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WATER RESOURCES RESEARCH PROGRAM

**THERMAL PLUMES FROM SUBMERGED DISCHARGES
AT ZION NUCLEAR POWER STATION:
PROTOTYPE MEASUREMENTS AND
COMPARISONS WITH MODEL PREDICTIONS**

by

**R. A. Paddock, A. A. Frigo,
and L. S. Van Loon**

GREAT LAKES PROJECT

ARGONNE NATIONAL LABORATORY

MASTER

ENERGY AND ENVIRONMENTAL SYSTEMS DIVISION

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R. A. Paddock, A. A. Frigo, and L. S. Van Loon

ABSTRACT

Several field surveys of thermal plumes from the two submerged discharges at the Zion plant were carried out during 1975. The survey results are presented in the form of horizontal isotherm maps at vertical intervals of 0.5 m from the surface to a depth of 3.0 m. Selected vertical cross sections are also presented. It was found that the direction of the ambient lake current, with respect to the initial discharge direction, can have a significant effect on initial dilution as well as subsequent plume size. The plumes from the two outfalls were found to interact significantly, resulting in the double-discharge plume being more than ten times as large as the sum of two separate single-discharge plumes.

The results of the field measurements are compared with several analytical model predictions and with the results of preoperational physical-model studies. The surface isotherm areas are also compared with data collected at several surface-discharge sites. Compared with the surface discharges, the submerged discharge at the Zion plant produces larger initial surface dilutions and much smaller high-temperature isotherm areas. The differences, however, become less striking after the excess temperature has dropped to about 20% of its initial value.

I. INTRODUCTION

A. General Discussion

Submerged diffuser discharges are increasingly being used in disposing of waste heat from once-through condenser cooling systems for power plants. They appear to be superseding shoreline surface discharges for new, large power-plant applications because they reduce the size of the surface areas associated with high-temperature elevation above ambient receiving water temperatures.

The Federal Water Pollution Control Act of 1972 targets heat as a pollutant and prohibits its discharge into navigable waterways such as the Great Lakes. New power plants, therefore, are required to use closed-cycle cooling methods. Section 316(a) of the Act, however, allows for the rescinding of the no-discharge requirement on a case-by-case basis when it can be demonstrated that the discharge of waste heat will not result in damage to aquatic organisms. As a part of obtaining an exemption from the no-discharge requirement, the extent of the thermal plume will probably have to be limited - hence the use of high-velocity submerged discharges. Requirements for obtaining a 316(a) exemption will probably involve the spatial and temporal delineations of the thermal plume from the power plant. In order to predict the size of the region affected by the thermal discharge before a plant begins operation, analytical and physical (hydraulic) predictive models must be used. After operation has begun, prototype field measurements can be made. The accuracy of various predictive models remains to be demonstrated as most have been tested only against laboratory data. Therefore, it will be necessary to evaluate the precision and limitations of the various models before their application to new power-plant discharges.

Argonne National Laboratory (ANL) has been studying since 1970 the effects of power-plant, waste-heat discharges into the Great Lakes. Initially, research was centered on thermal plumes from power plants employing shoreline surface discharges for once-through condenser cooling. Analytical and physical modeling techniques for predicting the fate of waste heat in large lakes were reviewed and evaluated.^{1,2} In addition, a review of available data from measurement of prototype thermal plumes was conducted.³ This review indicated a paucity of field data describing these plumes under various environmental conditions. It was clear that high-quality field data were needed to evaluate the various predictive techniques. Therefore, ANL began an extensive field program to study the physical phenomena related to shoreline surface waste-heat discharges into the Great Lakes. In addition to mapping thermal plumes, related physical phenomena, such as lake currents, ambient diffusivities, and meteorological conditions, were also measured.⁴⁻⁶ The results of the thermal plume measurements were analyzed and compared with model predictions.^{7,8} This four-year effort culminated in a comprehensive critical evaluation of mathematical-modeling techniques for surface discharges.⁹

Recent interest in high-velocity submerged discharges has resulted in ANL's undertaking a study of these discharges similar to the project carried out for surface discharges. This study includes field measurements of thermal plumes from submerged discharges on the Great Lakes, as well as an examination of physical- and analytical-modeling techniques for the prediction of the characteristics of thermal plumes from submerged discharges.

Sites for possible field surveys include the Zion and D. C. Cook plants on Lake Michigan, the Oswego Unit 5 and J. A. Fitzpatrick plants on Lake Ontario, and the Davis-Besse plant (cooling-tower blow-down) on Lake Erie. During 1973, six surveys⁶ were conducted at Zion Unit 1, one of the first large power plants using a submerged discharge to begin operation on the Great Lakes. In 1975, when ANL's submerged discharge study was instituted, thermal-plume surveys were carried out at both the Zion and D. C. Cook plants. Reference 10 is a preliminary report of the initial plume surveys at the D. C. Cook plant, and includes some comparisons with results of preoperational physical-model tests. The present report presents the results of plume measurements at the Zion plant and comparisons with results of several predictive models that have been applied to the Zion discharge.

B. Zion Nuclear Power Station

The Zion station, operated by Commonwealth Edison Co., is located in northeastern Illinois on the western shore of Lake Michigan about 5.1 km south of the Illinois-Wisconsin state line. An aerial view of the power station is shown in Fig. 1. The only other large source of waste heat in the immediate vicinity is the Waukegan Generating Station located 7 km to the south. The Zion station is situated in a low, shoreline sand-dune complex that rises about 3 m above lake level. The adjacent area consists of low marshlands isolated 30-600 m inland by the shoreline sand beaches and dunes. The lake bottom (immediately offshore) consists principally of sands and silty sands.

The climate at Zion, Illinois is similar to that of the Chicago region. Storms that move eastward across the northern United States and those that move northeastward from the southwestern states constitute the major weather disturbances. The direction of the wind is quite variable, and calm periods are few.

Fig. 1. Aerial View of Zion Nuclear Power Station

Lake-water temperature at Zion ranges from 0 to 28°C. Large temperature changes can occur rapidly in the near-shore waters during periods of thermal stratification. This variation is due to upwelling of cold deep-lake water or downwelling of warm surface water, caused by short-term wind effects. In the region where the intake and discharge structures are located, the prevailing wind-driven currents are shore parallel. Drogue measurements carried out for Commonwealth Edison by Industrial Bio-Test Laboratories¹¹ indicate currents from 20-330 mm/s, with the most common range being 60-150 mm/s. Wave action on the bottom sediments frequently causes the waters to be turbid.

The Zion facility 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. During the present study, the units did not exceed 85% of this value. Cooling water for the once-through cooling system is taken from Lake Michigan through a submerged intake crib (Fig. 2) located 792 m offshore in about 6.4 m of water. At maximum power, the condenser cooling-water flow rate is about 50 m³/s per unit. Water enters the system through two large-diameter pipes near the center of the intake structure. A "cap" is located above the large inlet pipes to prevent vortex formation in the inlet water. At full circulating flow, the maximum water velocity at the perimeter of the offshore intake structure during nonwinter operation is about 0.75 m/s. Condenser cooling water leaves each unit through separate piping and is discharged to the lake via two submerged, high-velocity discharge structures (Fig. 3). Each discharge structure is located 231 m offshore in about 4.5 m of water. The structures are spaced 47 m to either side of the centerline of the intake pipes. The top of each structure consists of a rectangular box with outlet louvers located on the offshore end and on the side away from the intake pipes. The outlet from the discharge structure consists of 14 ports, each of which is roughly 1.6 m wide by 0.9 m high (Fig. 4). The ports form a 45° angle with both the intake lines and the shore. At maximum discharge-flow conditions, the average velocity of the water at the face of the outlet ports is about 2.4 m/s. The nominal temperature rise of the cooling water is 11.1 C° at full power operation.

Much of the information in this section concerning the Zion site and the Zion station can be found in the environmental statement for the Zion Nuclear Power Station.¹¹

Fig. 2. Schematic Diagram of the Water-intake Structure at Zion Nuclear Generating Station

Fig. 3. Schematic Diagram of the Unit 2 Discharge Structure at Zion Nuclear Generating Station

Fig. 4. Schematic Diagram of the Discharge Ports at the Zion Nuclear Power Station

C. Results to be Presented

Chapter II presents: (1) the results of five field surveys of the thermal plumes at the Zion site in the form of horizontal and vertical sections showing plume isotherms and centerlines; (2) bottom contours in the vicinity of the power plant; (3) a study of a detailed time history of temperature at several depths at a fixed location in the plume; and (4) a summary of the temperature data, along with Zion thermal-plume data collected during 1973, in the form of plots of excess-temperature ratio versus isotherm area and distance along the centerline.

Chapter III examines the surface temperature data. Comparisons between ~~plumes arising from single-unit operation and those produced by double-unit~~ operation, as well as field data collected by others, are interpreted.

The results of predictive models that have been applied to the Zion discharge are discussed in Chapter IV. These include the preoperational physical-model studies carried out by Alden Research Laboratories and the analytical predictions of D. W. Pritchard that appear in the environmental statement for the Zion Nuclear Power Station. Pritchard's updated predictions, as well as predictions based on the analytical channel model of Jirka and Harleman, are also compared with the ANL temperature measurements. Finally, the thermal plume data from the Zion plant's submerged discharge are contrasted with data from shoreline surface-discharges.

II. FIELD MEASUREMENTS

A. Instrumentation, Data Collection, Data Reduction, and Data Handling

The instrumentation and techniques used to collect thermal-plume temperature data, and related data such as lake currents and meteorological conditions, are discussed in detail in Ref. 6. They are similar to equipment and procedures used in previous years by ANL to collect similar data at power plants using shoreline surface discharges. The thermal-plume temperature data were collected while underway in a 7.5-m-long survey boat (Fig. 5). These data were recorded on a shipborne data-acquisition system developed at ANL. Time, boat position, water depth, and water temperature were measured and recorded on both paper tape and magnetic-tape cassettes. Water temperature was sensed with YSI (Series 700) linearized thermistors that have a time constant of approximately 0.6 s. The absolute accuracy of these thermistors is ± 0.2 C° and the reproducibility of the thermistors is better than 0.1 C°. The sub-surface thermistors were attached to an aluminum temperature bar (Fig. 5). The water temperature was measured at the surface and at depths of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 m. The location of the survey boat was established with a Motorola Mini-Ranger system that gives distance from two shore-based transponders to an accuracy of ± 3 m. Specifications for all the equipment used in ANL's thermal-plume field work are given in Ref. 6. The data, on cassettes, generated during a thermal-plume survey were transcribed onto computer-compatible magnetic tapes and, along with calibration values, were used in a computer program that plots water temperature and water depth as a function of position. Isotherms and plume centerlines were then drawn by hand on these plots.

Ambient conditions were routinely measured in conjunction with plume-temperature mapping. Ambient lake-current profiles were measured from the boat with a Bendix Q-15, geomagnetic, ducted-impeller current meter. In addition, current speed and direction and lake temperature were measured with an in-situ current-meter/thermograph package for the duration of one of the field studies. The in-situ current meter is a Bendix Q-15R with a separate electronic recording package featuring a digital, cassette tape recorder. The recording package was designed by ANL's Electronics Division. The Q-15R is identical to the Q-15, but is inverted to allow the recording package to

Fig. 5. Survey Boat

be placed below the meter in a mooring string. The system has three analog inputs and one digital input. Analog inputs are digitized and are used to record two thermistor (temperature) signals and the current-direction output (a potentiometer coupled to a geomagnetic compass) from the Q-15R. The digital channel senses pulses from the Q-15R impeller and also senses the direction of rotation of the impeller. The digital input is stored in an add-subtract scalar during a preselected clock interval (eight seconds in this case) to minimize surface-wave biasing. Wind speed and direction were measured with a hand-held anemometer on the boat and by a shore-based meteorological station manufactured by Meteorology Research, Inc. (MKI). Air temperature, humidity, and lake surface conditions were also recorded during each thermal-plume field study.

Plant operating data were obtained from the appropriate power-plant personnel. In addition, for several surveys, a temperature-recording package was installed for continuous recording of cooling-water intake and outfall temperatures.

An ambient water-temperature survey was conducted before and/or after each plume mapping. While upcurrent from the power plant, the boat moved along a line perpendicular to the shoreline from a location about 2000 m offshore to a location as close to the shoreline as possible. Temperature data, at the surface and six depths, were recorded at about 100 locations during such ambient water-temperature surveys.

B. Results of Field Measurements

1. Bathymetry off the Zion Plant

On May 1, 1975, bathymetric data were collected in the vicinity of the Zion station using a digital Datamarine depth finder. The survey boat was run along transects perpendicular to the shoreline from as close to the shore as feasible out to a depth of approximately 8 m (1000 m offshore). The distance between transects was about 150 m. Contour lines (Fig. 6) were then hand drawn from the data. Although no particularly unusual features are apparent in the bathymetry, there is evidence of bottom scouring in the vicinity of the two discharges.

Fig. 6. Lake-bottom Contours near the Zion Site

The location of the intake and discharge structures for the Zion station cooling system are also shown in Fig. 6. In addition, a coordinate system for the site is shown. References will be made to this coordinate system later in the report to specify locations of current measurements, equipment, etc.

2. Dynamics of the Heated-discharge Jet at the Zion Plant

During 1973, field studies of the dynamics of heated-discharge jets were conducted at several power plants with shoreline surface discharges on Lake Michigan. The plants studied included the Point Beach, J. H. Campbell, and Waukegan power plants. Measurements of temperature and velocity were made from a small survey boat anchored in the near-field region of the thermal plumes from these plants. An aluminum bar equipped with six fast-response thermistors was lowered over the side of the boat so that water temperatures were sensed simultaneously from depths of 0.5-3.0 m. A full set of temperatures was sampled every two seconds. Simultaneously, the local water velocity was measured and recorded at similar time intervals. Coherent temperature oscillations were observed. Their magnitudes were as much as 5°C and their periods ranged from 2 to 20 min, depending on the plant. Oscillations in velocity were observed at the corresponding frequencies, and were coherent with the temperatures. Details of these studies are discussed in Ref. 12.

A similar study was conducted at the Zion plant on May 1, 1975. The survey boat was anchored about 395 m from the Unit 2 discharge structure on a line extending from the structure at approximately 45° (Fig. 6, $x = 437$ m, $y = 658$ m). Temperature data were collected for approximately 2000 s (at 4-s intervals) at depths of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 m. The temperature data are plotted as a function of time for the six different depths (Fig. 7). Temperature oscillations can be seen clearly in the figure, although the magnitude (approximately 2°C) is less than previously noted. For example, at the Point Beach Nuclear Power Plant oscillations up to 5°C were observed.¹² There seems to be some regularity in the fluctuations at Zion. Periods of about 2 min and 8 min can be seen in Fig. 7. A more-detailed analysis of these data is not presented because the reason for the study was to show merely that temporal fluctuations of temperature at one point within the thermal plume occur also at the Zion plant.

Fig. 7. Temperature vs Time at 0.0-3.0-m (intervals of 0.5 m) Depths near the Unit 2 Discharge: May 1, 1975, 1745-1815 hr CDT

Fig. 7 (Contd.)

The existence of temperature fluctuations at a given point in a thermal plume can affect individual temperature measurements during a plume survey and hence the exact position of individual segments of the resulting isotherms. However, because the total plume mapping operation extends over a time interval that is much longer than the period of these oscillations, the resulting isotherms will still be representative of the average size and shape of the thermal plume.

3. Thermal-plume Temperature Measurements

The results of the thermal-plume measurements at the Zion Nuclear Power Station follow. The 1975 Zion data are presented first, in sequence according to date. Thermal-plume drawings for the 0.5-m level for the 1973 Zion surveys (see Ref. 6 for details) are presented also, since they will be analyzed along with the 1975 data. Due to equipment malfunction, the surface temperature was not measured during the 1973 surveys. The thermal-plume drawings show the intake and discharge structures, the shoreline, and the lake bottom, where applicable. In general, each plume data set consists of the following:

- (1) a surface isotherm plot;
- (2) subsurface plots corresponding to the 0.5-, 1.0-, 1.5-, 2.0-, 2.5-, and 3.0-m depth levels;
- and (3) vertical cross-sectional plots, which are specified on the surface isotherm plots as A-A', B-B', etc.

The barely legible dots in the figures represent actual temperature values at the location indicated and hence also represent the boat path. The data are not legible because the figures have been reduced for presentation from much larger working drawings. The bold dots with accompanying temperature values were placed on the figures to yield readable representative temperatures corresponding to particular locations.

Both the horizontal and vertical sections of plume isotherms were drawn by hand; thus some degree of judgment and some latitude in interpolation were exercised. In most cases, the individuals who participated in plume contouring attempted to interpolate linearly between points, however, some subjectivity is inherent in the resulting plots. A more detailed explanation of this method of isotherm drawing, along with several others that were tried, appears in Ref. 5. The personnel involved in temperature contouring always

tried to factor into each depth level plot the insight and trends established in the adjacent levels so that a consistent set of plume maps might be obtained.

The vertical cross sections were drawn independently of the horizontal sections. Close inspection of the vertical and horizontal plots reveals some minor differences between the two sets in relationship to isotherm positions. Part of the problem is that the vertical sections were constructed by unfolding, into a straight line, the point-to-point distances. Minor position errors, due to range-equipment noise from one point to another, tend to increase the distances between locations designated by the cross-section markings. The first cross section (A-A') of each plume data set corresponds to the ambient temperature survey discussed in Sec. II.A. Up to three additional cross sections were chosen approximately perpendicular to the plume centerline — one near the discharge through the highest recorded temperatures, one about 750 m from the discharge, and one in the far field where the plume still retains notable definition.

The plume centerlines designated on the horizontal sections are subjective. When the temperature distribution is not symmetrical, the term "centerline" loses its meaning. In the near field, where the plume configuration is often bullet-shaped, the centerline is generally drawn to divide the plume symmetrically. Away from the immediate near field, the plume configuration can take an untold number of shapes, making it almost impossible to define a unique centerline. The location for the centerline in these reaches of each plume was generally chosen to be the locus of maximum temperatures. Where that was not practical, the centerline was drawn to bisect the areas of the higher temperature isotherms.

Temperatures along the centerlines were selected where either the boat path or an isotherm line crossed the centerline. These values were plotted with depth as a function of distance along the centerline from the geometric center of the discharge structure. Vertical centerline sections, similar to the other vertical sections mentioned above, were then drawn. Because the centerlines at each depth do not necessarily coincide exactly, the temperatures selected at a given distance from the discharge may not actually occur directly above or below one another. The discharge and bottom depth near the

discharge are indicated on these centerline vertical sections. The distorted vertical scale, with respect to the horizontal scale, causes the peculiar appearance of the lake bottom.

a. Zion Nuclear Power Station: May 1, 1975

On May 1, 1975, both units were operating relatively steadily at about 81% of capacity (~890 MWe gross generation each) and maximum cooling-water flow rate (all three pumps on each unit). Two plume surveys were conducted on this date — one in the late morning, from 1010-1300 hr CDT, and one in the mid-afternoon, from 1450-1715 hr CDT. During this period the skies were clear and the visibility unlimited. Wind speed and direction, as recorded by the MRI meteorological station, are reported in Fig. 8. During the periods of the plume surveys, the winds were relatively constant, at about 5.6 m/s from the west.

Before each survey, limnological and meteorological data were collected from the survey boat at a position about 2-1/2 km south of the plant, in about 4 m of water. These data are presented in Table 1. The precise boat position (lake location) is given in terms of x-y coordinates, which are with respect to the coordinate system specified in Fig. 6. The ambient lake current was approximately southward with some variation with depth. The first survey occurred at a time midway between the two current profiles of Table 1. All twelve measurements (six from each profile) were averaged to yield a depth-averaged current speed of 63 mm/s. The second survey occurred shortly after the second profile. The depth-averaged current speed for this profile is 53 mm/s. Calm lake-surface conditions existed for both surveys.

The seven horizontal isotherm maps for the late-morning survey are presented in Figs. 9-15. The vertical cross sections appear in Fig. 16 and the two centerline vertical sections in Figs. 17 and 18. The combined plume moved south due to the southward flowing current. Examination of Section A-A' of Fig. 16 indicates an ambient lake temperature for the survey that was relatively constant at 6.8°C both with depth and distance from shore. A well-defined interface between ambient and plume water existed on the upcurrent side of the combined plume, but not on the downcurrent or offshore sides. The plumes from the two discharges are quite distinct until the plume water temperature reaches about 1.5 C° above ambient lake temperature. The plume

Fig. 8. Wind-direction, Wind-speed, and Air-temperature
Data for Zion: April 28-May 1, 1975

Fig. 9. Thermal Plume at Surface for Zion: May 1, 1975, 1010-1300 hr CDT

Fig. 10. Thermal Plume at 0.5-m Depth for Zion: May 1, 1975, 1010-1300 hr CDT

Fig. 11. Thermal Plume at 1.0-m Depth for Zion: May 1, 1975, 1010-1300 hr CDT

Fig. 12. Thermal Plume at 1.5-m Depth for Zion: May 1, 1975, 1010-1300 hr CDT

Fig. 13. Thermal Plume at 2.0-m Depth for Zion: May 1, 1975, 1010-1300 hr CDT

Fig. 14. Thermal Plume at 2.5-m Depth for Zion: May 1, 1975, 1010-1300 hr CDT

Fig. 15. Thermal Plume at 3.0-m Depth for Zion: May 1, 1975, 1010-1300 hr CDT

Fig. 17. Centerline Vertical Section for Zion Unit 1: May 1, 1975, 1010-1300 hr CDT

Fig. 18. Centerline Vertical Section for Zion Unit 2: May 1, 1975, 1010-1300 hr CDT

Table 1. Limnological and Meteorological Data Collected
from Survey Boat: May 1, 1975

	Date and Time	
	May 1, 1975 (0845 hr CDT)	May 1, 1975 (1400 hr CDT)
Lake Location (m) ^a	x=2164, y=781	x=2219, y=789
Bottom Depth (m)	4.3	4.0
Dry Bulb Temperature (°C)	11.1	16.1
Relative Humidity (%)	64	55
Wind Speed & Direction (m/s & degrees)	5.3, 360	3.3, 275
Sky Conditions	Clear	Clear
Lake Surface Conditions	Calm	Calm
Ambient Current Speed & Direction (mm/s & degrees):		
0.5-m Depth	95, 185	56, 130
1.0-m	100, 180	78, 150
1.5-m	83, 190	72, 150
2.0-m	78, 200	56, 155
2.5-m	72, 210	44, 170
3.0-m	56, 210	33, 205

^aSee Fig. 6 for definition of coordinate system.

from the Unit 1 (south) discharge appears to be larger than the plume from the Unit 2 discharge. The plume size changes little with depth to the 3-m level (maximum depth measured). This is in sharp contrast to that observed in previous surveys at shoreline surface discharge sites. Examination of the vertical cross sections confirms the uniformity of the plume with depth; the isotherms are nearly vertical — particularly near the outfall. The isotherms, however, do become somewhat lens-shaped in the far field.

Figures 19-25 show the seven horizontal plume maps for the mid-afternoon survey. The vertical cross sections are shown in Fig. 26 and the two centerline vertical sections in Figs. 27 and 28. The plume is very similar to the plume mapped in the late morning, except that the ambient lake temperature has increased by about 0.4 C°. In both cases the plume eventually turns and runs southward parallel to the shore.

Fig. 19. Thermal Plume at Surface for Zion: May 1, 1975, 1450-1715 hr CDT

Fig. 20. Thermal Plume at 0.5-m Depth for Zion: May 1, 1975, 1450-1715 hr CDT

Fig. 21. Thermal Plume at 1.0-m Depth for Zion: May 1, 1975, 1450-1715 hr CDT

Fig. 22. Thermal Plume at 1.5-m Depth for Zion: May 1, 1975, 1450-1715 hr CDT

Fig. 23. Thermal Plume at 2.0-m Depth for Zion: May 1, 1975, 1450-1715 hr CDT

Fig. 24. Thermal Plume at 2.5-m Depth for Zion: May 1, 1975, 1450-1715 hr CDT

Fig. 25. Thermal Plume at 3.0-m Depth for Zion: May 1, 1975, 1450-1715 hr CDT

Fig. 26. Vertical Cross Sections for Zion: May 1, 1975, 1450-1715 hr CDT

Fig. 27. Centerline Vertical Section for Zion Unit 1: May 1, 1975, 1450-1715 hr CDT

Fig. 28. Centerline Vertical Section for Zion Unit 2: May 1, 1975, 1450-1715 hr CDT

b. Zion Nuclear Power Station: July 9-11, 1975

Three surveys were conducted during the period from July 9-11, 1975 — one on July 9 from 1132-1337 hr CDT, one on July 10 from 1040-1214 hr CDT, and one on July 11 from 1003-1219 hr CDT. Wind data collected during this entire period are shown in Fig. 29. Also during this period, a Q-15R current meter and recording package were moored in about 4 m of water at a depth of 1.5 m. They were located about 2-1/2 km south of the plant at coordinate location $x = 2338$ m, $y = 788$ m (see coordinate system of Fig. 6). The record from this current meter is shown in Fig. 30.

A temperature recording system was installed in the plant during this period. One thermistor probe was located in the northeast corner of the intake forebay and the other in the Unit 2 discharge pipe at the valve house. The data obtained from this system appear in Fig. 31. It is apparent from the figure that temperature variations of about $2\text{ }^{\circ}\text{C}$ occurred during the recording period. However, the difference between the intake and outfall temperatures remained relatively constant, which is indicative of the fact that the power level of Unit 2 was relatively steady during the period of observation. The intake temperature reported may not be precisely representative of the average intake temperature because the water in the forebay is not well mixed — temperature variations of $1\text{ }^{\circ}\text{C}$ or more were noted when a spot check was made at several locations there. The water in the discharge pipe is probably well mixed by the time it reaches the valve house so that the recorded temperatures are representative of the actual outfall temperature.

Before each plume survey, certain limnological and meteorological data were collected from the survey boat, while anchored, at the same position in the lake as the continuously recording, in-situ current meter. These data appear in Table 2. The information is recorded as a supplement to and a backup for the continuous records of the meteorological station and current meter.

The first plume survey of this series took place about midday on July 9, 1975. Unit 2 was operating at about 79% of capacity (864 MWe gross generation) and full cooling-water flow rate; Unit 1 was shut down but one of its main circulating pumps (three per unit) was operating. The wind was unsteady with an average value of 3.1 m/s from the west. The lake current,

Fig. 29. Wind-direction, Wind-speed, and Air-temperature
Data for Zion: July 8-11, 1975

Fig. 30. Lake-current Direction and Speed Data for Zion: July 9-11, 1975

Fig. 31. Intake- and Discharge-temperature Data for Zion Unit 2: July 8-11, 1975

Table 2. Limnological and Meteorological Data Collected
from Survey Boat: July 9-11, 1975

	Date and Time			
	July 9, 1975 (0930 hr CDT)	July 9, 1975 (1430 hr CDT)	July 10, 1975 (0950 hr CDT)	July 11, 1975 (0900 hr CDT)
Lake Location (m) ^a	x=2338, y=788	x=-185, y=1200	x=2338, y=788	x=2338, y=788
Bottom Depth (m)	4	7.3	4	3.7
Dry Bulb Temperature (°C)	22.8	25.6	19.4	18.9
Relative Humidity (%)	58	57	72	71
Wind Speed & Direction (m/s & degrees)	3.3, 010	N.A., 270	7.5, 30C	2.2, 300
Sky Conditions	Clear	Clear	Clear	Clear
Lake Surface Conditions	Swell, 0.3-0.4 m	Calm	Choppy, 0.5 m Waves	Light Swell, 0.1-0.2 m
Ambient Current Speed & Direction (mm/sec & degrees):				
0.5-m Depth	39, 280	N.A.	16, 16C	16, 020
1.0-m	16, 290		16, 15C	39, 035
1.5-m	0		16, 145	56, 010
2.0-m	16, 260		11, 15C	56, 015
2.5-m	0		22, 245	50, 350
3.0-m	0		22, 245	56, 330

^aSee Fig. 6 for definition of coordinate system.

as measured by the in-situ meter, increased gradually and uniformly during the day. The average value during the survey was 23 mm/s at 330°, which is somewhat onshore but essentially northward flowing. The isotherm maps for the seven levels are presented in Figs. 32-38. The plume does not appear to be bent from its original discharge direction by the small current. Some decrease in the area affected by the plume can be seen with depth. The surface isotherms of Fig. 32 appear more irregular than those of the deeper levels. This may be due to some slight surface heating caused by the midday sun and clear skies. The vertical cross sections appear in Fig. 39. The ambient section was chosen to be the one to the north of the plant, even though there is another segment of the boat path south of the plant that might have been chosen. The transect was taken at the end of the survey and therefore about two hours after the near-field data were acquired. The last transect was considered as not representative of the ambient temperatures that would have been present in the area before the introduction of the plume as mapped. The ambient temperature appears to vary slightly with depth — about 0.4 C° over the 3-m depth observed. Examination of the intermediate section (C-C') indicates that the plume was starting to float rather than being fully mixed as indicated by the near-field section (B-B'). The centerline vertical section of Fig. 40 also indicates that the plume started to float at a distance of about 750 m from the discharge. This apparent effect may be due in part to the variation of the ambient temperature with depth.

The second survey was started in the late morning of July 10, 1975. Unit 2 was operating at 80% of capacity (883 MWe gross generation) and Unit 1 was still out of operation. The wind was relatively steady at 3.7 m/s from the northwest. According to the in-situ current-meter data, the lake current was essentially zero at the start of the survey, increasing to the south as the survey proceeded. The data from the in-situ current meter was averaged over the time interval of the survey to yield a value of 22 mm/s to the south. The seven horizontal isotherm maps appear in Figs. 41-47. The effect of the south current is very noticeable, causing the centerline to bend significantly and a sharp interface to form on the upcurrent edge of the plume. The vertical cross sections of Fig. 48 show that the ambient lake temperature ($\approx 19.6^{\circ}\text{C}$) was uniform with depth and distance offshore. The intermediate section (C-C') exhibits a sharp vertical upcurrent interface

Fig. 32. Thermal Plume at Surface for Zion: July 9, 1975, 1132-1337 hr CDT

Fig. 33. Thermal Plume at 0.5-m Depth for Zion: July 9, 1975, 1132-1337 hr CDT

Fig. 34. Thermal Plume at 1.0-m Depth for Zion: July 9, 1975, 1132-1337 hr CDT

Fig. 36. Thermal Plume at 2.0-m Depth for Zion: July 9, 1975, 1132-1337 hr CDT

Fig. 37. Thermal Plume at 2.5-m Depth for Zion: July 9, 1975, 1132-1337 hr CDT

Fig. 38. Thermal Plume at 3.0-m Depth for Zion: July 9, 1975, 1132-1337 hr CDT

Fig. 39. Vertical Cross Sections for Zion: July 9, 1975, 1132-1337 hr CDT

Fig. 40. Centerline Vertical Section for Zion Unit 2: July 9, 1975, 1132-1337 hr CDT

Fig. 41. Thermal Plume at Surface for Zion: July 10, 1975, 1040-1214 hr CDT

Fig. 42. Thermal Plume at 0.5-m Depth for Zion: July 10, 1975, 1040-1214 hr CDT

Fig. 43. Thermal Plume at 1.0-m Depth for Zion: July 10, 1975, 1040-1214 hr CDT

Fig. 44. Thermal Plume at 1.5-m Depth for Zion: July 10, 1975, 1040-1214 hr CDT

Fig. 45. Thermal Plume at 2.0-m Depth for Zion: July 10, 1975, 1040-1214 hr CDT

Fig. 46. Thermal Plume at 2.5-m Depth for Zion: July 10, 1975, 1040-1214 hr CDT

Fig. 47. Thermal Plume at 3.0-m Depth for Zion: July 10, 1975, 1040-1214 hr CDT

Fig. 48. Vertical Cross Sections for Zion: July 10, 1975, 1040-1214 hr CDT

and shows that the plume was starting to float. The centerline vertical section of Fig. 49 also shows that the plume began to float about 500 m from the discharge.

The third and final plume survey of this series was conducted over a 2-1/4 hr period in the late morning of July 11, 1975 beginning at 1003 hr CDT. During this survey, Unit 2 was operating at about 79% of capacity (865 MWe gross generation). However, Unit 1 was brought on line about 0500 hr CDT that morning. The power level was increased slowly due to plant testing operations. By 1000 hr CDT, it had reached 24% of capacity. At 1400 hr CDT, the power level of Unit 1 was at about 60%. During the actual plume survey, the power level of Unit 1 was quite variable as was the cooling-water flow rate because the three circulating pumps were brought into operation one at a time. The wind was light and unsteady during the survey with an average speed of 2.3 m/s. It was out of the west for most of the survey but shifted to the south during the last half hour. The lake current, as recorded by the in-situ meter, was relatively constant for several hours before and during the survey. It was generally flowing northward with an average speed of 28 mm/s. Figures 50-56 are the seven isotherm maps constructed from the data of this survey. The northward flowing current appears to have caused the Unit 2 plume to meander northward. The low-power plume from Unit 1 does not appear to have interacted significantly with the Unit 2 plume in the near-field region. An area of water at near-ambient temperature exists between the plumes near the discharges. However, farther out the isotherms of the two plumes that are about 0.5 C° above ambient tend to merge at least in the surface layer. The vertical cross sections are presented in Fig. 57. In this case, both Section A-A' and D-D' can be considered ambient profiles. The first was taken at the beginning of the survey and the second after the survey. The first shows only about a 0.6 C° temperature variation over the 3-m depth, while the second shows about a 1.3 C° variation. The change can be attributed to both a 0.3 C° increase in the surface temperature and a 0.4 C° decrease in the 3-m temperature. Apparently lake water of a different character than was present when the survey began was brought into the area by the northward flowing current. The intermediate section (C-C') shows no sharp interface at the edges of the plume yet the two plumes still appear to be relatively distinct. Some interaction in the upper 1-m layer is apparent.

Fig. 49. Centerline Vertical Section for Zion Unit 2: July 10, 1975, 1040-1214 hr CDT

Fig. 50. Thermal Plume at Surface for Zion: July 11, 1975, 1003-1219 hr CDT

Fig. 51. Thermal Plume at 0.5-m Depth for Zion: July 11, 1975, 1003-1219 hr CDT

Fig. 52. Thermal Plume at 1.0-m Depth for Zion: July 11, 1975, 1003-1219 hr CDT

Fig. 53. Thermal Plume at 1.5-m Depth for Zion: July 11, 1975, 1003-1219 hr CDT

Fig. 54. Thermal Plume at 2.0-m Depth for Zion: July 11, 1975, 1003-1219 hr CDT

Fig. 55. Thermal Plume at 2.5-m Depth for Zion: July 11, 1975, 1003-1219 hr CDT

Fig. 56. Thermal Plume at 3.0-m Depth for Zion: July 11, 1975, 1003-1219 hr CDT

The centerline vertical sections are presented in Figs. 58 and 59. Again, the plume appears to have started to float after about 700 m, but the large stratification apparent in Section D-D' may be overemphasizing this effect.

c. Zion Nuclear Power Station: 1973 Data

During 1973, several surveys of the thermal plume from the Zion plant were conducted. At that time, only Unit 1 was in operation at about 50% of its full power capacity of 1100 MWe. These surveys are reported in detail in Ref. 6. Some of the isotherm maps are reproduced here to help clarify the comparisons and analyses discussed later in this report.

At the time of the 1973 surveys, the surface temperature probe used in the field measurements was not in operation, therefore the 0.5-m depth is the uppermost level reported. The intake and outfall temperatures were also not measured directly by ANL at the time of the surveys. In addition, the plant was just starting operations and standard monitoring, recording, and reporting procedures for cooling-water-system data had not yet been established by plant operating personnel. Therefore, the values for plant load and outfall temperature initially presented in Ref. 6 very likely were not correct. The revised values have been posted on the following isotherm maps.

Two surveys were conducted on September 19, 1973. The first one from 1041-1212 hr CDT covered most of the plume. The second survey from 1320-1357 hr CDT concentrated on only the region of the plume near the discharge. Only the 0.5-m results are reproduced in Figs. 60 and 61. The thermal plume was again mapped twice on October 10, 1973 — once in the late morning (1020-1237 hr CDT) and once in the late afternoon (1528-1632 hr CDT). Figures 62 and 63 show the 0.5-m depth results. Finally, on October 11, 1973, the plume was mapped from 1020-1115 hr CDT and the 0.5-m results are reproduced in Fig. 64.

4. Thermal-plume Isotherm Areas, Centerline Temperatures and Characteristic Parameters

Areas within closed isotherms have been determined with a planimeter for all seven horizontal sections of the five surveys of 1975. The results are tabulated in Table 3. When both units were in operation, the field measurements did not allow for the drawing of isotherms that completely

Fig. 58. Centerline Vertical Section for Zion Unit 1: July 11, 1975, 1003-1219 hr CDT

Fig. 59. Centerline Vertical Section for Zion Unit 2: July 11, 1975, 1003-1219 hr CDT

Fig. 60. Thermal Plume at 0.5-m Depth for Zion:
 September 19, 1973, 1041-1212 hr CDT

Fig. 61. Thermal Plume at 0.5-m Depth for Zion:
 September 19, 1973, 1320-1357 hr CDT

Fig. 62. Thermal Plume at 0.5-m Depth for Zion: October 10, 1973, 1020-1237 hr CDT

Fig. 64. Thermal Plume at 0.5-m Depth for Zion: October 11, 1973, 1020-1115 hr CDT

Table 3. Plume Areas as a Function of Isotherm and Depth

Power plant: Zion Nuclear Power Station Unit 1

Date and time of survey: May 1, 1975 (1010-1300)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
12.0	-	-	-	-	-	-	-
11.0	6.51×10^3	3.43×10^3	5.62×10^3	5.63×10^3	5.25×10^3	5.18×10^3	4.25×10^3
10.0	5.37×10^4	4.33×10^4	5.02×10^4	4.81×10^4	4.08×10^4	2.40×10^4	2.01×10^4
9.5	2.13×10^5	2.68×10^5	1.73×10^5	1.63×10^5	1.48×10^5	1.37×10^5	1.23×10^5
9.0	1.36×10^6	9.97×10^5	1.15×10^6	1.00×10^6	6.76×10^5	5.80×10^5	3.53×10^5

Power plant: Zion Nuclear Power Station Unit 2

Date and time of survey: May 1, 1975 (1010-1300)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
12.0	1.80×10^3	-	3.64×10^2	4.74×10^2	3.59×10^2	-	-
11.0	4.79×10^3	2.35×10^3	1.85×10^3	1.83×10^3	1.41×10^3	8.90×10^2	9.09×10^2
10.0	3.33×10^4	2.85×10^4	2.97×10^4	2.47×10^4	1.85×10^4	1.21×10^4	6.66×10^3
9.5	1.54×10^5	1.24×10^5	1.27×10^5	1.24×10^5	9.18×10^4	8.42×10^4	4.80×10^4
9.0	3.65×10^5	3.31×10^5	3.22×10^5	3.12×10^5	2.59×10^5	2.33×10^5	1.53×10^5

Table 3. (Cont'd.)

Power plant: Zion Nuclear Power Station Unit 1

Date and time of survey: May 1, 1975 (1450-1715)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
13.0	3.33×10^2	3.59×10^2	-	-	-	-	-
12.0	3.72×10^3	3.72×10^3	1.95×10^3	4.16×10^3	6.60×10^2	7.43×10^2	3.01×10^2
11.0	3.70×10^4	3.78×10^4	2.94×10^4	2.62×10^4	1.85×10^4	1.32×10^4	1.07×10^4
10.5	1.40×10^5	1.49×10^5	1.06×10^5	1.08×10^5	9.55×10^4	9.17×10^4	8.13×10^4
10.0	3.67×10^5	3.78×10^5	3.57×10^5	2.95×10^5	2.07×10^5	1.96×10^5	1.67×10^5
9.5	1.16×10^6	1.21×10^6	1.05×10^6	1.01×10^6	8.50×10^5	6.33×10^5	3.47×10^5
9.0	-	-	-	-	-	-	-

Power plant: Zion Nuclear Power Station Unit 2

Date and time of survey: May 1, 1975 (1450-1715)

Isotherm °C	Plume Area within Isotherm (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
13.0	-	-	-	-	-	-	-
12.0	4.93×10^2	3.20×10^2	-	-	-	-	-
11.0	6.21×10^3	8.17×10^3	8.33×10^3	7.88×10^3	1.92×10^3	-	-
10.5	2.27×10^4	4.69×10^4	5.06×10^4	1.72×10^4	1.10×10^4	1.26×10^4	1.00×10^4
10.0	1.25×10^5	1.23×10^5	1.03×10^5	6.74×10^4	4.81×10^4	4.55×10^4	2.83×10^4
9.5	2.92×10^5	3.01×10^5	2.69×10^5	2.35×10^5	1.68×10^5	1.50×10^5	1.02×10^5
9.0	-	-	-	-	-	-	3.08×10^5

Table 3. (Cont'd.)

Power plant: Zion Nuclear Power Station Unit 2

Date and time of survey: July 9, 1975 (1132-1337)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
24.0	6.46×10^2	7.90×10^2	1.24×10^3	4.58×10^2	2.14×10^2	-	-
23.0	4.47×10^3	4.59×10^3	4.28×10^3	4.11×10^3	2.19×10^3	1.78×10^3	7.94×10^2
22.0	4.18×10^4	4.52×10^4	3.00×10^4	2.72×10^4	1.96×10^4	1.35×10^4	9.47×10^3
21.5	1.45×10^5	1.99×10^5	1.10×10^5	5.74×10^4	4.22×10^4	3.96×10^4	2.26×10^4
21.0	-	-	4.66×10^5	3.99×10^5	2.20×10^5	1.11×10^5	6.93×10^4
20.5	-	-	-	-	-	6.39×10^5	2.28×10^5

Power plant: Zion Nuclear Power Station Unit 2

Date and time of survey: July 10, 1975 (1040-1214)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
25.0	2.15×10^2	-	-	-	-	-	-
24.0	1.60×10^3	2.15×10^3	6.68×10^2	5.44×10^2	3.89×10^2	5.32×10^2	1.74×10^2
23.0	8.09×10^3	6.46×10^3	3.96×10^3	2.93×10^3	2.00×10^3	2.59×10^3	1.75×10^3
22.0	5.00×10^4	3.93×10^4	2.72×10^4	2.35×10^4	1.37×10^4	1.32×10^4	8.95×10^3
21.5	1.71×10^5	1.72×10^5	1.48×10^5	1.17×10^5	5.08×10^4	3.09×10^4	2.11×10^4
21.0	4.06×10^5	3.85×10^5	3.66×10^5	3.26×10^5	2.12×10^5	1.49×10^5	1.04×10^5
20.5	9.89×10^5	7.17×10^5	7.16×10^5	6.83×10^5	6.43×10^5	5.41×10^5	2.81×10^5

Table 3. (Cont'd.)

Power plant: Zion Nuclear Power Station Unit 1

Date and time of survey: July 11, 1975 (1003-1219)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
24.0	-	-	-	-	-	-	-
23.0	-	-	-	-	-	-	-
22.0	-	-	-	-	-	-	-
21.5	-	1.67×10^3	2.44×10^3	2.26×10^3	-	-	-
21.0	1.75×10^4	1.58×10^4	1.18×10^4	1.14×10^4	9.18×10^3	1.05×10^4	4.19×10^3
20.5	-	-	1.74×10^5	9.21×10^4	4.32×10^4	6.16×10^4	3.20×10^4
20.0	-	-	-	-	9.27×10^5	9.52×10^5	4.09×10^5
19.5	-	-	-	-	-	-	1.94×10^6

Power plant: Zion Nuclear Power Station Unit 2

Date and time of survey: July 11, 1975 (1003-1219)

Isotherm, °C	Plume Area within Isotherm, (m ²)						
	Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
24.0	3.47×10^2	-	-	-	-	-	-
23.0	2.57×10^3	7.64×10^2	9.89×10^2	9.97×10^2	3.91×10^2	1.06×10^3	7.10×10^2
22.0	1.26×10^4	8.61×10^3	9.56×10^3	6.25×10^3	2.41×10^3	3.72×10^3	2.84×10^3
21.5	5.92×10^4	5.53×10^4	2.99×10^4	2.91×10^4	1.43×10^4	1.52×10^4	6.18×10^3
21.0	-	-	8.21×10^4	7.29×10^4	4.91×10^4	4.42×10^4	2.63×10^4
20.5	-	-	-	2.61×10^5	1.07×10^5	1.01×10^5	6.29×10^4
20.0	-	-	-	-	6.69×10^5	4.66×10^5	1.58×10^5
19.5	-	-	-	-	-	-	1.03×10^6

enclosed the plumes from both units. Therefore, areas are reported for each unit separately. Isotherm areas for the 1973 surveys have been previously tabulated in Ref. 6 and are not repeated here.* In addition, temperature information as a function of distance along the plume centerline has been extracted for all the horizontal sections. These results, not tabulated here, were used to develop the centerline vertical sections presented and described above in Sec. II.B.3.

To compare plumes that were mapped at different times, it is convenient to express temperatures in terms of excesses above the background ambient temperature that would have existed had the plume not been present. The assignment of this ambient temperature in a precise, rigorous way is difficult, if not impossible, when significant horizontal or vertical temperature variations exist in the lake. In an attempt to make a reasonable estimate of the ambient temperature, the ambient temperature survey conducted in conjunction with each plume mapping along with the entire map of measured temperatures was examined. A reasonable ambient-temperature range and a single most-representative value were assigned to each of the seven depths. Different values were allowed for different depths to account for the vertical stratification observed on occasion. These values are tabulated in Table 4 and the single representative values are used throughout this report wherever an ambient temperature or temperature excess is reported.

Average values for plant load (gross electric generation), cooling-water flow rate, intake temperature, discharge temperature, and ambient lake current for each survey are summarized in Table 5. Also included in this table are a discharge densimetric Froude number, F_o , and the ratio, K , of the magnitude of the ambient current to the average velocity of the heated water at the point of discharge. For purposes of calculating a densimetric Froude number, the discharge is considered to be a slot of length 22.7 m and height 0.91 m. The densimetric Froude number is then defined as

$$F_o = \frac{Q/(LB)}{\sqrt{\frac{\Delta\rho_o}{\rho_a} gB}},$$

*Some of the isotherm areas originally reported in Ref. 6 for the survey of September 19, 1973, 1320-1357 hr CDT are in error. The areas for the 1.0-, 1.5-, 2.0-, 2.5-, and 3.0-m levels should be divided by 4 to obtain the correct values.

Table 4. Ambient Lake Temperatures during Plume Surveys

Date of Survey	Time of Survey (hr CDT)	Ambient Water Temperature (°C)						
		Surface	0.5-m Depth	1.0-m Depth	1.5-m Depth	2.0-m Depth	2.5-m Depth	3.0-m Depth
Sept. 19, 1973	1041-1212	N.A.	16.5-16.9 ^a 16.7 ^b	16.5-16.9 16.7	16.5-16.9 16.7	16.4-16.9 16.7	16.4-16.9 16.7	16.4-16.9 16.7
Sept. 19, 1973	1320-1357	N.A.	16.8-16.9 16.9	16.9 16.9	16.9 16.9	16.8-16.9 16.8	16.8-16.9 16.8	16.8 16.8
Oct. 10, 1973	1020-1237	N.A.	13.5-14.5 13.7	13.5-14.5 13.7	13.5-14.5 13.7	13.5-14.5 13.7	13.6-14.5 13.7	13.5-14.5 13.7
Oct. 10, 1973	1528-1632	N.A.	14.5-15.3 14.8	14.5-15.3 14.8	14.5-15.3 14.7	14.5-15.3 14.7	14.4-15.2 14.7	14.4-15.2 14.7
Oct. 11, 1973	1020-1115	N.A.	13.2-14.0 13.3	13.2-14.0 13.3	13.3-14.0 13.3	13.2-14.0 13.3	13.2-14.0 13.3	13.1-14.0 13.2
May 1, 1975	1010-1300	6.7-7.1 6.8	6.6-7.1 6.8	6.6-7.1 6.8	6.6-7.1 6.8	6.5-7.0 6.8	6.5-7.0 6.8	6.5-6.9 6.7
May 1, 1975	1450-1715	7.0-7.8 7.2	7.0-7.8 7.2	7.0-7.7 7.2	7.0-7.7 7.2	6.9-7.6 7.1	6.9-7.5 7.1	6.9-7.5 7.1
July 9, 1975	1132-1337	20.1-20.7 20.5	20.0-20.7 20.5	19.9-20.6 20.4	19.8-20.5 20.4	19.7-20.4 20.3	19.7-20.3 20.2	19.7-20.2 20.1
July 10, 1975	1040-1214	19.6-19.8 19.7	19.5-19.7 19.6	19.5-19.7 19.6	19.5-19.7 19.6	19.5-19.7 19.6	19.5-19.7 19.6	19.5-19.6 19.5
July 11, 1975	1003-1219	19.9-20.2 20.0	19.7-20.1 20.0	19.6-20.0 19.8	19.3-19.8 19.6	19.2-19.6 19.3	19.2-19.7 19.3	18.8-19.3 19.0

^a Ambient temperature range^b Single most representative value for the ambient temperature

Table 5. Summary of Plant, Discharge, and Lake Data

Date of Survey	Time of Survey	Unit	Plant Load (MWe)	Flow Rate (m ³ /s)	Intake Temp. (°C)	Discharge Temp. (°C)	Ambient Current		F _o	K
							Speed (mm/s)	Direction (degrees)		
Sept. 19, 1973	1041-1212	1	540	49.5	16.9	22.6	62	360	23.0	.026
Sept. 19, 1973	1320-1357	1	550	49.5	17.5	23.3	87	30	21.8	.036
Oct. 10, 1973	1020-1237	1	550	35.6	14.2	22.3	165	10	14.4	.096
Oct. 10, 1973	1523-1632	1	550	35.6	14.9	23.0	165	10	14.3	.096
Oct. 11, 1973	1020-1115	1	550	35.6	14.3	22.4	149	10	14.0	.087
May 1, 1975	1010-1300	1	885	49.5	6.8	16.2	63	178	25.2	.026
		2	890	49.5	8.0	17.4	63	178	22.9	.026
May 1, 1975	1450-1715	1	894	49.5	7.1	16.6	53	155	24.6	.022
		2	892	49.5	8.2	17.7	53	155	22.6	.022
July 9, 1975	1132-1337	2	854	49.5	19.6	28.6	23	330	17.5	.010
July 10, 1975	1040-1214	2	833	49.5	19.3	28.7	22	166	16.8	.009
July 11, 1975	1003-1219	1	312 ^a	49.5	18.3	26.4 ^b	28	337	19.7	.012
		2	855	49.5	17.8	28.4	28	337	17.0	.012

^a Average value, power level changed during survey.

^b Measured after survey at 1415 hr CDT.

where

Q = discharge flow rate,

L = length of slot,

B = height of slot,

$\Delta\rho_o = \rho_a - \rho_o$,

ρ_a = density of ambient receiving water,

ρ_o = density of heated water at the outfall,

and

g = acceleration due to gravity.

The tabulated flow rates in Table 5 are in question. The plant personnel report $46.4 \text{ m}^3/\text{s}$ per unit for full flow operation. This value is simply three times the nominal value for each pump ($15.5 \text{ m}^3/\text{s}$) because there are three pumps per unit. In addition, service water at the rate of about $2.0 \text{ m}^3/\text{s}$ is added to the discharge, leading to a total discharge flow rate of $48.4 \text{ m}^3/\text{s}$. During December 1973, Hydrocon, Inc., under contract to Commonwealth Edison Co., attempted to measure the total discharge flow rate of Unit 1 by injecting dye at a constant rate into the cooling-water system and measuring its concentration just before discharge into the lake. They reported¹³ a total flow rate (including service water) of $49.5 \text{ m}^3/\text{s}$. Flow rates for combinations of one- and two-pump operation were also measured and reported. In July 1974, Hydrocon¹⁴ again measured the flow rate of Unit 1 and obtained a value of $44.5 \text{ m}^3/\text{s}$. They suggest that this decrease of 10% was due to a partially closed valve in the discharge line. The values chosen for this analysis and listed in Table 5 have therefore been based on the December 1973 Hydrocon study. The flow rate for Unit 2 was assumed to be the same as for Unit 1 as they are essentially identical systems. More recent studies by Hydrocon^{15,16} in February and April 1975 yielded values that are 17-36% higher than the December 1973 value. All the flow rates measured by Hydrocon, plus the flow rate reported by the plant personnel, are listed in Table 6. Again, the original value of $49.5 \text{ m}^3/\text{s}$ reported by Hydrocon was used throughout this report.

Table 6. Discharge Flow Rates at Zion

Date	Unit 1 Flow Rate (m ³ /s)	Unit 2 Flow Rate (m ³ /s)
Dec. 1973	49.5	-
Jul. 1974	44.5	-
Feb. 1975	59.9	67.1
Apr. 1975	57.8	NA
Pump Value	48.4	48.4

The centerline-temperature and area data extracted from the plume maps for both the 1975 and 1973 surveys are presented in Figs. 65-91. Centerline temperatures are plotted in terms of a centerline excess-temperature ratio, θ_c/θ_o , defined by:

$$\theta_c/\theta_o = \frac{T_c - T_a}{T_o - T_a},$$

where

T_c = local centerline temperature,

T_o = discharge temperature (from Table 5),

T_a = ambient temperature (from Table 4).

The distance along the centerline, s , is measured from the geometric center of the discharge box. Isotherm areas are plotted on a logarithmic scale simply because variations of several orders of magnitude occur. Isotherm temperature is expressed as an excess-temperature ratio, θ/θ_o , defined by:

$$\theta/\theta_o = \frac{T - T_a}{T_o - T_a}$$

where

T = isotherm temperature,

T_o = discharge temperature (from Table 5),

T_a = ambient temperature (from Table 4).

Little variation with depth is apparent, especially for the centerline-temperature data. There is a trend toward smaller isotherm areas as the 3-m

Fig. 65. Excess-temperature Ratio vs Centerline Distance
for Zion Unit 1: May 1, 1975, 1010-1300 hr CDT

Fig. 66. Excess-temperature Ratio vs Centerline Distance
for Zion Unit 2: May 1, 1975, 1010-1300 hr CDT

Fig. 67. Excess-temperature Ratio vs Centerline Distance
for Zion Unit 1: May 1, 1975, 1450-1715 hr CET

Fig. 68. Excess-temperature Ratio vs Centerline Distance
for Zion Unit 2: May 1, 1975, 1450-1715 hr CDT

Fig. 69. Excess-temperature Ratio vs Centerline Distance
for Zion Unit 2: July 9, 1975, 1132-1337 hr CDT

Fig. 70. Excess-temperature Ratio vs Centerline Distance for
Zion Unit 2: July 10, 1975, 1040-1214 hr CDT

Fig. 71. Excess-temperature Ratio vs Centerline Distance for
Zion Unit 1: July 11, 1975, 1003-1219 hr CDT

Fig. 72. Excess-temperature Ratio vs Centerline Distance for
Zion Unit 2: July 11, 1975, 1003-1219 hr CDT

Fig. 73. Excess-temperature Ratio vs Centerline Distance for
Zion Unit 1: September 19, 1973, 1041-1212 hr CDT

Fig. 74. Excess-temperature Ratio vs Centerline Distance for Zion Unit 1: September 19, 1973, 1320-1357 hr CDT

Fig. 75. Excess-temperature Ratio vs Centerline Distance for
Zion Unit 1: October 10, 1973, 1020-1237 hr CDT

Fig. 76. Excess-temperature Ratio vs Centerline Distance (Offshore)
for Zion Unit 1: October 10, 1973, 1528-1632 hr CDT

Fig. 77. Excess-temperature Ratio vs Centerline Distance (Onshore)
for Zion Unit 1: October 10, 1973, 1528-1632 hr CDT

Fig. 78. Excess-temperature Ratio vs Centerline Distance for Zion Unit 1: October 11, 1973, 1020-1115 hr CDT

Fig. 79. Isotherm Areas for Zion Unit 1: May 1, 1975, 1010-1300 hr CDT

Fig. 80. Isotherm Areas for Zion Unit 2: May 1, 1975, 1010-1300 hr CDT

Fig. 81. Isotherm Areas for Zion Unit 1: May 1, 1975, 1450-1715 hr CDT

Fig. 82. Isotherm Areas for Zion Unit 2: May 1, 1975, 1450-1715 hr CDT

Fig. 83. Isotherm Areas for Zion Unit 2: July 9, 1975, 1132-1337 hr CDT

Fig. 84. Isotherm Areas for Zion Unit 2: July 10, 1975, 1040-1214 hr CDT

Fig. 85. Isotherm Areas for Zion Unit 1: July 11, 1975, 1003-1219 hr CDT

Fig. 86. Isotherm Areas for Zion Unit 2: July 11, 1975, 1003-1219 hr CDT

Fig. 87. Isotherm Areas for Zion Unit 1: September 19, 1973, 1041-1212 hr CDT

Fig. 88. Isotherm Areas for Zion Unit 1: September 19, 1973, 1320-1357 hr CDT

Fig. 89. Isotherm Areas for Zion Unit 1: October 10, 1973, 1020-1237 hr CDT

Fig. 90. Isotherm Areas for Zion Unit 1: October 10, 1973, 1528-1632 hr CDT

Fig. 91. Isotherm Areas for Zion Unit 1: October 11, 1973, 1020-1115 hr CDT

level is approached. The isotherm areas at the 3.0-m depth are about 1/4 as large as the corresponding surface isotherm areas. It should be noted at this point that, due to the shallow water near the discharge, the temperature bar often had to be lifted so that the deepest probe was at a depth of 1.5 m. As a consequence, the centerline temperatures for the 2.0-, 2.5-, and 3.0-m depths near the discharge are usually based on isotherms sketched on the horizontal sections in regions where there is little or no field data. This could also affect the areas within the high-temperature isotherms for these deeper levels.

III. DISCUSSION OF PROTOTYPE DATA

A. ANL Field Data

1. Single-discharge Plumes

Of the ten plume surveys conducted at the Zion site, seven were made while only one of the two units was in operation. An eighth survey on July 11, 1975, was made when Unit 2 was in steady operation while Unit 1 was being brought on line and hence at a relatively low power level. Upon examination of the isotherm maps (Figs. 50-56) for that date, it appears that the small plume from Unit 1 had minimal effect on the Unit 2 plume. This survey might then also be considered to be a single-discharge case. The discharge densimetric Froude number, F_o , varied from 14 to 23 (Table 5) for the eight single-plume cases. The ambient to discharge current ratio, K , varied in magnitude from 0.009 to 0.096. To determine whether any trend with F_o or K could be discerned from the data, the centerline-temperature and isotherm-area information extracted from the surface (0.5-m depth for the 1973 surveys) plume maps were compared with one another. The near-surface results were used because they were found to be fairly representative of the upper 2-3 m of the plume. No distinct trends with respect to either F_o or K were apparent.

Two of the eight single-plume surveys were made when the ambient current was essentially in the same direction as the discharge. These are the surveys of July 9 and July 11, 1975, when Unit 2 was operating and the current was flowing northward at about 25 mm/s. The surface centerline temperatures and surface isotherm areas for these two surveys are plotted together in Figs. 92 and 93. The results are nearly identical. The other six surveys were for cases where the lake current and discharge velocity opposed each other. Note that the two were not exactly opposed because the discharge ports are set at an angle of 45° with respect to the shore-parallel direction. The centerline temperatures and isotherm areas for these six plumes are plotted together in Figs. 94 and 95. The 0.5-m depth data are plotted because surface data were not available for most of the six surveys. As noted in the previous discussion of the 1975 field surveys, little variation is expected between the surface and the 0.5-m depth. There is scatter in the data, but a comparison of these figures with the preceding figures (Figs. 92 and 93)

Fig. 92. Excess-temperature Ratio vs Centerline Distance at the Surface for Single Plumes Discharged with the Current

Fig. 93. Surface Isotherm Areas for Single Plumes Discharged with the Current

Fig. 94. Excess-temperature Ratio vs Centerline Distance at the 0.5-m Depth for Single Plumes Discharged Against the Current

Fig. 95. Isotherm Areas at the 0.5-m Depth for Single Plumes Discharged Against the Current

clearly shows that the "with current" plumes are smaller than the plumes in the "against current" group. They are smaller both with respect to isotherm area and distance along the centerline to a given excess temperature. Indeed, on the average, the surface areas of the "with current" plumes are only about 1/6 as large as those of the "against current" plumes. Figure 96 is a plot of the average isotherm areas for these two groups. The shaded region around the average indicates the observed variation within each group. The differences between these two groups, which appear to be significant, could arise from a combination of one or more effects. The opposing current may cause a more rapid dissipation of the initial jet momentum and thus decrease the ability of the jet to entrain ambient water as rapidly and effectively as when the discharge velocity and lake current are essentially in the same direction. In addition, the opposing current may cause the jet to reentrain some of the warm plume water. Another contribution to the difference might be due to the slight stratification of the ambient lake water that was present on the dates of the two surveys in the "with current" group. A temperature variation of 0.4-1.0 C° was observed over the 3-m depth measured. Variations on the dates of the "against current" surveys were only on the order of 0.1 C° or less. Because of this stratification, as the jet emerges from the discharge box and travels toward the surface, part of the water that it entrains is at a lower temperature than the surface ambient water with respect to which the plume excess temperature is defined. The cooler entrainment water could cause a more rapid reduction in plume temperature and smaller surface isotherms. However, since these ambient-temperature variations between the surface and the 3-m depth are only about 10% of the initial temperature difference between the discharge and the ambient water, it is unlikely that this effect could cause a reduction in plume surface areas of the order of 80%, especially in the case of the higher-temperature isotherms where the total dilution is only 2 or 3. The interaction of the jet with the ambient current is probably the major factor contributing to the difference in surface isotherm areas between the two groups.

2. Double-discharge Plumes

On May 1, 1975, two temperature surveys were conducted at the Zion site. At that time, both units were operating at 81% of capacity and maximum cooling-water flow rate. The lake current was southward at 50-60 mm/s. This

Fig. 96... Average Near-surface Isotherm Areas for Single Plumes

caused the plume from Unit 1 (south discharge, downcurrent) to bend over and travel parallel to the shoreline. The plume from Unit 2 (north discharge, upcurrent) also appears to have been bent by the current (Figs. 9-15 and Figs. 19-25), but the presence of the Unit 1 plume makes it difficult to accurately define its centerline.

The isotherms indicate that the plumes from the two units are distinct out to the point where the temperature has reached about 2.2°C above ambient ($\theta/\theta_0 \approx 0.23$). Yet, even though the isotherms are distinct, the plume from Unit 2 (upcurrent) appears to have had a large effect on the plume from Unit 1 (downcurrent). Figures 97 and 98 are plots of surface centerline temperatures and surface isotherm areas extracted as if the plumes were independent. It is clear that the Unit 1 plume is about seven times larger than the Unit 2 plume. The averages of the isotherm areas for Units 1 and 2 for both of these double-plume surveys are plotted in Fig. 99. The shaded region around each average indicates the observed variation between the two surveys. The average areas for the single-plume surveys discussed in Sec. III.A.1 are also plotted. The Unit 2 plume in the double-discharge case is about the size that might be expected for a single discharge opposite to the direction of the current. However, the plume from Unit 1 in the double-discharge case, which discharges in the same direction as the current, is about 40 times larger than would be expected from the "with current" single-plume surveys. Apparently the presence of the Unit 2 discharge has had a very significant effect on the Unit 1 plume. The plume from Unit 2 prevents the cool ambient lake water that is being brought in by the current from reaching the Unit 1 plume. This forces the Unit 1 plume to obtain most of its entrainment water from the warm Unit 2 plume.

The net result of the interference between the plumes from the two units during the May 1, 1975, surveys is expressed quantitatively in Fig. 100. If each unit were in operation separately under the influence of a southward current, one discharge would be opposed to the current while the other would be in the same direction as the current. Consequently, the total surface isotherm areas that would be expected, if the plumes did not interact or interfere, would be simply the sum of the areas found for the two cases discussed above in connection with the single-discharge plumes. The quantity, R , plotted in Fig. 100, is the ratio of the average total surface isotherm areas,

Fig. 97. Excess-temperature Ratio vs Centerline Distance at the Surface for Double Plumes

Fig. 98. Surface Isotherm Areas for Double Plumes

Fig. 99. Comparison of Near-surface Isotherm Areas for Double and Single Plumes

Fig. 100. Ratio of Double-plume Isotherm Areas to the Sum of Single-plume Areas

measured during the double-plume surveys, to the sum of the average areas obtained from the two groups of single-plume surveys. The ratio R should be unity if there were no effects due to interference. Larger values of R imply larger interference effects. The vertical bars indicate the uncertainty (spread) in R due to the scatter in the data. Figure 100 shows that the interference effect is small for the small, high-temperature isotherms near the discharge. As θ/θ_0 decreases, the effect increases exponentially so that when the excess-temperature ratio has dropped to 0.25, the double-unit plume is about 12 times larger than the sum of two single-unit plumes. Clearly, when designing or modeling a thermal discharge, the interaction with other nearby discharges must be taken into account.

B. Hydrocon, Inc., Field Data

Hydrocon, Inc., conducted four sets of field surveys of the plume at the Zion site during different seasons of the year. The first set of surveys¹³ was taken in December 1973 when only Unit 1 was in operation at about 55% of capacity and all three pumps were operating. The ambient lake-water temperature was about 4.8°C and relatively uniform with both depth and distance offshore. Surface isotherm maps and tabulated surface areas are reported in Ref. 13. Figure 101 is a plot of these surface isotherm areas along with the average single-plume results obtained by ANL for the "with current" and "against current" cases discussed in Sec. III.A.1. The Hydrocon results fall within the spread of the ANL data, indicating good agreement between the two independent sets of field measurements.

The second set of Hydrocon surveys occurred in late July, 1974. Again, only Unit 1 was in operation, but at 78% of capacity. The ambient lake water was significantly stratified in the vicinity of the plume. The surface temperature was approximately 20°C, but variations with depth on the order of 1.0–1.5 C° over the upper 3 m of water, and approximately 6 C° over the whole water column, were observed. Slight temperature variations with offshore distance were also present. Because much of the water entrained by the plume as it traveled to the surface was cooler bottom water, the areas of the surface excess-temperature isotherms were significantly smaller than for uniform temperature conditions (by a factor of 10–20) during several of the July surveys. In fact, on several occasions the plume carried significant

Fig. 101. Comparison of Single-plume, Near-surface Isotherm Areas Observed by Hydrocon and ANL

quantities of the cooler bottom water to the surface causing the surface plume to be surrounded by bands of water as much as 2°C below the local ambient surface temperature. This same effect was observed during two of the ANL surveys at the D. C. Cook submerged discharge site.¹⁰

In order to evaluate the extent of the sinking plume at Zion, Hydrocon undertook another set of surveys in February 1975. Four surveys were conducted during which time only Unit 2 was at a significant power level ranging from 55-78%. The ambient lake temperature was less than 1°C and relatively uniform in the vicinity of the plant. Water has its maximum density at about 4°C and consequently water at about 7°C has about the same density as the ambient receiving water. As the water from the heated discharge mixes with the ambient water, its temperature eventually drops below 7°C and becomes more dense than the lake water. The plume then has a tendency to sink and may even spread along the lake bottom. The Hydrocon group, therefore, present both surface and bottom isotherm maps in Ref. 15. There is some evidence of the plume spreading out over the bottom, but the major result was that the plume remained fully mixed over the entire water column and did not eventually float as had been observed during other seasons of the year.

The final series of Hydrocon field surveys reported was made during April 1975. Unit 1 was at about 81% of capacity and Unit 2 was at about 78%. The surveys took place during the period in which the existence of the spring thermal bar was expected. During the winter months, the lake water drops to near 0°C . In the spring the near-shore shallow water heats up first and at the time of the surveys had reached $7.5\text{--}8.0^{\circ}\text{C}$. A narrow region of water near its maximum density, called the thermal bar, develops between the warmer inshore water and the colder offshore water. Large temperature gradients can therefore occur normal to shore. Hydrocon reported temperature decreases of about 1.7°C per kilometer in the offshore direction during these surveys. The total surface isotherm areas for three of these double-unit plumes are plotted in Fig. 102. Isotherm temperatures are expressed as excess temperatures, θ , instead of excess-temperature ratios, θ/θ_0 , used throughout this report because outfall temperatures were not directly available from the Hydrocon report. The total isotherm areas for the two ANL double-plume surveys of May 1, 1975, are also plotted on Fig. 102. The power levels of the two units were about the same as in the Hydrocon case. However, large

Fig. 102. Comparison of Double-plume, Total Surface Isotherm Areas Observed by Hydrocon and ANL

ambient-temperature gradients in the offshore direction due to the thermal bar were not apparent even though the ANL surveys took place only a few days after the Hydrocon surveys. The thermal bar may have moved further offshore. The areas observed by Hydrocon for the double plumes are somewhat smaller than those observed by ANL. This may be due to cooler offshore water being entrained into the plume and lowering the measured plume temperatures. Cool offshore water was not observed during the ANL surveys. Nevertheless, the low-temperature Hydrocon double-plume areas still indicate a significant effect due to interference between the discharges as discussed in Sec. III.A.2.

IV. COMPARISON OF ANL PROTOTYPE DATA WITH PREDICTION MODELS USED FOR THE ZION PLANT

A. Analytical Models Applied to the Zion Plant

The discharge structures at the Zion plant are unique. They are not at all similar to the single submerged round ports or long multiport diffusers which have been modeled analytically. Also, they are located in very shallow water (~4.5 m) so that the bottom and surface boundaries can have a significant effect on the behavior of the resulting thermal plume. No general analytical models have been developed that apply directly to the geometry and shallow relative submergence of the discharge at the Zion plant. However, Pritchard has submitted predictions of the thermal-plume characteristics at the Zion plant based on modifications of a model for shoreline surface discharges. Comparisons of these predictions for surface isotherm areas with the prototype data are presented below. In addition, predictions of near-field surface temperatures, based on general analytical models for long submerged diffuser systems not strictly applicable to the Zion plant discharge, are also presented.

1. Pritchard's Preconstruction Predictions

Prior to the final discharge structure design for the Zion plant, D. W. Pritchard made predictions of the resulting thermal plumes from the two outfalls.¹⁷ The predictions were for full power operation and were based to some extent on Pritchard's first model for surface discharges (reviewed by ANL in Ref. 9). Several variations of the discharge design were considered. The original design had the heated water discharged from and normal to the offshore and two side faces of each discharge box. The proximity of the shore and the relative closeness of the two discharge structures to one another lead Pritchard to conclude that there would be considerable interaction between the discharges and with the shore. In the final design (in service at the Zion plant), an attempt was made to minimize the interaction between discharges by closing off the side of each box that faces the other box. Water was directed away from shore by setting louvers at 45° to the box centerline on the end and other side of each box. The surface isotherm-area predictions¹⁷ for these two designs are plotted in Fig. 103. Both sets of predictions are for the same environmental conditions

Fig. 103. Comparison of Double-plume, Total Surface Isotherm Areas Predicted by Pritchard and Observed by ANL

with no significant lake current. This was assumed by Pritchard to be the most common case. The predictions for the final discharge design indicated no significant interaction between the individual plumes. Also plotted on the figure are the average total isotherm areas measured by ANL on May 1, 1975 (both units operating at 81% power). A lake current of about 60 mm/s was measured on that date. This caused bending of the plumes resulting in some interaction between the plumes and with the shore. For the larger isotherms with excess-temperature ratios below about 0.35, the measured areas more closely resemble the predictions based on the original design that allowed for extreme interference effects.

Predictions for single-unit operation using the final discharge design can be obtained from the two-unit predictions by simply dividing the areas by two (no interference). These predictions along with the average of the ANL single-plume surveys are plotted in Fig. 104. The agreement is quite reasonable, especially considering the geometry and submergence of the discharge structure being modeled. The dilution in the extreme near field is underestimated by the predictions. The modified surface-discharge model apparently cannot account for the dilution that occurs before the heated effluent surfaces. The general agreement, beyond $\theta/\theta_o \approx 0.45$, indicates that Pritchard has successfully modeled the individual plumes. However, the assumption that the most common situation would be one of no current, and the conclusion that the revised discharge design (with the 45° louvers) would significantly reduce interference between the discharges may not be justified.

2. Pritchard's Modified Predictions

After Unit 1 at Zion went into operation at about 55% power and the data from the first set of Hydrocon field surveys were available, Pritchard adjusted his single-plume predictions in light of that data.¹³ Pritchard's thermal model had undergone changes and refinements by that time. In addition, several of the simplifying assumptions that were included in the original model predictions were found not to hold at the Zion site. In particular, the plume is often bent by the lake current so that it travels parallel to shore and remains in relatively shallow water. This restricts entrainment of dilution water from below. Also, the effects of recirculation

. 104. Comparison of Single-plume, Surface Isotherm Areas Predicted by Pritchard and Observed by AN

of heated water through the cooling-water intake, and of reentrainment of heated plume water following a current reversal were both included. After the July 1974 Hydrocon surveys (Unit 1 only, at about 78% power), the model was again modified to account for the significant vertical temperature stratification that was observed in the ambient receiving water.¹⁴ As a result, three sets of model predictions were developed to encompass the major seasonal effects expected at the Zion site. One set is for the winter case where the lake temperature is about 0°C, one set is for the fall/spring case where the lake temperature is uniform and above the point of maximum density, and one set is for the summer case when the lake has a temperature gradient in the vertical direction of about 0.25 C°/m. Within each set, subsets of predictions exist that cover situations of plume bending, recirculation, and reentrainment. Figure 105 is a plot of the fall/spring surface isotherm area predictions for the extreme cases of (1) no significant bending, recirculation, or reentrainment and (2) bending, recirculation, and reentrainment. The average results of the ANL single-plume field measurements are also plotted. The agreement has clearly been improved by the modification to the model as should be expected because the model was adjusted to actual field measurements at Zion.

3. Adams Model and Jirka-Harleman Model Predictions

Historically, most general analytical modeling of submerged jet discharges has been limited to deep-water discharges where boundary effects at the bottom and surface are assumed to be negligible. Recent interest in the application of submerged outfalls to large thermal discharges has prompted analytical modeling of the behavior of submerged diffusers in relatively shallow water. The large size of these thermal discharges, the gradual bottom slope in the nearshore regions of many lakes and coastal waters, and economic considerations often require that the outfalls be placed in shallow water. The analytical approach used to model such discharges must often be quite different from that used in the deep-water cases.

The behavior of long horizontal submerged diffuser discharges in shallow water has been studied by E. E. Adams.¹⁸ He observed that ideal propeller theory suggests that the flow over the diffuser, made up of flow induced by the diffuser plus flow due to an ambient current, will undergo

Fig. 105. Comparison of Pritchard's Modified Single-plume, Surface Isotherm-area Predictions with Average of ANL Observations

a contraction in the lateral direction downstream of the diffuser. Through the application of Bernoulli's theorem and conservation of momentum, he developed an expression for the dilution downstream of the discharge where the dilution flow and the discharge flow become fully mixed over the depth. The dilution S in the fully-mixed, flow-away region is defined as the ratio of the flow-away rate downstream of the discharge to the initial discharge flow rate. The resulting expression for the dilution can be written¹⁹

$$S = 1/2 V + 1/2(V^2 + 2H/B)^{1/2},$$

where

$$V = \frac{u_a H}{U_o B}$$

u_a = ambient crossflow velocity,

U_o = discharge velocity,

H = depth of water,

and

B = height of discharge slot.

In the derivation of this expression, the approximation was made that S is much larger than unity in order to simplify the solution procedure. If this approximation is not made, it can be shown that the solution takes the form

$$S = \frac{H/B - V}{(V^2 + 2H/B)^{1/2} - V}.$$

When this second form of the solution is applied to the Zion site with $H/B = 4.23$ and $V = 0$ (no ambient current), the predicted dilution is 1.45. If it is assumed that all the dilution water is at the ambient lake temperature, this dilution corresponds to an excess-temperature ratio θ/θ_o of 0.69. The ambient currents observed during the ANL field surveys were always less than 10% of the discharge velocity. Small currents such as these will only change the prediction by at most 3%. The applicability of Adams' analysis to the Zion discharge is clearly in question. The outfall structure is not a long diffuser and its proximity to the shoreline may affect the induced

flow. This analysis, however, is one of the few that is even remotely applicable to such a shallow discharge.

G. Jirka and D.R.F. Harleman have carried out a more complete analytical study of submerged diffuser discharges in shallow water.¹⁹ Their analysis is based on a model for a long slot-type discharge situated across the middle of a channel of length $2L$. The details of this channel model will not be discussed here. Four different types of diffuser behavior are possible, depending on the relative depth of the water H/B , discharge angle, and a discharge densimetric Froude number. For the situation at Zion, the model predicts that the solution will fall in the region of "full mixing." In the full-mixing case, the discharge momentum induces a flow through the channel and this flow fully mixes with the discharge flow to yield a single value for the dilution S . For the case of a horizontal discharge, the predicted dilution is given by (Eq. 3-227 of Ref 19)

$$S = \left(\frac{2H/B}{1 + \Phi/2} \right)^{1/2}.$$

An additional parameter, Φ , has been introduced to account for the effect of friction along the bottom of the channel. The parameter is defined by

$$\Phi = f_o L/H,$$

where

f_o = bottom shear stress coefficient

L = half-length of channel,

and

H = depth of water.

Again, this expression for the fully mixed dilution was derived assuming S to be much larger than unity. Large initial dilutions are not expected or observed at Zion and so the exact form of the solution must be used. It is given by²⁰

$$S = \frac{\Phi/8 - 1}{\Phi/4 + 1/2} + \left[\left(\frac{\Phi/8 - 1}{\Phi/4 + 1/2} \right)^2 - \left(\frac{\Phi/8 - 1}{\Phi/4 + 1/2} \right) + \left(\frac{H/B}{\Phi/4 + 1/2} \right) \right]^{1/2}.$$

Jirka and Harleman then attempt to relate the dilution resulting from their channel model to the case of a diffuser in open water. The only case considered is that of a diffuser that has discharge velocity components parallel to the length of the diffuser so as to eliminate the downstream contraction discussed in connection with the Adams model. Jirka and Harleman analyze the simple case of a vertical diffuser with no net horizontal momentum and find that, if the length of the channel is chosen to be approximately equal to the length of the diffuser, the resulting dilutions should be similar. The case of a diffuser with net horizontal momentum is more complicated and they suggest that the same result might hold.

The Zion discharge is horizontal but not constructed so as to eliminate the contraction effect. In addition, it is in very shallow water and has a relatively small initial discharge densimetric Froude number. Therefore application of the Jirka-Harleman model may not be appropriate but, again, it is one of the few, general, shallow-water models available. In order to apply the model, a value for the parameter Φ is needed. Typical values for the shear-stress coefficient f_0 are less than 0.1. This corresponds to a value of Φ between 0.3 and 0.0 and a predicted dilution between 1.77 and 1.80. If all the dilution water is at ambient temperature, the predicted excess-temperature ratio θ/θ_0 is about 0.56. The model is not very sensitive to Φ in this range. However, due to the extreme shallowness of the water, it is sensitive to H . A change of 0.5 m in H results in an 8% change in θ/θ_0 .

Figure 106 is a plot of the extreme near-field surface centerline temperatures for the eight single plumes measured by ANL. Smooth curves have been drawn through the data points to estimate the point at which the highest temperature occurred. This point occurred between 38 and 103 m from the discharge with an average value of 70 m. The highest surface excess-temperature ratios ranged from 0.49 to 0.73 with an average of 0.59. Although the position and temperature at which the plume surfaces is quite variable, there is a trend that the longer the plume stays submerged, the lower its temperature when it surfaces. The trend is indicated by a dashed curve on the figure. This effect decreases the temperature variation among the observations beyond about 125 m downstream of the discharge. Also indicated on this figure are the predictions of the Adams model and the

Fig. 106. Comparison of Near-field, Surface Temperatures with Predictions of the Adams and Jirka-Harleman Models

Jirka-Harleman model. These models both predict the temperature, not at the point at which the plume surfaces, but at an unspecified point downstream of the discharge where the induced flow and the discharge flow become fully mixed. With this in mind, the prediction of the Jirka-Harleman model agrees remarkably well with the average initial dilution observed at Zion. The Adams model, however, underpredicts the dilution by 15-20%.

B. Preoperational Physical Modeling

Preoperational physical-model studies of the buoyant jet from the Zion Unit 1 discharge were conducted by Alden Research Laboratories.²¹ Tests were performed for full power operation of the final discharge design and a few modified designs. The model was undistorted, with lengths in both the horizontal and vertical directions being reduced by a factor of 1/25 compared with the prototype dimensions. Other quantities, such as time and temperature (density) were scaled so as to maintain equality for Froude number and densimetric Froude number between the model and the prototype.

Preliminary tests (three are reported in Ref. 21) were conducted in a very small basin that extended, in terms of prototype dimensions, only 240 m offshore of the discharge and 180 m downstream. The basin was then enlarged for the rest of the tests (six are reported in Ref. 21). This basin, still relatively small, extended 420 m in the offshore direction and 240 m downstream. Only four of these tests (one in the small basin, three in the large basin) used the final discharge design. Of the three tests in the large basin, one was with low lake-level conditions that were not present during the ANL field measurements. Only two of the laboratory tests will be considered here. The first, designated Test 005, was conducted in the larger basin with a shore-parallel crossflow velocity of 54 mm/s in the same general direction as the initial discharge velocity. The discharge densimetric Froude number, F_o , was 16 and the discharge to ambient current ratio, K , was 0.024. The second test, designated Test 009, was also conducted in the larger basin but with a shore-parallel crossflow velocity of 63 mm/s in a direction essentially opposing the discharge. The discharge densimetric Froude number was 17 and the current ratio was 0.028.

The results of the model tests are presented in Ref. 21 in the form of excess-temperature isotherms. Surface centerline temperatures and

isotherm areas were extracted by the same procedure used in reducing the ANL field data. The results are plotted in Figs. 107 and 108. The average results obtained from the ANL single-plume field surveys for both ambient current directions are also plotted on the figures. The model tests underestimate the initial dilution when compared with the appropriate field results. However, the trend of lower dilutions when the ambient current is essentially opposed to the discharge velocity is reproduced by the model tests. Examination of the original surface-isotherm drawings for the model results indicates that the side boundary of the test basin significantly affected the flow pattern of the discharge beyond 120 m from the outfall. The relatively small basin probably accounts for much of the discrepancy between the model tests and the field measurements. In the case of Test 009, the plume actually appears to have impinged upon the basin wall before the crosscurrent had a chance to bend it.

Fig. 107. Comparison of Physical-model, Surface Centerline-temperature Predictions with Average of ANL Observations

Fig. 108. Comparison of Physical-model, Surface Isotherm-area Predictions with Average of ANL Observations

V. COMPARISONS BETWEEN SUBMERGED-DISCHARGE AND SURFACE-DISCHARGE PLUMES

High-velocity submerged discharges are expected to produce larger initial dilutions when compared to low-velocity surface discharges. The larger initial dilution will result in lower maximum surface temperatures and smaller high-temperature isotherm areas at the surface. However, the resulting plume from a submerged discharge will tend to extend over a deeper depth. As the initial discharge velocity is dissipated and buoyancy has a chance to govern the behavior of the plume, the distinction between plumes from submerged discharges and surface discharges is expected to become progressively less. The objective in designing a submerged discharge is to produce enough initial dilution so that acceptable temperatures will be reached before the initial velocity is dissipated and buoyancy takes over.

The surface isotherm areas observed at the Zion plant are compared with previous results from measurements at surface discharge sites in the following sections.

A. Previous ANL Field Data

The plumes from the submerged outfalls at the Zion plant are quite different in character compared with plumes from shoreline surface outfalls. ANL has mapped thermal plumes at the Point Beach Nuclear Power Plant at Two Creeks, Wisconsin, and at the Palisades Nuclear Power Plant near South Haven, Michigan, that have shoreline canal-type surface discharges.⁴⁻⁶ The Point Beach discharge canal is 10.7 m wide and 4.2 m deep; the Palisades canal is 28.3 m wide and 2.1 m deep. The discharge flow rates at the two plants are both about 25 m³/s, about half the normal flow rate from each Zion unit. Initial excess temperatures are comparable for all three plants.

In terms of surface centerline excess temperature, the discharge structures at the Zion plant produce the greatest initial dilution. In particular, a dilution of $2(\theta/\theta_0 = 0.5)$ is reached at the Zion site at a distance of 150 ± 50 m from the outfalls. At the Point Beach and Palisades sites, this point occurs at 400 ± 200 m and 850 ± 500 m from the outfalls, respectively.⁸ The surface area associated with the $\theta/\theta_0 = 0.5$ isotherm at the Zion site is, on the average for the available data, about 1/20 the

size of the corresponding area at Point Beach, and $1/100$ the size of the corresponding area at Palisades. Figure 109 indicates envelopes of the surface isotherm-area data obtained at the Point Beach and Palisades sites. The envelopes of the single-plume measurements at the Zion site, for the two ambient-current directions, are also plotted on Fig. 109. By the time the excess temperature has dropped to 20% of its initial value (Fig. 109), the difference in plume surface areas is no longer as striking. This indicates that, while the details of the outfall configuration may greatly influence initial turbulent mixing and, therefore, initial dilution, the effect on the far-field region of the plume is much smaller. It might be argued that a fair comparison of the far-field isotherm areas of plumes from different power plants requires that the different heat rejection rates be accounted for by reducing the Zion isotherm areas by a factor of 2 (the flow-rate ratio) as suggested by the Asbury-Frigo phenomenological model.²² However, such an adjustment on the semilog plot of Fig. 109 shifts the data only slightly and does not modify the above observations.

The discharge structures at the Zion plant are located in about 4.5 m of water and are only about 0.9 m high. The discharge jet quickly expands to fill the water column as indicated by the fact that the plume surfaces between 40 and 100 m from the outfall, yet still extends deeper than the 3.0-m depth observed in the surveys. Indeed, the plume clearly extends to a depth of more than 3.0 m over the entire region that was normally surveyed. However, there is some evidence that the plume eventually begins to float and becomes thinner when the initial discharge velocity is dissipated and buoyancy has a chance to influence the plume. The situation is quite different at the Point Beach and Palisades plants. At these sites, where the discharge velocity is only about $1/5$ as large as at the Zion plant, the plume begins to float much closer to the point of discharge. Although measurements were also made only to a depth of 3.0 m, it was possible to define and extract a half-depth along the plume centerline. The half-depth is defined as the depth at which the excess-temperature ratio has dropped to half its surface value. By the time the surface centerline excess-temperature ratio has dropped to 0.5, the plume thickness, as measured by the half-depth, has decreased to about $1/3$ its initial value. After this, there is a slight tendency for the thickness to increase, probably due to turbulent diffusion in the vertical direction.

Fig. 109. Comparison of Point Beach, Palisades, and Zion Surface Isotherm-area Measurements

B. Asbury-Frigo Phenomenological Model

Asbury and Frigo²² examined surface-discharge plume measurements reported in the literature for six power plants on large lakes with shoreline surface discharges. They attempted to plot the data so as to minimize the spread. The only variables consistently available for all the data were the outfall temperature and the discharge flow rate. It was found that plotting θ/θ_o versus isotherm area, A_θ , divided by discharge flow rate, Q , gave the best correlation among the data. Figure 110 shows a smooth curve that was drawn through the data along with an envelope that contains all the data. Subsequent ANL field surveys at three additional power plants yielded data points, most of which fell within this envelope. The spread in surface discharge plume data (Fig. 110) is almost two orders of magnitude in the region where the excess-temperature ratio is greater than 0.5. This is to be expected because initial turbulent mixing is strongly dependent upon outfall design. Farther from the outfall, where the excess-temperature ratio is less than 0.2, the spread is less than one order of magnitude. The size of the plume in this region depends mainly on the quantity of heat being discharged by the power plant. This dependency is somewhat accounted for by dividing the isotherm areas by the flow rate and expressing the temperatures as an excess-temperature ratio. In this far-field region, buoyant spreading and ambient turbulent diffusion are primarily responsible for dispersion of the heated effluent.

The average surface isotherm areas from the single- and double-plume surveys at the Zion site are also plotted in Fig. 110. The Asbury-Frigo correlation is not expected to be valid for the Zion site because it was developed from low-velocity, surface-discharge data. This is indicated by Fig. 110. Increased initial dilution due to the high-velocity submerged discharges at the Zion plant produces surface isotherm areas in the near field that are several orders of magnitude smaller than those observed for shoreline surface discharges. The difference in surface isotherm areas is much smaller at the lower temperatures of the far-field region. For the double plumes at the Zion site, there is no significant difference beyond $\theta/\theta_o \approx 0.3$ between the Zion and surface-discharge results (Fig. 110). The effect of the large initial dilution is somewhat cancelled by the fact that the dilution water is coming partially from the other discharge and is, therefore, not at ambient temperature.

Fig. 110. Comparison of Zion Surface Isotherm-area Measurements with Asbury-Frigo Phenomenological Model

VI. SUMMARY

Five field surveys of the thermal plume from the Zion Nuclear Power Station were conducted during 1975. During two of the surveys, both units were in operation and during the other three surveys only Unit 2 was operating at a significant power level. The results of these surveys are presented in the form of horizontal isotherm maps at 0.5-m intervals from the surface to a depth of 3.0 m, along with selected vertical cross sections. Isotherm areas and plume centerline temperatures were extracted from these isotherm maps, as well as from isotherm maps for five surveys carried out during 1973 (Ref. 6). The centerline temperatures were found to vary only slightly with depth. Isotherm areas, however, become slightly smaller with depth; at the 3.0-m depth they are about 1/4 as large as at the surface. The surface isotherm areas were compared to those resulting from field surveys at the Zion plant that were carried out by Hydrocon, Inc. The comparisons showed generally good agreement between these independent sets of plume measurements.

The direction of ambient lake currents relative to the direction of a single discharge has a significant influence on the size of a given thermal plume. On the average, when the discharge direction opposes that of the ambient lake current, the surface isotherm areas are six times larger and the initial dilution at the surface is 20% smaller than when the discharge and the ambient current are in essentially the same direction.

Large interference effects between the plumes from the two outfalls were observed. Comparison of surface isotherm areas with the results of the single-discharge plumes showed the double-discharge plumes to be more than ten times larger than the sum of two separate, single-discharge plumes.

Pritchard's preconstruction predictions were found to be reasonable for the single-discharge case. However, for the double-discharge case, the assumption that the most common situation would be one of no current, and the subsequent conclusion that there would be no significant interference between the discharges may not be justified.

The Jirka-Harleman model, which predicts a single dilution downstream of the discharge where the discharge and dilution waters are fully mixed, was found to predict quite well the average initial dilution observed at the

Zion site. The observed variation in the initial dilution due to current, wind, and other effects is not predicted by the model.

A comparison of the results of preoperational physical-model studies performed by Alden Research Laboratories with the ANL field data showed that the model was conservative. The Alden model predicted an initial dilution about 15% too low and surface isotherm areas about five times too large. However, the model did predict the general trend that ambient lake currents opposite to the direction of the initial discharge produce lower initial dilutions and larger isotherm areas than currents in the same direction as the discharge.

Finally, surface isotherm areas obtained from the plume measurements at the Zion plant were compared with plume areas from several surface-discharge sites. The submerged discharge at the Zion plant was found to produce greater initial dilutions and, therefore, much smaller high-temperature isotherm areas at the surface than the surface discharges. Yet, the difference in surface areas becomes much less striking when the excess temperature has dropped to about 20% of its initial value at the outfall.

This report presents thermal plume data from one power plant employing a submerged discharge. Additional data have been and will continue to be collected at other submerged-discharge sites in order to gain an understanding of the physical processes governing the behavior of these submerged discharges and to evaluate physical and analytical modeling techniques that can be applied to these discharges.

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