissa. The data were reduced by reading every sixth frame, which results in a 10-min average taken every hour. The height of the line indicates the directional variation of one 10-min period each hour. As can be seen from the graphs, flow is predominantly shore parallel, roughly moving southeast along the shoreline about half the time and northwest half the time.

Figure 136 shows each instrument's record of direction in the form of a bar graph of percentage of time in each of eight quadrants. Meters that were recording during the same time interval are shown on the same graph. The shoreline runs north-south at approximately 340 and 160° , which is about the middle of quadrants 8 and 4. The graphs indicate that although the current at each location is generally shore parallel; quite often there is a component at a given level either onshore or offshore. Since current speeds are not available with the direction information, it is difficult to judge when the vanes are not registering meaningful data due to very low currents and when waves may be influencing them.

From the actual record of current direction in Figs. 131-135, the direction and amount of variability of current direction can be estimated.

The direction is often stable for one to six or more days and the amount of swing of the vane would suggest fairly high and consistent currents at times. Often a direction change of 180° within an hour is evident, although several instances of more gradual shifts in direction do occur in the record.

Fig. 130. In Situ Current-meter Locations, Depths, and Recording Periods. ANL Neg. No. 190-575.

Fig. 131. Direction vs Time for In Situ Current Meters: August 26-September 5, 1971. ANI, Neg. No. 190-552.

Fig. 132. Direction vs Time for In Situ Current Meters:
September 5-15, 1971. ANI, Ncg. No. 190-553 Rev. 1.

Fig. 133. Direction vs Time for In Situ Current Meters: September 16-29, 1971. ANL Neg. No. 190-555.

Fig. 134. Direction vs Time for In Situ Current Meters: September 29-October 12, 1971. ANL Neg. No. 190-554.

Fig. 135. Direction vs Time for In Situ Current Meters: October 27–November 3, 1971. ANL Neg. No. 190-556 Rev. 1.

Fig. 136. Bar Graph Showing Percentage of Time in Each of Eight Directions for In Situ Current Meters. ANL Neg. No. 190-548 Rev. 1.

V. DISCUSSION OF RESULTS

A. Thermal-plume Measurements

1. During April 1971, Asbury and Frigo¹ adopted a completely phenomenological approach in attempting to find a relationship that could be used to predict buoyant plume surface areas. They plotted data collected by other field investigators on log-log paper with the fractional

excess temperature of the isotherm (θ/θ_0) plotted against the ratio A/Q^a , where A is the plume area contained within the isotherm at excess temperature θ , Q is the volumetric discharge flow rate, and a is an exponent that was to be determined. Figure 137 shows a schematic defining pertinent parameters for the data plot. The most consistent grouping of the buoyant plume data occurred for $a = 1$, that is, on a plot of the form $\log \theta/\theta_0$ versus $\log A/Q$.

Fig. 137. Schematic Defining Pertinent Parameters for Asbury-Frigo Data Plot.¹ ANL Neg. No. 190-301 Rev. 1.

The surface areas of the thermal plumes presented in this report were measured using a planimeter. The data are displayed on Fig. 138. (See addendum for discussion of discharge flow rate.) As can be seen, the data fall within the envelope of data originally plotted by Asbury and Frigo. The data for the Point Beach Nuclear Power Plant do consistently group below the curve, which indicates that the discharge from this plant apparently exhibits better mixing than the power plants studied by Asbury and Frigo.

When considered against the various causes of scatter, the clustering of the plume data is somewhat remarkable. Sources of scatter among the data include:

a. Large plume-to-plume variation in ambient diffusivity, ambient current velocity, atmospheric conditions and plume depth. Although plume size should be strongly dependent upon them, these variables have not been included in the data plot.

b. Inaccurate plume areas, especially in the far-field region, where ambient "noise" and plume meandering can produce significant errors in the mapping of thermal plumes.

c. Different outfall geometries. Although all the outfalls (except that for the State Line Generating Station) are of the channel type, orifice dimensions and bottom topographies differ considerably.

d. Power-plant transients.

There may also exist a more suitable ratio than A/Q that could lead to a more consistent grouping of the data.

Fig. 138. Asbury-Frigo Data Plot of Fractional Excess Temperature vs the Ratio of Surface Area to Discharge Flow Rate, Showing Data Presented in the Present Report. ANL Neg. No. 190-576.

The original plume data plotted by Asbury and Frigo, as well as that presented in this report (except the State Line Generating Station data), refer to channel outfall geometries. The curve, therefore, may not be applicable to other outfall geometries, particularly in the near-field region where θ/θ_0 is large. Allowing for this restriction and based on the data originally used by Asbury and Frigo and further strengthened by the data in this report, we believe that the curve represents a useful rule of thumb for predicting surface areas of buoyant thermal plumes. Reference 4 contains a more detailed discussion of this phenomenological curve.

2. An examination of the data contained in the appendix indicates that the area contained within a given isotherm decreases with depth. Average plume depth was found to be about 2 m in the far-field region. Plume volumes are uncertain due to a lack of data near the plant outfall.

3. The plume drawings contained within this report for different days indicate the extreme variability of the plume over long and short periods of time. Note, for example, the plume on June 25, 1971 (Fig. 39), and on August 31, 1971 (Fig. 71). Variation of the plume over a few hours is shown by the two plume drawings for July 21, 1971 (Figs. 50 and 57). Variations over even shorter times are shown by the infrared images (Figs. 76-83). Problems resulting from the time span needed to measure a plume are illustrated by the uncertainty (dotted lines) in the plume drawings for October 28, 1971 (Figs. 105-110). Variation in the size of the plume may also be due to changes in plant operating conditions as evidenced by data from the State Line Generating Station on August 4, 1971 (Figs. 63 and 65). An increase in plume areal extent was noted as the plant loading increased.

4. Although the influence of ambient current on plume areas is not clear from the data, it appears that the location of the plume in the far field is dominated by the current. The plume bends in the direction of the ambient current, and a sharp interface on the upcurrent side of the plume is typical. This interface, often marked by temperature gradients of as much as 5°C in less than 200 ft, may also be marked by debris at the surface, a change in water color, and/or a change in turbidity as shown in Figs. 84-91.

Shoreline heating and upwelling also make it difficult in certain instances to define the plume completely. This is particularly evident in the plume drawing for August 31, 1971 (Fig. 71).

5. The plume mapped on June 25, 1971 (Figs. 39-43) is an example of a plume not dominated by buoyant forces. This plume hugged the shoreline and interacted with the bottom for a considerable distance. Although the plume appears anomalous in this report, this type of behavior may be expected anytime there is an onshore wind of sufficient force and duration to generate strong currents. Unfortunately, this type of weather makes it unfeasible to use a small boat on Lake Michigan. The proximity of the plume to the shore makes it even more difficult to measure. For this reason, the frequency of plumes with this shoreline hugging feature remains undetermined.

6. Drogue data collected at the Point Beach outfall indicate plume velocities similar to those measured with the Q-15 and Ekman-Merz current meters both at the outfall and in the near field. The drogues were

sometimes affected by eddies and drifted out of the plume jet and some drogues exhibited a tendency to slow to a constant speed some distance from the discharge. Variations in both speed and direction of drogues released at the same point and same depth were also noted. Due to the paucity of data, a more detailed analysis was not carried out.

B. Jet-regime Study

The preliminary survey of the temperature and velocity structure in the near field indicates that meaningful information can be obtained in this area using readily available techniques. With the open-channel-type discharge of Point Beach, eddies appeared to cause rapid temperature fluctuations in the jet, even near the plume centerline. Large current-speed fluctuations were not observed, possibly because of the 25-sec time constant of the Q-15 current meter. Current direction varied somewhat, depending on location. It was possible to estimate the jet width from temperature and velocity measurements independently, but the results obtained from the small amount of data available are probably not significant. As expected, the current speed and water temperatures decreased as a function of depth. The limiting factor in taking velocity measurements of this type was found to be time. The number of data points that can be obtained in a single day is a function of the time it takes to set up an anchoring system. Due to the time-varying nature of a thermal plume, measurements made over a period in which the lake conditions changed markedly would be difficult to interpret.

C. Sinking-thermal-plume Experiment

Results of the sinking-thermal-plume experiment are discussed more completely in Ref. 6. This experiment confirmed the phenomenon of a sinking thermal plume occurring when the lake temperature is less than 4°C. The thermographs on the lake bottom recorded definite temperature excursions that could only be attributed to the power-plant cooling water. The maximum recorded temperature differential over ambient water temperature was 5.2°C at the thermograph nearest the discharge; it decreased with distance from the discharge. The maximum recorded temperature differential 5000 ft from the discharge was 2.6°C.

The ambient temperature showed relatively little fluctuation while the lake temperature was 0-2°C. The fluctuations became larger, particularly in shallow water, as the lake temperature rose to 4°C and above. Variations of up to 2°C were observed in the ambient water when the reactor was shut down. The normal daily variation throughout the experiment was 0-1°C.

D. Instrumentation and Data-collection Techniques

1. The use of a vertical array of temperature probes deployed from a small moving boat to specify the location and extent of a thermal

plume is an extremely valuable technique for mapping large-scale plume phenomena at the surface and at depth. Small-scale phenomena are lost due to the sampling interval and the time constant of the probes. This method gives a three-dimensional view of the plume over a short period of time and results in easily reduced data. It does not give an instantaneous picture of the surface plume, as do aerial infrared imagery techniques, nor does it give a continuous look at how a plume behaves, as does a fixed system of probes. These two methods also have drawbacks; the infrared technique gives two-dimensional data that must be related to ground truth measurements, and a fixed probe system is limited by the number of positions that can be permanently monitored. Perhaps the most important drawback to the use of a boat to measure thermal plumes is that measurements can only be made when and where the boat can safely operate. On Lake Michigan, with the size of boats used in this program, this restriction can be an important limitation. As a result, the thermal-plume data as well as the jet-regime data are biased toward fair-weather conditions. Just how important this bias is in terms of the size and location of the plume and the way it reacts with the lake in general is undetermined at this time.

Aside from the basic shortcomings mentioned above, the system used to map thermal plumes needs to be improved in the following areas to make more complete studies possible:

- a. Data collection at any position, regardless of prearranged buoy locations.
- b. Complete automation of data collection and reduction.
- c. Better information on bottom contours.
- d. Speedier plume measurements.
- e. More and better ambient measurements. Ambient current and its relation to wind are especially important.
- f. More extensive surveys to reduce the ambiguities caused by upwelling and shoreline heating.
- g. Faster-response temperature probes.
- h. More information near the plant outfall enabling plume volumes to be computed.

2. Besides mapping the plume in the far field, other measurements made were drogue measurements in the near field, current and temperature measurements in the near field, bottom temperature measurements during the winter, and in situ current measurements. Drogue measurements were made by tracking the movement of the drogues with transits. This method requires considerable time, effort, and personnel for relatively few data points. It is, of course, interesting, but assessing the meaning of such a

limited number of measurements is difficult. At approximately the same time that drogue measurements are made, plume measurements need to be made for meaningful analysis of the drogue data.

3. The jet-regime study carried out using the Q-15 current meter with attached thermistor appears to offer a reasonably efficient approach to specifying the near-field velocity and temperature structure. The Q-15 is especially well adapted to a study of this type, since it averages out boat and wave motion and mean flow is measured. Because of the time constant of the meter, this technique does not allow any high-frequency velocity changes to be measured.

4. The Geodyne thermographs used in obtaining data on the sinking-plume phenomena were not wholly acceptable. Only six of 11 instruments worked normally, and data reduction of even these six was laborious. Also, the experiment was designed so as to measure only water temperature on the bottom. For future work, information at several levels would be desirable, but the number of thermographs needed may then become prohibitive. A method of collecting data that could be precisely correlated in time from one instrument to the next is another requisite for a more complete study.

5. The in situ current-direction recordings were obtained using Savonius rotor current meters, which are not the most desirable meters to use in shallow-water regions. The speed records had to be discounted due to the effects of wave motion on the rotor, and without a true speed reading the directional data have less meaning. Data reduction of the filmed record was a very tedious and time consuming task.

E. Measurement Errors

Table V gives the accuracy of the instrumentation used to collect data for this report, and Table VI gives estimates of errors due to the data-collection and -reduction techniques. The points at which errors are introduced for each result are as follows:

1. Location of data points
 - a. Transit readings used to locate buoys
 - b. Assumption of a constant boat speed
 - c. Assumption of a straight-line path between buoys
 - d. Assumption of a constant sampling interval
2. Temperatures measured in the plume
 - a. Errors inherent in the thermistors
 - b. Thermistors failing to reach equilibrium before being read, due to time constant of thermistors
 - c. Errors in the digital thermometer

- d. Human errors in recording temperature (applies to first-generation system)
 - e. Unrecorded changes in probe depth due to boat motion
3. Isotherm drawings
 - a. All position and temperature errors apply here
 - b. Free-hand drawing of isotherms leads to probable errors as does individual interpretation of the data
 - c. Linear interpolation between data points
 - d. Lack of data in some areas
 - e. Assumption that plume does not change over the interval it is being measured
 4. Isotherm areas
 - a. All the above errors apply here
 - b. Use of planimeter
 5. Current velocity
 - a. From drogues
 - (1) Transit readings used to measure position
 - (2) Time between sitings
 - (3) Wind effect on surface float
 - b. From current meters
 - (1) Effects of boat motion
 - (2) Drifting of boat while anchored (two-point anchor used)
 - (3) Accuracy of meters

TABLE V. Instrumentation Accuracy

Instrument	Sensor	Accuracy	Resolution	Range	Remarks
Digitel Model 8500-1 Digital Thermometer	YSI No. 409 Thermistor	$\pm 0.25^{\circ}\text{C}^{\text{a}}$ $\pm 0.1^{\circ}\text{C}^{\text{b}}$	0.02°C	$0-100^{\circ}\text{C}$	YSI No. 409 thermistors have a 2.2-sec time constant in well-stirred water.
Digitel Model 251A/551-2 Digital Thermometer	YSI No. 709 Thermistor	$\pm 0.3^{\circ}\text{C}^{\text{a}}$ $\pm 0.1^{\circ}\text{C}^{\text{b}}$	0.01°C	$(-30.0)-(+100.0)^{\circ}\text{C}$	YSI No. 709 thermistors have a 2.2-sec time constant in well-stirred water.
Ekman-Merz Current Meter	Impeller	± 0.16 fps	-	$0.16-6.5$ fps	Directional accuracy estimated.
	Direction Vane	$\pm 15^{\circ}$	-	$0-360^{\circ}$	
Braincon Current Meter	Savonius Rotor	± 0.25 fps	0.015 fps	$0.2-8.5$ fps	
	Direction Vane	$\pm 4^{\circ}$	1°	$0-360^{\circ}$	
	Clock	± 2 sec per day	-		
Bendix Q-15 Current Meter	Impeller	± 0.05 fps	0.03 fps	$0.06-1.7$ fps	Low Scale: Time constant of speed read-out is 25 sec on low scale.
	Impeller	± 0.25 fps	0.17 fps	$0.06-8.5$ fps	High Scale: Time constant of speed read-out is 2.5 sec on high scale.
	Direction Vane	$\pm 12^{\circ}$	5°	$0-360^{\circ}$	
Weather Measure Cup Anemometer	Cup Anemometer	± 2 mph	1 mph	$0-100$ mph	Values estimated.
	Direction Vane	$\pm 15^{\circ}$	15°	$0-360^{\circ}$	Values estimated.
Geodyne Temperature Recorder	Bourdon Tube	0.15°C	0.15°C	$0-26^{\circ}\text{C}$	Thermal time lag is 15 sec/ $^{\circ}\text{C}$.
	Chart Advance	$\pm 2\%$	-	-	Advance moves paper 0.066 in. in 10 min.

^aBefore calibration.^bAfter calibration.

TABLE VI. Estimated Accuracy Inherent in Data-collection and -reduction Techniques

Operation	Accuracy	
	First-generation System	Second-generation System
A. Location of position		
1. Buoys with transits	± 3 ft	± 3 ft
2. Buoys with sextant	± 30 ft	± 30 ft
B. Assumption of a constant boat speed during one temperature transect	± 1.0 fps	± 1.0 fps
C. Deviation of boat from a straight line during one temperature transect	± 50 ft	± 50 ft
D. Sampling interval	± 2 sec	± 0.1 sec
E. Thermistor probe depth	± 1.0 ft	± 0.3 m
F. Planimeter measurements	$\pm 5\%$	$\pm 5\%$
G. Position measurement of drogues	± 3 ft	± 3 ft
H. Timing interval between drogue measurements	± 2 sec	± 2 sec

Of special interest are two sources of error that can lead to complications in drawing a picture of a thermal plume in the horizontal plane. Although the data are taken over a period of from one to several hours, the plume is drawn as though it existed in one instant of time. This can lead to contorted isotherms and paradoxical temperatures. An example of this is shown in Figs. 105-110, where a several-degree difference in temperature occurred at the same point. Another error comes as a result of the time constant of the thermistors. The fact that they do not respond instantaneously to changes in temperature, plus the fact that they are only sampled every 5-10 sec, leads to a loss of small-scale temperature structure in the plume as well as a smoothing of any abrupt changes in plume temperature. When a plume is being influenced by a strong ambient current, the upcurrent side of the plume typically exhibits quite a sharp interface. This interface is made less sharp and may be skewed, depending on the direction from which the measurements are made. Due to the scale of the drawings, this effect is not significant.

A further uncertainty in the position of isotherms is due to lack of data in some areas. This omission arises from use of a predetermined buoy grid, which limited the area in which the boat's position could be determined. When isotherms fell between two data transects, a linear interpolation between adjacent data points was used in establishing isotherms. Although this scheme may lead to errors, it is felt that this is as good an approximation as is available and one that is readily applied.

APPENDIX

Plume Areas as a Function of Isotherm and Depth

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: May 20, 1971 (1438-1550)
 Outfall water temperature: 17.5°C
 Ambient water temperature: 8.1-8.5°C

Isotherm, °C	Plume Area within Isotherm, ft ²				
	Surface	1-ft Depth	3-ft Depth	6-ft Depth	9-ft Depth
15.0	3.50×10^4	1.59×10^4	1.53×10^4	-	-
14.0	8.01×10^4	7.10×10^4	4.12×10^4	1.53×10^4	-
13.0	1.92×10^5	1.75×10^5	9.03×10^4	3.85×10^4	-
12.0	8.06×10^5	6.44×10^5	4.47×10^5	1.59×10^5	3.39×10^4
11.0	2.33×10^6	2.26×10^6	2.01×10^6	1.34×10^6	3.31×10^5
10.0	6.97×10^6	6.93×10^6	6.59×10^6	4.30×10^6	1.51×10^6

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: May 20, 1971 (1740-1850)
 Outfall water temperature: 17.5°C
 Ambient water temperature: 8.2-8.5°C

Isotherm, °C	Plume Area within Isotherm, ft ²				
	Surface	1-ft Depth	3-ft Depth	6-ft Depth	9-ft Depth
15.0	2.19×10^4	1.90×10^4	-	-	-
14.0	1.37×10^5	6.06×10^4	3.17×10^4	-	-
13.0	3.20×10^5	1.99×10^5	9.33×10^4	1.87×10^4	-
12.0	9.06×10^5	7.78×10^5	4.11×10^5	6.81×10^4	3.45×10^4
11.0	1.79×10^6	1.49×10^6	9.81×10^5	3.32×10^5	6.93×10^4

Power plant: Waukegan Generating Station
 Date and time of survey: June 2, 1971 (1140-1320)
 Outfall water temperature: 18.8°C
 Ambient water temperature: 10.2-11.3°C

Isotherm, °C	Plume Area within Isotherm, ft ²				
	Surface	1-ft Depth	3-ft Depth	6-ft Depth	9-ft Depth
16.0	5.11×10^5	2.19×10^5	-	-	-
15.0	9.49×10^5	7.45×10^5	4.38×10^5	-	1.00×10^4
14.0	2.01×10^6	1.85×10^6	7.86×10^5	2.40×10^5	4.00×10^4
13.0	3.64×10^6	3.06×10^6	1.81×10^6	4.20×10^5	8.50×10^4
12.0	8.51×10^6	6.98×10^6	5.59×10^6	6.71×10^5	2.02×10^5
11.0	-	-	-	-	3.82×10^5

Power plant: Waukegan Generating Station
 Date and time of survey: June 2, 1971 (1443-1723)
 Outfall water temperature: 18.3°C
 Ambient water temperature: 10.2-11.3°C

Isotherm, °C	Plume Area within Isotherm, ft ²				
	Surface	1-ft Depth	3-ft Depth	6-ft Depth	9-ft Depth
15.0	7.08×10^5	2.05×10^5	-	-	-
14.0	1.46×10^6	1.12×10^6	3.50×10^5	-	-
13.0	3.28×10^6	2.93×10^6	1.36×10^6	-	-
12.0	8.82×10^6	7.23×10^6	6.41×10^6	9.32×10^5	-

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: June 25, 1971 (1000-1215)
 Outfall water temperature: 20.1°C
 Ambient water temperature: 11.0°C

Isotherm, °C	Plume Area within Isotherm, ft ²			
	Surface	1-m Depth	2-m Depth	3-m Depth
18.0	3.02×10^4	2.16×10^4	-	-
17.0	2.71×10^5	1.83×10^5	1.21×10^5	-
16.0	5.34×10^5	4.09×10^5	1.77×10^5	1.90×10^4
15.0	9.03×10^5	6.40×10^5	2.56×10^5	3.74×10^4
14.0	2.12×10^6	1.58×10^6	8.48×10^5	7.08×10^4
13.0	-	-	1.86×10^6	1.61×10^5

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: July 20, 1971 (1632-1805)
 Outfall water temperature: 21.5°C
 Ambient water temperature: 12.6-12.8°C

Isotherm, °C	Plume Area within Isotherm, ft ²				
	Surface	1-ft Depth	3-ft Depth	6-ft Depth	9-ft Depth
19.0	2.89×10^4	-	-	-	-
18.0	8.52×10^4	6.95×10^4	2.62×10^4	-	-
17.0	3.29×10^5	2.36×10^5	7.67×10^4	-	-
16.0	7.61×10^5	6.11×10^5	2.46×10^5	4.33×10^4	-
15.0	1.86×10^6	1.56×10^6	8.77×10^5	1.25×10^5	3.61×10^4
14.0	-	-	-	2.53×10^5	1.29×10^5

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: July 21, 1971 (1020-1117)
 Outfall water temperature: 20.5°C
 Ambient water temperature: 11.5-11.9°C

Isotherm, °C	Plume Area within Isotherm, ft ²				
	Surface	1-ft Depth	3-ft Depth	6-ft Depth	9-ft Depth
17.0	9.18×10^4	4.92×10^4	-	-	-
16.0	3.68×10^5	1.92×10^5	5.31×10^4	-	-
15.0	1.66×10^6	1.18×10^6	1.27×10^5	6.03×10^4	-
14.0	-	-	-	1.04×10^5	-
13.0	-	-	-	-	5.90×10^4
12.0	-	-	-	-	1.51×10^5

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: July 21, 1971 (1508-1639)
 Outfall water temperature: 21.8°C
 Ambient water temperature: 11.1-11.5°C

Isotherm, °C	Plume Area within Isotherm, ft ²				
	Surface	1-ft Depth	3-ft Depth	6-ft Depth	9-ft Depth
18.0	4.13×10^4	-	-	-	-
17.0	9.18×10^4	5.44×10^4	1.64×10^4	-	-
16.0	1.64×10^5	1.35×10^5	6.03×10^4	-	-
15.0	5.40×10^5	4.79×10^5	1.62×10^5	1.25×10^4	-
14.0	1.23×10^6	9.63×10^5	5.50×10^5	5.18×10^4	-
13.0	3.26×10^6	2.44×10^6	1.95×10^6	1.48×10^5	-
12.0	-	-	-	-	1.44×10^5

Power plant: State Line Generating Station
 Date and time of survey: August 4, 1971 (1227-1550)
 Outfall water temperature: 25.3°C
 Ambient water temperature: 17.5°C

Isotherm, °C	Plume Area within Isotherm, ft ²				
	Surface	1-ft Depth	3-ft Depth	6-ft Depth	9-ft Depth
25.0	1.49×10^5	3.60×10^4	-	-	-
24.0	6.76×10^5	2.32×10^5	-	-	-
23.0	2.71×10^6	2.16×10^6	-	-	-
22.0	5.16×10^6	4.24×10^6	8.56×10^5	-	-
21.0	8.32×10^6	8.04×10^6	1.91×10^6	-	-
20.0	1.47×10^7	1.43×10^7	1.07×10^7	1.86×10^6	-

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: August 31, 1971 (1530-1631)
 Outfall water temperature: 26.2°C
 Ambient water temperature: 17.6°C

Isotherm, °C	Plume Area within Isotherm, ft 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	3.67×10^4	↑	↑	-	-	-	↑
23.0	2.56×10^5	↑	↑	-	-	-	↑
22.0	3.79×10^6	↑	↑	-	-	-	↑
21.0	-	Malfunctioned	Malfunctioned	2.82×10^4	-	-	Channel Turned Off
20.0	-	↓	↓	1.20×10^6	-	-	↓
19.0	-	↓	↓	-	-	-	↓
18.0	-	↓	↓	-	-	-	↓

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: September 1, 1971 (0950-1130)
 Outfall water temperature: 27.1°C
 Ambient water temperature: 17.4-17.8°C

Isotherm, °C	Plume Area within Isotherm, ft 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	3.48×10^4	↑	↑	-	-	-	-
23.0	1.28×10^5	↑	↑	-	-	-	-
22.0	3.82×10^5	↑	↑	-	-	-	-
21.0	1.39×10^6	Malfunctioned	Malfunctioned	4.59×10^4	-	-	-
20.0	2.97×10^6	↓	↓	1.89×10^5	2.95×10^4	-	-
19.0	6.42×10^6	↓	↓	6.15×10^5	2.13×10^5	1.12×10^4	-
18.0	-	↓	↓	-	1.30×10^6	5.22×10^5	1.56×10^5

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: September 1, 1971 (1445-1727)
 Outfall water temperature: 26.5°C
 Ambient water temperature: 17.4-17.8°C

Isotherm, °C	Plume Area within Isotherm, ft 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	2.69×10^4	↑	↑	-	-	-	-
23.0	9.05×10^4	↑	↑	2.30×10^4	1.57×10^4	-	-
22.0	1.98×10^5	↑	↑	5.05×10^4	3.41×10^4	2.30×10^4	1.57×10^4
21.0	4.89×10^5	Malfunctioned	Malfunctioned	7.93×10^4	5.84×10^4	3.93×10^4	3.61×10^4
20.0	1.55×10^6	↓	↓	1.32×10^5	8.72×10^4	6.16×10^4	7.34×10^4
19.0	3.58×10^6	↓	↓	4.20×10^5	1.75×10^5	9.05×10^4	9.97×10^4
18.0	-	↓	↓	-	-	-	2.81×10^5

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: October 28, 1971 (1402-1539)
 Outfall water temperature: 21.2°C
 Ambient water temperature: 12.8-12.9°C

Isotherm, °C	Plume Area within Isotherm, ft 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
19.0	4.53×10^4	2.52×10^4	-	-	-	-	-
18.0	3.70×10^5	1.20×10^5	6.11×10^4	3.32×10^4	-	-	-
17.0	7.78×10^5	4.83×10^5	1.54×10^5	9.49×10^4	5.98×10^4	-	-
16.0	1.83×10^6	9.99×10^5	7.44×10^5	2.23×10^5	1.83×10^5	3.25×10^4	-
15.0	-	-	-	-	-	1.18×10^5	2.79×10^4
14.0	-	-	-	-	-	-	5.31×10^4

Power plant: Point Beach Nuclear Power Plant (Unit 1)
 Date and time of survey: October 28, 1971 (2000-2100)
 Outfall water temperature: 21.2°C
 Ambient water temperature: 12.6-12.8°C

Isotherm, °C	Plume Area within Isotherm, ft 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
19.0	3.82×10^4	-	-	-	-	-	-
18.0	1.95×10^5	-	-	-	-	-	-
17.0	5.47×10^5	3.79×10^5	2.81×10^5	1.57×10^5	-	-	-
16.0	-	-	-	9.37×10^5	7.12×10^5	-	-
15.0	-	-	-	-	-	-	3.45×10^5
14.0	-	-	-	-	-	-	5.30×10^5

ADDENDUM

The discharge flow rate listed in the tables summarizing plant, meteorological, and ambient lake data on the thermal plume, vertical cross section, and jet-regime study figures for the Point Beach Nuclear Power Plant (Unit 1) is 771 cfs. This value was obtained from Point Beach Plant personnel during the 1971 field year. (They obtained this value from the circulating-water-pump curves furnished by the pump vendor.) A rough calculation of the discharge flow rate was made from the discharge velocity data listed in Table II. From this, the discharge flow rate was estimated as 878 cfs.

In July 1972, new data obtained from the Point Beach Plant personnel indicated the discharge flow rate to be 885 cfs. This value was obtained from measurements made at the plant by plant personnel. Argonne also made velocity measurements in the discharge flume for Unit 1 early in 1972. The results of this work indicate a discharge flow rate of about 898 cfs. The average value of the discharge flow rate for the 1971 and 1972 seasons, as measured by Argonne, is 888 cfs. This value is in excellent agreement with the value of 885 cfs obtained from the Point Beach Plant personnel in July 1972.

Based on the above discussion, it was decided that a discharge flow rate of 885 cfs as reported by the Point Beach Plant personnel during 1972 was the best value of discharge flow rate available for Unit 1 at full-load operation. Thus, this value of the discharge flow rate was used in plotting the Point Beach Plant data for Fig. 138.

ACKNOWLEDGMENT

We would like to thank Ms. Hope D. Rihel for her contributions in preparing and handling of the final figures for this report. Considering the number of figures involved, Ms. Rihel's drafting contribution is particularly important to this report.

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