

THE PHYSICAL EFFECTS OF A THERMAL DISCHARGE
ON AN ESTUARY



A THESIS

Presented to

The Faculty of the School of Marine Science
The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of
Master of Arts



by

Gary Cridlin Parker

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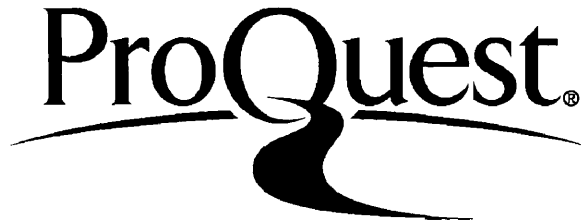
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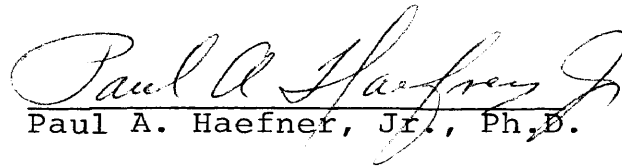
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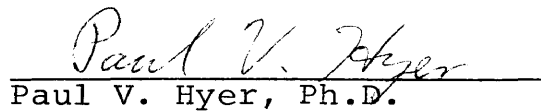

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ABSTRACT

Data on physical parameters in the James River around the condenser cooling water discharge of the Surry Nuclear Power Plant, taken prior to and during plant operation, were analyzed to determine the physical effects of the thermal discharge on the area and to compare the prototype distribution of excess temperature to predictions based on hydraulic model experiments.

Drogue experiments were conducted and infra-red imagery was available to investigate plume characteristics and movement during a tidal cycle. The instrumentation and design of the monitoring program used to obtain the data were evaluated.

The results of this investigation indicated that the increase in water temperatures due to the thermal discharge did not represent a significant alteration of the physical environment outside the mixing zone. The thermal discharge experienced turbulent mixing and entrainment near the outfall and temperatures decreased rapidly in this region.

Dissolved oxygen concentrations were not detectably affected by the discharge. Salinity in the outfall region was increased due to the intake of condenser cooling water from a higher salinity regime downstream of the outfall canal.

Field data on temperature distributions around the discharge, when compared to predictions based on hydraulic model experiments, indicate that the model predictions were conservative.

THE PHYSICAL EFFECTS OF A THERMAL DISCHARGE
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I. INTRODUCTION

With the increasing demand for energy and the accelerated construction of thermal electric power stations, one of the problems that has become increasingly important in recent years is that of predicting the ecological consequences of the discharges of waste heat from electric generating plants into various bodies of water.

Before the ecological impact of a thermal discharge can be determined, a detailed investigation must be performed in order to determine the temperature distribution resulting from such a discharge. These investigations fall basically into three categories: 1) Physical (hydraulic) modeling; 2) Mathematical modeling; and 3) Field studies.

Hydraulic modeling of a thermal discharge has several purposes, which include:

- 1) Qualitative visualization of the behavior of the prototype;
- 2) Quantitative estimates of some of the parameters, such as velocities, depths, and temperature distributions.

Meaningful hydraulic modeling requires that relations be established between model and prototype.

The decision as to what relationships should be established is governed by the physical processes that are important to the phenomena under investigation.

In many cases it is not practical to build a hydraulic model with the same vertical and horizontal scale. Vertical scale exaggeration may be necessary in a case where the horizontal extent of a plume is large compared to its depth. Vertical scale exaggeration may also be required in order to obtain a turbulent flow field. Results obtained from distorted scale hydraulic models must be carefully examined to determine the effects, if any, of scale distortion on the physical processes involved with plume behavior. Therefore, it may be better to model the thermal effects of a discharge with two separate models, one distorted model to cover the far field and one non-distorted to cover the near field, in order to model important physical processes which affect the plume in distinct regions.

A mathematical model for a thermal plume consists of a numerical solution to a set of equations which govern the movement and heat exchange of a parcel of heated water discharged into a body of water. Due to the complexity of the physical processes involved with plume movement, dispersion, diffusion, and heat exchange, the governing equations have to be simplified in order to obtain solutions. The simplified assumptions limit the models applicability.

A necessary part of any study of a thermal discharge is the field survey. Field data must be available in order to verify the accuracy of a hydraulic or mathematical model. The model which has been calibrated and verified with the largest amount of field data is generally the most accurate.

Until recently, there has been very little field data available for thermal discharges. Environmental regulations were instrumental in increasing the amounts of field data available, but in most cases the data is taken around existing power plants where there is little data on pre-operational conditions. Field data are most abundant for thermal discharges into large lakes; there is a lack of data for discharges into estuaries.

The present investigation involves a field survey which has been in operation since 1971. The field data consists of two years of pre-operational data and two years of post-operational data.

The objectives of this investigation are to:

- 1) Compare pre- and post-plant operation data to determine the physical effects of the thermal discharge on the survey area.
- 2) Compare field results with predictions of temperature distributions made with the James River hydraulic model to determine the applicability of the hydraulic model for far field temperature predictions.

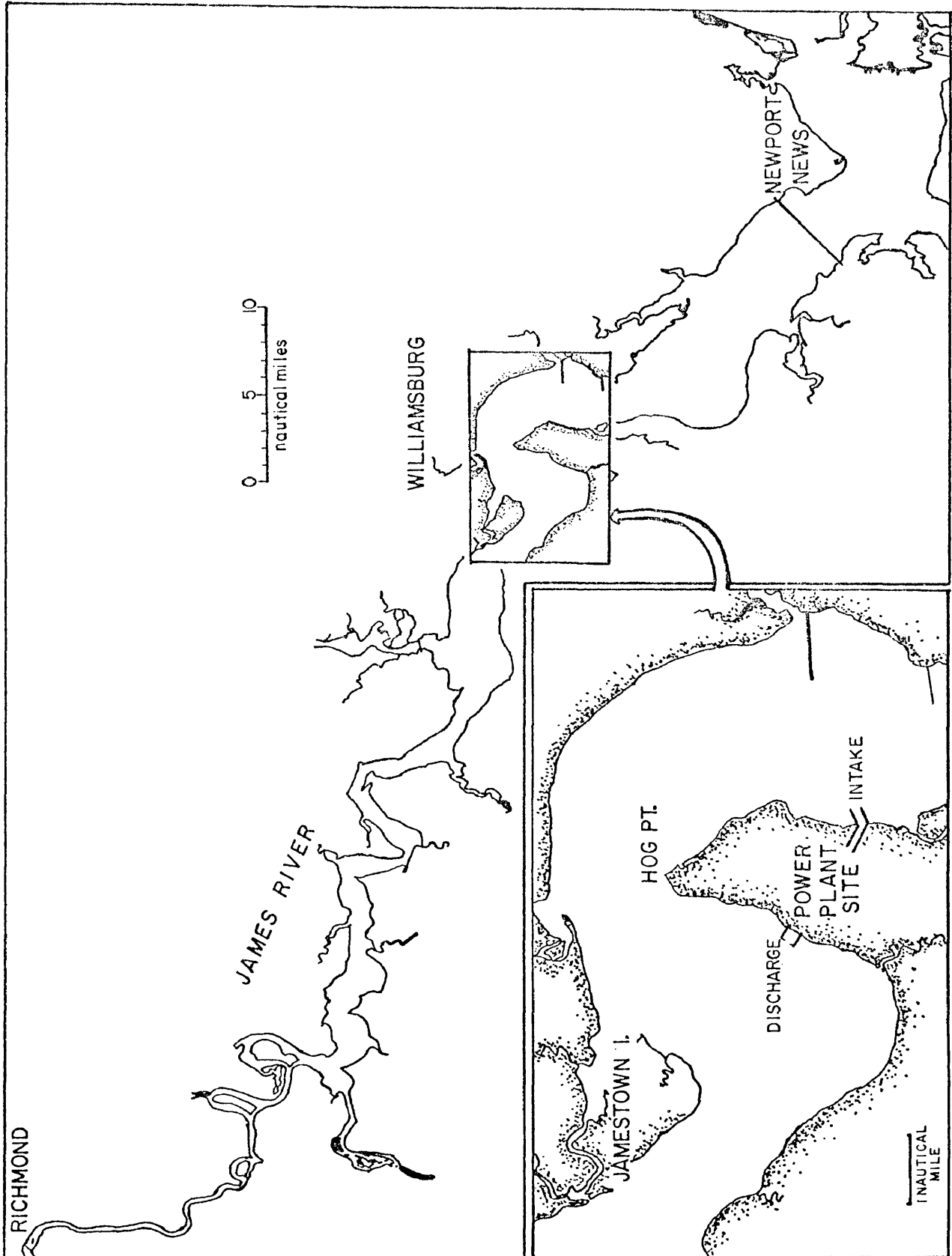
- 3) Evaluate the design of the established monitoring program and to make recommendations as to modifications which can improve the system.

The sampling program focuses on the region of the James River near Hog Point, Virginia, site of the Virginia Electric and Power Company's (VEPCO) Surry Nuclear Power Plant (Figure 1).

The Surry Power Plant (Surry) consists of two 822 MW nuclear reactors, the first of which began operation in December of 1972, the second in March of 1973. The power plant uses the once through cooling method. River water is drawn into the intake canal on the downstream side of Hog Point, pumped through the condensers and out through the discharge structure into the river upstream of Hog Point. The shoreline distance between intake and discharge points is about 5.7 miles and the intake canal is about 1.7 miles long.

Each unit requires 840,000 gpm of river water to supply condensing and service water needs. The maximum design temperature elevation of this water as a result of passage through the condensers is 14.9°F.

Figure 1. Location of the Surry Nuclear Power Plant.



II. LITERATURE SURVEY

In the past decade there has been a growing interest in the development of predictive models for the temperature distribution due to thermal discharge in the aquatic environment.

The development of a predictive model for temperature distribution is dependent upon a basic understanding of the heat exchange mechanisms between the air-water interface. These mechanisms have been known for some time and are well documented in relation to heat balance studies on bodies of water by Sundaram, et al. (1969), and by Edinger and Geyer (1965).

Young, et al. (1971) performed a study in which they examined the sensitivity of estuarine temperatures to various meteorologic parameters, such as wind conditions, dew point temperature, and solar radiation, and concluded that the dew point temperature exerts a major influence on water temperature. Water temperatures were more sensitive to variations in dew point temperature than any of the other parameters monitored.

Edinger (1971), in a discussion of natural estuarine temperature distributions, states that the temperature distribution, like the salinity distribution,

is controlled by the temperature of the freshwater inflow at the head of the estuary and conditions at the ocean end. He also asserts that although salinity dominates the density structure of an estuary, the influence of temperature on the density structure becomes important locally, in the vicinity of advective heat sources such as steam electric power plant condenser cooling water discharges and in the description of buoyant convection near the water surface.

To date, many predictive models, both mathematical and hydraulic, have been developed for thermal discharges. Policastro and Tokar (1972) critically review a number of the important mathematical models, while Silberman and Stefan (1970) examine the state-of-the-art in hydraulic modeling. One of the major drawbacks mentioned by these authors is the lack of comprehensive field data for model verification. In a discussion of field data available for thermal discharges in the Great Lakes, Tokar (1971) states that most of the data that has been collected is not extensive enough to be used for verification purposes. Tokar suggests that a thorough field study should not only include water temperature measurements, but also measurements of air temperature, relative humidity, wind speed, and direction, solar radiation, and ambient currents, as all of these factors affect heat loss, diffusion, and dispersion of the thermal plume.

Argonne National Laboratories has been involved in the past several years with thermal plume studies on the Great Lakes. Their studies have been reported by Frigo, et al. (1974), and Frye, et al. (1973).

Field surveys investigating thermal plumes in estuaries are much less abundant than for lakes. Such factors as tidal oscillation, fresh water inflow, and density stratification tend to make the analysis of thermal plumes in an estuarine environment much more difficult than for a lake environment.

Edinger and Geyer (1968) reported a case study on a power plant discharging into a small tidal embayment. In this study many simplifying assumptions could be made due to the geometry and hydrography of the embayment. There was no fresh water inflow, the only advection was due to the plant discharges, the embayment was of constant depth and constant width; and the embayment was vertically and laterally mixed. Such conditions lead to a relatively uncomplicated set of analytic equations to describe the temperature distributions in this situation, but such conditions occur infrequently.

Several predictive temperature distribution studies have been performed in partially mixed estuaries. Pritchard and Carter (1965) performed a temperature study in the Patuxent tidal estuary; Maryland, in the vicinity of Chalk Point. Their approach to the problem

of prediction of the excess temperature distribution resulting from the heated discharge involved 1) evaluation of the physical processes of movement and dispersion of the effluent in the estuary through the use of a tracer fluorescent dye to simulate the effluent; and 2) correction of the conservative distribution obtained from the tracer experiments for the nonconservative processes of boundary cooling.

Orth, et al. (1974) used the dye tracer method along with measurements of temperature, salinity, and tidal velocity to determine the far field dilution parameters for a shallow estuary. These parameters were then used in conjunction with a mathematical model to determine the temperature distribution in the estuary due to a proposed power plant discharge.

In summary, the increased emphasis on predictive modeling of thermal plumes has led to an increase in the collection of field data for verification purposes. Most of these field surveys have been conducted in large lakes, and data on discharges into estuarine environments is limited.

III. FIELD PROGRAM

This investigation used a moving boat sampling scheme. The parameters measured were water temperature at depths of 0.5, 3, and 6 feet, air temperature at 3 and 6 feet above the water surface, and dew point temperature. These data, along with salinity and dissolved oxygen samples taken at fixed stations, and meteorological data from nearby Ft. Eustis, were deemed sufficient to identify natural variations in river conditions and to isolate thermal effects of the heated water discharge.

The sampling frequency is determined by both the time scale and length scale of variations that one expects to find in the field parameters. In the far field region of the survey area, i.e., that region which is not affected by the physical characteristics of the discharge, thermal gradients were assumed to have time scales on the order of minutes and length scales of the order of tens of feet. With a moving boat sampling system, the length scale is the most important factor in determining a sampling frequency. During 1971, 1972, and 1973, samples were taken every 6 seconds, which spaces sampling points approximately 50 ft. apart at a constant

boat speed of 5 knots. After analyzing data for this period, it became obvious that sampling distances could be made farther apart in the far field region, and should be closer together in the near field. During 1974, samples were taken every 10 seconds for a spacing of approximately 85 feet in the far field, and every 3 seconds, with a spacing of approximately 25 feet, in the near field. Thus the total amount of data taken was reduced, with no significant loss of detail in the far field region and with an increased amount of detail in the near field region.

The designed survey frequency was two surveys per week during the periods March-May and mid September-November, and three surveys per week during June-mid September. These frequencies provided for reasonable confidence in monthly averages of the data, with greater confidence during the summer, when small water temperature variations are important because the water temperatures are closer to the critical values for organisms in the river.

A detailed description of the design and operation of the data acquisition system, calibration procedures, regression equations, and derived calibration curves is given in Bolus, et al. (1971).

A schematic diagram of the basic information gathering and recording system used on the boat is shown in Figure 2.

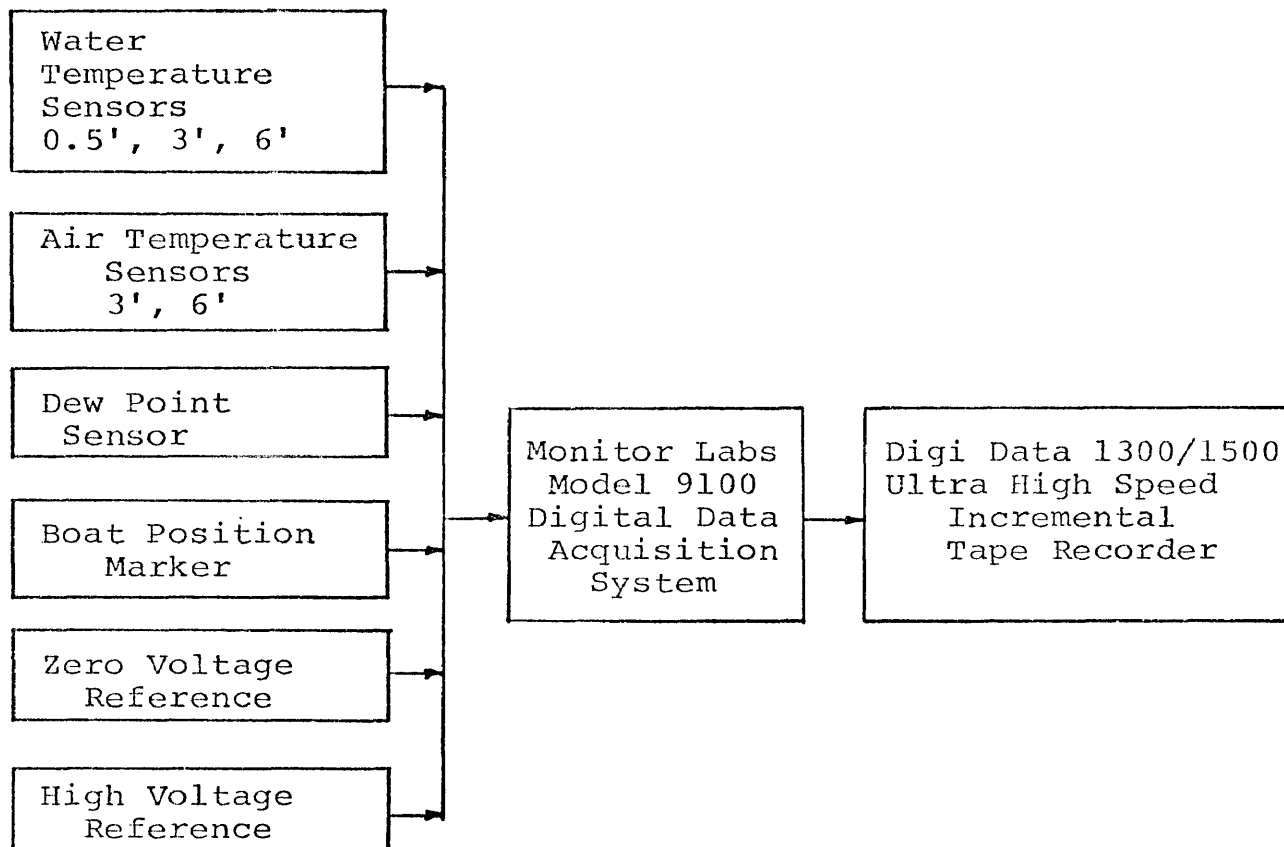
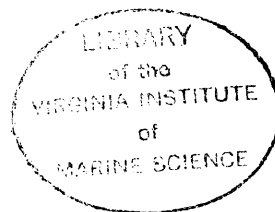


Figure 2. Boat instrumentation array.

Thermistors were used as water and air temperature sensors. Water temperatures were obtained at 0.5, 3, and 6 feet below the surface by mounting thermistors on a submerged boom attached to the boat. Thermistors were mounted in fan ventilated housings on the boat at 3 feet and 6 feet above the water surface to measure air temperatures. Dew point temperatures were measured using a hygrometer mounted in a housing attached to the boat.

These data, along with a zero reference voltage, a high voltage reference, and a boat position marker, were sampled sequentially every 10 seconds and multiplexed by a Monitor Lab Model 9100 digital data acquisition system, then recorded on IBM compatible tape by a Digi-Data 1300/1500 high speed incremental tape recorder, as the research vessel moved at constant speed along the sampling transects. A computer program was developed to reduce the field data in final form.

The sampling runs originated at Tower 2 and continued southward and ended at buoy C51 (Figure 3). The transects were chosen to closely approximate those monitored by Carpenter & Pritchard (1967) in their hydraulic model experiments. The near field transects (dashed lines, Figure 3) were added in July 1973 in order to obtain greater detail near the region of the outfall.

During each sampling run surface and bottom water salinity and dissolved oxygen (DO) samples were

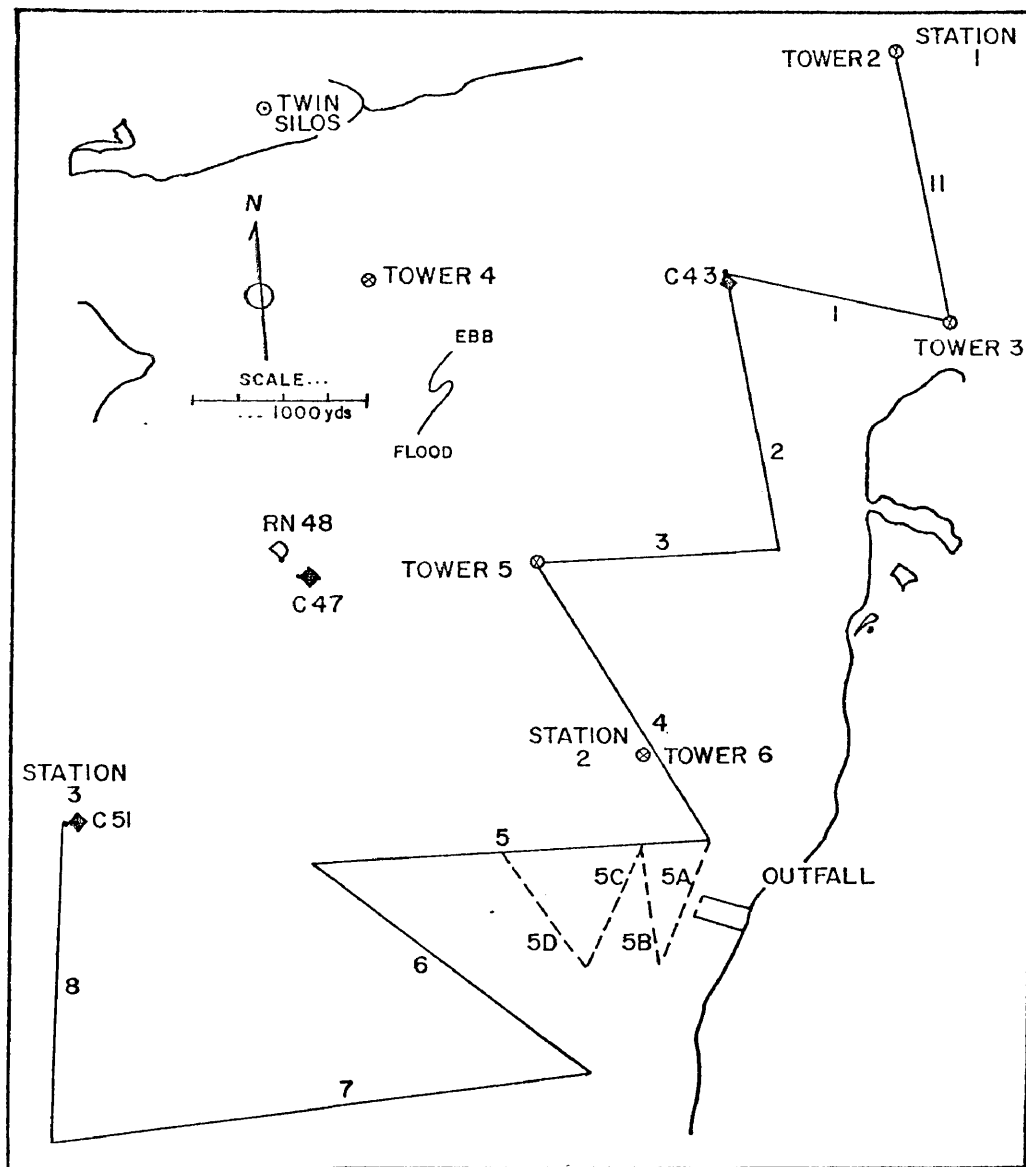


Figure 3. Survey area showing transects monitored and DO and salinity stations. Dashed lines indicate near field transects added July 20, 1973.

taken at the three fixed stations (Figure 3), and brought back to the lab for analysis.

This monitoring program allows approximately 650 samplings of all sensors to be taken during the one hour and forty minutes required to traverse the designated transects. After the data were reduced, isothermal maps were made by equally spacing the data for each transect between the end points of that transect. The isothermal lines were then drawn in by hand.

One of the problems associated with this approach was that the data were not synoptic; that is, data were taken over a finite amount of time rather than instantaneously at all points. This led to inaccuracies in isothermal plots drawn from the non-synoptic data due to the plume movement dictated by tidal currents. These inaccuracies were held to a minimum by starting sampling runs approximately 45 minutes before predicted slack water. In this way slack water occurred at approximately the middle of the run, with the entire run occurring during the period of minimum tidal currents in the river. Figure 4 illustrates this procedure.

Instrument and system accuracy has been discussed in detail by Shearls, et al., (1973). The starting point for an instrument error analysis was the instrument's accuracy as stated by the manufacturer. This represents the true instrument error. To this error were added system effects as line losses, voltage reference

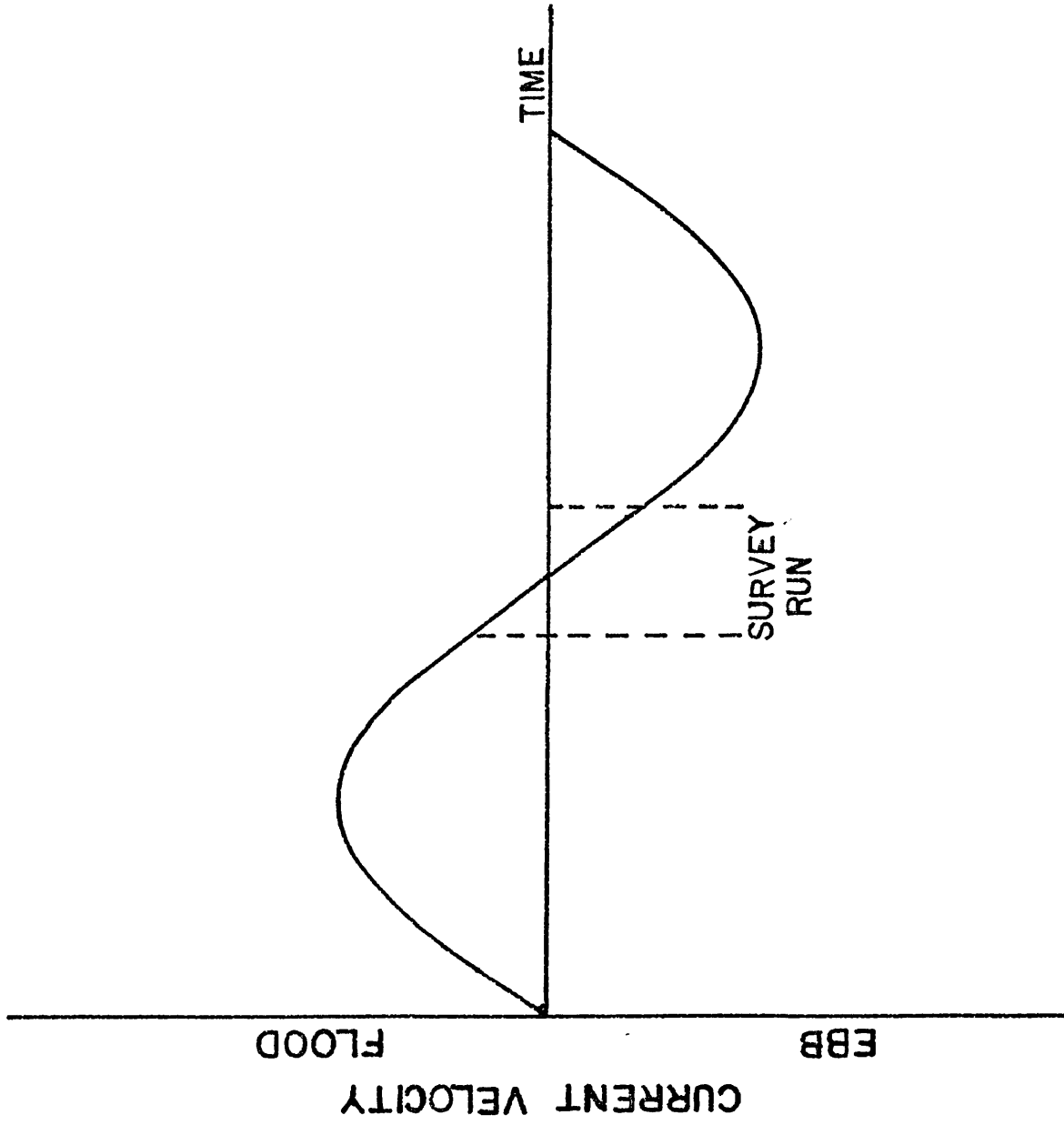


Figure 4. Sampling at slack water.

instabilities, and signal conditioning tolerances. The combined effect of these system errors has to be added to the instrument accuracy in order to determine the total system accuracy. Table 1, taken from Shearls et al., (1973) lists the instrument accuracies and the system accuracy for the instruments on the boat.

Finally, there are errors involved in boat positioning. The transects are run between fixed towers, navigational buoys, and marker buoys whose positions were determined by sextant fixes. These markers are always within sight during the running of the transects and deviations from the straight line paths between these objects can quickly be detected and corrected. Shearls, et al., (1973) determined that the maximum deviation from a transect was approximately 100 ft. to either side of the transect.

Table 1. Instrumentation System Accuracy

Measurement	Instrument Accuracy	Calculated System Accuracy	Expected System Accuracy
Water Temperature (boat)	0.2°F	0.4°F	0.5°F
Air Temperature (boat)	0.2°F	0.4°F	0.5°F
Dew Point Hygrometer	1.0°F	1.46°F	1.5°F

IV. THE JAMES RIVER PRIOR TO PLANT OPERATION

Introduction

Data collected during 1971 and 1972 represents background data prior to plant operation and can be used to identify the natural variations in physical parameters. In addition to data taken specifically for the Surry thermal monitoring program, other data, available from slack water runs, (Fang, et al., 1973), and hydrographic surveys of the James River, (Shidler and MacIntyre, (1967) and Fang, et al.), can be used to determine the natural conditions in the James River prior to plant operation.

The James River Around Hog Point

The Surry plant is located approximately 30 miles above the mouth of the James River estuary. This estuary has been classified as a partially mixed estuary where the salinity decreases from the mouth to the head and also with depth at any location. There usually occurs a layer near mid-depth, the so called halocline, in which the salinity increases more rapidly with depth than is the case in the overlying fresher layer or in the deeper, more saline layer. In spring and summer this intermediate layer is also a region of relatively rapid decrease in temperature with depth.

Hog Point is in the transition region between the fresh tidal river and the estuary proper. Salinity ranges in this transition region are greater than for any other portion of the estuary. Pritchard and Carpenter (1966) report that observed salinity has ranged from 0.0 to 12.20 ppt at the surface and from 0.0 to 14.20 ppt at the bottom at Hog Point.

The maximum observed surface water temperature in this area of the James River estuary was 92.8°F, the minimum was 35.2°F. Summer surface water temperatures usually fall in the 78.8 - 82.4°F range (Pritchard and Carpenter, 1966). During the spring and summer, water temperature decreases with depth. The vertical gradient is largest during the spring period, around 7°F over 20 feet of water depth. During the summer, the gradient over the same depth is between 2° and 4°F. There is usually no temperature gradient during the fall, while in the winter water temperatures are warmer on the bottom.

Fresh water discharge at the fall line at Richmond averages (based on 37 years of record) 7,108 cfs. The flow has ranged from 296,000 cfs to 370 cfs. Comparing these values to a half tidal cycle flow of approximately 190,000 cfs through a cross section at Hog Point, as calculated by Pritchard and Carpenter (1966), indicates that river discharge has little direct effect on the tidal currents except during periods of extreme river discharge.

Water Temperatures (1971-1972)

Water temperatures in the area of Hog Point followed a cyclic pattern with maximum water temperatures occurring in July and August (Figure 5). The monthly average water temperatures followed the same pattern during 1971 and 1972. The lowest monthly average water temperature recorded was 54.4°F in November of 1972, and the highest monthly average water temperature recorded was 81.4°F in July of 1971.

Mid-depth and bottom water temperatures were monitored continuously by VEPCO at each of the seven VEPCO towers located in the James River around Hog Point. The location of towers 2, 3, 4, 5, and 6 can be seen in Figure 3. Figure 6 shows the average daily mid-depth water temperatures at Tower 6 as reported by VEPCO. Although the temperature curve is basically sinusoidal in character, there are significant variations in temperatures during a month's period. Mid-depth water temperature at Tower 6 reached a minimum of 35.5°F during the first half of February, 1972, and a maximum of 86.7°F during the last half of July. Assuming typical stratification conditions, the surface water temperatures for February were probably close to temperatures at mid-depth, while they were probably 1-2°F higher than mid-depth temperatures during July.

In the upper six feet of the water column there was a slight thermal stratification during the pre-operational survey period. Average water temperature

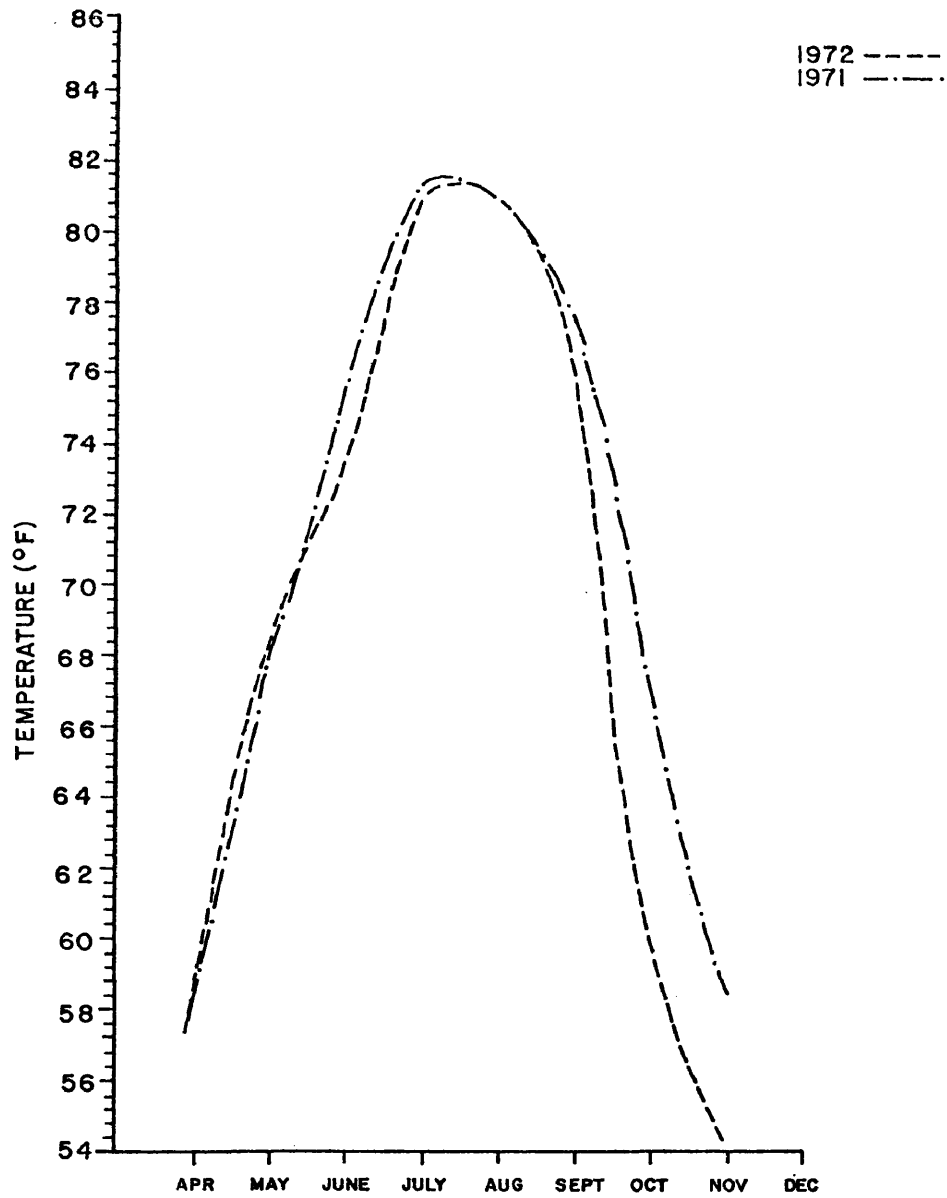
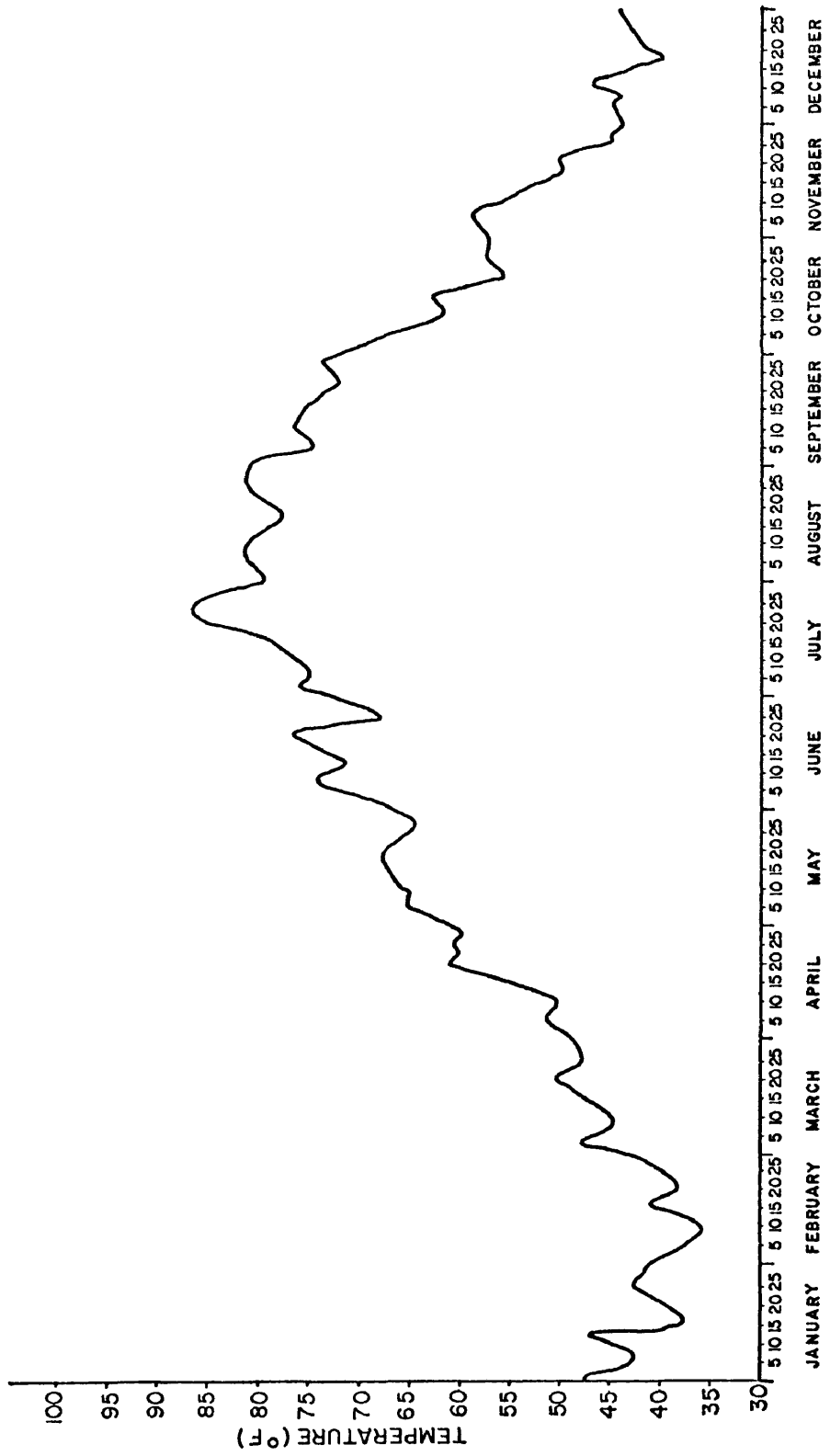


Figure 5. Monthly average surface water temperature for the entire survey area (1971, 1972).

Figure 6. Average daily water temperature (mid-depth)
at Tower 6 during 1972 (VEPCO data).



profiles for the months April through November, 1972 are shown in Figure 7. This figure indicates that temperatures at a depth of six feet were approximately 1°F cooler than surface temperatures during the summer (June through August), less than 1°F cooler in May and September, and approximately the same as surface temperature in April, October and November. The stratification during 1971 showed the same pattern as in 1972.

Horizontal temperature gradients in the study area were small; temperatures usually varied less than 4°F over the entire area. Figure 8 shows typical isothermal patterns during 1971, prior to plant operation. During the summer months (Figure 8b), water temperatures showed no particular pattern as distance from shore increased. In early spring and winter (Figure 8a, 8c), water temperature generally increased as distance from shore increased, but there were exceptions to this pattern.

Salinity, River Discharge, and Dissolved Oxygen

Monthly average surface salinity during 1971 and 1972 is shown in Figure 9. During both years, surface salinities were less than 1 ppt during the period from late fall to early spring. In 1971, salinities rose steadily from a June value of approximately 0.6 ppt to a peak value in September of 3.9 ppt, then dropped sharply to 0.5 ppt in November. Salinities during 1972 were lower than those for 1971, with the major increase not

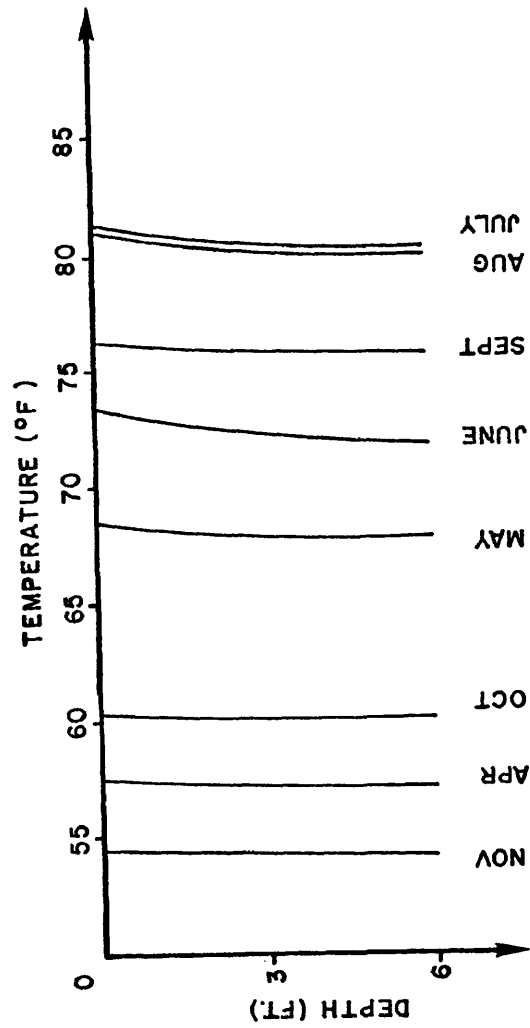


Figure 7. Monthly average water temperature profile (1972).

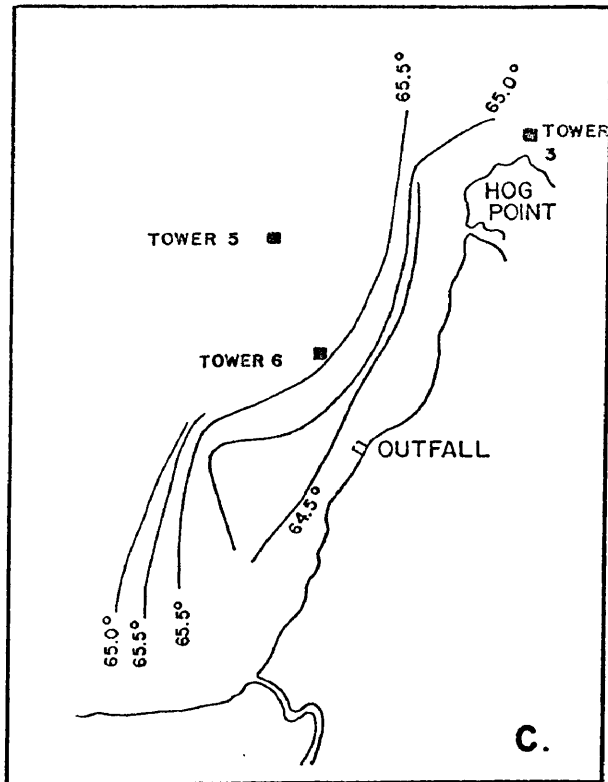
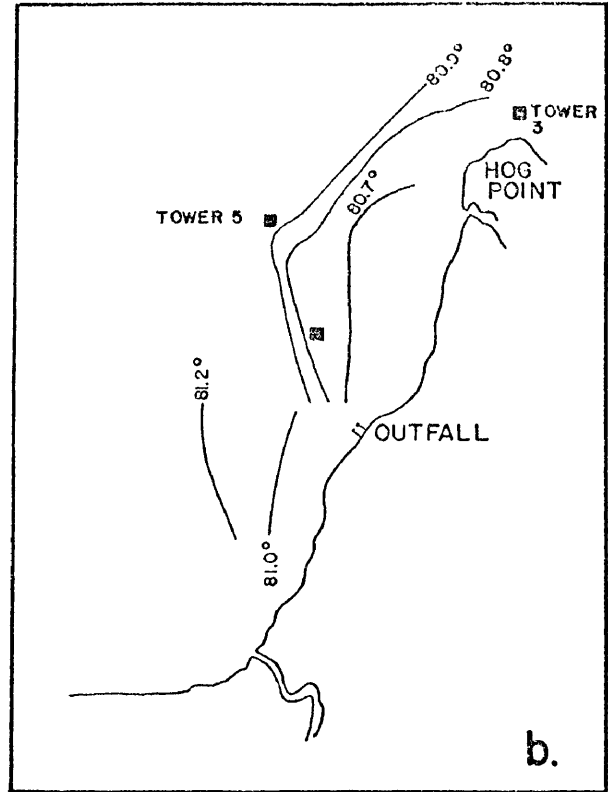
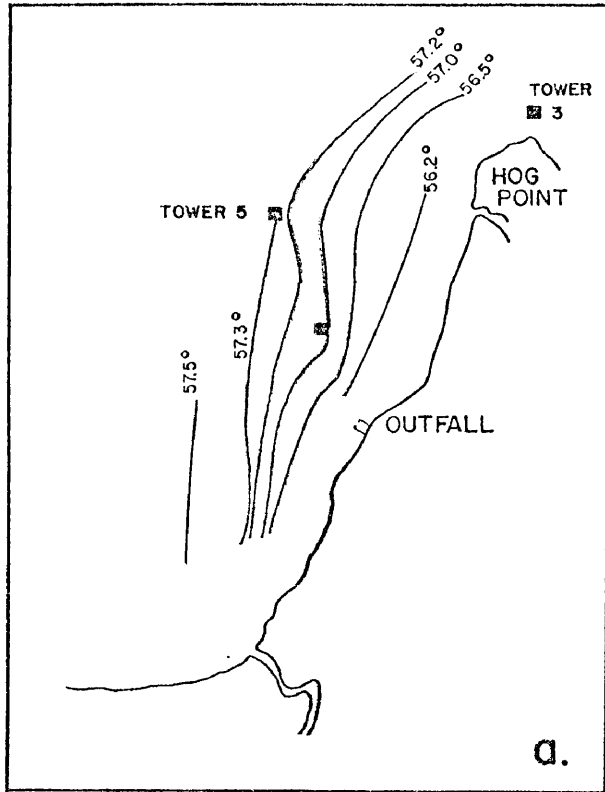


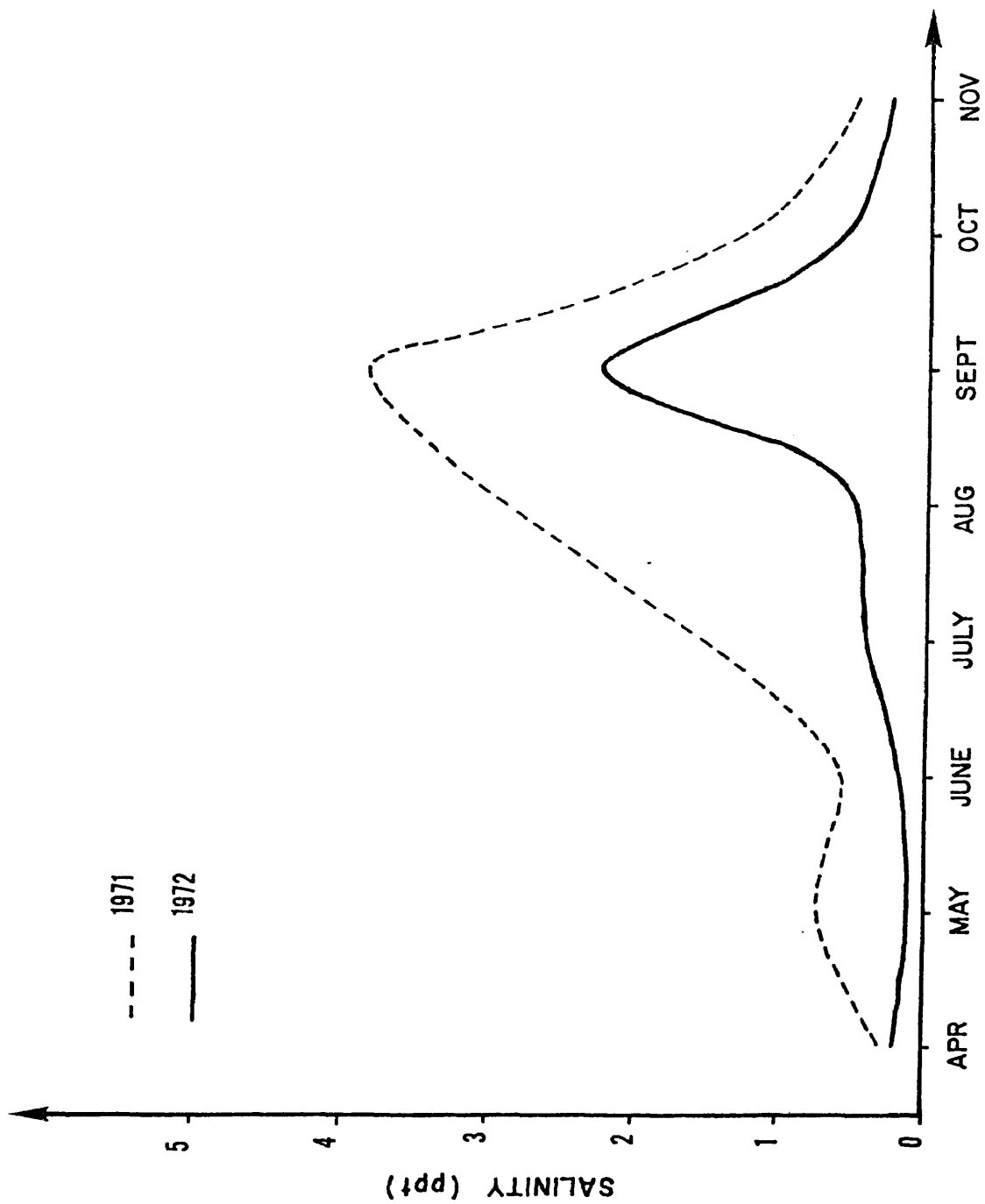
Figure 8. Typical temperature distributions prior to plant operation.

a.) Apr. 15, 1971; flood

b.) Aug. 12, 1971; flood

c.) Nov. 4, 1971; ebb

Figure 9. Monthly average salinity (1971, 1972).



occurring until late August. At this time, salinity increased from approximately 0.4 ppt in August to a maximum of 2.3 ppt in September. By October, salinity was down to the August level.

Grab samples for salinity were taken at top, middle, and bottom at three stations (Figure 3) during 1972. Bottom salinities were less than 1 ppt higher than surface on all but three occasions, and these occurred at station 1, the most downstream station.

Average monthly fresh water discharge (measured at Richmond) was considerably higher in 1972 than in 1971 (Figure 10). The occurrence of Hurricane Agnes in June, the weather that led to Columbus Day flooding in October, and frequent shower activity between these two catastrophic events combined to make 1972 the wettest year in recent Virginia history; abnormally large quantities of fresh water entered the James River watershed.

The salinity differences between these two years was a function of this rainfall pattern. The high fresh water discharge in June and July of 1972 had the effect of pushing the salinity intrusion farther downstream, resulting in low salinities during the summer of 1972. The typical pattern for salinity in this area is more closely represented by the 1971 salinity curve in Figure 9.

Surface dissolved oxygen concentrations for the area at both high (Figure 11) and low slack (Figure 12)

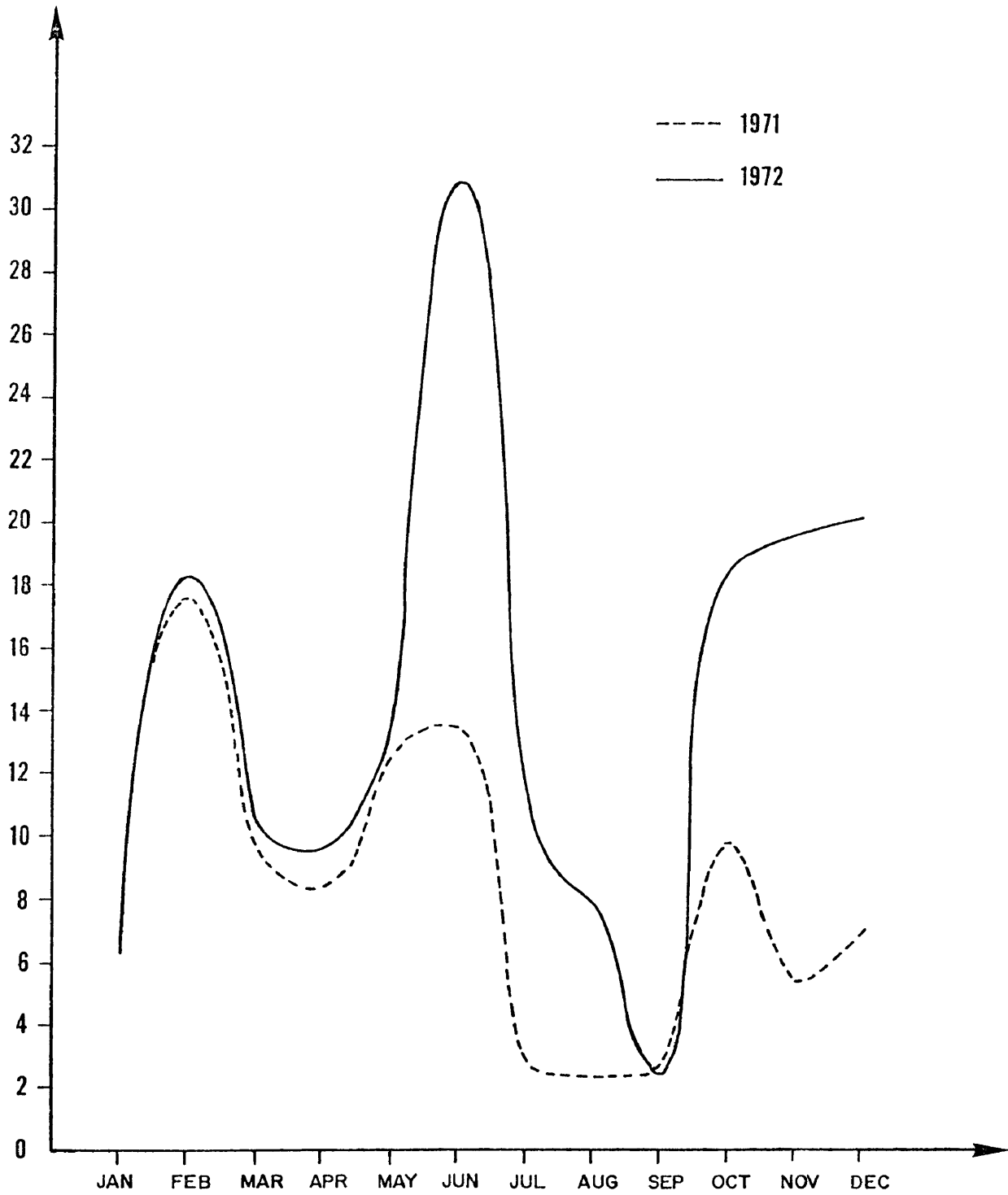


Figure 10. Monthly average fresh water discharge.

Figure 11. Average high slack DO concentration
(1972).

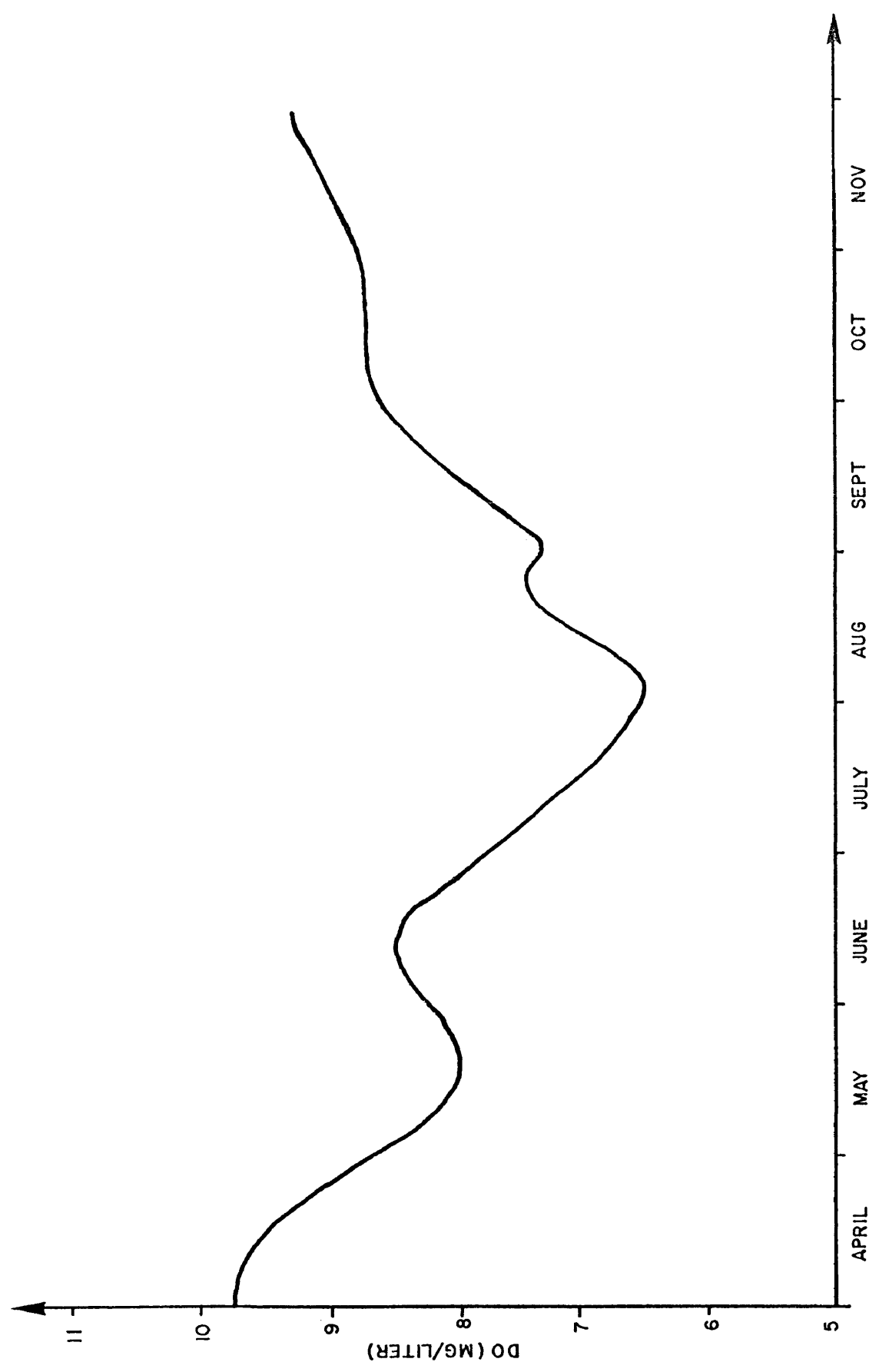
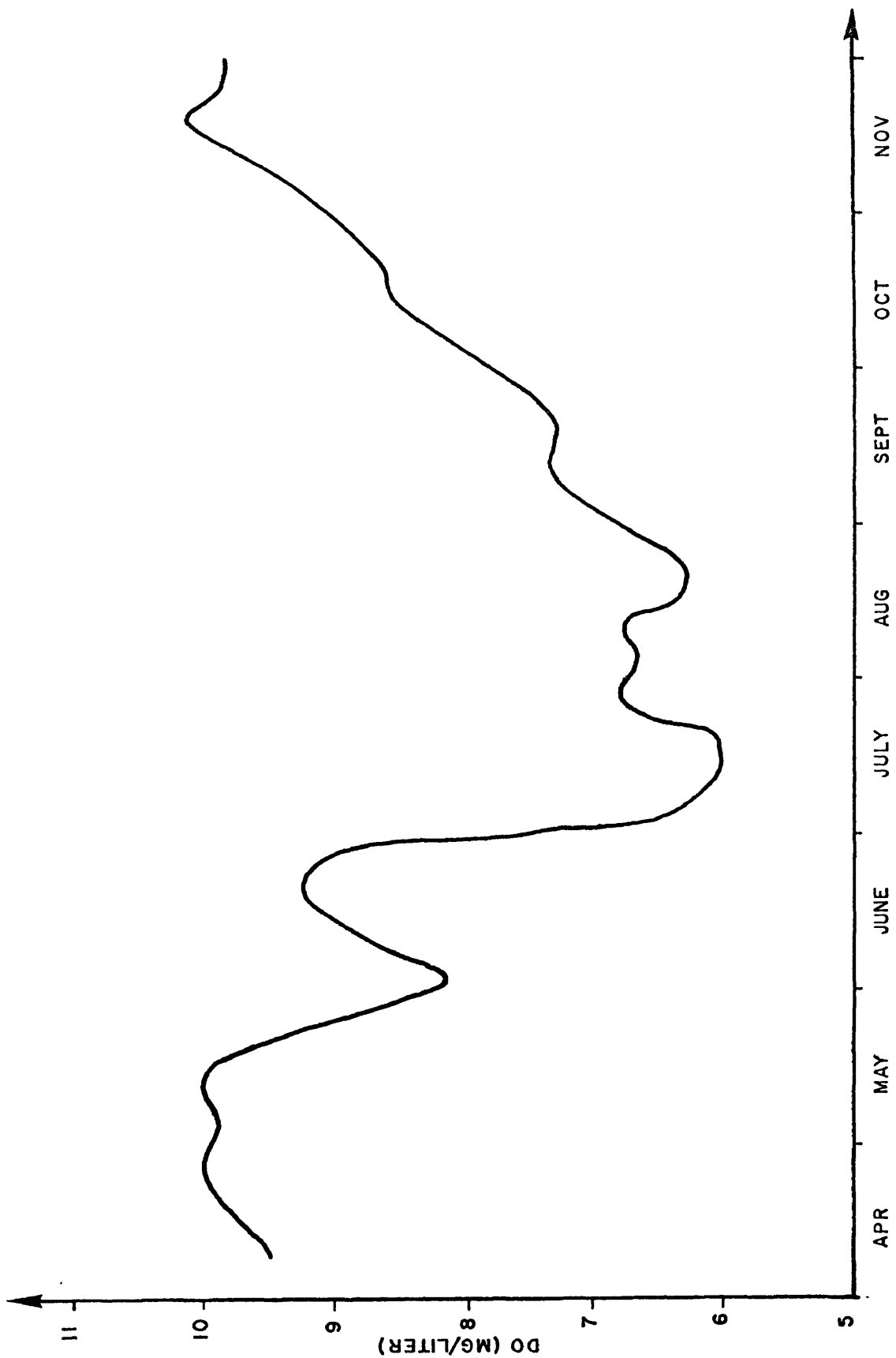


Figure 12. Average low slack DO concentration
(1972).



show that DO in 1972 decreased during the hottest months (July and August), with concentrations which ranged from 6.0 - 7.5 mg/l. In the winter months, DO concentrations attained values of 10 mg/l or higher.

Tidal Currents

Tidal current data contained in a data report of 'Operation James River - 1964' by Shidler and MacIntyre (1967) have been plotted for station 25, which was located approximately 400 yards south of Tower 2 at Hog Point (see Figure 3), and are shown in Figure 13. This figure shows the surface currents for August 14, 1200 hrs. to August 15, 0130 hrs. (a), August 17, 1330 hrs. to August 18, 0500 hrs. (b), and September 29, 1230 hrs. to September 30, 0630 hrs. (c). These graphs indicate that maximum flood current at the surface are within the range 1.5 - 2.5 ft/sec, while the maximum ebb currents are within the range of 2.0 - 2.5 ft/sec.

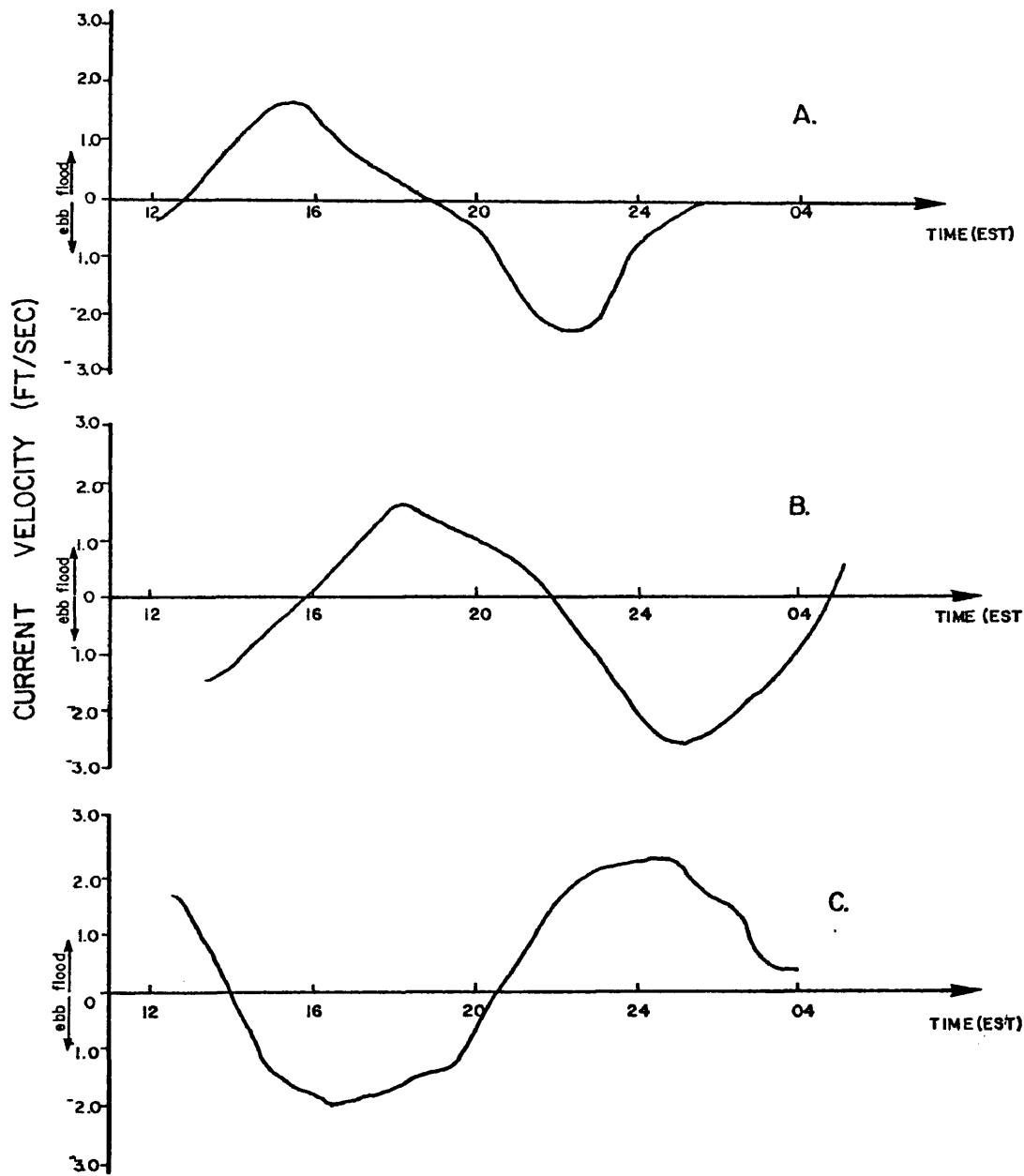
Although no current measurements have been taken in the shallow areas in Cobham Bay, tidal currents in this area would be lower than those in the channel. Lagrangian current measurements, using drogue buoys, have been made in the discharge plume, and will be discussed in a later chapter.

Figure 13. Surface tidal currents at Hog Point
(Station 25).

A) 1200 August 14 to 0130 August 15, 1964

B) 1330 August 17 to 0500 August 18, 1964

C) 1242 September 29 to 0630 September 30, 1964



V. THE JAMES RIVER DURING PLANT OPERATION

Operational Status of Surry, 1973-1974

Unit 1 of the Surry Plant began operation in December 1972, while Unit 2 began in March 1973. During the first year of plant operation, 1973, Surry averaged 67% of capacity on the days monitored. On 10% of the days monitored, plant operation was higher than 90% of capacity, while on 36% of the days monitored plant operation was greater than 85% of capacity. At the other end of the scale, plant operation was less than 50% capacity on 42% of the days monitored.

Although this type of low operating percentage was expected during the startup period for Surry, higher operating efficiency was expected for the second year of operation, 1974. This has not been the case.

During 1974, plant operation has averaged 62% of capacity during the days monitored. On 34% of the days monitored during this period, plant operation was 90% of capacity or greater, while on 56% of the days monitored, plant operation was 50% capacity or less.

On September 6, 1974 Unit 2 was shut down for repairs to a large steam turbine, and remained down for the rest of the year. From September 29 to October 25, Unit 1 was operating at approximately 60%. On October

25 Unit 1 was shut down completely. The plant did not operate from October 25 to the end of the year, and monitoring of the survey area was discontinued for the year.

The erratic operation of the Surry Plant makes it difficult to determine the maximum physical effects of the thermal discharge on the survey area. Some indications of the maximum effects can be gained by carefully examining those runs during which plant operation was higher than 85-90 percent. It will be difficult to predict any cumulative effects of the thermal discharge, because such effects, if they exist, will only appear after water temperatures have reached a "steady state" during high plant loading.

"Steady state" conditions would be obtained when plant loading was continuously high during the summer months, when natural water temperatures attain their maximum range for the year and the rate of water temperature change with respect to time is small. Figure 14 (A,B) shows power generation for Surry during the period January 1, 1973 - June 30, 1974, as taken from Vepco semi-annual operating reports. This figure indicates that the only periods when the conditions mentioned above were approximated were during the periods 20 June - 2 July, 10-25 July, and 5-18 September, 1973. The number of survey runs during these periods were four, six, and five, respectively. Although the daily

Figure 14. Surry power generation.

A. January - June 1974

B. January - December 1973

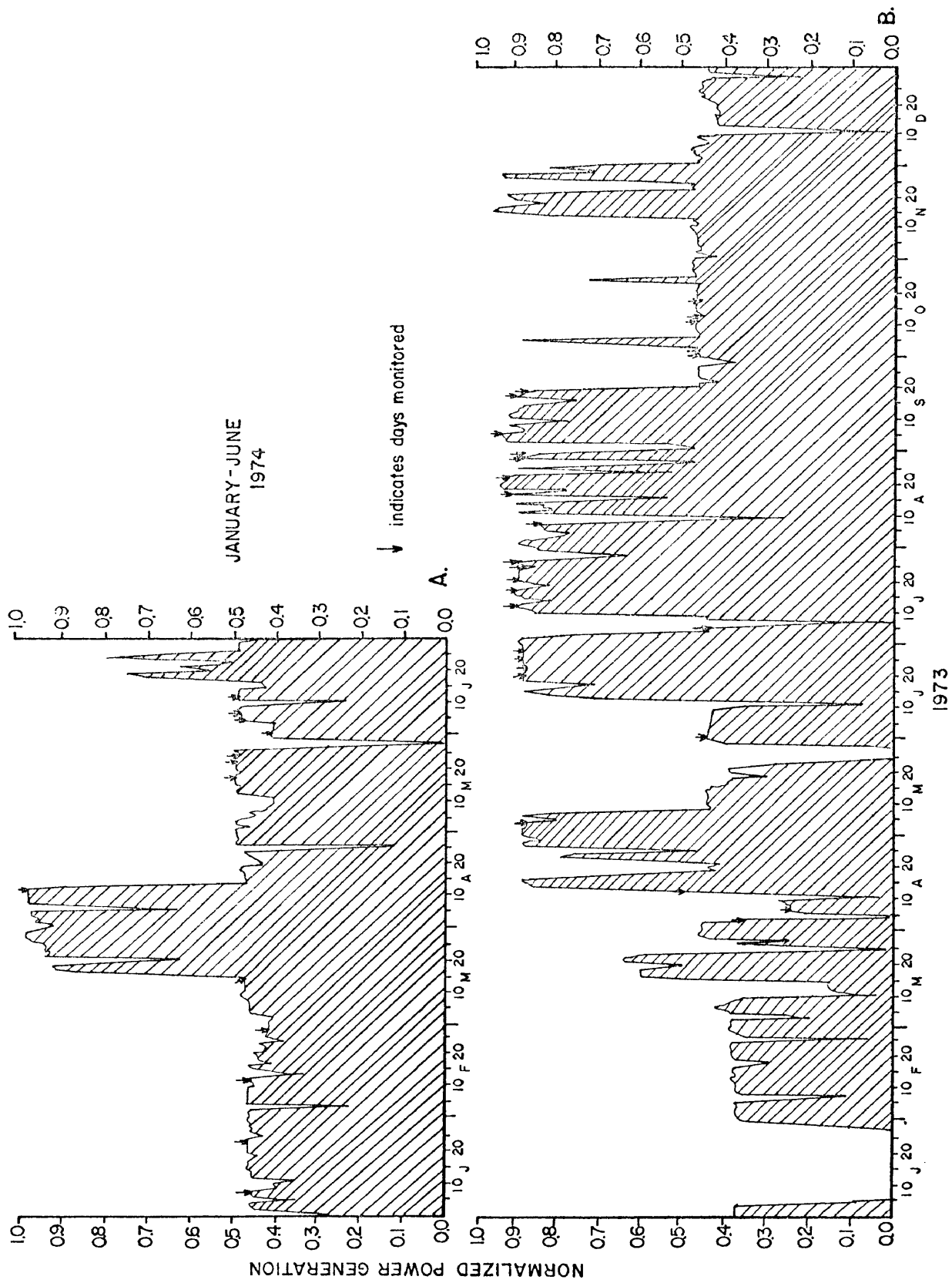
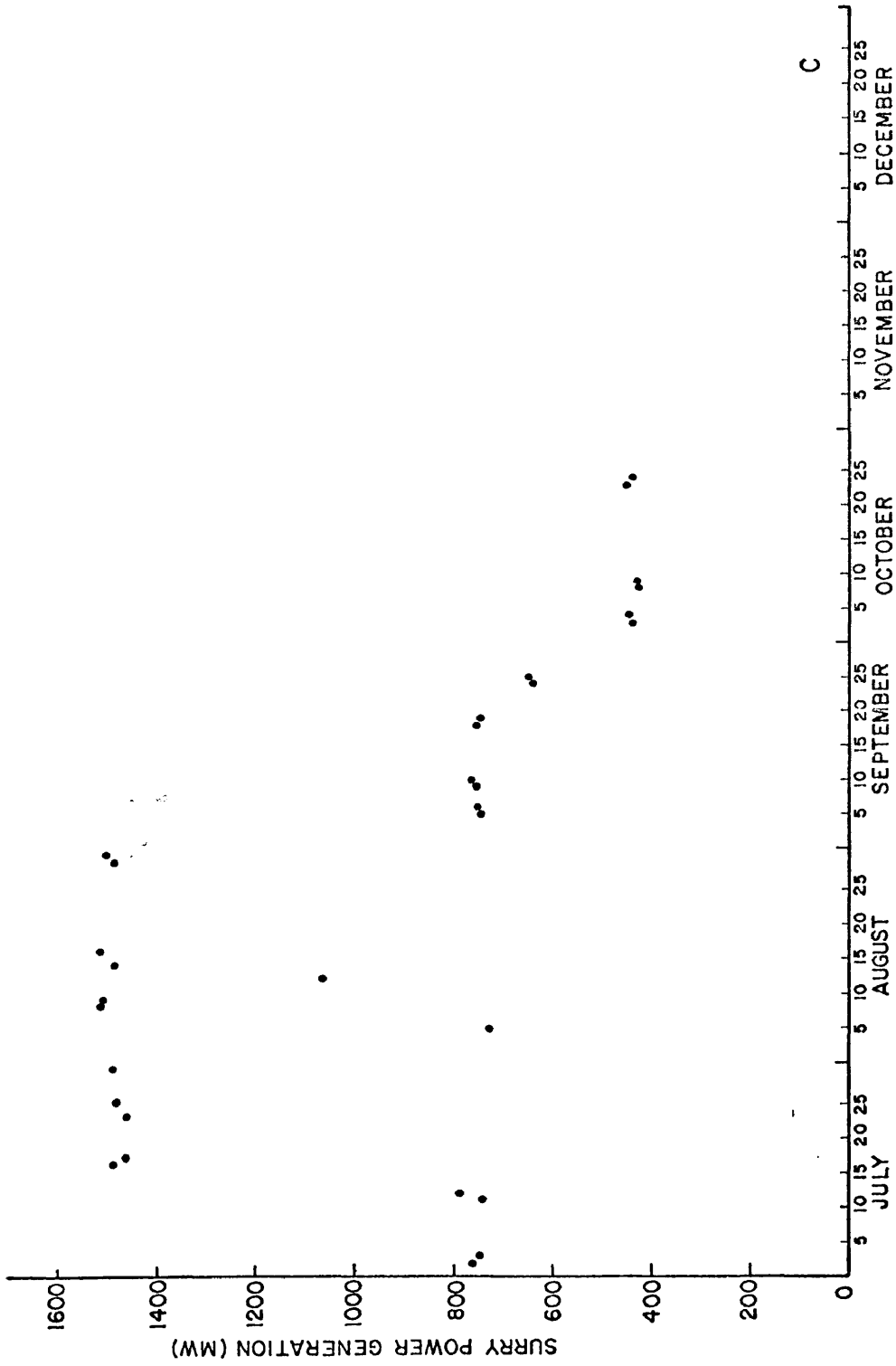


Figure 14 (Cont'd). Surry power generation.

C. July - December 1974



records of power generation for July through September, 1974, are not yet available from Vepco, reported power generation for the days monitored during this period shown in Figure 14C indicate that between 16 July - 1 August and 14 August - 30 August power generation was above 90 percent. A total of eleven survey runs were made during these two periods.

These 26 runs represent the data that is most suitable in judging the maximum temperature distributions due to the thermal discharge because they represent the only periods in which "steady state" conditions were approached.

Data Averaging

In order to discuss the effects of the thermal discharge on the study area, comparisons were made between pre-operational and post-operational data. Averages were taken over each transect for each month. During the summer months, data runs were made with a frequency on the order of 10 per month, which yielded monthly averages with typical standard deviations of 1.3°F for 1972.

Standard deviations of monthly transect averages were calculated for transects 1 and 4 for August 1972. These values are presented in Table 2.

Table 2. Monthly Averages of Data for Transects 1 and 4, August 1972, and August 1974.

Month/Year	Transect	Average Water Temperatures (°F)			Average Air Temperature (°F) at 6 Ft.		
		Surf.	3 Ft.	6 Ft.	Surf.	6 Ft.	6 Ft.
Aug./1972	1	80.60	1.13	80.09	1.36	81.45	2.30
Aug./1974	1	82.16	1.92	81.85	1.75	81.96	4.83
Aug./1972	4	81.17	1.24	80.22	1.26	82.22	2.84
Aug./1974	4	83.30	2.82	82.96	2.83	82.52	4.60

These data indicate:

- 1) standard deviations for water temperatures were approximately equal for transects 1 and 4 during August 1972;
- 2) standard deviations for water temperatures were approximately 1°F higher for transect 4 than for transect 1 during August 1974.
- 3) respective standard deviations for water temperatures were higher for August 1974 than for August 1972;
- 4) standard deviations of air temperatures were higher than for water temperatures in both August 1972 and August 1974.

These results were to be expected for several reasons. During 1972 there was no thermal discharge and water temperature variations would be expected to be approximately the same along each transect. During 1974, with the introduction of the thermal discharge, water temperatures along each transect vary greatly depending on plume position, and variations are higher for transects closer to the outfall. Finally, due to the high specific heat of water, water temperature variations are lower than air temperature variations over the same period of time.

The difference between August 1974 and August 1972 average surface water temperatures was 2.13°F for transect 4. The 95% confidence interval for this

difference $(\bar{X}_1 - \bar{X}_2)$ was $1.63^{\circ}\text{F} \leq (\bar{X}_1 - \bar{X}_2) \leq 2.63^{\circ}\text{F}$. This confidence interval indicates that the differences between the average values were significant.

On the basis of the above considerations, monthly averages of data along each transect were chosen as an appropriate means of comparing pre-operational and post-operational data.

Water Temperatures

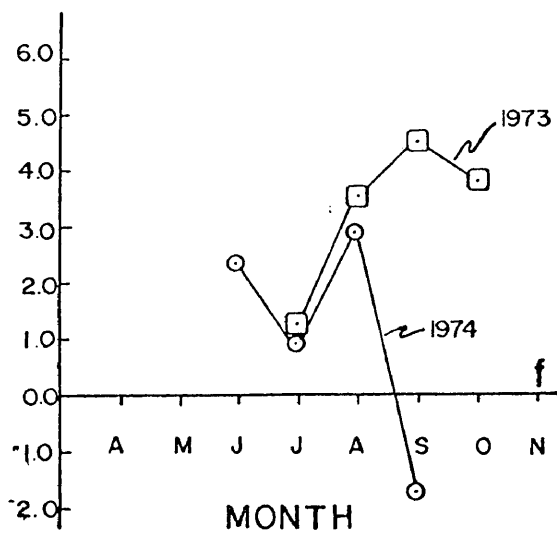
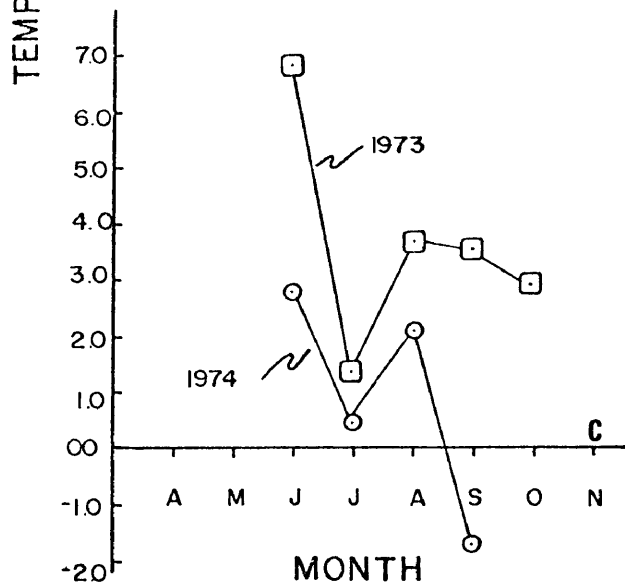
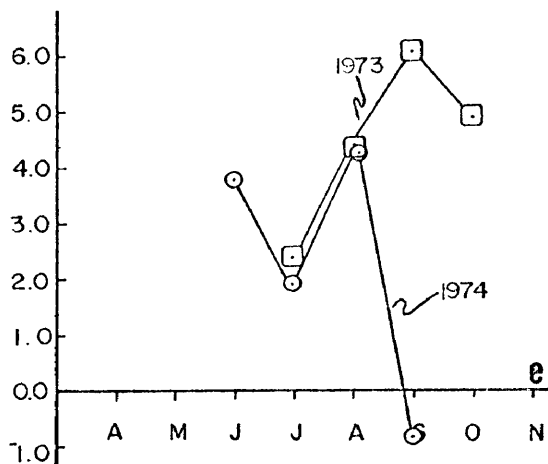
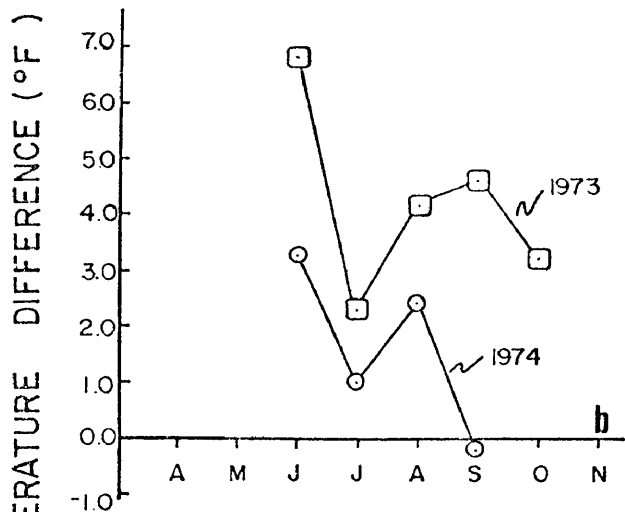
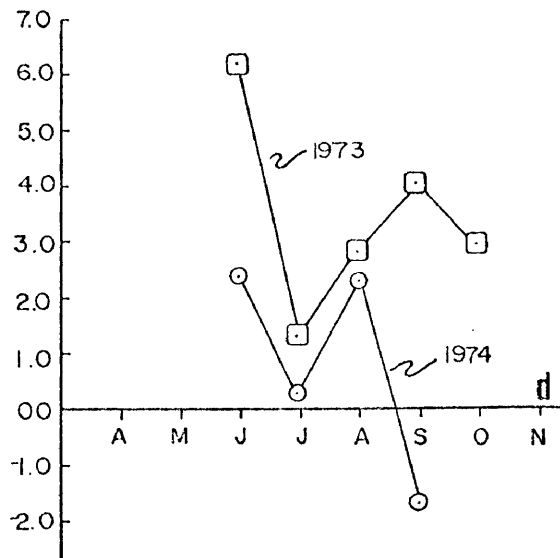
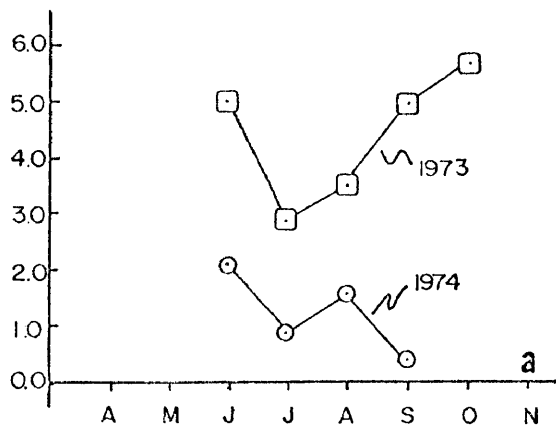
Surface water temperatures were averaged for each transect for each month during 1971 and 1972. The average of these two values was taken to represent typical water temperatures for a given transect and month under natural, pre-operational conditions. The difference between these averages and the averages for 1973 and 1974 were plotted for each transect and are shown in Figure 15.

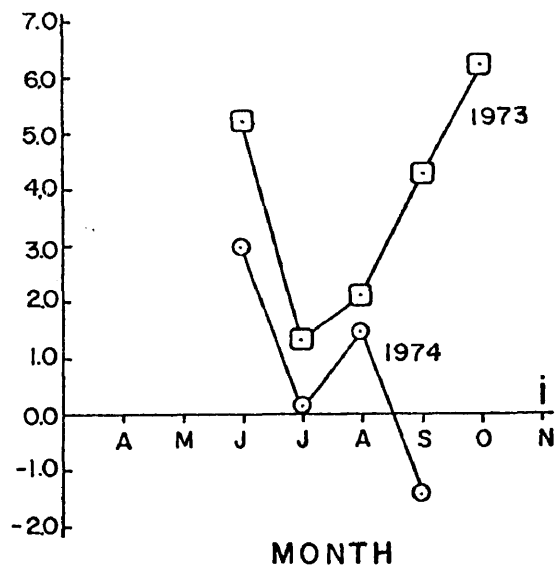
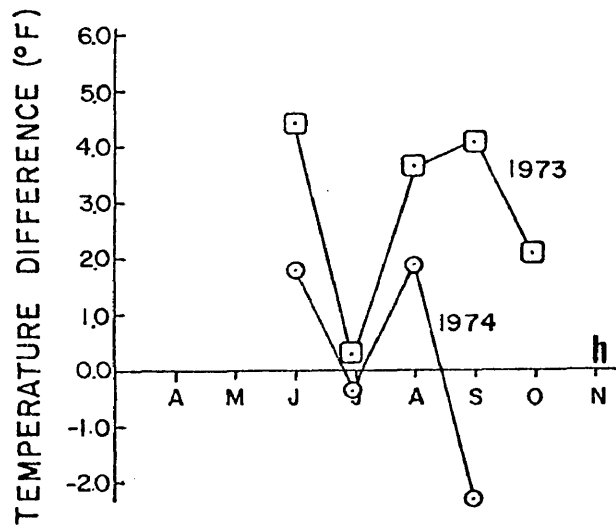
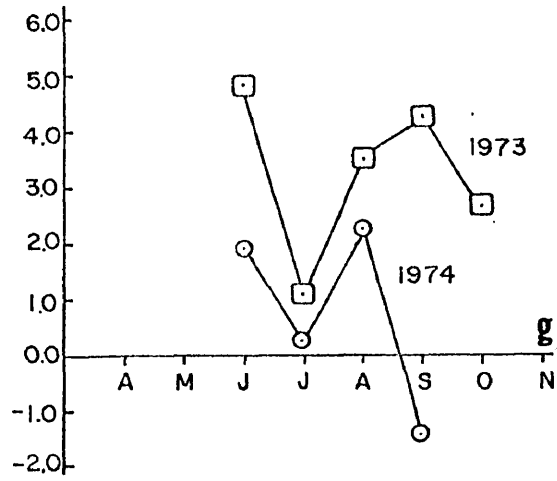
To compensate for some biased data, such as September 1973 data, which consisted of 5 sampling runs all in the first half of the month, all averaged data during 1973 and 1974 were compared to data averaged over the same period of time during 1971 and 1972. In other words, in the case of September 1973 data, the comparison was made with 1971 and 1972 data averaged over the first half of the month of September.

The averaged data shown in Figure 15 also had to meet the further requirement that at least 7 regularly spaced runs were made during a month, or at least 4 runs

Figure 15. Difference between monthly average surface water temperature for 1973, 1974, and the average of 1971 and 1972 combined.

- a.) Transect 1
- b.) Transect 2
- c.) Transect 3
- d.) Transect 4
- e.) Transects 5A,B,C combined
- f.) Transects 5D,5 combined
- g.) Transect 6
- h.) Transect 7
- i.) Transect 8





during a half-month, before an average value was considered representative and presented on the graphs.

Figure 15 shows that average water temperatures during 1973 were consistently higher than the average of 1971 and 1972 water temperatures, for each transect. The maximum temperature differences generally occurred in June and in September or October, with July and August temperature differences 2° - 5° F lower than the maximum differences.

During 1974, water temperature differences from the 1971, 1972 averages in all cases showed maximum values in June and August. For all transects except transect 1, September average temperatures were lower than the 1971, 1972 averages. Water temperature differences in 1974 were lower than those for 1973.

A major factor in the higher temperature differences in 1973 was the higher ambient water temperatures for 1973 when compared to 1974. For the purposes of this investigation, ambient water temperature is defined as the water temperature in the estuary excluding any excess temperature due to the thermal discharge. During 1973, ambient temperatures for the area were determined by averaging the water temperature at Tower 2 and at buoy C'51' (see Figure 3). Ambient temperatures for 1974 were determined by averaging these two water temperatures and the water temperature at Tower 4. These points were chosen to represent ambient conditions because

there was no evidence to indicate the thermal plume reached these locations, and they represent the upstream and downstream limits of the survey and therefore would reflect any natural longitudinal temperature gradients which may be found in the estuary.

Figure 16, showing the difference between 1973 and 1974 ambient surface water temperatures and the average for 1971 and 1972, indicates that in June and September, ambient temperatures were 2.6° and 5.0° F higher, respectively, in 1973 than in 1974. The August 1973 average ambient temperature was 0.5° F lower than the August 1974 temperature. This figure indicates that a major portion of the temperature differences between 1973-74 data and 1971-72 data was due to differences in ambient temperatures for these two years. Except for July and September of 1974, the 1973-74 ambient water temperatures were higher than the water temperatures for 1971 and 1972.

To compare actual excess temperatures due to the thermal discharge, the difference between the average surface water temperature and the average ambient surface water temperature for each transect was plotted by the month for 1973 and 1974 and is shown in Figure 17.

During 1973, the excess temperature curve shown in Figure 17 shows two peaks, one in June, and a higher peak in August. These peaks are apparent for all of the transects.

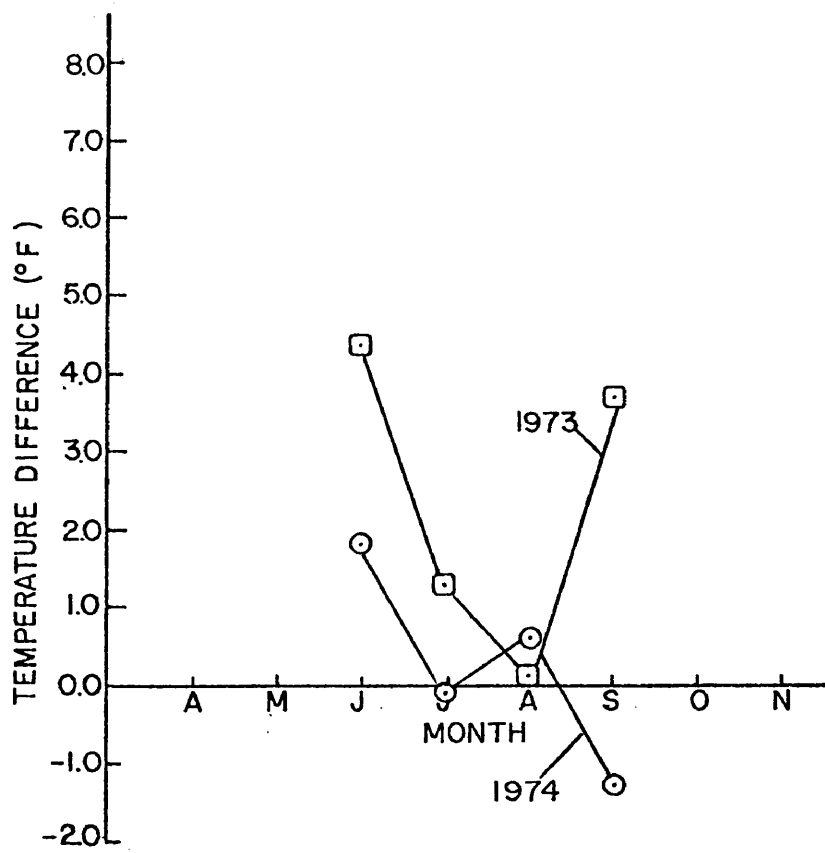
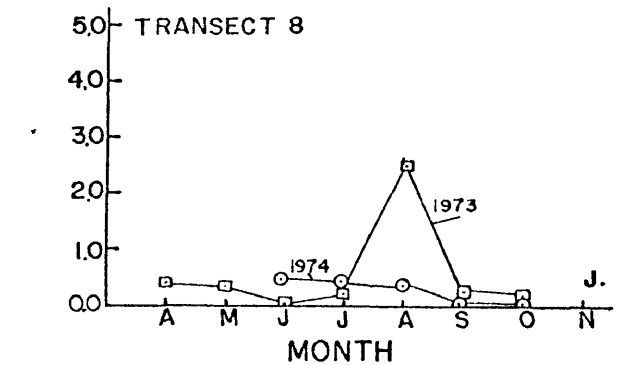
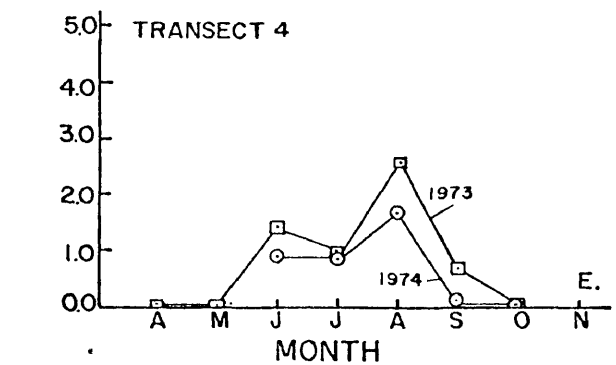
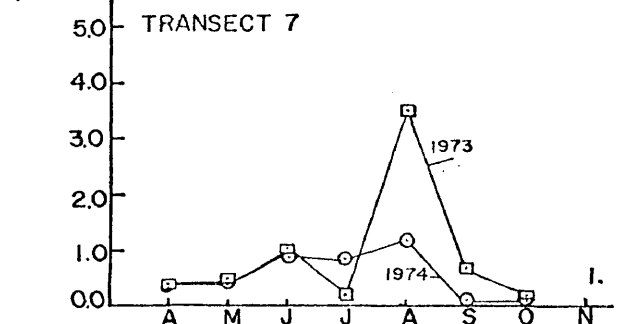
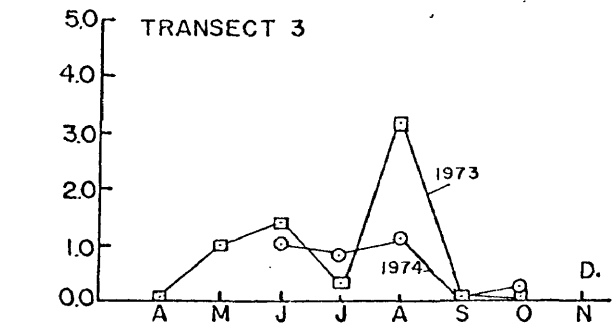
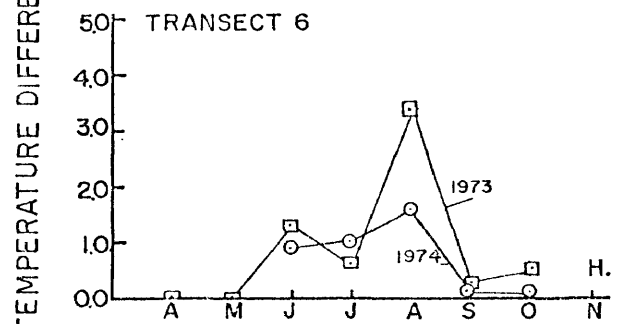
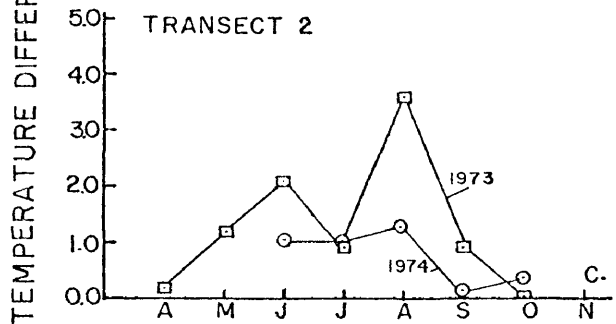
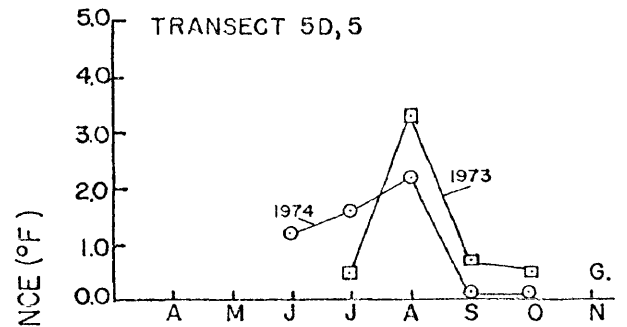
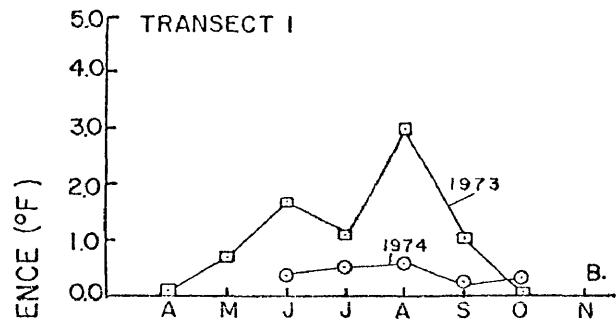
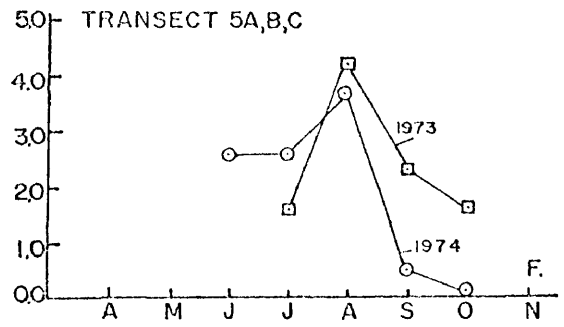
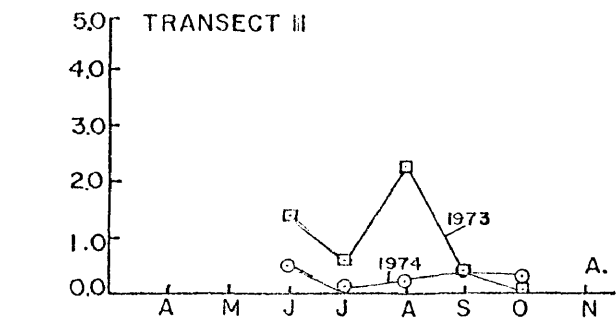


Figure 16. Difference between monthly average ambient surface water temperature for 1973, 1974 and average for 1971 and 1972.

Figure 17. Monthly average surface water temperature rise above ambient, 1973, 1974.



During 1974, peak excess temperatures occurred in August for all transects except transect 11. Excess temperature values are very low for transect 11 and the fact that September and October excess temperatures are slightly higher than the August values is not significant.

In Figure 17, graph (a), showing transect 11, and graph (j), showing transect 8, represent the most downstream and upstream monitored transects, respectively. Graph (f), showing the average of transects 5A, B, and C, represents the near field region near the outfall. These transects show the highest excess temperatures for both years, with maximums of 4.2°F and 3.7°F for August of 1973 and August 1974, respectively. Graphs (a) and (j) show the lowest average excess temperatures for both years. During 1974, the maximum average excess temperature occurring for any month was 0.5°F for both transect 11 and transect 8. These low excess temperatures along the most upstream and downstream transects indicate that these transects closely coincide with the upstream and downstream limits of thermal effects for the power plant during 1974. During 1973, the area affected was apparently larger during August, since excess temperatures were approximately 2.5°F during August for both transects.

Explanation of the patterns of excess temperature shown in Figure 17 requires comparison of the parameters which effect water temperature and heat transfer across the air-water interface. The terms involved in the

equation for the net rate of heat exchange across the air-water interface fall into two categories: temperature dependent, and temperature independent. The temperature independent terms involve the absorbed radiation, including short wave solar radiation, long wave atmospheric radiation, and the reflection of both of these types of radiation. For the purpose of this investigation, it will be assumed that the absorbed radiation was the same for 1973 and 1974. This assumption is justified since we are considering temperature rise above ambient and absorbed radiation is responsible for the cyclic pattern of ambient temperatures, therefore it is effectively cancelled out in the analysis.

The temperature dependent terms consist of back radiation (H_b), evaporation (H_e), and conduction (H_c). Back radiation and evaporation are mechanisms of heat loss, while conduction can be either a heat loss or heat gain mechanism. Back radiation, according to the Stephan-Boltzman fourth power radiation law, is directly related to the fourth power of the surface temperature. Back radiation of heat increases as temperature increases.

Heat is also lost from a body of water to the atmosphere through evaporation of the water. The rate of heat loss by evaporation can be expressed as the proportionality:

$$H_e \propto W (e_s - e_a)$$

where W is the wind speed, e_s is the saturation vapor pressure of water determined from the water surface temperature, and e_a is the air-vapor pressure, which is directly related to the dew point temperature. At a constant wind speed, heat loss by evaporation would decrease as dew point temperature increased.

The rate of conductive heat loss or gain can be related by the proportionality:

$$H_c \propto (T_s - T_a)$$

where T_s is the surface water temperature and T_a is the air temperature.

The normal ranges for the temperature dependent terms, as reported by Edinger and Geyer (1965), are:

$$\begin{aligned} H_b &= 2400-3600 \text{ BTU ft}^{-2}\text{Day}^{-1} \\ H_e &= 2000-8000 \text{ BTU ft}^{-2}\text{Day}^{-1} \\ H_c &= -320 - +400 \text{ BTU ft}^{-2}\text{Day}^{-1} \end{aligned}$$

These values indicate that back radiation and evaporation are the primary heat loss mechanisms; heat loss or gain by conduction is an order of magnitude less than back radiation and evaporation.

Back radiation will not be considered in explaining temperature differences between 1973 and 1974 because it depends solely on water temperatures. Other factors, such as plant power production, wind speed, air temperature and dew point temperatures will be considered.

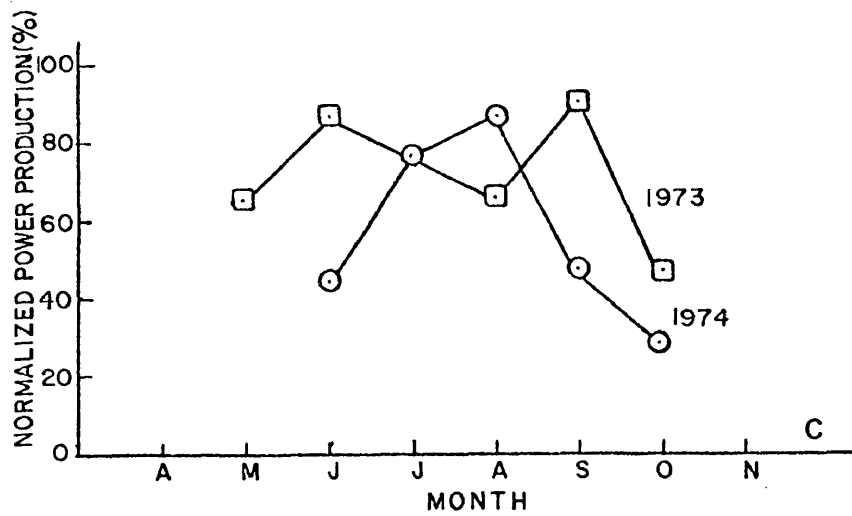
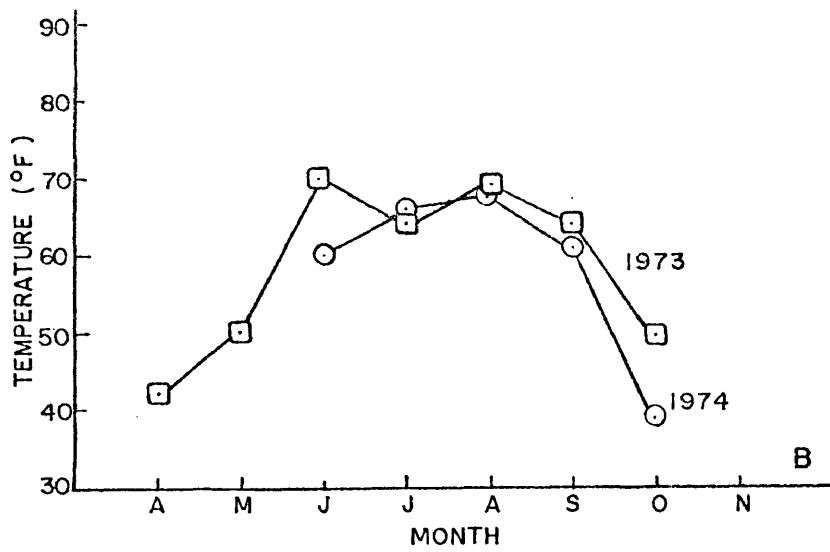
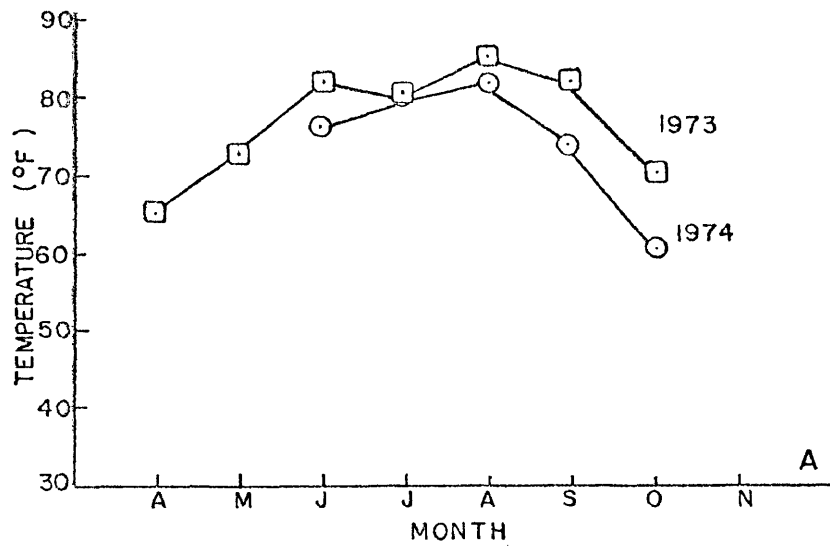
During 1973, excess temperatures dropped approximately 1°F from June to July (Figure 17). Air temperature, dew point temperature and plant production were lower in July than in June (Figure 18) while average wind speeds were higher (Figure 19). The combination of lower plant production and higher evaporative heat loss due to lower dew point and higher wind speeds were responsible for the lower excess temperatures during July.

Excess temperatures reached a peak for 1973 in August, while the monthly average power production was the lowest for the period June-September. Apparently the rise in excess temperature from July to August was more of a function of increased air and dew point temperatures (Figure 18), and decreased wind speed (Figure 19), resulting in lower evaporative heat loss, than it was of the 11 percent decrease in plant power production.

Excess temperatures during 1974 were lower than 1973 values except for the month of July. July 1973 and 1974 average power production and air temperatures were equal, while dew point temperatures in 1974 were 2°F higher and wind speeds were 2.4 mph higher. It appears that the higher dew point temperatures offset the effect of the higher wind speeds on the evaporative heat loss and was responsible for the slightly higher excess temperatures during July 1974.

Figure 18. Monthly average air temperature, dew point temperature, and power generation (1973,1974).

- A) Air temperature
- B) Dew point temperature
- C) Power generation



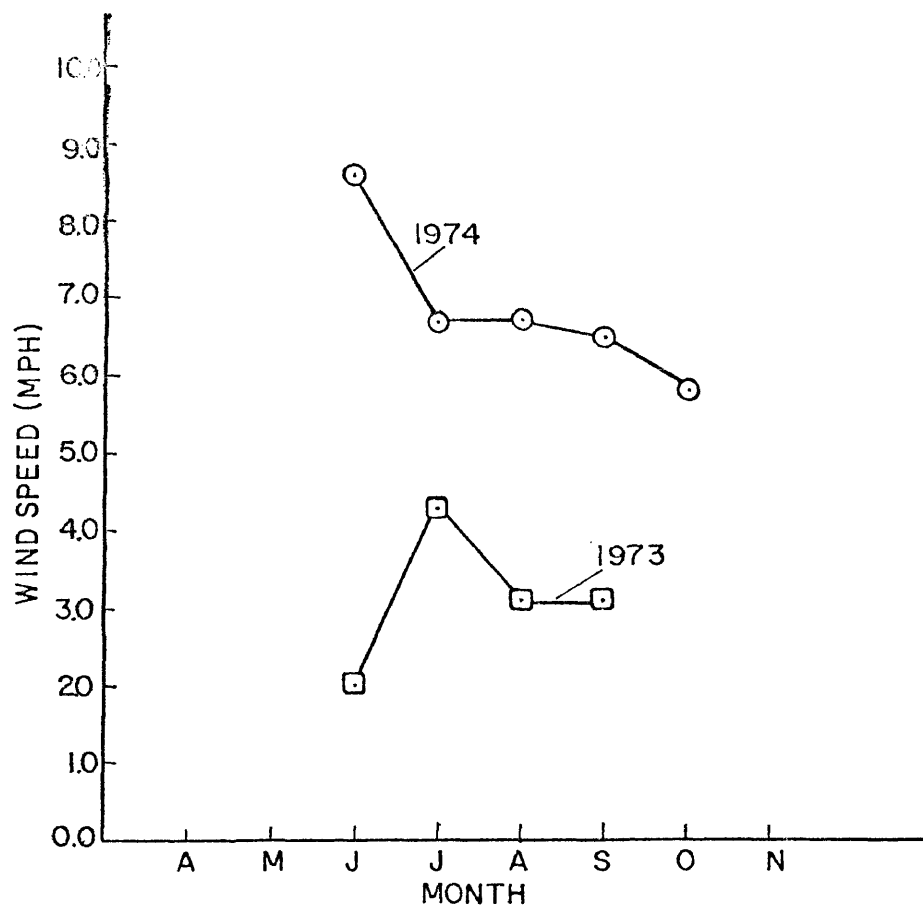


Figure 19. Monthly average wind speed (1973,1974).

August 1974 average plant production was higher than for August 1973, but excess temperatures for August 1974 were less than the August 1973 values. The effects of the 30 percent increase in rejected heat were apparently more than offset by the lower values of air temperature and dew point temperatures, and higher wind speeds, which resulted in higher values of evaporative heat loss during August, 1974.

It appears, then, that plant heat rejection, dew point temperature, air temperature, and wind speed are important factors involved in the determination of excess temperature. Evaporative heat loss and plant heat rejection have the greatest effect on excess temperatures.

Horizontal Temperature Distribution

During 1971 and 1972, prior to plant operation, horizontal temperature gradients were small and water temperatures usually varied less than 4°F over the study area. This pattern was changed during 1973 and 1974 due to the thermal discharge from the power plant. Figure 20 shows typical isothermal plots for 1973 and 1974. These isothermal plots indicate that water temperature gradients in the area were greater than for the pre-operational period. Water temperature variations in the far field region were in the range of 2-4°F;

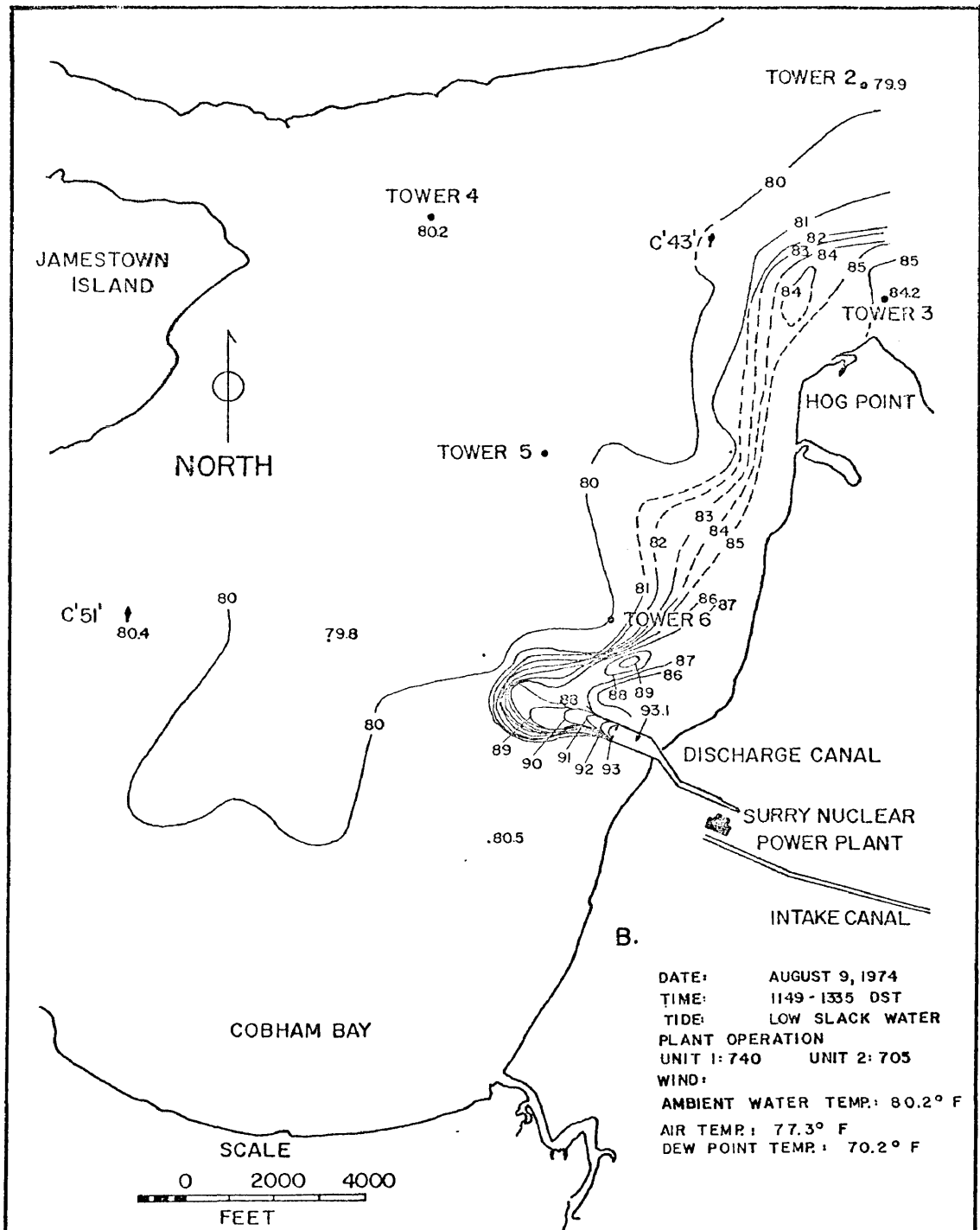
Figure 20. Typical isothermal plots for 1973,
1974.

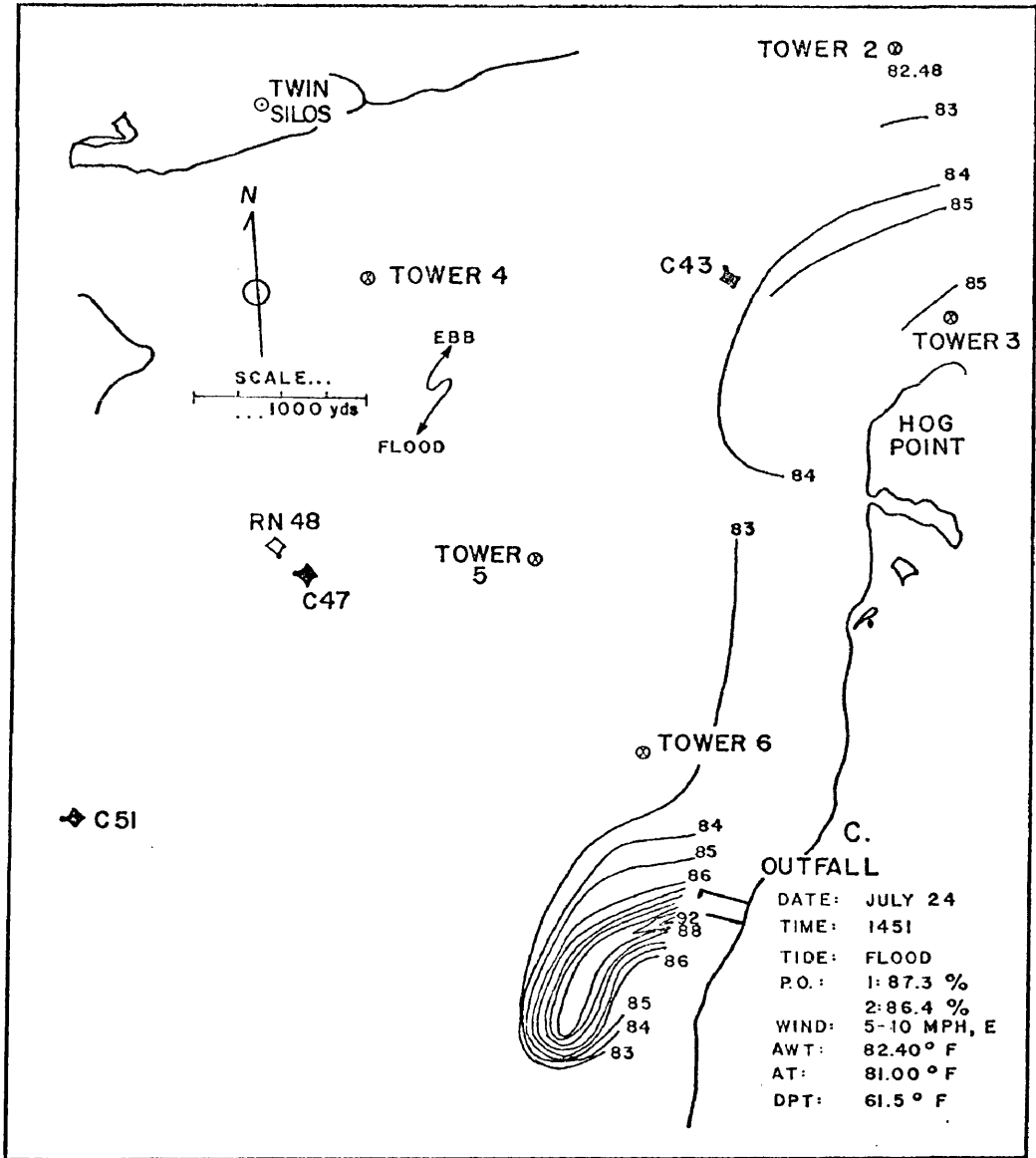
A.) June 28, 1973; ebb

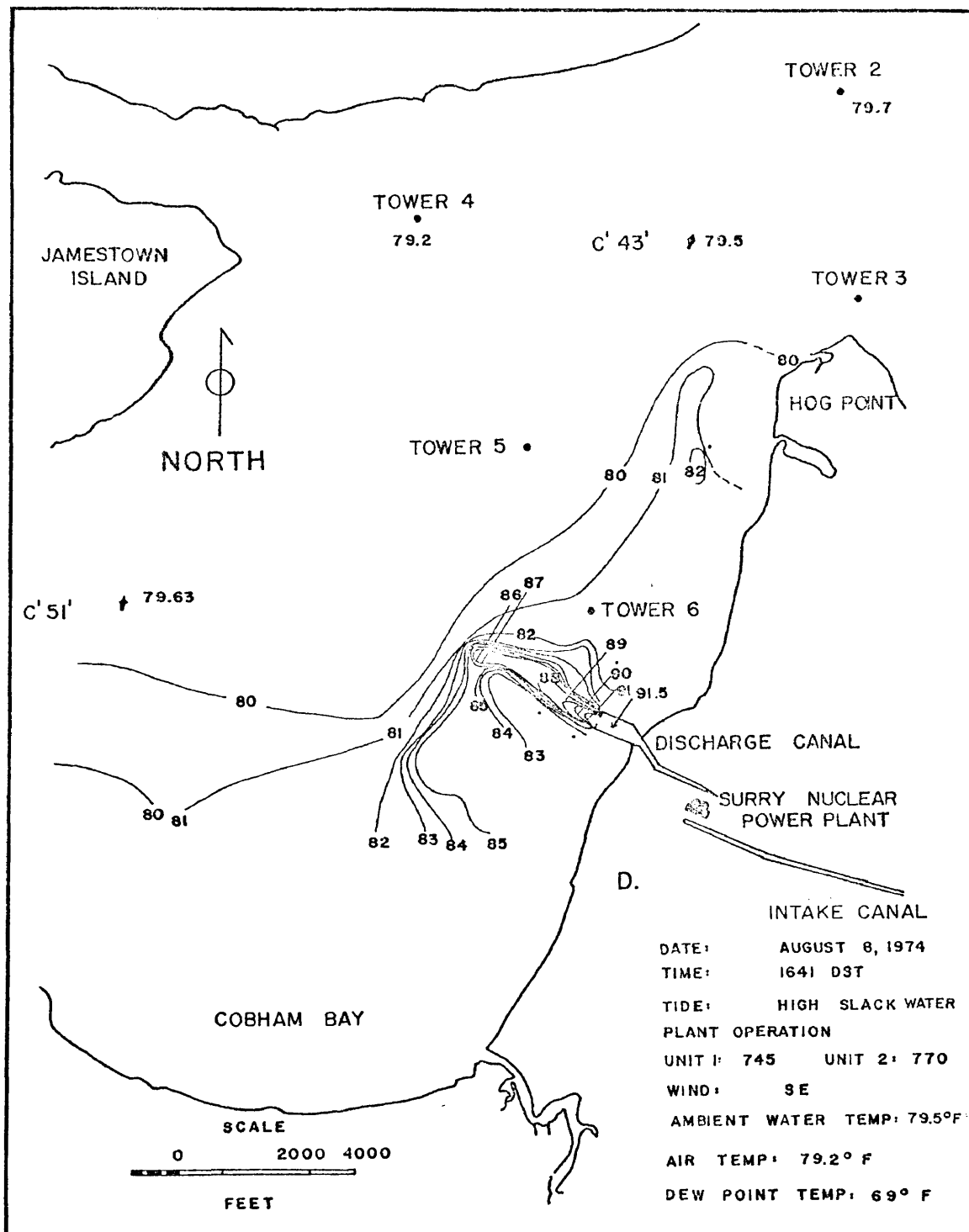
B.) August 9, 1974; low slack

C.) July 24, 1973; flood

D.) August 8, 1974; high slack







near field temperature variations were greater, generally in the range of 5-10°F. These temperature ranges are based on high power production, and would be lower for reduced plant operation.

From the isothermal plots shown in Figure 20, and the additional plots contained in the Appendix, several general statements can be made concerning the effects of tidal stage on the temperature distribution.

During the ebb tidal stage the thermal plumes moved downstream, towards Hog Point. During the period from early ebb to late ebb, the axis of the plume moved closer to the shoreline. Figure 20a, shows the temperature distribution on June 28, 1973. The tidal stage at the time the boat was in the area of the outfall was early ebb. On this day, the axis of the plume, located between the two 86°F isotherms, passed close to Tower 6. At low slack water, the thermal plume has reached its greatest downstream extent.

Extended surveys, starting on the downstream side of Hog Point, were made on June 22, August 7, and September 10, 1973 (Appendix). These runs were made in order to determine the maximum downstream extent of heated waters. These runs indicated that water up to 4°F above ambient extended to the downstream side of Hog Point. In all three cases, water with excess temperature of 1°F or greater did not extend more than half-way across the river at Hog Point, and the downstream extent was on the order of 1 nautical mile.

Figure 20b, shows the isothermal plot for August 9, 1974 at low slack water. On this day, 85°F water (5°F above ambient) was found close to shore at Hog Point. The axis of the ebb plume, which ran between the two 87°F isotherms, was very close to shore on the downstream side of the outfall. A second distinct plume, with an axis running directly along the axis of the outfall, appeared to be forming during the slack period. There was a large "pool" of heated water forming directly offshore of the outfall due to this "new" plume.

As the tidal stage changed from low slack water to flood, the plume was forced upstream. Figure 20c, showing the temperature distribution on July 24, 1973, on a flood tide, shows the plume veered upstream sharply after leaving the outfall canal. Around Hog Point, the isotherms were forced farther offshore than during ebb on low slack water.

At high slack water, for example August 8, 1974, shown in Figure 20d, isotherms were farther offshore than for any other tidal stage. As was noted for low slack water, there appears to be two distinct plumes at high slack water. The plume which was a remnant of the flood tidal stage has an axis which bends upstream from the outfall. For August 8, the axis of this plume was between the two 85°F isotherms on the upstream side of the outfall. The second "slack water" plume has an axis

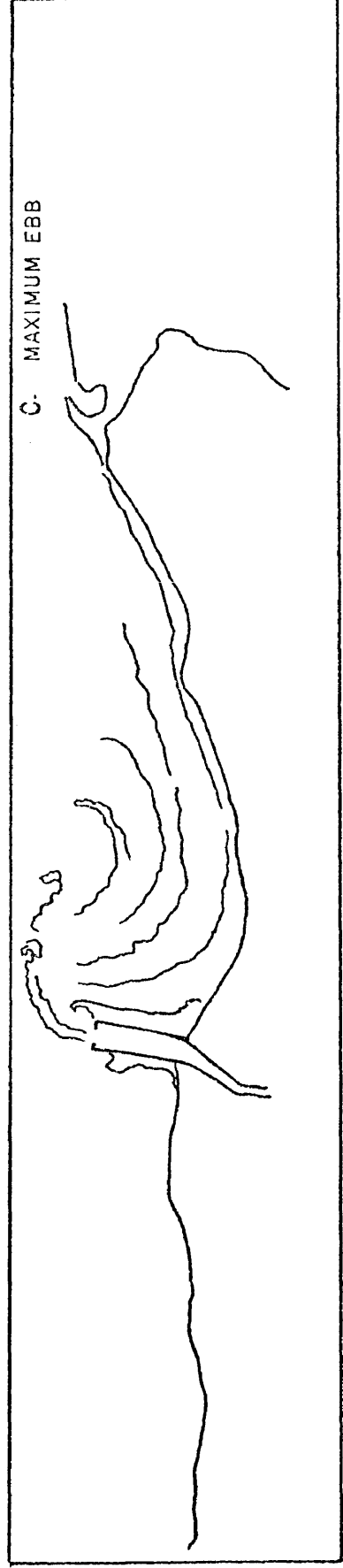
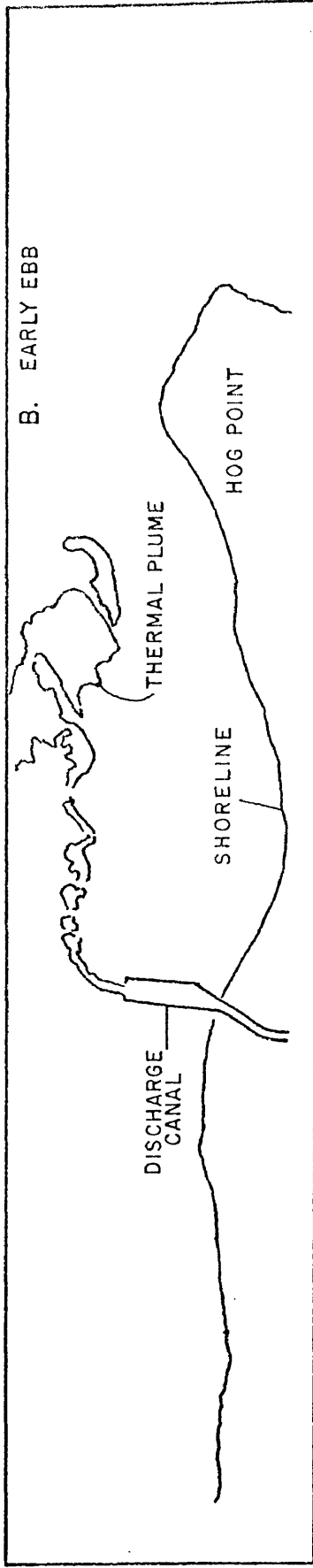
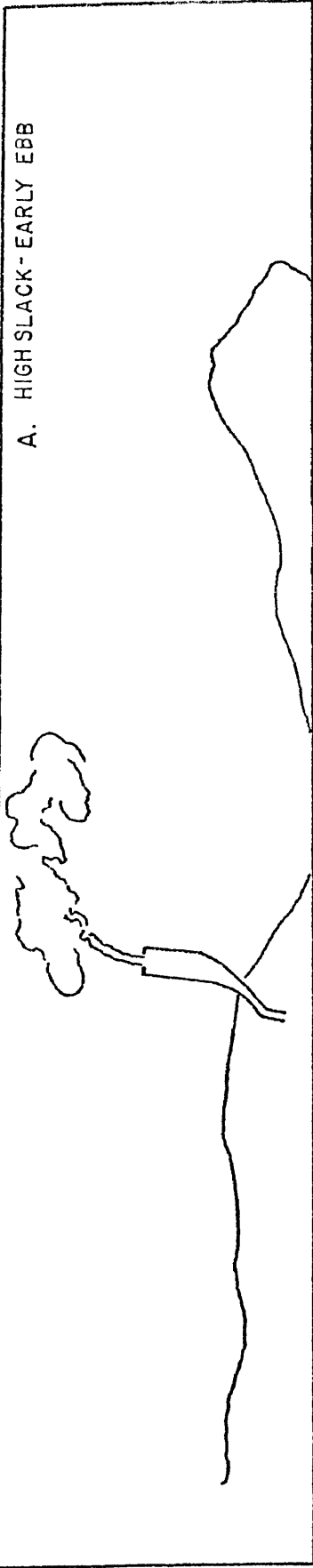
which was along the axis of the outfall. Although most of the heated waters were on the upstream side of the outfall, there were several isotherms which indicated that heated waters still remained downstream of the outfall.

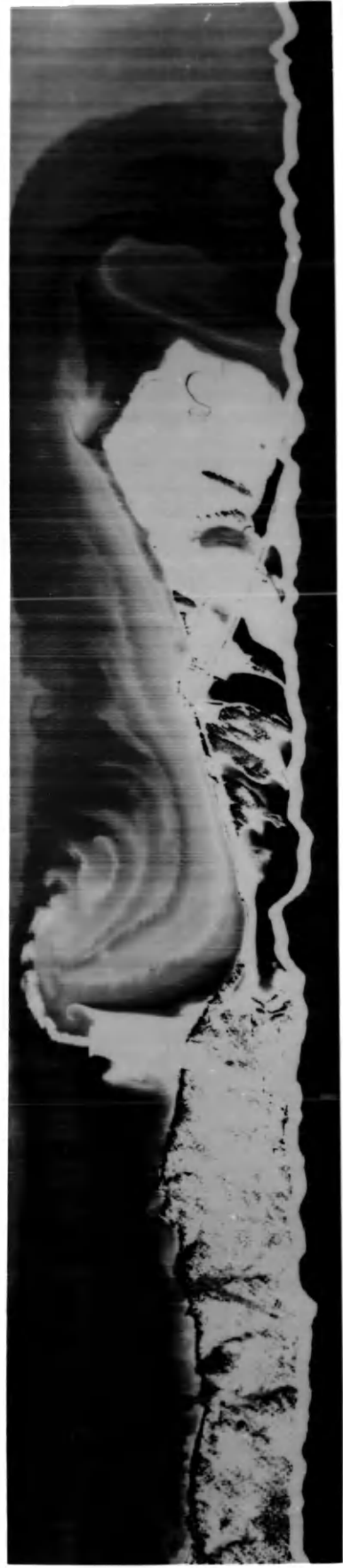
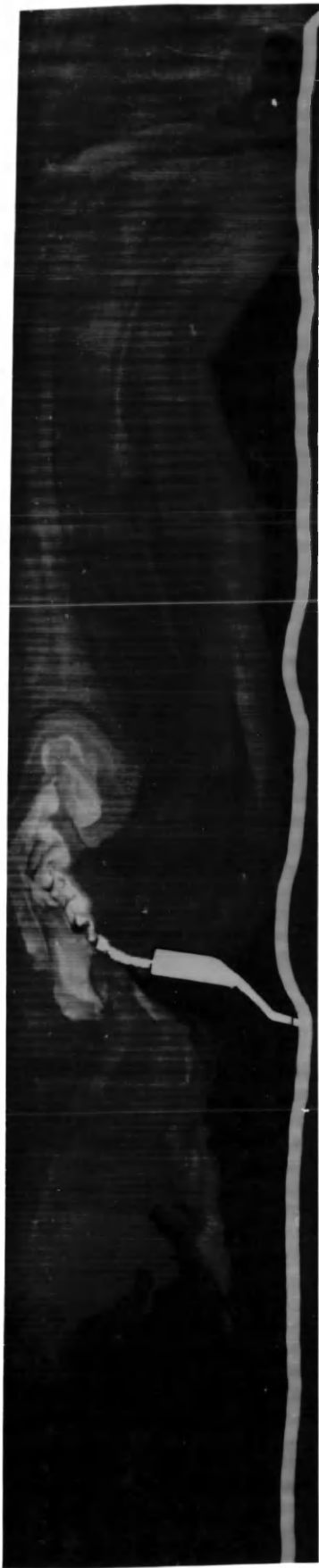
Although the isotherms drawn from the survey data give a good general idea of overall plume movement due to the tidal currents, they tend to "smooth out" some of the details because they are not synoptic. The isothermal plot shows a certain isotherm in which the various points of intersection along each transect were "fixed" at different times. In order to gain a synoptic picture of temperature distribution without the "smoothing" effect inherent in the moving boat system, remote sensing methods must be employed.

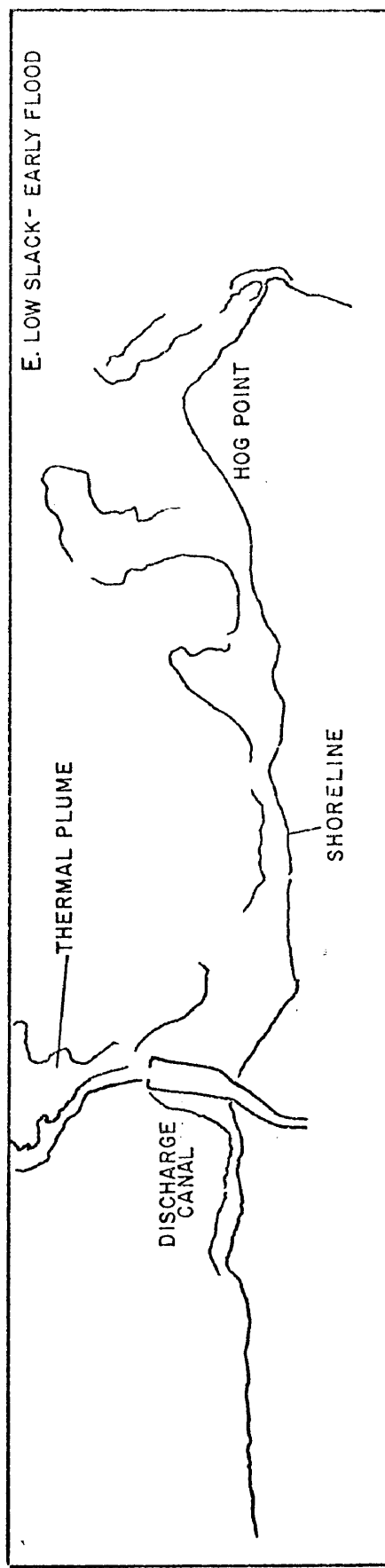
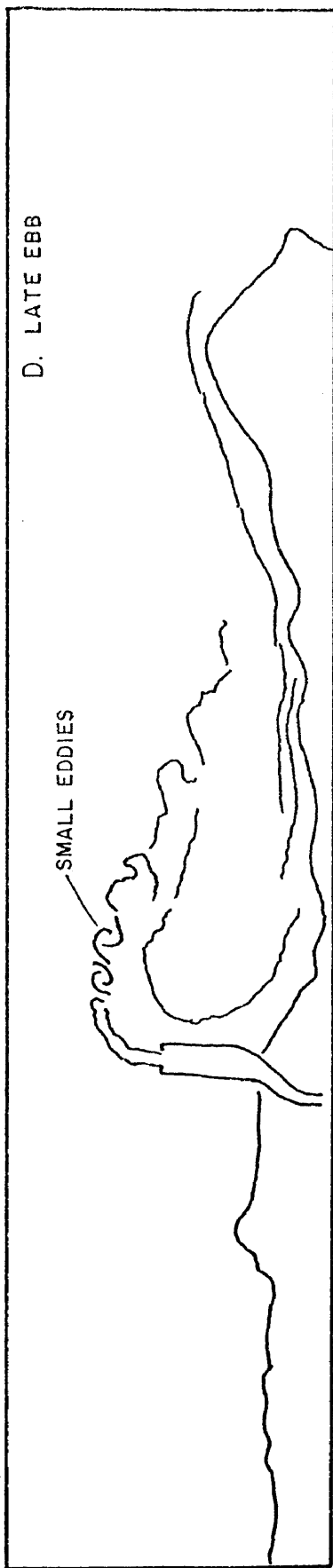
IR Scanning of the Survey Area

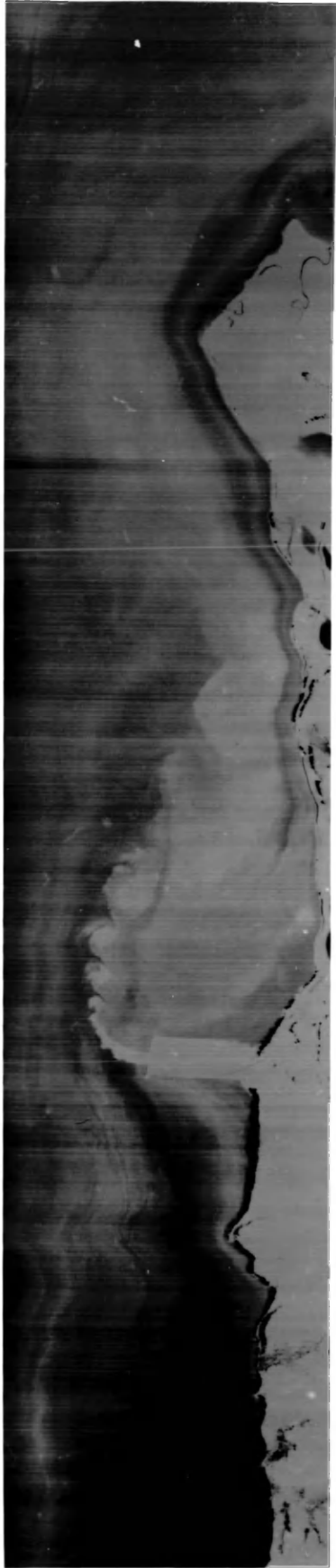
Although it is beyond the scope of this investigation to develop methods of quantitative temperature measurement using the Infra-Red (IR) imagery techniques, IR imagery of the survey area has been made available from Edgerton, Grierhansen, and Greer (EG&G) and can be used in a qualitative discussion of horizontal temperature distribution and plume movement according to tidal stage. Figure 21 shows IR imagery of the outfall area taken on March 15, 1974. On this day, Unit 2 was operating at approximately 96 percent capacity, while

Figure 21. IR imagery of the outfall area taken on March 15, 1974.

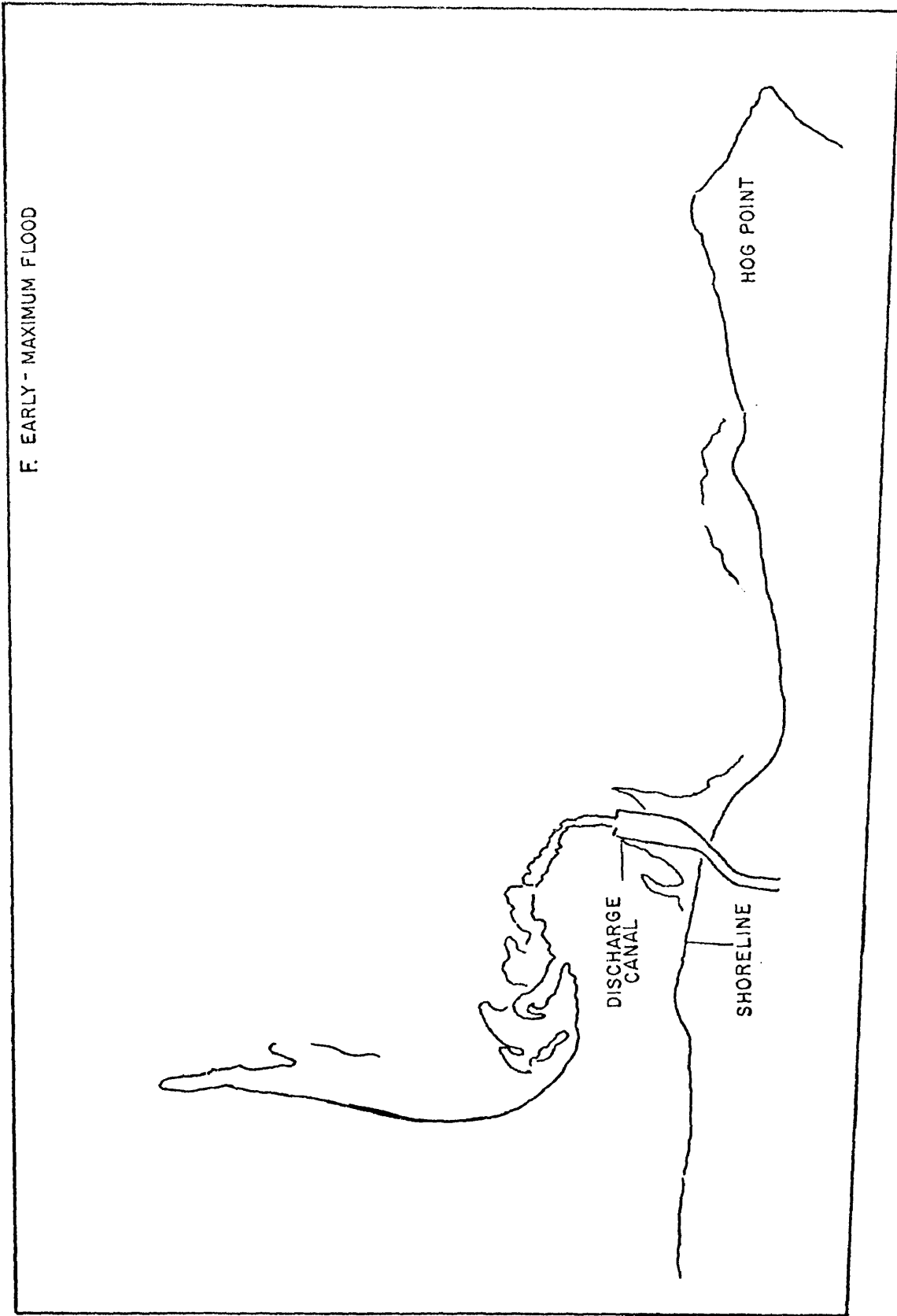


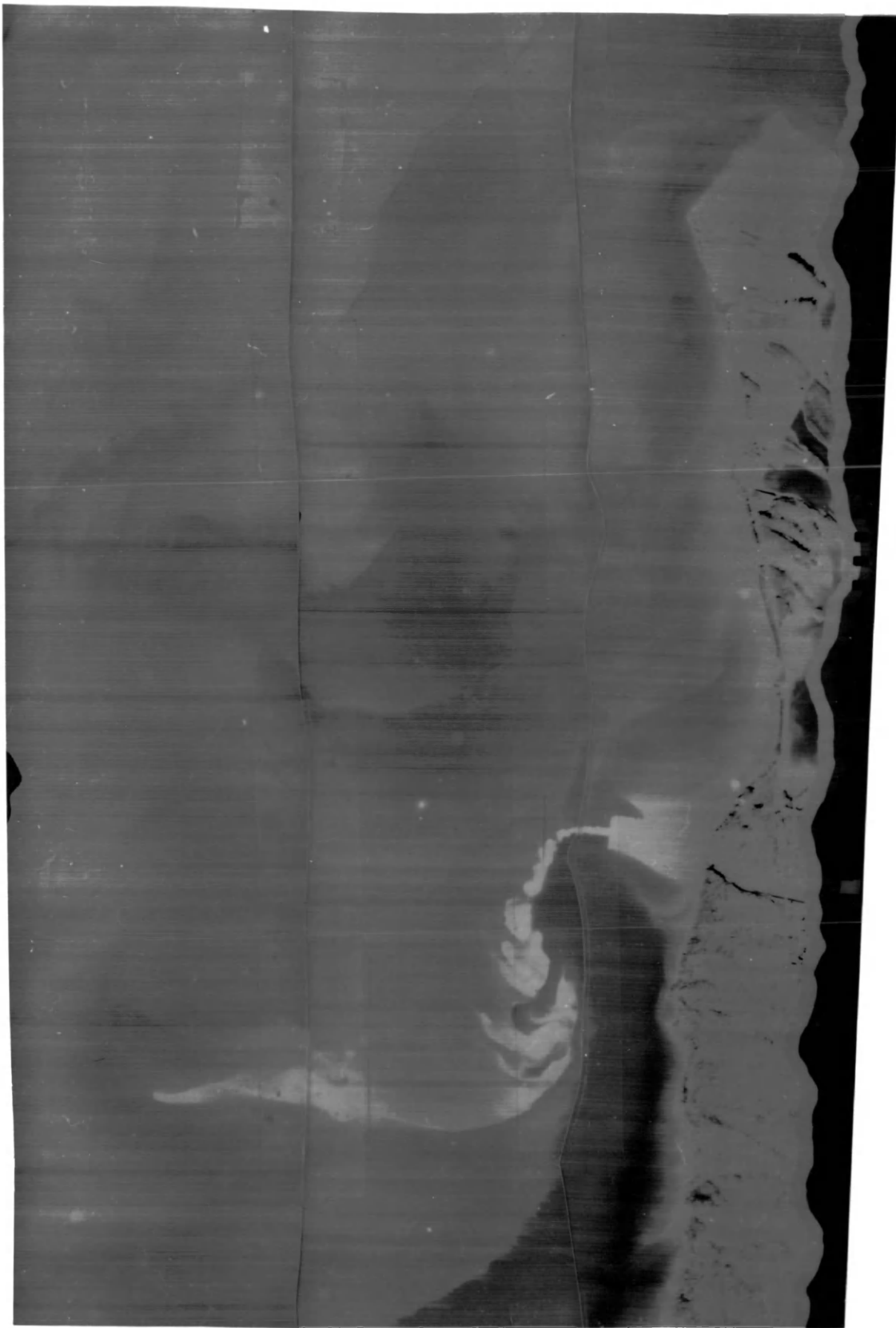






F. EARLY - MAXIMUM FLOOD





Unit 1 was not operating. Discharge temperature at the outfall was 59°F, while ambient water temperature was approximately 51°F. The tidal stages for the IR images of the outfall shown in Figure 21 are a) high slack-early ebb, b) early ebb, c) maximum ebb, d) late ebb, e) low slack-early flood, and f) early flood. North is towards the top of the page.

In Figure 21a, showing the thermal plume shortly after high slack water, the plume was beginning to head downstream towards Hog Point. The "pool" of heated water that formed during slack water was still distinct. Entrainment of cooler ambient water, which appears black (along with the cool land) in this early morning image, can be seen on the upstream side of the discharge jet. These cool patches remain distinct inside the "pool" for a period of time, and then disperse as heat is diffused into the cool patches from the surrounding heated waters. This indicates that the entrainment of ambient fluid is a major process in the reduction of temperatures in the thermal plume. In Figure 21b, taken approximately one half hour later, the plume extended farther downstream, with the slack water "pool" less distinct but still visible. In Figure 21c, showing the thermal plume at maximum ebb, there is an interesting pattern of alternating warm and cool water formed on the downstream side of the outfall. These "fronts" have been noted by Scarpace and Green (1972) in their remote

sensing investigations, but they did not offer any explanation at that time. In this case, the fronts seem to be caused by eddies formed in the thermal plume due to the shear between the edge of the plume and the ambient waters. The plume moved for some distance from the outfall as a continuous plume, and then broke off into eddies which continued to move downstream. These eddies entrained ambient water and as successive eddies were formed and moved downstream, the alternating pattern of warm and cold water was formed.

When a jet of fluid is introduced perpendicular to a cross current, Rouse (1957), among others, reports that an eddy such as shown in Figure 22 is formed on the downstream side of the jet.

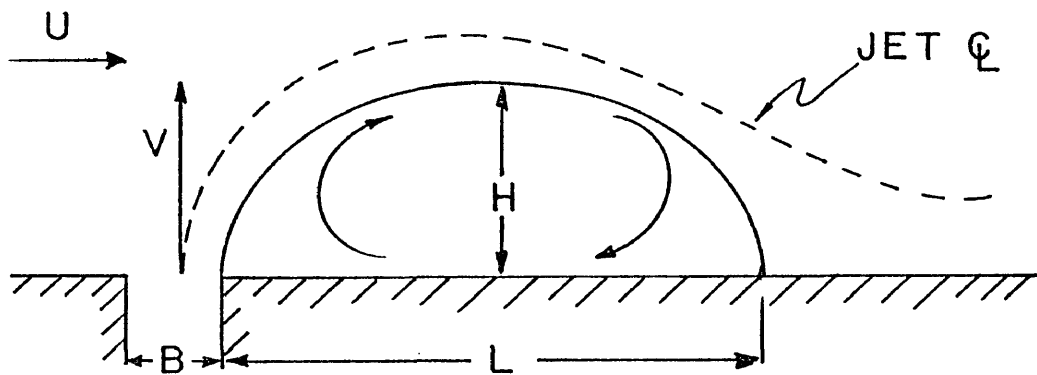


Figure 22. Eddy formed on the downstream side of a jet in a cross flow (From Rouse, 1957).

The situation shown in Figures 21c and d are analagous to the jet discharge in a cross current. The existence of the large eddy downstream of the discharge is evidenced by the small eddy at the downstream corner of the discharge canal structure in Figure 21c. Figure 21d, showing the temperature distribution at late ebb, indicated that the eddy has diffused the "fronts" seen in the previous image but that the majority of the heat is still concentrated in the area close to shore and directly downstream of the outfall.

Figure 21e shows the thermal plume at the beginning of the flood tide. A slight "pool" of heated water is visible offshore from the outfall, and the plume has started to move upstream from the discharge canal. Heated water on the downstream side of the discharge was moving upstream and offshore. A small patch of heated water appeared to be streaming from the tip of Hog Point and heading offshore and upstream.

Figure 21f shows the thermal plume before the time of maximum flood currents. This image shows a narrow filament approximately 1 mile long extending perpendicular to the shoreline. This indicates that tidal currents in this area have to have a component which is perpendicular to the shoreline. Eddies forming at the end of the narrow, distinct thermal plume were causing the "front" effect seen in the imagery at maximum ebb currents, but these fronts were not as extensive as

during the ebb currents. Heated waters were still apparent on the downstream side of the outfall, apparently left over from the previous ebb tidal plume. Concentration of heat on the upstream side of the outfall was not apparent in the image, although this concentration might have developed later in the tidal cycle.

These IR images confirm some of the basic thermal structures that have been identified by the isothermal plots drawn from boat system data, and they tend to show some of the small scale, transient phenomena which are lost in the non-synoptic sampling scheme.

Several points can be made from the boat system data and the IR imagery of the discharge:

- 1) Pools of heated water are formed directly offshore from the outfall during high and low slack water.
- 2) During flood and ebb tides, the plume moves for a distance on the order of 2000 feet as a distinct jet, then tends to break off into eddies.
- 3) These eddies are an important mechanism for entrainment of ambient water and the subsequent reduction of plume temperatures.
- 4) During late ebb the majority of the heated waters are concentrated close to shore and directly downstream of the outfall.

- 5) Heated water remains on the downstream side of the outfall during the flood cycle, apparently a remnant of the ebb tidal plume.

Salinity and Dissolved Oxygen

Monthly averages of salinity and dissolved oxygen concentrations for 1974 are shown in Figure 23. The two graphs show salinity and dissolved oxygen for the surface and the bottom. Salinity showed the same basic pattern in 1974 as in the previous years, with low salinities in the area during winter and spring and a rise in salinity which began in the summer. This pattern, as mentioned in the previous chapter, is determined by the fresh water discharge of the river, which usually attains maximum discharge during the winter, and minimum discharge during the summer. The actual pattern of average salinity varied from 1972 to 1973 (Figure 24). Peaks in the salinity during the summer months correspond to minimum river discharges, which are graphed for 1973 and 1974 in Figure 25, and for 1971 and 1972 in Figure 10.

During 1972, salinity at both the surface (Figure 24c) and bottom (Figure 24d) decreased with distance upstream, i.e., salinities were maximum at station 1, minimum at station 2, and intermediate at station 3 (Figure 3). During 1973 (Figure 24a,b) and 1974 (Figure 23a,b), after the plant began operation, surface and bottom salinities were maximum at station 3, except for

Figure 23. Monthly average salinity and dissolved oxygen at the sampling stations and outfall during 1974.

- A) Surface salinity and dissolved oxygen
- B) Bottom salinity and dissolved oxygen

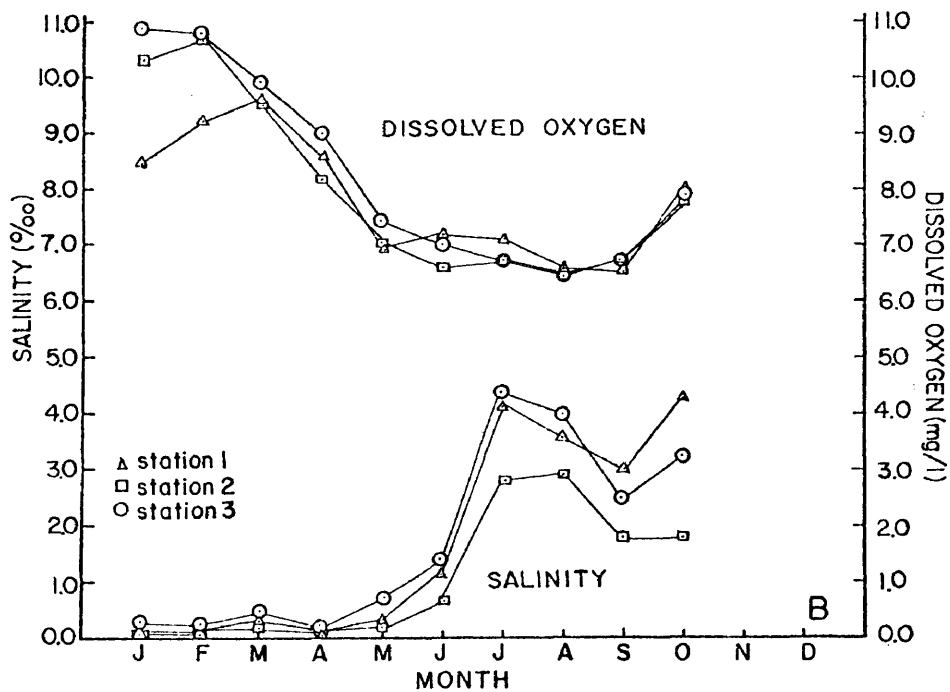
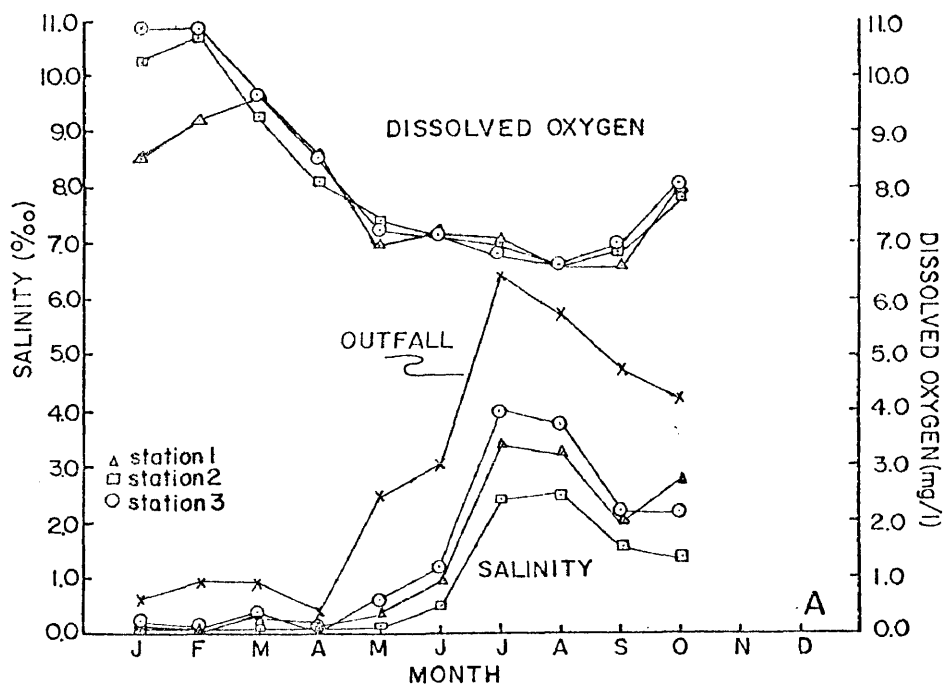
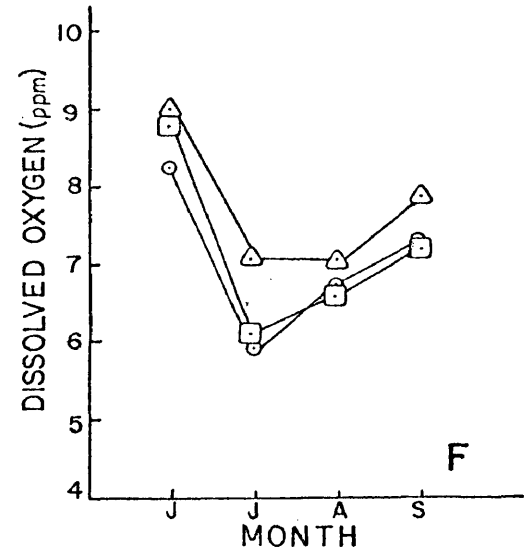
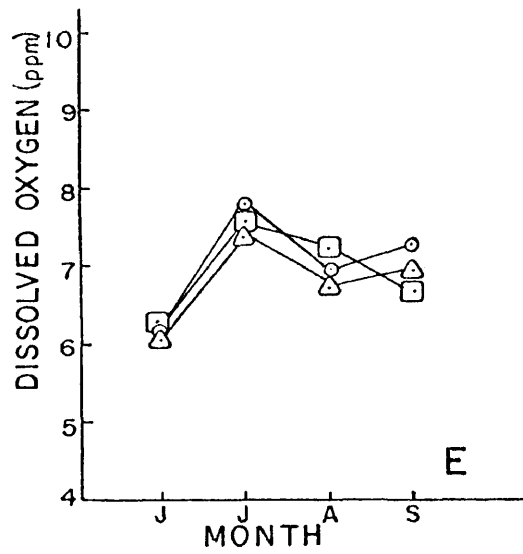
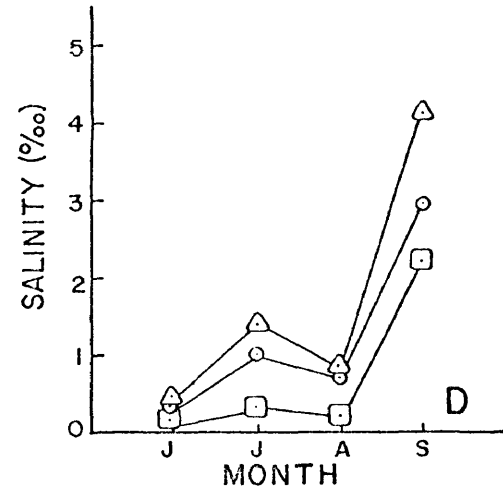
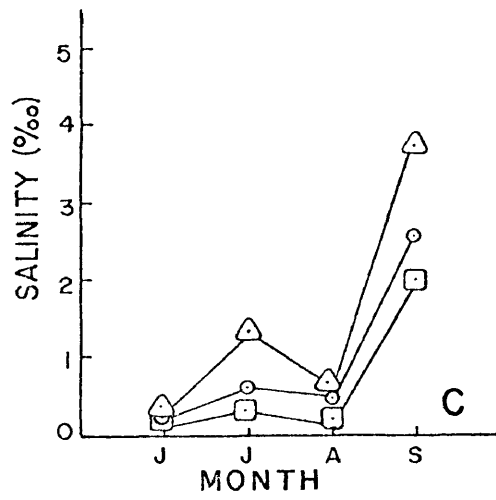
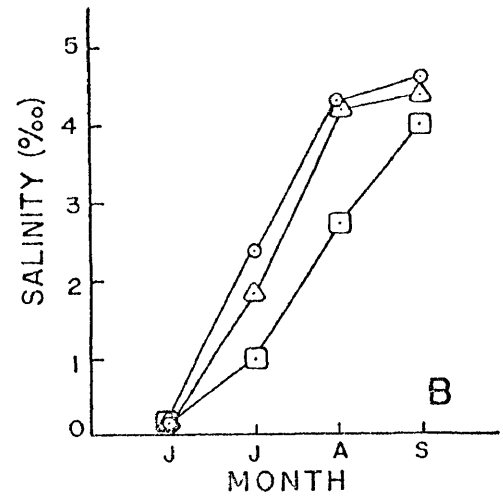
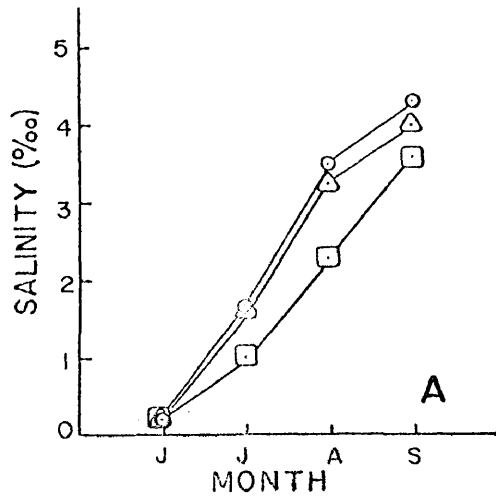


Figure 24. Monthly average salinity and dissolved oxygen (1972, 1973).

- A) Surface Salinity, 1973
- B) Bottom Salinity, 1973
- C) Surface Salinity, 1972
- D) Bottom Salinity, 1972
- E) Average DO, 1973
- F) Average DO, 1972



△ STATION 1 □ STATION 2 ○ STATION 3

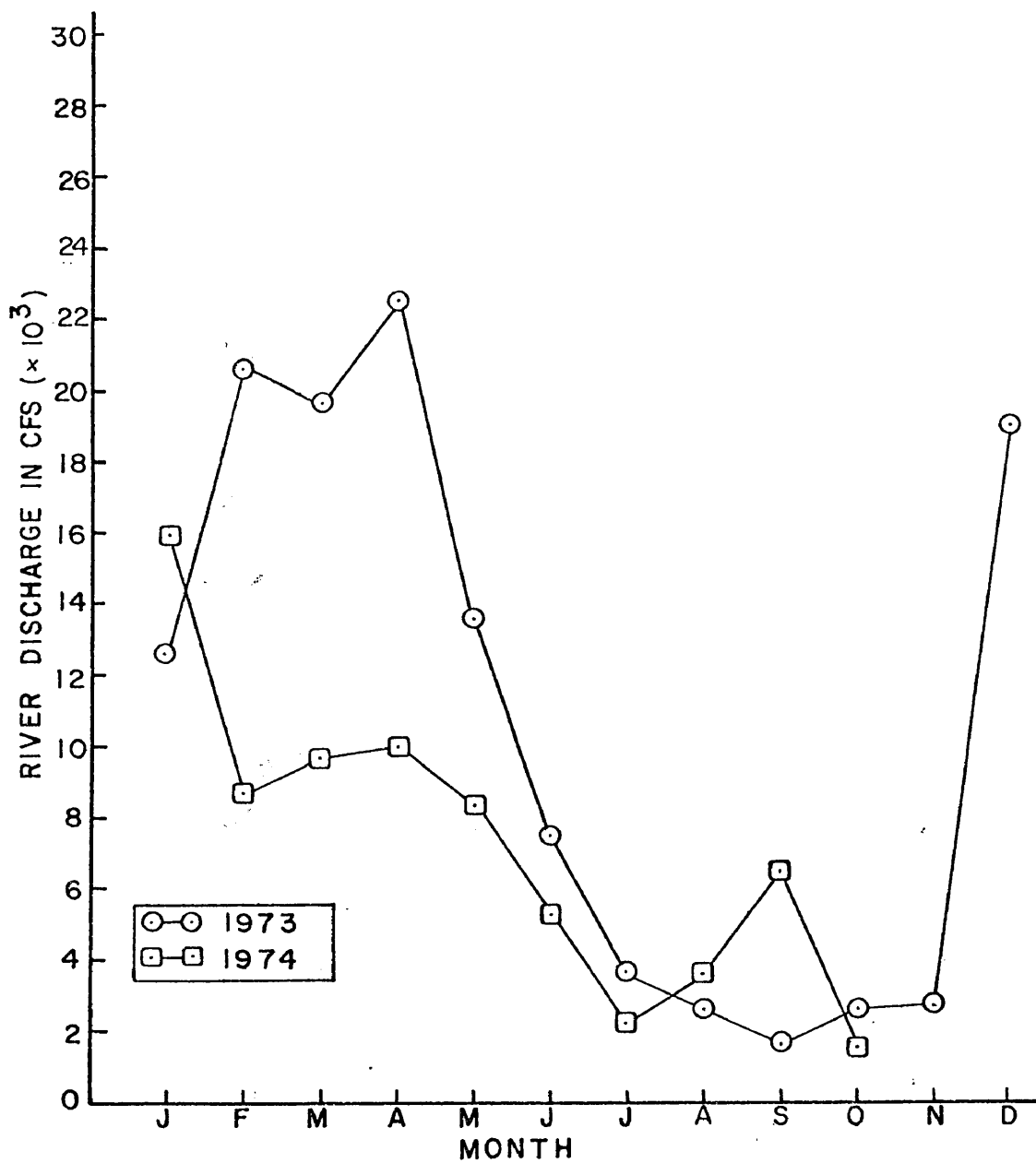


Figure 25. Monthly average fresh water discharge (1973,1974).

September and October, 1974. The monthly average salinity at the outfall (Figure 23a), was higher than for all stations during 1974. The higher outfall salinities are due to the downstream intake of condenser cooling water, and the discharge of this higher salinity water on the upstream side of Hog Point has increased the average salinity of the water near the outfall. This increase in salinity appears to be a localized effect, and would not be reflected by salinity measurements in the channel.

Average dissolved oxygen (DO) during the two post operational years fell within the same ranges as for the two pre-operational years, with a range of 6.0 - 7.5 mg/l during the summer, and a range of 8.5 - 11.0 mg/l during the winter. In 1974, no water samples had concentrations of less than 5.0 mg/l dissolved oxygen, while in 1973, approximately 4% had concentrations in the range 4-5 mg/l. The data indicate that the thermal discharge has not decreased the DO concentration in the survey area.

Temperature Stratification

Background data from 1971 and 1972 indicated that there was a slight thermal stratification, with water temperatures at 6 feet approximately 1^oF cooler than the surface, during May through September. The water column during the rest of the year showed little temperature stratification within the top 6 feet.

Monthly average water temperature profiles for 1973 and 1974 to a depth of 6 feet, (Figure 26a,b), show that temperature stratification in the top 6 feet of the water column remained slight. The month of June in both 1973 and 1974 showed the highest stratification, but the stratification was 1^oF or less in both cases.

During the period from October, 1973 to May, 1974, temperatures were sampled manually with an ARA thermistor due to problems with the boat system. Temperatures were taken at the beginning, middle, and end of each transect, with readings taken at the surface and at 3 foot intervals to the bottom.

Figure 27 shows the water temperature profiles for October 18, 1973 at several selected stations. The station locations are shown in Figure 28. On October 18, only one unit was operating at 93% capacity, the discharge rate was approximately 2800 cfs, air temperature was 67^oF, dew point temperature was 36.0^oF, and winds were 5-10 MPH from the southwest.

The water temperature for station A, approximately 100 yards from the outfall along the axis of the discharge, shows that the water surface temperature was 76.8^oF while the water temperature at the bottom (12 feet depth) was 75.5^oF. At stations B and C, 300 and 450 yards from the discharge respectively, the water surface temperatures were considerably lower, at

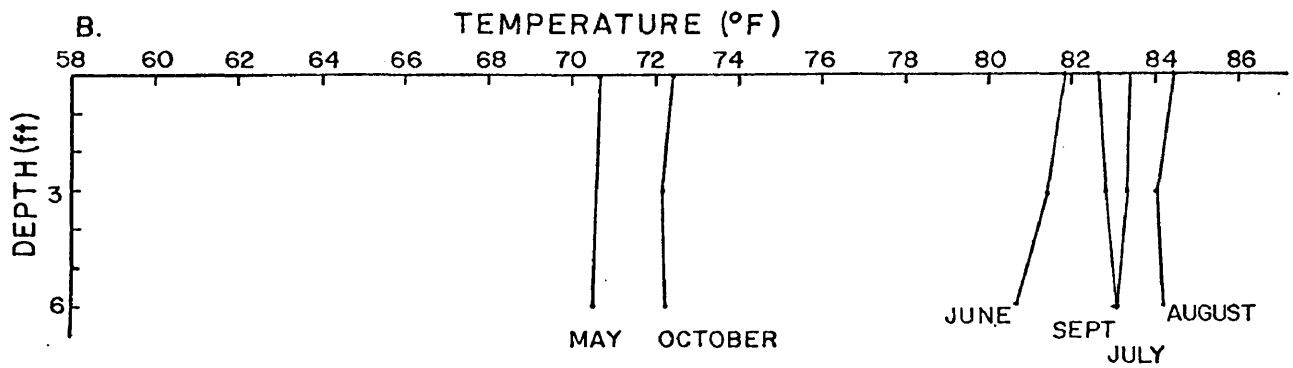
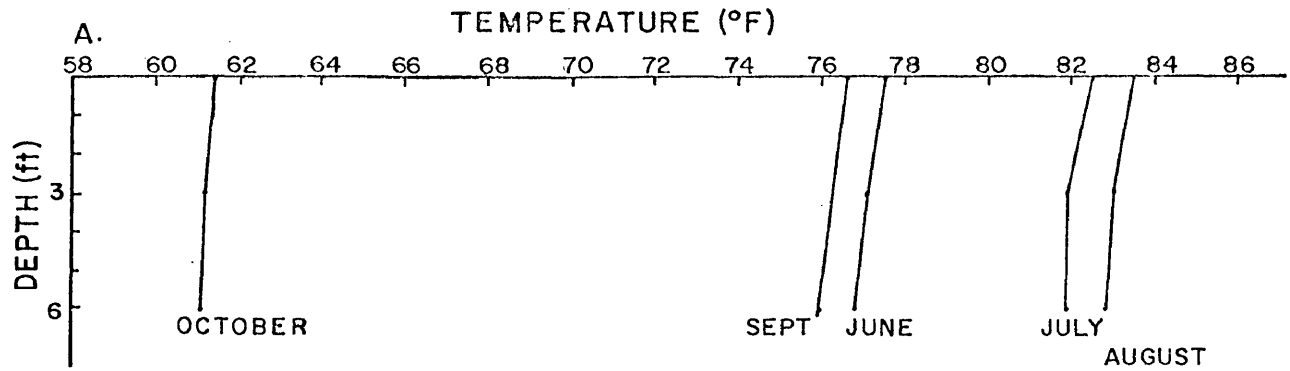
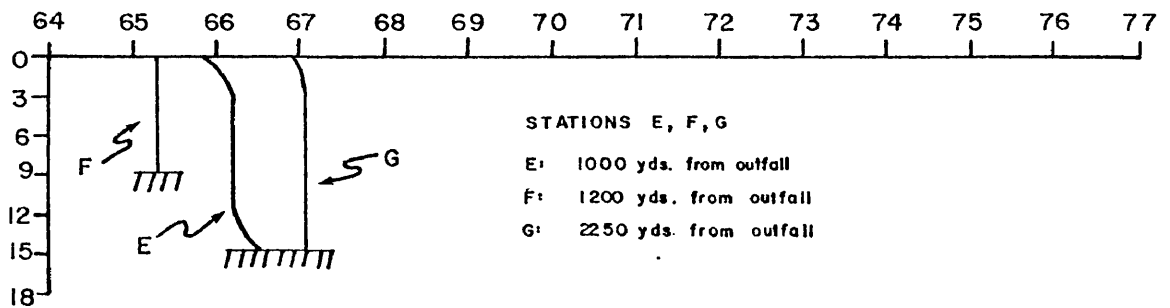
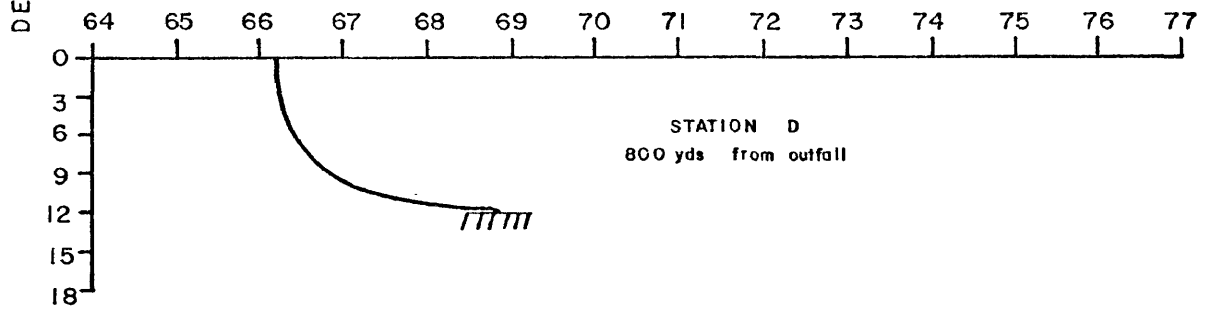
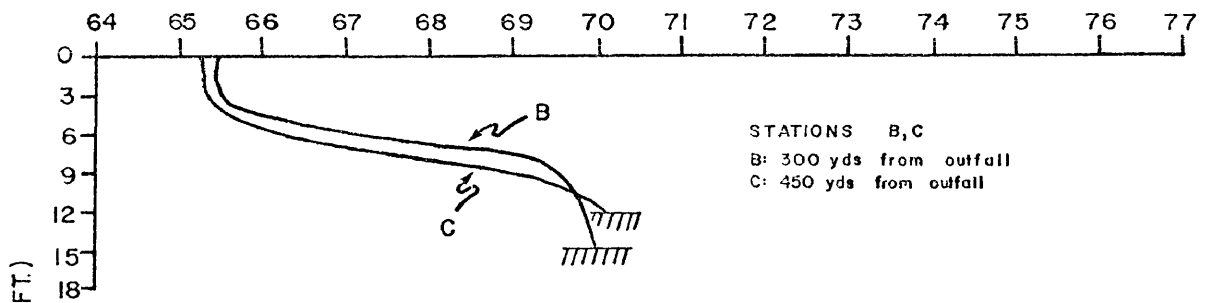
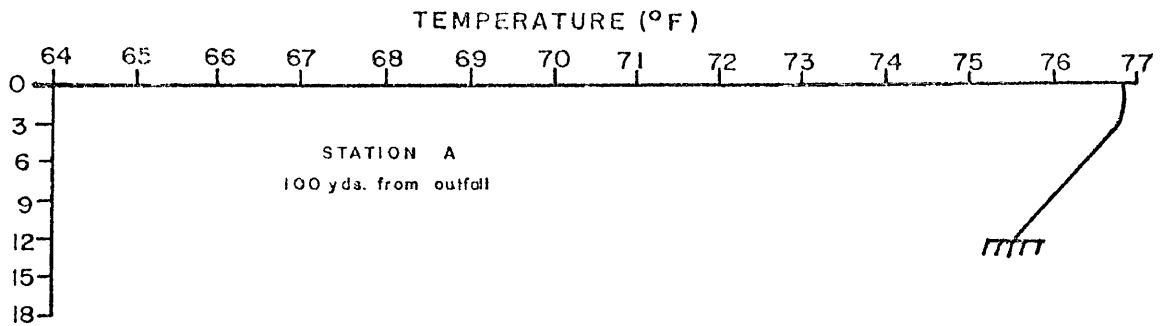


Figure 26. Monthly average water temperature as a function of depth.

A.) 1974

B.) 1973

Figure 27. Water temperature profiles for October 18, 1973 at selected stations (see Fig. 28).



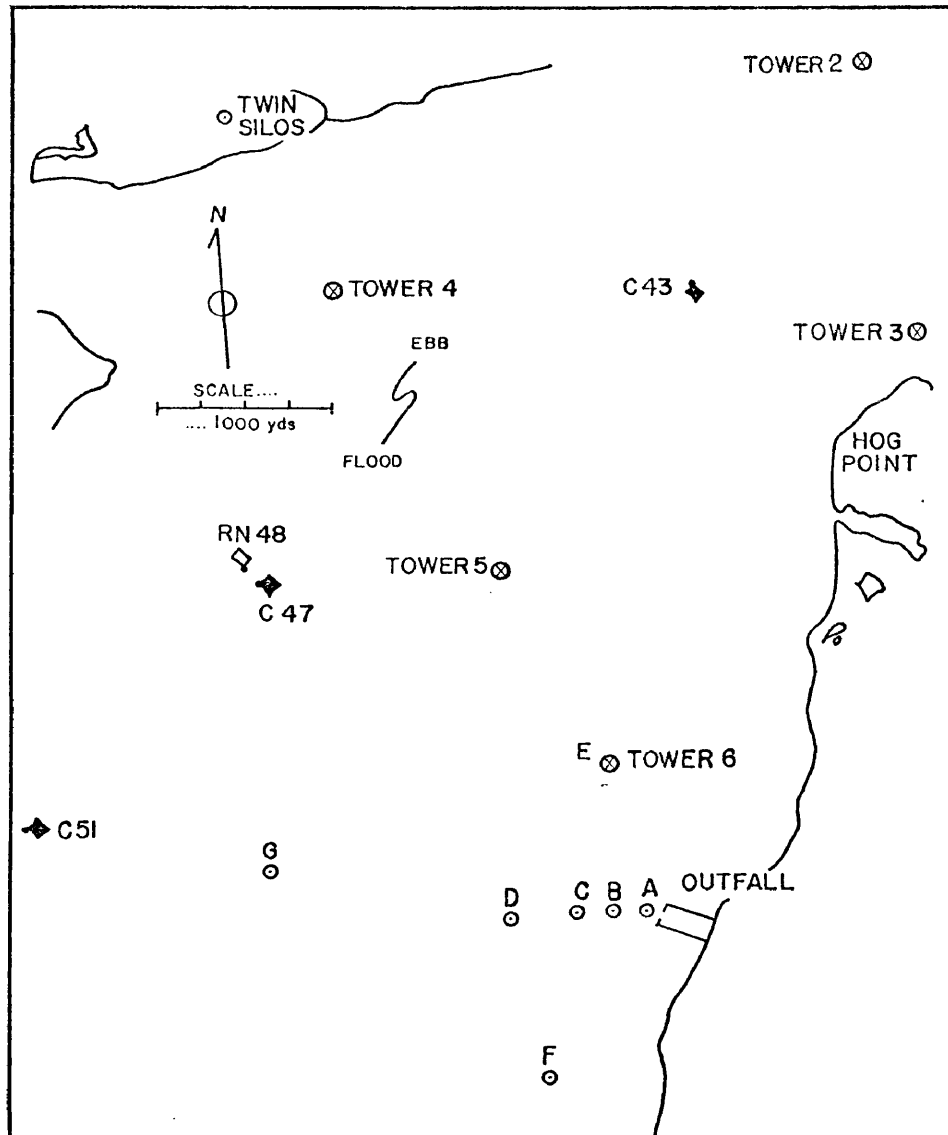


Figure 28. Station locations for temperature profiles on October 18, 1973.

approximately 65.4°F. Water temperatures at the 3 feet depth were the same as those at the surface. Water temperatures steadily increased from the 3 feet depth to approximately 70°F at the bottom. At these stations water temperatures at the 6 feet depth, the deepest depth normally sampled by the boat system, were only 1.0° to 1.5°F above surface temperatures. Station D, 800 yards from the discharge, shows the same pattern as stations B and C, but in this case, bottom temperatures reached a maximum of 68.8°F. Of the last three stations, E, F, and G, only station E, 1000 yards from the mouth of the discharge and 850 yards downstream, had warmer waters at the bottom. In this case, water temperatures from 3 feet to 12 feet were constant at 66.2°F and reached a maximum of 66.5°F at the bottom.

These water temperature profiles indicated that in the near field region of the outfall, water temperatures in the top 3 feet of the water column decreased rapidly, but that below this depth the temperature decrease was less rapid. This phenomena was observed in 4 of the 6 runs made during the month of October and indicated that either the plume was "sinking" in this region or that surface cooling was much more rapid than cooling at depth.

A "sinking" plume may be the result of salinity differences between the discharge waters and the surrounding waters. On the occasions when outfall salinity

samples were taken, the salinity of the discharge waters, originally drawn into the plant from the higher salinity downstream section of the river was 1-2 ppt higher than salinity samples at Tower 6. On October 18, the salinity of the discharge water was 4.82 ppt, while the salinity at Tower 6 was 3.69 ppt at the surface and 3.71 ppt at the bottom. Within the ranges of salinities and temperature found in this area, an increase in temperature of 6.3°F has the same effect on the density of the water as a decrease of 1 ppt in the salinity. This means that water which had a salinity of 1 ppt greater than ambient water would have to be 6.3°F warmer than the ambient water to have the same density. A simplified temperature-salinity- σ_{T} (density) diagram, Figure 29, shows this clearly.

Starting at point C, a decrease in salinity of 1 ppt at constant temperature results in point A, where σ_{T} (density) is σ_{t_1} . Starting at C and increasing temperature 6.3°F at constant salinity results in point B, where σ_{t} also equals σ_{t_1} . If A represents ambient conditions, an increase of 1 ppt salinity must be accompanied by an increase in temperature of 6.3°F in order for the densities to remain the same. As the discharge waters enter the river proper, temperatures and salinities decrease primarily due to the entrainment of ambient water. Heat transfer at the air water interface is an additional process affecting discharge water heat loss, therefore

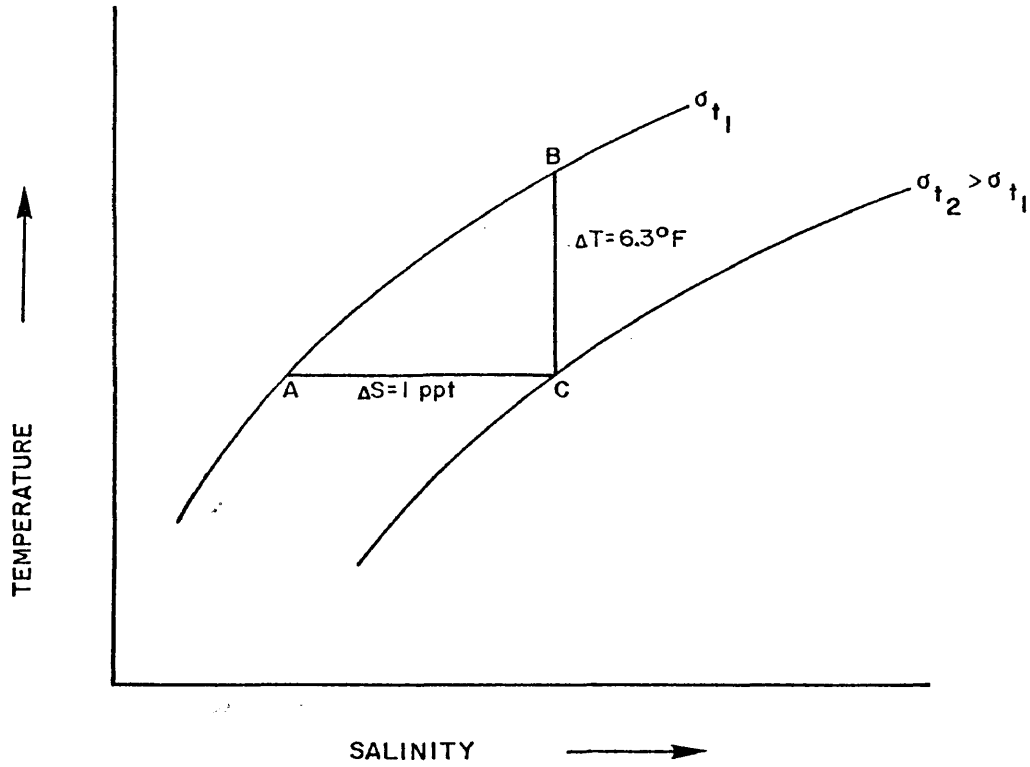


Figure 29. Temperature-salinity-density (σ_t) diagram.

the temperature of the discharge water decreases faster than its salinity. Eventually the increase in density of this water due to its heat loss is greater than the decrease in its density due to the decrease in salinity by diffusion and dispersion, and the denser plume waters "sink" with respect to the surrounding waters. Data suggest that this phenomena occurs only in the near field, within approximately 1000 yards of the outfall.

Outfall and ambient salinities were recorded on the manual runs during the period December 1973 - March 1974 to test the hypothesis that the "sinking" plume was due to the higher salinity of the discharge water. These data were compared with the water temperature profiles for a station located on the axis of the discharge canal and approximately 300 yards from the mouth of the discharge. The results of this comparison are shown in Table 3.

The data in Table 3 indicate that whenever the salinity of the outfall water is approximately 1 ppt greater than the salinity of the ambient water, as on Dec. 4, Feb. 27, and March 15, the plume shows evidence of "sinking". On December 4 the salinity difference was maximum, and the temperature differences between surface and bottom were maximum.

This "sinking plume" phenomena has been reported by Hoglund and Spigarelli (1972). In their investigations, sinking plumes were observed at the Point Beach

Table 3. Comparison of Outfall Salinity and Temperature Profile

Date	Outfall Salinity	Ambient Salinity		Temperature 300 Yards from Outfall				
		Top	Bottom	Surface	3'	6'	9'	12'
12-4-73	6.74	3.00	4.12	53.4	53.4	53.9	56.1	59.9
12-26-73	0.24	0.14	0.14	47.6	46.9	46.0	45.8	-
1-7-74	0.39	0.12	0.10	48.3	47.1	46.9	46.9	46.9
1-23-74	0.90	0.18	0.14	55.0	55.4	55.4	55.4	55.4
2-11-74	0.64	0.08	0.08	49.1	49.1	49.1	49.1	49.1
2-27-74	1.26	0.12	0.14	49.1	50.2	50.2	50.7	50.7
3-15-74	2.76	0.26	0.56	51.9	52.5	53.2	53.7	54.1

Nuclear Power Plant on Lake Michigan when lake temperatures were 39°F or less. In this case, sinking was due solely to temperature dependent density differences and not to salinity dependent density differences.

The phenomena is significant because it removes the heated waters from the air-water interface, and thus removes evaporation and conduction across the air-water interface as a means of heat exchange. In this case, water temperatures would decrease less rapidly than if the plume were not sinking. Heated waters might also adversely effect benthic organisms in the outfall area. Studies by Warinner & Brehmer (1966) at a thermal discharge on the York River indicate that such effects are apparent only during the summer months, when water temperatures are high. Communities in the outfall region show low diversity and decreased production during the summer. A study by Bender, et al., (1974) indicates that there has been no detectable effect on the benthic communities as a result of the thermal discharge at Surry.

Drogue Experiments Within the Plume

On September 11, 1974, two drogue experiments were conducted within the thermal plume. These experiments consisted of releasing a simple "window shade" drogue (see Figure 30) at the mouth of the discharge canal and following its movement for approximately one hour. The purpose

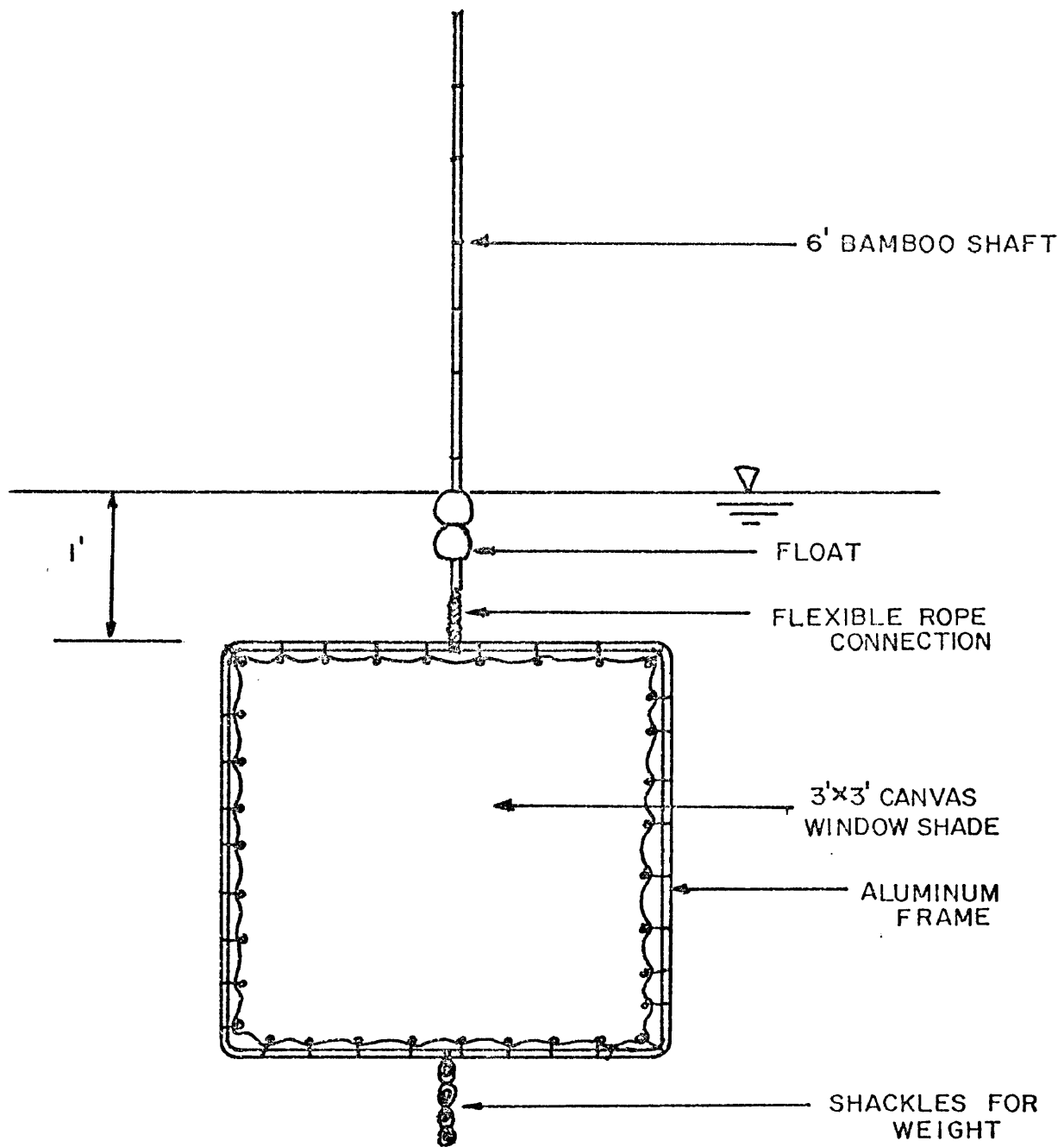


Figure 30. Drogue used in experiments on September 11, 1974.

of these experiments was to measure velocity and temperature decay along the centerline of the plume. It was felt that the drogue would follow the centerline of the thermal plume and by recording position, elapsed time from the release of the drogue, and a temperature profile at each position, a good approximation of centerline velocity and temperature decay could be obtained.

The tracking of the drogue was accomplished using a small boat. After release of the drogue, the boat moved out of the plume and waited for a short period of time, usually around 10 minutes, and then moved up along side of the drogue. While one person took a position fix with a sextant, another person, using a CSTD probe, recorded temperature and conductivity at the surface and at 3 foot intervals to the bottom.

Figure 31 shows the drogue tracks for the two releases. The numbers located beside each position indicate the time at which position and temperatures were recorded.

The first drogue was released at 1311 DST, near the time of maximum ebb currents (maximum ebb at 1253 DST as predicted for Hog Point by tidal current tables). This drogue traveled almost a mile downstream before it was retrieved 50 minutes after release. The drogue was released at the outfall for the second time at 1408 DST. After 40 minutes it had traveled approximately 3000 yards and its speed had decreased rapidly after the

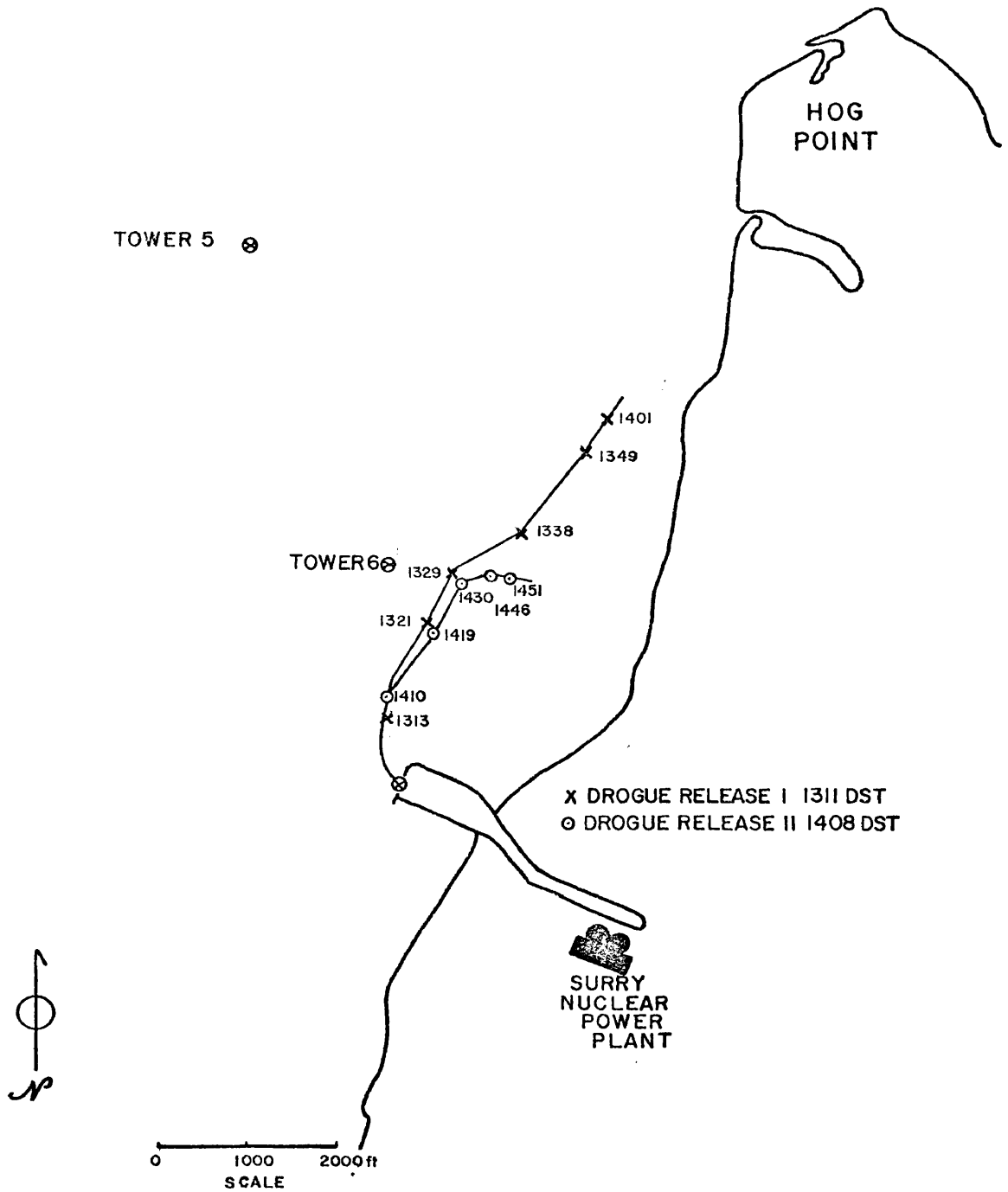


Figure 31. Drogue tracks on September 11, 1974.

third position fix. While the path of the drogue during the first run was approximately parallel to the shore, at the end of the second run the drogue was heading towards the shore.

In order to gain a qualitative idea as to how closely the drogue was following the centerline of the plume, an ARA thermistor was dragged behind the boat while it ran a course perpendicular to the drogue path when the drogue was near Tower 6. For the first run, the surface temperature increased as the boat moved towards the drogue from the shoreward side, reached a maximum near the drogue, and decreased as the boat headed away from the drogue towards Tower 6. This indicates that the drogue was following the approximate centerline of the plume. For the second run, water temperatures again increased as the boat approached the drogue from the shoreward side, reached a peak at the drogue, decreased slightly with movement away from the drogue and toward Tower 6, then increased to another peak as the boat approached Tower 6. This indicates that the drogue was not following the plume centerline but was possibly following an eddy which had formed on the shoreward side of the plume. This seems to be supported by the shoreward motion of the drogue near the end of the run.

The water temperature at 3 feet (drogue depth) as a function of distance along drogue path for drogue

releases I and II is shown in Figure 32. This figure shows that temperatures decreased rapidly in the first 2000 ft. of travel for both drogue releases. Figure 32 also shows the average velocity between each station for the two releases. The velocities showed the same rapid decrease within the first 2000 ft. of drogue travel. After 2000 feet of travel, the temperatures and velocities become erratic. In drogue release I the temperature generally decreased to a distance of 3500 ft., and then slightly increased. The average velocity remained relatively constant to a distance of 4800 ft., and then dropped slightly. In drogue release II, the temperature remained fairly constant between 2000 and 2850 feet along the path, and then showed an increase. The average velocity decreased from 2000 to 2850 feet and then showed a slight increase.

These data indicate that the temperature and velocity of the plume decrease rapidly in the first 2000 feet of travel from the outfall. As the distance increases, the rate of temperature and velocity decrease is lower. Drogue release I represents the centerline temperatures and velocities more closely than drogue release II, since the drogue in the second release appears to have been caught by an eddy and moved away from the plume centerline. This would explain the erratic temperature pattern for the second release.

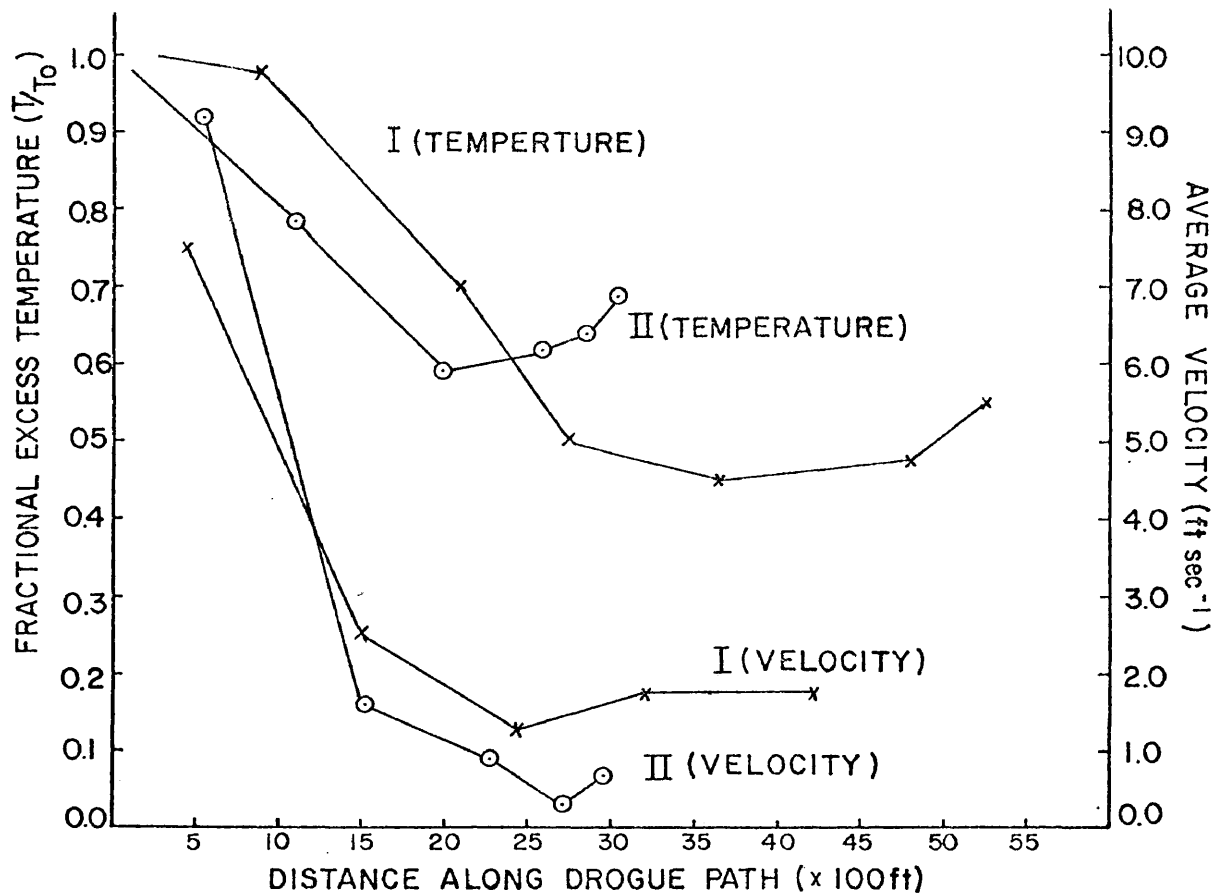


Figure 32. Water temperature and average velocity between stations for drogue releases I and II.

VI. HYDRAULIC MODEL PREDICTIONS

Studies conducted by Carpenter and Pritchard (1967) on the hydraulic model of the James River estuary resulted in predictions of excess temperature distributions which would result from the discharge of waste heat by the Surry Nuclear Power Station. One of the purposes of the present study was to compare these predictions to actual temperature distributions observed in the field in order to determine the reliability of hydraulic modeling as a method of predicting the effects of thermal discharges into an estuary.

The hydraulic model of the James River estuary is located at the U. S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi. The model covers the tidal waterway from Richmond to the mouth and has a horizontal scale of 1:1000, and a vertical scale of 1:100.

Two separate sets of experiments were run on the hydraulic model. In the first set of experiments the model was run for a total of 475 tidal cycles, corresponding to approximately 246 days of prototype time. During this set of experiments the river discharge at Richmond was at a simulated 2000 cfs. In the second set of experiments, river discharge at Richmond was at

6000 cfs and the model was run for a total of 784 tidal cycles, corresponding to about 379 days of prototype time.

During both sets of experiments a model thermal plant, releasing a simulated 12×10^9 BTU-hr⁻¹ of waste heat into the river, was operating at a location corresponding to the Surry Nuclear Power Plant site.

Temperatures in the model were measured using a rapid response thermistor head mounted on a trolley which ran across the model on a 16 foot beam. The beam could be moved to the desired transect and the thermistor sensor run across the model to obtain a plot of temperature versus lateral distance made on a strip chart recorder.

The hydraulic model was designed to reproduce the prototype velocity and salinity distribution. The relative pattern of excess temperature should be the same for model and prototype, however, the model was subject to different heat exchange coefficients than prevailed in the natural environment. It was therefore necessary to adjust the excess temperature distributions observed in the model to take into account the difference in the surface exchange coefficients between the model conditions and prototype conditions.

The correction procedure used by Carpenter and Pritchard was:

$$(A_{\theta})_P / (A_{\theta})_m = 1, \theta \geq 0.5 \theta_o$$

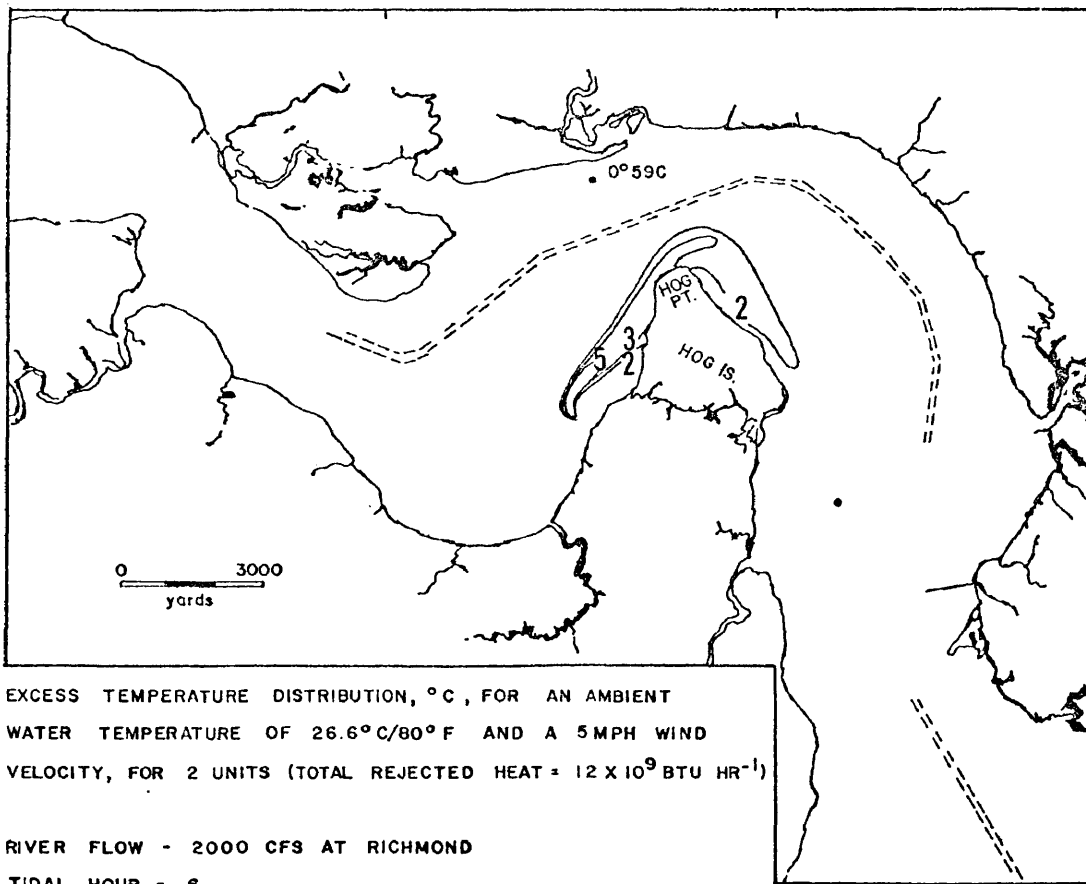
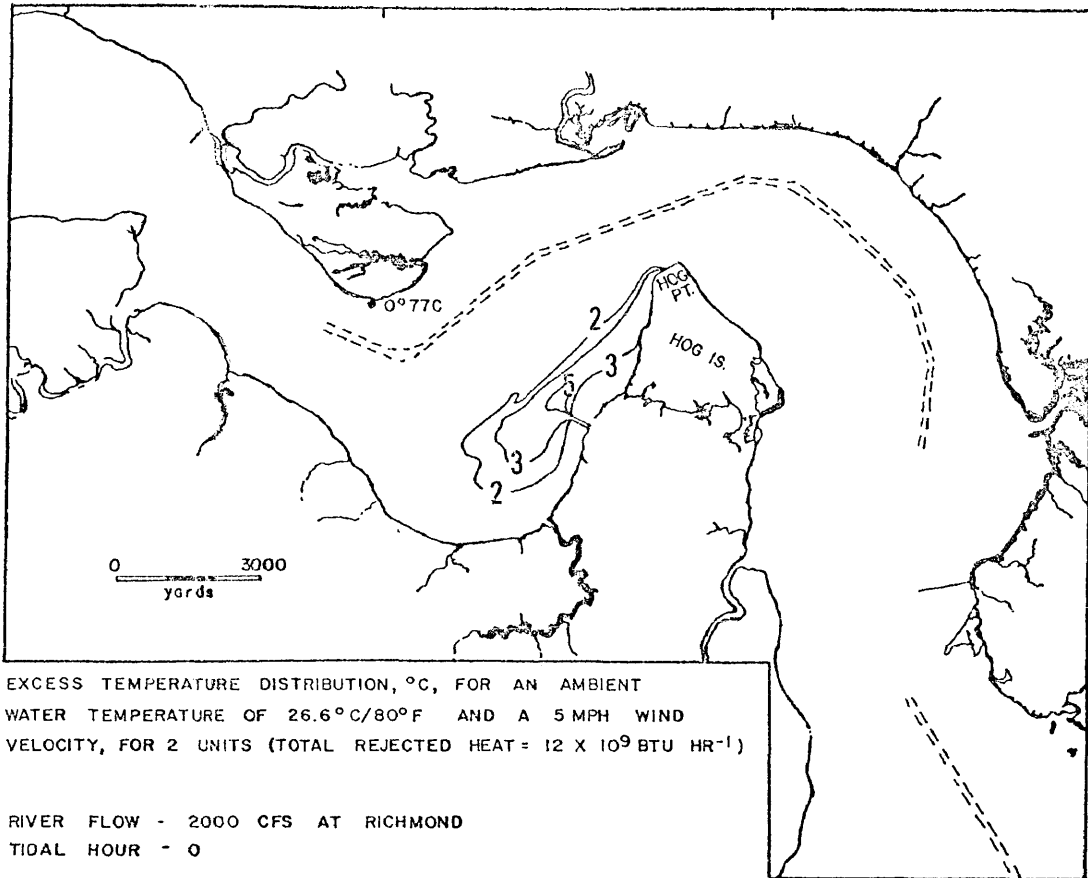
$$(A_{\theta})_P / (A_{\theta})_m = 0.9 \frac{\gamma_m}{\gamma_p}, \theta \leq 0.15 \theta_o$$

where $(A_{\theta})_P$ and $(A_{\theta})_m$ were areas within excess temperature isotherm θ for the prototype and model, respectively, and γ_m and γ_p were the heat exchange coefficients for the model and prototype, respectively. The initial excess temperature at the discharge canal (θ_o) determines the regions in which the two relationships were applied. For $0.15\theta_o < \theta < 0.5\theta_o$, the relationship was assumed to have a linear variation between the two given ratios.

The results of these experiments were presented as a series of excess temperature isothermal plots. Figure 33 shows two of these plots, for high slack water (tidal hour 0), and for slack water (tidal hour 6).

In order to compare prototype data with hydraulic model data, prototype data had to be selected so that heat rejection was as close as possible to the modeled heat rejection. As mentioned previously, hydraulic model tests were run for 2000 and 6000 cfs river discharges at Richmond. This factor should also be taken into account for the comparisons, but it was considered secondary when compared to heat rejection. The prototype data which had the maximum heat rejection also had river discharges

Figure 33. Typical excess temperature isotherms
as predicted by the hydraulic model
(from Carpenter and Pritchard, 1967).



in the range 2000-7000 cfs so that differences between model and prototype due to river discharge differences were minimal. This conclusion is justified since it has been previously shown that river discharge has little direct effect on tidal currents and excess temperature except for during periods of extreme river discharge.

The average values of ambient water temperature, wind speed, and heat rejection for the prototype data selected for comparison with the model were 81.7°F, 6.1 mph, 11.2×10^9 BTU-hr⁻¹ respectively. These values are relatively close to the modeled values of 80°F, 5.0 mph, and 12.0×10^9 BTU-hr⁻¹. For the purposes of this investigation, the effects of the differences between ambient water temperature and wind speed for the model and the prototype are considered negligible when compared to the effects due to the difference in rejected heat.

Areas within each excess temperature isotherm were determined from isothermal plots of the appropriate survey runs in 1973 and 1974 using a compensating polar planimeter. These areas, along with the areas within the excess temperature isotherms presented in the results of Carpenter and Pritchard's report, were plotted and are shown in Figure 34.

The figure indicates that the lower limit of the model data approximately coincides with the upper limit of the prototype data. There are only 4 prototype data

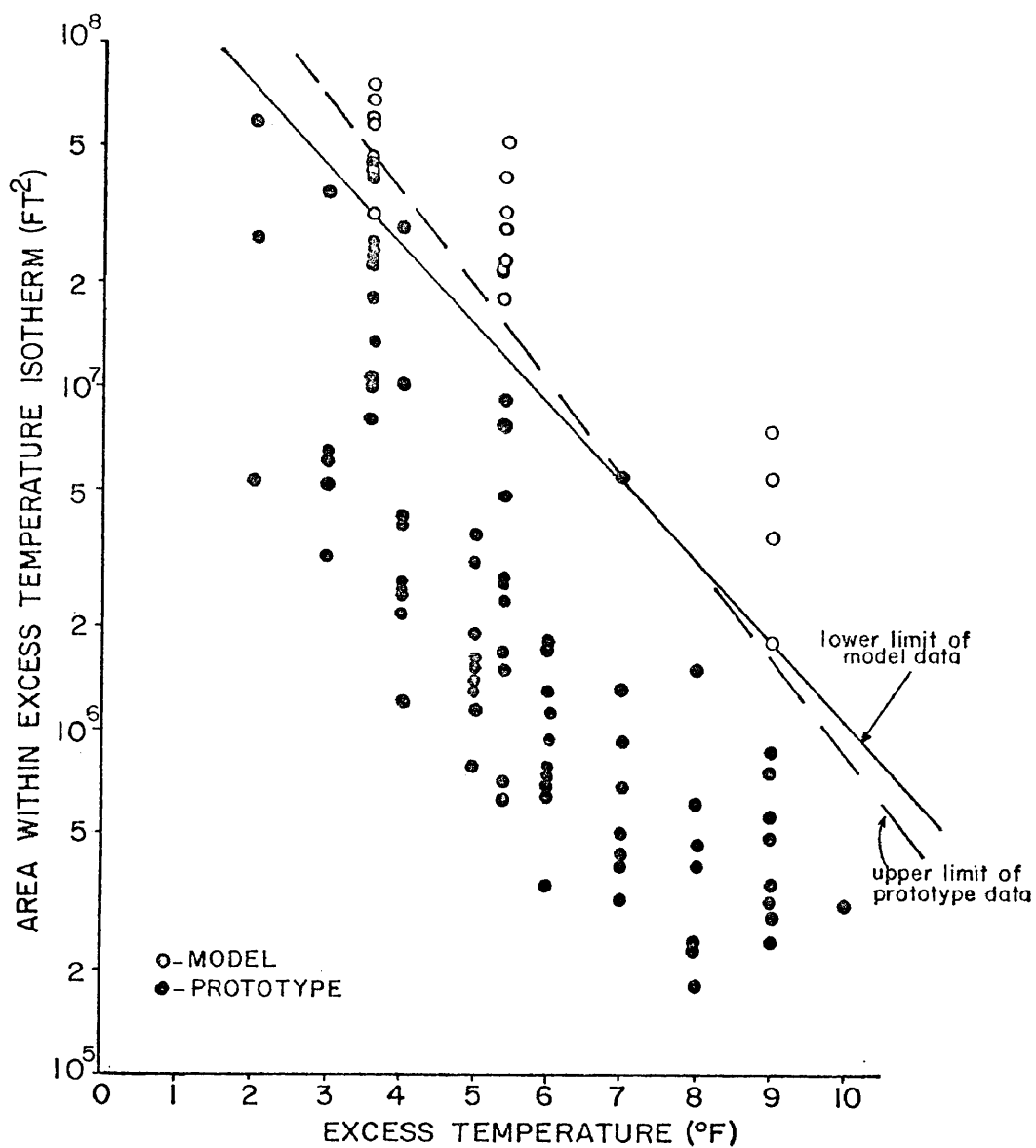


Figure 34. Comparison of areas within a given excess temperature isotherm for the hydraulic model and the prototype.

points which lie above the lower limit of the model data. To determine whether the difference between the model and prototype data was statistically significant, the means and 95 percent confidence intervals of the means were calculated for the area within the 3.6° , 5.4° , and 9.0°F excess temperature isotherms in both model and prototype. These particular isotherms represent the 2° , 3° , and 5°C excess temperature isotherms presented in the hydraulic model experimental results. In the prototype the area within the 3.6° and 5.4°F isotherms was obtained by linear interpolation between the area within next higher and next lower whole degree isotherms.

The means of the area and the 95 percent confidence interval of these means are presented in Figure 35. The fact that the confidence intervals do not overlap for any of the model and prototype data indicates that the differences between the data were significant. The model enclosed areas were significantly greater than the corresponding prototype enclosed areas in all three cases. For the 3.6°F excess temperature isotherm, the model predictions were greater than prototype data by a factor of five, while for the other two isotherms, model predictions were greater than prototype data by an order of magnitude or more.

The prototype data indicate that the excess heat dissipated more rapidly than was predicted by the hydraulic model. The model predictions for the area with

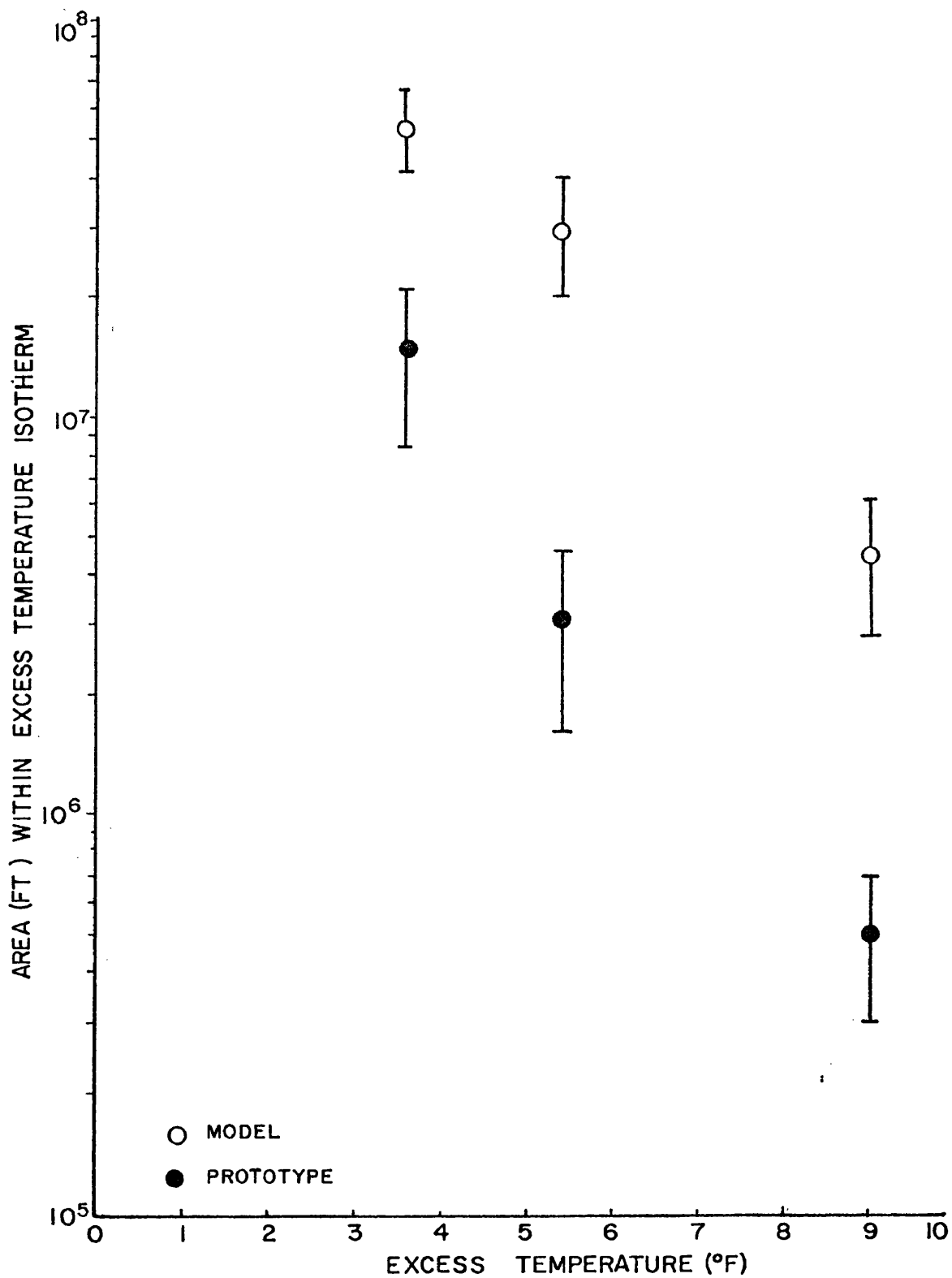


Figure 35. Comparison of mean areas and 95 percent confidence intervals for the hydraulic model and the prototype.

the 3.6°F excess temperature isotherms were more accurate than those for the higher excess temperatures. Qualitatively, the temperature distributions in the field, as a function of tidal cycle, were similar to those predicted by the model.

Lower heat rejection in the prototype was partially responsible for the smaller areas within each excess temperature isotherm. Heat rejection on the days compared with the hydraulic model predictions were from 8-14 percent lower than the modeled heat rejection. If it is assumed that at full plant capacity the areas in the prototype would be 10-20 percent larger, which is probably an over-estimation, the differences between the model predictions and the prototype would still be significant.

Carpenter and Pritchard assumed that in the near field region, which they define as $\theta \geq 0.5\theta_o$, cooling has had little time to act. To reflect this, the correction factor applied to this area, $(A_\theta)_p / (A_\theta)_m$, had a value of unity. With an average value of θ_o of approximately 11.0°F, the field data indicate that for values of $\theta \geq 0.5\theta_o$, the ratio $(A_\theta)_p / (A_\theta)_m$ had a value of approximately 0.1.

For the region removed from the outfall, with values of $\theta \leq 0.15\theta_o$, Carpenter and Pritchard applied the correction factor $(A_\theta)_p / (A_\theta)_m = 0.9 (\gamma_m / \gamma_p)$. The field data indicate that the ratio $(A_\theta)_p / (A_\theta)_m$ had a value of 0.2 for values of $\theta = .33\theta_o$. Since the field data were

compared to the corrected model results, the actual correction factor should have been of the form

$$(A_{\theta})_p / 0.9 \left(\frac{\gamma_m}{\gamma_p}\right) (A_{\theta})_m = 0.2$$

which reduces to

$$(A_{\theta})_p / (A_{\theta})_m = 0.18 \left(\frac{\gamma_m}{\gamma_p}\right)$$

It would appear, then, that a more accurate set of correction factors than those used by Carpenter and Pritchard have the form.

$$(A_{\theta})_p / (A_{\theta})_m = 0.1, \theta \geq 0.50\theta_o$$

$$(A_{\theta})_p / (A_{\theta})_m = 0.18 \left(\frac{\gamma_m}{\gamma_p}\right), \theta \leq 0.33\theta_o$$

with a linear variation for intermediate values of θ .

The inability of the hydraulic model to predict the areas within the higher excess temperature isotherms to the same order of magnitude was most probably due to scale distortion. In a discussion of hydraulic modeling, Silberman and Stefan (1970) indicate that it is necessary to model three regions: near field, the joining region, and far field, in order to completely model a given plume. In the near field region near the outfall, entrainment of ambient fluid is the major process to be modeled. In the joining region, entrainment is still important, but buoyancy, surface cooling, and convection are also

important. Surface cooling, dispersion, and convection are the most significant processes in the far field. The different physical phenomena involved within each region mean that in most situations these regions cannot be combined in one hydraulic model.

Abraham (1965), and Fan and Brooks (1966) stress the importance of entrainment in determining the mixing properties of a jet. Silberman and Stefan (1970) show that entrainment in the near field can only be modeled at an undistorted scale, i.e., it is necessary to maintain geometric ratios and to use two miscible fluids of different densities such that densimetric Froude numbers are the same for the model and the prototype. This type of model cannot include the joining region because of the physical phenomena which become important in that region. The near field and the joining region may be combined by using a more complicated model. The far field model requires a distorted scale due to size limitations. Such a model can correctly model the important processes of surface cooling, advection, and dispersion.

One of the most important considerations when modeling parts of the plume separately, is the placement of the proper boundary condition on the separate models. As an example, in a far field model, the initial thickness and momentum of the plume are determined by the end conditions in the joining region.

Carpenter and Pritchard (1967) have attempted to model all three regions of the thermal plume using a distorted model. The model does not accurately model entrainment in the near field and joining region. Field data indicate that the heat dissipation was higher in the near field than predicted by the model. This indicates that entrainment was lower in the model than in the prototype. The correction factors used by Carpenter and Pritchard did not account for this entrainment in the near field, which resulted in predictions which were factors of five to ten times greater than the observed field conditions. The modified correction factors, derived from field data and model comparisons, can be applied to other sites or to other hydraulic models, provided that the discharge geometries and velocities are similar, and the hydraulic model has the same scale distortion.

VII. SUMMARY AND CONCLUSIONS

The operation of the Surry Nuclear Power Plant during 1973 and 1974 has increased water temperatures over approximately 45 percent of the surface area of the James River shown in Figure 3.

Monthly average surface excess temperatures were generally greater than 0.5°F for all survey transects during May through October in 1973, and from June through September in 1974. The maximum excess temperatures occurred in August of both 1973 and 1974. In August, 1973, the average excess temperatures for the transects had a range of 2.3°F to 4.2°F , while in August, 1974 the range was 0.2°F to 3.7°F . Excess temperatures as high as 12.0°F have been found in the immediate vicinity of the outfall, but excess temperature decreased rapidly as distance from the outfall increased, and temperatures outside a distance of approximately 1000 yards were rarely greater than 5°F above ambient.

The heat rejection of the power plant was the most important factor determining the excess temperature distribution in the survey area. Other factors which were related to the excess temperature were dew point temperature, air temperature, and wind speed.

The salinity during 1973 and 1974 was higher near the outfall than it was for the most downstream sampling station. During 1971 and 1972, the salinity near the outfall was lower than for the most downstream sampling station. The discharge of higher salinity cooling waters drawn in downstream of Hog Point has increased the salinity near the outfall. On several occasions a "sinking" plume was detected in the near field. This phenomena was caused by the higher salinity discharge water.

Isothermal plots of the survey runs and IR imagery of the survey area indicate that the thermal plume tended to stay close to shore and reached, or, in some cases, extended around Hog Point during ebb tides. During the slack tides, both high and low, the plume tended to form a pool directly offshore of the outfall, while on flood tides, the plume headed upstream and away from shore. This movement was primarily a function of the tidal currents in the area.

Comparisons of field data with Carpenter and Pritchard's predictions of excess temperatures made from hydraulic model experiments indicate that their predictions were conservative. Coefficients used by Carpenter and Pritchard to adjust hydraulic model results to environmental heat exchange conditions did not account for entrainment in the near field, which resulted in

predictions that were higher than the observed field temperature distributions.

Conclusions that can be drawn from this investigation are:

- 1) The operation of the Surry Nuclear Power Plant has increased water temperatures in the James River between Hog Point and Cobham Bay on the south side of the channel. The increased water temperatures were found to extend to a depth of at least 6 feet, but did not extend to more than half of the width of the estuary at its narrowest point.
- 2) The increased water temperatures did not represent a serious alteration of the natural environment in the far field. The heated effluent experienced rapid mixing in the near field region around the outfall. The rapid mixing in the outfall area was due to the relatively high discharge velocities and entrainment near the outfall.
- 3) Dissolved oxygen concentration was not adversely affected in the survey region, while salinity was increased in the outfall region.

- 4) The James River hydraulic model, due to its scale distortion, did not properly model entrainment in the near field. The correction coefficients used by Carpenter and Pritchard to adjust the hydraulic model results to expected prototype conditions did not account for entrainment and resulted in predictions of excess temperature that were conservative. Coefficients based on the field results are applicable to similarly distorted hydraulic models of open channel discharges of similar geometry and velocity to the survey discharge.

VIII. DISCUSSION AND RECOMMENDATIONS

The field program that was developed for the thermal monitoring program around the Surry Nuclear Power Plant has provided adequate data to meet its initial objectives. Experience gained through the four years of monitoring can be used as guidance for planning future hydrothermal monitoring programs in estuaries.

Instrumentation

One of the most important considerations in the design of a thermal monitoring program is the choice of instruments. In addition to economics, the primary factors to be considered when choosing instrumentation are:

- 1) reliability in the field;
- 2) instrument characteristics, such as accuracy, precision;
- 3) frequency of calibration;
- 4) ease of data reduction; and
- 5) ease of maintenance and repair.

Instrumentation that is to be used in the field should be specifically designed for field applications. Such instrumentation, in order to be reliable, must be

relatively weather resistant and shock proof, simple to calibrate, and should record the data on magnetic tape cassettes.

Reliability of the data acquisition system (DAS) used for the Surry monitoring program was a major problem during the first three years of operation. The system required constant maintenance. This low level of reliability was a direct result of the complexity of the equipment. The DAS and the tape recorder used in this study were complicated and shock sensitive and were more appropriate to a laboratory environment than to field applications. The DAS had more features than were required and the added complexity led to failures. During 1974 the system was fairly reliable due to extensive design modifications, weather-proofing, and shock mounting.

During field operations it is important to calibrate the instruments frequently. The methods used during the Surry monitoring program proved to be adequate. At the beginning and end of each survey run high and low calibrations of the thermistors were made. The output of each thermistor on the water temperature profiler was also recorded and compared to the output of a well calibrated thermistor. Any discrepancy between the calibrated thermistor and the profiler were accounted for in the data reduction program. Thermistors should be replaced periodically and brought back to the lab for an extensive calibration.

A backup system for an automatic DAS is a necessity. The ability to obtain data in the event of DAS failure can save time and effort in a field program. A suitable backup system would consist of a variable frequency switching circuit and a visual digital display of the output. Output data can be recorded manually and the frequency of the switch adjusted so that the operator can record the data at a constant rate. The switching arrangement for the Surry monitoring system was manual and resulted in uneven spacing of the data.

Experimental Design

Aspects of experimental design such as sampling frequency and the optimal number of runs per month have been mentioned in the chapter concerning the field program. For the Surry survey, sampling periods of 10 seconds in the far field and 3 second in the near field offered the best compromise between detail and amounts of data.

The design survey frequency of two/week during March-May and mid September-November was not achieved, but during the period June-mid-September the optimal sampling frequency of three/week was approached or exceeded. As a result, the summer average values have a high degree of confidence and were used for comparisons of pre-operational and post-operational data.

An important consideration in the design of the monitoring program is the method of positioning. An

effective means of positioning for such a program is the use of a range finder interfaced with the data acquisition system so that distances from two fixed stations on shore are recorded along with the field data. This system can provide accurate positioning for each data set and would allow the survey to follow the plume. A range finder system could also reduce the time required to make a survey because monitoring of water at ambient temperature would be cut to a minimum. With the fixed transect system used in the Surry survey, portions of the plume were sometimes missed because they did not fall within the area covered by the transects.

Ambient temperature for an estuary are difficult to determine due to tidal fluctuations. They should be based on averages of several sets of temperature measurements taken at a distance greater than the tidal excursion upstream and downstream from the discharge, and on the opposite side of the estuary from the discharge. If the temperature measurements can be continuously recorded at the upstream and downstream sites so that during each survey it is not necessary to sample these points, the time required for a single survey could be kept to a minimum.

A drogue experiment such as described in a previous section is a simple means of obtaining plume centerline temperature and velocity decay rates in the

near field region. The position of the drogue can be determined by sextant on the sampling boat, or by transits located at two fixed stations on shore. Experience has shown that drogue movement close to the outfall is rapid and positioning by transits is the most desirable.

The use of a series of drogues deployed across the mouth of the outfall, in conjunction with aerial photographs of the drogue pattern, could be an alternative approach to the single drogue release and could yield some insight on drogue movement with respect to the plume centerline. Investigations of this type should be undertaken because they represent an inexpensive and valuable means of obtaining near field current and temperature data.

Monitoring Systems

A moving boat sampling scheme is essential in order to obtain field data for a thermal plume in an estuary. Fixed stations with continuous recording instrumentation can supply information on vertical temperature profiles, time scales, ambient conditions, and temperature decay rates. The number and location of the fixed stations should be chosen so that the vertical thermal structure of the plume as well as that of the river itself can be monitored. In order to place the fixed stations in the most useful and strategic locations,

they should be installed after the plant has begun operation, or, if hydraulic model results are available, the location of the stations can be selected on the basis of plume movement as predicted by the model.

Prior to the inception of the monitoring program for the Surry Nuclear Power Plant, VEPCO constructed a series of seven towers in the James River to support instrument packages which were to monitor water temperature. The data taken during 1973 and 1974 indicate that Tower 6 and Tower 3 (see Figure 3) were the only towers which were ever affected by the discharge, and that they were affected usually only during ebb or low slack tidal stages. Five of the VEPCO towers were never affected by the effluent. One of these towers, for example, Tower 4, could be used to monitor ambient temperatures, but the remaining four towers are of little use.

The poor choice of siting for the VEPCO towers was apparently due to a lack of understanding of plume characteristics in estuaries and a disregard for the James River hydraulic model results.

Fixed stations should be primarily used to monitor the vertical water temperature profile. Such monitoring should consist of, at the minimum, measurements at the surface, mid-depth, and at the bottom. A more desirable configuration would consist of measurements at the surface, at 3' intervals from the surface to mid-depth,

and at the bottom. The temperature monitoring conducted by VEPCO consists of measurements taken at mid-depth and bottom. Such a monitoring scheme is inadequate because the thermal plume is confined to the upper half of the water column, except in the near field region.

The monitoring of several plant parameters is an obvious necessity for any thermal monitoring program. The required parameters are: intake temperature, discharge temperature, discharge salinity, discharge velocity, and plant loading. All of these parameters, except for plant loading, should be obtained by the monitoring personnel to insure accuracy and consistency of the data. The utility will have to be relied upon to furnish plant loading data.

In the Surry survey, plant loading and intake and discharge temperatures were supplied by VEPCO. The intake and discharge temperatures that were reported were values for noon on the days monitoring runs were made. Although this was the most practical way for VEPCO to report the data, the daily variations of discharge temperatures made it necessary to record the discharge temperature at the time of the monitoring run.

Discharge flow rates were not monitored by VEPCO. The discharge flow rates used in this investigation were estimated using information on the pumping procedures

used by VEPCO. This method is inadequate for certain types of analysis. A current meter and a tide gauge should be set up at the discharge opening if accurate discharge flow rates are to be obtained.

APPENDIX

Figure 36. Temperature distribution on June 22,
1973, low slack.

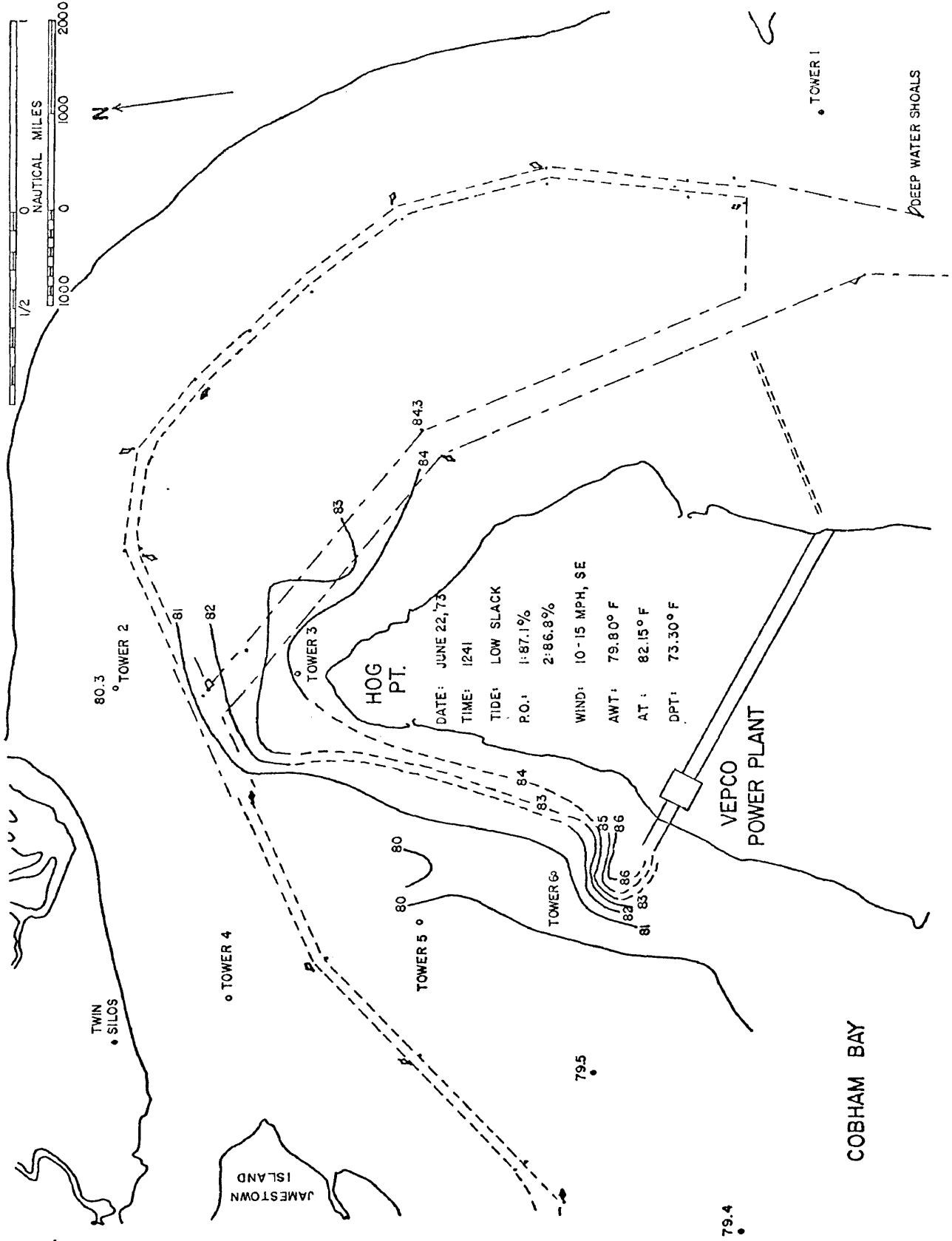


Figure 37. Temperature distribution on August 7,
1973, flooding.

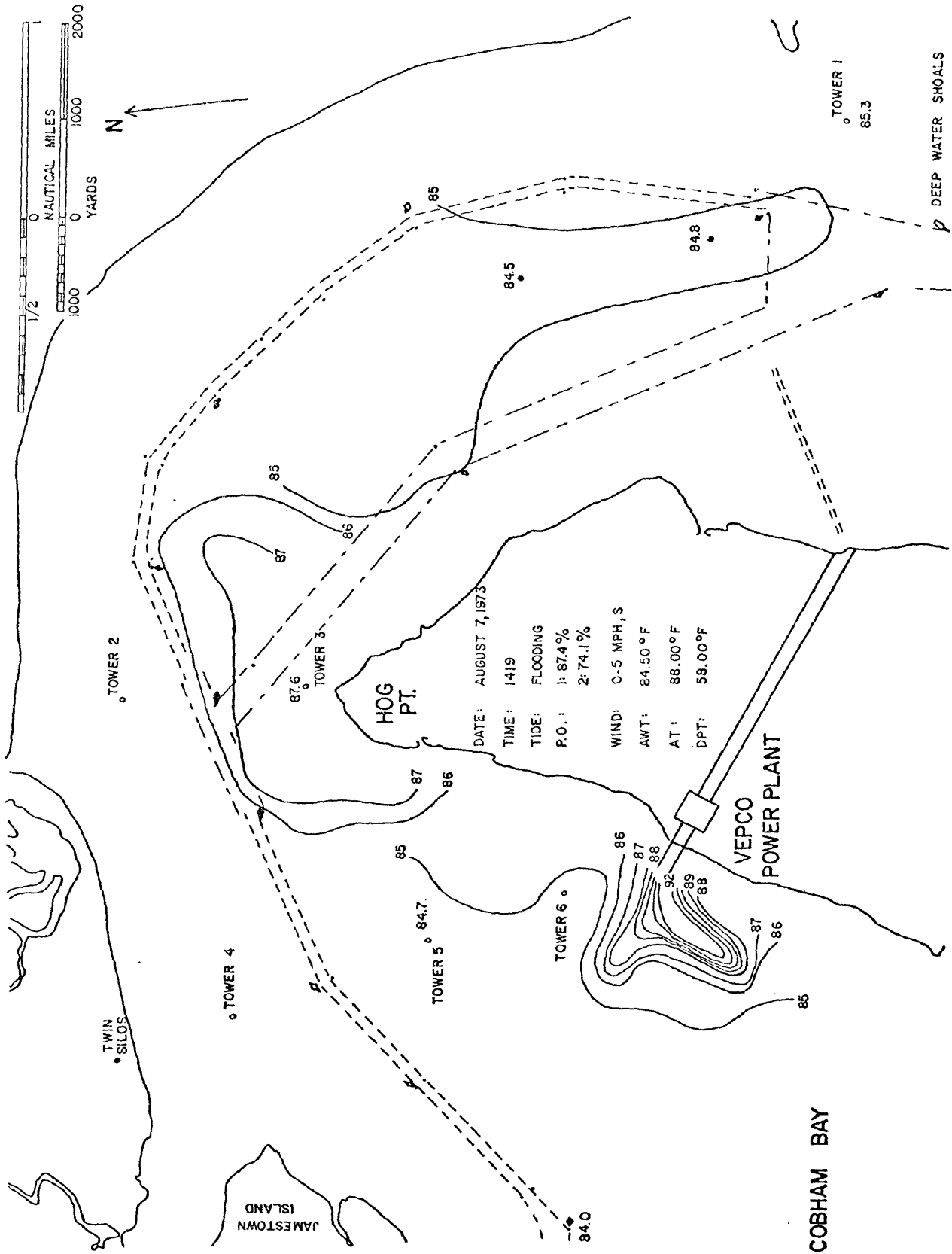


Figure 38. Temperature distribution on September 10,
1973, ebb.

Figure 39. Temperature distribution on June 18,
1974, high slack.

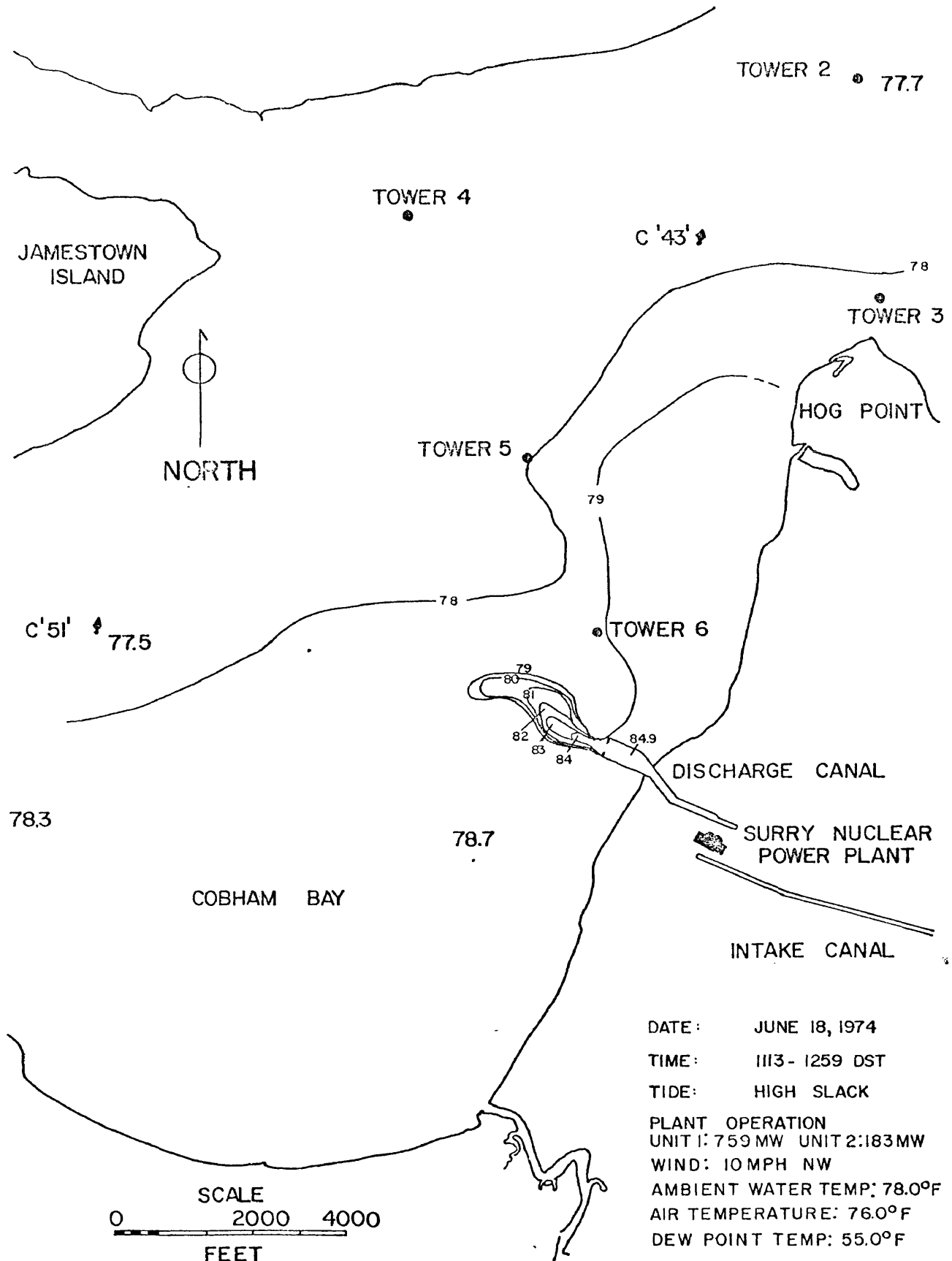
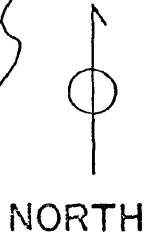


Figure 40. Temperature distribution on July 2, 1974,
high slack.

120.
TOWER 2
76.3

TOWER 4
79.6

JAMESTOWN
ISLAND



C'43'

TOWER 3
77

HOG POINT

TOWER 5

C'51' 78.1

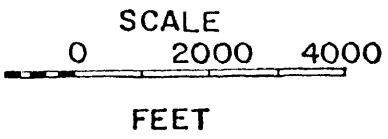
TOWER 6

DISCHARGE CANAL

SURRY NUCLEAR
POWER PLANT

INTAKE CANAL

COBHAM BAY



DATE: JULY 2, 1974
TIME: 1118 - 1254 DST
TIDE: HIGH SLACK
PLANT OPERATION
UNIT 1: 76.6 MW UNIT: 0
WIND: CALM
AMBIENT WATER TEMP: 77.9°F
AIR TEMP: 80.3°F
DEW POINT: 72.0°F

Figure 41. Temperature distribution on July 30, 1974,
low slack.

TOWER 2 81.8

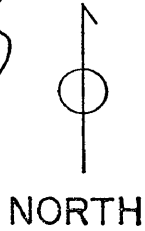
TOWER 4 81.3

C '43'

JAMESTOWN ISLAND

TOWER 3

HOG POINT



TOWER 5

C '51' 81.7

TOWER 6

DISCHARGE CANAL

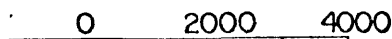
SURRY NUCLEAR POWER PLANT

INTAKE CANAL

COBHAM BAY

DATE: JULY 30, 1974
 TIME: 1022-1208 DST
 TIDE: LOW SLACK
 PLANT OPERATION
 UNIT 1: 741 MW UNIT 2: 750 MW
 WIND: 5-10 MPH
 AMBIENT WATER TEMP: 81.6°F
 AIR TEMPERATURE: 80.7°F
 DEW POINT TEMP: 72.5°F

SCALE



FEET

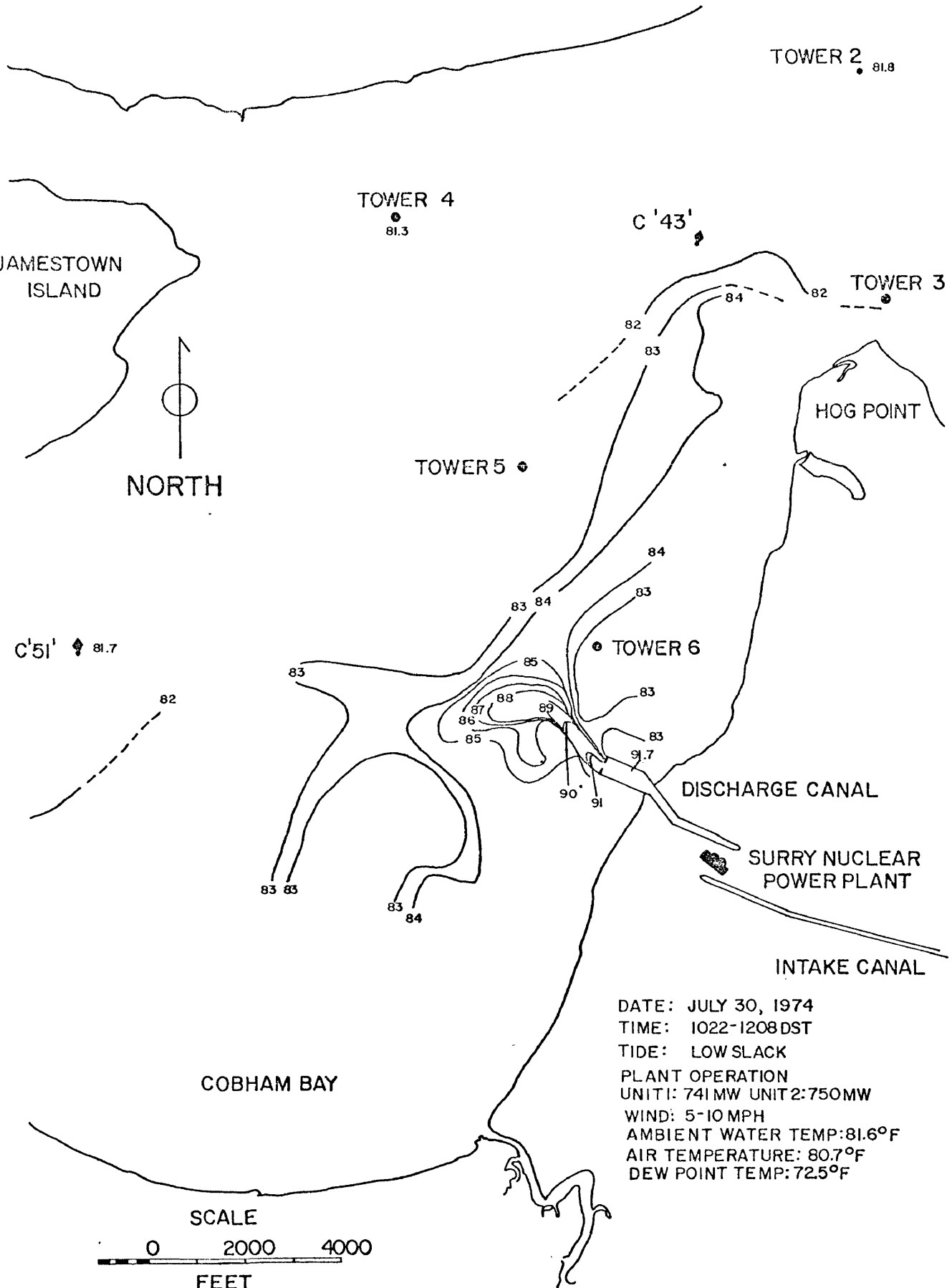


Figure 42. Temperature distribution on August 16,
1974, high slack.

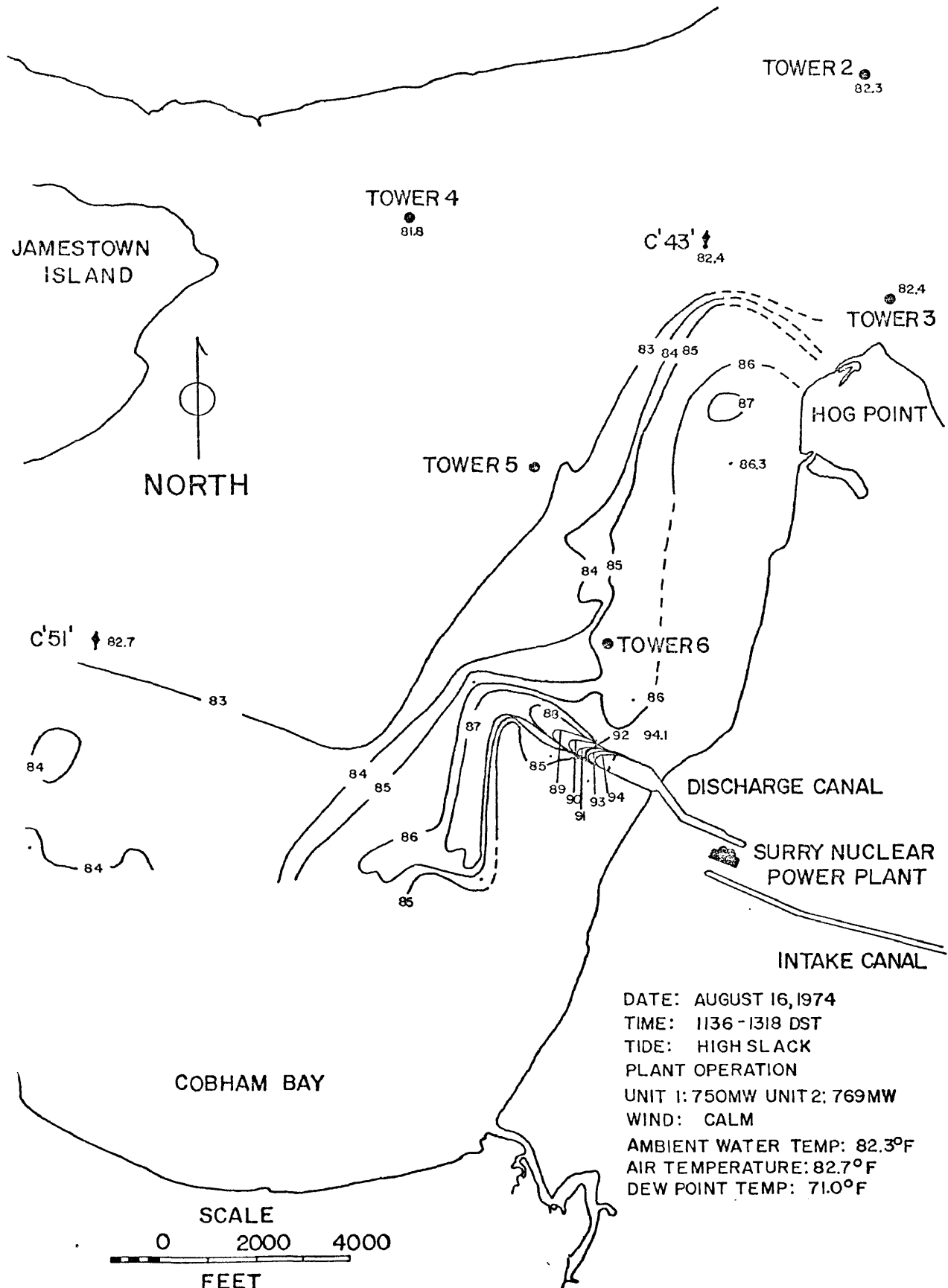


Figure 43. Temperature distribution on September 5,
1974, low slack.

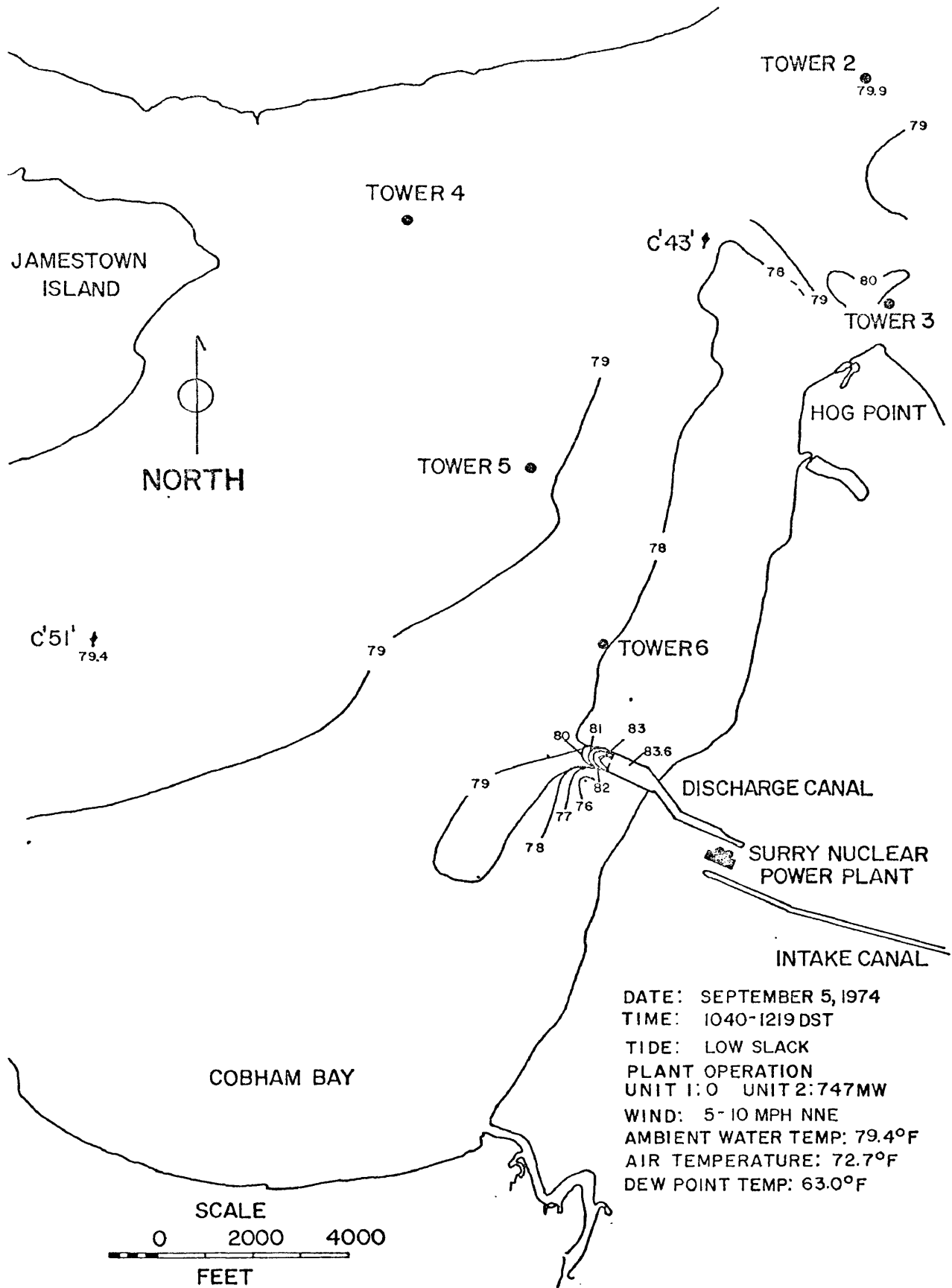
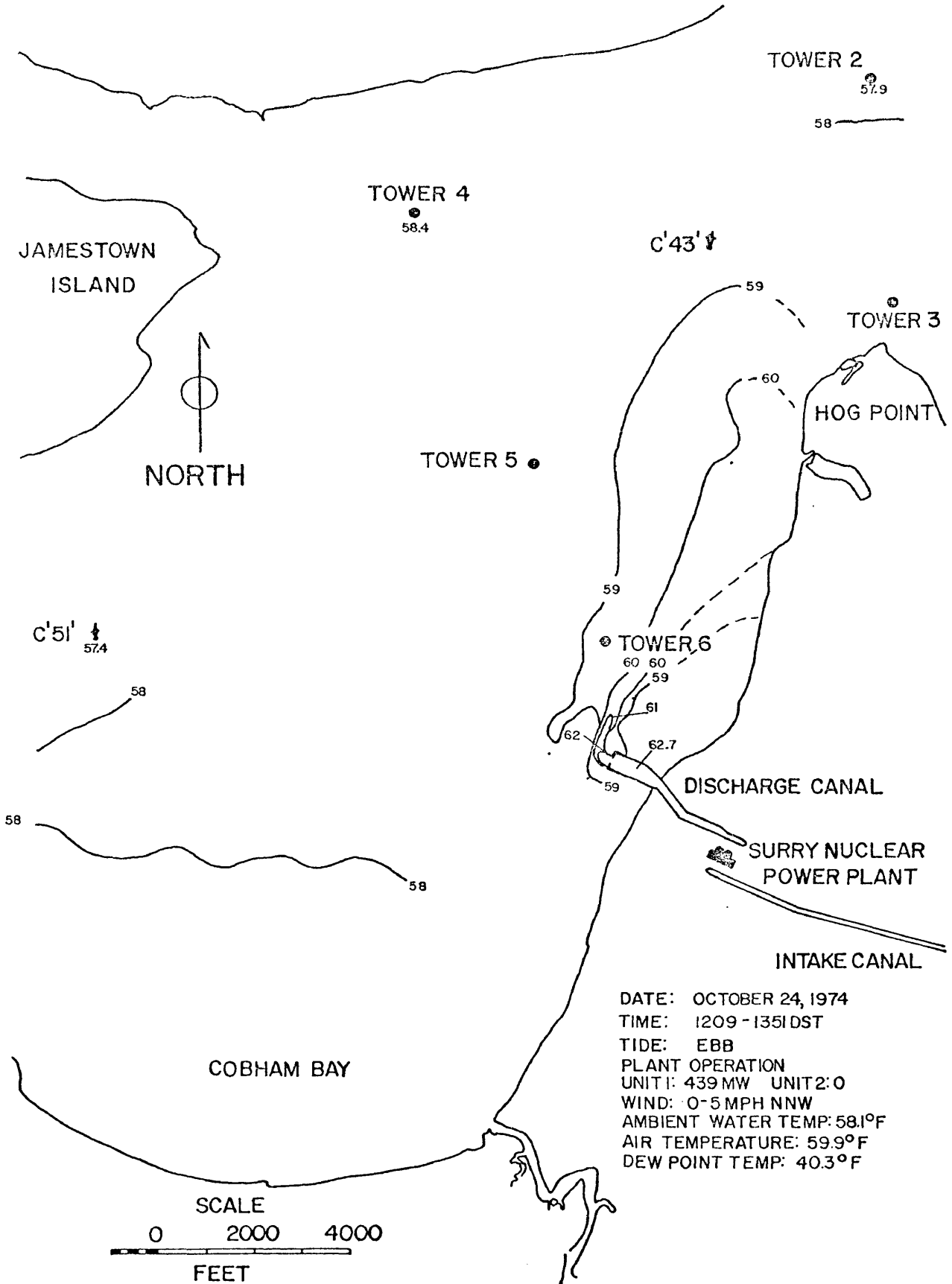


Figure 44. Temperature distribution on October 24,
1974, ebb.



REFERENCES CITED

- Abraham, G. 1965. Horizontal Jets in Stagnant Fluid of other Density. Proc. ASCE. 91:HY4. 139-154.
- Asbury, J. G. 1970. Effects of Thermal Discharges on the Mass/Energy Balance of Lake Michigan. Argonne Nat. Lab. Special Rep. ANL/ES-1. 24p.
- Asbury, J. G. and A. A. Frigo. 1971. A Phenomenological Relationship for Predicting the Surface Areas of Thermal Plumes in Lakes. Argonne Nat. Lab. Special Rep. ANL/ES-5. 20p.
- Bender, M., R. Jordan, M. Ho, and M. Cavell. 1974. Progress Report to Virginia Electric and Power Company. Ecological Survey - Upper James River Surry Nuclear Power Station Site. VIMS. 30p.
- Bolus, R. L., S. N. Chia, and C. S. Fang. 1971. The Design of the Monitoring System for the Thermal Effect Study of the Surry Nuclear Power Plant on the James River. Va. Inst. of Mar. Sci. SRAMSOE No. 16. 71p.
- Chia, S. N., C. S. Fang, R. L. Bolus, and W. J. Hargis, Jr. 1972. Thermal Effects of the Surry Nuclear Power Plant on the James River, Virginia. Part II. Results of Monitoring Physical Parameters of the Environment Prior to Plant Operation. Va. Inst. of Mar. Sci. SRAMSOE No. 21. 343p.

- Edinger, J. E. 1971. Estuarine Temperature Distributions. Estuarine Modeling, an assessment. Tracor, Inc. Austin, Texas. 174-207.
- Edinger, J. E., and J. C. Geyer. 1965. Heat Exchange in the Environment. Johns Hopkins University, Baltimore, Md. 259pp.
- Edinger, J. E., and J. C. Geyer. 1968. Analyzing Stream Electric Power Plant Discharges. Proc. ASCE 94:SA4. 611-623.
- Fan, L. N., and N. H. Brooks. 1966. Discussion of Horizontal Jets in Stagnant Fluid of Other Density. Proc. ASCE 92:HY2. 423-429.
- Fang, C. S., A. Y. Kuo, P. V. Hyer, and W. J. Hargis, Jr. 1973. Hydrography and Hydrodynamics of Virginia Estuaries. Part IV. Mathematical Model Studies of Water Quality in the James Estuary. Va. Inst. of Mar. Sci. Special Rep. 41. 295p.
- Frigo, A. A., D. E. Frye, and P. Siebold. 1973. Temperature and Velocity Measurements in the Near Field Region of Thermal Plumes. Argonne Nat. Lab. 26p.
- Frigo, A. A., D. E. Frye, and J. V. Tokar. 1974. Field Investigations of Heated Discharges from Nuclear Power Plants on Lake Michigan: 1972. Argonne Nat. Lab. ANL/ES-32. 24lp.
- Frye, D., A. A. Frigo, and B. Hoglund. 1973. Data Collection and Reduction Techniques Used for Investigation of Thermal Discharges. Argonne Nat. Lab. 17p.

- Hoglund, B., and S. A. Spigarelli. 1972. Studies of the Sinking Plume Phenomena. Proc. 15th Conf. of International Assoc. of Great Lakes Res., Madison, Wisconsin. 22p.
- Koh, R. C. Y., and L. N. Fang. 1970. Mathematical Models for the Prediction of Temperature Distributions Resulting from the Discharge of Heated Water into Large Bodies of Water. Tetra Tech. for W.Q.O. E.P.A. 220p.
- Orth, R. C., H. H. Carter, and M. T. Miyasaki. 1974. A Field Measurement Program to Determine Far Field Plume Dilution Parameters. Proc. Thermal Pollution Analysis Conf. VPI. 70-82.
- Paddock, R. A., A. J. Policastro, A. A. Frigo, D. E. Frye, and J. V. Tokar. 1973. Temperature and Velocity Measurements and Predictive Model Comparisons in the Near Field Region of Surface Thermal Discharges. Argonne Nat. Lab. Rep. ANL/ES-25 170p.
- Parker, G. C., E. A. Shearls, and C. S. Fang. 1974. Thermal Effects of the Surry Nuclear Power Plant on the James River, Virginia. Part IV. Results of Monitoring Physical Parameters During the First Year of Plant Operation. Va. Inst. of Mar. Sci. Special Rep. 51. 464p.

- Policastro, A. J., and J. V. Tokar. 1972. Heated Effluent Dispersion in Large Lakes: State of the Art in Analytical Modeling. Argonne Nat. Lab. Rep. ANL/ES-11. 374p.
- Pritchard-Carpenter, Consultants. 1966. Hydrology of the James River Estuary with Emphasis Upon the Ten-Mile Segment Centered on Hog Point, Va. A Report Prepared for VEPCO, Richmond, Va. 25p.
- Pritchard-Carpenter, Consultants. 1967. Temperature Distribution in the James River Estuary which will Result from the Discharge of Waste Heat from the Surry Nuclear Power Station. A Report Prepared for VEPCo, Richmond, Va. 79p.
- Pritchard, D. W., and H. H. Carter. 1965. On the Prediction of the Distribution of Excess Temperature from a Heated Discharge in an Estuary. Ches. Bay Inst. Tech. Rep. 33. 45p.
- Pritchard, D. W. and R. E. Kent. 1953. The Reduction and Analysis of Data from the James River Operation Oyster Spat. Ches. Bay Inst. Tech. Rep. VI.
- Rouse, H. 1957. Diffusion in the Lee of a Two-Dimensional Jet. Proc. 9th International Congress of Applied Mechanics. (Brussels, 1956). 1: 9p.
- Scarpace, F. L., T. Green III. 1972. The Use of a Thermal Line Scanner in the Remote Sensing of Water Pollution. U. of Wisconsin Sea Grant Program. Tech. Rep. 13, 15p.

- Shidler, J. K., and W. G. MacIntyre. 1967. Hydrographic Data Collection for "Operation James River-1964". Va. Inst. Mar. Sci. Data Rep. 5. 455p.
- Silberman, E., and H. Stefan. 1970. Physical (hydraulic) Modeling of Heat Dispersion in Large Lakes: A Review of the State of the Art. Argonne Nat. Lab. Special Rep. ANL/ES-2. 112p.
- Sundaram, T. R., C. C. Easterbrood, K. R. Piech, and G. Rudinger. 1969. An Investigation of the Physical Effects of the Thermal Discharges into Cayuga Lake (analytical study). Cornell Aeronautical Lab., Inc., Buffalo. 306p.
- Tokar, J. V. 1971. Thermal Plumes in Lakes: Compilations of Field Experience. Argonne Nat. Lab. Rep. ANL/ES-3. 169p.
- VEPCO. 1973. Semi-Annual Operations Report, Surry Units 1 and 2. Jan. 1 - June 30, 1973. Docket No. 50-280/50-281. Vol. 2.
- VEPCO. 1973. Semi-Annual Operations Report, Surry Units 1 and 2. July 1 - Dec. 31, 1973. Docket No. 50-280/50-281. Vol. 2.
- VEPCO. 1974. Semi-Annual Operation Report, Surry Units 1 and 2. Jan. 1 - June 30, 1974. Docket No. 50-280/50-281. Vol. 2.

Warinner, J. E., and M. L. Brehmer. 1966. The Effects of Thermal Effluents on Marine Organisms. Air and Wat. Pollut. Int. J. Vol. 10, pp. 277-289.

Young, G. K., M. T. Tseng, and R. S. Taylor. 1971. Estuary Water Temperature Sensitivity to Meteorologic Conditions. Water Resources Res. 7:5. pp. 1173-1181.

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