CHAPTER 173

FIELD STUDIES OF SUBMERGED-DIFFUSER THERMAL PLUMES WITH COMPARISONS TO PREDICTIVE MODEL RESULTS

by

A. A. Frigo, R. A. Paddock, and J. D. Ditmars*

Abstract

Thermal plumes from submerged discharges of cooling water from two power plants on Lake Michigan were studied. The system for the acquisition of water temperatures and ambient conditions permitted the three-dimensional structure of the plumes to be determined. The Zion Nuclear Power Station has two submerged discharges structures separated by only 94 m. Under conditions of flow from both structures, interaction between the two plumes resulted in larger thermal fields than would be predicted by the superposition of single non-interacting plumes. Maximum temperatures in the near-field region of the plume compared favorably with mathematical model predictions. A comparison of physical-model predictions for the plume at the D. C. Cook Nuclear Plant with prototype measurements indicated good agreement in the near-field region, but differences in the far-field occurred as similitude was not preserved there.

Introduction

Submerged discharges and multiport diffusers are finding wider use as means of disposing of waste heat from once-through condenser cooling-water systems for power plants. These discharges appear to be superseding surface shoreline discharges for large power plant applications. A reason for employing submerged discharges is that they may create greater initial dilution of the effluent than surface discharges.

The Federal Water Pollution Control Act of 1972 targets heat as a pollutant and hence prohibits its discharge into navigable waterways such as the Great Lakes. However, Section 316(a) of the Act allows for rescinding the no-discharge requirement when it can be deomonstrated that the discharge of waste heat will not result in damage to the aquatic environment. It authorizes, on a case-by-case basis, the easing of any thermal limitation that is more stringent than necessary "to assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife" in the receiving water. This may mean that the surface temperature rise and the extent of the plume will have to be limited — hence the use of high-velocity submerged discharges. One of

*Energy and Environmental Systems Division, Argonne National Laboratory, Argonne, Illinois, 60439, USA.

the requirements for obtaining a 316(a) exemption will probably be a prediction of the spatial and temporal characteristics of the thermal plume from a power plant. Before a plant begins operation, analytical and physical (hydraulic) models must be used for prediction. After operation has begun, actual prototype field measurements can be made.

Few predictive models have been verified at prototype scales, and little is known regarding the limitations and applicability of many models. The evaluation of predictive techniques, through prototype-model comparison, is one of the main objectives of the program of which a portion is discussed in this paper.

Argonne National Laboratory (ANL) has been studying the effects of power-plant waste-heat discharges into the Great Lakes since 1970. The initial effort involved the study of thermal plumes from power plants employing shoreline surface discharges. A review of analytical and physical modeling techniques for predicting the fate of waste heat in large lakes was carried out.[1] In addition, a review of available prototype data on thermal plumes was conducted.[2] This review indicated a paucity of field data describing these plumes under various environmental conditions. Because it was clear that detailed field data of good quality were needed to evaluate the various predictive techniques, ANL began an extensive field program to measure the physical phenomena related to surface shoreline waste-heat discharges into the Great Lakes. Approximately 75 sets of thermal-plume data along with related physical parameters such as lake currents, ambient diffusivities, and meteorological conditions were measured at six different discharge sites on Lake Michigan.[3,4,5] The results of the thermal-plume measurements were analyzed and compared with model predictions. This four-year effort culminated in a comprehensive critical evaluation of mathematical modeling techniques for surface discharges in which many models were examined and eleven of the most promising models were reviewed in detail.[6]

In response to recent interest in high-velocity submerged discharges, ANL began a study of the physical aspects of these discharges similar to the program carried out for surface discharges. Again, there is a lack of detailed prototype data of good quality for thermal plumes from submerged discharges. This study includes field measurements of the three-dimensional structure of thermal plumes from submerged discharges on the Great Lakes and an evaluation of physical and mathematical models for submerged discharges.

Field studies have been conducted at four power plants with submerged discharges located on the Great Lakes. The power plants being studied include the Zion Nuclear Power Station and Donald C. Cook Nuclear Plant on Lake Michigan and the Oswego Steam Station Unit 5 and James A. FitzPatrick Nuclear Power Plant on Lake Ontario (Fig. 1). Ten sets of thermal-plume data have been collected at the Zion site, nine sets at Donald C. Cook site, three sets at the Oswego Unit 5 site, and four sets at the James A. FitzPatrick site. In addition to thermal-plume temperature data, related information such as limnological, meteorological, and plant operating data have been collected for the times of the thermal-plume surveys. Results of some of the surveys at the Zion and Donald C. Cook plants are discussed in References 7 and 8, respectively.

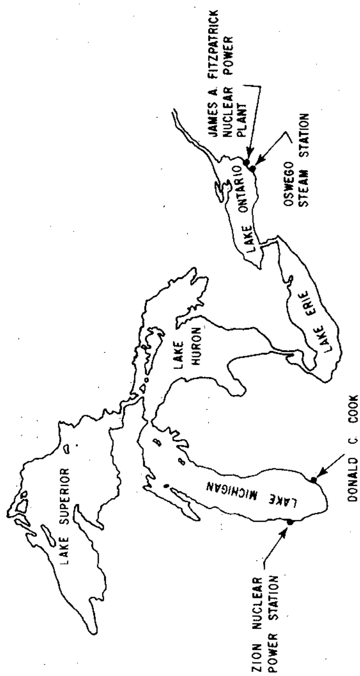

Fig. 1. Sites of Submerged Discharges Under Study by ANL

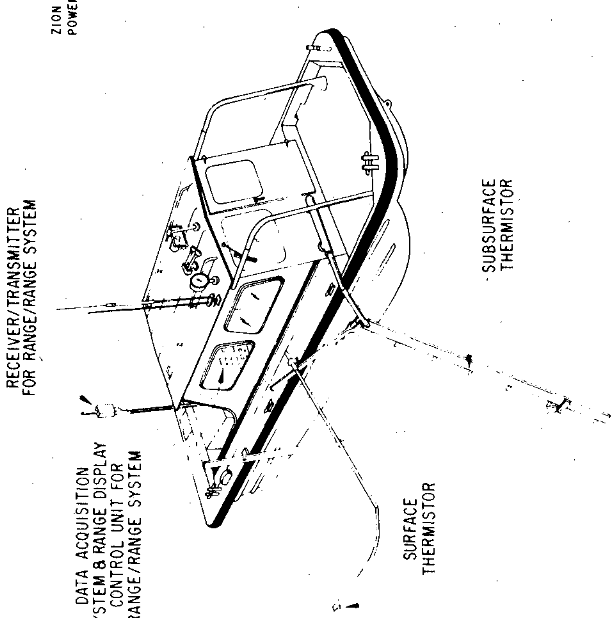

Fig. 2. Schematic Diagram of Survey Boat

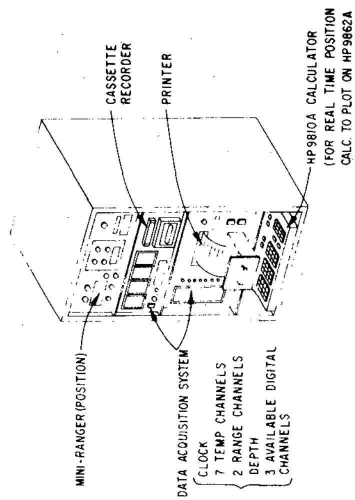

Fig. 3. Schematic Diagram of Data Acquisition System

In this paper, the equipment and techniques used by ANL to collect and handle thermal-plume and related data are discussed. In addition, some results are presented for the case of two adjacent submerged discharges with thermal plumes which effect each other. Comparisons are made between ANL prototype data and pre-operational mathematical- and physical-model predictions.

Field Measurements and Data Handling System

A measurement and data-acquisition system for relatively rapid measurement of the three-dimensional temperature structure of thermal plumes from submerged discharges was developed at ANL. The system was designed for use aboard a small (7.5 m) boat (Fig. 2). The acquisition system (Fig. 3) was interfaced with seven thermistors, a navigational ranging system, a depth sounder, and a real-time boat-position plotting system. The thermistors were mounted at 0.5-m intervals on a 3-m long aluminum bar with streamlined cross section which is towed through the water from the boat. Temperature data at seven depths along with water-depth data are recorded by the system as a function of time and boat position on both paper tape and magnetic-tape cassettes. In addition, the aluminum bar can be replaced with a towed thermistor chain which was developed to allow the measurement of water temperatures in water columns of depths to 10 m. The sampling time interval is variable; typically, data were acquired at eight-second intervals. The data acquisition system allows the collection of data at approximately 1000 points over a linear distance of 10 km in one hour. The real-time plotting system permits the boat operator to know the boat location at any time and, therefore, to adjust the boat's course so as to map completely and in varying detail the study area. The plume data, originally recorded on the magnetic-tape cassettes, are transcribed onto computer-compatible magnetic tapes. These tapes, along with calibration data, are used by a computer program to produce plots of the water temperature and bathymetry as a function of position for each of the depths of measurement. Isotherms and plume centerlines for each level are then drawn by hand on these plots. Figures 5 and 6 are examples of plume isotherm plots at the surface obtained using these techniques. In addition to horizontal plots, vertical cross sections through the plume can also be obtained. The small dots in the figures are the actual temperature values at the location indicated and hence also represent the boat path. The temperature values accompanying the bold dots are representative temperatures corresponding to particular locations.

An ambient water temperature survey is conducted before each plume mapping. Upcurrent from the power plant, the boat is moved from a location offshore to a location as close to the shoreline as possible along a line perpendicular to the shoreline. Ambient water temperatures at the surface and six depths are recorded at about 100 locations during this survey. Ambient lake currents are measured from the boat at fixed locations with a ducted-impeller current meter. In addition, for the duration of the field study, current speed and direction are measured along with lake temperatures at a fixed position and depth by an in-situ current meter/thermograph package. These data are recorded by digital, cassette tape recorder. Wind speed and direction, air temperature, relative humidity, and lake surface conditions are monitored during each thermal-plume field study. Plant operating data and records of wind speed and direction and air temperature from utility meteorological stations are obtained from the utility records. In addition, thermographs which have been calibrated along with the ANL data acquisition system, are installed in the plant to measure cooling water intake and discharge temperatures to insure temperature data consistency.

Measurements at the Zion Nuclear Power Station

The Zion station is located in northeastern Illinois on the western shore of Lake Michigan about 5.1 km south of the Illinois-Wisconsin state line (Fig. 1). It consists of two units (Unit 1 to the south, Unit 2 to the north) employing pressurized water reactors. Each unit is capable of a gross generating capacity of 1100 MWe. Each unit has its own discharge structure located 232 m from shore, about 47 m on either side of the plant centerline, in about 4.5 m of water (Fig. 4a.). Each discharge structure consists of a rectangular box with 14 ports on the offshore and outboard edges. The ports are 0.9 m high and 1.6 m wide and are oriented at 45° to the box centerline. The discharge flow rate at full power operation is about 50 m^3/s for each unit and the average velocity at the outlet ports is 2.4 m/s. The nominal temperature rise of the cooling water is 11 C°.

Plumes were surveyed at the Zion site on ten occasions. On eight occasions cooling water was discharged from only one discharge structure. In most cases, the ambient current was approximately shore-parallel, and thus was either in the direction of the discharge or in a direction opposite to the discharge. An example of the surface isotherms for a single discharge in the direction of the ambient current is shown in Fig. 5. Subsurface isotherms also indicate the same general orientation of the plume. The surface isotherms for a single discharge opposed to the ambient current are shown in Fig. 6. The plume is bent in the direction of the ambient current in the far field, and the near-field surface dilutions are decreased below those for the case of discharge in the direction of the ambient current. Again, subsurface isotherms indicate that the plume far field has been bent in the direction of the ambient current. The case of discharges from both units, one plume with and the other plume opposed to the ambient current, is shown in Fig. 7. While two plumes can be distinguished on this surface isotherm plot, the far-field region is a combination of plumes from both discharges.

One basis for describing and comparing thermal plumes is an isotherm-surface-area plot. The area refers to the surface area enclosed within an isotherm of particular temperature or normalized temperature. The isotherms here are characterized by the excess-temperature ratio, θ/θ_o, that is, the ratio of the difference between the actual isotherm temperature and the ambient water temperature and the difference between the discharge and ambient water temperatures. Figure 8 shows the results from the surveys at the Zion site for single discharges opposed to the ambient current, and for discharges from both units. The envelope about each average line reflects the range of values determined from the measurements. This scatter appears due to variations in discharge conditions and ambient current magnitude and direction which resulted in variation in values of the discharge densimetric Froude number, F_s, and velocity ratio, K, where,

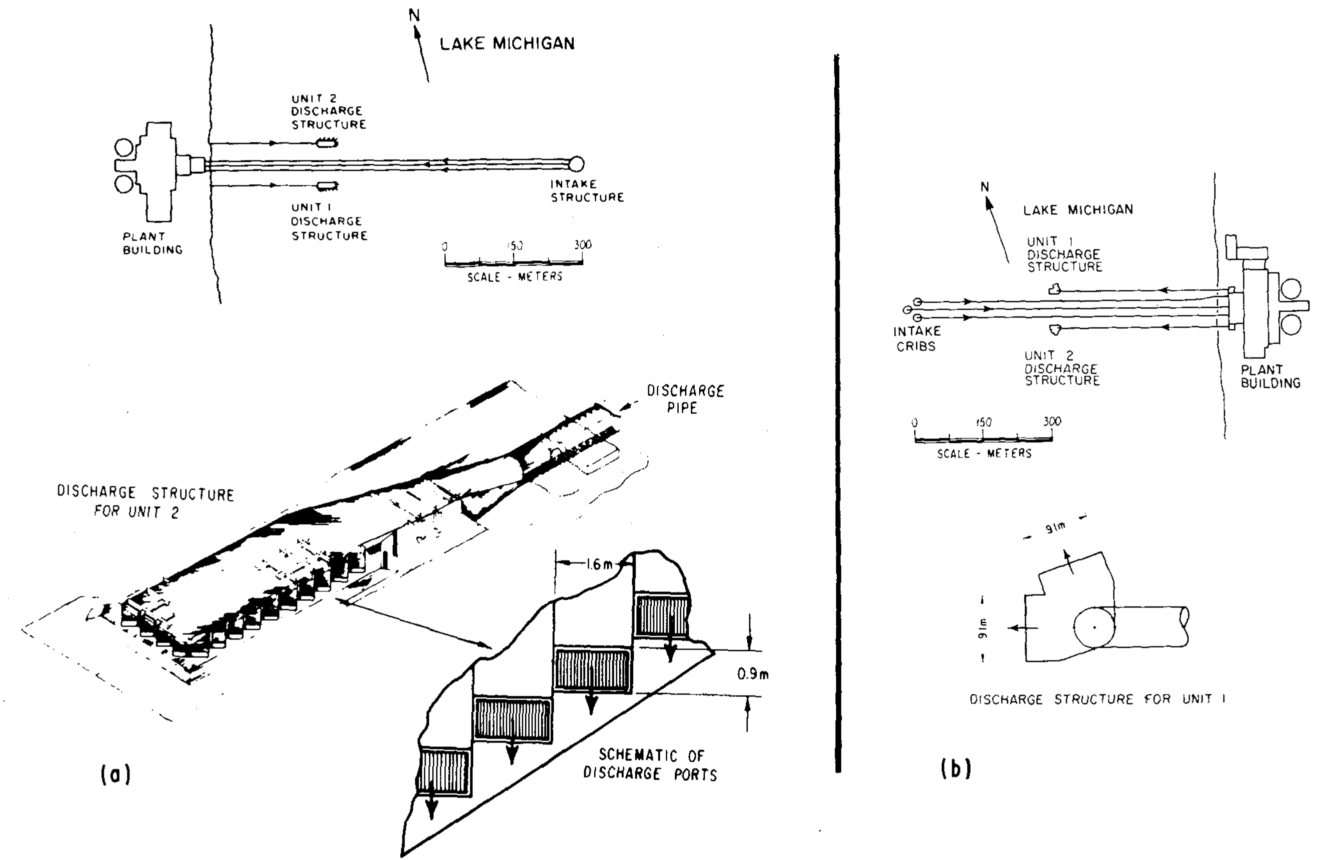

Fig. 4. Schematic Diagram of Cooling-water System and Discharge Structures: (a) Zion Nuclear Power Station and (b) Donald C. Cook Nuclear Plant

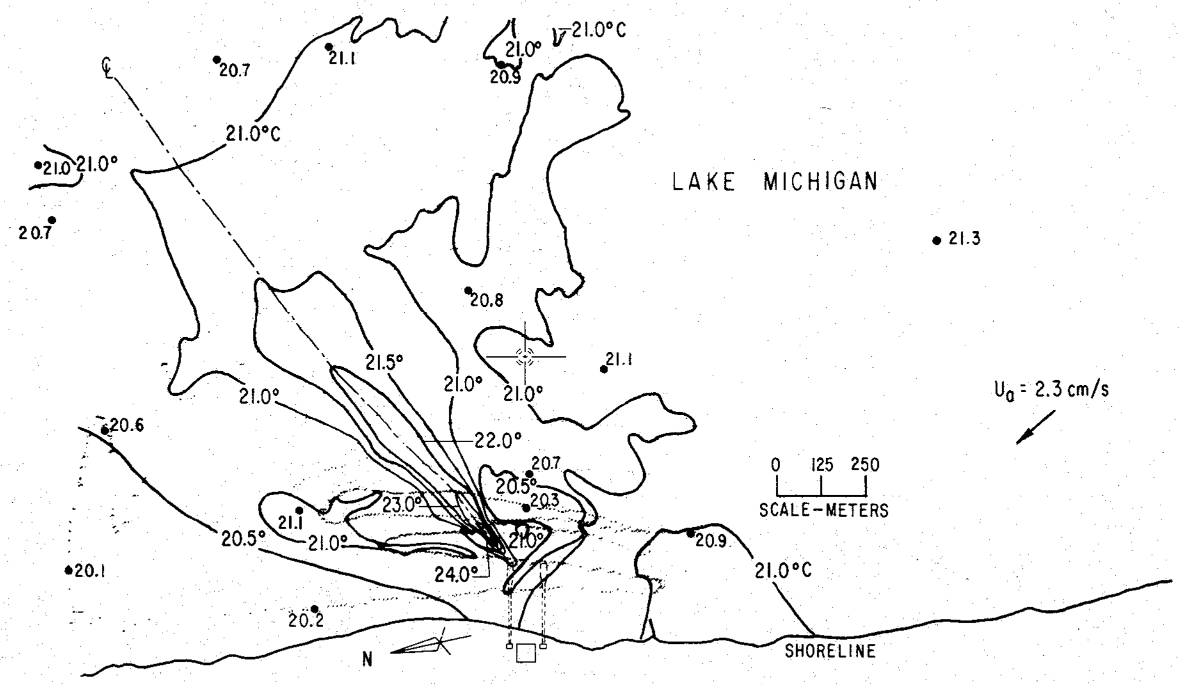

Fig. 5. Thermal Plume at Surface for Zion: July 9, 1975, 1132-1337 hr CDT; Discharge Temperature 28.6°C for Unit 2

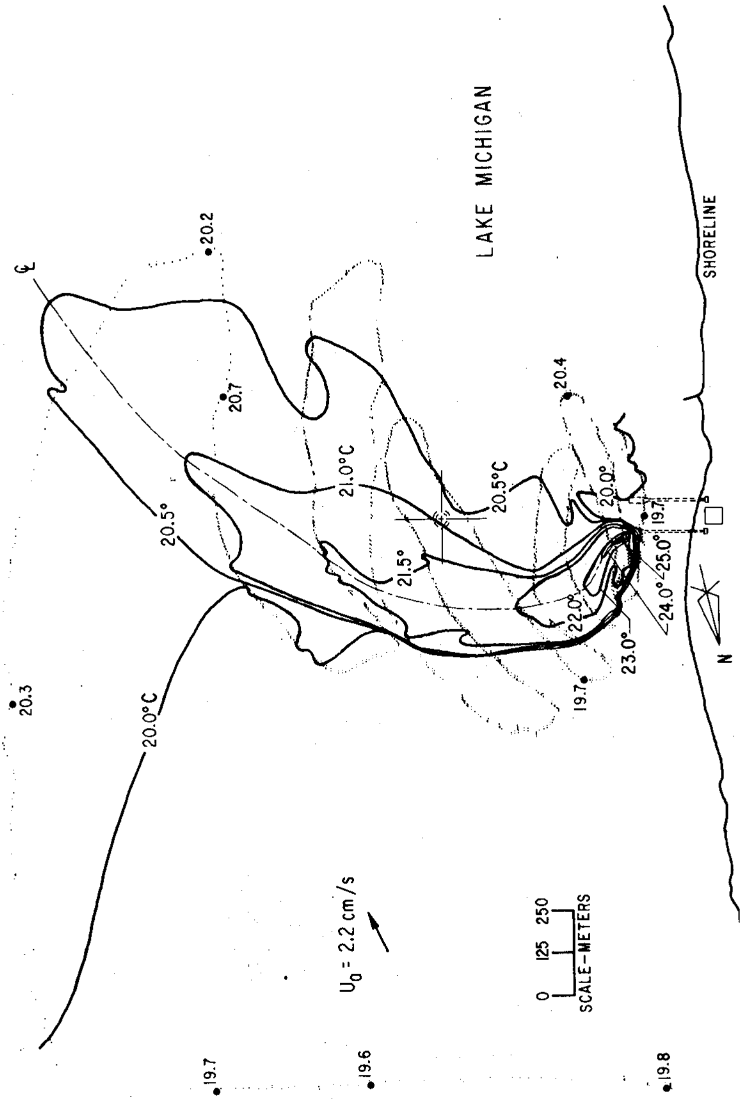

Fig. 6. Thermal Plume at Surface for Zion: July 10, 1975, 1040-1214 hr CDT; Discharge Temperature 28.7°C for Unit 2

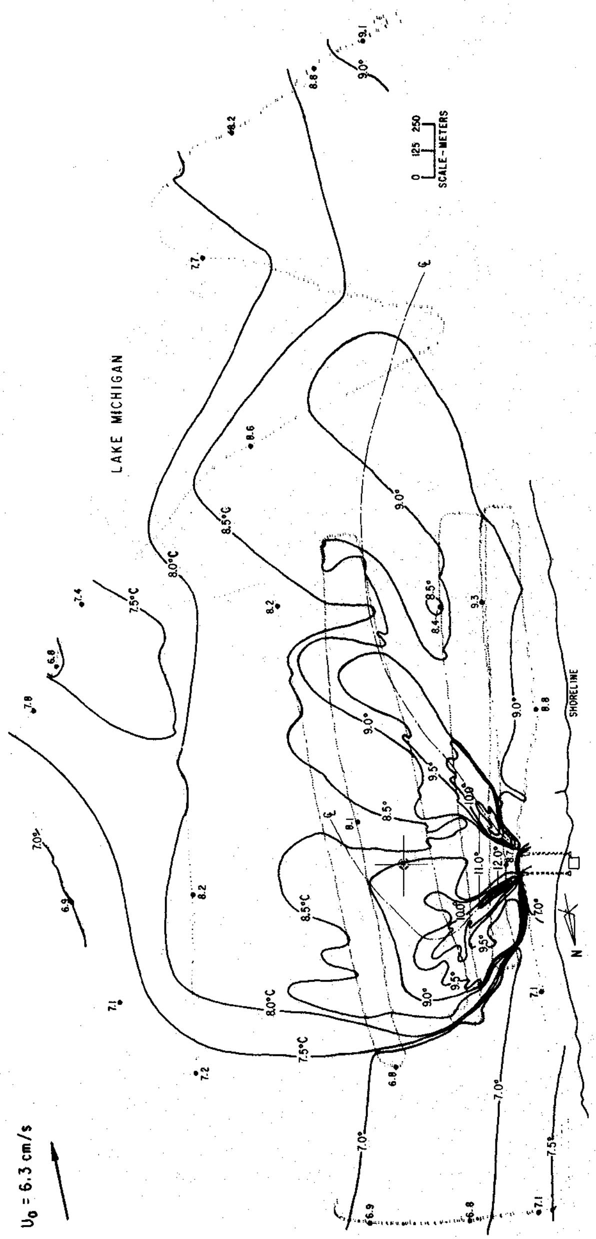

Fig. 7. Thermal Plume at Surface for Zion: May 1, 1975, 1010-1300 hr CDT; Discharge Temperature 16.2°C for Unit 1 and 17.4°C for Unit 2

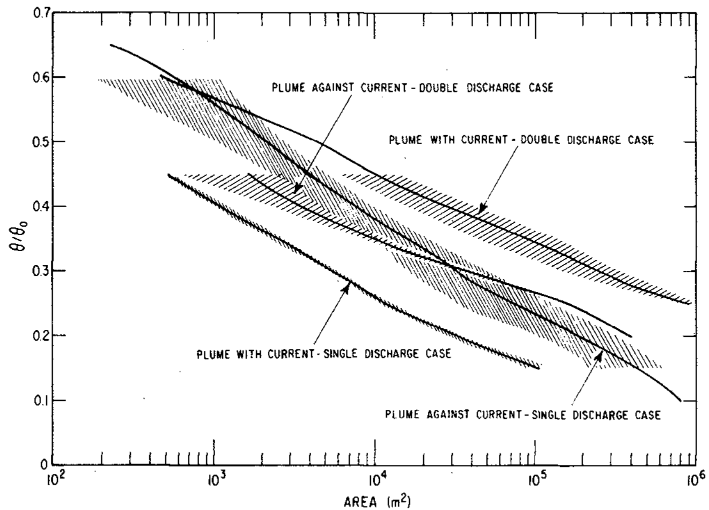

Fig. 8. Comparison of Near-surface Isotherm Areas for Single and Double Discharges, With and Against the Ambient Current

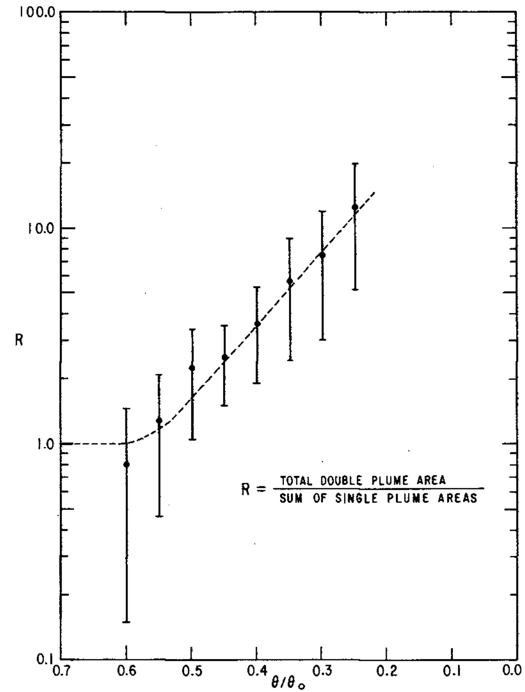

Fig. 9. Ratio of Double-discharge Plume Surface Isotherm Areas to the Sum of Single-discharge Plume Areas

$$F_s = \frac{U_o}{\left(\frac{\Delta\rho_o}{\rho} g\, B\right)^{1/2}}$$

and $K = \frac{U_o}{U_a}$;

U_o = slot discharge velocity,

U_a = ambient current velocity,

B = slot width,

$\frac{\Delta\rho_o}{\rho}$ = discharge density difference.

The ranges of variation of F_s and K are shown in Table 1.

Table 1

Variations of Parameters for ANL Studies at the Zion Nuclear Power Station

	With Current	Against Current	Double Discharge
F_s Range	17.0 - 17.5	14.0 - 23.0	22.6 - 25.2
K Range	83 - 100	10 - 111	38 - 45

Single discharges opposite to the ambient-current direction result in larger areas for given isotherm excess-temperature ratios than single discharges in the direction of the ambient current. In the case of discharges from both units (double discharge), Fig. 8 indicates that the plume of the discharge opposed to the ambient current has an isotherm-area relationship similar to that of a single discharge opposed to the current. However, that plume of the pair, with the discharge in the direction of the ambient current, has larger surface areas associated with a given isotherm than a single discharge with the ambient current. It appears that interaction or interference between the adjacent discharge plumes is responsible for the increased areas or decreased dilution in the downcurrent plume of the pair. Entrainment of the heated water from the upcurrent plume into the second plume and thus the blocking of cool ambient water on the upcurrent side results in increased temperature elevations in the downcurrent plume over those experienced by a single discharge in the direction of the ambient current.

The degree of interaction between the plumes in the case of discharges from both units at the Zion site is manifested further by the following comparison. Consider a prediction of the isotherm-area relation for the double-discharge situation at the Zion site which neglects any interaction between the two discharges. In such a case, the total surface area associated with a given excess-temperature-ratio isotherm would be the sum of the corresponding areas for two single-discharge plumes, one discharged with the ambient current and one discharged opposite to the ambient current. A comparison of measured total surface areas for double plumes and the areas resulting from the linear superposition of single-plume areas is reflected in the ratio, R, shown as function of θ/θ_o in Fig. 9. If the superposition were valid and interactions were thus negligible, the ratio, R, would be 1.0. However, as shown in Fig. 9, measurements of double plumes indicated far-field areas as much as ten times larger than simple superposition would predict. The ranges in R values for a given value of θ/θ_o reflect the envelopes of results, and the dots represent mean values.

The double-discharge measurements at the Zion site point out an interesting feature of the design and evaluation scenarios associated with the environmental assessment of thermal discharges. The often postulated idea that the critical situation for surface temperature fields occurs under conditions of small or zero ambient currents appears valid at the Zion site for single discharges but not for double discharges. Relatively small ambient currents appear to result in significant interaction between plumes for the double-discharge case with increases in surface areas affected over those which would be predicted for two non-interacting plumes discharged into a stagnant environment.

Predictive mathematical models applied to the thermal plumes at the Zion site are of two types: a site specific model developed by Pritchard and general models for thermal discharges in shallow water developed at MIT.

Pritchard[9] made predictions of plume temperatures and geometry for full power operation prior to construction based on a model similar to an earlier model for surface discharges. This modeling effort considered the case of no ambient lake currents and no significant interaction between plumes. Subsequently, on the basis of field observations, the model was modified and refined to include the case of bending of the plume into shallow water by currents.[10,11] Predictions for this case reflect the effects of reduced entrainment from below the plume, recirculation of heated water through the cooling water intake, and reentrainment of heated plume water following a current reversal. Direct comparison between the Pritchard single plume predictions and the ANL field measurements is not possible as the predictions are for seasonal "worst cases." However, a comparison of the isotherm-area predictions for the fall/spring cases of bent and unbent plumes with the average of the ANL data for single discharge against the current indicates good agreement for $\theta/\theta_o < 0.5$ and conservative predictions for $\theta/\theta_o > 0.5$.

No general models for submerged discharge are strictly applicable to the Zion site and discharge geometry. Integral-similarity models for buoyant plumes, such as those reported by Fan and Brooks,[12] are not appropriate for the shallow submergence (depth is only 4.2 slot widths) of the Zion discharge structure. Adams[13] studied the behavior of horizontal thermal discharges from long, multiport diffusers into shallow water with current directed over the discharge. This model accounts for the acceleration of the flow downstream from the diffuser due to the addition of the discharge momentum and predicts the dilution of the discharge in a well-mixed region downstream of the discharge. Although the proximity of the Zion discharge structure to the shoreline does not conform strictly to the idealized unbounded flow field of the model and the well-mixed region geometry is not predicted by the model, dilution predictions in the well-mixed region were found to be about 1.45 (or

θ/θ_o = 0.7) for single discharge conditions at the Zion site. Jirka and Harleman[14] provided a more detailed study of submerged diffuser discharges in shallow water based on a two-dimensional analysis of a long slot-type discharge in a channel with no ambient currents. Several regimes of flow were found possible depending on the hydraulics of the heated water flow on the surface away from diffuser and the entrainment flow on the bottom toward the diffuser. The range of parameters for the horizontal Zion discharge result in the prediction of a flow instability or "full-mixing" region near the diffuser. The uniform vertical temperatures measured at the Zion site in the near-field region confirm that this is approximately the case there. The Jirka-Harleman model gave predictions of the discharge dilution in this "full-mixing" region to be about 1.8 (or θ/θ_o = 0.6) for single-discharge conditions at the Zion site.

Although the models of Adams and of Jirka and Harleman are not strictly applicable to the Zion discharge and although temperature measurements do not indicate the extensive, well-defined "full-mixing" region postulated for the models, comparisons of model predictions were made with near-field surface centerline temperatures for eight single plumes measured by ANL. The location of the point of the highest surface temperature on the centerline occurred between 40 and 100 m from the discharge with an average of 70 m, and the corresponding surface excess-temperature ratios ranged from 0.49 to 0.73 with an average of 0.59. There is remarkably good agreement with the model predictions. However, the fact that vertically well-mixed conditions actually exist in the near-field region is probably the primary factor responsible for the good agreement with the effects of finite diffuser length and boundary geometry being of secondary importance.

In addition to preoperational mathematical-model predictions of the thermal-plume characteristics at the Zion site, physical model studies were performed.[15] These studies employed an undistorted model with geometric scale reduction of 1:25 and Froude and densimetric Froude number similitude. The model boundaries appeared to influence the model results significantly. Comparison of model predictions for single discharges, with and against the ambient current, with the ANL field measurements in terms of centerline temperatures and isotherm-area plots indicate that the model results underestimate the initial near-field dilutions.

Detailed discussion of the comparisons between the field data from the Zion site and the predictions of plume characteristics from mathematical and physical modeling techniques is found in Ref. 7.

Measurements at the Donald C. Cook Nuclear Plant

The Donald C. Cook Nuclear Plant is located near Bridgman, Michigan on the southeastern shore of Lake Michigan, about 18 km south of Benton Harbor (Fig. 1). The two D. C. Cook nuclear reactors are nearly identical, pressurized-water units. Each is capable of a gross generating capacity of 1090 MWe. During 1975, only Unit 1 was operational. The Unit 1 discharge structure is located 365 m offshore, in about 5.7 m of water. The cooling-water discharge from Unit 1 is through two horizontal slots each 9.1 m wide by 0.6 m high, about 0.5 m above the lake bottom (Fig. 4b). One slot is directed offshore while the other is set at 70° to the offshore direction. The discharge flow rate is 48 m^3/s and the average discharge velocity is about 4.3 m/s. The nominal temperature rise for the condenser cooling water is about 12 C°.

Plumes were surveyed at the D. C. Cook site on nine occasions during the spring and summer of 1975 by ANL. Comparisons of field data with model predictions require careful examination of all prototype data over a range of conditions. However, as an example, a limited portion of the available data for plumes at the D. C. Cook site is presented here.

Preoperational physical-model studies were undertaken by Alden Research Laboratories[16] for prediction of the characteristics of the thermal plumes due to the discharges from both of the proposed units of the D. C. Cook plant. An undistorted hydraulic model with geometric scale reduction of 1:75 was employed and resulted in an area modeled which extended about 2300 m along the shoreline and about 1100 m offshore. Temperatures and velocities were scaled to preserve both Froude and densimetric Froude numbers. Near-surface temperatues in the model were measured using a fixed grid of 137 thermocouples for a variety of submerged discharge designs and of discharge and ambient receiving water conditions. Examples of the model-study predictions of near-surface isotherms for the case of cooling-water discharge from the final design Unit 1 slots only are shown in Figs. 10 and 11.[17] These figures indicate, in prototype dimensions, the excess-temperature-ratio isotherms for the case of a constant temperature ambient receiving water, uniform, shore-parallel ambient currents in a northerly direction, and maximum cooling-water flows with full-power-generation discharge temperatures about 11.7 C° above ambient water temperature. The magnitude of the ambient current is 6.1 cm/s for the case shown in Fig. 10 and 15.2 cm/s for the case in Fig. 11.

Comparison of prototype data with the physical-model results requires that dynamically similar conditions be found among the prototype surveys. In regard to the near-field dilution of the plume, that requires that the same densimetric Froude number, F_s, and velocity ratio, K, exist. For the model cases reported above, the densimetric Froude number is about 27 for both cases and the velocity ratios are 65 and 26 for Figs. 10 and 11, respectively. For the small relative discharge submergence (water depth to slot width) of 8.5 and large densimetric Froude number, laboratory experiments and analysis[14] indicate that "full mixing" conditions may exist in the near-field region, similar to those found at the Zion site discussed above. The physical-model studies for the D. C. Cook discharge show a vertically well-mixed region in the near field for the range of conditions investigated. Prototype temperature measurements confirm the existence of this near-field feature. Analysis, and to a degree laboratory experiments,[14] indicate that the dilution of the discharge in the near-field "full mixing" region is independent of densimetric Froude and is dependent primarily on the relative submergence. Since scaling of the relative submergence is assured by geometric similitude between model and prototype, dilutions in "full-mixing" regions in the near field should be comparable in model and prototype for cases of similar ambient-current direction and velocity ratio, K. Plume characteristics in the intermediate and far-field regions, however, are not likely to scale so simply. In the

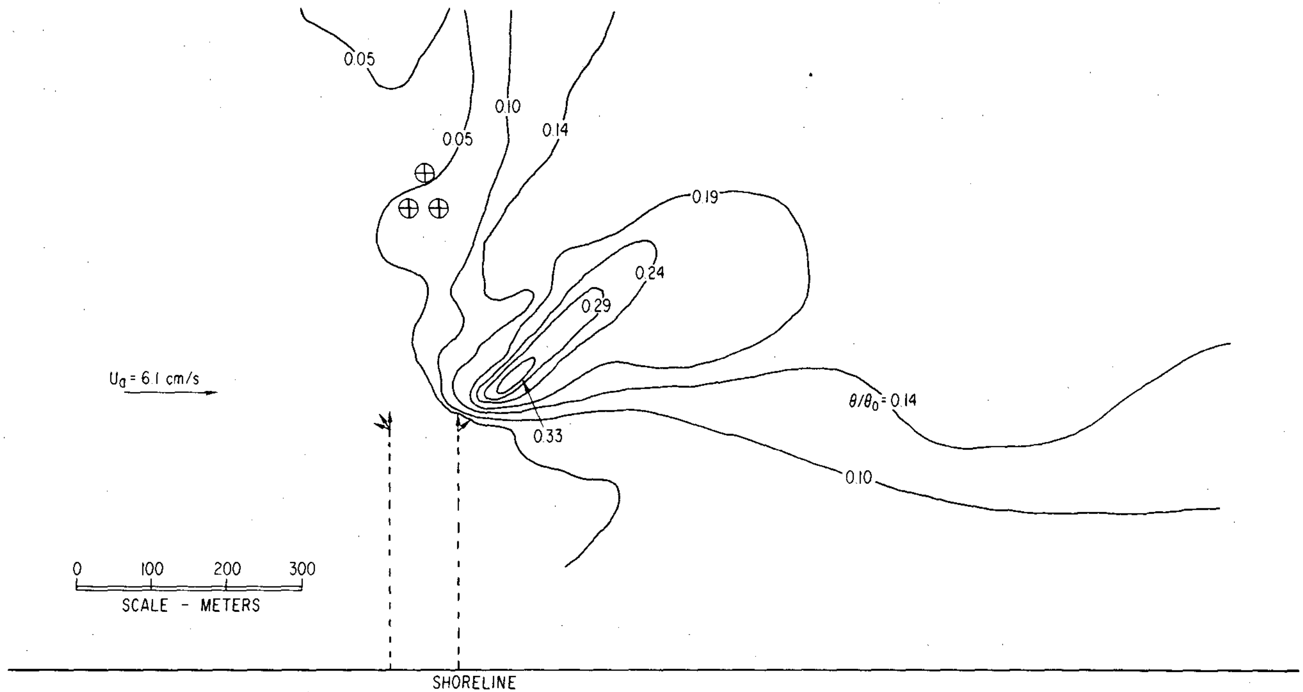

Fig. 10. Surface Excess Temperature Ratio Isotherms From Physical-model Study for D. C. Cook Unit 1 with an Ambient Current of 6.1 cm/s

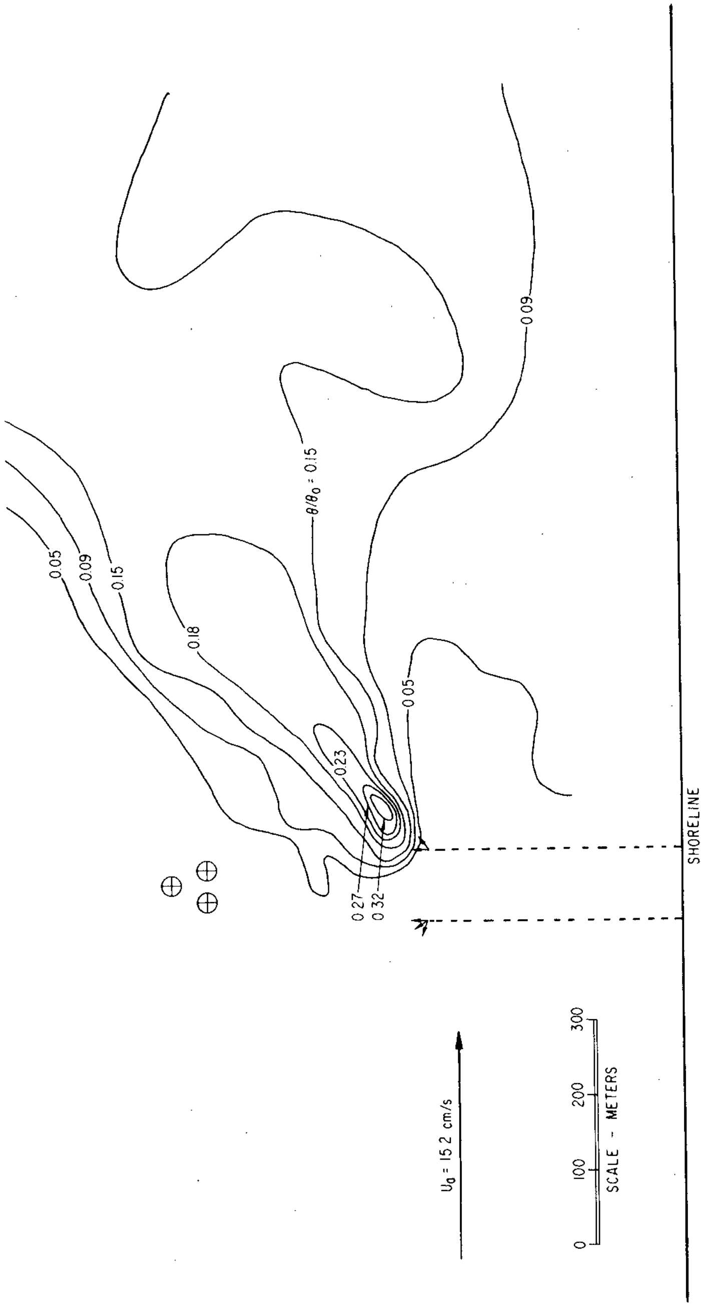

Fig. 11. Surface Excess Temperature Ratio Isotherms from Physical-model Study for D. C. Cook Unit 1 with an Ambient Current of 15.2 cm/s

intermediate region, beyond the "full-mixing" region, preservation of local densimetric Froude number is probably important to produce proper gravitational spreading in the surface region. However, in the intermediate and in the far-field regions interfacial friction should also be scaled properly, and it is not clear that that is possible in an undistorted model of this scale.[18] Moreover, the far-field mixing is primarily governed by ambient mixing processes which may not be scaled properly in the model. Thus, complete similitude between a single model and prototype plume temperatures is unlikely over the range of regimes from the near field to the far field. For the undistorted model studies conducted, the comparison between model predictions and prototype measurements is most appropriate in the near-field region.

An example of prototype surface-temperature measurements at the D. C. Cook site made under conditions providing a degree of similarity is shown in Fig. 12. The ambient lake temperature was uniform, and a plant power generation at about 80% of capacity resulted in a discharge-temperature elevation of 7.4 C° above ambient. The depth-averaged ambient current (measured upcurrent and offshore of the discharge) had a magnitude of 5.8 cm/s and was directed at about 40° from north or about 20° from being shore-parallel as in the model studies. These conditions produce a discharge densimetric Froude number of about 54 and a velocity ratio of about 75. The Froude number associated with the prototype case is about twice as large as that for the model tests mentioned above. However, the prototype Froude number is large enough to indicate "full-mixing" conditions in the near-field region, and such conditions are observed in the near-field temperature data. Thus, as argued above, near-field mixing should be independent of the exact value of densimetric Froude number, and, for similar values of velocity ratio, model and prototype similarity should exist. Comparison of Figs. 10 and 12 indicates reasonable agreement between the near-field surface excess-temperature ratios ($\theta/\theta_o > 0.27$). However, the general surface-isotherm pattern of the prototype resembles that for the model case with larger ambient current ($K = 26$) shown in Fig. 11. The offshore isotherms in the prototype case are more closely spaced than in either model case and do not indicate the proximity to the intake structures shown in the model case of $K = 65$ (Fig. 10). The comparison between prototype and model plume centerline excess-temperature ratios is shown in Fig. 13. Isotherm-area plots for the prototype and model cases are given in Fig. 14. The agreement for these gross plume characteristics is good, although the prototype data indicate slightly larger centerline temperatures and areas.

Several explanations are possible for the differences between the model and prototype surface-isotherm patterns. The prototype ambient lake current in the vicinity of the discharge did not appear to be shore-parallel as in the model study. The current had a component in the onshore direction. Moreover, the wind was from the west in an onshore direction and, with the current, may have contributed to the close spacing of the prototype offshore isotherms. This effect is not, however, realized on the inshore side of the plume. The difference in power generation levels, as manifested by lower discharge temperature excess in the prototype case, may not be significant in the near-field region but certainly affects the intermediate- and far-field spreading. Since these regions of the model plumes contain larger temperature

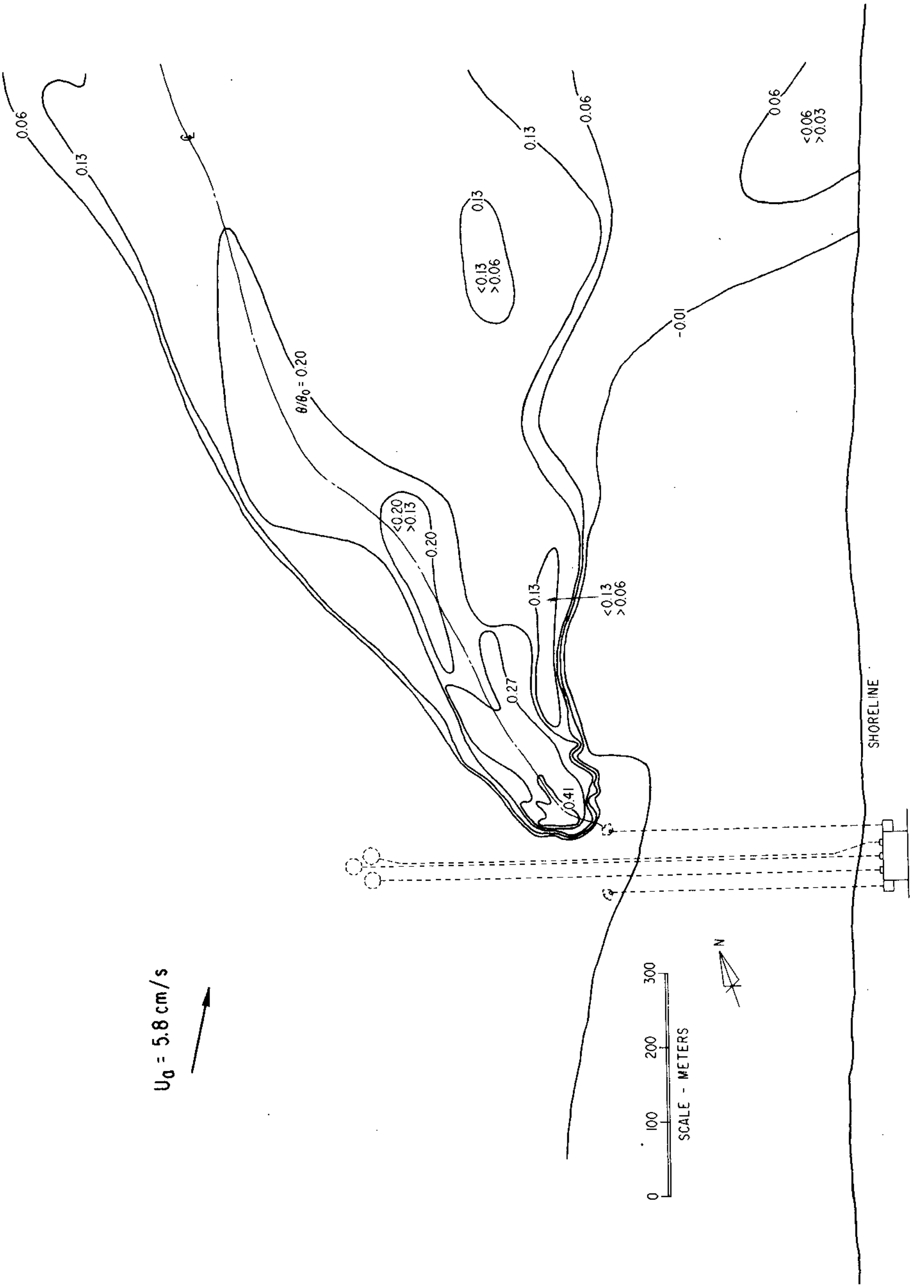

Fig. 12. Surface Excess Temperature Ratio Isotherms from ANL Field Measurements at D. C. Cook: May 14, 1975, 1158-1318 hr CDT. Ambient Current = 5.8 cm/s.

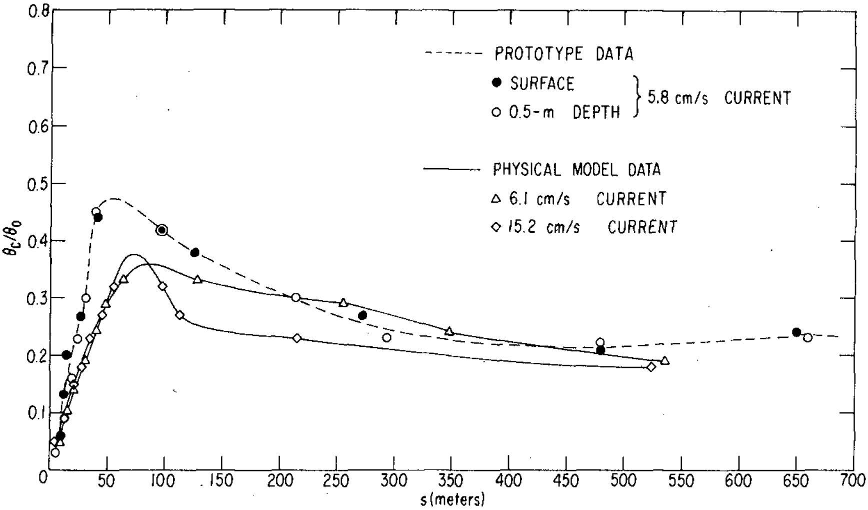

Fig. 13. Comparison of Centerline Temperature Decay from Physical-model and Prototype Data for D. C. Cook Unit 1

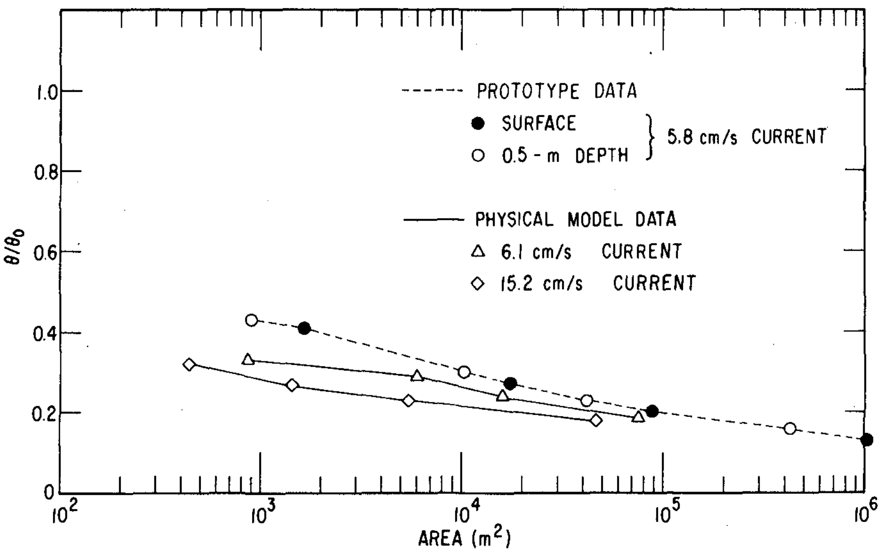

Fig. 14. Comparison of Isotherm Areas from Physical-model and Prototype Data for D. C. Cook Unit 1

excesses than the prototype plume, larger lateral gravitational spreading would be expected in the model cases than in the prototype case. The offshore, far-field region of the model may also be affected by the presence of the model boundary. The offshore model boundary is indicated by the end of the offshore isotherms in Figs. 10 and 11. Its proximity to the plume may result in reduced transport of heat in the downcurrent direction and an increase in temperature in that region.

Evaluation of a physical-model prediction on the basis of a single prototype condition, dynamically similar or not, is hardly proper. The comparison presented is for the purpose of demonstrating the problems associated with such model and prototype comparisons. A comprehensive evaluation requires a set of such comparisons for all the prototype data obtained.

Conclusions

The examples of comparisons between model predictions and prototype measurements demonstrate that while predictions of maximum near-field temperatures may be reasonably good for these cases, prediction of other plume characteristics is not so straight-forward. The cases considered have been relatively simple; that is, ambient receiving-water stratification and ambient current shear have been negligible. Measurements at the Zion site indicated that the direction of the ambient current was an important parameter governing plume dilution and extent. The interaction between plumes from the two discharges at the Zion site resulted in heated surface areas as much as ten times larger than would be predicted by models assuming the superposition of two independent discharges. The example of temperature measurements at the D. C. Cook site indicates the difficulty of obtaining dynamic similarity for comparisons between physical models and prototype cases. The need for prototype measurements at submerged discharge sites is clear. Evaluation of predictive mathematical and physical models requires detailed measurements of the temperature field produced as well as carefully monitoring of ambient conditions. Comparisons between model predictions and prototype measurements require a reconciliation of the idealizations necessary for model predictions and the complex nature of the prototype conditions and an appreciation of the capabilities and limitations of the modeling techniques. Only continued comparisons of model predictions with carefully gathered and interpreted prototype data will enhance the value of either technique for design or environmental assessment.

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