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WATER RESOURCES RESEARCH PROGRAM

ANALYSIS OF THREE YEARS OF
COMPLETE-FIELD TEMPERATURE DATA FROM
DIFFERENT SITES OF HEATED SURFACE DISCHARGES
INTO LAKE MICHIGAN

by

J. M. Kyser, R. A. Paddock,
and A. J. Policastro

GREAT LAKES PROJECT

ENERGY AND ENVIRONMENTAL
SYSTEMS DIVISION

ENVIRONMENTAL STATEMENT PROJECT

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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Energy and Environmental Systems Division
Great Lakes Project

August 1974

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ABSTRACT

A systematic analysis has been made of temperature measurements of surface thermal plumes under varying environmental conditions. In total, 15 plumes from Palisades, 22 from Point Beach Unit 1, 6 from Point Beach Units 1 and 2, 2 from Waukegan, and 1 from State Line were analyzed.

Plume characteristics of centerline temperature decay, temperature half-widths, and isotherm areas showed wide variation at a site as environmental conditions changed. It was found, however, that the Palisades and Point Beach Unit 1 data each fit rather neatly into five categories distinguished by ranges in current, wind, and lake conditions.

Plumes from these different sites were compared for similar environmental conditions. The Waukegan site demonstrated the most rapid plume dilution in terms of centerline temperature decay and isotherm areas due to its large outfall densimetric Froude number (≈ 9.7). The State Line site with its low initial densimetric Froude Number (≈ 1) showed the least rapid plume dispersion. The Point Beach Unit 1 and Palisades discharges, although having nearly equal heat-rejection rates and initial densimetric Froude Numbers (≈ 2.4), had significantly differing plume characteristics due to the large outfall aspect ratio difference. The plumes at Palisades had a generally slower centerline temperature decay and larger areas than at Point Beach.

1. INTRODUCTION

Systematic analyses of thermal plumes at existing plant sites are most lacking in the literature on physical effects of thermal discharges from steam electric power plants. Such analyses are important for the proper design of future power-plant outfalls as they aid in:

- (a) establishing the performance of various discharge designs in satisfying specific water quality standards, as well as serving as an aid in the determination of such standards,
- (b) understanding the physical characteristics of the plume required for the prediction of possible ecological effects associated with the heated discharge, and
- (c) understanding the mechanism of recirculation between intake and outfall and learning how it may be minimized to avoid loss of power plant efficiency.

The goal of this report is to increase our understanding of surface thermal-plume behavior by analyzing large amounts of data taken under a wide range of environmental conditions at two sites on Lake Michigan. Supporting data from two other sites on the lake are also analyzed. A second

goal is to provide data on plume characteristics that may be used to verify mathematical models for thermal plumes.

The paucity of prototype data for surface thermal discharges has often been documented. [1], [2] This lack of data on thermal-plume behavior fostered the development of numerous mathematical models, each attempting to predict thermal-plume dispersion from shoreline canal discharges. To date, however, none of those models has been sufficiently verified with prototype data to allow them to be used comfortably in a predictive sense. With a more complete library of plume data at hand, plume models can be further verified. More importantly, our increased understanding of plume physics will allow improved models to be developed. Model assumptions may be checked and improved by analysis of the experimental data. Also, the data will indicate which of the observed characteristics of thermal plumes may be predicted by present-day deterministic models. The significance of the data and analysis given below transcends shoreline surface discharges: plumes from submerged discharges eventually reach the surface and disperse by the same mechanisms as surface plumes under like environmental conditions.

To date, the majority of analytical models for surface thermal plumes have been verified using only hydraulic scale model data or sparse field data. Most of the available data on surface thermal plumes has been acquired in hydraulic-model studies. Nearly all of this data are from undistorted models of the near-field region of the plume. Such physical models are flexible and allow numerous tests to be made, each test varying important plume parameters. In this way, various physical phenomena involving plume dispersion may be studied under laboratory-controlled conditions. This provides a definite advantage in any basic study of thermal plume dispersion. These undistorted hydraulic models, however, cannot adequately simulate far-field phenomena such as surface-heat loss, interfacial friction, ambient turbulence, and wind and wave effects. These phenomena become important in regions of the plume where jet momentum has essentially dissipated. The impossibility of simultaneously satisfying all the appropriate model-scaling parameters in either an undistorted or distorted model leads to only a partial picture of the plume.

Most of the prototype field data available in the literature are sketchy in that the data are not sufficiently refined to extract the major plume characteristics. Moreover, in much of the data, not all the important plume parameters were measured. Only recently have some large efforts been undertaken other than by Argonne National Laboratory, attempting to provide more complete sets of data. Noteworthy is the data collected at the Lakeview Generating Station on Lake Ontario, [3] the Pilgrim Plant in Massachusetts on Cape Cod Bay, [4] and the Surry Plant on the James River. [5] As long as the value of a mathematical model remains determined by how well it predicts results in the field, thorough monitoring programs will be required to obtain a large body of data under a wide range of conditions to fully and fairly evaluate and improve these models.

2. THE PLANT SITES AND DATA ACQUISITION

Three-dimensional temperature data were taken [6], [7], [8] at four sites of heated surface discharges on Lake Michigan during the 1971, 1972, and 1973 field years. Chosen were the Point Beach, Waukegan, and State Line sites on the western or southwestern shore of the Lake, and the Palisades site on the eastern shore. Figure 1 sketches the outfall and shoreline configuration of these plants. Table I (appearing with Fig. 4) summarizes the basic characteristics of the outfalls and their warm-water discharges. The Point Beach Plant has two identical units with condenser cooling water dis-

charging from two outfalls, each at a 60° angle to the Lake Michigan shoreline. In total, for the 1971 and 1972 surveys, there are 22 plumes from Point Beach Plant Unit 1, 12 from the Palisades Plant, two from the Waukegan Plant, and one from the State Line Plant. The 1973 field-year data discussed in this paper consists of six Point Beach plumes in which both units were operating at nearly full power.

The sites chosen represent a significant diversity in discharge designs. Point Beach and Palisades have nearly the same power level with very similar low densimetric Froude Numbers ($F_0 \approx 2.4$), yet with significantly different aspect ratios (outfall width divided by its depth). The Point Beach outfall has a width-to-depth ratio of 2.5, while at Palisades the same ratio is 13.5. Consequently, the Palisades plume is discharged as a longer and more slender sheet of heated water at the surface of the Lake. The State Line Plant has an even larger aspect ratio of 30.9, with an extremely low densimetric Froude Number (≈ 1). This low-velocity discharge is in contrast to the high-velocity Waukegan discharge, $F_0 \approx 9.7$; State Line and Waukegan both have rather large aspect ratios, the Waukegan Plant having a value of 20.1. The effect on the plume of initial densimetric Froude Number, aspect ratio, and plant power level will be described in more detail in the sections analyzing the data from the above sites.

Figures 2-4 illustrate sample surface isotherms from each of the power plants studied. Examples of plumes from Point Beach with Unit 1 operational and then both units operational are given in Fig. 2.

The three-dimensional temperature data obtained in 1972 and 1973 were acquired using a 5.5-m cathedral-hull fiberglass boat traveling in a serpentine path from the outfall to the far expanses of the plume. A submerged boom was attached to the boat's gunwale to which six thermistors were fastened at 0.5-m intervals to 3 m. A surface float with a similar thermistor attached was used to measure surface temperature.

Analog information proportional to temperature from these seven Yellow Springs Instruments Type 709 linearized thermistors was sampled at time intervals determined by a solid-state clock and selected by the operator. The signals from the thermistors were digitized and displayed on light emitting diodes, printed on paper tape, and recorded on magnetic tape. Each time the thermistors were sampled, information from the clock, the depth-finder, and the positioning equipment was also displayed and recorded. It was possible to measure temperature as a function of depth from the moving boat at about 1800 known locations in about 1 hour, typically covering about 8 linear kilometers. The positioning system that made this possible is the Motorola Mini-Ranger which consists of two shore-based transponders and a receiver/transmitter unit and range console on board the boat.

The plume data were transcribed from the original cassette and read on to magnetic tape. With additional calibration data, the magnetic tape was used in a computer program that was developed to plot the data. Seven horizontal plots representing data taken at seven depths were plotted by a Calcomp Digital Incremental Plotter. The isotherms and centerlines were drawn by hand on this output. The surface isotherms in Figs. 2-4 were obtained by this process. During the 1972 field year alone, these automated data-collection and -reduction techniques have allowed the acquisition and reduction of about 30 plumes, consisting of about 200 horizontal (as well as 200 vertical) sections.

Ambient conditions were routinely measured in conjunction with the plume mapping. Ambient lake current was measured with a Bendix Q-15 geomagnetic ducted-impeller current meter. Wind speed and direction were measured with a hand-held anemometer on the boat and by a shore-based Meteorology Research, Inc. (MRI) portable meteorological station. Air temperature, humidity, lake conditions, etc., were also measured for each plume. Table II lists the instrument specifications for the 1972 and 1973 field year data.

The 1973 data-gathering system was improved over the 1972 system only in the use of faster response YSI Series 700 linearized thermistors for temperature measurements. These thermistors were specially made with 0.6-s time constant.

The system for data acquisition was somewhat less sophisticated in field year 1971. The major difference was that data were taken only in paths between numbered buoys located in the plume. The recording technique used involved manually switching from one probe to another, and transcribing by hand the temperature displayed on the digital thermometer. A constant speed was maintained by the boat between buoys, and a constant time interval between interrogations of each probe was assumed. A second-generation plume-measuring system, which eliminated the manual interrogation and recording of temperature information, was used from August 16, 1971 until the end of the 1971 field year. Ambient current measurements were made in that year using an Ekman-Merz current meter; as with the Bendix Q-15, it has an impeller with a directional vane which orients the impeller. Meteorological measurements were taken solely on the boat; wind measurements were made using a Weather-Measure Three-Cup anemometer with direction vane and a meter read-out. Consequently, the 1971 data were not as refined as for the field year 1972. References 6-8 describe the data collection and instrumentation as well as the individual plumes themselves in more detail.

The isotherm maps drawn from the plots of the boat measurements were then analyzed for plume characteristics: centerline trajectories, centerline temperature decays, temperature half-widths, surface isotherm areas, and temperature half-depths along the centerline. These characteristics will vary with current magnitude and direction, wind speed and direction, ambient lake turbulence, and surface heat loss, as perhaps the most important parameters. Most plumes from the same site were found to have similar excess temperatures and discharge flow rates; this is no surprise since they are all base-loaded plants. Consequently the flow rate and excess temperature variation were not considered as important in determining plume characteristics as were the environmental conditions.

Tables III, IV, and V summarize the data acquired at the above four sites during the 1971, 1972, and 1973 field years. The large amounts of data taken at the Point Beach and Palisades sites were required for an understanding of the different types of plumes possible at the given site as ambient conditions vary. It was possible to classify the plumes measured at Point Beach and Palisades into five categories. These categories are listed in Tables III and IV and specified by the variation in ambient current and wind at these sites. Figure 5 illustrates the wide range in excess-temperature ratios measured along the plume centerline at the Palisades and Point Beach sites as ambient conditions changed from plume to plume. The letters in this figure refer to specific plumes listed in Tables III and IV. The division of data into like environmental conditions as done in Tables III-V thus becomes advantageous. (It should be kept in mind that additional data at these sites might indicate some new categories.) The sets of plume data presented in Tables III-IV were analyzed each within its own category, and finally the averaged characteristics were inter-compared. The results are discussed below.

3. DISCUSSION OF PALISADES PLUMES

The Palisades data are plotted in Figs. 6-17, grouped according to environmental conditions. This was found to be the most productive approach in attempting to explain physically the variations found in the data. It thereby aided in understanding the causes of the large scatter (see Fig. 5)

that appears when all 15 Palisades plumes are plotted together for each of the major plume characteristics. These categories (for Point Beach Unit 1 as well as Palisades) attempt to separate the plumes in terms of major physical processes involved in plume dispersion.

To obtain the plots in Figs. 6-13, plume characteristics were plotted by categories using letters to signify the data points. Straight line segments were drawn between data points of the same plume. Then values of θ_c/θ_0 (ratio of centerline excess temperature above ambient to initial excess temperature above ambient) and W_T (left or right temperature half-width) were then averaged at 50 m increments of centerline distance. "Left" and "right" half-widths are defined as the left and right (looking offshore) lateral distances from the centerline to one-half the local centerline excess temperature. The area averaging was accomplished at θ/θ_0 increments of 0.05; here θ is the excess temperature above ambient of the isotherm of interest.

Standard deviations were also calculated at each averaging. The "averaged data" curves are plotted as solid curves and the envelope of $\pm$ one standard deviation for θ_c/θ_0 , W_T , and isotherm areas is also shown as the shaded region in each of Figs. 6-13. Categories or sub-categories which consist of one plume only are plotted as dashed lines. Centerline temperature and widths are plotted versus centerline distance, s . Plotted in Figs. 14-17 are the averaged data curves for each category and each plume characteristic: centerline temperature decay, left and right temperature half-widths, and isotherm areas.

At Palisades, Category I represents 7 plumes which have moderate shore-parallel currents with light or moderate wind. The six plumes A, B, D, E, F, G were taken under calm lake conditions and have similar centerline temperatures, widths, and areas; together they are denoted Category I(a). Plume H was taken under like current and wind conditions except that the lake condition was rough, indicating that greater ambient turbulence was present. All plumes in Category I are significantly bent by the ambient current with a consequent prevention of inshore water entrainment. The additional dilution water to be provided by the moderate ambient current is thus significantly offset by the downcurrent shoreline interference.

Plumes X, Y, Z, which make up Category II, were taken under very similar environmental conditions. Here, extremely large currents ($R \equiv$ ambient velocity/discharge velocity = 1.3 - 1.9) forced the Palisades plumes to hug the shoreline for many kilometers downcurrent. The correlation of the X, Y, Z data in terms of centerline temperatures, half-widths, and areas is remarkable. The rough conditions provide much ambient turbulence that erodes the bottom interface between the plume and ambient water causing a deeper and more vertically-mixed plume. These plumes are characterized by their long, slender shape located adjacent to the shoreline for large distances downcurrent.

Categories III and IV represent plumes under stagnant and onshore current conditions, respectively. These plumes are characterized by their wide, fan-shaped configuration much like the spread of a pool of hot water on a stagnant or near-stagnant ambient body of water. Only one plume was available for each category. Both plumes are similar in appearance partly because the low-moderate onshore current does not significantly distort the plume isotherms. The stagnant lake plumes and the onshore current plumes are often thought to be the most critical in the design of outfall in terms of their expectedly large surface areas and minimal plume-dilution capability.

Category V represents the case of a low or moderate offshore current and wind. Correlation of the data within this category for plume characteristics (except plume C for isotherm areas) is again quite remarkable. Plumes here appear to be directed offshore with less dispersion laterally than occurs under stagnant or onshore conditions. Calm or rough lake conditions

did not seem to be very significant here; rougher conditions did give slightly better dilution with smaller plume widths, as expected.

The results of the five-category comparison will now be discussed. Categories III and IV have the largest plume temperatures, widths, and areas; this is to be expected. (Category I(a) has comparably large centerline temperatures and isotherm areas; this will be discussed later.) The stagnant-lake plume in Category II has a reduced amount of available entrainment water due to the lack of a current to flush the heat offshore or downstream. Plume half-depth measurements¹ indicate an average plume thickness of about 0.6 m for plume I of Category III. The thin nature of this plume is due to the effect of buoyancy and consequent plume stratification (due to the absence of current advection and mixing) occurring a short distance from the outfall. Conservation of heat energy would then imply high temperatures and large surface areas for this category. The onshore current Category IV indicates slightly reduced areas and widths than Category III but increased centerline temperatures. The average half-depth of plume J was a deeper 0.75-1.25 m. This increased depth is probably due to the fact that a portion of the plume is being swept into the return current under the lake surface that must exist due to the presence of the shoreline. The usual effect of an ambient current is muted here since its onshore nature cuts off an edge of possible entrainment water due to the presence of the shoreline.

More data are required before one can more surely conclude that the stagnant lake situation is the most critical situation for outfall design; the subsurface return current that exists due to a skew onshore ambient current apparently aids in the advection of some power plant waste heat away from the plant.

Categories I and II involve Palisades plumes under moderate and large shore-parallel ambient currents. The scatter that exists within Category I may be explained in part as a result of increased ambient stratification during the day as plumes were taken. Note from Table III that plumes A, B, and D, E, F, G were taken on the same days; ambient temperatures with depth increased during the day. The effect of ambient stratification should be to reduce vertical mixing and consequently increase horizontal spread. The general trend of the data in Category I(a) is indeed an increase in θ_c/θ_0 , plume widths, and areas at the surface. Plume depth for June 20 (plumes D, E, F, and G) was noted to decrease during the day from 1.25 m to 0.3 m as ambient stratification strengthened.

Rough lake conditions as exist for Category I(b) are quite significant in increasing vertical mixing and plume depth (plume H has a half-depth of 1.0 m) and consequently reducing centerline temperatures. Horizontal ambient turbulence apparently increases the plume width with the overall effect of reducing plume areas.

The differences between the plume characteristics of centerline temperature decay and isotherm areas between Categories I(a) and III seem minimal. Thus, Category I(a) can be considered just as critical, with the data presently available, as Categories III and IV. The advantage in Category I(a) of the moderated shore-parallel current is significantly offset by the cut-off of inshore entrainment. When the ambient current becomes sufficiently large, however, as exists in Category III, significant reduction in areas and widths do occur.

Category II plumes closely resemble rapid river plumes in which a large current compresses the thermal plume against the shoreline. As with such river plumes, there is rather rapid temperature decay and dilution near the

¹Half-depth is defined as the vertical distance from the local surface centerline to one-half the local centerline excess temperature.

outfall as the ambient current/plume interaction is greatest; however, after the plume has mixed vertically from lake surface to bottom, the predominant mixing and dispersion process becomes lateral spreading due to ambient lake turbulence. Mixing occurs both laterally and vertically in an initial 100 m downcurrent region. Plume widths increase very slowly after that 100 m distance downcurrent. This slow increase in width is probably due to the ambient turbulence slowly eroding the offshore side of the plumes and not to any significant buoyant spreading. The slow erosion of the bottom of the plume by ambient turbulence is probably the cause of the rather rapid centerline temperature decay from 100 m to 1000 m. The minimal temperature decay beyond 1000 m is due mainly to the cutoff of inshore entrainment by the shoreline and the establishment of a vertically-mixed plume, surface to bottom.

Plume areas are quite small due to the large plume depth caused by the significant vertical mixing. This mixing allows the distribution of the plant heat over a larger depth, yielding smaller surface areas.

The averaged areas and widths in Category II indicate that this rapid current situation is not the most critical case for lake plumes if isotherm areas or widths are judged most important. If the criteria of importance is centerline temperatures at distances far from the outfall or perhaps whether regions of shallow or shoreline waters are affected, then this case is significant.

Category V represented by plumes C, K, and L yields the best mixing and dilution. Plant waste heat is advected offshore not merely by outfall momentum, but by the presence of an offshore current. Here, entrainment can occur from both sides of the plume (as opposed to one side for plumes in Categories I and III). Average plume depths in this category were the largest at 1.25-1.5 m. The offshore current, as well as its deeper return current, probably aids in the generation of additional vertical turbulence which assists in that larger plume depth. The offshore current (or better, the skew offshore current) avoids the possibility of a significant re-entrainment of ambient water that probably occurs for the stagnant and on-shore Categories III and IV.

The areas for Category V are biased to be larger than the average of plumes K and L by an inordinately large area for plume C. It is speculated that isotherm areas for C might be too large because of difficulties in contouring resulting from a rather large horizontal stratification on that day. The outer extremities of plume C could not, therefore, be very satisfactorily determined. It might be best, under these circumstances, to expect isotherm areas more in line with the average of K and L than that indicated in Fig. 13.

4. DISCUSSION OF POINT BEACH UNIT 1 PLUMES

The Point Beach Unit 1 data are plotted in Figs. 18-28 in terms of five categories of environmental conditions. The technique of data reduction and plotting is the same as done for the Palisades plumes. The scatter within the data is significantly less at Point Beach than at Palisades as evidenced, for example, in Fig. 5. This is true for centerline temperature decay, half-widths, and areas. This may be explained in that environmental conditions do not vary as greatly as they do at Palisades.

The term "moderate" or "strong" in reference to currents at Point Beach refers only to the range in magnitude of currents at that site only. The same terms applied to Palisades will refer to a different range in current magnitudes. Having a smaller range in currents at Point Beach seemed an advantage at first; however, this was found to cause more difficulty in defin-

ing categories to which the plume data might belong. Further complicating the Point Beach data reduction is the fact that ambient currents were not measured on seven occasions² and that the smaller currents observed at Point Beach lend themselves to greater inaccuracies in magnitude and direction. Consequently, plume categories were determined by a combination of measured currents and plotted trajectories. Wind speed and direction were also considered but on a secondary basis. Notice that the measured currents in Categories I and II overlap. Current measurements were generally made before and after a plume survey; the average of these measurements can be significantly different from the actual currents felt by the plume during the survey, especially under low-current or stagnant-lake conditions. However, it was found that plumes with similar trajectories also had similar plume characteristics, even though their measured currents might have differed by a factor of 2.

The 60° southward orientation of the Unit 1 outfall at Point Beach required distinguishing between the north and south shore-parallel currents. Categories I and II include plumes with an ambient current directed north.³ An example appears in the left side of Fig. 2. The discharge momentum is here opposing the current. Once the effluent momentum has become dissipated by the oncoming current, the plume drifts passively to the north. The centerlines of these plumes bend greatly in the presence of the north current for those categories. The interaction between the plume and ambient current dominates the dispersion. The data in Category I (strong north current ≈ 15 cm/s) shows very little variation within itself. In this category the plume trajectories were nearly coincident. The most rapid dilution occurred for these plumes. Smaller north currents (≈ 10 cm/s) are grouped together in Category II. Category II results are similar to those of Category I, but less exaggerated. Also, more variation (spread within the group of data) existed for Category II.

The left widths for Categories I and II are nearly the same (with that of Category I being a little larger), but the right widths for Category I are about half those of Category II. The skewness of the lateral temperature distribution is clearly seen by comparing left and right half-widths in the same category for I and II. Category I, for instance, has a left half-width about three times its right half-width. This is due to the compactness of isotherms on the upcurrent side of the plume (here, the right side); the larger the current, the closer the isotherms become due to the sharper upcurrent interface, causing smaller half-widths. A larger current will have the tendency to spread or fan out the plume on the lee (left) side due to the shearing effect caused by the velocity distribution that exists from plume surface to ambient water below the plume bottom interface.

An examination of plume half-depths for these categories yielded 1.5-2.75 m, significantly larger than for the zero current or south current plumes, Categories III-V. Deepening of the plumes for the north-directed currents is expected since plume entrainment is commonly considered to be proportional to the magnitude of the vector difference of the plume centerline velocity and ambient current velocity. The deeper plumes for Categories

²Due to the failure of an in situ current meter, ambient current measurements were not obtained for these plumes.

³Plume U was not used in the averaging of Category II due to its extremely large areas (about ten times greater than any other Point Beach Unit 1 plume for $\theta/\theta_0 \leq 0.5$). It is thought that this plume was measured under changing current conditions and does not represent a quasi steady-state entity.

I and II are the main causal factor in the rapid centerline temperature decays observed and the lower surface isotherm areas for these two categories. As expected, plume areas for Category I are smaller than for Category II due to the greater ambient current interaction.

Another factor that aids in dilution for Category I and II plumes is the long distance (≈ 700 m) it takes these plumes to dissipate their discharge momentum and initiate a bending to the north. This long distance coupled with the deeper extent of these plumes provides a larger area of interaction of these plumes with the oncoming colder ambient current. This long plume expanse during bending also does much to reduce any cutoff of inshore entrainment on the left side of the plume which might have been caused due to the presence of the 62-m discharge canal jutting out into the lake. Ambient water cannot pass to the lee side of the plume directly due to this canal and must go around to the offshore side or under the plume or mix directly with the plume. If plumes with larger north-directed currents than obtained in Categories I and II were observed, one would expect a greater centerline temperature decay, reduced right half-widths, nearly equal left half-widths, greater half-depths, and smaller isotherm areas. Additional data at Point Beach Unit 1 may verify our intuition, based upon the above data.

The plumes in Category III (small to zero current) show the most variation in the spread of data points. This may indicate that when the current is small, other lake and atmospheric parameters become important. The difference in data between the sub-categories III(a) (zero current; light, moderate wind), III(b) (small current; light wind), and III(c) (zero current, zero wind) is quite broad and quite difficult to explain. First, there was quite a variation in trajectories throughout Category III. Five plumes had a measured ambient current of zero but slightly curved trajectories (the threshold of the current meter is 2 cm/s so any current less than that figure will be read as zero); however, low current plumes H and L had trajectories not much different from these. Another complicating factor was the presence of horizontal ambient stratification. The variation in ambient temperature in the offshore direction made it difficult to determine if the trajectory headed north or south for the plumes with near-zero ambient currents. Basically, any doubt in the location of isotherms made it especially difficult to draw trajectories from the data and thus categorize the plumes. The plumes with north currents showed no such problem. The plumes for Categories III and IV were difficult to distinguish.

In spite of these difficulties, the data in Category III appeared to fall into three subcategories: Category III(c) represents the true stagnant lake plume. It has the slowest centerline temperature decay and largest areas of Category III. Category III(a) with a zero current and light, moderate wind showed better dilution in terms of smaller centerline temperatures and areas. Category III(b) with a small current and light wind had even smaller centerline temperatures and areas. The widths are somewhat enigmatic. Right half-widths could only be extracted for Category III(a) since, for Categories III(b) and III(c), the presence of the south shoreline fostered re-entrainment of heated water to the point that the lateral temperature excess did not drop to one-half the centerline value on that side of the plume. The total plume widths (left plus right), therefore could not be compared. Still unexplained is the relative orientation of the left half-widths for Categories III(a), (b), and (c) in the bottom diagram of Fig. 20. Also difficult to explain is the unexpected success in reducing centerline temperatures and surface areas exhibited by the small current Category III(b), in comparison to the north current Categories I and

II. Our analysis of Category III can only indicate the sensitivity that current and wind have on plume characteristics at their low-to-zero values.

Categories IV and V represent the moderate- and strong-current groups for Point Beach Unit 1. Category V, with its large south currents, has larger areas and a less rapid centerline temperature decay than does Category IV. Category V plumes are pushed against the shoreline with a significant cutoff of inshore entrainment and re-entrainment of already mixed plume water. Plumes in Category IV (currents ≈ 10 cm/s) also have this cutoff of inshore entrainment. Right half-widths did not exist for these categories due to warm water between the centerline and the shore preventing temperatures from reaching half their centerline values. The 60° outfall at Point Beach fosters this re-entrainment phenomenon into the generation of wide, shore-touching plumes for any plume in Categories III-V. To further underscore the difficulty in obtaining meaningful half-width data within a category for Point Beach, consider Fig. 21, Category V. The wide variation in widths here is partly due to:

- (1) probability of a very large current for plume Q compared to plume Y, causing it to hug the south shoreline for many kilometers downstream (as expected from observing isotherm maps for that date), and
- (2) the presence of horizontal ambient stratification for plume Y, making it difficult to extract a good centerline and significant left half-widths.

Surprisingly, plume areas for Q and Y are very nearly equal.

Comparing Categories IV and V to Categories I-III, it appears that higher temperatures and areas are to be expected when moderate and strong south currents are present for Point Beach Unit 1 plumes. There is much overlap, however, between envelopes of these categories. Left half-widths do not vary much among all five categories; right half-widths are generally nonexistent due to shoreline interaction and cutoff of inshore entrainment, except for plumes directed north.

The small variation in current that exists at Point Beach has clearly made analysis of the data difficult since we are working with current magnitudes that challenge the precision of measurement. Just as troubling is the horizontal and vertical temperature stratification that becomes more visible in near-stagnant cases.

For plumes under moderate or large currents at Palisades, increased turbulence as a result of these currents causes the nearshore waters to mix quite well. We see little or no variation in the ambient temperature for these cases. The choice of a single ambient temperature was thus more straight-forward. Only for the stagnant lake and onshore current plumes at Palisades was the ambient temperature not well defined due to shoreline surface heating. For Point Beach, especially Category III, we observed that small to zero currents in the nearshore waters exist with little or no mixing while maintaining both vertical and horizontal stratification. As a result, a large variation on the order of 1-2 deg C is typical for the variation in local ambient temperature. This makes it difficult to distinguish between differences in temperature caused by natural ambient variations and the smaller temperature differences typically observed at the outer boundaries of the plume. Since half-widths and centerline temperature excesses are dependent upon the ambient temperature, an ill-defined ambient yields uncertain and quite possibly erroneous values of W_T and θ . Fortunately, any such errors become significant only for the lower isotherms.

5. DISCUSSION OF POINT BEACH UNITS 1 & 2 PLUMES

For the double-unit plumes at Point Beach, the discharges are treated as separate plumes with respect to centerline temperature decay and outside widths. Table V lists the six double plumes studied with their discharge and environmental characteristics in terms of data for each unit. For example, the June 5, 1973 double plume is listed as plume A from flume 1 and plume B from flume 2. The characteristics of these double plumes are given in Fig. 29 and compared to Point Beach Unit 1 Category III(a) plumes in Fig. 30. The only half-widths that could be obtained were the left half-width for the Unit 2 discharge and the right half-width for the Unit 1 discharge. Areas for the double plumes were taken as the sum of the isotherm areas of both plumes; the θ_0 used in the area plot of Fig. 29 is the average of the θ_0 values of plumes from Units 1 and 2. Also, in the area plot in Fig. 29, the sum of the isotherm areas for both plumes are plotted using the Unit 1 symbol, i.e., areas for plumes A and B, for example, are summed and plotted with the symbol A. All averages of the double plumes in Fig. 30 exclude plume G-H.

It was found that the plumes from Units 1 and 2 did not significantly interact until considerable distances offshore (≈ 600 m). Due to insufficient refinement in the data resulting from the limited number of boat transects made, plume widths and isotherm areas were extracted only to the region of significant interaction of both plumes. Data was too sparse beyond there to close isotherms and extract centerlines and half-widths.

It can be seen from Table V that five of the six double plumes were taken under small- or zero-current conditions except plume G-H which interacted with an ≈ 10 cm/s current to the south. Note that the temperature half-widths are comparable to the single-unit half-widths under similar conditions of small- to zero-ambient current.

The double-unit plumes have clearly twice the area as the single-unit plumes for the higher temperature isotherms. This is expected as the plumes disperse as individual plumes near the outfall and before any significant interaction. After the excess temperature ratio drops below 0.8, i.e., $\theta/\theta_0 < 0.8$, it is difficult to distinguish between the double-plume areas and the scatter and uncertainty that exists within the single-unit Category III(a) areas (see Fig. 30). Since the double-unit plumes must disperse twice as much heat as the single plumes, it is expected that it is the very low temperature isotherms ($\theta/\theta_0 \leq 0.3$) which are very large in the double-plume case. This would probably also lead to a more gradual centerline temperature decay farther out from the outfalls. Note from Fig. 30 that the centerline temperature decay and isotherm areas appear to be leveling off for centerline distances greater than 600 m (for temperature decay) and $\theta/\theta_0 < 0.3$ (for areas). The curvature of the area curves in Fig. 30 are quite opposite. The single-unit average curve is concave downward as is the Asbury-Frigo average curve for single-unit plumes on the Great Lakes. [9] The double-plume average area curve is more concave upward, indicating that large areas are expected for lower isotherms if extrapolation of the area curve is permitted.

As stated above, double plumes under small or zero currents did not appear to significantly interact within 600 m of the outfall. Plume G-H, however, bends over fairly strongly due to its ≈ 10 cm/s shore-parallel current causing considerable early interference between plumes. The plume eventually becomes shore-parallel. The boat data for the G-H plume were more refined than on other double-plume dates, allowing centerline temperatures, widths, and areas to be extracted at further distances from the outfall than the location of initial interaction and at lower temperatures.

The plume interference here causes a less rapid centerline temperature decay and larger areas in spite of the existence of the shore-parallel current as can be seen in Fig. 29. Apparently the shielding effect that the Unit 2 plume has over the Unit 1 plume overpowers the effect of the extra entrainment water brought in by the current. The Unit 1 plume G clearly entrained Unit 2 plume water on its left side. The current also advects the plume downcurrent with warm water being trapped on the lee side of the double-unit plume. In this case only a few points of half-width on the right side of the Unit 1 plume could be extracted, and those, very near the outfall; the left half-width for the Unit 2 plume was measured to 2500 m offshore and was found to be very narrow. Still unexplained are the higher temperatures from plume H facing the current and lower temperatures for plume G, although plume G is sheltered from ambient dilution water by the presence of plume H. The shallower bottom off the Unit 2 discharge might inhibit vertical dispersion to such an extent as to cause higher plume temperatures. More refined data needs to be taken to obtain a better insight into the mechanisms involved.

6. DISCUSSION OF STATE LINE AND WAUKEGAN PLUMES

The State Line and Waukegan plumes (see Table V and Figs. 31 and 32) were taken under small ambient currents inferred from the appearance of the isotherms, as no ambient currents were measured on those dates. Note that data were not taken closer than 350 m from the outfall at Waukegan due to the shallow area (≈ 1.5 m) near the discharge outfall. The effect of the initial densimetric Froude number and aspect ratio of the discharge outfalls is important in explaining the measured centerline temperature decays, half-widths, and areas. The very low velocity discharge at State Line ($F_0 \approx 1$) results in a thin pool of warm water floating on the ambient water. This plant was designed with the express purpose of minimizing mixing with lake water and maximizing surface-heat transfer to the atmosphere. Density currents here are the primary means of plume spreading. Examination of the isotherms indicates (see Fig. 3) a slight onshore current might have been present. Centerline temperatures decay very slowly and widths are large for centerline distances less than about 800 m. The sharp drop off in centerline temperature after 800 m is probably caused by the sharp interface at the edge of the density current or perhaps the compactness of isotherms caused by a small onshore current that may have been present. A combination of both hypotheses might be more correct.

The Waukegan plumes show more rapid dilution probably due to its high discharge velocity. Both left and right half-widths are smaller than at State Line, in addition to the centerline temperature ratios and isotherm areas. Note that the Waukegan plant has a 25% increase in excess temperature over State Line but only a 9% increase in flow rate; from this fact alone, one might expect higher temperatures as well as larger widths and areas from the Waukegan site. The opposing trend likely indicates that the outfall parameters were most significant in causing such differences in the plume characteristics since the environmental conditions were apparently similar for the plumes taken at State Line and Waukegan.

7. INTER-COMPARISON OF PLUMES BY SITES

Under similar environmental conditions, centerline temperature decays, average half-widths (left and right) and isotherm areas are compared for plumes at Palisades, Point Beach Unit 1, State Line, and Waukegan (see Fig. 33). Since the plumes measured at State Line and Waukegan were taken under

nearly stagnant conditions, categories representing similar conditions to these were chosen to represent Palisades and Point Beach Unit 1. Thus Category III of Palisades and Category III(a) of Point Beach Unit 1 are re-plotted in this figure.

In order to compensate for the difference in power levels of these plants, isotherm temperature excesses are plotted versus isotherm area, normalized by the heat-rejection rate of the plant (above ambient). In this way we are comparing the area per unit of plant waste heat rejected, for any isotherm (here θ , the temperature excess above ambient, is used, not the temperature excess ratio θ/θ_0). As expected, it is found that higher temperatures, larger areas, and larger widths are generated as the outfall densimetric Froude Number is decreased. For Point Beach and Palisades with nearly equal densimetric Froude numbers, the larger aspect ratio situation of Palisades yields the trend of higher temperatures, larger areas, and longer widths. Differences between plant performances are quite large. The distance along the centerline to a specific θ_c/θ_0 can differ by a factor of 5, area per unit plant heat rejected for a given isotherm can differ by a factor of 10, and average half-widths for a given centerline distance can vary by a factor of 2 for closely related environmental conditions at the four different sites. This large variation in plume characteristics demonstrates the effect of various discharge designs.

8. CONCLUSIONS

1. Much variation in centerline temperature decay, temperature half-widths, and surface isotherm areas exists for the Palisades and Point Beach Unit 1 plumes due to variation in ambient current, wind, and lake conditions. Much of that variation can be explained if the data are divided into different categories on the basis of the predominance of different physical processes. Diurnal changes in excess temperature and densimetric Froude Number (with constant plant power level) are insignificant as compared to changes in current, wind, and lake conditions.

2. At Palisades, the greatest dilution in terms of centerline temperatures and areas occurs for an offshore current. The least dilution in terms of the highest centerline temperatures and largest isotherm areas occurs for the stagnant lake, onshore current, and moderate shore-parallel current situations. The stagnant case has the largest plume widths, the onshore current situation has the highest temperature ratios at a given centerline distance, and the moderate shore-parallel current case has the greatest areas. Rough lake conditions with either a moderate or large shore-parallel current give very rapid centerline temperature decays, small isotherm areas, and small half-widths. The most critical condition in terms of centerline temperatures is the stagnant-lake case; for isotherm areas the critical condition appears to be the moderate shore-parallel current case under calm lake conditions.

3. For Point Beach Unit 1, the environmental conditions do not vary as greatly as for Palisades and, consequently, the scatter in the data on plume characteristics is not as large. North-directed currents opposing the south-oriented discharge cause significant interaction and mixing and smaller, more slender, and deeper plumes than for currents directed south. South-directed currents cut off entrainment water to the inshore side of the plume resulting in larger, wider and more shallow plumes. The near-stagnant conditions for Point Beach Unit 1 plumes caused difficulty in accurately measuring ambient currents as well as accurately determining ambient temperature due to horizontal and vertical stratification from shoreline heating.

4. Double plumes at Point Beach give smaller centerline temperatures and smaller areas (for $\theta/\theta_0 < 0.8$) than corresponding Unit 1 plumes. This occurs for near-stagnant ambient conditions. The trend, however, seems to

be toward much larger double-unit areas and centerline temperatures than the single unit for $\theta/\theta_0 < 0.3$. Since much scatter exists within the corresponding single and double unit categories of data, indicating an overlap in data envelopes, additional data are required for verification.

5. The State Line plume shows a very slow centerline temperature decay until a sharp drop off occurs at the outer plume boundaries. The plume is large and thin and spreads over a large area. Under similar environmental conditions, the Waukegan plumes are more quickly mixed due to the high-velocity discharge yielding rapid decays in temperatures and areas.

6. A comparison between plumes at the Palisades, Point Beach, State Line, and Waukegan sites for similar environmental conditions yields a wide range in centerline temperatures, widths, and areas. The differences are due mainly to the outfall densimetric Froude Number and the outfall aspect ratio. The larger the initial densimetric Froude Number and the smaller the aspect ratio, the smaller are the plume centerline temperatures and isotherm areas.

7. Plume monitoring at existing power plant sites cannot be adequate unless plumes under a wide range of environmental conditions are sampled. Plume characteristics will vary greatly depending upon current speed and direction, wind speed and direction, and lake conditions. Monitoring should allow for the fact that significant scatter can occur even within intelligently defined categories of environmental parameters. The present practice of monitoring a plant about a half-dozen times a year is inadequate for determining the types of plumes to be observed there and the range in plume characteristics.

8. Presently available mathematical models of plumes are known to be generally inadequate in treating such important phenomena affecting plume dispersion as bottom and shoreline interaction, ambient lake turbulence, as well as the effect of current and wind magnitude and direction. The variations in plume characteristics observed in the above data are larger than predicted in most models that attempt to simulate these phenomena.

Point Beach Nuclear Power Station, Two Creeks, Wisconsin

Palisades Nuclear Generating Plant, South Haven, Michigan

State Line Generating Station, Hammond, Indiana

Waukegan Generating Station, Waukegan, Illinois

Fig. 1. Outfall Configurations for Lake Michigan Power Plants Studied

Fig. 2. Sample Isotherm Plot for Point Beach Unit 1 Plumes (left) and Point Beach Units 1 & 2 Plumes (right)

Fig. 3. Sample Isotherm Plot for Palisades Plumes (left) and State Line Plume (right)

Fig. 4. Sample Isotherm Plot for Waukegan Plumes

TABLE I. Outfall Information for Power Plants Studied

Plant	Point Beach ^{a,b} (Each unit identical unless otherwise noted)	Palisades ^a	Waukegan	State Line
Capacity (MWe)	497	715	1100	992
Maximum Discharge Flow Rate (m ³ /s)	25.1	25.5	55.2	52.5
Maximum Temperature Drop across Condensers (deg C)	10.7	13.9	7.1	5.8
Outfall Width (m)	10.7	28.3	30.5	92.8
Outfall Depth (m)	4.2	2.1	1.5	3.0 ^c
Average Outfall Velocity (m/s)	0.56	0.43	1.2	0.19
Initial Densimetric Froude Number (Nominal)	2.5	2.3	9.7	1.0
Aspect Ratio ^d	2.5	13.5	20.1	30.9
Angle to Shoreline	60° (Unit 1) 120° (Unit 2)	90°	90°	90°
Number of Plumes Measured				
Unit 1 only	23	15	2	1
Unit 2 only	2	-	-	-
Unit 1 and 2	7	-	-	-

^aNuclear Power Plant.

^bThere are four cases listed under Unit 1 only in which Unit 2 is partially operational. For these cases typical parameters for Unit 2 are: power load = 69 MWe, discharged flow rate = 13.9 m³/s, maximum temperature drop across condensers = 4.2 deg C, average outfall velocity = 0.31 m/s, initial densimetric Froude Number = 1.98. Those values are also typical for the two plumes for which only Unit 2 was in operation.

^cApproximate value due to irregular variation of discharge depth.

^dAspect Ratio = $\frac{\text{outfall width}}{\text{outfall depth}}$

TABLE II. Instrument Specifications for 1972 and 1973 Plume Data Acquisition

INSTRUMENT	SENSOR	ACCURACY	THRESHOLD	RANGE	RESOLUTION	TIME CONSTANT	REMARKS
Bendix Q-15 Current Meter	Speed; impeller	±4% of full scale	0.04 knot	0-1.0 knot; low scale 0-5.0 knots; high scale	0.02 knot; low scale 0.1 knot; high scale	25 s; low scale 2.5 s; high scale	Vane has adjustable length; 0.3-3.0 m For the 1973 data, the time constant was selectable from 2-30 s.
	Direction; vane	± 12°	-	0-360°	5°		
Temperature Measurement System	Thermistor	±0.2 degC	-	0-50°C	0.1 degC	For 1972 data: 2.5 s in well stirred water For 1973 data: 0.6 s	Thermistor type YSI #709 - water-proofed Thermistor YSI Series 700 specially made with 0.6 s + mc constant
Motorola Mini-Ranger	-	±3 m	-	0.1-35 km	1 m	-	Accuracy applies to each range measurement. System accuracy varies with position of transponders rela- tive to boat. For most measurements, ± 3 m applies
Data-Marine Depth-Sounder	Model 2301 (Transom mounted)	±1 ft; low range ±1 fathom; high range	2 ft; low range 2 fathoms; high range	2 - 99 ft; low range 2 - 99 fathoms; high range	1 ft 1 fathom	-	
MRI Meteorological Station	Speed; 3 cup anemometer	±2%	0.75 mph	0.75 - 100 mph	0.2 mph	18 ft (response distance)	
	Direction; vane	±5°	0.75 mph	0.75 - 100 mph	5°	8 ft (response distance)	
	Temperature; Bimetallic coil	±3 degF	-	-30+ +120 °F	1 degF	unknown	
	Clock	±60 s/24 h	-	32 d	-	-	Clock specifications are open to question

Conversion factors:

1 knot = 0.514 m/s

1 mph = 0.447 m/s

1 ft = 0.305 m

1 fathom = 1.829 m

degC = (degF - 32) 5/9

TABLE III. Thermal Plumes Measured at Palisades During 1972

Plume	Date	Time	Outfall Temp. (°C)	Ambient Temp. (°C)	Excess Temp. (degC)	Disch. Flow (m³/s)	Disch. Vel. (cm/s)	Magn. of Current (cm/s)	Dir. of Current (°cw from north)	Magn. of Wind (m/s)	Dir. of Wind (°cw from north)	Lake Conditions	Wave Height (m)	R	F _o	$\frac{K}{\rho C_p}$ (m/s x 10 ⁻⁶)
CATEGORY I (a): Moderate Shore-parallel Current; Light, Moderate Wind; Calm Lake Conditions																
A	13 Jun 72	1242-1443	21.6	14.5	7.1	25.6	43.1	13.3	012	2.7	265	Calm	0.0-0.3	0.31	2.62	4.1
B	13 Jun 72	1516-1615	21.8	15.8	6.0	25.6	43.1	22.7	000	2.6	265	Calm	0.0	0.53	2.79	4.0
D	20 Jun 72	1027-1109	20.6	14.5	6.1	25.6	43.1	15.0	025	3.6	220	Calm	0.0-0.3	0.35	2.87	5.0
E	20 Jun 72	1110-1200	21.2	14.9	6.3	25.6	43.1	27.7	030	3.2	220	Calm	0.0-0.3	0.64	2.78	4.6
F	20 Jun 72	1330-1425	21.7	15.8	5.9	25.6	43.1	27.1	025	3.0	220	Calm	0.0-0.3	0.65	2.81	4.4
G	20 Jun 72	1430-1515	21.4	16.7	4.7	25.6	43.1	27.1	025	2.7	220	Calm	0.0-0.3	0.65	3.12	4.4
I (b): Moderate Shore-parallel Current; Moderate Wind; Rough Lake Conditions																
H	17 Jul 72	1600-1655	29.3	22.2	7.1	25.6	43.1	19.4	030	4.5	220	Swells	0.3-1.0	0.45	2.19	7.6
CATEGORY II: Large Shore-parallel Current; Moderate Wind; Rough Lake Conditions																
X	7 Aug 72	1730-1900	19.4	11.3	8.1	25.6	43.1	80	205	4.4	340	Rough	1-2	1.9	2.69	5.2
Y	8 Aug 72	1415-1745	21.5	12.5	9.0	25.6	43.1	40-70	025	4.6	231	Rough	1	1.3	2.41	5.6
Z	11 Oct 72	1410-1630	22.0	13.5	8.5	25.6	43.1	60-80	025	6.0	213	Rough	1	1.6	2.42	7.2
CATEGORY III: Zero Current; Zero Wind; Calm Lake Conditions																
I	18 Jul 72	1952-2055	29.3	22.0	7.3	25.6	43.1	0.0	—	0.0	—	Calm	0.0	0.0	2.17	1.4
CATEGORY IV: Low-Moderate Onshore Current; Light Wind; Calm Lake Conditions																
J	19 Jul 72	1546-1710	28.9	23.5	5.4	25.6	43.1	10.0	170	1.8	010	Calm	0.0	0.23	2.49	4.0
CATEGORY V: Low, Moderate Offshore Current; Low, Moderate Wind; Calm, Rough Lake Conditions																
C	19 Jun 72	1630-1730	19.6	14.9	4.7	25.6	43.1	14.4	010	2.0	165	Calm	0.0	0.33	3.30	3.4
K	10 Oct 72	1625-1748	22.2	12.9	9.3	25.6	43.1	8.9	345	2.3	130	Calm	0.0-0.3	0.21	2.33	4.3
L	13 Oct 72	1015-1155	22.0	12.6	9.4	25.6	43.1	11.1	010	3.4	205	Rough	0.3-1.0	0.26	2.33	4.5

Notes:

R = Ratio of Ambient Velocity u_a to the Discharge Velocity u_o .F_o = Initial Densimetric Froude Number. $\frac{K}{\rho C_p}$ = Surface-heat-transfer Parameter.

TABLE IV. Thermal Plumes Measured at Point Beach Unit 1 During 1971 and 1972

Plume	Date	Time	Outfall Temp. (°C)	Ambient Temp. (°C)	Excess Temp. (degC)	Disch. Flow (m³/s)	Disch. Vel. (cm/s)	Magn. of Current (cm/s)	Dir. of Current (°cw from north)	Magn. of Wind (m/s)	Dir. of Wind (°cw from north)	Lake Conditions	Wave Height (m)	R	F ₀	$\frac{K}{\rho C_p}$ (m/s x 10 ⁻⁶)
CATEGORY I: Strong North Current; Moderate Wind																
T	21 Jul 71	1908-1639	21.8	11.1	10.7	25.1	57.	18.	335	6.7	205	Moderately Calm	0.3-0.6	0.32	2.13	7.2
W	1 Sep 71	1445-1727	26.5	17.4	9.1	25.1	57.	—	355	4.9	135	Moderately Calm	0.3-0.6	—	1.98	7.0
A	17 May 72	1646-1806	18.9	7.9	11.0	25.1	56.	8.3	000	4.5	190	Calm	0.0-0.3	0.15	2.31	4.8
CATEGORY II: Moderate North Current; Moderate Wind																
R	20 Jul 71	1642-1805	21.5	12.6	8.9	25.1	57.	9.0	015	6.5	205	—	0.0-0.3	0.16	2.29	7.4
U	31 Aug 71	1550-1631	26.2	17.6	8.6	25.1	57.	—	350	2.7	045	—	0.6-0.9	—	2.04	4.4
V	1 Sep 71	0950-1130	27.1	17.4	9.7	25.1	57.	—	360	4.9	135	Moderately Calm	0.3-0.6	—	1.91	7.0
G	11 Jul 72	1245-1355	20.5	10.9	9.6	25.1	56.	15.0	300	4.3	175	Choppy	0.3-0.6	0.27	2.24	5.1
I	6 Sep 72	1115-1300	25.2	15.0	10.2	24.7	55.	18.8	020	5.2	205	Choppy	0.6-1.0	0.34	1.87	6.7
CATEGORY III (a): Zero Current; Light, Moderate Wind																
S	21 Jul 71	1020-1117	20.5	11.5	9.0	25.1	57.	—	—	3.4	205	Moderately Calm	0.3-0.6	—	2.36	4.3
C	24 May 72	0925-1040	21.3	10.7	10.6	25.1	56.	0.0	—	1.4	015	Calm	0.0	0.0	2.11	2.5
D	24 May 72	1045-1145	21.3	11.9	9.4	25.1	56.	0.0	—	2.2	015	Calm	0.0	0.0	2.19	3.3
E	24 May 72	1145-1225	21.3	11.0	10.3	25.1	56.	0.0	—	2.0	015	Calm	0.0	0.0	2.13	3.0
F	7 Jul 72	1830-2015	20.5	11.3	9.2	25.1	56.	—	—	—	—	—	—	—	2.27	1.2
J	9 Sep 72	1525-1630	24.5	14.5	10.0	24.7	55.	0.0	—	4.8	175	Choppy	0.0-0.3	0.0	1.92	6.2
III (b): Small Current; Light Wind																
H	13 Jul 72	1805-1903	20.3	13.3	7.0	25.1	56.	2.2	245	2.4	165	Calm	0.0	0.039	2.52	3.6
L	29 Sep 72	1545-1705	20.4	11.2	9.2	24.7	55.	2.2	300	2.6	300	Calm	0.3-0.6	0.040	2.24	3.6
III (c): Zero Current; Zero Wind																
B	18 May 72	1645-1751	18.0	9.5	8.5	24.7	55.	0.0	—	—	—	Calm	0.0	0.0	2.53	1.2
CATEGORY IV: Moderate South Current; Light, Moderate Wind																
O	20 May 71	1431-1550	17.5	8.1	9.4	25.1	57.	9.0	125	6.7	315	—	0.0-0.3	0.16	2.64	6.6
P	20 May 71	1744-1850	17.5	8.2	9.3	25.1	57.	9.0	125	5.6	270	—	0.0-0.3	0.16	2.65	5.8
X	28 Oct 71	1401-1539	21.2	12.8	8.4	25.1	57.	—	170	2.0	155	Slightly Choppy	0.0-0.3	—	2.36	3.2
CATEGORY V: Strong South Current; Moderate Wind																
Q	25 Jun 71	1004-1215	20.1	11.0	9.1	25.1	57.	—	—	6.5	045	Rough	0.6-0.9	—	2.38	7.0
Y	28 Oct 71	2004-2100	21.2	12.6	8.6	25.1	57.	15.0	180	3.1	050	Calm	0.0-0.3	0.26	2.34	3.2

Notes: R = Ratio of Ambient Velocity u_a to the Discharge Velocity u_d .

F₀ = Initial Densimetric Froude Number.

$\frac{K}{\rho C_p}$ = Surface-heat-transfer Parameter.

TABLE V. Thermal Plumes Measured at Point Beach Units 1 & 2 During 1973 and Waukegan, State Line During 1971

Plume	Date	Time	Outfall Temp. (°C)	Ambient Temp. (°C)	Excess Temp. (degC)	Disch. Flow (m ³ /s)	Disch. Vel. (cm/s)	Magn. of Current (cm/s)	Dir. of Current (°cw from north)	Magn. of Wind (m/s)	Dir. of Wind (°cw from north)	Lake Conditions	Wave Height (m)	R	F _o	$\frac{K}{\rho C_p}$ (m/s x 10 ⁻⁶)
POINT BEACH --- DOUBLE PLUMES																
	5 Jun 73	1150-1400		7.4				5.6	353	5.6	232	Calm	0.3			5.7
A			17.3		9.9	24.3	54.							0.10	2.47	
B			17.3		9.9	24.3	60.							0.09	2.89	
	6 Jun 73	1120-1255		9.6				0.0	—	3.8	202	Calm	0.0-0.3			4.4
C			17.7		8.1	24.3	54.							0.0	2.56	
D			17.5		7.9	24.3	60.							0.0	3.04	
	7 Jun 73	1102-1230		7.7				6.1	115	7.0	265	Slightly Choppy	0.3			6.8
E			17.4		9.7	24.3	54.							0.11	2.47	
F			17.1		9.4	24.3	60.							0.10	2.95	
	10 Aug 73	1416-1500		7.5				—	—	3.8	273	Slightly Choppy	0.3			4.2
I			17.4		9.9	24.3	54.							—	2.46	
J			17.8		10.3	24.3	60							—	2.79	
	23 Aug 73	1156-1304		17.6				—	—	2.1	250	Calm	0.0-0.3			3.8
K			28.5		10.9	24.3	54.							—	1.66	
L			28.7		11.1	24.3	60.							—	1.91	
	12 Jun 73	1515-1647		10.1				9.4	150	2.4	028	Calm	0.0-0.3			3.3
G			18.5		8.4	24.3	54.							0.17	2.44	
H			18.2		8.1	24.3	60.							0.16	2.92	
WAUKEGAN																
A	2 Jun 71	1140-1320	18.8	10.2	8.6	45.9	99	—	—	4.7	270	—	0.0-0.3	—	7.29	5.3
B	2 Jun 71	1443-1723	18.3	10.2	8.1	44.4	96.	—	—	3.8	270	—	0.0-0.3	—	7.36	4.5
STATE LINE																
C	4 Aug 71	1227-1550	25.3	17.5	7.8	52.4	19	—	—	4.2	045	—	0.0-1.0	—	≈ 1.	6.2

Notes:

R = Ratio of Ambient Velocity u_a to Discharge Velocity u_o .

F_o = Initial Densimetric Froude Number.

$\frac{K}{\rho C_p}$ = Surface-heat-transfer Parameter.

Fig. 5. Centerline Temperature Decay for all Plumes at Palisades and Point Beach Unit 1

Fig. 6. Palisades Centerline Temperature Decay: Categories I and II

Fig. 7. Palisades Centerline Temperature Decay: Categories III, IV, and V

Fig. 8. Palisades Temperature Half-widths: Left Side - Category I and Left/Right Side - Category II

Fig. 9. Palisades Temperature Half-widths (Left Side):
Categories III, IV, and V

Fig. 10. Palisades Temperature Half-widths (Right Side): Categories I and III

Fig. 11. Palisades Temperature Half-widths (Right Side): Categories IV and V

Fig. 12. Palisades Isotherm Areas: Categories I and II

Fig. 13. Palisades Isotherm Areas: Categories III, IV, and V

Fig. 14. Palisades Centerline Temperature Decay: Averaged Data for Categories I-V

Fig. 15. Palisades Temperature Half-widths (Left Side): Averaged Data for Categories I-V

Fig. 16. Palisades Temperature Half-widths (Right Side): Averaged Data for Categories I, III, IV, and V

Fig. 17. Palisades Isotherm Areas: Averaged Data for Categories I-V

Fig. 18. Point Beach Unit 1 Centerline Temperature Decay:
Categories I, II, and III

Fig. 19. Point Beach Unit 1 Centerline Temperature Decay:
Categories IV and V

Fig. 20. Point Beach Unit 1 Temperature Half-widths (Left Side):
Categories I, II, and III

Fig. 21. Point Beach Unit 1 Temperature Half-widths (Left Side): Categories IV and V

Fig. 22. Point Beach Unit 1 Temperature Half-widths (Right Side):
Categories I, II, and III

Fig. 23. Point Beach Unit 1 Isotherm Areas: Categories I, II, and III

Fig. 24. Point Beach Unit 1 Isotherm Areas: Categories IV and V

Fig. 25. Point Beach Unit 1 Centerline Temperature Decay: Averaged Data for Categories I-V

Fig. 26. Point Beach Unit 1 Temperature Half-widths (Left Side): Averaged Data for Categories I-V

Fig. 27. Point Beach Unit 1 Temperature Half-widths (Right Side): Averaged Data for Categories I-III

Fig. 28. Point Beach Unit 1 Isotherm Areas: Averaged Data for Categories I-V

Fig. 29. Point Beach Units 1 & 2 Centerline Temperature Decay, Temperature Half-widths (Outside), and Isotherm Areas

Fig. 30. Point Beach Units 1 & 2: (top) Comparison of Centerline Temperature Decay with Unit 1 Plumes, (middle) Comparison of Temperature Half-widths with Unit 1 Plumes, (bottom) Comparison of Isotherm Areas with Unit 1 Plumes

Fig. 31. State Line and Waukegan Centerline Temperature Decay and Isotherm Areas

Fig. 32. State Line and Waukegan Temperature Half-widths:
Left Side and Right Side

Fig. 33. Comparison of Centerline Temperature Decay, Isotherm Areas (per Unit Plant Heat Rejected), and Average Widths for Palisades, Point Beach Unit 1, Waukegan, and State Line

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