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WATER RESOURCES RESEARCH PROGRAM

FIELD STUDIES OF THE THERMAL PLUME FROM
THE D. C. COOK SUBMERGED DISCHARGE
WITH COMPARISONS TO HYDRAULIC-MODEL RESULTS

by

A. A. Frigo, R. A. Paddock,
and D. L. McCown

GREAT LAKES PROJECT

MASTER

ENERGY AND ENVIRONMENTAL
SYSTEMS DIVISION

ENVIRONMENTAL STATEMENT PROJECT

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Energy and Environmental Systems Division
Great Lakes Project

June 1975

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	7
I. INTRODUCTION.	7
A. General Discussion	7
B. Donald C. Cook Nuclear Plant	10
II. DISCUSSION OF FIELD MEASUREMENTS	11
A. Instrumentation, Data Collection, and Data Reduction.	11
B. Results of Thermal-plume Measurements	12
III. COMPARISONS OF SUBMERGED-DISCHARGE AND SURFACE-DISCHARGE DATA	23
IV. COMPARISONS OF HYDRAULIC-MODEL PREDICTIONS WITH PROTOTYPE DATA	26
V. NEW INSTRUMENTATION AND DATA-COLLECTION TECHNIQUES	31
VI. SUMMARY OF RESULTS	33
ACKNOWLEDGMENTS	34
REFERENCES	35

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Typical Intake Crib and Screen House for D. C. Cook Nuclear Plant	10
2.	Schematic of Two-slot Discharge Structure for D. C. Cook Nuclear Plant Unit 1	11
3.	The ERDA-1 Survey Boat Equipped with Temperature-measuring, Range/Range, and Data-acquisition Equipment.	11
4.	Data-acquisition System	11
5.	Water Temperatures, Current Speed and Direction, Air Temperature, and Wind Speed and Direction near D. C. Cook Nuclear Plant	14
6.	Ambient Water Temperature as a Function of Depth.	15
7.	Thermal Plume at Surface for D. C. Cook Nuclear Plant: May 14, 1975	16
8.	Thermal Plume at 0.5-m Depth for D. C. Cook Nuclear Plant: May 14, 1975	17
9.	Isotherm Areas for Plume 1.	18
10.	Isotherm Areas for Plume 2.	19
11.	Isotherm Areas for Plume 3.	19
12.	Centerline Excess-temperature Ratio vs Distance from Outfall for Plume 1.	20
13.	Centerline Excess-temperature Ratio vs Distance from Outfall for Plume 2.	20
14.	Centerline Excess-temperature Ratio vs Distance from Outfall for Plume 3.	21
15.	Variation with Depth of Areas within Isotherms of Specific Excess-temperature Ratios for Plume 1.	21
16.	Variation with Depth of Areas within Isotherms of Specific Excess-temperature Ratios for Plume 2.	21
17.	Variation with Depth of Areas within Isotherms of Specific Excess-temperature Ratios for Plume 3.	22
18.	Variation with Depth of Specific Centerline Excess-temperature Ratios vs Distance from Outfall for Plume 1.	22
19.	Variation with Depth of Specific Centerline Excess-temperature Ratios vs Distance from Outfall for Plume 2.	22

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
20.	Variation with Depth of Specific Centerline Excess-temperature Ratios vs Distance from Outfall for Plume 3	23
21.	Comparison of Surface-centerline Temperature Decay between Point Beach Unit 1 and D. C. Cook Unit 1	24
22.	Comparison of Surface-centerline Temperature Decay between Palisades and D. C. Cook Unit 1	24
23.	Comparison of Areas within Surface Isotherms between Point Beach Unit 1 and D. C. Cook Unit 1	25
24.	Comparison of Areas within Surface Isotherms between Palisades and D. C. Cook Unit 1	25
25.	Hydraulic-model Surface Results for D. C. Cook Unit 1 with No Ambient Current	27
26.	Hydraulic-model Surface Results for D. C. Cook Unit 1 with an Ambient Current of 6.1 cm/sec.	28
27.	Hydraulic-model Surface Results for D. C. Cook Unit 1 with an Ambient Current of 15.2 cm/sec.	28
28.	Results of Field Measurements at D. C. Cook Unit 1 on May 14, 1975, at Surface with Northerly Ambient Current of 5.8 cm/sec	29
29.	Results of Field Measurements at D. C. Cook Unit 1 on May 14, 1975, at 0.5-m Depth with Northerly Ambient Current of 5.8 cm/sec	29
30.	Comparison of Centerline Temperature Decay from Hydraulic-model and Prototype Data for D. C. Cook Unit 1.	30
31.	Comparison of Isotherm Areas from Hydraulic-model and Prototype Data for D. C. Cook Unit 1.	31
32.	Schematic of Towed Thermistor Array.	32
33.	Cable Breakout for Towed Thermistor Array	33

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Operating Data for D. C. Cook Nuclear Plant Unit 1	13
II.	Limnological and Meteorological Data Collected from Survey Boat.	13
III.	Ambient-water-temperature Data at D. C. Cook Site.	14
IV.	Plume Areas as a Function of Isotherm and Depth: D. C. Cook Nuclear Power Plant, Unit 1.	18

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ABSTRACT

The Donald C. Cook Nuclear Plant at Bridgman, Michigan, uses submerged-diffuser discharges as a means of disposing waste heat into Lake Michigan. This report presents preliminary results of temperature surveys of the thermal plume at the D. C. Cook Plant. Indications are that the spatial extent of the plume at the surface is much smaller than previous results for surface shoreline discharges, particularly in the near and intermediate portions of the plume. Comparisons of limited prototype data with hydraulic (tank)-model predictions indicate that the model predictions for centerline temperature decay at the surface are too high for the initial 200 m from the discharge, but are generally correct beyond this point to the limits of the model. In addition, the hydraulic-model results underestimate the areal extent of the near and intermediate portions of the plume at the surface.

Because this is the first report of a new field program, several inadequacies in the field-measurement techniques are noted and discussed. New techniques that have been developed to remedy these deficiencies, and which will be implemented for future field work, are also described.

I. INTRODUCTION

A. General Discussion

Once-through condenser cooling has historically been used by steam-electric power stations along the shores of many major water bodies as the most economical means for disposing of system-cycle waste heat. Recently, however, heat has been targeted by the Federal Water Pollution Control Act Amendments of 1972¹ as a pollutant, and Sec. 301 of the Act prohibits the discharge of pollutants into navigable waters. There are basically two exceptions for existing sources: (1) The level of discharge must reflect the best practicable control technology currently available by 1977, and (2) by 1983, the

level must reflect the best available control technology economically achievable. For new sources (Sec. 306), the discharge is to conform to the best available demonstrated control technology.

The identification of the control technologies and limitations for existing and new sources was assigned by the Act to the Administrator of the U. S. Environmental Protection Agency. In October 1974, the EPA Administrator established thermal guidelines for steam-electric facilities pursuant to the Act's directives. The guidelines are summarized briefly as follows:

1. Any plants that began operation before January 1, 1970, have no limitations on their thermal discharges.
2. Any plants that began operation between January 1, 1970, and January 1, 1974, with a plant capacity less than 500 MWe have no limitation on thermal discharges. Plants with a capacity greater than 500 MWe are limited to closed-cycle cooling by July 1, 1985.
3. Any new sources that have a capacity greater than 25 MWe are required to use closed-cycle cooling.

The limitations, where applicable, permit the discharge of heat during closed-cycle system blow-down.

Note that Sec. 316(a) of the Act provides for the relaxation of the limitations and requirements under certain conditions. Section 316(a) is unique in that it applies only to heat; it authorizes, on a case-by-case basis, the easing of any thermal limitation that is more stringent than necessary "to assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife" in the receiving water. The Act gives the EPA Administrator the authority to make the final determination of a "satisfactory" or "unsatisfactory" 316(a) demonstration. Section 316(a) of the Act must be viewed in terms of dollar savings and decreased fuel (energy) needs, in addition to its environmental and regulatory implications.

The EPA is soon to issue guidelines for obtaining 316(a) exemptions. Early 316(a) guideline drafts call for the spatial and temporal delineation of the thermal plume associated with waste-heat discharges as a fundamental requirement. For new or relatively new plants, the only recourse available is to use validated predictive models, either analytical or hydraulic (tank), to determine thermal-plume features as a function of design, operating, and environmental parameters. For operating power plants, actual field measurements can be made.

To fulfill the requirements for obtaining 316(a) exemptions, the spatial extent of the thermal plume will probably have to be limited. In addition, it is desirable to prevent the plume from interacting with the shoreline. The best way to achieve these objectives, while employing once-through condenser cooling methods, may be by discharging waste heat water via high-velocity offshore submerged diffusers.

This report is the first of a series that will provide information on thermal plumes from submerged-diffuser discharges. There are four objectives of Argonne National Laboratory's submerged-discharge study program:

1. To describe the three-dimensional structure of thermal plumes at a number of operating, submerged-diffuser sites.
2. To test the validity of hydraulic- and analytical-model predictions for thermal plumes.
3. To develop a tested, analytical, thermal-plume model for application to submerged-diffuser outfalls.
4. To evaluate the effectiveness of various submerged-diffuser outfall designs.

The present report deals mainly with the field plume-mapping effort and comparisons of prototype data with hydraulic modeling data and with field data collected at power plants on Lake Michigan using surface shoreline discharges.

The field effort at Argonne is concentrating on obtaining three-dimensional thermal-plume maps under a variety of environmental conditions at a number of plant sites where submerged diffusers have gone into operation. Experience with submerged diffusers is extremely limited because of the relative newness of these systems to the utility industry. To date, thermal plumes have been mapped by ANL at the Zion and Donald C. Cook Nuclear Power Plants.

Initial temperature surveys were conducted at the Zion Plant in the fall of 1973. At that time, one unit was operating at approximately 50% of full power and the second unit was not in operation. Results of this initial survey along with a description of the Zion Plant are presented in Ref. 2. Two temperature surveys were conducted in May 1975 at the Zion Plant. At this time, both units were operating at about 85% of full power. Results of the latest surveys at Zion will be presented in a later report.

This report presents the results of three surveys conducted at the Donald C. Cook Nuclear Plant on May 13-14, 1975. Isotherm maps at the surface and 0.5-m depth for one of the temperature surveys are presented. Isotherm maps for temperature data collected at seven depths (0.0, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 m) along with vertical temperature cross sections will be presented in a later report. This report also presents data on centerline temperature decays and isotherm areas for the three plume surveys at the seven depths measured. Hydraulic modeling data are compared with the field data, and the field data for the submerged discharges are compared with previous field data collected at the Point Beach and Palisades Nuclear Power Plants. These latter two plants use surface shoreline discharges to dispose of waste heat.

B. Donald C. Cook Nuclear Plant

The Donald C. Cook Plant is located near Bridgman, Michigan, on the southeastern shore of Lake Michigan, about 18 km south of Benton Harbor. The two D. C. Cook nuclear reactors are nearly identical, pressurized-water units. Each is capable of a gross generating capacity of 1090 MWe, and a net capacity of 1054 MWe. At present, only Unit 1 is operational.

The design condenser-cooling-water flow-rate requirement at full power is about $45 \text{ m}^3/\text{sec}$ for Unit 1 and $59 \text{ m}^3/\text{sec}$ for Unit 2. The cooling water is taken from three intake cribs located about 685 m offshore in about 7.3 m of water. The intake cribs (see Fig. 1) consist of smoothly rounded elbows set in the lake bottom and surrounded by sacked concrete and riprap to prevent erosion. Each elbow is further surrounded by an octagonal-shaped, heavy structural frame, provided with bar racks and $20 \times 20\text{-cm}$ grating on all eight sides. The top of each frame is covered with a solid steel roof. At full flow, the intake water velocity through the grating interstices is about $39 \text{ cm}/\text{sec}$.

Fig. 1. Typical Intake Crib and Screen House for D. C. Cook Nuclear Plant

The cooling water is discharged to the lake via two discharge pipes. These pipes are completely buried under at least 0.5 m of sand along the lake bottom. The cooling-water discharges are located in about 5.7 m of water, 365 m offshore. The two outfall structures are about 91 m apart. Each discharge pipe is connected to a structure that discharges slot-type jets in a generally offshore direction. The design exit velocity is about $4 \text{ m}/\text{sec}$. The Unit 1 structure (see Fig. 2) has two discharge slots, each 9.1 m wide $\times$ 0.61 m high and 0.46 m above the lake bottom. The Unit 2 structure has three discharge slots, each 6.1 m wide $\times$ 0.84 m high and 0.53 m above the lake bottom. At full power, the temperature rise for the condenser cooling water is expected to be 12.1°C for Unit 1 and 9.3°C for Unit 2.

Fig. 2

Schematic of Two-slot Discharge Structure
for D. C. Cook Nuclear Plant Unit 1

II. DISCUSSION OF FIELD MEASUREMENTS

A. Instrumentation, Data Collection, and Data Reduction

The techniques used to collect the temperature data discussed in this report are covered in detail in Ref. 2 and are the same as those used in earlier years by Argonne to collect data from power plants with surface shoreline discharges. Basically, time, location, water depth, and water-temperature data (at the surface and six depths) are measured from a moving 7.5-m survey boat (Fig. 3), and are recorded on a shipborne data-acquisition system (Fig. 4)

Fig. 3. The ERDA-1 Survey Boat Equipped with
Temperature-measuring, Range/Range
and Data-acquisition Equipment

Fig. 4. Data-acquisition System

developed at Argonne. The data are recorded on paper tape and on magnetic-tape cassettes. The plume data are transcribed onto computer-compatible magnetic tapes from the original cassettes and, along with calibration values, are used in a computer program that plots the water temperature and bathymetry as a function of position. Isotherms and plume centerlines are drawn by hand on the plots.

Ambient conditions are routinely measured in conjunction with plume-temperature mapping. Ambient lake current is measured from the boat with a Bendix Q-15, geomagnetic, ducted-impeller current meter. In addition, current speed and direction are measured along with lake temperatures at various depths with an in situ current-meter/thermograph package for the duration of the field trip. The in situ current meter is a Bendix Q-15R with a separate electronic recording package featuring a digital, cassette tape recorder. The recording package was designed by Argonne's Electronics Division. The Q-15R is identical to the Q-15, but is inverted to allow the recording package to be placed below the meter in a mooring string. The system has three analog inputs and one digital input available. The analog inputs are digitized and are used to record two thermistor (temperature) signals and the current-direction output (a potentiometer coupled to a geomagnetic compass) from the Q-15R. The digital channel senses pulses from the Q-15R impeller and also senses direction of rotation of the impeller. With this system, the digital input is stored in an add-subtract scalar during a preselected clock interval, thus giving true, steady-state flow rate. Wind speed and direction are measured with a hand-held anemometer on the boat and by a shore-based meteorological station manufactured by Meteorology Research, Inc. (MRI). Air temperature, humidity, lake conditions, etc., are also measured during each thermal-plume field study.

An ambient temperature survey is conducted before each plume mapping. Upcurrent from the power plant, the boat is driven from a location about 1500 m offshore to a location as close to the shoreline as possible along a line perpendicular to the shoreline. Temperature data at about 100 locations for the surface and six depths are recorded during this survey.

Plant operating data are obtained from the appropriate power-plant personnel. In addition, records of wind speed and direction and air temperature are obtained from utility meteorological stations located near specific power plants, when available.

B. Results of Thermal-plume Measurements

Temperature data were collected at the D. C. Cook Plant on May 13 and 14, 1975. One survey was conducted during the afternoon of May 13, and surveys were conducted during the early and late afternoon of May 14. Dates and times of the three temperature surveys are:

1. Plume 1: May 13, 1975 (1529-1700 hr EDT).
2. Plume 2: May 14, 1975 (1158-1318 hr EDT).
3. Plume 3: May 14, 1975 (1600-1717 hr EDT).

Plant operating data³ for these three surveys are listed in Table I.

TABLE I. Operating Data for D. C. Cook Nuclear Plant Unit 1

	Date and Time of Survey		
	May 13, 1975	May 14, 1975	May 14, 1975
	(1529-1700 hrs)	(1158-1318 hrs)	(1600-1717 hrs)
Plant Load (%)	80	80.4-80.6	80.8
Discharge Flow Rate (m ³ /sec)	51	51	51
Outfall Temperature (°C)	16.2	16.2	16.6
Intake Temperature (°C)	7.3	7.3	8.3

Limnological and meteorological data collected from the survey boat at appropriate times on May 13-14 are presented in Table II. Figure 5 presents

TABLE II. Limnological and Meteorological Data Collected from Survey Boat

	Date and Time			
	May 13, 1975 (1415 hrs)	May 14, 1975 (1100 hrs)	May 14, 1975 (1500 hrs)	May 14, 1975 (1740 hrs)
Lake Location ^a				
Bottom Depth (m)	7.3	6.7	5.2	6.1
Dry Bulb Temperature (°C)	10.6	15.6	17.8	17.2
Relative Humidity (%)	81	53	61	70
Wind Speed & Direction (m/sec & degrees)	0.8, 245	2.8-3.6, 185	Calm	Calm
Sky Conditions	Clear	Cloudy	Partly Cloudy	Cloudy with haze
Lake Surface Conditions	Calm	Calm	Calm	Calm
Ambient Current Speed & Direction (cm/sec & degrees):				
0.5-m Depth	7.2, 055	9.4, 040	4.4, 075	0
1.0-m Depth	7.2, 035	10.6, 048	4.4, 075	0.6, 285
1.5-m Depth	6.7, 015	9.4, 050	5.0, 043	1.1, 270
2.0-m Depth	7.8, 015	8.9, 050	5.6, 038	1.1, 280
2.5-m Depth	7.8, 015	7.2, 030	3.3, 035	1.7, 325
3.0-m Depth	7.8, 015	6.1, 020	2.2, 020	1.7, 325
4.0-m Depth	7.2, 015	5.0, 010	5.0, 355	2.2, 360
5.0-m Depth	7.2, 010	5.6, 360	4.4, 350	2.2, 025
6.0-m Depth	5.6, 010	2.8, 360		1.1, 035

^aSurvey boat anchored approximately 400 m offshore, 1 km south of the D. C. Cook Nuclear Plant.

Fig. 5. Water Temperatures, Current Speed and Direction, Air Temperature, and Wind Speed and Direction near D. C. Cook Nuclear Plant

results of the data collected with Argonne's in situ current-meter/thermograph package, along with data on wind speed and direction and air temperature collected at the D. C. Cook meteorological towers. In addition, Table III lists values for ambient temperatures as a function of depth for all three plumes. The data listed in this table give two indications of ambient temperature. First, the temperature range for the ambient-temperature survey is given at each depth for each plume. Second, a value representing the average ambient temperature at each depth for the region upcurrent from the major portion of the thermal plume is also listed. These single values for ambient temperature are needed for the analysis and comparisons that follow and are plotted as a function of depth in Fig. 6.

TABLE III. Ambient-water-temperature Data at D. C. Cook Site

Plume Number	Date of Survey (1975)	Time of Survey (hrs EDT)	Ambient Water Temperature (°C)						
			Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
1	May 13	1529-1700	9.9-10.6 ^a 10.2 ^b	9.8-10.5 10.2	8.1-10.0 8.6	7.7-9.4 8.6	7.6-8.8 8.4	7.6-8.8 8.4	7.4-8.6 8.3
2	May 14	1158-1318	8.7-9.2 9.1	8.3-9.1 8.8	8.4-9.1 8.8	8.4-9.0 8.8	8.5-9.1 8.8	8.5-9.0 8.8	8.4-8.9 8.7
3	May 14	1600-1717	10.3-11.1 10.6	9.7-10.1 9.8	9.3-9.7 9.4	9.0-9.7 9.1	8.9-9.6 9.1	8.8-9.6 8.9	8.8-9.6 8.9

^aAmbient temperature range.

^bRepresentative average value for the ambient temperature.

Fig. 6. Ambient Water Temperature as a Function of Depth

An examination of the ambient-temperature data listed in Table III and plotted in Fig. 6 indicates that the lake was fairly well mixed in the upper 3 m for Plume 2, but strongly stratified near the surface for Plumes 1 and 3. The higher surface temperatures for Plumes 1 and 3 are attributed to surface solar heating. A temperature gradient of about 1.8°C from the surface to 3 m is evident for Plumes 1 and 3; the temperature variation is only 0.4°C for Plume 2.

Figures 7 and 8 are isotherm maps of Plume 2 for the surface and 0.5-m level. The intake and outfall structures and the shoreline are also shown in these figures. Isotherms are labeled in terms of the excess temperature ratio θ/θ_0 , where θ is the local water temperature minus the ambient water temperature at a

specific depth and θ_0 is the outfall temperature minus the same ambient temperature. The values chosen for the ambient temperatures are probably uncertain by as much as 0.2°C . This uncertainty could affect the excess-temperature ratios used in this report, but will not significantly influence the comparisons and conclusions that follow. Complete maps for all surveys for all levels along with vertical cross-section isotherm drawings will be presented in a later report.

Although figures for all the D. C. Cook temperature surveys are not presented in this report, a few comments concerning the general plume characteristics can be made. The plumes head north because of the northward ambient current, although Plume 3 is not bent nearly as much as Plumes 1 and 2. The reason for this is apparent when examining the ambient-current records (Table II and Fig. 5), which indicate a decrease in ambient current during the afternoon of May 14. Plume 2 is well defined at all depths (e.g., Figs. 7 and 8) due, in part, to the well-mixed receiving water in the upper 3 m. Plumes 1 and 3 are difficult to interpret in the upper 0.5-m layer. Below this level, Plumes 1, 2, and 3 are similar, at least in general characteristics. In the upper 0.5-m layer, the plume water for Plumes 1 and 3 is at about the same temperature as the ambient water. The plume is still recognizable, because it is surrounded by a band of cooler water. This cooler water is probably the result of the entrainment and upwelling to the surface of cooler bottom water at the edge of the discharge jet. This condition may also exist for Plume 2, but would not be apparent because the temperature of the deeper water is similar to that at the surface.

Fig. 8. Thermal Plume at 0.5-m Depth for D. C. Cook Nuclear Plant: May 14, 1975 (1158-1318 hr)

Even though isotherm maps of the plumes are not presented for all surveys, isotherm areas and centerline temperatures have been extracted from the temperature-survey maps. Table IV lists plume areas within isotherms as a function of depth. Figures 9-11 are plots of excess-temperature ratio θ/θ_0 versus the plume area within an isotherm of excess temperature θ for the various depths. Where the results for two or more depths overlap, a new symbol has been introduced on the graph. In general, the plots are essentially the same for all three surveys. The only data that appear different are the surface and 0.5-m data for Plumes 1 and 3. In these cases, θ/θ_0 reaches negative values. This is due to the surface heating, as described earlier. Figures 12-14 are plots of centerline excess-temperature ratio, θ_c/θ_0 , versus the distance, s , along the centerline from the outfall. These curves are similar for all three plumes, except once again for the surface and 0.5-m levels for Plumes 1 and 3. The maximum temperatures for the plumes occur at 50-75 m from the outfall for the seven depths measured.

TABLE IV. Plume Areas as a Function of Isotherm and Depth: D. C. Cook Nuclear Plant, Unit 1

Isotherm (°C)	Plume Area within Isotherm, m ²						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
Date and Time of Survey: May 13, 1975 (1529-1700 hrs EDT)							
11.0	-	-	-	-	-	6.43×10^2	8.12×10^2
10.0	6.55×10^4	4.71×10^4	4.63×10^4	3.71×10^4	4.10×10^4	3.60×10^4	2.93×10^4
9.5	-	-	-	-	-	1.53×10^5	1.18×10^5
Date and Time of Survey: May 14, 1975 (1158-1318 hrs EDT)							
12.0	1.64×10^3	9.12×10^2	-	2.43×10^2	2.25×10^2	3.40×10^2	4.47×10^2
11.0	1.73×10^4	1.04×10^4	8.19×10^3	1.02×10^4	9.00×10^3	8.62×10^3	7.25×10^3
10.5	8.81×10^4	4.19×10^4	1.96×10^4	2.20×10^4	2.02×10^4	1.74×10^4	1.29×10^4
10.0	1.06×10^6	4.30×10^5	1.83×10^5	1.83×10^5	1.48×10^5	1.11×10^5	6.22×10^4
9.5	-	-	-	-	4.93×10^5	4.04×10^5	2.67×10^5
Date and Time of Survey: May 14, 1975 (1600-1717 hrs EDT)							
11.0	3.36×10^4	2.33×10^4	1.96×10^4	2.00×10^4	2.01×10^4	1.06×10^4	1.42×10^4
10.5	1.63×10^5	1.28×10^5	7.01×10^4	6.13×10^4	6.23×10^4	4.97×10^4	3.97×10^4
10.0	-	-	4.90×10^5	3.55×10^5	3.49×10^5	2.13×10^5	1.60×10^5

Fig. 9. Isotherm Areas for Plume 1

Fig. 10. Isotherm Areas for Plume 2

Fig. 11. Isotherm Areas for Plume 3

Fig. 12. Centerline Excess-temperature Ratio vs Distance from Outfall for Plume 1

Fig. 13. Centerline Excess-temperature Ratio vs Distance from Outfall for Plume 2

Fig. 14. Centerline Excess-temperature Ratio vs Distance from Outfall for Plume 3

Figures 15-17 show the variation with depth of the areas within isotherms of specific excess-temperature ratios. Figure 16 for Plume 2 indicates that areas are fairly constant with depth until θ/θ_0 becomes less than 0.2. At that point, areas increase significantly as the surface is approached. Figures 15 and 17 for Plumes 1 and 3 do not contain much information and have been included mainly for completeness. However, where data are available, areas are similar to those measured for Plume 2.

Fig. 15. Variation with Depth of Areas within Isotherms of Specific Excess-temperature Ratios for Plume 1

Fig. 16. Variation with Depth of Areas within Isotherms of Specific Excess-temperature Ratios for Plume 2

Fig. 17. Variation with Depth of Areas within Isotherms of Specific Excess-temperature Ratios for Plume 3

Figures 18-20 show the variation with depth of specific excess-temperature ratios along a vertical cross section through the plume centerline for the three surveys. The discharge structure and lake bottom are indicated on the figures. For Plumes 1 and 3, the higher-temperature isotherms do not intersect the surface, probably because of the stratification near the surface. Figure 19, for Plume 2, indicates that the plume is well mixed vertically for the initial 400 m because of the high initial inertial forces and shallow receiving water.

Beyond this point, the plume becomes dominated by buoyant forces and is no longer influenced by the lake bottom.

Fig. 18. Variation with Depth of Specific Centerline Excess-temperature Ratios vs Distance from Outfall for Plume 1

Fig. 19. Variation with Depth of Specific Centerline Excess-temperature Ratios vs Distance from Outfall for Plume 2

Fig. 20. Variation with Depth of Specific Centerline Excess-temperature Ratios vs Distance from Outfall for Plume 3

Note that the observations made in this section are based on a limited amount of data. When more data become available, more definite conclusions can be drawn concerning the behavior of plumes from submerged-diffuser discharges. This report serves as an example of the type of studies being carried out by Argonne National Laboratory at power plants using these types of discharges.

III. COMPARISONS OF SUBMERGED-DISCHARGE AND SURFACE-DISCHARGE DATA

Over the past several years, Argonne has carried out an extensive study of the thermal plumes from several large steam-electric power plants on Lake Michigan that employ once-through cooling and surface shoreline discharges.^{2,4,5} Much of this work was concentrated at the Point Beach Nuclear Power Station (Unit 1) at Two Creeks, Wisconsin, and the Palisades Nuclear Generating Station at South Haven, Michigan. The Point Beach Plant (Unit 1) is a 497-MWe unit with a cooling-water flow rate of 25.0 m³/sec. The discharge channel makes an angle of 60° with respect to the shoreline and is 10.7 m wide and 4.2 m deep at the point of discharge. This leads to an initial densimetric Froude number of about 2.2 and an average discharge velocity of 0.56 m/sec. The Palisades Plant is a 715-MWe unit with a discharge flow rate of 25.6 m³/sec. The discharge canal is oriented perpendicular to shore and is 28.3 m wide and 2.1 m deep at the point of discharge. This produces an average initial densimetric Froude number of about 2.6 and an average discharge velocity of 0.43 m/sec.

Many sets of temperature measurements were made at each plant under varying environmental conditions. These data were systematically analyzed, and the results have been discussed in detail in Ref. 6. Figures 21 and 22 present the surface-centerline temperature-decay results for Point Beach (Unit 1) and Palisades, respectively. The areas within specific-excess-temperature ratio isotherms at the surface are presented in Figs. 23 and 24.

Fig. 21. Comparison of Surface-centerline Temperature Decay between Point Beach Unit 1 and D. C. Cook Unit 1

Fig. 22. Comparison of Surface-centerline Temperature Decay between Palisades and D. C. Cook Unit 1

Fig. 23. Comparison of Areas within Surface Isotherms between Point Beach Unit 1 and D. C. Cook Unit 1

Fig. 24. Comparison of Areas within Surface Isotherms between Palisades and D. C. Cook Unit 1

Also plotted on these four figures are the surface results extracted from the three recent temperature surveys at the D. C. Cook Plant (Unit 1). In review, the plant was discharging $51 \text{ m}^3/\text{sec}$ through a submerged diffuser located about 5 m below the lake surface in about 5.7 m of water. The average discharge velocity was 4.6 m/sec, and the initial densimetric Froude number was 60-65. In an attempt to place the isotherm areas for the D. C. Cook Plant on an equal basis with those from Point Beach and Palisades, the D. C. Cook areas have been multiplied by the ratio of the discharge flow rate at Point Beach or Palisades to that at D. C. Cook. The reasoning behind this is as follows: The excess heat rejection rate of a given power plant depends on the product of the

discharge flow rate, Q , and the initial excess temperature, θ_o . The area within an isotherm of a specific excess temperature θ , denoted by A_θ , should depend directly on the excess heat rejection rate and inversely on the excess temperature of the isotherm θ . Assuming the simplest first-order linear relationship results in

$$A_\theta \propto \frac{Q\theta_o}{\theta}.$$

Upon rearrangement, this becomes

$$A_\theta/Q \propto (\theta/\theta_o)^{-1}.$$

This type of correlation, relating A_θ/Q to θ/θ_o , has been used fairly successfully by Asbury and Frigo⁷ to compare plume areas from different power plants employing surface shoreline discharges.

It is clear from Figs. 21 and 22 that maximum surface temperatures are greatly reduced using the submerged discharge. Areas within the higher excess-temperature isotherms are also smaller for the submerged discharge case. However, there seems to be a tendency for the surface areas of the plumes to become comparable when θ/θ_o becomes less than 0.1-0.2 (see Figs. 23 and 24). This is probably because the waste heat must eventually reach the surface and be transferred to the overlying atmosphere. Note that the above conclusions hold, even without the discussed discharge-flow-rate adjustments.

IV. COMPARISONS OF HYDRAULIC-MODEL PREDICTIONS WITH PROTOTYPE DATA

In March 1971, the American Electric Power Service Corporation commissioned Alden Research Laboratories to construct a laboratory-scale hydraulic model⁸ of the Donald C. Cook Nuclear Plant discharge and the adjacent region of Lake Michigan. Various discharge structures were developed and tested in an attempt to minimize surface temperatures, shoreline heating, and recirculation of heated discharge water into the cooling-water intakes. The test basin was approximately 30 by 14 m. To correctly model the interaction between the heated discharge and the lake flow, an undistorted model was used with both horizontal and vertical dimensions scaled by a factor of 1/75. Therefore, about 2300 m of shoreline and a distance of 1100 m in the lakeward direction were modeled in the test basin. Because gravitational forces are predominant in governing the flows involved, other parameters such as time, velocity, and temperature were scaled so that Froude numbers and densimetric Froude numbers retained the same values in the model as in the prototype situation. In addition to modeling the heated discharge and shoreline, bottom topography and lake currents were also simulated in the

test basin. Near-surface temperatures were measured, with a fixed grid of 137 thermocouples, under varying discharge and lake-current conditions. Reference 8 presents a complete description of the model and instrumentation along with many of the test results in the form of isotherm contours.

Additional hydraulic-model test results were obtained from J. Markowsky⁹ of the American Electric Power Service Corporation. Several of these tests correspond to the final design of the discharge structures with only Unit 1 in operation. Isotherm contours from three of these tests are presented in Figs. 25-27. Figure 25 is the result of measurements in a stagnant basin; Figs. 26 and 27 represent situations with ambient crosscurrents in a northerly direction of 6.1 and 15.2 cm/sec, respectively. Examination of the prototype data gathered in May 1975 and discussed in Sec. II of this report indicated that the conditions prevailing during the measurements of May 14, 1975, from 1158 to 1318 hr (Plume 2) correspond quite well to the hydraulic-model conditions of Fig. 26. In particular, the ambient water temperature was fairly uniform with depth, and there was an average cross-current of about 5.8 cm/sec in a northerly direction (average value obtained from Fig. 5). The measured isotherm contours for the surface and 0.5-m depth are presented in Figs. 28 and 29 for this case. These drawings are to approximately the same scale as the hydraulic-model results of Figs. 25-27 and represent about the same region of the lake. Two differences between the model and the prototype situations should be noted. The model corresponds to the plant operating at full power, while during the field measurements the plant was at only 80% of full power. This results in the temperature rise at the

Fig. 25. Hydraulic-model Surface Results for D. C. Cook Unit 1 with No Ambient Current

Fig. 26. Hydraulic-model Surface Results for D. C. Cook Unit 1 with an Ambient Current of 6.1 cm/sec

Fig. 27. Hydraulic-model Surface Results for D. C. Cook Unit 1 with an Ambient Current of 15.2 cm/sec

Fig. 28. Results of Field Measurements at D. C. Cook Unit 1 on May 14, 1975 (1158-1318 hr), at Surface with Northerly Ambient Current of 5.8 cm/sec

Fig. 29. Results of Field Measurements at D. C. Cook Unit 1 on May 14, 1975 (1158-1318 hr), at 0.5-m Depth with Northerly Ambient Current of 5.8 cm/sec

discharge being reduced by about 20%. The isotherms are labeled in terms of excess-temperature ratio θ/θ_0 (ratio of isotherm excess temperature above ambient to initial excess temperature) in an attempt to somewhat compensate for this difference. There is also a small difference in the discharge flow rates. The model studies are based on the design flow rate of $45 \text{ m}^3/\text{sec}$; recent measurements at the power plant⁹ indicate that the actual flow rate, while Unit 1 is operating alone, is about $51 \text{ m}^3/\text{sec}$.

The low excess-temperature isotherms are quite different in character in the hydraulic-model results compared with the field measurements. For example, in Fig. 26 the predicted isotherms for $\theta/\theta_0 < 0.15$ head almost directly in the offshore direction, passing near the intake structures. The data of Fig. 28 show a well-defined interface between the plume and the ambient water, with the corresponding isotherms remaining close to the plume centerline and heading in a northerly direction. This discrepancy is significant and persists to a certain extent in the model results for a 15.2-cm/sec current (Fig. 27) where a well-defined interface with closely-spaced isotherms would normally be expected. Heat buildup in the tank may be partially responsible for the distortion of the isotherms.

To place this comparison of model predictions and prototype data on a more quantitative basis, isotherm areas and plume centerline temperatures have also been extracted from the model results. Figure 30 shows the average centerline temperature decay for the surface and 0.5-m data for Plume 2 as a dotted line, along with the results of the three model tests described above. The 6.1-cm/sec -current case shows very good agreement beyond 200 m from the discharge. The model, however, predicts maximum excess-temperature ratios (occurring $50\text{--}75 \text{ m}$ from the discharge) that are about 20% lower than those observed in the field. Figure 31 is a semilogarithmic plot of areas within specific excess-temperature-ratio isotherms. The predicted areas of the

Fig. 30. Comparison of Centerline Temperature Decay from Hydraulic-model and Prototype Data for D. C. Cook Unit 1

Fig. 31. Comparison of Isotherm Areas from Hydraulic-model and Prototype Data for D. C. Cook Unit 1

surface and the areas of the lower-excess-temperature isotherms are predicted quite well. The small, higher-temperature isotherms, however, are somewhat underestimated. Note that this can only be considered a preliminary test of the hydraulic model, since it is essentially based on only one set of field measurements. However, the other two sets of field measurements agree with the one set compared to the model, except near the surface, where solar heating has apparently distorted the isotherms. These measurements help confirm the reliability of the single set of measurements used in the comparisons. More field data and additional comparisons under various ambient conditions are needed for a complete evaluation of the predictive ability of this hydraulic model.

higher-temperature isotherms are too small by a factor of seven, but the lower-temperature isotherms are in good agreement. No adjustment, such as described in Sec. III of this report, has been made to compensate for the different flow rates. Such an adjustment would be quite small on this semilogarithmic scale.

The overall agreement between the model and the field data seems to be satisfactory. The location of the point at which the heated water reaches the

V. NEW INSTRUMENTATION AND DATA-COLLECTION TECHNIQUES

During the course of initial temperature surveys conducted at the D. C. Cook and Zion Plants, several inadequacies in the measurement techniques were noted. First, using the fixed-length thermistor bar to measure plume temperatures from a plant with a submerged discharge does not allow for complete mapping of the plume. This method is adequate for surface shoreline discharges because the plume is discharged in such a way that most of the plume water is normally at depths of less than 3 m. For plants with submerged discharges, this is not necessarily true. Second, because the exact location of a submerged discharge cannot be determined visually, it would be desirable to have a real-time plot of the path of the boat.

The first problem has been solved by the development of a towed (cable) thermistor array. Such a cable array will allow for the measurement of water temperatures at depths greater than 3 m, the limit of the existing temperature boom used for past studies. The towed thermistor array consists basically of an electrical cable with a number of molded breakouts to accommodate nine

thermistors and one pressure transducer (see Fig. 32). The cable array is surrounded by molded, hydrofoil-shaped sections to reduce both cable drag and vibration (strum).

Fig. 32
Schematic of Towed
Thermistor Array

Towed cable arrays have been under research and development by the Canada Centre for Inland Waters (CCIW) for some time, but for somewhat more demanding needs. After extensive consultations with CCIW personnel, it was concluded that, with minimal research and development on the part of Argonne, the Canadian technology and experience could be borrowed so as to have a working system on line in less than 6 months. To give some perspective to something that at first appears relatively simple, the Canadian towed-cable development program is at least 4 years old.

A schematic view of a cable section is shown in Fig. 33. Some distinctive features of the system are as follows:

1. An external wire-rope strain member.
2. A polyurethane, 27-conductor electrical cable.
3. Flexmore fairing, featuring an extremely low drag coefficient due to its wing shape.
4. Molded polyurethane breakouts.
5. Potted thermistor plugs for easy replacement.

6. A dynamic-depressor fin working on a negative-lift principle, yielding depressive forces proportional to velocity.

7. A pressure transducer housed in a body that eliminates dynamic pressure, a source of error that is proportional to the square of the velocity, and becomes unacceptable at higher speeds (>3 m/sec).

Fig. 33
Cable Breakout for
Towed Thermistor Array

One change from CCIW's design is the use of polyurethane as opposed to a neoprene jacket. Polyurethane has a wide range of selectable properties and, due to its liquid nature before curing, bonds much more securely with the cable, thereby reducing occurrences of parting and ensuing water leakage at breakout locations. The cable has already been tested at towing speeds up to 5 m/sec and has performed quite well. Hence, the towed thermistor array should facilitate more extensive coverage of large areas at greater depths.

In addition to a towed thermistor array, another improvement to Argonne's plume-mapping technique is the interfacing of a plotter to the ranging system. A Hewlett-Packard 9810A programmable calculator with a 9862A plotter has been interfaced with the Motorola Mini-ranger. This will enable a real-time plot of the position of the boat to be visually available to the boat operator and the experimenters. By preparing maps of the experiment location ahead of time, important points of interest, such as the discharge and intake structures, can be easily located. In addition, transects can be more evenly spaced and past analysis problems due to data gaps can be eliminated.

VI. SUMMARY OF RESULTS

Based on the limited amount of prototype data collected at the D. C. Cook site with equipment and techniques developed for surface-discharge plume mapping, the following conclusions and observations can be summarized.

1. Examination of the field data indicates that surface solar heating can at times make it difficult to distinguish the plume in the surface and near-surface layers.
2. The maximum temperatures for the plumes occur from 50 to 75 m from the outfall down to a depth of, at least, 3 m.
3. The plume is well mixed vertically to a depth of at least 3 m for the initial 400 m and then begins to stratify.
4. Areas within higher-temperature isotherms are fairly constant with depth, and lower-temperature isotherms are significantly larger at and near the surface.
5. Comparisons of submerged-diffuser results with some previous surface-discharge results on Lake Michigan indicate that the maximum surface temperature is greatly reduced by using a submerged diffuser and that areas within higher-temperature isotherms are significantly reduced.
6. Isotherms, particularly on the upcurrent side of the plume, are less closely spaced for the hydraulic model than for the field data.
7. Comparisons with the hydraulic-model results show that the centerline temperature decay of the model agrees quite well with the field data between a point 200 m from the discharge to the limits of the model (1100 m). Between the discharge and 200 m, the model predicts centerline-temperature excesses that are as much as 20% lower than the prototype data.
8. With regard to isotherm areas, the hydraulic-model predictions appear to be somewhat optimistic, particularly at higher excess temperatures.
9. New instrumentation and associated techniques will improve field mapping considerably.

This report has presented some preliminary results from an expanding program for the study of thermal plumes from submerged-diffuser discharges. Temperature surveys using the towed thermistor cable and the position-plotting system are planned for the Oswego Unit 5 and Fitzpatrick Plants on Lake Ontario and the Quad-Cities Plant on the Mississippi River as well as the Zion and D. C. Cook Plants on Lake Michigan. The results of these surveys will be analyzed and, where possible, compared with preoperational hydraulic-model results and engineering-design predictions. In addition, the effectiveness of the various diffuser designs in dispersing the waste heat will be compared and contrasted. The results will also be used in the testing, evaluation, and development of analytical models for the plumes from submerged-diffuser discharges.

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REFERENCES

1. Public Law 92-500, 92nd Congress (Oct 18, 1972).
2. J. V. Tokar, S. M. Zivi, A. A. Frigo, L. S. Van Loon, D. E. Frye, and C. Tome, Measurements of Physical Phenomena Related to Power Plant Heat Discharges: Lake Michigan, 1973 and 1974, Water Resources Research Program, ANL/WR-75-1 (Mar 1975).
3. J. Barnes, Donald C. Cook Nuclear Plant, Bridgman, Michigan, private communication (May 22, 1975).
4. A. A. Frigo and D. E. Frye, Physical Measurements of Thermal Discharges into Lake Michigan: 1971, ANL/ES-16 (Oct 1972).
5. A. A. Frigo, D. E. Frye, and J. V. Tokar, Field Investigations of Heated Discharges from Nuclear Power Plants on Lake Michigan: 1972, ANL/ES-32 (Mar 1974).
6. J. M. Kyser, R. A. Paddock, and A. J. Policastro, Analysis of Three Years of Complete-field Temperature Data from Different Sites of Heated Surface Discharges into Lake Michigan, Water Resources Research Program, ANL/WR-75-2 (Aug 1974).
7. J. G. Asbury and A. A. Frigo, A Phenomenological Relationship for Predicting the Surface Areas of Thermal Plumes in Lakes, ANL/ES-5 (Apr 1971).
8. P. J. Smith and G. E. Hecker, Hydrothermal Model Study, Lake Cooling Water Structures, Donald C. Cook Nuclear Plant, American Electric Power Service Corporation, Alden Research Laboratories, Holden, Mass. (Oct 1973).
9. J. Markowsky, American Electric Power Service Corp., New York, private communication (June 1975).