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**THERMAL PLUMES IN LAKES:
COMPILATIONS OF FIELD EXPERIENCE**

by

J. V. Tokar

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J. V. Tokar

Center for Environmental Studies

August 1971

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ABSTRACT

This report is one part of a three-part survey attempting to delineate the state-of-the-art on the available methods for predicting the extent and temperature structure of thermal plumes existing at power-plant outfalls. Emphasis is placed on plumes within large stratified lakes. Two companion reports include a review of analytical, numerical, and hydraulic modeling of thermal plumes and have concentrated on predictive techniques. This report has attempted to inventory field data and experience that could possibly be used to validate the predictive methods. This report also includes an inventory of the existing or proposed power plants sited along the shores of the Great Lakes.

I. GENERAL OBSERVATIONS AND RECOMMENDATIONS

1. One of the primary objectives of this work was to identify existing thermal-plume field data which could be used to support or verify analytical methods used to predict temperature patterns associated with heated-water discharges into the Great Lakes. The relatively modest amount of field data that exists has been accumulated here. It is felt that none of this reported data is suitable for general model verification. The reasons the data are unsuitable are discussed elsewhere in this report. The major difficulties are summarized below.

a. The occurrence of transient phenomena in lakes is able to continuously distort plume configurations. It is therefore unlikely that temperature and current measurements made by boat traverses or by point-by-point sampling over prolonged periods of time are sufficiently meaningful to delineate the temporal and spatial structure of a thermal plume and the surrounding ambient waters. The suitability of boat data-acquisition methods can be significantly improved if field survey methods can be reduced in time to one-half hour or less to complete a survey. Further improvements in field methods will come about when boat surveys are supplemented with data acquired from permanently and strategically placed in situ sensors recording on a continuous basis. Obviously, some tailored combination of boat acquisition methods which can yield considerable spatial information, together with a coarse network of continuously recording,

permanent, in situ instrumentation yielding temporal truth, would be desirable. Unfortunately, the use of permanently located in situ instrumentation grids will probably continue to be little utilized for thermal-plume investigations because this type of equipment is often quite expensive; the deployment of such equipment involves significant logistic problems and disproportionate maintenance problems are to be anticipated.

Further refinements in plume survey investigations can be achieved using airborne remote-measurement techniques such as infrared imagery, spectral dye dispersion studies, and drogue studies. There has already been some activity using airborne techniques on large lakes. However, except for a few notable exceptions, this work has been of either a reconnaissance or a pioneering nature. Airborne measurements by themselves are no panacea, however, because for the most part they yield water-surface or near-surface conditions which must be supplemented by in situ measurements taken either from a boat or from permanently located instrumentation. The whole field of airborne remote sensing is rapidly developing on many fronts, but, as it presently stands, such measurements continue to be relatively expensive for comprehensive thermal-plume investigations, particularly if quantitative results are sought.

b. Most of the thermal-plume field investigations on the Great Lakes have been incomplete for numerous reasons. For example, there has been no attempt to simultaneously and comprehensively perform, at a particular outfall, aerial infrared overflights, in situ temperature and current measurements, dye and drogue dispersion studies, and meteorological measurements. Usually these studies are performed by groups of different investigators, perhaps at the same location but on different days, or they may be done on the same day but at different locations. This dilution of effort appears to be quite common on the Great Lakes. Budgetary or other limitations will always mitigate the hopes of an individual group of investigators to obtain synoptic plume data. It therefore makes more sense for such groups to pool their efforts and mount a coordinated set of field programs, something like that anticipated for the forthcoming International Field Year on Lake Ontario, in which one or more thermal plumes selected by mutual agreement of participants are comprehensively investigated from a biological as well as a physical point of view.

c. There are many mathematical models available on various levels of sophistication to predict the dispersion of a heated effluent after entering a receiving body of water, whether the receiving body is a lake, stream, estuary, reservoir, or marine coastal environment. Surprisingly, however, there has been minimal activity to validate these models, largely because little "suitable" data are available for such purposes. Contemporary modeling, to a large extent, involves discretionary fashioning and whittling of a classic set of partial, nonlinear differential equations. Therefore, what could be considered to be a "suitable" or "sufficient" amount of field data to validate one particular model might likely be "unsuitable" for other models.

It is clear, therefore, that guidelines for making thermal-plume field investigations are needed to specify the kind, location, amount, and priority of the measurements required to validate analytical or hydraulic model studies. But before guidelines can be established, it is first necessary to analyze existing models with available data in an effort to better define those necessary parameters to be sought. From the limited amount of work extant in this regard, it has become obvious that many field investigations completed thus far could have become significantly more meaningful had these investigations additionally incorporated a few very important measurements--for example, ambient current speed and wind speed. It should be recognized, however, that thermal-plume field measurements are not always made with the objective of validating the data acquired against some model.

2. Considering the number of field surveys that have been performed, not only on large lakes but also elsewhere, it is surprising to find that relatively little field data have been accumulated within the jet regime of a thermal discharge. Most of the field surveys have either deliberately or unconsciously concentrated on the far-field regions of the plume where advection, ambient turbulence, buoyant forces, and surface heat loss dictate plume dispersion. Since the near-field jet regime of a heated discharge is where the largest temperature and velocity gradients exist and hence may be biologically important, since the behavior of the heated effluent is most influentially controlled by the design of the outfall, and since many theoretical jet models are available in the literature, it is imperative that some effort be expended in investigating this regime for prototype conditions. Thus far, most of the present knowledge concerning this regime has come from hydraulic model studies, and to date there is little evidence demonstrating the fact that hydraulic studies are suitable analogies for prototype situations.

3. Acquisition of the field data from numerous sources was a difficult and time-consuming task. Considering that waste-heat discharges from steam-electric power plants has become a first-order environmental concern, it would be desirable for the experience that has already been acquired and documented, or that which will be acquired, to be forwarded to a data center to be catalogued for ready reference and transmittal.

4. Most of the thermal-plume mathematical models require the use of functional relationships for the eddy-transport parameters. Very little investigative effort has been allotted to delineate these parameters on the Great Lakes, whereas a vast amount of such data has been collected for open-sea situations. Several authors have used the open-sea experience for lake applications. The validity of such an extrapolation to near-shore shallow areas in lakes where heated effluents will be discharged is questionable. The eddy-transport parameters are fundamental to the basic understanding of thermal-plume dispersion, and a considerable amount of effort should be expended in evaluating these parameters in the Great Lakes.

II. INTRODUCTION

An extensive literature survey was made to accumulate information that would be helpful in delineating the dynamics of a thermal plume discharging into a large stratified lake. The survey encompassed both the open literature and the unpublished utility "file" literature. Historically, the really significant contributions in this area could be found in the open literature. More recently, however, a good portion of this material is being issued in the form of private or semiprivate utility reports generated either by hired consulting firms or, in a few instances, by in-house investigators. This private literature was obtained directly from the utilities or from their consulting firms.

The Federal Water Quality Act of 1965 required all 50 states to submit for approval to the U.S. Department of Interior interstate water quality standards which were to consider public water supplies, propagation of fish and wildlife, recreation, agriculture, industrial, and other legitimate uses. Before 1965, very few states had such well-rounded water-quality criteria. Although it was recognized that thermal discharges were potentially dangerous to fish and other aquatic biota, they were seldom a threat to public water supplies, and therefore little attention was directed to them. Consequently, except for several well-conceived and -implemented programs, relatively little research on thermal discharges was conducted until recently. Today there are numerous ongoing programs involving thermal-effects research financed by both the Federal Government and the utilities.

A dated listing of the Federally supported work in this area is available.³ The utility spectrum has issued several bibliographies through the Edison Electric Institute concerning water-related environmental studies, the most recent arriving at press time of this publication.^{4,5} Another very recent bibliography of thermal research programs sponsored by Federal, state, and private agencies has been published by Ulrickson and Stockdale.⁶ This work, as in the above situation, became available at press time. Both Refs. 5 and 6 appear to be quite comprehensive.

As was indicated earlier, the utility literature is generally available, if one could determine whom to ask. Sixty-six utilities within the U.S. were contacted for pertinent literature on thermal-plume research within any receiving body of water. The responses ranged from complete cooperation to no reply.

III. LITERATURE SURVEY

A primary objective of the literature survey was to identify existing field data which could be used to validate analytical lake-plume models. For the purposes of this publication, only references pertinent to the Great Lakes were considered. Data from small ponds or reservoirs, rivers, and estuaries were not considered. The applicability of coastal plume data to a Great Lakes situation is not entirely clear at this time. Tidal reversals certainly provide a changing supply of dilution water to coastal plumes as well as an ever-changing ambient turbulence structure; no such parallel phenomena exist in a lake. Therefore, except for slack tide periods, one would intuitively feel that there would be no simple set of scale factors which could be applied to equate the two. Slack periods on either ebb or flood tides are perhaps too short in duration for equating plume behavior; this possibility should be thoroughly examined however.

A. Studies on the Great Lakes

In a series of studies, Ayers et al. have reported on plume-temperature measurements taken at several power plants on Lake Michigan.⁷ The temperature measurements were made to establish the zone of influence of thermal discharges on benthos and plankton since, in the authors' words, "Since, in a lake situation fish can swim away from local warm water areas such as those set up by power plant effluents, their value as thermal pollution indicators is questionable. However, the other biota found in a lake; zooplankton, phytoplankton, and benthos, are slower to migrate to new environments and may thus be better pollution indicators." Temperature and biota samplings were taken from The University of Michigan's 50-ft research vessel "Mysis." Temperature measurements were made at the surface and bottom and at intervals in between. Thermistors were used for the temperature sensor(s), and positions were determined from radar ranges and bearings. The Big Rock Nuclear Plant located near Charlevoix, Michigan, was surveyed on June 18, 1968. Only water surface temperatures were recorded. The results of this survey are shown in Fig. 1 and Table 1. The authors of Ref. 7 noted that "Most of the warmed water from the plant dissipated its heat within 500 yards of the outfall." Another survey was made at the Port Washington power plant located in Port Washington, Wisconsin, on August 13, 1968. Table 2 and Fig. 2 summarize these results. Ayers et al. call attention to the fact that, due to solar heating, shallow areas present near the outfall exhibited a zone of higher temperature than at the outfall.

In a more recent publication,⁸ Ayers et al. have reported plume temperature measurements at the Michigan City plant in Michigan City, Indiana, and at the Waukegan plant in Waukegan, Illinois. The results of these measurements are shown in Figs. 3 and 4 and Table 3, Fig. 5 and Table 4, respectively. The June 26, 1969, Michigan City data were taken with a single

Fig. 1. Big Rock Point Nuclear Plant Surface Temperatures: June 18, 1968⁷

TABLE 1. Big Rock Survey Tabular Data: June 18, 1968⁷

Consumers Power Company, Big Rock Point Nuclear Generating Plant. Wind south 5-10 mph. Ambient lake temperature 10.7-11.3°C. Outfall temperature 18.0°C, top to bottom.

100	feet offshore north of outfall mouth, surface	18.00C
140	" " " " " "	18.0
240	" " " " " "	18.0
300	" " " " " "	17.9
400	" " " " " "	15.1
600	" " " " " "	15.9
800	" " " " " "	14.5
850	" " " " " "	13.9
950	" " " " " "	11.3
1150	" " " " " "	11.8
1350	" " " " " "	11.3
1850	" " " " " "	11.2

TABLE 1 (Contd.)

<u>100 yards west of outfall:</u>				
100	feet	north	offshore	11.1
140	"	"	"	11.1
200	"	"	"	10.9
300	"	"	"	10.8
360	"	"	"	10.8
400	"	"	"	10.8
600	"	"	"	10.7
700	"	"	"	10.7
800	"	"	"	10.7
850	"	"	"	10.7
<u>200 yards east of outfall</u>				
100	feet	north	offshore	13.0
140	"	"	"	12.9
200	"	"	"	12.9
300	"	"	"	13.6
400	"	"	"	15.2
500	"	"	"	16.0
600	feet	north	offshore	17.2
700	"	"	"	15.4
760	"	"	"	14.3
800	"	"	"	12.5
850	"	"	"	12.5
1050	"	"	"	12.0
1350	"	"	"	11.8
1750	"	"	"	11.3
2050	"	"	"	11.3
<u>400 yards east of outfall (opposite tip of first point)</u>				
100	feet	north	offshore	
120	"	"	"	14.0
200	"	"	"	14.0
300	"	"	"	13.9
400	"	"	"	13.5
450	"	"	"	13.0
500	"	"	"	13.0
600	"	"	"	12.8
700	"	"	"	12.3
800	"	"	"	11.6
900	"	"	"	11.3
<u>500 yards east of outfall</u>				
100	feet	north	offshore	12.9
140	"	"	"	12.8
200	"	"	"	11.7
300	"	"	"	11.2
400	"	"	"	11.2
500	"	"	"	11.2

TABLE 1 (Contd.)

<u>600 yards east of outfall</u>				
<u>100 feet north offshore</u>				11.8
160	"	"	"	11.8
200	"	"	"	11.2
300	"	"	"	11.1
340	"	"	"	11.1
<u>700 yards east of outfall</u>				
<u>140 feet north offshore</u>				12.2
200	"	"	"	11.9
300	"	"	"	11.8
400	"	"	"	11.7
500	"	"	"	11.7
600	"	"	"	11.6
700	"	"	"	11.3
800	"	"	"	11.3
900	"	"	"	11.3

TABLE 2. Port Washington Survey: August 13, 1968⁷

Wisconsin Electric Company, Port Washington Generating Plant. Coal fired, 500,000 gpm cooling water flow, maximum delta-T 6°, no water treatment ordinarily. Outflow temperature 12.0°C, 53.6°F. Light W. wind.

Station PW-1 (intake)

0 meters	0 feet	9.3°C	48.7°F
1	3.3	9.3	48.7
2	6.6	9.3	48.7
3	9.8	9.3	48.7
4	13.1	9.3	48.7
4.6	15.0	9.3	48.7

Benthos and plankton samples at this station.
Bottom: Slightly silty fine brown sand.

Station PW-2

0	0	15.0	59.0
1	3.3	12.2	54.0
2	6.6	10.3	50.5
3	9.8	9.1	48.4
4	13.1	8.4	47.1
5	16.4	8.0	46.4
6	19.7	7.8	46.0
7	23.0	7.7	45.9
8	26.2		
9	29.5		
9.1	30.0		

TABLE 2 (Contd.)

Station PW-3

0	0	12.1	53.8
1	3.3	12.1	53.8
2	6.6	12.1	53.8
3	9.8	12.1	53.8
4	13.1	11.5	52.7
5	16.4	11.0	51.8
6	19.7	10.5	50.9
6.7	22.1	10.3	50.4

Station PW-4

0 m	0 ft	15.3°C	59.5°F
1	3.3	13.5	56.3
2	6.6	11.8	53.2
3	9.8	10.0	50.0
4	13.1	10.0	50.0
5	16.4	10.0	50.0
6	19.7	9.9	49.8
7	20.1	9.9	49.8

Station PW-5

0	0	15.8	60.4
1	3.3	14.5	58.1
2	6.6	13.6	56.5
3	9.8	12.7	54.9
4	13.1	11.9	53.4
5	16.2	11.2	52.2

Station PW-6

0	0	11.9	53.4
1	3.3	11.6	52.9
2	6.6	11.4	52.5
3	9.8	11.2	52.2
4	13.1	11.0	51.8
5	16.4	10.8	51.4
5.5	18.2	10.6	51.1

Station PW-7

0	0	15.0	59.0
1	3.3	14.2	57.6
2	6.6	13.3	55.9
3	9.8	12.5	54.5
4	13.1	11.6	52.9
5	16.4	10.8	51.4
5.5	18.2	10.3	50.5

TABLE 2 (Contd.)

Station PW-8

0	0	14.9	58.8
1	3.3	14.0	57.2
2	6.6	13.0	55.4
2.4	7.9	12.6	54.7

Station PW-9

0 m	0 ft	12.5°C	54.5°F
1	3.3	12.7 ok	54.9 ok*
2	6.6	12.8 ok	55.0 ok*
3	9.8	13.0 ok	55.4 ok*
4	13.1	12.9 ok	55.2 ok*
5	16.4	12.8 ok	55.0 ok*
6	19.7	12.5	54.5
6.1	20.1	12.5	54.5

* Submerged outflow from sun-warmed creek and harbor basins.

Station PW-10 is PW-3 re-occupied for plankton and benthos samples. Bottom: 3" grey silt over hard red clay.

Station PW-11

0	0	12.8	54.3
1	3.3	12.3	54.1
2	6.6	12.1	53.8
3	9.8	12.0	53.6
4	13.1	11.5	52.7
5	16.4	11.0	51.8
6	19.7	10.4	50.7
7	23.0	9.8	49.6
8	26.2	9.3	48.7
9	29.5	8.8	47.8
10	32.8	8.8	47.8
10.1	33.0	8.8	47.8

Station PW-12

0	0	11.8	53.2
1	3.3	11.7	53.1
2	6.6	11.5	52.7
3	9.8	11.4	52.5
4	13.1	11.2	52.2
5	16.4	11.0	51.8
6	19.7	10.2	50.4
7	23.0	9.4	48.9
8	26.2	9.2	48.6
9	29.5	9.0	48.2
10	32.8	8.6	47.5
11	36.1	8.2	46.8
11.3	37.3	8.2	46.8

TABLE 2 (Contd.)

Station PW-13

0 m	0 ft	11.0°C	51.8°F
1	3.3	10.4	50.7
2	6.6	9.8	49.6
3	9.8	9.2	48.6
4	13.1	9.0	48.2
5	16.4	8.9	48.0
6	19.7	8.7	47.7
7	23.0	8.6	47.5
8	26.2	8.6	47.5
9	29.5	8.6	47.5
9.8	32.3	8.6	47.5

Plankton samples at this station, almost to end of visible plume. Bottom: Hard red clay, no sample obtained.

Station PW-14

0	0	15.5	59.9
1	3.3	14.4	57.9
2	6.6	13.3	55.9
3	9.8	12.2	54.0
4	13.1	11.4	52.5
5	16.4	10.6	51.1
6	19.7	9.8	49.6
7	23.0	8.9	48.0
8	26.2	8.9	48.0
9	29.5	8.9	48.0
9.8	32.3	8.9	48.0

Fig. 2
Port Washington Harbor Temperatures
and Survey Stations: August 13, 1968⁷

Fig. 3. Michigan City Power Plant Isotherm Map;
Surface Temperature: June 26, 1969⁸

A. Isotherm Map: Surface

B. Isotherm Map: 1-ft Depth

C. Isotherm Map: 2-ft Depth

D. Isotherm Map: 3-ft Depth

Fig. 4. Michigan City Isotherm and Station-location Maps: June 28, 1969⁸ (wind WSW, 2 mph; temperatures: °C)

E. Isotherm Map: 4-ft Depth

F. Isotherm Map: 5-ft Depth

G. Isotherm Map: 6-ft Depth

H. Isotherm Map: 7-ft Depth

Fig. 4 (Contd.)

I. Isotherm Map: 8-ft Depth

J. Station Location Map

Fig. 4 (Contd.)

TABLE 3. Michigan City Power Water-temperature Data: June 28, 1969⁸Sta. MCP-1

Surface	-	25.2°C	77.4°F
1 ft. depth	-	25.2	77.4
2 ft. "	-	25.2	77.4
3 ft. "	-	25.2	77.4
4 ft. "	-	24.5	76.1
5 ft. "	-	22.0	71.6
6 ft. "	-	20.6	69.1
7 ft. "	-	19.8	67.6
8 ft. "	-	19.1	66.4
9 ft. "	-	19.0	66.2
10 ft. "	-	18.6	65.2
11 ft. "	-	18.2	64.8
12 ft. "	-	18.2	64.8
13 ft. "	-	18.2	64.8

Sta. MCP-2

Surface	-	20.0°C	68.0°F
1 ft. depth	-	19.4	66.9
2 ft. "	-	19.2	66.6
3 ft. "	-	18.8	65.8
4 ft. "	-	18.6	65.5
5 ft. "	-	18.6	65.5
6 ft. "	-	18.5	65.3
7 ft. "	-	18.5	65.3

Sta. MCP-3

Surface	-	23.0°C	73.4°F
1 ft. depth	-	21.4	70.5
2 ft. "	-	20.6	69.1
3 ft. "	-	19.0	66.2
4 ft. "	-	18.6	65.5
5 ft. "	-	18.5	65.3
6 ft. "	-	18.5	65.3
7 ft. "	-	18.2	64.8

Sta. MCP-4

Surface	-	22.0°C	71.6°F
1 ft. depth	-	20.9	69.8
2 ft. "	-	19.2	66.6
3 ft. "	-	19.0	66.2
4 ft. "	-	18.9	66.0
5 ft. "	-	18.9	66.0
6 ft. "	-	18.9	66.0
7 ft. "	-	18.9	66.0

Sta. MCP-5

Surface	-	21.7°C	71.1°F
1 ft. depth	-	21.0	69.8
2 ft. "	-	20.0	68.0

Sta. MCP-6

Surface	-	22.4°C	72.3°F
1 ft. depth	-	22.0	71.6
2 ft. "	-	21.5	70.7
3 ft. "	-	21.0	69.8
4 ft. "	-	19.8	67.6
5 ft. "	-	19.6	67.3

Sta. MCP-7

Surface	-	22.4°C	72.3°F
1 ft. depth	-	21.0	69.8
2 ft. "	-	20.6	69.1
3 ft. "	-	20.1	68.2
4 ft. "	-	19.5	67.1
5 ft. "	-	19.5	67.1
6 ft. "	-	19.5	67.1
7 ft. "	-	19.4	66.9
8 ft. "	-	19.4	66.9
9 ft. "	-	19.2	66.6
10 ft. "	-	19.2	66.6

Sta. MCP-8

Surface	-	20.2°C	68.4°F
1 ft. depth	-	20.2	68.4
2 ft. "	-	20.2	68.4
3 ft. "	-	20.2	68.4
4 ft. "	-	20.0	68.0
5 ft. "	-	20.0	68.0
6 ft. "	-	19.8	67.6
7 ft. "	-	19.2	66.6
8 ft. "	-	19.0	66.2
9 ft. "	-	18.8	65.8

Sta. MCP-9

Surface	-	19.8°C	67.6°F
1 ft. depth	-	19.0	66.2
2 ft. "	-	19.0	66.2
3 ft. "	-	18.8	65.8
4 ft. "	-	18.6	65.5
5 ft. "	-	18.6	65.5

TABLE 3 (Contd.)

Sta. MCP-9 (Contd.)

6 ft. depth	-	18.6°C	65.5°F
7 ft. "	-	18.6	65.5
8 ft. "	-	18.6	65.5
9 ft. "	-	18.6	65.5
10 ft. "	-	18.6	65.5
11 ft. "	-	18.6	65.5
12 ft. "	-	18.6	65.5
13 ft. "	-	18.6	65.5
14 ft. "	-	18.6	65.5
15 ft. "	-	18.6	65.5
16 ft. "	-	18.2	64.8
17 ft. "	-	18.2	64.8

Sta. MCP-10

Surface	-	21.0°C	69.8°F
1 ft. depth	-	20.1	68.2
2 ft. "	-	19.8	67.6
3 ft. "	-	19.2	66.6
4 ft. "	-	19.0	66.2
5 ft. "	-	19.0	66.2
6 ft. "	-	19.0	66.2
7 ft. "	-	18.8	65.8
8 ft. "	-	18.6	65.5
9 ft. "	-	18.2	64.8
10 ft. "	-	18.1	64.6
11 ft. "	-	18.0	64.4
12 ft. "	-	18.0	64.4
13 ft. "	-	18.0	64.4
14 ft. "	-	18.0	64.4
15 ft. "	-	18.0	64.4
16 ft. "	-	18.0	64.4
17 ft. "	-	18.0	64.4
18 ft. "	-	18.0	64.4
19 ft. "	-	18.0	64.4
20 ft. "	-	18.0	64.4
21 ft. "	-	18.0	64.4

Sta. MCP-11

Surface	-	20.0°C	68.0°F
1 ft. depth	-	18.5	65.3
2 ft. "	-	18.4	65.1
3 ft. "	-	18.0	64.4
4 ft. "	-	17.9	64.2
5 ft. "	-	17.9	64.2
6 ft. "	-	17.9	64.2
7 ft. "	-	17.9	64.2
8 ft. "	-	17.9	64.2
9 ft. "	-	17.9	64.2
10 ft. "	-	17.8	64.0
11 ft. "	-	17.8	64.0
12 ft. "	-	17.8	64.0

Sta. MCP-11 (Contd.)

13 ft. depth	-	17.8°C	64.0°F
14 ft. "	-	17.8	64.0
15 ft. "	-	17.8	64.0
16 ft. "	-	17.8	64.0
17 ft. "	-	17.8	64.0
18 ft. "	-	17.8	64.0
19 ft. "	-	17.8	64.0
20 ft. "	-	17.8	64.0

Sta. MCP-12

Surface	-	21.0°C	69.8°F
1 ft. depth	-	19.8	67.6
2 ft. "	-	19.0	66.2
3 ft. "	-	18.0	64.4
4 ft. "	-	17.4	63.3
5 ft. "	-	17.4	63.3
6 ft. "	-	17.4	63.3
7 ft. "	-	17.2	63.0
8 ft. "	-	17.2	63.0
9 ft. "	-	17.2	63.0
10 ft. "	-	17.0	62.6
11 ft. "	-	17.0	62.6
12 ft. "	-	17.0	62.6
13 ft. "	-	17.0	62.6
14 ft. "	-	17.0	62.6
15 ft. "	-	17.0	62.6
16 ft. "	-	17.0	62.6
17 ft. "	-	16.8	62.2
18 ft. "	-	16.8	62.2
19 ft. "	-	16.8	62.2
20 ft. "	-	16.8	62.2
21 ft. "	-	16.8	62.2
22 ft. "	-	16.8	62.2
23 ft. "	-	16.8	62.2
24 ft. "	-	16.8	62.2
25 ft. "	-	16.8	62.2
26 ft. "	-	16.8	62.2
27 ft. "	-	16.8	62.2
28 ft. "	-	16.8	62.2
29 ft. "	-	16.8	62.2
30 ft. "	-	16.8	62.2
31 ft. "	-	16.8	62.2
32 ft. "	-	16.8	62.2
33 ft. "	-	16.8	62.2
34 ft. "	-	16.8	62.2
35 ft. "	-	16.8	62.2
36 ft. "	-	16.8	62.2
37 ft. "	-	16.8	62.2
38 ft. "	-	16.8	62.2
39 ft. "	-	16.8	62.2
40 ft. "	-	16.8	62.2

TABLE 3 (Contd.)

Sta. MCP-13

Surface	-	21.5°C	70.7°F
1 ft. depth	-	21.5	70.7
2 ft. "	-	21.0	69.8
3 ft. "	-	20.6	69.1
4 ft. "	-	20.5	68.9
5 ft. "	-	20.4	68.7
6 ft. "	-	20.4	68.7
7 ft. "	-	20.4	68.7
8 ft. "	-	20.4	68.7
9 ft. "	-	20.2	68.4
10 ft. "	-	19.9	67.8
11 ft. "	-	19.9	67.8
12 ft. "	-	19.8	67.6
13 ft. "	-	19.5	67.1
14 ft. "	-	19.0	66.2
15 ft. "	-	18.0	64.4
16 ft. "	-	17.9	64.2
17 ft. "	-	17.8	64.0
18 ft. "	-	17.8	64.0
19 ft. "	-	17.8	64.0
20 ft. "	-	17.5	64.0
21 ft. "	-	17.5	64.0
22 ft. "	-	17.4	63.3
23 ft. "	-	17.4	63.3
24 ft. "	-	17.4	63.3
25 ft. "	-	17.4	63.3
26 ft. "	-	17.2	63.0
27 ft. "	-	17.0	62.6
28 ft. "	-	17.0	62.6
29 ft. "	-	17.0	62.6
30 ft. "	-	17.0	62.6
31 ft. "	-	17.0	62.6
32 ft. "	-	17.0	62.6
33 ft. "	-	17.0	62.6
34 ft. "	-	17.0	62.6
35 ft. "	-	17.0	62.6
36 ft. "	-	17.0	62.6
37 ft. "	-	17.0	62.6
38 ft. "	-	17.0	62.6
39 ft. "	-	17.0	62.6
40 ft. "	-	17.0	62.6
41 ft. "	-	17.0	62.6
42 ft. "	-	17.0	62.6
43 ft. "	-	17.0	62.6
44 ft. "	-	17.0	62.6
45 ft. "	-	17.0	62.6
46 ft. "	-	17.0	62.6
47 ft. "	-	17.0	62.6

Sta. MCP-14

Surface	-	21.0°C	69.8°F
1 ft. depth	-	20.5	68.9
2 ft. "	-	20.0	68.0
3 ft. "	-	19.8	67.6
4 ft. "	-	19.2	66.6
5 ft. "	-	19.2	66.6
6 ft. "	-	19.2	66.6
7 ft. "	-	18.8	65.8
8 ft. "	-	18.4	65.1
9 ft. "	-	18.2	64.8
10 ft. "	-	18.0	64.4
11 ft. "	-	18.0	64.4
12 ft. "	-	18.0	64.4
13 ft. "	-	18.0	64.4
14 ft. "	-	18.0	64.4
15 ft. "	-	18.0	64.4
16 ft. "	-	17.4	63.3

Sta. MCP-15

Surface	-	21.6°C	70.9°F
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Sta. MCP-16

Surface	-	18.0°C	64.4°F
1 ft. depth	-	18.0	64.4
2 ft. "	-	18.0	64.4
3 ft. "	-	18.0	64.4
4 ft. "	-	18.0	64.4
5 ft. "	-	18.0	64.4
6 ft. "	-	18.0	64.4
7 ft. "	-	18.0	64.4
8 ft. "	-	18.0	64.4
9 ft. "	-	18.0	64.4
10 ft. "	-	18.0	64.4
11 ft. "	-	18.0	64.4
12 ft. "	-	18.0	64.4
13 ft. "	-	18.0	64.4
14 ft. "	-	18.0	64.4
15 ft. "	-	18.0	64.4
16 ft. "	-	18.0	64.4
17 ft. "	-	18.0	64.4
18 ft. "	-	18.0	64.4

Fig. 5. Waukegan Isotherm and Station-location Maps: June 30, 1969⁸ (wind WSW, 2 mph; temperatures: °C)

G. Isotherm Map: 6-ft Depth

H. Isotherm Map: 7-ft Depth

I. Isotherm Map: 8-ft Depth

J. Isotherm Map: 9-ft Depth

K. Station Location Map

Fig. 5
(Contd.)

TABLE 4. Waukegan Water Temperature Data: June 30, 1969⁸Sta. WP-1

Surface	-	16.6°C	61.9°F
1 ft. depth	-	16.5	61.7
2 ft. "	-	16.5	61.7
3 ft. "	-	16.5	61.7
4 ft. "	-	16.5	61.7
5 ft. "	-	16.5	61.7
6 ft. "	-	16.4	61.5
7 ft. "	-	16.4	61.5

Sta. WP-2

Surface	-	12.8°C	55.0°F
1 ft. depth	-	12.6	54.7
2 ft. "	-	12.6	54.7
3 ft. "	-	12.6	54.7
4 ft. "	-	12.6	54.7
5 ft. "	-	12.6	54.7
6 ft. "	-	12.6	54.7

Sta. WP-3

Surface	-	13.0°C	55.4°F
1 ft. depth	-	13.0	55.4
2 ft. "	-	13.0	55.4
3 ft. "	-	13.0	55.4
4 ft. "	-	13.0	55.4
5 ft. "	-	13.0	55.4
6 ft. "	-	13.0	55.4
7 ft. "	-	13.0	55.4
8 ft. "	-	13.0	55.4
9 ft. "	-	13.0	55.4
10 ft. "	-	13.0	55.4
11 ft. "	-	13.0	55.4
12 ft. "	-	12.8	55.0
13 ft. "	-	12.8	55.0
14 ft. "	-	12.8	55.0
15 ft. "	-	12.8	55.0
16 ft. "	-	12.8	55.0
17 ft. "	-	12.8	55.0
18 ft. "	-	12.6	54.7
19 ft. "	-	12.6	54.7

Sta. WP-4, 1/4 mile East of
outfall channel

Surface	-	12.8°C	55.0°F
1 ft. depth	-	12.8	55.0
2 ft. "	-	12.8	55.0

Sta. WP-4 (Cont.)

3 ft. depth	-	12.8°C	55.0°F
4 ft. "	-	12.8	55.0
5 ft. "	-	12.8	55.0
6 ft. "	-	12.8	55.0
7 ft. "	-	12.8	55.0
8 ft. "	-	12.8	55.0
9 ft. "	-	12.8	55.0
10 ft. "	-	12.8	55.0
11 ft. "	-	12.8	55.0
12 ft. "	-	12.8	55.0
13 ft. "	-	12.8	55.0
14 ft. "	-	12.8	55.0
15 ft. "	-	12.8	55.0
16 ft. "	-	12.8	55.0
17 ft. "	-	12.8	55.0
18 ft. "	-	12.8	55.0

Sta. WP-5, 1/2 mile North of WP-4

Surface	-	13.0°C	55.4°F
1 ft. depth	-	13.0	55.4
2 ft. "	-	13.0	55.4
3 ft. "	-	13.0	55.4
4 ft. "	-	13.0	55.4
5 ft. "	-	13.0	55.4
6 ft. "	-	13.0	55.4
7 ft. "	-	13.0	55.4
8 ft. "	-	13.0	55.4
9 ft. "	-	13.0	55.4
10 ft. "	-	13.0	55.4
11 ft. "	-	13.0	55.4
12 ft. "	-	13.0	55.4
13 ft. "	-	13.0	55.4
14 ft. "	-	13.0	55.4
15 ft. "	-	13.0	55.4
16 ft. "	-	13.0	55.4
17 ft. "	-	13.0	55.4
18 ft. "	-	12.9	55.2
19 ft. "	-	12.9	55.2
20 ft. "	-	12.9	55.2
21 ft. "	-	12.9	55.2
22 ft. "	-	12.9	55.2
23 ft. "	-	12.9	55.2
24 ft. "	-	12.8	55.0
25 ft. "	-	12.8	55.0
26 ft. "	-	12.8	55.0
27 ft. "	-	12.8	55.0

TABLE 4 (Contd.)

Sta. WP-6, 1/2 mile North of WP-5

Surface	-	13.0°C	55.4°F
1 ft. depth	-	13.0	55.4
2 ft. "	-	13.0	55.4
3 ft. "	-	13.0	55.4
4 ft. "	-	13.0	55.4
5 ft. "	-	13.0	55.4
6 ft. "	-	13.0	55.4
7 ft. "	-	13.0	55.4
8 ft. "	-	13.0	55.4
9 ft. "	-	13.0	55.4
10 ft. "	-	13.0	55.4
11 ft. "	-	13.0	55.4
12 ft. "	-	12.8	55.0
13 ft. "	-	12.8	55.0
14 ft. "	-	12.8	55.0
15 ft. "	-	12.8	55.0
16 ft. "	-	12.8	55.0
17 ft. "	-	12.6?	
18 ft. "	-	12.8	55.0
19 ft. "	-	12.8	55.0
20 ft. "	-	12.8	55.0
21 ft. "	-	12.8	55.0
22 ft. "	-	12.8	55.0
23 ft. "	-	12.8	55.0
24 ft. "	-	12.8	55.0
25 ft. "	-	12.8	55.0
26 ft. "	-	12.8	55.0
27 ft. "	-	12.5	54.5
28 ft. "	-	12.0	53.6
29 ft. "	-	12.0	53.6

Sta. WP-7, 1/2 mile North of WP-6

Surface	-	13.0°C	55.4°C
1 ft. depth	-	13.0	55.4
2 ft. "	-	13.0	55.4
3 ft. "	-	13.0	55.4
4 ft. "	-	13.0	55.4
5 ft. "	-	13.0	55.4
6 ft. "	-	12.8	55.0
7 ft. "	-	12.8	55.0
8 ft. "	-	12.8	55.0
9 ft. "	-	12.8	55.0
10 ft. "	-	12.8	55.0
11 ft. "	-	12.8	55.0
12 ft. "	-	12.8	55.0
13 ft. "	-	12.8	55.0
14 ft. "	-	12.8	55.0
15 ft. "	-	12.8	55.0
16 ft. "	-	12.8	55.0
17 ft. "	-	12.8	55.0
18 ft. "	-	12.8	55.0
19 ft. "	-	12.8	55.0
20 ft. "	-	12.8	55.0

Sta. WP-7 (Contd.)

21 ft. depth	-	12.8°C	55.0°F
22 ft. "	-	12.8	55.0
23 ft. "	-	12.8	55.0
24 ft. "	-	12.8	55.0
25 ft. "	-	12.8	55.0
26 ft. "	-	12.8	55.0
27 ft. "	-	12.8	55.0
28 ft. "	-	12.8	55.0
29 ft. "	-	12.8	55.0
30 ft. "	-	12.8	55.0
31 ft. "	-	12.8	55.0

Sta. WP-8, halfway to shore from WP-7

Surface	-	12.8°C	55.0°F
1 ft. depth	-	12.8	55.0
2 ft. "	-	12.8	55.0
3 ft. "	-	12.8	55.0
4 ft. "	-	12.8	55.0
5 ft. "	-	12.8	55.0
6 ft. "	-	12.6	54.7
7 ft. "	-	12.5	54.5
8 ft. "	-	12.5	54.5
9 ft. "	-	12.2	54.0
10 ft. "	-	12.2	54.0
11 ft. "	-	12.2	54.0
12 ft. "	-	12.2	54.0
13 ft. "	-	12.0	53.6
14 ft. "	-	12.0	53.6

Sta. WP-9, direction - towards shore
from WP-8, location - as close to
shore as possible (approx. 100 yds.
from shore)

Surface	-	13.6°C	56.5°F
1 ft. depth	-	13.4	56.1
2 ft. "	-	13.2	55.8
3 ft. "	-	13.2	55.8
4 ft. "	-	13.0	55.4
5 ft. "	-	13.0	55.4
6 ft. "	-	13.0	55.4

Sta. WP-10, 3/4 mile North of WP-9

Surface	-	13.0°C	55.4°F
1 ft. depth	-	13.0	55.4
2 ft. "	-	13.0	55.4
3 ft. "	-	13.0	55.4
4 ft. "	-	13.0	55.4
5 ft. "	-	13.0	55.4
6 ft. "	-	13.0	55.4
7 ft. "	-	12.9	55.2
8 ft. "	-	12.9	55.2
9 ft. "	-	12.8	55.0

TABLE 4 (Contd.)

Sta. WP-10 (Contd.)

10 ft. depth	-	12.8°C	55.0°F
11 ft. "	-	12.8	55.0

Sta. WP-11, 1/2 mile South of WP-9

Surface	-	14.0°C	57.2°F
1 ft. depth	-	14.0	57.2
2 ft. "	-	14.0	57.2
3 ft. "	-	14.0	57.2
4 ft. "	-	13.8	56.8
5 ft. "	-	13.6	56.5
6 ft. "	-	13.6	56.5
7 ft. "	-	13.5	56.3
8 ft. "	-	13.2	55.8
9 ft. "	-	13.0	55.4

Sta. WP-12, 1/2 mile from shore,
outside WP-11

Surface	-	14.0°C	57.2°F
1 ft. depth	-	13.8	56.8
2 ft. "	-	13.8	56.8
3 ft. "	-	13.8	56.8
4 ft. "	-	13.8	56.8
5 ft. "	-	13.8	56.8
6 ft. "	-	13.6	56.5
7 ft. "	-	13.6	56.5
8 ft. "	-	13.6	56.5
9 ft. "	-	13.6	56.5
10 ft. "	-	13.6	56.5
11 ft. "	-	13.6	56.5
12 ft. "	-	13.0	55.4
13 ft. "	-	13.0	55.4
14 ft. "	-	13.0	55.4
15 ft. "	-	12.9	55.2
16 ft. "	-	12.9	55.2
17 ft. "	-	12.9	55.2
18 ft. "	-	12.9	55.2
19 ft. "	-	12.9	55.2
20 ft. "	-	12.8	55.0
21 ft. "	-	12.8	55.0
22 ft. "	-	12.6	54.7
23 ft. "	-	12.4	54.3
24 ft. "	-	12.4	54.3

Sta. WP-13, halfway to shore from WP-5

Surface	-	14.9°C	58.8°F
1 ft. depth	-	14.8	58.6
2 ft. "	-	14.8	58.6
3 ft. "	-	14.8	58.6
4 ft. "	-	14.6	58.3
5 ft. "	-	14.6	58.3
6 ft. "	-	14.2	57.6
7 ft. "	-	14.2	57.6
8 ft. "	-	14.2	57.6

Sta. WP-14, halfway to outfall
lite from WP-4

Surface	-	13.0°C	55.4°F
1 ft. depth	-	13.0	55.4
2 ft. "	-	13.0	55.4
3 ft. "	-	13.0	55.4
4 ft. "	-	13.0	55.4
5 ft. "	-	13.0	55.4
6 ft. "	-	13.0	55.4
7 ft. "	-	13.0	55.4
8 ft. "	-	13.0	55.4
9 ft. "	-	13.0	55.4
10 ft. "	-	13.0	55.4
11 ft. "	-	13.0	55.4
12 ft. "	-	13.0	55.4
13 ft. "	-	13.0	55.4
14 ft. "	-	13.0	55.4

thermistor supported by the "Mysis" bowsprit and positioned in the water to be ahead of the ship's bow wave. Except for one position, only surface measurements were taken, because strong currents and windage on the ship precluded the use of thermistor chains. The investigators noted that at that particular position within the axis of the plume for which vertical measurements were taken, ambient water temperatures were reached within 1 ft from the surface. The Michigan City data of June 28, 1969, included vertical temperature measurements. The ambient current was from the southwest, as dictated by the strong southwest wind of the day before. Station location was determined from sextant fixes to shoreline landmarks. Shallow-water measurements were taken from a skiff. The investigators observed that at station 13 the temperature within 1 ft of the surface was only 0.5°C above ambient. They concluded from this and other facts that about 93% of the heat from the plant was lost within 4000 ft from the outfall.

The June 30, 1969, Waukegan plume data were taken using radar ranges and bearings. A northward shoreline current was present, being the residual of the previous day's 18-mph south wind.

A series of plume temperature measurements representing nine different data sets is shown for the J. R. Whiting plant on Lake Erie.* The information described herein is unpublished; however, it is on file at Consumers Power Company in Michigan. Figure 6A describes the location of the measurement stations. Readings were taken and reported at the surface and at 1-ft intervals down to 5 ft and at the bottom. The dots in Fig. 6A represent fixed buoy positions; the X's represent positions reached by lining up adjacent buoys. The temperature-measurement technique was not stated. Base-line definitions for the nine sets of data are given in Table 5. The results are shown in Figs. 6B-6J. Figure 6K represents a rather interesting plot of the vertical temperature profile for the June 29, 1967 data.

Beer and Pipes have reported plume temperature data for the Waukegan power plant taken on April 30, 1968.⁹ Water temperatures were measured using 10 thermocouples spaced at 1-ft intervals along a rod that could be lowered up to 30 ft in depth. The thermocouple outputs were recorded on a multichannel recorder. The measurement positions were located by surveying and shore triangulation. These data are reported on in Fig. 7. Table 6 shows the tabular values.

Beer, Pipes (Industrial BioTest Laboratories, September 15, 1970), and other investigators are presently undertaking perhaps the most comprehensive study of the effects of cooling-water discharges on the Great Lakes. This work is being performed primarily in connection with the siting of the Zion nuclear power plant on Lake Michigan. Most of this work is yet unpublished, as the studies have not been completed. Many plume profiles are being recorded for the Waukegan plant in connection with these studies.

*Obtained by personal correspondence with Consumers Power Company of Michigan.

A. Points for Determining Thermal Expansion

B. Lake Erie Water-temperature Study: June 29, 1967

Fig. 6. J. R. Whiting Plant Location and Water-temperature Study Points for Determining Thermal Dispersion

C. Lake Erie Water-temperature Study: July 7, 1967

D. Lake Erie Water-temperature Study: July 14, 1967

Fig. 6 (Contd.)

E. Lake Erie Water-temperature Study: July 20, 1967

F. Lake Erie Water-temperature Study: August 3, 1967

Fig. 6 (Contd.)

Fig. 6 (Contd.)

I. Lake Erie Water-temperature Study: September 5, 1967

J. Lake Erie Water-temperature Study: September 7, 1967

K. Vertical Temperature Survey: June 29, 1967

TABLE 5. J. R. Whiting Plant Lake Erie Temperature Study: 1967

Date	Units on Line	Load MW	Circ. Pumps on	Lake Level	Wind Direction	Wind Speed MPH	Wet Bulb F°	Dry Bulb F°	Rel. Hum. %	GPM Cond. Flow	Inlet Temp. F°	Outlet Temp. F°
6/29	1 2 3	339	6	572.4	SW	12	69.5	77.5	67	$\times 10^3$ 214	73	88
7/7	1 2 —	198	4	572.8	ESE	5	67.5	70.5	82	120	73.7	93.5
7/14	1 2 3	330	6	572.4	NW	5	59	64	74	214	72.5	88.5
7/20	1 2 3	329	6	572.6	SW	6	66.5	72	75	214	75.8	89
8/3	1 2 3	332	6	572.8	SW	6	77	83	75	214	79	93
8/10	1 2 3	329	6	572.3	N	10	59	61	89	214	75	89
8/24	1 2 3	333	6	572.9	NE	12	70	73	86	214	70.2	84.5
9/5	1 2 3	330	6	572.3	calm	calm	69	78	63	214	72.1	86.5
9/7	1 2 3	329	6	572.2	W	0-5	65.5	74.0	63	214	73.0	87.4

A. 1 ft below Surface

B. 4 ft below Surface

C. 8 ft below Surface

D. 10 ft below Surface

E. 14 ft below Surface

F. 18 ft below Surface

Fig. 7. Temperature Studies; Waukegan Station: April 1968⁹

G. Northeast Section

H. East Section

I. Southeast Section

J. Easterly Discharge Section (random)

K. April 30, 1968 Data

Fig. 7 (Contd.)

TABLE 6 (Contd.)

Position	Time	Dir.-Dist.	Depth	°F @ FT-Depth	Position	Time	Dir.-Dist.	Depth	°F @ FT-Depth
10	- 9:00 am	E 1974 FT	20 FT	51° @ 0- 3' 50° @ 3-15' 49° @ 15-20'	18	- 9:35 am	ENE 1027 FT	8 FT	52° @ 0- 1' 51° @ 1- 2' 50° @ 2- 3' 49° @ 3- 4' 48° @ 4- 5' 47° @ 5- 6' 46° @ 6- 8'
11	-	E 2335	24	49° @ 0- 3' 48° @ 3-17' 47° @ 17-22' 46° @ 22-24'	19	-	ENE 1320	12	52° @ 0- 1' 51° @ 1- 6' 50° @ 6- 9' 49° @ 9-12'
12	-	E 2938	29	48° @ 0-13' 47° @ 13-24' 46° @ 24-29'	20	9:40 am	ENE 1622	13	51° @ 0- 8' 50° @ 8-12' 49° @ 12-13'
13	9:10 am	E 3212	32	48° @ 0- 7' 47° @ 7-20' 46° @ 20-27' 45° @ 27-30'	21	-	ENE 2027	17	51° @ 0- 5' 50° @ 5- 7' 49° @ 7- 9' 48° @ 9-11' 47° @ 11-14' 46° @ 14-17'
End Of East Section Begin NE Section					22	-	ENE 2228	18	49° @ 0- 4' 48° @ 4- 6' 47° @ 6-10' 46° @ 10-14' 45° @ 14-18'
14	-	ENE 239 FT	4 FT	51° @ 0- 2' 50° @ 2- 3' 49° @ 3- 4'	23	- 9:45 am	ENE 2411	20	46° @ 0- 6' 45° @ 6-20'
15	9:30 am	ENE 402	5	56° @ 0- 4' 55° @ 4- 5'	24	-	ENE 2672	21	46° @ 9- 4' 45° @ 4-21'
16	-	ENE 651	4	50° @ 0- 1' 49° @ 1- 3' 48° @ 3- 4'	End Of NE Section Begin SE Section				
17	-	ENE 827	9	52° @ 0- 5' 50° @ 5- 6' 48° @ 6- 7' 47° @ 7- 9'					

TABLE 6 (Contd.)

Position	Time	Dir.-Dist.	Depth	Of @ FT-Depth	Position	Time	Dir.-Dist.	Depth	Of @ FT-Depth
25	9:50 am	ESE 130 FT	5 FT	49° @ 0- 2' 48° @ 2- 4' 47° @ 4- 5'	39	-	EENE 1120 FT	12 FT	54° @ 0- 9' 53° @ 9-12'
26	-	ENE 97	6	57° @ 0- 6'	40	-	EENE 1377	13	53° @ 0-11' 52° @ 11-13'
27	10:05	ESE 325	4	49° @ 0- 1' 48° @ 1- 3'	41	10:35 am	EENE 1598	16	51° @ 0- 3' 50° @ 3- 9' 49° @ 9-12' 48° @ 12-16'
28	-	ESE 587	3	48° @ 0- 3'	42	-	EENE 1930	20	51° @ 0- 5' 50° @ 5- 8' 49° @ 8-17' 48° @ 17-20'
29	10:10	ESE 767	8	48° @ 0- 8'	43	10:45 am	E 2324	23	50° @ 0- 3' 49° @ 3- 4' 48° @ 4- 6' 47° @ 6-14' 46° @ 14-17' 45° @ 17-23'
30	-	ESE 1020	11	48° @ 0-11'	44	-	E 2936	29	50° @ 0- 2' 49° @ 2- 7' 48° @ 7-15' 47° @ 15-24' 46° @ 24-27' 45° @ 27-29'
31	-	ESE 1269	12	48° @ 0-12'	45	-	E 3342	33	48° @ 0-15' 47° @ 15-25' 46° @ 25-29' 45° @ 29-30'
32	10:15	ESE 1458	15	49° @ 0- 3' 48° @ 3-12' 47° @ 12-15'	End Of Easterly Discharge Section				
33	10:20	ESE 1619	21	49° @ 9- 3' 48° @ 3- 5' 47° @ 6-18' 46° @ 18-21'					
End Of SE Section Begin Easterly Discharge Section									
34	-	E 78 FT	5 FT	57° @ 0- 5'	End Of Easterly Discharge Section				
35	-	EENE 279	5	54° @ 0- 5'					
36	-	EENE 514	5	54° @ 0- 4' 55° @ 4- 5'					
37	-	EENE 681	8	55° @ 0- 5' 56° @ 6- 8'	End Of Easterly Discharge Section				
38	-	EENE 868	9	55° @ 0- 9'					

TABLE 6 (Contd.)

Begin Bottom Samples

Position	Time	Dir.-Dist.	Depth	°F @ FT Depth	Ambient Temp
46	11:30 am	S 1850 FT	11 FT	48° @ 1'	54° F
47	11:55	E 922	13	54° @ 1'	59° F
48	12:05	NE 1800	11	47° @ 1'	61° F

Plume-temperature data for the Big Rock Point Nuclear Power Plant May 21 and September 9, 1968, and on June 11, 1969; the J. H. Campbell plant on July 3 and July 30, 1968; the Karn and Weadock plants on July 16, 1968; the Harbor Beach plant on July 17, 1968; and the Traverse City power plant on July 1, 1968, have been obtained from the Water Resources Commission of the State of Michigan (MWRC).¹⁰ These data with accompanying narrative are presented through the next several pages.

A temperature survey was conducted at the Big Rock Point Nuclear Station on May 21, 1968, between 2:00 and 4:00 p.m. During the survey, the maximum air temperature was 66°F and the wind was from the WNW at 0-3 mph. The plant was operating at full power with a discharge of approximately 90 cfs. The water intake temperature was 45°F, and the discharge temperature was 61°F.

Surface and bottom temperatures were recorded at all locations, and middepth readings were recorded at those stations having depths greater than 10 ft. A thermistor was used to take all water temperatures.

Figure 8A graphically illustrates the areas having temperatures above the ambient surface temperature of 45°F. Approximately 15 acres of surface waters were raised 3-5°F, and an additional 5 acres were raised 0-3°F. The above areas were generally confined to the shallow inshore waters, west of the plant site. Although Fig. 8A was drawn showing finite boundaries, they should not be taken as absolute because the discharge plume pattern varies with changes in wind conditions. The ambient surface-water temperature of the open-water area was 45°F and probably varied less than 1°F.

Figure 8B presents temperature-profile data at seven offshore locations near the heated cooling-water discharge. Middepth temperatures were recorded only at those stations where the depth was greater than 10 ft.

Additional field work was conducted at the Big Rock Nuclear Station on September 9, 1968, when the ambient nearshore Lake Michigan temperature varied with depth from 64 to 68°F; no depth range was specified for these temperatures. The measurements were made from a 16-ft outboard boat. Instrumentation included a thermistor for water-temperature measurements.

The measurements were made between 10:00 and 11:00 a.m., while the Big Rock station generated 70 MWe. The temperature rise (Δt) through the condensers was 17°F, and the cooling-water requirement was 90 cfs. The stated Δt and flow rate correspond to a thermal discharge rate of roughly 101 MWt. This figure seems to be too low in relation to the 70-MWe operating level. The same comment applies for the May 21, 1968 testing date. The intake water temperature was 68°F, and discharge was 85°F. During the observation period, winds were moderate, generally 10-15 mph from the west-northwest.

*This was originally 48°F, but has been corrected.

A. Increases in Water Temperatures

B. Water-temperature Profiles

Fig. 8. Lake Michigan Water Temperatures in Big Rock Nuclear Power Plant Vicinity: May 21, 1968¹⁰

A horizontal isothermal map representing surface-water temperatures is provided in Fig. 9. Plume configuration was oriented east-west with a maximum extent of 2500 ft, a north-south maximum extent of 900 ft, which comprises an area of approximately 51 surface acres. Stratification did occur within the area of influence as four isotherm areas containing temperature ranges 1-3, 4-6, 7-10, and 11-17°F above the ambient lake temperature of 68°F were found. Approximately 12 of the 51 surface-water acres had been raised greater than 7°F.

Fig. 9. Horizontal Isothermal Surface-water Temperatures in Big Rock Nuclear Power Plant Vicinity: September 9, 1968¹⁰

Thermal measurements were again made at the Big Rock Nuclear Power Plant between 1:30 and 2:30 p.m. on June 11, 1969, while the station operated at 71 MWe, with a temperature rise through the condensers of 14°F and a cooling-water requirement of 107 cfs. The stated flow rate and Δt correspond to a 98.6-MWt discharge rate. Again this magnitude should be considered suspect in relation to the stated operating level of 71 MWe. The intake temperature was 47°F with a discharge temperature of 61°F. During the survey, winds were light (0-3 mph from the south), and a light rain was falling. The air temperature was 54°F.

Figure 10A graphically illustrates three isothermal areas which had surface-water temperatures above the ambient nearshore temperature of 51°F. Thirty-four surface-water acres were affected by the discharge. Eight of the 34 acres were raised 7-10°F, nine acres 4-6°F, and 17 acres 3°F. Although Fig. 10A was drawn showing finite boundaries, it is not intended that they be taken as absolute. The discharge plume pattern changes as a result of changing meteorological conditions and lake currents.

Figure 10B presents temperature-profile data at various locations near the cooling-water discharge. The discharge warm water was found floating on the surface at locations beyond the discharge channel.

A temperature survey was made at the J. H. Campbell Power Plant, located 1/2 mile inland from the southeastern shore of Lake Michigan approximately four miles west of West Olive, Michigan. Heated water is discharged into a 5/8-mile-long canal that flows directly to Lake Michigan.

On July 3, 1968, Lake Michigan water temperatures were taken at the surface and at 2½-, 5-, and 10-ft depths along 12 east-west transects located from 1½ miles south of the discharge canal to 2½ miles north of the canal. The temperatures were also taken along the bottom. The survey was conducted between 12:00 and 6:30 p.m. At noon, the air temperature was 68°F and the winds were from the west at 10 mph. At 6:30 p.m., the air temperature was 68°F and the wind was from the SW at 7 mph. During this time, the plant was using 579 cfs with an intake temperature of 66°F and a discharge temperature of 84°F. The ambient lake temperature was 65°F. A thermistor was used to take all water temperatures.

Figure 11 shows the 65.5, 70, and 75°F isotherms at the surface and at 2½- and 5-ft depths, respectively. The 65.5 and 70°F isotherms are similar at the surface and at 2½ ft, but the 75° isotherm encompasses a much larger area at the surface than it does at 2½ ft. At the surface this 75° water extended out into the lake for almost 3/4 mile, and it flowed south of the discharge nearly 1/2 mile, but at 2½ ft it was merely a narrow strip extending into the lake less than 1/4 mile.

The area of lake that showed more than a 0.5°F increase in temperature (65.5°) was almost the same at the surface and at 2½ ft. Its furthest penetration into the lake, almost a mile, occurred 3/8 mile south of the discharge. This body of warmer water gradually receded until it reached a minimum width of less than 1/4 mile, 2 miles north of the discharge. At 1½ miles south of the discharge, this could be detected 5/8 mile off shore. Due to rough water, the southern boundary of this water was not determined. The total length of the affected area measured was 3½ miles.

At 5 ft, none of the lake water was heated to more than 67.3°F. The water that showed more than a 0.5° increase extended into the lake a maximum distance of 1/2 mile out from the Pigeon River Breakwater. The total length of the affected area was about 2 miles. No warming of the lake water occurred at 10 ft or more in depth.

A. Horizontal Isothermal Surface-Water Temperatures

B. Temperature-profile Data

Fig. 10. Temperature Data in Big Rock Nuclear Power Plant Vicinity: June 11, 1969¹⁰

A. 65.5, 70, and 75°F Isotherms at Surface

B. 65.5, 70, and 75°F Isotherms at 2½-ft Depth

C. 65.5°F Isotherm at 5-ft Depth

Fig. 11. Lake Michigan Isotherms near Consumers Power Co. Campbell Plant: July 3, 1968¹⁰

The approximate $1\frac{3}{4}$ square miles of water affected by the Campbell plant's discharge on July 3, 1968, constitutes a considerable volume of water. However, this survey was conducted on a calm, warm day, when the amount of mixing was probably at a minimum. Therefore, it is probable that the area affected by this discharge is much smaller under more normal conditions.

Another survey was conducted at the J. H. Campbell plant between 12:30 and 5:30 p.m. on July 30, 1968. During this time, the air temperature varied from a low of 76°F at 12:30 p.m. to a high of 80°F at 4:00 p.m. The wind was from the SSW at 10-15 mph for most of the day; however, after 4:00 p.m., it gusted up to 23 mph. The plant was operating at full power during this time, with a discharge temperature of 69°F and an intake temperature of 51°F.

Figure 12 illustrates the lake temperatures in definite zones. Although this figure is drawn showing finite boundaries, they should not be taken as absolute. The water temperature was constantly changing, and this drawing is a graphic attempt to describe a dynamic situation. The open-water area, shown as being 62-66°F, probably varied less than 1 or 2°F at any given time, but it appeared to have warmed from about 62°F at 12:30 p.m. to 66°F at 5:30 p.m.

The cooler water (54.0-61.0°F) was present 1 mile north of the discharge and at least as far south as the Pigeon River Breakwater. The thermal load introduced by the Campbell plant (62.0-65.0°F) was "dissipated" in an area of about $1/8$ mile wide and less than 1 mile long. The area warmed by this discharge was considerably smaller than that reported by Water Resources Commission staff on previous occasions (Water Temperature Survey, Lake Michigan, Port Sheldon, August 31, 1966; and The Effects of the Consumers Power Company's Campbell Plant Discharge on the Water of Lake Michigan, July 3, 1968).

Temperature surveys were performed at the J. C. Weadock and the D. E. Karn generating plants located at the mouth of the Saginaw River. The Karn and Weadock plants pump water from the Saginaw River and discharge their cooling water into Saginaw Bay through a common flume. They use 844,000 gal/min (1,880 cfs) of water when running at plant capacity. Table 7 lists the megawatt load of each plant by individual units, along with the intake and discharge temperatures and flow rates.

The survey started at 1:00 p.m. on July 16, 1968. The air temperature was 89°F. It was a bright, sunny day, with the wind out of the west at 5-10 mph. The water temperatures were taken with thermistor at the surface and, where possible, at $2\frac{1}{2}$ -, 5-, 10-, 20-ft depths and at the bottom. Figure 13 shows the stations at which readings were taken, and Tables 7 and 8 give the depths and temperatures at each. The area of Saginaw Bay that was affected by the heated discharge was very shallow with the deepest spot at station 8, being 9 ft deep.

Fig. 12. Lake Michigan Water Temperatures near Consumers Power Co.
Campbell Plant: July 30, 1968¹⁰

TABLE 7. Plant Data Supplied by Consumers Power Co.:
July 16, 1968¹⁰

J. C. Weadock Plant

Unit	MW Load	Condenser Cooling Water GPM	Inlet °F	Outlet °F
1	31	46,000	79	88
2	32	46,000	79	87
3	47	52,000	78	92
4	Off	(52,000)*	--	--
5	68	54,000	79	95
6	65	54,000	79	97
7	165	120,000	78	91
8	162	120,000	78	88

D. E. Kern Plant

Unit	MW Load	Condenser Cooling Water GPM	Inlet °F	Outlet °F
1	282	150,000	77	93
2	279	150,000	77	93

* For information only. Flow was zero as unit was out of service.

TABLE 8. Water Temperatures (°F) and Transparency;
Saginaw River Mouth: July 16, 1968¹⁰

Station No.	Surface	2.5'	5'	10'	20'	30'	Bottom depth in feet	Secchi transparency in feet
1	84	81	79	77	72		17	1½
2	81	81	78	76	72*		16	1½
3	80	79	77	74	69	69*	21	2
4	89	91	91	91*			6	
5	80	80*					2½	2
6	86	84	83*				3	
7	82	83	79*				5	2
8	80	80	80	76*			9	
9	83	84	78	77*			7	
10	83	82	80	77*			8	
11	86	91*					2½	
12	91	91*					2½	
13	88	87	78*				5	
14	86	79*					2½	
15	86	86*					2½	
16	87	87*					2½	
17	87	84	80*				5	
18	87	85	80	78*			7	
19	83	83	79	77*			7	
20	82	82	79	77*			7	
21	86	86	80*				5	
22	83	85	80	78*			7	
23	82	82	80	78*			7	
24	81	81	80	78*			7	

* Temperature at bottom.

The two plants have a common flume, which discharges into the Saginaw Bay. The temperatures at the mouth of the flume were 89°F at the surface and 91°F all the way to the bottom, which was 6 ft deep. West of the flume, there was an area 400 by 100 yards, which had a temperature of 90-91°F. The temperature was raised to 85-95°F for a distance of at least 1300 yards to the west and 300 yards out from shore. To the west of the discharge, shallow water prevailed, which had a definite influence toward warming the water. The Saginaw River had surface temperatures of 84, 81, and 80°F at stations 1, 2, and 3 respectively. For unknown reasons, surface temperatures at stations 4, 11, and 22 were lower than the 2½-ft readings.

A survey was made at the Harbor Beach steam-generating plant, which uses 90,000 gpm (200 cfs) of water for cooling. During the week, the plant operates at its maximum capacity, 110 MW.

The survey started at 10:30 a.m. on July 17, 1968. The air temperature was 83°F, and the intake temperature at the plant was 63°F. The discharge temperature at the flume was 75°F. The wind was from the northeast at 1-5 mph and subsequently switched to a southeast wind at 10 mph.

Figure 14 shows the locations of the temperature recording stations. The water temperatures were taken at the surface at 2½, 5, 10, and 20 ft deep, and at the bottom, where depth permitted. The harbor has a maximum depth of 28 ft at station 15. The average depth of the 28 stations in the harbor was 12 ft. The harbor has been dredged to permit boats to unload coal at the power plant.

The highest surface temperature recorded was 71°F at the station 11,500 ft south of the entrance of the heated discharge. The lowest surface temperature (64.6°F) was observed at station 8. Based on temperature readings during the survey, the water temperature was raised for approximately 3000 ft south of the flume. Part of the temperature rise would appear to be the result of shallow water along the shore. A maximum rise of 4°F was observed within an area 750 ft from discharge.

The Traverse City power plant was studied between 4:30 and 6:30 p.m., on July 1, 1968. The air temperature was 85°F, and winds were blowing from the west southwest at 20 mph. The plant had been producing 12,000 kW/hr since 7:00 a.m.

Figure 15 shows the temperatures recorded and the locations of the discharges. Temperatures were taken at the surface, at 2½, 5, and 10 ft, and at the bottom. They are recorded in Fig. 15 in descending order.

Fig. 14. Surface Water Temperatures at Harbor Beach, Michigan: July 17, 1968¹⁰

Fig. 15. Water Temperatures around the Traverse City Power Plant: July 1, 1968¹⁰

The ambient surface temperature of the bay averaged just slightly above 43°F. The water at the surface was heated 3°F, 75 yards directly downwind from the large discharge at station 7. The surface water was 1°F warmer at stations 1 and 9, but temperatures were also taken along the shore, and there was no increase in temperature at any distance greater than 50 yards from the discharges.

Argonne National Laboratory is currently investigating several power-plant cooling-water outfalls on Lake Michigan in conjunction with its Great Lakes Research Program sponsored by the U.S. Atomic Energy Commission.¹² As part of the overall effort, plume temperature measurements are being obtained. Temperature measurements are made with thermistor probes affixed to a submerged boom at 1-, 3-, 6-, and 9-ft depths. The boom itself is mounted along the gunwale of an 18-ft outboard powered boat, which traverses between marking buoys; the buoys are deployed on a predetermined but adjustable grid so as to be located in the immediate vicinity of the plume before any set of temperature runs. Surface-temperature measurements are made with a thermistor mounted on a float and pulled through the water by the boat. All five thermistors are read by a digital voltmeter with a mechanical-register readout. Sequencing from one thermistor to another is done manually, as is the recording of the data. Temperatures are measured along lines between buoys while the boat is operated at constant speed. Usually each thermistor is sampled four times in each minute of running time. Lake-depth readings are also taken four times a minute. Thus the accuracy to which the true position of the boat and hence the temperature is measured depends on the consistency of the speed of the boat between any two buoys, the regularity with which the switching was done from one thermistor to another, and the accuracy of determining the buoy positions. Because of the variable nature of the plume, the maximum time allotted to acquire a complete plume data set is limited to less than 2 hr. Automated equipment is presently being assembled which should substantially decrease the time required to measure the plume. Other relevant parameters such as sea state, wind velocity, wet- and dry-bulb temperatures, lake-current velocities, discharge-canal velocity, and plant operating conditions are obtained.

Initial observations of the plume data collected thus far show the extreme complexity and variability of the plume structure and of the near-shore waters: frequent upwellings and warm surface-water incursions, shoreline currents occasionally running counter to prevailing winds, patchy temperature distributions within a plume, and temperatures changing markedly with time. Figure 16 demonstrates the variability of measured plume temperatures within 7- to 8-min time intervals; the boat wake is probably contributing to some of this variability.

Figure 17 shows plume temperature data obtained at the Waukegan Power Plant on August 5, 1970. The power plant was operating at 730 MWe.

Fig. 16. Waukegan Power Plant Plume Temperature Traverses

Fig. 17. Temperature Profiles for the Waukegan Plant:
August 5, 1970.¹² ANL Neg. No. 149-4275.

The cooling-water intake and discharge temperatures were 22.2 and 26.7°C, respectively. The cooling-water flow rate was 37 m³/sec, and the discharge-canal velocity was 1.4 m/sec. The dry- and wet-bulb temperatures were 23.1 and 19.2°C, respectively. The wind was from the east at 3.6 m/sec. Upwelling conditions were present. The ambient lake-surface temperature was selected to be the lowest observed temperature adjacent to the plume, 22.3°C. The lake current was flowing in a northerly direction at 0.5 m/sec. Plume measurements lasted from 16:27 to 18:04 CST.

Figure 18 shows Waukegan plant plume data for August 12, 1970, for 12:00 to 13:26 CST. The ambient lake-surface temperature was between 23 and 23.5°C. There was a southerly flowing current present with a speed of 0.18 m/sec. The wind was from the east at 3.1 m/sec. The air dry- and wet-bulb temperatures were 25.7 and 23.4°C, respectively. The plant was operating at 970 MWe. The cooling-water intake and discharge temperatures were 25.0 and 31.1°C, respectively. The condenser flow rate was 49 m³/sec, and the discharge velocity within the outfall canal was 1.6 m/sec.

Plume temperature data were also acquired on September 23, 1970, between 14:05 and 15:27 CST. Shoreline upwelling was present during data acquisition. The ambient lake-surface temperature was assumed to be 13°C, and the lake current magnitude was 0.09 m/sec, flowing in a NNE direction. The wind was from the east at 10.3 m/sec. During this period, the plant was operating at 930 MWe. The cooling-water and discharge temperatures were 14.4 and 19.4°C, respectively. Condenser flow was 49 m³/sec. Figure 19 shows the September 23 data.

Fourteen additional plumes were measured at the Waukegan power plant over the period from July through September 1970. These data exist in crude form and therefore are not included here. Tables 9-16 show values of surface area, volume, and heat contents for various temperature ranges and depths for all 17 Waukegan plumes acquired.

An airborne infrared study of the behavior of power-plant effluents discharging into Lake Ontario has been reported on by Chermack.¹³ This work was initiated in July 1969 and appears to be continuing. Thus far, the surveys have concentrated on the Nine Mile Point, R. E. Ginna, and Oswego power plants. These locations were chosen because each of the three power plants release their heated effluent into the lake in a different manner, and therefore they offer a good opportunity to study and compare alternate discharge schemes.

The basic instrumentation consisted of an infrared radiometer mounted outboard on a light single-engine aircraft. The output of the radiometer was recorded on a strip-chart recorder. Since the study was concerned mainly with temperature gradients, no attempt was made to correct the data collected for atmospheric transmission influences. The flights were

Fig. 18. Temperature Profiles for the Waukegan Plant: August 12, 1970¹²

C. 3-ft Depth. ANL Neg. No. 149-4471.

Fig. 18 (Contd.)

D. 6-ft Depth. ANL Neg. No. 149-4473.

E. 9-ft Depth. ANL Neg. No. 149-4472.

F. Vertical. ANL Neg. No. 149-4276 Rev. 1.

Fig. 18 (Contd.)

A. Surface. ANL Neg. No. 149-4468.

B. Vertical. ANL Neg. No. 149-4467.

Fig. 19. Temperature Profiles for the Waukegan Plant: September 23, 1970¹²

TABLE 9. Plume Identification and Plant Operation Data¹²

Plume No.	Date, 1970	Plume Measurement Time		Plant Load, MWe	Intake Temp, °C	Discharge Temp, °C	Discharge Volume, m ³ /sec
		Start	End				
1	July 14	12:30	13:37	960	18.6	23.9	53
2	July 14	14:50	17:10	960	18.6	23.9	53
3	July 16	12:20	13:30	920	14.4	19.4	50
4	July 16	13:40	15:00	920	14.4	19.4	50
5	July 16	17:37	20:02	920	14.4	19.4	50
6	Aug 5	10:25	11:12	460	22.2	26.7	37
7 ^a	Aug 5	16:27	18:04	730	22.2	26.7	37
8 ^a	Aug 12	12:00	13:57	970	25.0	31.1	49
9	Aug 12	16:22	17:53	870	25.0	31.1	49
10	Aug 13	10:17	11:10	920	23.3	30.6	46
11	Aug 13	12:12	13:26	920	23.3	30.6	46
12	Aug 20	12:18	12:45	960	17.8	22.8	49
13	Aug 20	12:55	13:15	970	17.8	22.8	49
14	Aug 24	10:30	11:15	430	21.1	23.3	21
15	Aug 24	11:14	12:15	430	21.1	23.3	21
16	Sept 23	13:10	13:40	950	14.4	19.4	49
17 ^a	Sept 23	14:05	15:27	930	14.4	19.4	49

^aTabular data representing figures in this report.

TABLE 10. Lake Conditions¹²

Plume No.	Assumed Ambient, °C	Vertical Stratification, °C/m	Upwelling Index (1 = warm water offshore), °C/km	Velocity, m/sec	Direction (to)
1	17	0.49	2	-	-
2	17	0.18	0	0.4	20°
3	10	0	3	-	-
4	11	0.03	3	-	-
5	12	0.03	4	-	-
6	21	0.18	0	0.4	0°
7 ^a	22	0	0	0.5	0°
8 ^a	23	0.18	-1	0.2	180°
9	23	0	-1	-	-
10	22	0	1	0.1	200°
11	23	0.03	0	-	-
12	16	0.15	3	0.6	0°
13	17	0.06	3	-	-
14	18	0.18	2	0.1	20°
15	18	0.21	2	0.3	20°
16	13	0	3	0.1	60°
17 ^a	13	0	3	0.1	60°

^aTabular data representing figures in this report.

TABLE 11. Meteorological Conditions¹²

Plume No.	Wind		Air Temp	
	Velocity, m/sec	Direction (from)	Dry Bulb, °C	Wet Bulb, °C
1	-	300°	26.9	22.5
2	-	240°	29.4	23.9
3	-	270°	-	-
4	-	270°	-	-
5	-	170°	-	-
6	4.0	130°	22.9	17.2
7 ^a	3.6	90°	23.1	19.2
8 ^a	3.1	90°	-	-
9	3.6	110°	25.7	23.4
10	3.1	300°	-	-
11	4.5	90°	28.3	21.1
12	2.7	120°	-	-
13	3.1	60°	-	-
14	-	-	-	-
15	-	-	-	-
16	9.4	75°	-	-
17 ^a	10.3	85°	-	-

^aTabular data representing figures in this report.

TABLE 12. Surface Area of Plume as a Function of Temperature above Ambient¹²

Plume No.	Total Enclosed Area, 10 ⁴ m ²	Percentage of Area in Given Temp Range				
		1-2°C	2-3°C	3-4°C	4-5°C	>5°C
1 ^a	51	40	53	6	1	<0.1
2	34	-	60	26	9	5
3 ^a	29	-	-	-	77	23
4 ^a	55	-	-	66	28	5
5	230	29	41	27	3	0.6
6	40	79	21	<0.1	-	-
7 ^b	130	56	24	17	2	0.6
8 ^b	250	28	60	11	1	0.3
9	260	12	60	25	2	1
10 ^a	67	-	66	30	4	<0.1
11	270	69	25	6	0.4	0.2
12 ^a	42	52	35	13	<0.1	-
13 ^a	32	61	36	3	<0.1	-
14 ^a	17	87	9	4	<0.1	-
15 ^a	33	90	9	1	<0.1	-
16 ^{a,c}	32	47	20	24	9	<0.1
17 ^{a-c}	22	-	61	28	10	<0.1
Median values	41	54	35	15	2	<0.1

^aUpwelling.

^bTabular data representing figures in this report.

^cConsiderable wave action.

TABLE 13. Volume of Plume Water as a Function of Temperature above Ambient¹²

Plume No.	Total Volume of Enclosed Plume, 10 ⁴ m ³	Percentage of Volume at Given Temp Range above Ambient				
		1-2°C	2-3°C	3-4°C	4-5°C	5°C
1 ^a	71	51	40	9	0.1	0.1
2	27	-	69	22	4	4
3 ^a	24	-	-	-	72	28
4	50	-	-	64	30	6
5 ^a	440	64	25	10	1	0.4
6	33	95	5	<0.1	-	-
7 ^{a,b}	160	56	32	10	1	0.2
8 ^b	320	58	36	5	0.6	0.1
9	400	52	39	7	1	0.5
10 ^a	77	-	75	22	3	0.4
11	210	77	18	4	0.5	0.1
12 ^a	31	62	26	12	0.1	-
13 ^a	12	70	26	4	0.1	-
14 ^a	15	96	3	1	0.1	-
15 ^a	23	85	14	1	0.1	-
16 ^{a,c}	68	60	22	13	4	0.1
17 ^{a-c}	38	-	71	21	8	0.1
Median values	50	63	26	10	1	0.1

^aUpwelling.^bTabular data representing figures in this report.^cLarge swells.TABLE 14. Volume of Plume Water as a Function of Depth below Surface¹²

Plume No.	Total Heat Content of Enclosed Plume, 10 ⁹ kg-cal	Depth below Surface, ft (meters)			
		0-1 (0-0.3)	1-3 (0.3-0.9)	3-6 (0.9-1.8)	6-9 (1.8-2.7)
1 ^a	71	20	33	31	16
2	27	33	41	23	3
3 ^a	24	28	33	28	11
4 ^a	50	29	35	24	12
5 ^a	440	18	35	30	17
6 ^a	33	35	40	19	6
7 ^{a,b}	160	24	41	31	4
8 ^b	320	22	37	31	10
9	400	20	40	34	6
10 ^a	77	24	36	31	9
11	210	31	37	25	7
12 ^a	31	49	26	18	7
13 ^a	12	50	32	18	0
14 ^a	15	30	38	25	7
15 ^a	23	31	32	27	10
16 ^{a,c}	68	14	26	38	20
17 ^{a-c}	38	17	31	35	17
Median values	50	28	35	27	9

^aUpwelling.^bTabular data representing figures in this report.^cConsiderable wave action.

TABLE 15. Heat Content of Plume as a Function of Temperature above Ambient¹²

Plume No.	Total Heat Content of Enclosed Plume, 10 ⁹ kg-cal	Percentage of Heat Content in Given Temp Range				
		1-2°C	2-3°C	3-4°C	4-5°C	>5°C
1 ^a	1.5	36	48	15	0.3	<0.1
2	0.8	-	59	27	7	7
3 ^a	1.2	-	-	-	65	35
4 ^a	2.0	-	-	58	33	9
5 ^a	8.8	48	31	17	3	1
6	0.5	92	8	<0.1	-	-
7 ^b	3.3	40	38	18	4	<0.1
8 ^b	6.2	44	45	10	1	<0.1
9	8.2	37	46	12	3	2
10	2.2	-	68	27	4	1
11 ^a	3.8	64	26	9	1	<0.1
12 ^a	0.6	46	32	22	<0.1	-
13 ^a	0.2	57	35	8	<0.1	-
14 ^a	0.2	93	6	1	<0.1	-
15 ^a	0.4	77	20	3	<0.1	-
16 ^{a,c}	1.4	43	25	21	11	<0.1
17 ^{a-c}	1.1	-	62	25	13	<0.1
Median values	1.4	47	35	16	3	<0.1

^aUpwelling.^bTabular data representing figures in this report.^cConsiderable wave action.TABLE 16. Heat Content of Plume as a Function of Depth below Surface¹²

Plume No.	Total Heat Content of Enclosed Plume, 10 ⁹ kg-cal	Depth below Surface, ft (meters)			
		0-1 (0-0.3)	1-3 (0.3-0.9)	3-6 (0.9-1.8)	6-9 (1.8-2.7)
1 ^a	1.5	21	32	30	17
2	0.8	34	40	22	4
3 ^a	1.2	27	32	28	13
4 ^a	2.0	30	35	25	10
5 ^a	8.8	22	37	27	14
6	0.5	36	39	18	7
7 ^b	3.3	24	42	31	3
8 ^b	6.2	26	38	28	8
9	8.2	25	41	29	5
10	2.2	25	37	30	8
11 ^a	3.8	32	37	25	6
12 ^a	0.6	45	27	21	7
13 ^a	0.2	53	31	16	0
14 ^a	0.2	31	38	25	6
15 ^a	0.4	31	32	27	10
16 ^{a,c}	1.4	16	27	37	20
17 ^{a-c}	1.1	18	32	34	16
Median values	1.4	27	37	27	8

^aUpwelling.^bTabular data representing figures in this report.^cConsiderable wave action.

flown typically between 300 and 400 ft above the lake. Predetermined flight patterns were chosen at the particular site locations. Parallel flight legs were flown normal to the coastline and spaced at selected intervals between 300 and 1000 m, depending on the proximity to the outfall region and temperature gradients present. The length of each leg varied between 3 and 6 km. Position was determined by visual ground checks at the start of each leg and by indicated course, air speed, and timing.

The total data collected thus far have only been partially reported. Figure 20 represents data available up to March 1970. Figures 20A-E show selected data of the Oswego harbor region. The Oswego power plant effluent actually mixes with the Oswego River within the harbor before discharging into the lake through the breakwater complex. Figure 20A shows the Oswego isotherms taken while a light southerly wind was present. Upwelling was evident near the shore north of the breakwater. Ambient lake-water temperature approximately 2-3 km offshore was approximately 18.5°C. Figure 20B shows a modest westward shift of the effluent along the breakwater. During the period from August 25 through 27, the wind shifted from southerly, to strong northerly on August 26, to light and variable on August 27. Ambient lake-water temperature 2-3 km offshore was 23.5°C. Figure 20C again shows a modest drift of the plume toward the west. Winds were variable and light. The offshore ambient water averaged about 22.5°C. Figure 20D shows the effect of a strong westerly wind which tended to trap the effluent between the cooler river flow and the lake current induced by the wind. Mixing of the heated effluent appeared to be quite rapid within the breakwater complex under these conditions, because no evidence of the plume is seen outside the larger east breakwater. Figure 20E again demonstrates the effect of a strong westerly current which promotes good mixing of the river and power-plant effluent within the breakwaters. According to Chermack, mixing during the summertime is not as pronounced within the breakwaters. Figures 20F and 20G show the isotherms resulting from the Nine Mile Point discharge. The power plant was under shakedown operation when these measurements were taken. Figure 20F indicates only a modestly warmed shoreline area. Figure 20G shows evidence of shoreline puddling under light wind conditions and light easterly currents. The power plant was operating between 525 and 600 MW in both situations. The Ginna thermal surveys are shown in Figs. 20H and 20I. As in the case of the Nine Mile Point plant, the Ginna facility was under shakedown operation when these two surveys were conducted. Figure 20H shows the plume, not too different in temperature than the ambient surroundings, to extend eastward about 4 km. Figure 20I shows the plume to be puddled in the immediate vicinity of the outfall. The relatively small size of the plume may arise from the fact that the plume possesses negative buoyancy as it reaches the 4°C isotherm and would therefore sink out of the view of the infrared radiometer which measures the temperature of the first tens of microns of the surface water.

A. Oswego Harbor: July 24, 1969, 1704 EDT

B. Oswego Harbor: August 26, 1969, 1715 EDT

C. Oswego Harbor: September 4, 1969, 1500 EDT

D. Oswego Harbor: October 18, 1969, 0930 EDT

E. Oswego Harbor, November 21, 1969, 1530 EST

F. Nine Mile Point Power Plant:
December 12, 1969, 1530 EST

Fig. 20. Airborne Infrared Temperature Surveys¹³

G. Nine Mile Point Power Plant:
December 17, 1969, 1530 EST

H. R. E. Ginna Power Plant: Decem-
ber 13, 1969, 1530 EST

I. R. E. Ginna Power Plant: January 31, 1970, 1300 EST

Fig. 20
(Contd.)

A relatively comprehensive plume temperature survey is presently under way at the R. E. Ginna plant near Ontario, New York. Measurements are being made at least once a month with a minimum of 15 days between consecutive measurement periods. The temperature measurements are being made with four thermistors, which are to be checked periodically against a thermometer certified by the National Bureau of Standards. The thermistors are suspended on a taut wire over the side of a boat and spaced so that the top thermistor is within 1 ft of the surface and the others at intervals no more than 3 ft apart, bottom topography permitting. Temperature recordings are being made on a continuous basis as the boat maneuvers over triaxial transects spaced on 1000-ft intervals. The transects are run sufficiently beyond plume dimensions to always reach ambient water-temperature conditions. Climatological data such as air temperature, sky condition, lake surface condition, and five-day averages for wind velocity are being recorded. In addition, hourly logs of the cooling-water intake and discharge temperature and flow are being obtained. Sufficient data are being gathered to plot the results on a 1°F isotherm interval basis for all four depths measured. It is alleged that data are being gathered on relatively calm days when shoreline puddling of the plume is most probable. The data are publically unavailable until they have been submitted and reviewed by the New York State Department of Health.

Five plume temperature surveys were made by John Storr of the University of Buffalo at the Nine Mile Point Nuclear Power Station on Lake Ontario during the first year of plant operation.¹¹ This work is continuing, since present plans call for a second unit to be in operation by 1977 at this Niagara Mohawk Power Corporation facility. The present unit uses an offshore discharge and intake. The top of the discharge is approximately 10 ft below the low-water datum level and was roughly 13 ft below the actual lake-surface level during the periods of plume measurement, July 22 through October 21, 1970. Temperature measurements were made by the taut-wire method described above. For the most part, the data-acquisition methods were similar to those employed at the Ginna station. The only significant difference between the Ginna and Nine Mile Point temperature surveys is that the former uses triaxial transects while the latter uses shore perpendicular transects. In addition, a series of radial transects was made at the Nine Mile Point station using the plant's discharge as the central axis. The results of the Nine Mile Point investigations are shown in Figs. 21-25. On July 22, 1970, the plant was operating at approximately 450 MWe. The average cooling-water inlet and discharge temperatures over some unstated period of measurement were 64°F (17.8°C) and 92°F (33.3°C), respectively; the flow rate was stated to be 2.5×10^5 gpm. Light westerly winds were present during the survey. Before the survey, westerly winds were present, but they were neither strong enough or of sufficient duration to create a strong current along the plant's shoreline. According to the investigators, a "slow" west-to-east current was present. The ambient lake-surface temperature was assumed to be about 66.2°F (19°C), but declined further from shore. The investigators also noticed the presence of clockwise surface gyre in the vicinity of the discharge. Extensive current measurements made before the operation of the plant found no such circulation patterns present, therefore, it was speculated that plant operation may have led to the gyre's formation. Figure 21 shows the July 22 data.

On August 14, 1970, weather conditions were variable. Northwest winds were light, 5-8 mph, falling off during the afternoon. A shore-parallel easterly current was present. The air temperature was 80°F. The plant was operating at 500 MWe. The average condenser cooling water intake and discharge temperatures were 73°F (22.8°C) and 103°F (39.4°C), respectively, with a flow rate of 2.6×10^5 gpm. Temperatures were measured at the 0.25-, 3.7-, 7.1-, and 10.5-ft-depth levels. The ambient lake-surface temperature was taken as 78.8°F (26°C). A fairly "weak" northeasterly current was present. Between transect locations W1 and E1 there was a small right-handed gyre carrying the warmer discharge initially countercurrent to the west and then north. East of the gyre, the temperature pattern was broken due to the presence of upwelling. Evidence of upwelling occurred in offshore areas as well as along the shore. Figure 22 shows the isotherms plotted for the August 14 data.

Figure 23 shows isotherm data plotted for September 23, 1970. Two thermistors were used for temperature sampling at the $3\frac{1}{2}$ - and $7\frac{1}{2}$ -ft depths.

A. Surface Temperatures

Fig. 21. Nine Mile Point Temperatures ($^{\circ}\text{C}$): July 22, 1971¹¹

Fig. 21A (Contd.)

B. Surface Temperatures: Detail-discharge Area

Fig. 21 (Contd.)

C. 3.7-ft-depth Temperatures

Fig. 21 (Contd.)

Fig. 21C (Contd.)

D. 3.7-ft-depth Temperatures: Detail-discharge Area

Fig. 21 (Contd.)

E. 7.1-ft-depth Temperatures: Detail-discharge Area

Fig. 21 (Contd.)

F. Vertical Temperature Profiles

Fig. 21 (Contd.)

A: Surface Temperatures

Fig. 22. Nine Mile Point Temperatures ($^{\circ}\text{C}$): August 14, 1970¹¹

Fig. 22A (Contd.)

B. Surface Temperatures: Detail-discharge Area

Fig. 22 (Contd.)

C. 3.7-ft-depth Temperatures

Fig. 22 (Contd.)

Fig. 22C (Contd.)

D. 3.7-ft-depth Temperatures: Detail-discharge Area

Fig. 22 (Contd.)

E. Vertical Profiles

Fig. 22 (Contd.)

A. Surface Temperatures

Fig. 23. Nine Mile Point Temperatures ($^{\circ}\text{C}$): September 23, 1970¹¹

Fig. 23A (Contd.)

B. Surface Temperatures: Detail-discharge Area

Fig. 23 (Contd.)

A. Surface Temperatures

Fig. 24. Nine Mile Point Temperatures ($^{\circ}\text{C}$): August 16, 1970¹¹

Fig. 24A (Contd.)

B. Surface Temperatures: Detail-discharge Area

Fig. 24 (Contd.)

C. 3.7-ft-depth Temperatures

Fig. 24 (Contd.)

Fig. 24C (Contd.)

D. 3.7-ft-depth Temperatures: Detail-discharge Area

Fig. 24 (Contd.)

E. Vertical Temperature Profiles

Fig. 24 (Contd.)

A. Surface Temperatures

Fig. 25. Nine Mile Point Temperatures ($^{\circ}\text{C}$); Detail-discharge Area: October 21, 1970¹¹

B. 2.8-ft-depth Temperatures

Fig. 25 (Contd.)

C. 5.3-ft-depth Temperatures

Fig. 25 (Contd.)

D. 7.9-ft-depth Temperatures

Fig. 25 (Contd.)

The day was partially overcast and calm; winds were from the west at 2-6 mph. The air temperature was about 75°F; the ambient lake-surface temperature was 68°F (20°C). There was a residual current toward the ENE, as well as the small right-handed gyre. The plant was operating at 500 MWe. The average condenser cooling-water inlet and exit temperatures were 64°F (17.8°C) and 93°F (33.9°C), respectively. The corresponding average cooling-water flow was 2.6×10^5 gpm.

Figure 24 shows isotherm data for August 16, 1970. At this time the plant was at 500 MWe. The average inlet and outlet cooling-water temperatures were 79°F (26.1°C) and 107°F (41.8°C), respectively. The average condenser flow was 2.6×10^5 gpm. The investigators noted that during the early part of August this area experienced an extended period of high humidity, very light winds, and temperature inversion, which led to exceptionally high ambient lake-surface temperatures. On August 16, the ambient surface temperature was 78.8°F (26°C), whereas the usual maximum ambient temperature for this date should have been 72-75°F. Before data acquisition on August 16, there was a period of light NW and westerly winds, which appeared to have set up a fairly strong SW-NE residual current along the shoreline.

Plume measurements were made on October 21, 1970. These are shown in Fig. 25. The wind before the day of study had been from the SE quadrant and established a slow, shore-parallel, westerly current. On October 21, the winds were from the SE at 5 to 12 mph. The ambient lake-surface temperature was 56.3°F (13.5°C). The plant was operating at 500 MWe. The average cooling-water inlet and discharge temperatures were 58°F (14.4°C) and 81°F (27.2°C), respectively. Condenser flow was 2.6×10^5 gpm.

Csanady, Crawford, and Pade¹⁴ have made plume-temperature studies in an attempt to ascertain the amount of heat lost directly to the atmosphere from thermal plumes. They chose to determine this quantity indirectly by measuring the amount of heat retained inside the "identifiable plume" within the lake. The identifiable plume was defined to be the boundary of the plume given by either the 1 or 0.5°C excess isotherm. To this end, the authors conducted field investigations on several plumes associated with the operation of the Douglas Point nuclear station on Lake Huron. The presence of shore-parallel currents and plume motion allowed the investigators to establish longitudinal range positions 400, 800, 1200, and 1600 m from the outfall from which lateral plume temperature and current measurements with depth were made. By vertically mapping the plume temperature and current profiles at the four locations, the authors estimated the amount of energy retained within the plume as a function of longitudinal position from the point of discharge. Thus, with the initial rate of energy discharged by the station known, the rate of energy released directly to the atmosphere is the resultant of the initial discharge rate minus the energy flowing through a vertical section of a plume at any particular range position.

For most of the experimental work, the investigators used a twin-hulled aluminum outboard-powered boat equipped with an anemometer, speedometer, and odometer. The experimental technique involved using two thermistor temperature probes affixed to a boom and separated by a 1-ft interval. The boom was attached to the front of the boat by means of a hinge. The boom was lowered into place at prescribed depth intervals so that while the boat traveled laterally across the plume for any particular range position, the temperatures at two different depths were simultaneously recorded on strip-chart recorders. The boat was then turned around, and another run was taken with the boom readjusted to sample two other depth intervals. This would continue until the bottom of the plume was found. The boat traveled at about 5 knots for each crossing. The distance scale was determined by maintaining, as closely as possible, a uniform boat speed between predetermined flag positions established for the ranges. The point at which the flags were passed were appropriately marked on the strip-chart recorder, thus establishing the needed length scale. Each run required 6-10 min. Since the propellers and boat wake mixed the water during each pass, the investigators made each return pass about 30 yards upstream of the previous one. The actual plume depth during the investigations was found to be roughly 1.5 m (5 ft) while averaging 1 m, and therefore each range position presumably required three to four passes. In addition, for each range the boat was appropriately anchored near the warmest part of the plume, and a depth-temperature profile, water current, wind velocity, and relative humidity were recorded. The water current measured at this point was applied to the entire plume for that particular range. The authors indicated that additional current data would have been desirable; however, this would have required much more time. Considering that the plume configuration was slowly changing its shape, any prolongation in measurement time at a given range could have introduced errors.

After the last range was measured, the boat returned to the outfall and in the process obtained an axial centerline temperature plot of the plume versus distance.

The authors noted that each temperature run was continued until the plume was too cold to plot accurately. The criterion was a temperature rise of about 0.5-1°C above the ambient receiving-water temperature, as was indicated earlier. The investigators found that the ambient lake temperature on the offshore side of the plume was easy to determine as it was fairly steady. Defining ambient conditions on the shoreward side of the plume was not easy, because the water near the shore was usually warmed by the sun, making it difficult to determine where the plume ended and the shore heating began.

Within Ref. 14 there are numerous charts, tables, and figures, which may be useful for further interpretation. For the purposes of this present report, Fig. 26 has been selected to summarize the work of these investigators. Table 17 summarizes the atmospheric conditions for the four observation sets. During the times when the data were being accumulated on

--- SURFACE WATER CURRENT
 R11-8.8 CM/SEC
 R22-9.3 CM/SEC
 R33-8.3 CM/SEC
 WIND SPEED 4 METRES/SEC

A. August 24 Isotherms at 1.5-ft Depth

--- SURFACE WATER CURRENT
 R11-21.2 CM/SEC
 ... WIND SPEED 6 METRES/SEC

B. August 25 Isotherms of Plume at 1.5-ft Depth

--- SURFACE WATER CURRENT
 R11-10.3 CM/SEC
 R22-10.3 CM/SEC
 R33-7.2 CM/SEC
 WIND SPEED 4 METRES/SEC

C. August 26 Isotherms at 1.5-ft Depth

WIND DIRECTION
 STRONG NW UNTIL 0600 EDT
 NE FROM 0600-1000 EDT
 N FROM 1000-2000 EDT
 DATA RECORDED FROM 1200 EDT TO 1500 EDT

--- SURFACE WATER CURRENT
 R11-12.9 CM/SEC
 R22-16.5 CM/SEC
 WIND SPEED 2 METRES/SEC

D. August 29 Isotherms at 6-in. Depth

Fig. 26. Douglas Point Isotherms¹⁴

TABLE 17. Atmospheric Conditions for the Douglas Point Studies

Date	Air Temp, °C	Relative Humidity, %	Wind Velocity, m/sec
Aug 24	20.5 (sunny)	75	4 W
Aug 25	21.0 (sunny)	78	6 SW
Aug 26	22.8 (sunny)	80	4 SW
Aug 27	19.8 (overcast)	60	2 NW

the plume, the facility was operating at full capacity, which corresponds to a 435-MWt discharge rate and a 178,000-gpm flow with a corresponding condenser cooling-water temperature rise of about 8°C.

To my knowledge, this establishes the extent of thermal-plume measurements on the Great Lakes resulting from heated discharges. This statement may be somewhat unfair in several ways. First, it is known the EPA (the Federal Environmental Protection Agency), various State water pollution control agencies, the National and Ontario authorities in Canada, and other organizations have directly or contractually conducted surveys on many of the steam-electric facilities throughout the Great Lakes. For instance, since 1968 the New York State Atomic and Space Development Authority has been scanning, by aerial infrared techniques, all major water bodies within New York in an attempt to provide baseline data as to the extent and location of existing natural and artificial heat sources. Another example is the infrared imagery work being performed by the U.S. Geological Survey (USGS) in Albany, New York, and the Rome Air Development Center (RADC), Griffiss AFB, New York. Most of the work performed by the USGS and RADC has been of a qualitative nature, but some is quantitative. They have infrared scans for portions of Lake Ontario at Oswego Harbor, for Nine Mile Point and Rochester shore areas, and at Cayuga Lake during various portions of the year. Although this work was not performed in connection with power-plant studies, it is interesting to note that power plants are located in the above-mentioned areas and that some of the imagery data they have accumulated do indeed show the effluents from these plants.

Usually most of the work described above is not reported for outside distribution for many reasons; the data are too sketchy, are not reduced, are qualitative, were acquired for other reasons, or were acquired for in-house use only. Even if one wished to acquire these data, they would be in the form of "back-of-the-envelope" data sheets or in a form that would, in all probability, be unintelligible except to the originating agencies or individuals.

It is quite certain that various utilities have also acquired plume temperature data, if only to ascertain the possible extent of recirculation. Again, these data are mostly of the "back-of-the-envelope" variety and are not generally available. As was mentioned earlier, many utilities are currently adopting, and some implementing, extensive work in this topical area; however, this information will not be available for some time to come.

B. Other Lake Studies

There have been several field efforts reported other than on the Great Lakes which are germane to this present review. Ten sets of plume temperature data have been obtained for the Allen S. King plant on Lake St. Croix in Minnesota.¹⁵ The King plant actually uses a variable-cycle cooling tower to limit the thermal discharges to the lake during certain periods of the year. Lake St. Croix actually represents a relatively large water expanse on the St. Croix River. This portion of the river is called a lake because the average discharge is such that the mean velocities are of the order of 0.015 fps and the water surface is nearly level.

Temperature measurements were made with a single thermistor lowered from an anchored boat to various prescribed depths: 3 in. and 5, 10, and 15 ft, with occasional measurements at other levels. The measurement stations were on a 200-ft grid near the discharge. Boat positioning was both by bearing and by boat-to-shore stadia measurements. A station location was judged acceptable if it was within a 25-ft tolerance radius. Two boats were used, each having a normal crew of four people; two shore personnel were also used to communicate necessary positioning information over FM radio. Generally, 131 measuring stations were included in a normal survey. Each survey was said to last typically from 9:00 a.m. to 5:00 p.m. or approximately 8 hr. The survey days were chosen to approach maximal conditions of plant loading, ambient lake temperatures, dry- and wet-bulb temperatures, and minimum river flow and including moderate wind velocities. Measurements were taken in the inlet and outfall canals at the beginning and end of each survey to account for natural variations such as solar heating. Thus, temperature measurements obtained by the boat crews were later "adjusted" either upward or downward, depending on the time they were taken in relation to the survey temporal midpoint. Meteorological recordings and averages were made of the wet- and dry-bulb temperatures, wind velocities (taken at two positions), sky cover, solar radiation as recorded from a pyrliometer, and computed heat-rejection rates to the lake after accounting for the heat extracted by the towers and the discharge canal. No cooling-water discharge rates were stated for the periods of measurement. The data are shown in graphical form in Figs. 27-36. Table 18 lists the pertinent meteorological conditions for the field test periods.

A. 3-in. Depth

B. 5-ft Depth

C. 10-ft Depth

AVER. DRY BULB TEMP.	85.0 °F
AVER. WET BULB TEMP.	73.6 °F
AVER. WIND VELOCITY	9.0 MPH
AVER. WIND DIRECTION	SSW
AVER. HEAT REJECTION TO CONDENSER	2.27×10^9 BTU/HR
AVER. HEAT REJECTION TO RIVER	1.36×10^9 BTU/HR
AVER. RIVER FLOW	2554 CFS
AVER. CIRCULATING WATER FLOW	660 CFS
AVER. SHORT WAVE SOLAR RADIATION	168 BTU/FT ² /HR
AVER. PERCENT SKY COVER	86 %
AVER. BAROMETRIC PRESSURE	29.28 IN. HG

D. River and Meteorological Data for Temperature Contours at Various Depths in St. Croix River

Fig. 27. Allen S. King Generating Plant Circulating-water Temperature Contours: July 30, 1969¹⁵

A. 3-in. Depth

B. 5-ft Depth

C. 10-ft Depth

AVER. DRY BULB TEMP.	78.7 °F
AVER. WET BULB TEMP.	64.7 °F
AVER. WIND VELOCITY	6.0 MPH
AVER. WIND DIRECTION	ESE
AVER. HEAT REJECTION TO CONDENSER	2.15×10^9 BTU/HR
AVER. HEAT REJECTION TO RIVER	1.72×10^9 BTU/HR
AVER. RIVER FLOW	1924 CFS
AVER. CIRCULATING WATER FLOW	660 CFS
AVER. SHORT WAVE SOLAR RADIATION	197 BTU/FT ² /HR
AVER. PERCENT SKY COVER	22%
AVER. BAROMETRIC PRESSURE	29.23 IN. HG

D. River and Meteorological Data for Temperature Contours at Various Depths in St. Croix River

Fig. 28. Allen S. King Generating Plant Circulating-water Temperature Contours: August 20, 1969¹⁵

A. 3-in. Depth

B. 5-ft Depth

C. 10-ft Depth

AVER. DRY BULB TEMP.	79.0 °F
AVER. WET BULB TEMP.	75.5 °F
AVER. WIND VELOCITY	10.0 MPH
AVER. WIND DIRECTION	SSE
AVER. HEAT REJECTION TO CONDENSER	2.37×10^6 BTU/HR
AVER. HEAT REJECTION TO RIVER	2.08×10^6 BTU/HR
AVER. RIVER FLOW	2070 CFS
AVER. CIRCULATING WATER FLOW	660 CFS
AVER. SHORT WAVE SOLAR RADIATION	87 BTU/FT ² /HR
AVER. PERCENT SKY COVER	98 %
AVER. BAROMETRIC PRESSURE	29.33 IN. HG

D. River and Meteorological Data for Temperature Contours at Various Depths in St. Croix River

Fig. 29. Allen S. King Generating Plant Circulating-water Temperature Contours: September 4, 1969¹⁵

A. 3-in. Depth

B. 2-ft Depth

C. 5-ft Depth

D. 10-ft Depth

AVER. DRY BULB TEMP.	78.2°F
AVER. WET BULB TEMP.	65.0°F
AVER. WIND VELOCITY	9.0 MPH
AVER. WIND DIRECTION	ESE
AVER. HEAT REJECTION TO CONDENSER	2.15×10^9 BTU/HR
AVER. HEAT REJECTION TO RIVER	1.986×10^9 BTU/HR
AVER. RIVER FLOW	8207 CFS
AVER. CIRCULATING WATER FLOW	447 CFS
AVER. SHORT WAVE SOLAR RADIATION	221.2 BTU/FT ² /HR
AVER. PERCENT SKY COVER	23%
AVER. BAROMETRIC PRESSURE	29.41 IN. HG

Fig. 30

Allen S. King Generating Plant
Circulating-water Temperature
Contours: June 5, 1970¹⁵

E. River and Meteorological Data for Temperature
Contours at Various Depths in St. Croix River

A. 3-in. Depth

B. 2-ft Depth

C. 5-ft Depth

D. 10-ft Depth

AVER. DRY BULB TEMP.	81.2 °F
AVER. WET BULB TEMP.	66.0 °F
AVER. WIND VELOCITY	14.0 MPH
AVER. WIND DIRECTION	SE
AVER. HEAT REJECTION TO CONDENSER	2.40×10^8 BTU/HR
AVER. HEAT REJECTION TO RIVER	2.27×10^8 BTU/HR
AVER. RIVER FLOW	3784 CFS
AVER. CIRCULATING WATER FLOW	618.6 CFS
AVER. SHORT WAVE SOLAR RADIATION	150.4 BTU/FT ² /HR
AVER. PERCENT SKY COVER	100 %
AVER. BAROMETRIC PRESSURE	29.29 IN. HG

Fig. 31

Allen S. King Generating Plant
Circulating-water Temperature
Contours: June 12, 1970¹⁵

E. River and Meteorological Data for Temperature
Contours at Various Depths in St. Croix River

A. 3-in. Depth

B. 2-ft Depth

C. 5-ft Depth

D. 10-ft Depth

AVER. DRY BULB TEMP.	90.4 °F
AVER. WET BULB TEMP.	76.6 °F
AVER. WIND VELOCITY	CALM
AVER. WIND DIRECTION	CALM
AVER. HEAT REJECTION TO CONDENSER	2.992×10^9 BTU/HR
AVER. HEAT REJECTION TO RIVER	2.321×10^9 BTU/HR
AVER. RIVER FLOW	2784 CFS
AVER. CIRCULATING WATER FLOW	627.1 CFS
AVER. SHORT WAVE SOLAR RADIATION	243.3 BTU/FT ² /HR
AVER. PERCENT SKY COVER	37%
AVER. BAROMETRIC PRESSURE	29.26 IN. HG

Fig. 32

Allen S. King Generating Plant
Circulating-water Temperature
Contours: June 29, 1970¹⁵

E. River and Meteorological Data for Temperature
Contours at Various Depths in St. Croix River

A. 3-in. Depth

B. 2-ft Depth

C. 5-ft Depth

D. 10-ft Depth

AVER. DRY BULB TEMP.	77.2 °F
AVER. WET BULB TEMP.	57.6 °F
AVER. WIND VELOCITY	3.1 MPH
AVER. WIND DIRECTION	NORTH
AVER. HEAT REJECTION TO CONDENSER	2.333×10^9 BTU/HR
AVER. HEAT REJECTION TO RIVER	2.103×10^9 BTU/HR
AVER. RIVER FLOW	1978 CFS
AVER. CIRCULATING WATER FLOW	614.8 CFS
AVER. SHORT WAVE SOLAR RADIATION	225.6 BTU/FT ² /HR
AVER. PERCENT SKY COVER	60%
AVER. BAROMETRIC PRESSURE	29.41 IN. HG

Fig. 33

Allen S. King Generating Plant
Circulating-water Temperature
Contours: July 9, 1970¹⁵

E. River and Meteorological Data for Temperature
Contours at Various Depths in St. Croix River

A. 3-in. Depth

B. 2-ft. Depth

C. 5-ft Depth

D. 10-ft Depth

AVER. DRY BULB TEMP.	87.5 °F
AVER. WET BULB TEMP.	64.7 °F
AVER. WIND VELOCITY	4.4 MPH
AVER. WIND DIRECTION	WNW
AVER. HEAT REJECTION TO CONDENSER	2.480×10^9 BTU/HR
AVER. HEAT REJECTION TO RIVER	1.736×10^9 BTU/HR
AVER. RIVER FLOW	3351 CFS
AVER. CIRCULATING WATER FLOW	591.1 CFS
AVER. SHORT WAVE SOLAR RADIATION	221.2 BTU/FT ² /HR
AVER. PERCENT SKY COVER	20 %
AVER. BAROMETRIC PRESSURE	29.32 IN. HG

Fig. 34

Allen S. King Generating Plant
Circulating-water Temperature
Contours: July 17, 1970¹⁵

E. River and Meteorological Data for Temperature
Contours at Various Depths in St. Croix River

A. 3-in. Depth

B. 2-ft Depth

C. 5-ft Depth

D. 10-ft Depth

AVER. DRY BULB TEMP.	88.8 °F
AVER. WET BULB TEMP.	68.2 °F
AVER. WIND VELOCITY	9.1 MPH
AVER. WIND DIRECTION	SSW
AVER. HEAT REJECTION TO CONDENSER	2400x10 ⁶ BTU/HR
AVER. HEAT REJECTION TO RIVER	1.853x10 ⁶ BTU/HR
AVER. RIVER FLOW	1826 CFS
AVER. CIRCULATING WATER FLOW	623.7 CFS
AVER. SHORT WAVE SOLAR RADIATION	205.7 BTU/FT ² /HR
AVER. PERCENT SKY COVER	24 %
AVER. BAROMETRIC PRESSURE	29.27 IN. HG

Fig. 35

Allen S. King Generating Plant
Circulating-water Temperature
Contours: August 13, 1970¹⁵

E. River and Meteorological Data for Temperature
Contours at Various Depths in St. Croix River

A. 3-in. Depth

B. 2-ft Depth

C. 5-ft Depth

D. 10-ft Depth

AVER. DRY BULB TEMP.	87.2 °F
AVER. WET BULB TEMP.	62.0 °F
AVER. WIND VELOCITY	4.2 MPH
AVER. WIND DIRECTION	WEST
AVER. HEAT REJECTION TO CONDENSER	2.324×10^9 BTU/HR
AVER. HEAT REJECTION TO RIVER	1.906×10^9 BTU/HR
AVER. RIVER FLOW	1707 CFS
AVER. CIRCULATING WATER FLOW	613.7 CFS
AVER. SHORT WAVE SOLAR RADIATION	154.8 BTU/FT ² /HR
AVER. PERCENT SKY COVER	10 %
AVER. BAROMETRIC PRESSURE	29.21 IN. HG

E. River and Meteorological Data for Temperature Contours at Various Depths in St. Croix River

Fig. 36

Allen S. King Generating Plant
Circulating-water Temperature
Contours: September 4, 1970¹⁵

TABLE 18 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Date	Time Survey Data Were Collected	River Depth	River Temp - F	Temp Rise Or Nat Riv Temp	Area Within Isotherm Acres	Wind Data Dir	Vel. mph	Dry Bulb Temp - F	Wet Bulb Temp - F	Barometric Pressure In. Hg.	Short Wave Solar Radiation Btu/sq ft/hr	Percent Sky Cover	Load MW	Heat to Condenser Mega Btu/hr	Heat to River Mega Btu/hr	Cooling Water Temp. Lvg. Disch. Canal - F	Max. Distance From Mouth of Discharge Canal - Ft.
6-05-70	9 a.m.	3"	84	14	0.775	ESE	9	78.2	63.0	29.41	221.2	23	498.3	2,180	1,986	84.0	270
	to		83	13	2.83												610
	2 p.m.		82	12	4.52												653
			81	11	6.30												690
			80	10	9.35												1,160
			79	9	14.42												2,230
			78	8	23.75												2,320
			77	7	33.8												2,630
			76	6	59.7												2,740
			75	5	95.0												2,670
			74	4	110.3												2,980
			72	2	144.0												3,070
		2'	80	10	0.17											84.0	330-570
			78	8	1.32												220-665
			76	6	3.70												690
			75	5	22.73												1,810
			74	4	45.8												2,810
			72	2	85.7												3,000

TABLE 18 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Date	Time Survey Data Were Collected	River Depth	River Temp- F	Temp Rise On Nat Riv Temp	Area Within Isotherm Acres	Wind Data		Dry Bulb Temp - F	Wet Bulb Temp - F	Barometric Pressure In. Hg.	Short Wave Solar Radiation Btu/sq ft/hr	Percent Sky Cover	Load MW	Heat to Condenser Mega Btu/hr	Heat to River Mega Btu/hr	Cooling Water Temp. Lvg. Disch. Canal- F	Max. Distance From Mouth of Discharge Canal - Ft.	
						Dir	Vel. mph											
6-29-70	9 a.m. to 3 p.m.	3"	92	13.2	0.33	Calm	Calm	90.4	76.6	29.26	243.3	37	559	2,392	2,321	91.5	213	
			90	11.2	1.22												340	
			88	9.2	5.21												920	
			86	7.2	9.83												1,160	
			84	5.2	28.60												2,100	
			82	3.2	139.7												3,580	
			80	1.2	324.8												4,770	
			2'	89	10.3	0.13											91.7	195
			88	9.3	0.43												230	
			86	7.3	1.16												350	
			84	5.3	2.84												515-850	
			82	3.3	32.0												3,500	
			80	1.3	144.3												4,720	
			5'	80	3.1	2.20											91.5	3,300
			78	1.1	33.2												3,500	
			10'	78	2.0	2.30											91.5	1,820
7-09-70	9:30 a.m. to	3"	92	11.1	0.32	North	3.1	77.2	57.6	29.41	225.6	60	538	2,333	2,103	91.7	210	
			90	9.1	2.44												500-780	

TABLE 18 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Date	Time Survey Data Were Collected	River Depth	River Temp - F	Temp Rise Over Nat Riv Temp	Area Within Isotherm Acres	Wind Data Dir	Vel. mph	Dry Bulb Temp - F	Wet Bulb Temp - F	Barometric Pressure In. Hg.	Short Wave Solar Radiation Btu/sq ft/hr	Percent Sky Cover	Load MW	Heat to Condenser Mega Btu/hr	Heat to River Mega Btu/hr	Cooling Water Temp. Lvg. Disch. Canal - F	Max. Distance From Mouth of Discharge Canal - Ft.
7-17-70		3'	84	2.9	267												5,500
			82	0.9				temperatures extend off map									
		2'	86	5.0	1.36											94.2	550-885
			84	3.0	181.1												5,280
			82	1.0				temperatures extend off map									
			85	4.8	1.10											93.5	3,600
			83	2.8	30.9												4,450
		5'	82	1.8	114.3												4,590
			81	0.8				temperatures extend off map									
			81	1.1	1.29											92.1	3,170
8-13-70	Noon to 4 p.m.	3"	90	8.7	0.09	SSW	9.1	88.8	68.2	29.27	205.7	24	550	2,400	1,853	92.3	320-400
			88	6.7	3.90												615
			86	4.7	12.27												1,590
			84	2.7	58.9												2,590
			83	1.7	101.8												2,875
			82	0.7				temperatures extend off map									
		2'	88	7.0	0.10											92.0	182
			86	5.0	6.52												315-1470

TABLE 18 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Date	Time Survey Data Were Collected	River Depth	River Temp - F	Temp Rise Or Nat Riv Temp	Area Within Isotherm Acres	Wind Data Dir	Vel. mph	Dry Bulb Temp - F	Wet Bulb Temp - F	Barometric Pressure In. Hg.	Short Wave Solar Radiation Btu/sq ft/hr	Percent Sky Cover	Load MW	Heat to Condenser Mega Btu/hr	Heat to River Mega Btu/hr	Cooling Water Temp. Lvg. Disch. Canal - F	Max. Distance From Mouth of Discharge Canal - Ft.
8-13-70		2'	84	3.0	56.1												2,870
			83	2.0	102.0												2,950
			82	1.0		temperatures extend off map upstream											
		5'	84	3.2	25.08											92.0	2,570
			83	2.2	61.6												2,635
			82	1.2		temperatures extend off map upstream											
		10'	83	2.7	3.68											91.8	2,200
9-04-70	12:45p.m. to 4:30p.m.	3"	86	10	0.36	West	4.2	87.2	62.0	29.21	154.8	10	541	2,323.5	1,906	88.4	410
			84	8	4.58												1,000
			82	6	61.9												4,840
			81	5	136.5												4,900
			80	4	219												5,000
		2'	temperatures below 80° extend off map both up and down stream.														
			82	6.7	21.05											88.4	4,850
			81	5.7	63.2												4,900
			80	4.7	123.8												5,000
			79	3.7	212.5												5,100
			temperatures below 79° extend off map both up and down stream.														

TABLE 18 (Contd.)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Date	Time Survey Data Were Collected	River Depth	River Temp - F	Temp Rise Or Net Riv Temp	Area Within Isotherm Acres	Wind Data Dir	Vel. mph	Dry Bulb Temp - F	Wet Bulb Temp - F	Barometric Pressure In. Hg.	Short Wave Solar Radiation Btu/sq ft/hr	Percent Sky Cover	Load MW	Heat to Condenser Mega Btu/hr	Heat to River Mega Btu/hr	Cooling Water Temp. Lvg. Disch. Canal - F	Max. Distance From Mouth of Discharge Canal - Ft.
9-04-70		5'	81	6.3	0.20											88.4	4,050
			80	5.3	18.9												4,840
			78	3.3	77.5												5,000
			77	2.3	136.1												5,100
		10'	temperatures below 77F extend off map														
			76	2.3	0.36											88.4	1700-1890
			75	1.3	2.32												1580-2000
			74	0.3	33.7												3,400

A rather comprehensive study of thermal outfalls has been conducted in Lake Monona at Madison, Wisconsin, by Hoopes, Zeller, and Rohlich.¹⁶ The overall objective of this work was first to determine by observation the existing temperature and velocity distributions in the immediate vicinity of the intakes and outfalls throughout one year. Secondly, mathematical models for predicting the observed temperature and circulation patterns were to be generated so as to be able to predict what the temperature distribution might be under changing loadings. The details of the mathematical modeling effort will not be considered here, other than to state that the model developed was for the immediate forced-jet regime. No effort was made to treat the entire plume.

Drogue and temperature surveys were made in the jet vicinity of the plant outfalls. Drogues are submerged floats set to drift with currents present at any desired depth. The drogues were placed in the water at depths of 0.3, 1.0, and 1.5 m and as close to the outfalls as possible. The drogues were used to follow the pathlines of the jet out to about 1/4 mile. Drogue position with time was monitored from the shore by stadia measurements. When two transit operators were available, the drogues were located more accurately by triangulation. The drogues were also used to measure the ambient shoreline currents somewhat removed from the outfalls. The temperature was measured at the surface and at various depth intervals within the plume. The temperature measurements were made simultaneously with the drogue studies when it was found that there were inconsistencies in jet location and shape when the drogue and temperature studies were done independently. This the authors of Ref. 15 attributed to the meandering characteristics of the jets. The temperature-measurement positions, as in the case of the drogues, were determined by stadia measurement. Wind speed and direction were determined independently by a hand-held anemometer in a boat at 1.5 m and the directional drift of the smoke plume from the power plant. Air temperature at the water surface and at 1.5 m was measured. A sling psychrometer was used for humidity determinations again at 1.5 m above the water.

A limited number of fluorescent dye studies (Rhodamine WT) using an instantaneous-injection (as opposed to the steady-state) technique were used to further substantiate or provide additional data for the jet-stream plume characteristics. Continuous sampling of the water at 0.3 m was provided by a fluorometer. However, the fluorometer results needed to be interpreted in terms of dye concentrations which are dependent on unknown local diffusivities and therefore the dye work was found to be unusable. An aerial infrared survey was made on one occasion involving six passes. The raw data were not included in the reference; however, several important observations were made concerning the data.

On several occasions, whenever sufficient data were available to make a judgment, the plume attained a fairly uniform depth of 1 m within

400 ft of the outfall. It was noted that the average lake depth within 200 ft of shore is 1 m or less. The authors called attention to the fact that Ellison and Turner and Csanady also noticed this stratification phenomenon, which under certain conditions of the bulk Richardson number being greater than a critical value, allows only minimal vertical mixing between the plume and the cooler bottom waters. Further comments to this effect are given on p. 153 of this report. The authors also found that the rate of change of the jet centerline in relation to its initial discharge centerline could not be accurately correlated with wind speed, i.e., with the induced shoreline currents. The rate of spread of the jet was approximately linear and constant for several surveys, although not always so. The authors also noted that their data could not be used for transverse velocity and temperature analysis because of the limited number of measurements made in this direction. Their measuring techniques placed almost complete emphasis on the axial direction of the plume.

In my opinion, the most complete and thorough study to assess the physical effects of thermal discharges into a lake thus far has been reported on by Sundaram *et al.*¹⁷ This work was done in connection with the Milliken plant (an existing fossil facility) and a proposed nuclear facility (Bell station) on Cayuga Lake in New York State. The overall effort entailed an accumulation of vast amounts of experimental data from the Milliken plant, which were then incorporated into a semiempirical model to determine the possible physical changes to be produced by the proposed Bell facility on the lake. Space limitations preclude a detailed review of this work, which is both analytical and experimental. Only the experimental effort will be reviewed from this point.

Neumaier and Bock,¹⁸ in a companion report, discuss the results of the 12-month investigation of the heat-release patterns associated with the Milliken plume. Techniques for obtaining large amounts of synoptic temporal and spatial data were used. Lake-surface temperatures were obtained using a continuous-recording aerial infrared radiometer (a Barnes PRT-5) with a field of view of 2°. Cameras aligned with the radiometer were used to correlate the surface-temperature data with ground position. Water surface-temperature data were also collected by a ground crew, which furnished "ground truth" to the airborne radiometer results. For each data set, 15 aerial passes were made across the lake in the area of the outfall; most of the passes, however, were done in the immediate area of the plume. Seven flights were made and were purposely conducted under different meteorological conditions. Each flight took about 1½ hr. "Very little" change in plume position and temperature occurred during this interval. This was attributed to the fact that the power plant was held at a constant load for 4 hr before the flight and during the flight, and that weather conditions were chosen that were not anticipated to vary over this period. The results of the seven flights are shown in Figs. 37-43. Table 19 summarizes the flight conditions experienced during these periods. The power plant was

Fig. 37. Isotherms Derived from Flight: June 20, 1968.¹⁸ Wind NW 20 mph, gusting to 35 mph.

Fig. 38. Isotherms Derived from Flight: July 11, 1968.¹⁸ Wind calm.

Fig. 39. Isotherms Derived from Flight: August 12, 1968.¹⁸ Wind E to SW, 5 mph, varying during flight.

Fig. 40. Isotherms Derived from Flight: September 17, 1968.¹⁸ Wind SE to S, 6 mph.

Fig. 42. Isotherms Derived from Flight: January 8, 1969.¹⁸ Wind NW, 15-20 mph.

Fig. 43. Isotherms Derived from Flight: March 7, 1969.¹⁸ Wind NNW, 15 mph, gusting to 20 mph.

TABLE 19. Summary of Flight Conditions¹⁸

FLIGHT	DATE	WIND DIRECTION	WIND VELOCITY	AIR TEMPERATURE	OUTLET WATER TEMPERATURE	LAKE TEMPERATURE	CLOUD CONDITION	TIME OF DAY
1	JUNE 20, 1968	NW	20 GUSTING TO 30 MPH	15.5°C	18.5°C	13.5°C	CLEAR	12:00 NOON
2	JULY 11, 1968	—	CALM	18.5°C	20.5°C	18°C	CLEAR—SLIGHT GROUND HAZE	7:30 am
3	AUGUST 12, 1968	E TO SW	VARYING 5 MPH	24.2°C	26.5°C	22°C	CLEAR	4:00 pm
4	SEPTEMBER 17, 1968	SE TO S	6 MPH	23.5°C	31°C	19°C	FEW SCATTERED CLOUDS	12:00 NOON
5	DECEMBER 10, 1968	NNW	8 MPH	-6.5°C	14.8°C	4.5°C	OVERCAST	12:00 NOON
6	JANUARY 8, 1969	NW	15-20 MPH	-7.0°C	15.5°C	2.5°C	HIGH ALTITUDE CLOUDS	2:00 pm
7	MARCH 7, 1969	NNW	15 GUSTING TO 20 MPH	-2.0°C	10.5°C	2.0°C	SCATTERED CLOUDS	2:00 pm

at full load during these flights, which represents a 45.5×10^9 -Btu/day discharge rate into the lake. Figures 42 and 43 represent rather interesting situations, in which the plume is shown to sink rather than float.

In situ measurements, in addition to the ground-truth boat observations made for the aerial surveys, were made to collect temperature and current data. As Sundaram *et al.* very importantly noted, the isotherms in a stratified lake are not stationary, but rather, are being continuously distorted by seiches, internal waves, and other transient phenomena. The characteristic times of these transient phenomena vary over wide ranges from an order of several minutes to an order of several days. It would thus be almost impossible to isolate these transients from those of interest when taking measurements from a boat. A monitoring scheme was therefore devised in which near-continuous measurements of the vertical temperature structure and currents were made at selected positions within the lake. These are shown in Fig. 44, together with the selected instrumentation intervals. Except for position E, which is a fixed pole, floating buoys were used to secure the transducers, because the lake bottom is quite deep near the outfall and because the lake level is known to fluctuate, and this would necessarily involve transducer depth-position corrections if a rigidly fixed structure were used. The buoys and the post locations were established on the basis of several arguments, which will not be repeated here. Pages 26-29 in Ref. 17 detail this rationale in great depth.

It was stated above that the temperature and current measurements were made on a near-continuous basis. The temperature (obtained from thermistors) and current-flow data were transmitted from the buoys and the post over coaxial cables by a frequency-modulated signal. Time-division multiplex was used for sampling and to permit transmission of the

data for each buoy over one coaxial cable. At the shore, the data were extracted and recorded in either analog or digital format. The sampled signals were also connected to a telephone line to permit remote access. A complete set of measurements was made every 2 min, and roughly 300,000 bits of data were recorded each week. Hourly-averaged data obtained by averaging thirty, 2-min intervals were used for data interpretation. Sundaram *et al.* note that significant variations in vertical temperatures can be found when using 2-min data, hourly averages as obtained from thirty 2-min intervals, between hourly intervals, and between hourly averages and weekly averages; this is shown in Figs. 45 and 46. In addition, meteorological measurements were made at position E and from a 250-ft tower on the Bell site. The wind velocity on the tower was determined at the lake and at 50 and 250-ft levels. The ambient air temperature was taken at the lake and at 50-ft levels, and temperature differentials were obtained between the 50- and 150- and the 50- and 250-ft levels. Lake-level air temperature was obtained from position E. The atmospheric data were averaged over hourly periods.

An overall interpretation of the results obtained from this 12-month experimental program would be incomplete without some discussion of the semiempirical modeling effort which was done in connection with the entire study. Such a discussion would be too lengthy to be included here. The reader is strongly advised to refer to Ref. 17.

Some brief comments on these field efforts are made in the next section. Recommendations as to what a typical field effort on the Great Lakes should consist of are also discussed.

Fig. 44. Locations of Fixed Instrument Stations¹⁷

Fig. 45. Comparison of Individual Measurements and the Hourly Average¹⁷

Fig. 46. Comparison of Hourly Averages and the Weekly Average¹⁷

IV. DISCUSSION OF THE FIELD WORK

The thermal-plume measurements reported by Ayers *et al.*, the early work of Beer and Pipes, the State of Michigan Water Resources Commission, Chermack, and by the New York State Atomic and Space Development Authority, typically relate to what Edinger and Geyer¹⁹ characterize as "reconnaissance surveys." Such surveys usually consist of measuring temperatures at selected times and positions in a thermal plume; other easily determinable parameters such as wind velocity, power-plant loading, condenser flow, and temperature rise are usually but not always included in such surveys. The objectives of reconnaissance surveys may vary; however, for the most part, these surveys are used to gauge the physical and thermal extent of a plume under certain power-plant loading and environmental conditions. For example, it is desirable to know whether a power plant operating at full capacity during a particularly hot, windless summer day in July or August might violate its State water-quality criteria, or whether, for certain conditions of current flow, there is an appreciable recirculation problem, or whether the addition of more capacity at a power-plant location may potentially create water-quality problems. Problems such as these can be answered relatively easily by performing reconnaissance-type surveys. Unfortunately, however, such surveys are not for the most part suitable for supplying the basic field information needed for validating thermal plume predictive models since generally they are too coarse either in the number of measurements taken, the type of measurements, or how the measurements were made. For instance, in the Ayers *et al.* work, the temperatures were measured at relatively too few locations to realistically obtain 1° temperature contours over the entire plume. Further, although current direction was often noted, its magnitude was not. Other than for wind velocity, no other meteorological variables or plant operating conditions were reported, although presumably such information can be reconstructed from local weather-station data and power-plant operating records. Although not reported, it is presumed that the period of data acquisition lasted many hours, since a good portion of the Ayers *et al.* effort involved biological sampling of the water and bottom sediment. Figure 16 had previously shown the distortion that isotherms can undergo within short time intervals. It is not clear therefore whether field data accumulated in a piecewise fashion, even over relatively short time periods, is suitable for plume analysis, especially when such data are usually acquired in an arbitrary, and sometimes convenient, fashion, rather than in a way somehow chosen to minimize probable temporal changes. It is almost imperative that a network of continuous or near-continuous sensors be used over the entire extent of a plume if such data are to be used for the validation of plume models.

In the Ginna, Nine Mile Point, and Argonne investigations, greater emphasis was/is placed on obtaining a sufficient amount of temperature data to plot 1° isolines, yet no apparent attempt was/is made to delineate the ambient-current structure during these measurements, except perhaps for

the Argonne work. In the case of the King plant, measurements for one set of data typically lasted up to 8 hr, which required the investigators to later "adjust" their raw data. Since plume data from the Ginna plant are not yet available, it would be fair to estimate that the contemplated measurements, if taken from a single boat, would entail 2-3 hr. Again, it is not clear to me whether a 1- or 3-hr period is suitably short to regard the plume data as being essentially instantaneous. As Sundaram *et al.* point out, transient phenomena, which can distort a plume, vary over characteristic times ranging from several minutes to several days. It may well be that the observed "Gaussian-like" temperature distribution within various observed plumes arises from the fact that the measurements were taken over prolonged periods. In such situations, the meandering of a relatively sharp plume interface could possibly give rise to a smeared Gaussian-like effect. Thus it is important to obtain relatively instantaneous temperature contours, should analysis with purely deterministic models be desired.

Although the Csanady *et al.*¹⁴ temperature measurements were suitable for estimating the surface heat exchange rate from a thermal plume, they cannot be used for general plume definition, because of the coarse grid utilized for data acquisition. Only four lateral temperature traverses were made separated by 400-m intervals. These measurements, together with a longitudinal centerline traverse, were used to obtain the isotherm plots shown here for each plume. It would be presumptive to state that the investigators intended for these plots to indicate more than a good qualitative picture of the surface isotherms.

The Hoopes *et al.*¹⁶ effort represented a rather comprehensive attack on the jet or near-field regime of a plume. The work entailed current as well as temperature measurements, and, in addition, dye-dispersion studies and remote infrared mapping were also attempted. In essence, this was the first lake-plume study that solely attempted to acquire a detailed look at the plume kinetics and dynamics. Perhaps another reason why this study stands out is that the field work was preceded by an analytical modeling effort which essentially dictated the objectives and goals for the field work. It is perhaps foolhardy to expect to measure the spatial temperature distribution of a plume, hoping later to fit this data with some as yet unknown analytical model. In such situations, the absence of some measured parameter, such as the ambient current, may render all the information essentially useless.

In my opinion, Sundaram *et al.*¹⁷ have presented the most thorough investigation of thermal discharges into a lake thus far. Complete emphasis was placed upon remote and nearly continuous data acquisition for reasons already elaborated. It is unlikely, however, that these data could be used for general model testing, since relatively little temperature-with-depth information was acquired to plot three-dimensional isotherms. Personal communication with Sundaram revealed that he would have liked to

increase the number of buoy positions for remote sensing and to have supplemented these measurements with measurements taken from boat traverses; however, budgetary limitations precluded this. In any event, sufficient data were obtained for Sundaram *et al.* to supplement their analytical modeling effort and make predictions suitable for their purposes.

If there is a desire to use the experimental data for something more than reconnaissance (like attempting to evaluate the data in terms of existing analytical formulations), it becomes necessary to obtain more than spatial temperature data which seem to make up the bulk of the information contained within the present literature survey.

The dispersion of a heated effluent into a lake is governed by many factors, such as the meteorological conditions above the lake, the way the effluent is discharged into the lake, the local topography, lake stratification, and ambient currents. Not all these factors influence the dispersion process to the same degree; therefore it is usually convenient to separate the plume into regimes in which dominating influences can be isolated. This is discussed in Sec. VI and will not be repeated here.

Before any field study is attempted, the parameters to be measured must be determined by the analytical model(s) of the plume regimes to be considered.

The classical analytical approach to hydrodynamic problems with heat transfer involves solving the basic equations of continuity, momentum, and energy with the appropriate boundary conditions and transport coefficients. Since mass, momentum, and heat transport, within any large body of water such as a lake, can be assumed to be governed by turbulent mechanisms, the needed transport coefficients are not simple properties of the water alone, as they would be in laminar flows, but are dependent on the geometric and environmental characteristics of the flow. The functional relationship of the transport coefficients to these geometric and environmental characteristics is not generally known. Therefore, to provide solutions to turbulent problems, recourse is often made to "turbulent equations of state," which relate the turbulent coefficients to local or global mean flow properties. Analytical solution of turbulent flows then becomes a "fashioning" and "whittling" process in which simplifications are made to the governing equations, boundary conditions, and transport coefficients in order to obtain solutions.

It is not surprising to find that in the fashioning and whittling process, various investigators may choose to use or eliminate various terms of the governing equations and may also assume various functional relationships for velocity, temperature, and the transport coefficients. Doing this makes each newly fashioned set of equations somewhat unique, each requiring somewhat different parameters to be supplied or acquired from

experimental field experience. For example, the following parameters have appeared in various analytical models used for plume analysis: densimetric Froude, Richardson, Peclet, eddy Schmidt and Prandtl numbers, eddy diffusivity, eddy viscosity, drag, spread, entrainment and dilution coefficients, and a multitude of different constants. Therefore, unless one knows a priori what analytical model he wishes to validate, it is imperative that field measurements be thoroughly synoptic. The following paragraphs will attempt to outline most of the pertinent measurements that should be taken in the field to possibly provide a "standard (universal)" test-data set.

Meteorological variables, such as air velocity and temperature, relative humidity, cloud cover and cloud height, net short- and long-wave radiation, and atmospheric pressure can affect plume behavior. Air temperature should be monitored at a tower located at least 1000 ft offshore and somewhat removed from the plume vicinity. The temperature measurements should be made at four levels: preferably 2, 6, and 10 m and within the water surface. The temperature profile will indicate atmospheric stability, which in turn indicates whether there may be a strong or weak interaction between prevailing winds and the water surface. The eddy-transport coefficients, within the surface of a lake, are strongly influenced by wind-induced turbulence. Wind velocities (speed and direction) should also be measured at the tower location at two elevations of 2 and 10 m. The velocity profiles thus obtained can be used with stability information to predict the wind velocity near the water surface, which also influences surface cooling rates as well as the eddy-transport coefficients.

The tower should be equipped with a radiometer and two pyranometers. The radiometer measures the net solar (short-wave) and terrestrial (long-wave) radiation accepted by the water. The pyranometer indicates only the solar radiation incident on the water surface. If two pyranometers are used, the net solar radiation accepted by the water surface can be determined. Thus, with these instruments, the mechanisms by which heat is radiantly exchanged between the water surface and the atmosphere can be delineated.

The relative humidity (or dew point) at 2 and 10 m should be measured. Relative humidity measurements are needed to estimate the absolute rates of evaporative heat transfer. At this point, several comments should be made to describe two frames of reference for looking at the heat-exchange processes from a thermal plume. One method is to reference the plume energy-exchange processes to the ambient receiving water. By doing this, one only has to look at the relative energy losses of the plume with respect to the ambient receiving water. The ambient receiving water is also undergoing energy-exchange processes with the atmosphere, but this need not be considered. In other words, the temperature difference between the plume and the ambient water can remain constant while the plume's absolute temperature fluctuates because of diurnal or seasonal changes. This technique

is particularly convenient, because thermal water-quality standards are usually promulgated with some specified incremental temperature over ambient water temperature (i.e., temperature excess) in addition to a maximum temperature limitation.

Another way of looking at the plume's energy-exchange processes is from an absolute viewpoint, wherein the heat-transfer rates are referenced to an "equilibrium temperature," defined as that temperature for which the net heat transfer from a water surface is zero. This method is generally used in cooling-pond applications where energy and mass budgets are particularly critical and for which there is no natural ambient conditions. See Brady, Graves, and Geyer²⁰ for an up-to-date treatise of cooling-pond technology.

While humidity is not needed for making relative-heat-loss calculations, it is needed for estimating absolute evaporation losses, should they be desired. Furthermore, sometime in the near future there may be some interest in looking for meteorological modifications due to thermal discharges in which, for instance, the added humidity and heat could make the local atmosphere above the plume less stable, which in turn would modify air-water interactions. Obviously, there is some feedback between the air and water; whether it is significant enough to worry about, particularly with respect to its influence on plume kinetics and dynamics, is open to question.

Cloud cover (in percent) and cloud altitude should also be recorded. This information is often used along with other information to calculate the net long-wave radiation accepted by a body of water by using empirical formulations. It would be interesting to systematically compare these empirical calculations with the results obtained by subtracting the net short-wave measurements obtained from the net radiometer.

Atmospheric pressure should be recorded, because it is needed to calculate the water-surface heat losses due to conduction. The atmospheric pressure is also necessary to convert dew-point readings to vapor pressure should a dew-point cell be used in the field work.

In situ water measurements should include temperature data on an appropriate three-dimensional grid to be able to obtain 1° isolines over the entire plume. A significant portion of these data should be acquired by continuous-recording remote instrumentation, since sole reliance on measurements taken from a boat is liable to be misleading for the reasons already stated.

Although not an in situ measurement, airborne infrared imagery might be particularly useful in delineating the overall surface-temperature distribution of a plume. Measurements should be made to elucidate the

near-shore ambient current structure on a continuous basis. These measurements should also be taken on a three-dimensional grid; however, the grid need not be as closely spaced as what would be required for the temperature measurements. Several current meters should also be located in the hypolimnion of the lake. Drogues could be used to supplement current-meter readings and would be particularly useful in delineating the interaction between shoreline currents and the jet regime of the plume. Dye-dispersion studies should also be performed to bracket lateral and vertical eddy-transport coefficients. Wave amplitude and frequencies and lake level should also be monitored; this information, along with other measured parameters, such as atmospheric stability, wind velocity, eddy coefficients, temperature distributions and currents, may give some insight to the wind-water interaction mechanisms controlling the heat-dispersion processes, albeit only for the location at which the particular measurements are performed.

Power-plant parameters, which should be monitored continuously during field measurements, include condenser-cooling-water flow rate, intake and outfall temperatures, and power-plant loading. Caution is recommended in accepting the condenser flow rates as calculated from pump curves, unless the pumps have recently been calibrated.

The lake-bottom topography should be mapped in the vicinity of the outfall before or after a series of field investigations. Bottom sediment is known to shift and sometimes build up over the course of time in the vicinity of intake and outfall structures. Further, and particularly with shoreline-type canal outfalls, the actual dimensions of the outfall may change with time because of sedimentation; therefore, it is important to measure the actual dimensions of the structure. The outfall position and characteristics are important parameters, and care should be taken to define them accurately.

V. SUPPLEMENTARY INFORMATION

To better assess various aspects of once-through condenser cooling on the Great Lakes, an inventory of all the steam-electric power plants greater than 10 MWe sited directly on the Great Lakes and interconnecting bodies of water has been compiled and is shown in Table 20. Figure 47 shows the relative positions of these plants with respect to each other and also indicates their approximate geographic location. Table 21 indicates both the State- and Lake-wise distribution of these plant facilities; Table 22 indicates their respective cooling-water requirements. These statistics represent not only those facilities already in operation, but also those which are either under construction or which have been publicly announced. Insofar as the Great Lakes are concerned, the State of Michigan presently has the largest steam-electric generating capacity on the Lakes, since most of the capacity listed for Ontario, Canada, will not be in operation for several years to come. Lake Michigan is the most heavily used for once-through cooling. A recent publication by H. C. Acres Limited²¹ has inventoried and estimated all the major thermal inputs to the Great Lakes Basin for 1968-2000. The work reported here was done independently of this cited work and was in good agreement with Acres' work, except for a few minor differences in power-plant capacities and in recent changes by several utilities to convert from once-through condenser cooling to the use of evaporative cooling towers. Recent actions by the National Environmental Protection Agency (see Note 3 within the appendix pertaining to the Lake Michigan Enforcement Conference, March 23-25, 1971) leads me to believe that, at least in the near future, additional generating capacity contemplated for the U.S. portion of the Great Lakes shorelines will necessarily involve the use of alternate cooling techniques such as cooling towers. Caution is therefore advised when using the Acres' figures and extrapolations.

At this point it would be informative to list several general statistics concerning the Great Lakes so that some perspectives may be acquired for future reference. It has often been stated that the Great Lakes as a whole form the largest body of fresh water in the world. On a surface-area basis, this is certainly correct; in fact, Lake Superior alone is the single largest fresh-water lake, having a surface area of roughly 31,700 square miles. On a volumetric basis, however, Lake Baikal in Siberia is the largest single body of fresh water, containing roughly 5,520 cubic miles of water, and it is larger than all of the Great Lakes with a combined capacity of 5,473 cubic miles.²²

In order of surface area, the Great Lakes are ranked with Lake Superior the largest, followed by Lakes Huron, Michigan, Erie, and Ontario. However, if the lakes were ranked according to the volume of water they contained, that is, volumetrically, the ranking would change. Lake Superior would again be the largest; however, the remaining four would descend in the following order: Michigan, Huron, Ontario, and Erie. Further physical features of the Great Lakes and other lakes are enumerated in Tables 23 and 24.

TABLE 20. Steam-Electric Power Plants Sited on the Great Lakes and Interconnecting Bodies of Water (May 1, 1971)

Plant Name	Estimated Gross Output, MWe		Plant Location	Operating Utility or Concern
ILLINOIS				
Zion ^a Nuclear No. 1 and 2	2100	PWR's ^b	Zion	Commonwealth Edison Company
Waukegan	1107.8		Waukegan	Commonwealth Edison Company
Winnetka	25.5		Winnetka	Winnetka Municipal Electric and Water Department
South Works	105		Chicago	U.S. Steel Corporation
INDIANA				
State Line	964		Hammond	Commonwealth Edison Company
D. H. Mitchell	414.3		Gary	Northern Indiana Public Service
Michigan City ^a	715		Michigan City	Northern Indiana Public Service
Bailly	615.6		Dune Acres	Northern Indiana Public Service
Bailly Nuclear ^{a,c}	660	BWR ^d	Dune Acres	Northern Indiana Public Service
MICHIGAN				
D. C. Cook ^a Nuclear No. 1 and 2	2200	PWR's	Bridgman	Indiana and Michigan Electric
Palisades ^{a,c} Nuclear	840	PWR	So. Haven	Consumers Power Company
J. H. Campbell	647		Pigeon Lake	Consumers Power Company
B. C. Cobb	531		Muskegon, on Muskegon Lake	Consumers Power Company
J. DeYoung	48.5		Holland, on Macatawa Lake	Holland Board of Public Works
Traverse City	35.0		Traverse City	Traverse City Light and Power
Big Rock Nuclear	75	BWR	Charlevoix	Consumers Power Company
Presque Isle	143		Marquette	Upper Peninsula Power Company
Harbor Beach	117		Harbor Beach	Detroit Edison
D. E. Karn	530		Essexville	Consumers Power Company
J. E. Weadock	614.5		Essexville	Consumers Power Company
Marysville	300		Marysville	Detroit Edison
St. Clair	1842		Belle River	Detroit Edison
Conners Creek	628		Detroit	Detroit Edison
Mistersky	174		Detroit	Detroit Public Lighting Commission
Delray	375		Detroit	Detroit Edison
Trenton Channel	1119		Trenton	Detroit Edison
River Rouge	860		River Rouge	Detroit Edison
Wyandotte	41.5		Wyandotte	Wyandotte Municipal Service Commission
Enrico Fermi Nuclear No. 1	150	FRR ^e	Lagoona Beach	Detroit Edison
Enrico Fermi ^{a,c} Nuclear No. 2	1126	BWR	Lagoona Beach	Detroit Edison
J. R. Whiting	342		Erie	Consumers Power Company
Monroe ^a	3200		Monroe	Detroit Edison
Escanaba	25		Escanaba	Escanaba Municipal Electric Utility
Alpena	33.5		Alpena	Huron Portland Cement Company
J. H. Warden	15.6		L'Anse	Upper Peninsula Power Company
Pennsalt	37		Wyandotte	Detroit Edison Company
MINNESOTA				
Taconite Harbor	225		Tofte	Erie Mining Company
Silver Bay	132		Silver Bay	Reserve Mining Company
M. L. Hibbard	124.5		Duluth	Minnesota Power and Light Company
NEW YORK				
Dunkirk	628		Dunkirk	Niagara Mohawk Power Corporation
J. A. Fitzpatrick ^a Nuclear	850	BWR	Scriba	Power Authority of the State of New York
Nine Mile Point Nuclear	500	BWR	Scriba	Niagara Mohawk Power Corporation
Oswego ^a	1266		Oswego	Niagara Mohawk Power Corporation
C. R. Huntley	828		Tonawanda	Niagara Mohawk Power Corporation
R. E. Ginna Nuclear	420	PWR	Ontario	Rochester Gas and Electric Corporation
Russell	252.6		Greece	Rochester Gas and Electric Corporation
OHIO				
Bay Shore	636		Oregon	Toledo Edison Company
Edgewater	193		Lorain	Ohio Edison Company
Avon Lake	595		Avon Lake	Cleveland Electric Illuminating Company
Lake Road	193		Cleveland	Cleveland Division of Light and Power
Lake Shore	518		Cleveland	Cleveland Electric Illuminating Company
Eastlake	577		Eastlake	Cleveland Electric Illuminating Company
Ashtabula	456		Ashtabula	Cleveland Electric Illuminating Company
East 53rd	50		Cleveland	Cleveland Division of Light and Power
Painesville	21		Painesville	International Rayon Corporation
Ashtabula	160		Ashtabula	Union Carbide Corporation
Davis-Besse ^{a,c} Nuclear	872	PWR	Locust Point	Toledo Edison and Cleveland Illuminating Company
ONTARIO, CANADA				
J. C. Keith	320		Windsor	Ontario Hydro
Richard L. Hearn	1200		Toronto	Ontario Hydro
Lakeview	2400		Toronto	Ontario Hydro
Lambton	2000		Sarnia	Ontario Hydro
Nanticoke ^a	4000		Nanticoke	Ontario Hydro
Lennox ^a	2000		Kingston	Ontario Hydro

TABLE 20 (Contd.)

Plant Name	Estimated Gross Output, MWe		Plant Location	Operating Utility or Concern
ONTARIO, CANADA (Contd.)				
Thunder Bay	100		Lakehead	Ontario Hydro
Douglas Point Nuclear	200 HWR ^f		Port Elgin	Ontario Hydro
Pickering ^a Nuclear No. 1, 2, 3, 4	2000 HWR's		Pickering	Ontario Hydro
Bruce ^a Nuclear No. 1, 2, 3, 4	3200 HWR's		Port Elgin	Ontario Hydro
PENNSYLVANIA				
Front Street	118.8		Erie	Pennsylvania Electric Company
WISCONSIN				
Pulliam	392.5		Green Bay	Wisconsin Public Service Company
Kewaunee ^a Nuclear	527 PWR		Carlton	Wisconsin Power and Light Company, Wisconsin Public Service Company, Madison Gas and Electric Company
Point Beach ^a Nuclear No. 1 and 2	1030 PWR's		Two Creeks	Wisconsin Electric Power Company
Winslow	25.2		Superior	Superior Water, Light and Power Company
Bay Front	82.2		Ashland	Lake Superior District Power Company
Manitowoc	69.0		Manitowoc	Manitowoc Public Utilities
Edgewater	460		Sheboygan	Wisconsin Power and Light Company
Port Washington	400		Port Washington	Wisconsin Electric Power Company
Lakeside	344.7		St. Francis	Wisconsin Electric Power Company
Oak Creek	1670.0		Oak Creek	Wisconsin Electric Power Company

Plant	Scheduled Operation
Zion (two units)	1972 and 1973
Bailly Nuclear	1976
Michigan City	1973 (500 MWe)
D. C. Cook (two units)	1972 and 1973
Palisades	1971
Enrico Fermi	1973
Monroe (four units)	1971, 1972, 1973, 1973
J. A. Fitzpatrick	1973
Davis-Besse	1974
Nanticoke (eight units)	1972, 1973, 1973, 1974, 1975, 1976, 1977, 1977
Lennox (four units)	1975, 1976, 1977, 1977
Pickering (four units)	1971, 1972, 1973, 1974
Bruce (four units)	1976, 1977, 1978, 1979
Kewaunee	1972
Point Beach (two units)	1970 and 1971
Oswego Unit 5	1972

^aPressurized Water Reactor(s).^dBoiling Water Reactor.^bPortions of plant under construction or design.^eFast Breeder Reactor.^cPlant will use evaporative cooling tower(s).^fHeavy Water Reactor.

TABLE 21. Great Lakes Steam-Electric Power-plant Siting; State and Lake Distribution (May 1, 1971)

State	Great Lakes and Interconnecting Bodies of Water		Great Lakes Only		Lake Erie		Lake Huron		Lake Michigan		Lake Ontario		Lake Superior	
	MWe	Plants	MWe	Plants	MWe	Plants	MWe	Plants	MWe	Plants	MWe	Plants	MWe	Plants
Illinois	3,338	4	3,338	4	-	-	-	-	3,338	4	-	-	-	-
Indiana	2,709	4	2,709	4	-	-	-	-	2,709	4	-	-	-	-
Michigan	14,084	25	8,128	14	3,692	3	1,295	4	2,982	5	-	-	159	2
Minnesota	482	3	482	3	-	-	-	-	-	-	-	-	482	3
New York	4,745	7	3,917	6	628	1	-	-	-	-	3,289	5	-	-
Ohio	3,399	10	3,399	10	3,399	10	-	-	-	-	-	-	-	-
Ontario, Canada	17,420	10	15,100	8	4,000	1	3,400	2	-	-	7,600	4	100	1
Pennsylvania	119	1	119	1	119	1	-	-	-	-	-	-	-	-
Wisconsin	5,001	10	5,001	10	-	-	-	-	4,893	8	-	-	107	2
Total	51,297	74	42,193	60	11,838	16	4,695	6	13,922	21	10,889	9	848	8

Fig. 47. Steam-Electric Power Plants Sited on the Great Lakes and Interconnecting Bodies of Water

TABLE 22. Approximate Condenser Cooling-water Flow Rates and Temperature Rises for Various Power Plants Sited on the Great Lakes

State or Province	Approximate Values	
	Condenser Max. ΔT Ranges for Individual Units or Overall Max. Plant Average	Flow Rate, gpm
ILLINOIS		
Zion ^d	19.6°F	1,463,000
South Works ^a		
Waukegan	9.9	870,000
Winnetka	11-12	a
INDIANA		
State Line	11.7	745,000
Dean Mitchell	10	414,000
Michigan City ^d	9	246,000
Bailly	11	308,000
Bailly Nuclear ^{b,d} (Will use natural-draft evaporative cooling towers.)		
MICHIGAN		
D. C. Cook ^c	21	1,570,000
Palisades (Will use natural-draft evaporative cooling towers.)		
J. H. Campbell	15-19	300,000
B. C. Cobb	10-18	405,000
J. DeYoung ^a		
Traverse City ^a		
Big Rock	22	48,000
Presque Isle	20-31	83,000
Harbor Beach	13	90,000
D. E. Karn	13-15	300,000
J. E. Weadock	10-16	543,000
Marysville	12-20	522,000
St. Clair	12-17	1,022,000
Conners Creek	14-21	646,000
Mistersky ^a		
Delray	10-22	561,000
Trenton Channel	8-21	958,000
River Rouge	14	447,000
Wyandotte ^a		
Enrico Fermi No. 1	16	170,000
Enrico Fermi No. 2 ^d (Will use natural-draft evaporative cooling towers.)		
J. R. Whiting	14-18	214,000
Monroe ^d	21.8	1,400,000
Escanaba	16	40,000
Alpena ^a		
J. H. Warden	26	10,500
Pennsalt ^a		
MINNESOTA		
Taconite Harbor	10	119,500
Silver Bay	12-13	a
M. L. Hibbard	8-10	144,000
NEW YORK		
Dunkirk	13.7	400,000
Fitzpatrick ^d	32.4	352,000
Nine Mile Point	32	250,000

TABLE 22 (Contd.)

State or Province	Approximate Values	
	Condenser Max. ΔT Ranges for Individual Units or Overall Max. Plant Average	
		Flow Rate, gpm
NEW YORK (Contd.)		
Oswego;	12.6;	225,000;
Oswego Unit 5 ^d	28.6	285,000
Huntley	12.7	580,000
Ginna	19.6	341,000
Russell	19	123,000
OHIO		
Avon Lake	10.1	802,000
Lake Road ^a		
Lake Shore	14.1	438,000
Bay Shore	13	500,000
Edgewater	12-15	120,000
East Lake	14	485,000
Ashtabula	8.9	488,000
East 53rd ^a		
Painesville	10-12	12,000
Ashtabula	15	120,000
Davis-Besse (Will use a natural-draft evaporative cooling tower.)		
ONTARIO		
Keith	23.5	136,000
Hearn	16.6-22.8	696,000
Lakeview	16.9	1,280,000
Lambton	26.4	696,000
Nanticoked	15	2,488,000
Lennox ^d	17.7	1,044,000
Thunder Bay	10.3	104,000
Douglas Point	14.6	230,000
Pickering ^d	20.1	1,680,000
Bruce ^d	18.1	2,672,000
PENNSYLVANIA		
Front Street	14	100,000
WISCONSIN		
Pulliam ^a		
Kewaunee ^d	19.2	401,000
Point Beach ^d	19.3	700,000
Winslow ^a		
Bay Front ^a		
Manitowoc ^a		
Edgewater	18	178,600
Port Washington	7	550,000
Lakeside	8	241,000
Oak Creek	10	1,100,000

^aInformation not acquired.^bIn conceptual design phase.^cNot confirmed.^dUnits under construction or design.

TABLE 23. Data on the Great Lakes System
Source: U.S. Lake Survey, Detroit, Michigan, December 1969

	Lake Superior	Lake Michigan	Lake Huron	Lake St. Clair	Lake Erie	Lake Ontario
General Lake Dimensions						
Length (right line in clear), miles	350	307	206	26	241	193
Breadth (right line), miles	160	118 ^a	183 ^b	24	57	53
Length of coastline (including islands), miles	2,980	1,660	3,180 ^c	169	856	726
U.S. shoreline (mainland only), miles	909	1,395	564		424	294
National boundary line, miles	282.8	None	260.8		251.5	174.6
Areas in square miles:						
Water surface, United States	20,600 ^d	22,300 ^e	9,150 ^f	198 ^g	4,980	3,560 ^h
Water surface, Canada	11,100 ^d	None	13,900 ^f	292 ^g	4,930	3,990 ^h
Water surface, total	31,700 ^d	22,300 ^e	23,050 ^f	490 ^g	9,910	7,550 ^h
Drainage basin land, United States	16,900 ^d	45,600 ^e	16,200 ^f	2,850 ^g	18,000	15,200 ^h
Drainage basin land, Canada	32,400 ^d	None	35,500 ^f	4,080 ^g	4,720	12,100 ^h
Drainage basin land, total	49,300 ^d	45,600 ^e	51,700 ^f	6,930 ^g	22,700	27,200 ^h
Drainage basin (land and water), total	81,000 ^d	67,900 ^e	74,800 ^f	7,420 ^g	32,600	34,800 ^h
Maximum depth, ft	1,333	923	750	21 ⁱ	210	802
Average depth, ft	489	279	195	10	62	283
Volume of water, cubic miles	2,935	1,180	849	1	116	393
Significant Lakes Stages, ft (1860-1968)						
Elevations above mean water level at Ratier Point, Quebec, on International Great Lakes Datum (1955).						
Highest monthly mean elevation	602.06	581.94	581.94	575.70 ^j	572.76	248.06
Lowest monthly mean elevation	598.23	575.35	575.35	569.86 ^j	567.49	241.45
Mean elevation	600.37	578.68	578.68	573.01 ^j	570.37	244.77
Average seasonal fluctuation	1.1	1.1	1.1	1.6	1.5	1.8
General Hydrologic Data (1860-1968)						
Average annual precipitation, in.	30	31	31		34	34
Mean outflow, cubic ft/sec	75,000	52,000 ^k	187,000	188,000	202,000 ^l	239,000
Highest monthly mean outflow, cfs	127,000	-	242,000	242,000	254,000 ^l	314,000
Lowest monthly mean outflow, cfs	41,000	-	99,000	100,000	116,000 ^l	154,000
Diversions, cfs	+5,400 ^m	-3,200 ⁿ				
Length of Outflow River, miles (approx)						
Length shown under lake from which it flows.						
St. Marys	70					
St. Clair			27			
Detroit				32		
Niagara					37	
St. Lawrence						502

^aMeasured at wide point through Green Bay.
^bMeasured at wide point through Georgian Bay.

^cIncludes Georgian Bay and North Channel.

^dIncludes St. Marys River above Brush Point.

^eLake Michigan, including Green Bay.

^fIncludes St. Marys River below Brush Point, North Channel and Georgian Bay.

^gLake St. Clair and St. Clair and Detroit Rivers.

^hLake Ontario, including Niagara River and St. Lawrence River above Iroquois Dam.

ⁱMaximum natural depth. Dredged navigation channel has 27.5-ft depth.

^jPeriod 1898-1968.

^kEstimated flow through Straits of Mackinac and does not include diversion at Chicago into Mississippi River basin.

^lDoes not include diversion from Lake Erie to Lake Ontario through Welland Canal.

^mLong Lake-Ogoki inflow.

ⁿChicago outflow.

TABLE 24. Comparative Data on the Lakes of the World

Name	Continent	Area, mi ²	Volume, mi ³	Length, mi	Max Depth, ft	Avg Depth, ft	Surface (MSL) Elevation, ft	Comments
Caspian Sea	Asia-Europe	143,550 ^a	19,040 ^b	760 ^c	3,264 ^d	100	-92 ^e	Saline
Superior	North America	31,700 ^c	2,935 ^c	350 ^c	1,333 ^c	489	600 ^c	
Victoria	Africa	26,828 ^a	650 ^b	250 ^c	265 ^d	128	3,120 ^e	
Aral Sea	Asia	25,300 ^a	230 ^b	280 ^c	223 ^d	48	-174 ^e	Saline
Huron	North America	23,050 ^c	849 ^c	206 ^c	750 ^c	195	579 ^c	
Michigan	North America	22,300 ^c	1,180 ^c	307 ^c	923 ^c	279	579 ^c	
Tanganyika	Africa	12,700 ^a	4,550 ^b	420 ^c	4,710 ^d	1,892	2,534 ^e	
Great Bear	North America	12,275 ^a	Unknown	192 ^c	1,356 ^d	Unknown	390 ^e	
Baikal	Asia	11,780 ^a	5,520 ^b	395 ^c	5,315 ^d	2,474	1,493 ^e	
Nyasa	Africa	11,430 ^a	2,020 ^b	360 ^c	2,226 ^d	933	1,550 ^e	
Great Slave	North America	10,988 ^a	423 ^b	298 ^c	2,015 ^d	203 ^d	510 ^e	
Erie	North America	9,910 ^c	116 ^c	241 ^c	210 ^c	62	570 ^c	
Winnipeg	North America	9,465 ^a	750 ^b	266 ^c	60 ^d	418	713 ^e	
Ontario	North America	7,550 ^c	393 ^c	193 ^c	802 ^c	283	245 ^c	
Ladoga	Europe	6,835 ^a	220 ^b	120 ^c	738 ^d	170	13 ^e	

^aNational Geographic Society, Washington, D.C.

^bRef. 22.

^cU.S. Lake Survey.

^dRef. 24.

The Great Lakes, their interconnecting rivers and canals, and the St. Lawrence River provide a vast waterway connecting mid-North America with the Atlantic coast. This waterway is used quite extensively for maritime commerce. For example, in 1968,²³ the domestic port-to-port use of the Great Lakes involved 214 million short tons. Imports and exports involving the United States amounted to an additional 62 million tons of cargo. Thus, the total U.S. commercial use of the Great Lakes in 1968 amounted to 276 million short tons or, in another way, approximately 112 billion ton-miles. In comparison, the Mississippi River System, which comprises all the main channels and tributaries of the Mississippi, Illinois, Missouri, and Ohio Rivers, in 1968 handled 344 million short tons or 120 billion ton-miles of freight.

The Great Lakes are also used as commercial fisheries. In 1969, roughly 122 million pounds of fish were caught on the Lakes by U.S. and Canadian commercial fishermen, representing a total value to the fishermen of roughly 10.2 million dollars. Of the five lakes, Lake Erie was the leading producer with a total catch of 59 million pounds, next Lake Michigan with 47 million, Lake Superior with 7.9 million, Lake Huron with 5.5 million, and Lake Ontario with less than 3 million pounds. The U.S. commercial fisheries for 1969 accounted for roughly 54% of the total catch. Table 25 indicates some rather interesting comparative statistics concerning commercial fishing within the U.S.

TABLE 25. Selected U.S. Regional Fishery Data for 1968⁴⁰

	Catch, lb	Value to Fishermen, dollars
Gulf States	1,280,920,000	124,787,000
Pacific Coast States	1,099,337,000	162,108,000
New England States	634,900,000	75,700,000
Chesapeake Bay States	437,858,000	36,559,000
South Atlantic States	339,180,000	33,513,000
Middle Atlantic States	186,500,000	25,200,000
Mississippi River System	70,500,000	7,000,000
Great Lakes	68,983,000	5,863,000

Over the past several decades, there has been a decline in the catch of prime fish on the Great Lakes, such as lake trout, white fish, and lake herring, and an accompanying increase in fish caught of lower commercial value, such as yellow perch. The reasons for this are manifold and complex. The contributing factors to this situation are thought to be the invasion of the alewife and sea lamprey, changes in water quality, and possibly over-fishing. Although catch records can be used to indicate rough trends, the use of them without some background information can be misleading. For instance, some states have curtailed the fishing of certain species due to high

levels of DDT (chubs) and mercury (walleyed pike). Records during the periods of curtailment would indicate only that the catches for these fish were down from previous years. From the statistics only, one could be misled into believing that the populations for these species were down when in reality they were not fished.

In addition to the commercial value of the Great Lakes for shipping and fishing, the recreational counterparts of these activities amount to considerable expenditures of time and money. Unfortunately, it is indeed very hard, if not impossible, to quantify the recreational use of the Great Lakes for such things as fishing, boating, camping, hunting, sightseeing, and walking. Some estimates have been made, however. It has been estimated that the Lake Ontario Basin attracts 2.5 million dollars annually in this respect. It also has been estimated that tourism in the Lake Erie Basin adds hundreds of millions of dollars annually to the basin's economy. It was also estimated that in 1960 there was roughly 180 million activity days spent in water-oriented activities in the Lake Michigan Basin. Although these figures can at best be considered approximate, they strongly indicate rather extensive and intensive use of the Great Lakes region for recreation. There is little doubt that, from a monetary point of view, these recreational activities probably approach the value of the Lakes for commercial shipping. In 1968 the total waterborne trade on the Great Lakes amounted to 2.6 billion dollars.

APPENDIX A

Thermal Water Quality Standards for the
States Bordering the Great Lakes

All states have submitted water quality standards to the Secretary of the Interior for approval pursuant to the Water Quality Act of 1965. In establishing these standards, five general areas of water use were to be considered: public water supplies, propagation of fish and wildlife, agricultural, recreational, and industrial. The temperature criteria of most states reflect to some extent the guidelines set forth in the National Technical Advisory Committee (NTAC) Report, "Water Quality Criteria." The guidelines recommend no more than a 5°F artificial increase above "natural" ambient (at the expected minimum daily flow for that month) for streams classified for either warm- or cold-water fish. In lakes and reservoirs, a 3°F increase limit (in the epilimnion) is suggested, based on the monthly average of the maximum daily temperatures. The NTAC report did not recommend the practice of withdrawing from or discharging into the hypolimnion. For estuarine and marine waters, a 1.5°F limit was advised during the summer months and 4°F limit for the rest of the year, based on the monthly means of the maximum daily temperatures. The ΔT limits were established to preserve the natural daily and seasonal temperature variations. The NTAC report, in addition, recommended maximum temperature criteria for various species of fish ranging from 48 to 93°F.

The NTAC report also discussed the concept of mixing zones. Certain areas of mixing are unavoidable in the vicinity of pollutional outfalls, and these zones could be harmful to the biota. In such cases it was recommended that adequate passageways, in which at all times the water quality is to be favorable to the biota, should be provided to allow for the movement or drift around these potentially harmful mixing zones. For estuaries and streams, it was recommended that the passageways be preferably 75% of the cross-sectional area and/or volume flow. Numerical mixing-zone limitations were not delineated for coastal, lake, or reservoir situations. However, the report did recommend keeping the mixing zones as small as possible: "Mixing should be accomplished as quickly as possible through the use of devices which insure that the waste is mixed with the allocated dilution water in the smallest possible area."

As of January 1970, 18 states have not had their thermal criteria fully approved by the Secretary of the Interior. In particular, the following states have important portions of their temperature criteria not as yet approved and in which nuclear plants are operating, being built, or planned: California, Illinois, Maine, Michigan, New Jersey, North Carolina, Ohio, South Carolina, and Virginia. Thus, at any time in the near future, changes in their water-temperature criteria may have a serious effect on power-plant design or operation. Even for those states with approved temperature

standards, changes are being made or contemplated. For instance, in May 1970, an Interior Department policy statement read before the Lake Michigan Enforcement Conference stated that no more than a 1°F temperature rise above ambient be allowed for any effluent discharged into Lake Michigan. At the moment, the policy statement is a recommendation which must be acted upon by Illinois, Indiana, Michigan, and Wisconsin and their deliberations then appropriately negotiated and approved. Of these states, only Michigan does not have approved thermal criteria for Lake Michigan. There are eight nuclear power units under later stages of construction and one under operation on Lake Michigan at present. Thus, the 1°F limitation, if accepted by the states, would necessarily predicate reliance on alternate forms of cooling, such as cooling ponds or towers, for these facilities. If alternate cooling methods can be accommodated by these nuclear facilities, it is highly likely that extensive turbine and condenser modifications would have to be made, should near-original design efficiencies be desired.

Although meeting temperature requirements can be difficult because of evolving standards as indicated above, even the uncertainty in existing criteria poses problems. For example, unless specific dimensions are specified for mixing zones, it is difficult to interpret where the maximum temperature and temperature rise above ambient should be enforced. Although most states recognize the necessity for mixing zones, only a few have stipulated actual numerical limitations as to their sizes.

Table 26 lists the pertinent temperature standards that presently apply for the States bordering the Great Lakes. Table 27 lists the addresses and telephone numbers of the Great Lakes States water pollution control agencies.

TABLE 26. Temperature Criteria for Great Lakes States

Illinois

Illinois Pollution Control Board Thermal Standards for Lake Michigan
No. R 70-2, June 9, 1971

All sources of heated effluents in existence or under construction as of January 1, 1971, shall meet the following restrictions, outside of a mixing zone that shall be no greater than a circle with a radius of 1000 ft or an equal fixed area of simple form.

Temperature: The maximum temperature rise at any time above natural temperatures shall not exceed 3°F. In addition, the water temperature shall not exceed the following monthly limits:

Monthly Maximum Temperatures, °F											
<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Aug</u>	<u>Sept</u>	<u>Oct</u>	<u>Nov</u>	<u>Dec</u>
45	45	45	55	60	70	80	80	80	65	60	50

TABLE 26 (Contd.)

Illinois (Contd.)

Any effluent source under construction as of January 1, 1971, but not in operation shall meet the following additional requirements:

1. Neither the bottom, the shore, the hypolimnion, nor the thermocline shall be affected by any heated effluent.
2. No heated effluent shall affect spawning grounds or fish-migration routes.
3. Discharge structures shall be so designed as to maximize short-term mixing and thus reduce the area whose temperature is significantly raised.
4. No discharge shall exceed ambient temperatures by more than 20°F.
5. Heated effluents from more than one source shall not interact.

No source of heated effluent which was not in operation or under construction as of January 1, 1971, shall discharge more than a daily average of 0.1 billion Btu/hr.

See Notes 1-3 at the end of this table.

Indiana

Regulations SPC-4, SPC-5, SPC-6, and SPC-1R for Lake Michigan Open, Shore, and Inner Harbor Basin Water

Temperature: Not more than 85°F (SPC-4 through -6).

The following criteria are for evaluation of conditions for the maintenance of a well-balanced warm-water fish population. They are applicable at any point in the stream (lake) except for areas immediately adjacent to outfalls. In such areas, compliance will be given to opportunities for the admixture of waste effluents with the receiving water (SPC-1R).

Implementation Plan: Drastic or sudden temperature changes will not be permitted. The Board will insist upon gradual changes in temperature, not to exceed 2°F per hour nor more than a total change in 24 hr of the maximum diurnal change or 9°F, whichever is greater.

Indiana Lake Michigan water quality standards have been approved by the U.S. Department of Interior.

See Notes 1-3 at the end of this table.

TABLE 26 (Contd.)

Michigan

Temperature Standards for Michigan, for the Great Lakes, and Connecting Water Ways

There shall be no heat load in sufficient quantity to create conditions which are or may become injurious to the public health, safety, or welfare, or which are, or may become injurious to domestic, commercial, industrial, agricultural, recreational, or other uses which are being, or may be made, of such waters, or which are, or may become, injurious to the value or utility of riparian lands, or which are, or may become, injurious to livestock, wild animals, birds, fish or aquatic life or growth or propagation thereof.

Michigan water quality standards have not been approved by the U.S. Department of Interior. Michigan has proposed the following amendments as of February 1970.

Michigan Amendments: February 1970.

General Considerations:

1. There shall be no abnormal temperature changes that may affect aquatic life, unless caused by natural conditions.
2. The normal and daily seasonal temperature fluctuations that existed before the addition of artificial heat loads shall not be prevented.
3. No heat load shall be discharged in quantity sufficient to be injurious to fish, wildlife, or other aquatic life or the growth or propagation thereof. Regardless of the standards established, if significant environmental damage is measurable, modifications must be made.
4. Natural water temperatures may, at times, be higher than the standard. However, it is intended that the water quality for a designated use be maintained, except insofar as the standard is exceeded as a result of natural conditions.
5. Maximum water temperatures shall not exceed the limits in the temperature-limitation table below. In all lakes and Great Lakes connecting waters, the point of measurement shall be in the surface one meter.

Definitions: Ambient--Ambient water temperature is the temperature of the water in a zone to be selected by the Michigan Water Resources Commission on the basis of reasonable representation of natural conditions, and will be selected from a physical situation similar to that zone receiving the heated discharge.

TABLE 26 (Contd.)

Michigan (Contd.)

Thermal mixing zones--Thermal mixing zones will be established to provide rapid cooling to the atmosphere and mixing with the receiving waters. These zones will be designed to minimize effects on the aquatic biota in the receiving waters and to permit fish migration at all times. The mixing zone will be related to the value of the aquatic life to be protected and the physical characteristics of the receiving water body.

In the Great Lakes and Connecting Waters:

Lake Michigan, below the 43° 45' latitude (a line extended due west from Pentwater, Michigan), Saginaw Bay, and Lake Erie: No increase greater than 5°F above ambient lake temperature, nor above the maximum allowable temperature shown in the temperature-limitation table (Group F).

Lake Michigan, above the 43° 45' latitude, Lake Huron (except Saginaw Bay), St. Clair River, Lake St. Clair, and the Detroit River: No increase greater than 5°F above the ambient water temperature, nor above the maximum allowable temperature shown in the temperature-limitation table (Group G).

Lake Superior and the St. Mary's River: No increase greater than 5°F above the ambient water temperature, nor above the maximum allowable temperature shown in the temperature-limitation table (Group H).

Temperature-limitation Table (Great Lakes and connecting waters)

<u>Waters</u>	<u>Monthly Maximum Allowable Temperatures, °F</u>											
	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>May</u>	<u>June</u>	<u>July</u>	<u>Aug</u>	<u>Sept</u>	<u>Oct</u>	<u>Nov</u>	<u>Dec</u>
<u>Group F</u>	50	50	60	65	75	85	85	85	85	70	60	50
<u>Group G</u>	50	50	60	65	70	80	80	80	80	70	60	50
<u>Group H</u>	50	50	55	65	70	75	75	75	75	65	60	50

Comments on Proposed Revisions to Temperature Standards

Temperature-limitation Table: Establishment of monthly maximum allowable water temperatures ensures that normal seasonal temperature variations necessary for various life processes of aquatic life will be maintained. For example, the monthly allowable maxima are tailored to provide appropriate temperatures for fish species spawning at different times of the year.

Great Lakes and Connecting Waters: The monthly maxima and variable maxima for different areas are based on a review of ambient temperatures of these waters. The areas were grouped according to their thermal similarity.

TABLE 26 (Contd.)

Michigan (Contd.)

By providing numerical monthly maxima in Great Lakes waters, we will meet the FWPCA recommendations for "open water" of Lakes Michigan and Superior which were developed by the FWPCA and the U.S. Bureau of Commercial Fisheries to protect the fishery resources of the lakes.

Mixing Zones: In areas adjacent to outfalls, the standard for the designated water use or uses shall apply after admixture of waste effluents with the public waters, but in no instance shall the mixing zone act as a barrier to fish migration or interfere unreasonably with the designated water use or uses for the area. The Commission will have discretion in determining the extent of the mixing zone.

Various formulas have been proposed to identify the extent of a mixing zone on the basis of volume of discharge. Such systems overlook the possible desirable effects or the magnitude of undesirable effects. Severely limited mixing zones are necessary where valuable water uses are threatened. However, limits on thermal mixing zones may not be necessary where water uses are not threatened.

See Notes at the end of this table.

Minnesota

Minnesota Standards WPC-15 for Lake Superior

The quality of this class (2A, Fisheries and Recreation) of interstate waters of the state shall be such as to permit the propagation and maintenance of warm- or cold-water sport or commercial fishes and be suitable for aquatic recreation of all kinds. Temperature: no material increase.

The quality of this class (3A, Industrial Consumption) of interstate waters of the state shall be such as to permit their use without chemical treatment-- for which a high quality of water is required. The quality shall be generally comparable to Class B waters for domestic consumption, except for temperatures 5°F above natural, and in no case shall it exceed 90°F.

Mixing Zone: Means for expediting mixing and dispersion of waste effluents in the receiving interstate waters shall be provided so far as practicable when deemed necessary by the Minnesota Pollution Control Agency.

Minnesota Lake Superior water quality standards have been approved by the U.S. Department of Interior.

See Note 4 at the end of this table.

TABLE 26 (Contd.)

New YorkCriteria Governing Thermal Discharges in Lakes

The water temperature at the surface of a lake shall not be raised more than 3°F over the temperature that existed before the addition of heat of artificial origin, except that within a radius of 300 ft or equivalent area from the point of discharge; this temperature may be exceeded. In lakes subject to stratification, the thermal discharges shall be confined to the epilimnetic area.

It is recognized that a radius of 300 ft or equivalent area may be too liberal or too restrictive and that a lesser or a greater area may be required or permitted under the procedures set forth in "Additional Limitations or Modifications."

Additional Limitations or Modifications

1. The Commissioner of Health may impose limitations and/or conditions in addition to the stated criteria where he determines, in the exercise of his discretion, that such additional limitations and/or conditions are necessary to maintain the quality of the receiving waters for the "best usage" classifications and standards assigned by the Water Resource Commission pursuant to Public Health Law, Article 12, §1205.
2. The Commissioner may authorize a conditional modification of the stated criteria upon application. Upon receipt of such application, the Commission shall confer with the Federal Water Pollution Control Administration and shall transmit to that agency information to enable the Secretary of the Interior to fulfill his responsibilities under Federal law. The applicant shall have the burden of establishing to the satisfaction of the Commissioner of Health that one or more of the criteria are unnecessarily restrictive as to a particular project in that a modification of such criterion, or criteria, as the case may be, would not impair the quality of the receiving waters so as to adversely affect them for the "best usage" classifications and standards assigned by the Water Resources Commission. The Commissioner may, when he determines it to be in the public interest, hold a public hearing upon the application.
3. Any such modification shall be conditioned upon postoperational experience. Plans for additional treatment of, or change in, the thermal discharge shall be developed and submitted as part of the application to the Commissioner, which shall be implemented upon order of the Commissioner in the event that postoperational experience shows a trend toward impairment by the discharge of the quality of the receiving waters for the assigned "best usage" classifications and standards.

TABLE 26 (Contd.)

New York (Contd.)

Except for the thermal discharge policy, New York water quality standards have been approved by the U.S. Department of Interior.

Ohio

Water Quality Criteria for Lake Erie for Various Uses

The Stream-Water Quality Criteria for Various Uses adopted by the Ohio Water Pollution Control Board on June 14, 1966, shall apply as a minimum to all Lake Erie waters in Ohio, and the existing lake water quality shall apply where better than the criteria for streams adopted by the Board. The existing lake water quality shall be as reported by the FWQA in the chapter on Water Quality in the report "Program for Water Pollution Control - Lake Erie - 1967." (This report has never been published.)

The following criteria are for evaluation of conditions for the maintenance of well-balanced warm-water fish population. They are applicable at any point except for areas necessary for the admixture of waste effluents with stream water. Temperature: There shall be no abnormal changes that may affect aquatic life, unless caused by natural conditions. The normal daily and seasonal temperature fluctuations that existed before the addition of heat due to other than natural causes shall be maintained.

Ohio Lake Erie standards have not been approved by the U.S. Department of Interior. At the time of this writing, there was proposed legislation before the Ohio legislature recommending a 1°F discharge limit for Lake Erie.

Pennsylvania

Water Quality Criteria for Lake Erie--Article 301

For New York to Ohio State Lines: Temperature shall not be increased by more than 5°F above natural temperatures nor be increased above 85°F.

For Erie Harbor and Presque Isle Bay: Temperature shall not exceed 5°F rise above ambient temperature or a maximum of 87°F, whichever is less; it shall not be changed by more than 2°F during any 1-hr period.

Pennsylvania uses an undefined mixing-zone concept and therefore considers thermal discharges on an individual basis.

Pennsylvania water quality standards for Lake Erie have been approved by the U.S. Department of Interior.

TABLE 26 (Contd.)

Wisconsin

Interstate Standards Published in the REGISTER RD 3.04 and 3.06

Lake Superior and Lake Michigan are used for recreation, commercial and recreational fishing, shipping, municipal water supply, industrial and cooling water, and waste assimilation. Lake Superior and Lake Michigan open waters should meet the criteria and requirements for all water uses. Harbor areas and shoreline sections in the vicinity of pollutional outlets should meet minimum criteria plus requirements for cooling and industrial water supply. Beach waters of Lake Superior and Lake Michigan should meet the standards for whole body contact recreation.

Limiting Criteria: The following are applicable to surface waters where maintenance of fish is of primary importance. Temperature shall not exceed 84°F. There shall be no change from natural unpolluted background by more than 5°F at any time nor at a rate in excess of 2°F per hour.

The following are applicable to surface waters where fishing is desirable in conjunction with other uses: Temperature shall not exceed 89°F for warm water fish. There shall be no abrupt change from background by more than 5°F at any time.

The following is applicable to surface waters designated for industrial processes and cooling purposes: Temperature shall not exceed 89°F.

Mixing Zone: The Wisconsin Department of Natural Resources may require management of waste-admixture zones depending on such factors as effluent quality and quantity, available dilution, temperature, current, and restrictions to the movement of fish.

Wisconsin standards for Lake Superior and Lake Michigan have been approved by the U.S. Department of Interior

See Notes 1-3 at the end of this table.

Ontario, Canada

June 1970 Guidelines and Criteria for Water Quality Management in Ontario

Section 2.1. Zones of Passage and Mixing: Mixing zones in the vicinity of outfalls should be restricted as much as possible in extent and should provide for the safe passage of both fish and free-floating drift organisms. Every precaution should be taken to ensure that at least two-thirds of the total cross-sectional area of the river or stream is characterized by a

TABLE 26 (Contd.)

Ontario, Canada (Contd.)

quality that is naturally favorable to the aquatic community at all times. In most cases, this would preclude the use of a diffuser outfall which would distribute effluent uniformly across the river or stream. The water quality standard which defines acceptable concentration of a substance contained in a waste discharge will apply at the periphery of the mixing zone or other specified sampling locations.

Within mixing zones, it should be recognized that toxic wastes which will evoke an avoidance response on the part of fish or other organisms should not be permitted. Where toxic materials are being discharged, it should be assumed that the various components in the waste, regardless of the form in which they are present, may eventually be altered to the most toxic form in the aquatic environment. Adequate treatment of all waste should be provided, and mixing zones should in no way be considered as a substitute for proper treatment.

Section 2.4. Water Quality Temperature Criteria for the Protection of Fish, Other Aquatic Life, and Wildlife

1. General--Unless a special study shows that discharge of a heated effluent into the hypolimnion of a lake will be desirable, such practice is not recommended and water for cooling should not be permitted to be discharged from the hypolimnion into the main body of water.

The normal daily and seasonal temperature values that were present before the addition of heat due to other than natural causes should be maintained.

Wherever possible, heated discharges should be located where elevated temperature will enhance public utilization of the water by supporting a wider variety of water usage.

2. Great Lakes and Connecting Waters

a. Heated discharges are not permitted that may stimulate production of nuisance organisms or vegetation, or that are or may become injurious to wildlife, water fowl, fish, or aquatic life, or growth and reproduction thereof. For each discharge of a heated effluent, acceptable mixing zones will be established on the basis of feature and fact pertinent to that specific situation.

TABLE 26 (Contd.)

Ontario, Canada (Contd.)

b. Heat may not be discharged in the vicinity of spawning areas or where increased water temperatures might interfere with recognized movements of spawning or migrating fish population.

Section 2.6. Criteria for public water supply maximum allowable temperature of 85°F.

Notes

1. In a policy statement read to the Lake Michigan Enforcement Conference, May 1970, the Department of Interior proposed that no more than a 1°F rise above ambient temperature be allowed for any effluent discharged into Lake Michigan.
2. In a report, "Physical and Ecological Effects of Waste Heat on Lake Michigan," issued one week before the September 28 through October 2, 1970 Lake Michigan Enforcement Conference, the Department of the Interior recommended that "no significant amounts of waste heat should be discharged into Lake Michigan."
3. In a letter dated March 23, 1971 to the Lake Michigan Enforcement Conference conferees, William D. Ruckelshaus, Administrator of the National Environmental Protection Agency, recommended "that limitations should be placed on large-volume heated-water discharges by requiring closed-cycle cooling systems using cooling towers or alternative cooling systems on all new power plants and addition of such cooling facilities to plants now under construction." This announcement in effect supersedes the two previous announcements. At the moment, the EPA policy statement is a recommendation which must be acted upon by the states involved (Wisconsin, Illinois, Indiana, and Michigan) and their deliberations approved by EPA. As of this writing, it appears that only Illinois and Michigan will not accept the proposed regulations without some modifications.
4. The Lake Superior Enforcement Conference Technical Committee, April 1970, suggested as a guideline that no material increase be allowed in temperature in Lake Superior.

TABLE 27. Great Lakes States Water Pollution Control Agencies

<u>Illinois</u>	<u>New York</u>
Illinois Environmental Protection Agency Bureau of Water Pollution Control 2200 Churchill Road Springfield, Illinois 62706 Telephone: (217) 525-6171 FTS Springfield 8-217-525-4200	New York State Department of Environmental Conservation Division of Pure Waters 50 Wolf Road Albany, New York 12201 Telephone: (518) 474-2121/3329 FTS Albany 8-518-472-4411
<u>Indiana</u>	<u>Ohio</u>
Indiana State Board of Health Stream Pollution Control Board 1330 West Michigan Street Indianapolis, Indiana 46206 Telephone: (317) 633-5369 FTS Indianapolis 8-317-633-7000	Water Pollution Control Board Ohio Department of Health 450 East Town Street P.O. Box 118 Columbus, Ohio 43216 Telephone: (614) 469-4891 FTS Columbus 8-614-649-6600
<u>Michigan</u>	<u>Pennsylvania</u>
Department of Natural Resources Water Resources Commission Stevens T. Mason Building Lansing, Michigan 48926 Telephone: (517) 373-356(0,1,2) FTS Lansing 8 517-372-1910	Sanitary Water Board Pennsylvania Department of Health P.O. Box 90 Harrisburg, Pennsylvania 17120 Telephone: (717) 787-4056 FTS Harrisburg 8-717-787-2200
<u>Minnesota</u>	<u>Wisconsin</u>
Minnesota Pollution Control Agency 717 Delaware Street, S.E. (Oak and Delaware Streets, S.E.) Minneapolis, Minnesota 55440 Telephone: (612) 378-1320 FTS Minneapolis 8-612-725-4242	Department of Natural Resources P.O. Box 450 Madison, Wisconsin 53701 Telephone: (608) 266-2879 FTS Madison 8-608-256-4441
<u>Ontario (Canada)</u>	
Ontario Water Resources Commission Water Quality Surveys Branch 135 St. Clair Avenue, West Toronto 7, Ontario, Canada Telephone: (416) 363-1211	

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