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**A Critical Evaluation of the
Nonradiological Environmental
Technical Specifications**

Vol. 2: Surry Power Plant Units 1 and 2

S. M. Adams
P. A. Cunningham
D. D. Gray
K. D. Kumar

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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ENERGY DIVISION

A CRITICAL EVALUATION OF THE NONRADIOLOGICAL
ENVIRONMENTAL TECHNICAL SPECIFICATIONS

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
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for the
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

FOREWORD

Under the sponsorship of the Office of Regulatory Research of the U.S. Nuclear Regulatory Commission, Argonne National Laboratory, Batelle Northwest Laboratory, and Oak Ridge National Laboratory have collaborated in conducting a one-year study on the evaluation of the nonradiological environmental monitoring programs and Technical Specifications requirements at various operating nuclear power plants. As a result of this work, a series of reports is being prepared by the three laboratories. The titles of these reports are given below.

Argonne National Laboratory

The following reports were prepared by Argonne National Laboratory scientists:

<u>Report Title</u>	<u>Report Number</u>
An Evaluation of Environmental Data Relating to the Kewaunee Nuclear Power Plant Site	ANL/EIS-1
An Evaluation of Environmental Data Relating to the Quad Cities Nuclear Power Station	ANL/EIS-2
An Evaluation of Environmental Data Relating to the Duane Arnold Energy Center	ANL/EIS-3
An Evaluation of Environmental Data Relating to the Three Mile Island Site	ANL/EIS-4
An Evaluation of Environmental Data Relating to the Zion Nuclear Power Plant	ANL/EIS-5
An Evaluation of Environmental Data Relating to the Prairie Island Site	ANL/EIS-6
An Evaluation of Environmental Data Relating to the Nine Mile Point - 1	ANL/EIS-7
An Evaluation of Environmental Data Conclusions and Recommendations for Nonradiological Environmental Monitoring	ANL/EIS-8

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Batelle Northwest Laboratory

The following reports were prepared by Batelle Northwest Laboratory scientists:

<u>Report Title</u>	<u>Report Number</u>
Evaluation of Monticello Nuclear Power Plant Environmental Impact Prediction, Based on Monitoring Program	BNWL-1250
Evaluation of Haddam Neck (Connecticut Yankee) Nuclear Power Plant Environmental Impact Prediction, Based on Monitoring Program	BNWL-1251
Evaluation of Millstone Nuclear Power Plant, Unit 1, Environmental Impact Prediction, Based on Monitoring Program	BNWL-1252
Evaluation of Three Nuclear Power Plants, Environmental Prediction, Based on Monitoring Program. A Summary Report	BNWL-1253

Oak Ridge National Laboratory

The following reports were prepared by Oak Ridge National Laboratory scientists:

<u>Report Title</u>	<u>Report Number</u>
A Critical Evaluation of the Nonradiological Environmental Technical Specifications: Conclusions and Recommendations	ORNL/NUREG/TM-69
A Critical Evaluation of the Nonradiological Environmental Technical Specifications: Surry Power Plant Units 1 and 2	ORNL/NUREG/TM-70
A Critical Evaluation of the Nonradiological Environmental Technical Specifications: Peach Bottom Atomic Power Station Units 2 and 3	ORNL/NUREG/TM-71
A Critical Evaluation of the Nonradiological Environmental Technical Specifications: San Onofre Nuclear Generating Station Unit 1	ORNL/NUREG/TM-72

ABSTRACT

A comprehensive study of the data collected as part of the environmental Technical Specifications program for Units 1 and 2 of the Surry Nuclear Power Plant was carried out for the Office of Regulatory Research of the U.S. Nuclear Regulatory Commission. The program included an analysis of the hydrothermal and ecological monitoring data collected from 1973 through 1975.

The hydrothermal analysis includes a discussion of models used in plume predictions prior to plant operation and an evaluation of the present hydrothermal monitoring program. The two primary methods used for temperature monitoring employ a fixed thermographs network and boat measurements. Review of data indicates that both the application and formulation of the hydrothermal monitoring program are inadequate to fully characterize the operation of the plant and the behavior of the thermal plume. Furthermore, there are no existing data that can be used to adequately verify or disprove the validity of the various Surry plume predictions.

The ecological analysis includes validation of impacts predicted in the Final Environmental Statement using the operational monitoring data. Phytoplankton cell concentrations, chlorophyll *a*, and carbon-14 measurements were used to monitor changes in the primary producers. Densities of consumers (i.e., zooplankton, benthos, and fish) were used to monitor changes in the primary producers. Models based on operating data were constructed to determine whether changes were occurring at each trophic level. Analysis of the monitoring data suggests that the thermal discharges at Surry are having a negative effect on the phytoplankton and zooplankton but are enhancing the benthic and nekton populations in the discharge area.

Specific recommendations are made for improving both the present hydrothermal and ecological monitoring programs. Hydrothermal monitoring would be improved by more complete reporting of inplant operating parameters. In addition, the present monthly boat surveys should be discontinued and monitoring effort should be redirected toward expanding the present

thermograph network to more completely characterize the thermal plume, particularly during its sinking phase. Ecological monitoring programs could be improved by increasing sampling frequency for specific trophic groups, by standardizing collection techniques, by using consistent reporting formats, and by performing statistical analysis of the data and presenting it in an annual analysis report. In light of observed changes in the various trophic groups in the discharge area, the present ecological monitoring program should be continued. Additional data need to be collected during periods when both units are operating at full capacity. In this manner, an assessment of the potential ecological impact of the Surry facility can be made under conditions of maximum plant-induced perturbations.

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I. PLANT DESIGN AND CHARACTERISTICS

Surry Power Station is owned and operated by Virginia Electric and Power Company (Vepco). The architect-engineer for Units 1 and 2 was Stone and Webster Engineering Corporation. Construction has not begun on Units 3 and 4. Units 1 and 2 are essentially identical and share common intake and discharge facilities. Each consists of a Westinghouse pressurized-water reactor (PWR) with a rated core thermal power of 2441 MW(t) and a design core thermal power of 2546 MW(t). Each unit has a rated net electrical output of 778 MW(e), a maximum dependable capacity of 788 MW(e) net, and a design net electrical output of 820 MW(e). Therefore, the total heat rejected to the environment by both units is 3306 MW(t) at rated conditions and 3452 MW(t) at design conditions.

This heat is rejected by once-through cooling. As shown in Fig. 2.1, cooling water enters from the James River through a shoreline intake structure on the downstream side of Hog Point, flows through an open canal to a high-level intake structure, passes through the condensers into a discharge canal, and re-enters the James River on the upstream side of Hog Point.

An intake channel 5000 ft long, 150 ft wide, and 13 ft deep has been dredged into the river bottom in front of the shoreline intake structure. This structure contains eight 468-cfs capacity pumps, and each pump is protected by trash racks with 3.5-in. open spaces. The velocity through these spaces is about 1 fps. The structure was originally equipped with an air bubbler to prevent fish entrainment, but this system was replaced

Fig. 2.1. Surry - Site plan of Surry Power Station.

Source: Directorate of Licensing, U.S. Atomic Energy Commission, *Final Environmental Statement - Surry Power Station Unit 2*, Docket No. 50-281, June 1972.

by Ristolph traveling screens in May 1974. The continuously moving screens have openings that are 3/8-in. square, and the maximum velocity through them is 1.6 fps. Impinged fish are washed by gentle sprays into baskets attached to each section of screen. As the section reaches the highest point of its travel, the fish are dumped into a sluiceway and are returned to the river at a shoreline site near the intake. After passing through the intake pumps, the water flows 1.7 miles through a concrete-lined trapezoidal open channel to the high-level intake structures. These structures, one for each unit, are protected by 3.5-in. open space trash

racks and conventional traveling screens with 3/8-in. square openings. Water flows by gravity through the condensers and into the discharge canal.

The discharge canal ranges in width from 200 ft to 400 ft and has an overall length of about 2900 ft. The 1800-ft section of the canal extending from the power station to the river shoreline is lined with concrete, while the 1100-ft section extending into the river is lined with and enclosed by limestone rocks. The velocity of the water flowing through the discharge canal is approximately 2.2 fps, but the terminal discharge velocity can be maintained at 6 fps by a velocity control structure at the end of the discharge canal. This control structure, consisting of a timber trestle containing five 10-ft-wide bays in which timber gates may be placed, extends about halfway across the opening of the discharge canal. When circulating water flow is reduced, the gates can be installed to reduce the area available for water flow in order to maintain the desired discharge velocity. The time required for water to travel from the shoreline intake structure to the exit of the discharge canal is approximately 61 min, of which the residence time from the inlet of the condensers to the exit of the discharge canal is about 28 min.

When all eight intake pumps are operating, the total flow is 3742 cfs and the temperature rise across the condensers is 13.4°F at rated power and 14.0°F at design power. If only seven pumps are operating, these temperature increases become 15.4 and 16.0°F respectively. Because of the six-river-mile separation of the intake and discharge and the long intake

and discharge canals, the condenser temperature rise cannot be directly related to the excess temperature of the effluent with respect to the local ambient water temperature.

Additional information about the Surry Power Station can be found in the Final Environmental Statement (FES) for Unit 2¹ and for Units 3 and 4.²

II. PLANT SITE CHARACTERISTICS

A. HYDROLOGY³

The Surry Power Plant is located on the James River in Virginia, about 30 miles above Chesapeake Bay and 55 miles below Richmond (as shown in Fig. 2.2). The northernmost tip of the peninsula is known as Hog Point. The intake is on the eastern side of the peninsula opposite Deep Water Shoals, and the discharge is on the western or upstream side of the peninsula in a region known as Cobham Bay.

ORNL DWG 76-12395

Fig. 2.2. Surry - James River Basin, Coastal Plains Section.
 Source: Directorate of Licensing, U.S. Atomic Energy Commission,
Final Environmental Statement - Surry Power Station Unit 2, Docket
 No. 50-281, June 1972.

The James River as far inland as Richmond is subject to a semidiurnal tide of period 12.4 hr. The mean tidal range at Hog Point is 2.1 ft, and the mean spring tidal range is 2.5 ft. Figure 2.3 shows the bottom contours referenced to mean low water (MLW). Depths are seen to vary from about 6 ft at the outfall to more than 30 ft near the shipping channel. Wave heights range from dead calm to about 3 ft and depend on wind speed, wind direction, and tidal phase.*

Under normal conditions, the back and forth tidal current is the largest component of flow at Hog Point. The typical flow in a half tidal cycle is 190,000 cfs, but during spring tides this value may reach 270,000 cfs. This tidal motion has two additional flows superimposed: (1) the net freshwater discharge from the watershed and (2) the estuarine flow induced by salinity differences.

There is no gaging station at Hog Point, but freshwater flows there can be estimated by correcting the observations made at the Richmond gaging station for the additional drainage that occurs in the intervening reach. On the basis of records from 1935 to 1976, the daily average freshwater flow at Hog Point has been as low as 680 cfs, while the maximum instantaneous flow was 420,000 cfs after Hurricane Agnes in 1972.² Because the time of travel for a flow from Richmond to Hog Point depends on the flow rate and is about 20 days for a 14,000 cfs freshwater flow, it is more meaningful to discuss monthly average freshwater flows. Figure 2.4 is a flow duration curve for Hog Point based on data collected from 1935 through 1965. The minimum monthly average freshwater flow is 857 cfs,

Fig. 2.3. Surry - The bottom topography of the James River in the vicinity of Hog Point. Source: Directorate of Licensing, U.S. Atomic Energy Commission, *Final Environmental Statement - Surry Power Station Unit 2*, Docket No. 50-281, June 1972.

Fig. 2.4. Surry - Estimated monthly mean freshwater flow duration curve at Hog Point.

while the maximum is 39,778 cfs. The median monthly flow is 7860 cfs, about twice the design flow rate of the Surry Power Plant Units 1 and 2. This upstream flow due to the plant exceeds the freshwater discharge at Hog Point about 19% of the time. Figure 2.5 shows the monthly average freshwater flows at Richmond for 1971 and 1972, the two years prior to plant operation. Monthly average freshwater discharges at Richmond for 1973, 1974, and 1975 are shown in Fig. 2.6. The multiplicative correction factor for the added watershed between Richmond and Hog Point is 1.41.

Estuarine flow in the James River is caused by the intrusion of denser, more saline water from Chesapeake Bay along the river bottom, inducing an outflow of less saline water in the surface layer. There is a tendency for the surface layer to be deeper on the right side of the estuary when looking seaward, due to Coriolis effects. The difference between these flows at any cross section must equal the freshwater discharge, but the flow in any layer can greatly exceed this value. Salinity decreases with upstream distance and increases with depth. The limit of the salinity intrusion ("salt wedge") moves upstream as the freshwater discharge decreases. At a freshwater discharge of 7500 cfs, the limit of measurable salt concentration is upstream of Jamestown Island, the salinity is about 0.5 ppt in Cobham Bay, 2 ppt at Hog Point, and about 3.5 ppt at Deep Water Shoals. At a freshwater discharge of 10,000 cfs, the upstream limit of detectable salinity is at Hog Point and the salinity at Deep Water Shoals is about 1 ppt. The upper boundary of the estuary moves downstream of Deep Water Shoals at freshwater discharges of about 14,000 cfs. Referring

Fig. 2.5. Surry - Monthly average freshwater flow at Richmond, 1971 and 1972.

DRS: DWG 7b-12319

Fig. 2.6. Surry Monthly average freshwater flow at Richmond, 1973 through 1975.

to Fig. 2.4, measurable salinities occur naturally near the intake about 75% of the time and near the outfall more than 50% of the time.

In June 1950, measurements at Deep Water Shoals showed a net seaward flow in the surface layer of 18,000 cfs and a deep counterflow of 12,000 cfs, the difference being the 6000 cfs freshwater discharge. The net flow in the surface layer was thus three times the freshwater discharge. Because the strength of the estuarine circulation at a given location increases as the freshwater discharge decreases, a relatively constant flushing rate is maintained. The half-tidal cycle flow at the time of the above measurements was 130,000 cfs. The surface salinity was 4.2 ppt, and the bottom salinity was 6.1 ppt.

The superposition of tidal, freshwater, and estuarine circulations results in a distorted tidal flow in which the average near-surface ebb current exceeds the flood current (2.2 to 1.9 fps) and the time of ebb exceeds the time of flood (7 hr 5 min to 5 hr 20 min) at mean freshwater discharge. The upstream tidal excursion is about 4 miles and the downstream excursion is about 6 miles. In the estuarine regime, the strength and duration of ebb flow decreases with depth, while the strength and duration of the flood phase increases with depth. The times of slack water are not coincident with the times of maximum and minimum water level.

Water temperature measurements made near Hog Point between 1942 and 1965 had a maximum value of 92.8°F (33.8°C) and a minimum value of 35.2°F (1.8°C). Moderate to heavy ice has been known to occur in the region,

usually in January or early February.⁷ Turbidity has been observed to range from 15 to 20 Jackson Candle Units.⁴

B. METEOROLOGY²

Data from Richmond and Norfolk (50 miles NW and 35 miles SE of the site respectively) can be used to characterize the local meteorology of the Surry site. Richmond data exhibit more continental characteristics, and Norfolk data are characteristically more marine. Mean monthly temperatures at Richmond range from 39°F in January to 78°F in July, while mean monthly temperatures at Norfolk range from 41°F in January to 79°F in July. Record minimum temperatures have been -12°F at Richmond (January 1940) and 2°F at Norfolk (February 1895); record maximum temperatures have been 107°F at Richmond (August 1918) and 105°F at Norfolk (August 1918). Temperatures of 90°F and above can be expected about 43 days/year at Richmond and 31 days/year at Norfolk. Temperatures of 32°F or below can be expected about 92 days/year at Richmond and only 62 days/year at Norfolk.

Annual average precipitation in the area is between 44 and 45 in., with the maximum monthly means occurring in June and July when between 5.5 and 6.0 in. can be expected. The maximum monthly precipitation recorded at Richmond was about 19 in. (July 1945). Snowfall varies greatly in the region, with Richmond expecting an annual snowfall of 14.7 in. and Norfolk expecting 7.4 in. annually. The maximum 24-hr snowfall reported at Richmond was 21.6 in. (January 1940), while Norfolk has reported 17.7 in. in a 24-hr period (December 1892).

Wind data from the Surry site for the 150-ft level, representing the period 1968 to 1969, indicate predominant wind directions from the NW (9%) and from the SW (8.2%). South-southeasterly winds occurred least frequently at just under 4%. The prevailing wind direction at Richmond is S, and at Norfolk the prevailing wind direction is SW. Mean wind speeds are 7.6 mph and 10.5 mph at Richmond and Norfolk respectively.

III. OPERATING HISTORY

Construction permits for Surry Power Plant Units 1 and 2 were issued in June 1968. Unit 1 achieved initial criticality in July 1972 and began commercial operation in December 1972.⁵ Unit 2 reached initial criticality in March 1973 and started commercial operation in May 1973. Construction for Units 3 and 4 has not yet begun.

Graphs of daily average operating level for each unit, as a fraction of authorized level, are presented in the Semiannual Operating Reports (SOR)⁶ as SOR Figs. 10.1.2-1 and 11.1.2-1. Figure 2.7 is representative of these graphs, in which the sporadic nature of the reactor operation is evident. Such a presentation is qualitatively interesting, but difficulty arises in extracting the information it contains for further analysis. SOR Tables 10.1.1-1 and 11.1.1-1, titled "Power Generation Summary," are more readily useful. They list (among other quantities) the gross thermal energy generated each month, the net electrical energy output, and the time the reactor was critical. These quantities allow the calculation of the quantity which is of greatest environmental interest, that is, the average heat rejection rate for the entire plant. We recommend that daily and monthly tables of this quantity be included in the operating reports and made available on magnetic tape. Figure 2.8 presents the monthly average heat rejection rate for both units for 1973 through 1975. The May 1973 data for Unit 2 presented in SOR-2 Table 11.1.1-1 were inconsistent; consequently, the heat rejection rate was estimated on the basis of SOR-2 Fig. 11.1.1-1. Values for the last six months of 1975 are based on the Nuclear Regulatory Commission (NRC)

Fig. 2.7. Surry - Typical power generation histogram from Surry Semiannual Operating Report. Source: Surry Power Station Units 1 and 2, Semiannual Operating Report Number 6, January 1, 1975, through June 30, 1975.

Operating Plants Status Reports.⁷ Figure 2.8 shows that some power was generated in every month except for November and December of 1974 but that the two units have not yet completed a simultaneous calendar month of capacity operation. This implies that the most severe thermal stresses have yet to be exerted on the environment. The yearly average heat rejection rates for the years 1973 through 1975 were 1730, 1510, and 2420 MW(t) respectively.

Fig. 2.8. Surry - Units 1 and 2 monthly average heat rejection rate.

During its period of precommercial operation in 1972, Unit 1 rejected an average of 554 MW(t) for 46 days. The heat rejected during the first days of commercial operation from December 21 through 31, 1972, could not be found in the Semiannual Operating Reports. The precommercial heat rejection of Unit 2 is included in Fig. 2.8.

There is no direct provision for measuring the flow of cooling water at Surry. The best that can be done is to count the number of operating pumps and assume that they are operating at capacity. There is no special section in which the number of operating pumps is reported, but during 1975 the weekly average number was reported in the section on impingement studies (SOR Sect. 3.6). By using these numbers to estimate the monthly average number of pumps operating, it was possible to estimate the monthly average cooling water flow for 1975. These results are presented in Fig. 2.9 and, when compared to Fig. 2.8, show that the rate was adjusted to follow the plant's power production curve.

A discussion of the temperature rise caused by the plant is quite complicated because of the spatial and temporal separation of the intake and discharge and because of the tidal flow of the river. Since this aspect of plant operation is regulated by Technical Specification 4-14,³ it will be discussed in Sect. IV.A.2.a.

ORNL DAG 76-12492

Fig. 2.9. Surry - Units 1 and 2 monthly average cooling water flow rate (1975).

IV. CONFIRMATORY ASSESSMENT

A. HYDROTHERMAL MONITORING

1. Predicted hydrothermal impactsa. Vepco hydrothermal predictions

Because of the great complexity of the James River tidal estuary, Vepco based its preoperational analysis of the Surry thermal plume primarily on a physical model study performed for the utility by Professor D. W. Pritchard.² Experiments were performed at the U.S. Army Corps of Engineers Waterways Experiment Station at Vicksburg, Mississippi. The model used simulates the entire reach from Richmond, Virginia, to beyond the mouth of the river at Old Point Comfort. The horizontal scale is 1:1000 and the vertical scale is 1:100; consequently, the model is about 550 ft long and 0.7 in. deep at the Surry outfall and has a maximum depth of about 4 in. in the Hog Point region. The time scale is 1:100; one prototype day is simulated in about 14.5 min in the model. Density, temperature, and salinity are scaled 1:1. The report³ asserts that all pertinent features of tide, current, and salinity distribution are correctly scaled, but insufficient data were presented to support this conclusion.

Tests were conducted for heat rejection rates corresponding to one, two, and four reactors; river flows at Richmond of 2000 and 6000 cfs; and various intake and discharge velocities and configurations. Results have been reported for two and four reactors, river flows at Richmond of

2000 and 6000 cfs, and for the intake and discharge as constructed and reversed. Only the results corresponding to the power plant as constructed will be discussed here.

The two-reactor prototype was assumed to reject 3516 MW(t) by heating 3530 cfs by 15°F. A prototype discharge velocity of 6 fps was simulated. Temperatures were measured by towing thermistors at an unspecified speed across transects at an unspecified depth. Two thermistors spaced 18 in. apart laterally were used. One was towed along the transects shown in Fig. 2.10. The outputs were recorded on strip charts, and data were obtained every 1.5 hr in the prototype tidal cycle. There is no indication as to whether the data presented were collected for each transect during the same tidal cycle or how much the plume might vary from cycle to cycle, nor is there any discussion of the possible disturbing effect of towing the thermistors through the flow.

The model was operated for 379 days of prototype time or about four days of clock time. During this period, the building containing the model was kept closed in order to simulate windless conditions. For part of the test, lower Cobham Bay was blocked off by a rubber dam. The water in this region was heated 20°F above the surrounding ambient water temperature and then circulated by large paddle wheels at a speed corresponding to the mean tidal current. The temperature decay of this water allowed an estimation of the surface heat transfer coefficient, which was in agreement with the assumption of windless conditions.

Fig. 2.10. Surry - Temperature measurement transects, Vepco physical model. Source: Pritchard-Carpenter, *Temperature Distribution in the Savannah River Estuary, which will result from the Discharge of Waste Heat from the Surry Nuclear Power Station*, August 1967.

Because the base temperature of the model was observed to increase during the tests, records were kept of ambient temperature using fixed thermistors located at unspecified positions "well upstream and well downstream from the plant site."³ In order to reduce the temperature distributions measured in the model to those which would occur with an ambient water temperature of 80°F and wind speed of 5 mph, the following correction was applied to the areas within given isotherms:

$$\frac{(A_{\theta})_p}{(A_{\theta})_m} = \begin{cases} 1, & \theta \geq 0.5\theta_o \\ 0.9 \frac{K_m}{K_p}, & \theta \leq 0.15\theta_o \end{cases} \quad (1)$$

where

$(A_{\theta})_p$ = area within the θ excess temperature isotherm in the prototype,

$(A_{\theta})_m$ = area within the θ excess temperature isotherm in the model,

K_m = surface heat exchange coefficient in the model,

K_p = surface heat exchange coefficient in the prototype,

θ_o = outfall excess temperature.

A linear variation in the ratio was used for intermediate temperatures. This formula was supported by a theoretical argument and the particular values were said to be selected "on the basis of available data,"⁹ but the details of their justification were not presented. Such a formula appears to interpret the measured temperature distribution as a surface distribution.

Having made this correction, isotherm maps at 1.5 hr intervals in the tidal cycle were presented, starting at high slack. Figures 2.11, 2.12, 2.13, and 2.14 show plume configurations with a freshwater flow at Richmond of 2000 cfs. Figure 2.11 shows the plume at high slack. The 2°C (3.6°F) excess temperature isotherm is predicted to extend from Hog Point to lower Cobham Bay and about one-third of the way across the

ORNL-DWG 76-12404

Fig. 2.11. Surry — Physical model prediction for river flow of 2000 cfs ($56.63 \text{ m}^3/\text{sec}$) at Richmond, tidal hour 0. Source: Pritchard-Carpenter, *Temperature Distribution in the James River Estuary which will Result from the Discharge of Waste Heat from the Surry Nuclear Power Station*, August 1967.

UMNL-DWG 76-12405

Fig. 2.12. Surry - Physical model prediction for river flow of 2000 cfs (56.63 m³/sec) at Richmond, tidal hour 1-1/2. Source: Pritchard-Carpenter, *Temperature Distribution in the James River Estuary which will Result from the Discharge of Waste Heat from the Surry Nuclear Power Station*, August 1967.

ORNL-DWG 76-12406

Fig. 2.13. Surry - Physical model prediction for river flow of 2000 cfs ($56.63 \text{ m}^3/\text{sec}$) at Richmond, tidal hour 6. Source: Pritchard-Carpenter, *Temperature Distribution in the James River Estuary which will Result from the Discharging of Waste Heat from the Surry Nuclear Power Station*, August 1967.

ORNL-DWG 76-12407

Fig. 2.14. Surry - Physical model prediction for river flow of 2000 cfs ($56.63 \text{ m}^3/\text{sec}$) at Richmond, tidal hour 7-1/2. Source: Pritchard-Carpenter, *Temperature Distribution in the James River Estuary which will Result from the Discharge of Waste Heat from the Surry Nuclear Power Station*, August 1967.

river at the outfall. At low slack, as shown in Fig. 2.13, the 2°C (3.6°F) isotherm extends more than 1.5 miles downstream from Hog Point. Figures 2.12 and 2.14 follow Figs. 2.11 and 2.13 by 1.5 hr and illustrate the change in plume configuration that occurs in this period of time. Figures 2.15 and 2.16 show the plume at high slack and low slack with a freshwater flow of 6000 cfs at Richmond. At high slack, the 6000 cfs isotherms extend farther out from shore into Cobham Bay but do not reach as far north toward Hog Point as do the corresponding 2000 cfs isotherms. At low slack, the 6000 cfs plume is slightly larger than the 2000 cfs plume but the shapes are similar. In general, the plumes at these two flow rates are similar in size but the 2000 cfs plume tends to remain closer to shore. Averaged over the tidal cycle, the area having an excess temperature of 3.6°F or more extends less than one-third of the way across the estuary at the outfall. The highest excess temperature observed on the far shore is 1.4°F and the average over a tidal cycle is 1.2°F .

The following shortcomings of this model study should be realized:

1. Insufficient information on experimental techniques has been presented.
2. The degree to which the model correctly simulates the isothermal hydraulics of the river has not been established.
3. The depth to which the measurements apply is uncertain.

ORNL-DWG 76-12408

Fig. 2.15. Surry - Physical model prediction for river flow of 6000 cfs (169.90 m³/sec) at Richmond, tidal hour 0. Source: Pritchard-Carpenter, *Temperature Distribution in the James River Estuary which will Result from the Discharge of Waste Heat from the Surry Nuclear Power Station*, August 1967.

ORNL-DWG 76-12409

Fig. 2.16. Surry - Physical model prediction for river flow of 6000 cfs ($169.90 \text{ m}^3/\text{sec}$) at Richmond, tidal hour 6. Source: Pritchard-Carpenter, *Temperature Distribution in the James River Estuary which will Result from the Discharge of Waste Heat from the Surry Nuclear Power Station*, August 1967.

4. The results apply to a very long period of constant heat rejection 6% above the rated capacity of Units 1 and 2 coincident with a constant freshwater flow rate. These conditions are extremely unlikely.
5. The model is geometrically distorted. Consequently, near-field dilution cannot be correctly simulated.¹⁰
6. No discussion has been given as to whether or not the plume sinks due to higher salinity at the intake than in the discharge region.
7. No indication of the amount of variability from cycle to cycle, which would occur even under these ostensibly constant conditions, has been given.
8. The correction for surface heat exchange is not well established.
9. The influence of wind on current patterns is not accounted for.

In addition to this physical model study, Vepco also presented the results of two studies carried out using a numerical model by D. W. Pritchard.^{11,12} The numerical model is not described except to say that it "is based on our most recent knowledge of the processes of momentum entrainment, turbulent mixing, and surface cooling."¹¹ The first report¹¹ presents summer computations for the present discharge and for four alternatives. The later report¹² predicts the winter plume from the present discharge. Only cases appropriate to the plant as constructed will be discussed here.

The plant was assumed to consist of two reactors rejecting a total of 3223 MW(t) by heating 3500 cfs by 14°F and discharging this water at 6 fps. For the summer case, surface cooling appropriate to an ambient water temperature of 70°F and a wind speed of 10 mph was used. Note that these values are less conservative than those used with the physical model. The winter surface cooling assumes an ambient water temperature of 40°F and a wind speed of 10 mph. Both computations are for the late ebb tidal phase with a tidal current of 1.2 fps. This phase was believed to be the most critical, based on the results of the physical model study.

The isotherms predicted for summer and winter cases are presented in Figs. 2.17 and 2.18. The depth to which these isotherms apply is not stated. The area within a specified isotherm was predicted to be about 1.8 times larger for the winter case than for the summer case. One would expect the average winter plume to be smaller than the average summer plume because the average wind speed is higher during the winter. These calculations have conservatively assumed that the winter wind is the same as wind during the summer. These studies predicted that the highest excess temperature to reach the far shore of the James River would be 1.63°F for the winter case and 1.40°F for the summer case. These temperatures were termed closure temperatures.

Fig. 2.17. Surry - Numerical model prediction for summer conditions.
 Source: Pritchard-Carpenter, *Predicted Distribution of Estuary Temperature in the James River Estuary Adjacent to the Surry Nuclear Power Station for Several Different Discharge Structure Configurations*, September 1970.

Fig. 2.18. Surry - Numerical model prediction for winter conditions.
 Source: Pritchard-Carpenter, Distribution of Excess Temperature in the
 James River Estuary Adjacent to the Surry Nuclear Power Station for Winter
 Conditions, January 1971.

b. Oak Ridge National Laboratory (ORNL) hydrothermal prediction

In the FES,¹ ORNL attempted to check Vepco's predictions using the numerical model of Motz and Benedict.¹³ This is a steady-state near-field model for predicting surface discharges into a uniform cross flow. Shoreline and bottom interactions are ignored, and the lateral spreading of the plume due to buoyancy is neglected. Among the weaknesses of this model are the uncertainty of the correct values for the entrainment and drag coefficients.¹⁴

This model was developed using field data from lakes and rivers rather than from estuaries. Therefore, the model is not well suited to the Surry situation, particularly because it is a steady-state model and the James River never achieves a steady state. Nevertheless, it was judged to be the most appropriate model available at the time. Table 2.1 compares areas within the 3 and 5°F surface isotherms, distances to these isotherms, and maximum excess temperature on the Northern shore, as predicted by the Motz and Benedict model and by the Vepco models. The input data used by ORNL in the Motz and Benedict model were not specified. Presumably, the data were the same as were used in the summer and winter numerical predictions presented by Vepco. Unfortunately, the ambient and outfall salinity (which were assumed) are unknown. The plume predicted by ORNL is considerably smaller than Vepco's prediction.

Table 2.1. Surry - Comparison of results of thermal plume studies^a

	Isotherm (°F) (°C)	Distance from discharge that isotherm will extend (ft) (m)	Area bounded by isotherm (acres) (hectares)	Closure temperature (°F) (°C)
Pritchard's physical model, summer operation	5 (2.6) 3 (1.6)	15,600 (4,755) 49,700 (15,149)	615 (249) 1900 (769)	1.44 (0.8)
Pritchard's analytical model, summer operation	5 (2.6) 3 (1.6)	12,900 (3,932) 33,100 (10,089)	630 (255) 4,200 (1,700)	
AEC Regulatory Staff's analytical model, summer operation	5 (2.6) 3 (1.6)	9,100 (2,774) 24,000 (7,315)	415 (168) 3,000 (1,215)	1.63 (0.91)
Pritchard's analytical model, winter operation	5 (2.6) 3 (1.6)	17,100 (5,212) 47,500 (14,478)	1,100 (445) 8,600 (3,482)	
AEC Regulatory Staff's analytical model, winter operation	5 (2.6) 3 (1.6)	9,300 (2,835) 26,780 (8,163)	430 (174) 3,850 (1,559)	

^aAll plume predictions listed are for the period of late ebb tide.

2. Observed hydrothermal impacts

a. Hydrothermal monitoring required by Technical Specifications

The portions of the Surry Power Plant Technical Specifications (TS)⁶ that pertain to hydrothermal impacts are TS 4.13, "Nonradiological Environmental Monitoring Program," and TS 4.14, "Temperature Limitations on Condenser Cooling Water."

The objective of the monitoring program required by TS 4.13 is

"to determine (1) the relationship between the thermal discharge and the physical-chemical characteristics of the water mass within the ten-mile tidal segment of the James River [centered on Hog Point], (2) the planktonic, nektonic, and benthic characteristics of this segment, and (3) the effects of the operation of the Surry Power Station on the physical, chemical, and biological variables of the James River Estuary."

Technical Specification 4.13.A.2 specifies that temperatures be continuously recorded at the 13 fixed stations shown in Fig. 2.19. Near-surface temperature was to be recorded at all stations, and near-bottom temperature was to be recorded at stations 3, 5, 6, and 10. Although this specification went into effect "not later than December 31, 1972," (TS 4.13.C), it was not correctly met until the latter part of 1975.

As part of their preoperational monitoring, Vepco installed towers in 1969 at locations 2 through 8. These towers were equipped with Taylor liquid expansion thermographs having continuously operating circular charts. Mid-depth temperature was recorded at each tower, and near-bottom temperature was measured at towers 3, 5, 6, and 8. With the initial Technical Specification issuance in May 1972, Vepco contracted with Westinghouse to provide a monitoring system using hard-wire telemetry to meet the requirements of TS 4.13.A.2. This system was plagued by defective components, broken cables, electrical interference, loss of key Westinghouse personnel, and other problems; it never functioned properly. On January 17, 1975, Vepco informed NRC¹⁵ that the Westinghouse system was being replaced. ENDECO instruments, which take a one-hour time exposure photograph of a mercury-in-glass thermometer each hour, were mounted at stations 2 through 12. The film is retrieved monthly, and hourly average temperatures accurate to $\pm 0.4^{\circ}\text{F}$ can be determined. This system became operational on April 29, 1975,¹⁶ but large data loss rates were experienced during 1975 because of an unsuspected change in the emulsion used by the film supplier. This problem has now been overcome. As a result of these difficulties, data

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Fig. 2.19. Surry - Vepco fixed temperature monitoring positions.
 Source: Surry Power Station Units 1 and 2, Semiannual Operating Report Number 7, July 1, 1975, through December 31, 1975.

from the original preoperational tower system were included in the first six Semiannual Operating Reports (SOR).⁶ These data did not satisfy TS 4.13.A.2 because four of the required locations were not monitored and also because mid-depth rather than near-surface temperatures were measured. Semiannual Operating Reports 1 through 6 contained graphs of the daily maximum and minimum temperatures measured by each Taylor

thermograph. Figure 2.20 is typical of these plots. Although this type of presentation is qualitatively interesting, the data are hard to use in further analysis.

The hourly ENDECO data are reduced from photographic film and recorded on magnetic tape. Semiannual Operating Report 7 (ref. 6) contains tables of the monthly means of daily high, mean, and low temperature for each station. Although this information is of some use in assessing the average position of the plume, magnetic tapes containing the hourly temperatures would be needed for further analysis. Finally, hindsight indicates that the placement of the stations is not optimal. In fact, stations 2, 4, 7, 8, 10, and 11 are seldom, if ever, influenced to a measurable degree by the plume.

Technical Specification 4.13.A.4 requires that mid-depth temperature and salinity be continuously monitored at the shoreline intake. The intended intake temperature sensor was part of the ill-fated Westinghouse system. This was replaced in 1975 by an Aquatemp thermistor sensor, apparently mounted in a near-surface position, whose output is recorded about once each minute on a multipoint strip chart in the reactor control room. A Taylor liquid expansion thermograph was used to provide graphs of daily maximum and minimum intake temperatures in Semiannual Operating Reports 1 through 6. Beginning with SOR-7, the Aquatemp sensor has been used to provide monthly means of daily high, mean, and low intake temperatures.

Fig. 2.20. Surry - Typical results from Vepco Taylor thermograph monitoring tower. Source: Surry Power Station Units 1 and 2, Semiannual Operating Report Number 6, January 1, 1975, through June 30, 1975.

No intake salinity data are contained in SOR-1 through SOR-5. In SOR-6, a table of daily high, mean, and low salinity for 52 days is provided. These values were derived from data measured every 15 min by a Westinghouse salinometer mounted at the shoreline intake structure. In SOR-7, a table of monthly means of daily high, mean, and low salinity is provided. The type of instrumentation used to provide these data could not be determined. For quantitative analysis, magnetic tapes of the original readings should be made available. A continuous graph showing the variation of salinity over several days would also be useful in order to get a feel for how salinity varies with tidal phase at the intake.

Technical Specification 4.13.A.5 specifies that mid-depth temperature shall be continuously monitored in the discharge canal. Since the canal is 2900 ft long, this wording is undesirably vague. The sensor intended to provide this information was part of the unsuccessful Westinghouse system and was replaced in 1975 by an Aquatemp thermistor system. The output of the Aquatemp sensor is recorded on a multipoint strip chart in the control room. The location and depth of the Aquatemp sensor could not be clearly determined.

No discharge temperatures are reported in SOR-1. Graphs of daily maximum and minimum discharge temperatures similar to Fig. 2.20 are presented in SOR-2 through SOR-6. These data were measured by a Taylor liquid expansion thermograph with circular chart recorder mounted at mid-depth on the discharge control structure. In SOR-7, monthly means of daily high, mean, and low Aquatemp readings replace these graphs.

Technical Specification 4.13.A.3 directs that once each month at low-slack tide, temperature and salinity shall be measured at 2-m depth intervals at the 11 stations shown in Fig. 2.21. In these surveys, a small boat travels to each position in turn, starting with station 1. The probe of a Beckman Temperature-Salinity bridge is lowered over the side, and readings are recorded to the nearest 0.1°F and 0.1 ppt. The boat is positioned by siting against landmarks, a method which Vepco believes has an uncertainty of about 75 ft. The surface reading is taken at a depth of about 15 cm. Depths are determined by noting the length of cable that has been lowered over the side. The duration of a sampling cruise varies from about 40 min to 2 hr, 17 min. All of the cruises have been made during daylight, the earliest starting time being 0825 and the latest being 1510. From June 1972 through December 1975, 21 out of 42 cruises have started between 0900 and 1200.

In SOR-1, the cruise data are reported in tabular form, with the time at each station noted. In SOR-2 through SOR-7, a semi-graphical presentation such as Fig. 2.22 was used, and only the month of the cruise was noted. Temperature is reported in degrees Celsius in SOR-1 and SOR-6. Fahrenheit units were used in the other reports.

The data from these cruises confirm that salinity increases with depth and decreases with upstream position in an extremely regular manner. Figure 2.23 shows the surface salinities measured at stations 4, 6, 7, and 11 from July 1973 through December 1975. The fact that these curves never cross indicates that salinity decreases with upstream position

Fig. 2.21. Surry - Sampling stations for Vepco monthly temperature and salinity cruise. Source: Surry Power Station Units 1 and 2, Semi-annual Operating Reports Covering the Period May 1, 1972, through December 31, 1975.

without exception. This means that the increased salinity due to the Surry plume has never been detected by the monthly cruises. In fact, given the spacing of these stations, it is clear that they could never be used to define the Surry plume with any accuracy. A comparison of Fig. 2.23 with Fig. 2.5 shows that there is a tendency for a high monthly

Fig. 2.22. Surry - Typical results from Vepco monthly salinity cruise. Source: Surry Power Station Units 1 and 2, Semiannual Operating Report Number 7, July 1, 1975, through December 31, 1975.

Fig. 2.23. Surry - Surface salinity at low-slack measured during monthly salinity cruises, July 1973 through December 1975.

average freshwater discharge at Richmond to be correlated with lower salinities near Surry. Nevertheless, this result should not be taken as conclusive, due to the infrequency and bias of the cruises. The degree of bias that might be expected is indicated by Fig. 2.24, which compares the monthly means of the daily high, mean, and low salinity measured at mid-depth at the intake structure with the average salinity measured at the nearest station (station 4) during the last half of 1975. Only twice was the station 4 salinity within 1 ppt of the monthly mean of daily means at the intake. During October, the station 4 salinity was 0.9 ppt lower than the monthly mean of daily minimum intake salinities.

From July 1973 through December 1975, the surface salinity at station 4 (near the intake) was 0 for six of 30 cruises. At station 7 (near the discharge), the salinity was 0 for 13 cruises. At station 11 (the farthest upstream), salinity was 0 for 20 cruises. During this period, the maximum surface salinity was 7.4 ppt at station 4, 4.1 ppt at station 7, and 2.9 ppt at station 11.

Unlike the salinity observations, no particular pattern emerges from studying the temperature measurements taken during these cruises.

Technical Specification 4.13.A.6 requires that the daily average freshwater discharge at Richmond be tabulated and the corresponding value at Hog Point calculated. This has been done in tabular form in all Semiannual Operating Reports. The Hog Point flows are calculated by multiplying the

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Fig. 2.24. Surry - Comparison of monthly average intake salinity and monthly cruise salinity at station nearest intake, July through December 1975.

daily Richmond values by the ratio of upstream watershed areas, 1.41. This procedure assumes that there is no time lag between Richmond and Hog Point. Although it is known that the time lag does exist and depends on flow rate, telephone calls to the U.S. Geological Survey and U.S. Army Corps of Engineers revealed that the relationship has not been adequately studied. Converting daily flows at Richmond into daily flows at Hog Point without consideration of time lag is misleading.

The monitoring of chlorine used to control biofouling is considered in TS 4.13.A.7 and TS 4.13.A.8. Chlorine has never been needed at Surry. TS 4.13.B and TS 4.13.E relate to biological monitoring and are discussed in Sect. IV.A.2. The provisions of TS 4.13.A go into effect no later than December 31, 1972, as stated in TS 4.13.C.

Technical Specification 4.13.D requires that the results of monitoring under TS 4.13.A "shall be analyzed as they are collected and shall be compared with model predictions and with analytical predictions and with preoperational data."³ A report of these results is to be submitted at the end of each six-month period, and a final report summarizing these results is due 50 days after the third anniversary of the date Unit 2 is licensed to operate, that is, by July 1976. None of these reports have been reviewed. Section 4.13.D of the Technical Specifications further states that if these reports indicate that no major adverse environmental impact has resulted or is likely to result from operation, the monitoring shall then be discontinued. If, on the basis of any Semiannual Operating Report or the summary report, it is concluded that

the results of the monitoring program are inconclusive, either in whole or in part, the utility is required to propose changes to yield conclusive results. Based on this review of the data, the hydrothermal program carried out by Vepco is inconclusive.

Technical Specification 4.14 was added to the Surry Technical Specifications in January 1973 in order to limit the stress to the aquatic ecosystem caused by the thermal discharge. This specification includes limits on effluent temperature, temperature rise, and rate of change of effluent temperature. The original limitation on effluent temperature was designated TS 4.14.1 and read as follows:

1. The condenser cooling water discharge temperature shall not exceed 98°F, as measured continuously at the control structure in the discharge canal and without dilution of the water which passes through the condensers.⁸

In August 1973, the wording "without dilution of the water which passes through the condensers" was replaced by "without flow augmentation for the sole purpose of meeting the 98°F criterion," and the phrase "for more than 3 hours each day" was added.⁸ The designation of this section was also changed to TS 4.14.A.1. Originally, TS 4.14.2 read as follows:

2. The difference (ΔT) between the river water ambient temperature measured at the station intake and cooling water at the discharge control structure shall not exceed 14°F, except for brief fluctuations during changes in power levels.⁸

In August 1973, the specification was redesignated TS 4.14.A.2, "station intake" became "station high level intake," and the limit was raised to 15°F.⁸ At the same time, TS 4.14.B.2 was added to allow a ΔT of

23°F across condensers which are partially shut down for repair or inspection. If this condition is expected to persist for more than 24 hr, authorization from the Directorate of Licensing is required.^d

According to TS 4.14.A.3, normal plant operations shall be controlled so that changes in cooling water temperature at the discharge control structure are not greater than 3°F/hr, except for brief fluctuations.

Technical Specification 4.14.B.1 allows Vepco to exceed these limitations in order to assure safe reactor shutdown or to meet emergency or exceptional system loads. TS 4.14.C.1 states that if the limitations of TS 4.14.A are exceeded and the extenuating circumstances allowed in TS 4.14.B are not present, the appropriate NRC offices must be notified within 24 hr. All operations in excess of TS 4.14.A, whether allowed by TS 4.14.B or not, must be noted in the Semiannual Operating Report, according to TS 4.14.C.2. In addition, any significant environmental impacts occurring during periods when the limitations of TS 4.14.A are being exceeded in accordance with TS 4.14.B must be reported to NRC within 24 hr. Specifications 4.14.B and C were adopted in August 1973.

During August 1975, difficulties in complying with TS 4.14.A.1 were experienced for the first time. The text of the following letter¹⁷ from Vepco to NRC explains the situation.

This is to notify you in accordance with the Surry Power Station Technical Specifications of two incidents where the thermal limitations on the condenser cooling water discharge were exceeded.

On August 2 and 3, 1975, with both units operating at full power, the condenser cooling water discharge temperature exceeded 98 degrees F for more than the three hour limit stated in Technical Specification 4.14.A.1. On August 2, 1975, the condenser cooling water discharge temperature exceeded 98 degrees F for five hours and 30 minutes and reached a maximum temperature of 100 degrees F. The initial action taken was to ramp-down on Unit No. 1 at the maximum permissible rate prior to reaching the three hour technical specification limit. On August 3, 1975, the condenser cooling water discharge temperature exceeded 98 degrees F for five hours and reached a maximum temperature of 99.5 degrees F. The initial action taken during this incident was to reduce the load on both units at the maximum permissible rate before reaching the three hour limit. In both instances there was no evidence of any environmental impact.

Analysis of the incidents have shown them to be the result of the river water temperature rising into the high 80's due to the abnormally higher than normal daily air temperature during that period. Also, one low level intake circulating water pump was out of service which may have amplified the situation relative to the average condenser cooling water discharge temperatures.

On August 4, 1975, Vepco requested and was granted an emergency relaxation of TS 4.14.A.1, effective until August 6, 1975. (Letter dated August 5, 1975, Vepco to NRC, Serial No. 634 and two letters dated August 5 and 6, 1975, NRC to Vepco.) On August 7, 1975, a meeting between Vepco and the NRC was held to discuss a further waiver of TS 4.14.A.1. On August 8, 1975, as a result of this meeting, Vepco requested and was granted that TS 4.14.A.1 be waived on an interim basis until September 20, 1975 (letter dated August 8, 1975, Vepco to NRC, Serial No. 640, and letter dated August 15, 1975, NRC to Vepco). We shall submit a proposed change to TS 4.14.A.1 in the near future.

If the plant is operating at the allowed ΔT of 15°F, variations with TS 4.14.A.1 will occur whenever the high level intake temperature exceeds 83°F. Table 2.2, derived from data presented in a letter from Vepco to NRC,¹⁸ shows that this is not an uncommon occurrence. It appears necessary to develop a method for forecasting episodes of high intake water temperature in order for TS 4.14.A.1 to be implemented efficiently.

Table 2.2. Surry -- Periods of 3 hr or greater when intake temperature was 93°F (28.3°C) or greater

Year	Number of occurrences	Duration (hr)			Total (days)
		Mean	Standard deviation	Maximum	
1972	11	11.0	5.5	20	5.1
1973	51	10.3	5.4	27	21.9
1974	23	6.2	2.7	12	6.0
1975 ^a	29	9.1	4.2	16.5	9.7

^aThrough August 4, 1975, only.

Some difficulties have also arisen from TS 4.14.A.2. In order to understand the nature of these problems, the location of the in-plant temperature sensors should be reviewed. As discussed in Sect. IV.A.2.a, Taylor circular chart thermographs were mounted at the shoreline intake structure and at the discharge control structure. These were to have been replaced by Westinghouse thermistors monitored continuously in the control room. The failure of the Westinghouse system led to the mounting of Aquatemp thermistors at the shoreline intake and in the discharge canal in 1975. These sensors also read out in the control room. Because of the long separation between shoreline intake and discharge canal, the temperature difference between these stations may not reflect the temperature rise experienced as a result of passage through the condenser. Differences may arise because of heat transfer to the atmosphere in each canal, ambient water intrusion into the discharge canal, the time lag between changes in reactor power and water discharge, and because tidal oscillations may advect water of different natural temperature to the shoreline intake. Consequently, additional thermal sensors were needed after TS 4.14.A.2 was adopted. A letter from Vepco to NRC¹⁹ in May 1973 describes the imminent acquisition of

an Ikon Industries thermistor system whose output is recorded on a multiple instrument strip chart in the control room. Sensors are reported to be located at the high-level intake and at the points where each condenser discharges into the discharge canal. A letter from Vepco to NRC in July 1973²⁰ reports that the Ikon system went into operation on May 25 and that a fourth sensor at the end of the discharge canal was added on June 10, 1973.

A letter from Vepco to NRC²¹ in August 1975 stated the following.

Under normal weather conditions the above constraint has presented no problem; however, in recent periods of excessively high temperatures we have experienced difficulty in staying within that ΔT limit during periods of tidal change. As a result of the above constraint, we have had to reduce the station load by as much as 120 MW(t) on certain occasions with a resultant shift in load to our fossil fuel units.

The letter went on to suggest changing TS 4.14.A.2 to allow a ΔT of greater than 15°F for up to 4 hr during periods of tidal change.¹⁸

To investigate the basis for the requested change, NRC officials met with Vepco representatives on September 17, 1975. The meeting report²² included the following statements.

It appears that the ΔT problem is caused in part by a rising tide affecting the water temperature at the high level intake approximately 30 minutes before affecting the temperature at the discharge control structure. The effects of this natural phenomenon apparently may last for 3 or 4 hours at a time.

Vepco indicated that the problem of maintaining a ΔT within a range of 15°F was not unique to periods of hot weather. This was a change from Vepco's remarks in the meeting of September 9, 1975, and from the letter of August 29, 1975.

The staff suggested, as it had at the September 9 meeting, that the problem with ΔT might be resolved by measuring temperatures immediately across the condenser. (Water temperature monitoring would continue at the discharge control structure.) VEPCO indicated that the design of the canals, pumps, and condenser would not permit accurate temperature measurements to be taken near each side of the condenser. (emphasis added)

No decision was reached and, later in September 1975 in a letter to NRC,²³ Vepco indicated that during the next refueling one of the circulating water pumps that had been out of service would be repaired. The letter continued, "Full circulating water flow capability will allow station operation below the 15°F (ΔT) limit at all times."²³ The request for a change was withdrawn, although Vepco stated its intention to seek a change at a later date. In summary, the Ikon system is apparently not satisfactory for measuring the condenser temperature rise, and difficulties in meeting the temperature rise limitation were due primarily to the failure of one of the intake water pumps.

With this background surrounding the measurement of temperature rise, it is interesting to compare the measured temperature rise between the shoreline intake and the discharge control structure with the temperature rise calculated from the monthly average heat rejection rate (Fig. 2.8) and the monthly average cooling water flow rate (Fig. 2.9), estimated from the number of operating pumps reported in 1975. This comparison, which is shown in Fig. 2.25, indicates that although the agreement is usually within 1°F, discrepancies of as much as 4.1°F have occurred. The reasons for such a large deviation over a month's time are not clear.

Fig. 2.25. Surry — Comparison of monthly average calculated temperature rise across condenser (solid line) with measured temperature/rise (dashed line) between shoreline intake and discharge control structure, 1975.

No violations of the rate of temperature change limitation TS 4.14.A.3 have been reported. Since hourly temperature data are not routinely reported, it is difficult to determine how often this limit is approached. The highest rate of change reported at the high level intake structure was 2.5°F/hr between 1400 and 1500 on August 5, 1975.

In order to effectively analyze the compliance of Surry with TS 4.14, magnetic tapes with temperatures at the shoreline intake, high level intake, condenser discharges, and discharge canal control structure, as well as heat rejection rate and flow rate, would have to be analyzed. Because of the peculiar time lags involved, these data should be recorded simultaneously at least every 15 min. The same data on an hourly or at least on a daily basis are essential for adequately assessing the plant's impact on the James River.

b. Vepco monitoring not required by Technical Specifications

Thermal discharges from the Surry Power Plant are also regulated by Permit VA 0004090, titled "Authorization to Discharge Under the National Pollutant Discharge Elimination System and the Virginia State Water Control Law," issued January 24, 1975.¹⁸ Environmental Special Studies Condition Number 2 of this permit requires that three-dimensional plots of excess temperature at high and low tide be submitted for at least two days in July-August 1975 and January-February 1976. The surveys were to be made at or near full power, and the power levels for the preceeding five days were to be furnished with the plots. Vepco was also required to recommend an appropriate mixing zone.

Figure 2.26 shows the type of plot that was produced. A small boat traveled to 28 stations distributed across six transects. The farthest downstream transect (T1) ran from the intake to Deep Water Shoals; the farthest upstream was near Jamestown Island (T6). At each station, a temperature probe was lowered over the side and readings were taken at 2-m intervals to the bottom. In very shallow water, 1-m intervals were used. Surface temperatures were measured at about 15 cm. Readings were taken using either a Whitney T-C5 or a Beckman RS-4 device, calibrated in a circulating water bath against National Bureau of Standards (NBS) thermometers before and after each survey. Ambient temperature was defined to be the average of all measurements on transect T6. If a stratification of more than 2°C (3.6°F) was noticed at T6, ambient was allowed to vary with depth by averaging all T6 readings in 4-m depth intervals. The numbers presented in Fig. 2.26 are the differences of the temperature at each location and the appropriate ambient.

In interpreting these figures, one must take care to note the degree of subjective judgment used in interpolating between transects. The lack of transects in lower Cobham Bay makes it almost impossible to detect heated water at high tide.

c. VIMS hydrothermal monitoring program

Because little was known about the discharge of heated water into tidal estuaries, the AEC (now ERDA) funded an ambitious program of field measurements conducted by the Virginia Institute of Marine Sciences (VIMS). Data

Fig. 2.26. Surry — Results of Vepco plume survey of August 22, 1975, at low slack conducted for State of Virginia. Source: Letter from C. M. Stallings to D. R. Muller, Docket No. 50280-439, August 12, 1975.

were collected in the years from 1971 through 1975, and the results were reported in a series of VIMS reports.²⁴⁻²⁹ The aims of the study were to define the preoperational thermal regime of the Surry area, observe the physical changes produced by plant operation, and use this information to evaluate the validity of the physical model used by Vepco (Sect. IV.A.1.a). The original plan called for three major observational systems: fixed instruments, airborne infra-red imaging, and a moving boat system. The fixed instruments were attached to the existing Vepco instrument towers. Recording tide gages were placed on Tower 1, near Deep Water Shoals (location 2 on Fig. 2.19) and Tower 7, near Jamestown Island (location 8 on Fig. 2.19). Tower 6, near the outfall (location 5 on Fig. 2.19), was more extensively instrumented. Tower 6 was equipped to measure water level, water temperature at two depths, air temperature and humidity at two heights, wind speed at three heights, wind direction, and net heat radiation. These sensors were sampled every 20 min, and the outputs were recorded on digital magnetic tape. Wind speed, wind direction, and net heat radiation were also recorded continuously on strip charts. Various electrical and mechanical problems were experienced with this system. Consequently, no report on these data was ever issued.

Airborne infra-red imaging of the Surry area was to be carried out by NASA-Wallops. Difficulties in scheduling resulted in only six overflights being reported, one of which was flown by EG&G. Although these did provide valuable insights into the behavior of the Surry plume, the overflights constitute only an adjunct to the moving boat system and will be discussed in that light here.

The moving boat system was the main tool of the VIMS study, and it provided most of the data discussed in this section. During 1971 and 1972 the R. V. Investigator, a 30-ft Chesapeake Deadrise inboard, was used. This boat was replaced in 1973 by a faster boat, the 26-ft twin engine cabin cruiser R. V. Bernoulli. The initial complement of sensors included the following:

- (1) A temperature profiler used thermistors to measure water temperature at 0.5, 3, and 6 ft, and air temperature at 3 and 6 ft.
- (2) A Barnes infra-red thermometer, mounted on a boom projecting from the bow, measured water surface temperature.
- (3) An EG&G dew-point hygrometer was mounted at 6 ft and was shielded from the effects of wind generated by the moving boat.
- (4) A Martek salinometer was mounted on the side of the boat. Water was pumped from a depth of about 2 ft into a bucket containing the salinometer.
- (5) A two-direction drag-sphere water-current meter was mounted in front of the bow to detect water velocity.

The drag-sphere water current meter proved to be difficult to calibrate, and no results from its operation were ever reported. The meter was removed from the boat in 1972. Vibration and corrosion problems limited the effectiveness of the Barnes infra-red thermometer, and its use was discontinued during the 1972 field program. The Martek salinometer failed during 1973 and was not replaced. The dew-point sensor was

reportedly in use throughout the sampling program, but no analysis of its measurements was presented. The raw dew-point readings were not even tabulated in the reports of the last two years of the program,^{23,24} nor was there any dew-point data on the 1975 magnetic tapes.

The outputs of these sensors were periodically sampled, digitized, and recorded on magnetic tape. Table 2.3 lists the time constants and accuracies for the measurements of water temperature, air temperature, and dew point. The instrument accuracy is the value reported by the manufacturer. When the errors caused by reference voltage shifts, line losses, signal conditioning, and quantization are added, the calculated system accuracy results. The expected system accuracy is a subjective value recommended by the experimenter on the basis of field experience.

Table 2.3. Summary - Characteristics of VIMS moving boat instrumentation

Instrument	Instrument time constant (s)	Instrument accuracy (°F) (°C)	Calculated system accuracy (°F) (°C)	Expected system accuracy (°F) (°C)
Water thermistor	0.4	0.2 (0.11)	0.4 (0.22)	0.5 (0.28)
Air thermistor	1.0	0.2 (0.11)	0.4 (0.22)	0.5 (0.28)
Dew point hygrometer	1.0	1.0 (0.56)	1.46 (0.81)	1.5 (0.83)

A data acquisition system was used to interrogate the sensors and digitize their signals. During 1971 and the first eight runs of 1972, a Datum data acquisition system (DAS) was used. Each sensor was interrogated every 1.2 sec, although the tables in the reports present data every 6 sec. Except for two runs using a Monitor Labs Model 7200

DAS, the remainder of the 1972 data was taken using a manual back-up system. Typical manual sampling intervals were on the order of 40 sec. Beginning in 1973, a Monitor Labs Model 9100 DAS was utilized. The sampling interval in 1973 was said to be 6 sec, but the tabular data indicate that various intervals including 3, 7, and 15 sec were used. In October 1973, the boat system was down; temperatures at the beginning, middle, and end of each run were sampled manually using an ARA thermistor. Readings were taken at the surface and at 3-ft intervals to the bottom. In 1974 and 1975, the normal boat sensors were usually digitized every 10 sec in the far field and every 3 sec close to the outfall with the Monitor Labs Model 9100 DAS. Data were recorded as the boat moved at an approximately constant speed (nominally 5 knots) along fixed transects. The beginning and end of each transect were noted on the magnetic tape by a manually activated signal, and data points were assumed to be equally spaced along the appropriate transect during subsequent analysis.

The finite sampling rate limited the size of events that could be resolved correctly using this type of system. Features smaller than the distance traveled by the boat between readings may obviously be missed entirely. Moreover, periodic events whose spatial scale is less than twice the sampling interval will be aliased. For a boat traveling at 5 knots, the length scales corresponding to the various sampling intervals used in this program are tabulated in Table 2.4. During 1975, the mean boat speed was 6 knots, and the lengths associated with this speed are also listed. The lateral boat position with respect to the transects was maintained by visual alignment with landmarks. The maximum error in lateral position was estimated to be 100 ft.

Table 2.4. Surry — Sampling periods and spatial intervals for a moving boat

Time interval (s)	Boat speed 5 knots 'length interval' (ft) (m)	Boat speed 6 knots 'length interval' (ft) (m)
1.2	10 (3.05)	12 (3.66)
3	25 (7.62)	30 (9.14)
6	50 (15.24)	61 (18.59)
7	59 (17.98)	71 (21.64)
10	84 (25.60)	101 (30.78)
15	127 (38.71)	152 (46.33)
40	338 (103.02)	404 (123.14)
45	379 (115.52)	455 (138.68)

The boat path was modified somewhat as a result of field experience. Figure 2.27 shows the transects monitored in 1971, 1972, and 1973. During 1971 only transects 1 through 7 were monitored. Transect 8 was added at the start of 1972, and transect 11 was added in the beginning of 1973. In July 1973, transect 5 was modified to give more detail near the outfall. This path was continued in 1974, but in 1975 transects 5 through 10 were completely changed, as shown in Fig. 2.28. The 1975 path allowed the most detailed resolution of the near outfall region. Only transects 1 through 4 remained unchanged during the entire course of the VIMS study.

The time required to complete the boat survey increased from about 60 min in 1971 to a mean of about 97 min in 1975 as a result of these additions. Because the currents in this area never remain still for such a long time, the data measured by the boat system do not depict the instantaneous plume. Most of the runs were made near high- or low-slack water because currents were lowest at these times and because the plume was expected

Fig. 2.27. Surry - VIMS survey area showing transects monitored and DO and salinity stations. Dashed lines are the near-field transects added July 20, 1973. Source: G. C. Parker, E. A. Shearls, and C. S. Fang, *Thermal Effects of the Surry Nuclear Power Plant on the James River, Virginia. Part IV.* Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 51, February 1974.

Fig. 2.28. Surry - 1975 VIMS transects (solid lines); dashed lines indicate 1974 transects. Transects 11, 1, 2, 3, and 4 are the same for both years. Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part VI.* Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE, No. 109, May 1976.

to reach its maximum extent then. In such cases, an attempt was made to begin the run before slack so that predicted slack water at Hog Point would occur as the boat passed in front of the outfall. Since the boat always began its run from the Hog Point end of the course, this technique would probably result in measuring plumes of lesser downstream extent and greater upstream extent than would be expected to occur at the moment of low-slack water. Runs conducted near high-slack water probably resulted in plumes of greater downstream extent and lesser upstream extent than the instantaneous high-slack water plume. Of course, these comments are oversimplified since it is unlikely that slack water occurs simultaneously throughout the sampled region; but in the absence of fine grain current data in the Surry area, one is limited to such speculation.

Significant changes in ambient water temperature due to natural heating did not appear to take place during the time the VIMS boat was collecting data. Through the cooperation of Dr. Morris L. Brehmer of Vepco, ORNL obtained a magnetic tape containing half-hour temperatures measured by the ENDECO thermographs between April 29, 1975, and July 2, 1975. Although the data recovery rate was very low during this period, it was possible to determine the temperature change measured by the near-surface thermograph at position 8 near Jamestown Island (see Fig. 2.19) during each of the 13 coincident VIMS boat runs. The extreme changes were $+0.5^{\circ}\text{F}$ and -0.7°F . The mean temperature change was $+0.06^{\circ}\text{F}$. This supports the conclusion that natural temperatures remained essentially constant during the boat runs.

Data recorded during the boat runs were later decoded and transferred to computer-compatible magnetic tapes. These tapes are filed at VIMS, but the pre-1975 data may have been partially destroyed during processing. Edited tables of the individual measurements for essentially all of the 1971 through 1973 runs are included in the corresponding VIMS reports.²⁵⁻²⁷ Not all are legible, however. Temperatures are recorded to the nearest 0.01°F on the tapes and in the tables. Horizontal isotherm maps were drawn for most of the runs. Table 2.5 lists the number of isotherm maps and data tabulations on a yearly basis. The initial report²⁴ was primarily concerned with describing the instrumentation and contained virtually no field data. Generally, isotherm plots were only prepared for the 0.5-ft depth (WT.5), but a few subsurface plots were also made. No maps were prepared from the 1972 data.

Table 2.5. Surry - Yearly total of isotherm maps and data tables

Report reference number	Year	Number WT 5 ^a isotherm maps	Earliest date	Latest date	Number WT 3 ^b isotherm maps	Number WT 6 ^c isotherm maps	Number runs tabulated	Earliest date	Latest date
24	1971	0			0	0	0		
25	1971	12	4-15	11-4	8	10	48	4-12	11-16
26	1972	0			0	0	68 ^d	3-24	12-4
27	1973	46 ^e	3-27	10-18	1	1	42	3-27	9-18
28	1974	34	5-30	10-24	0	0	0		
29	1975	43	6-3	9-15	1	1	0		
Total		135	3-27	11-4	10	12	150	3-24	12-4

^aWT 5 - water temperature at 0.5 ft (0.15 m)

^bWT 3 - water temperature at 3 ft (0.91 m)

^cWT 6 - water temperature at 6 ft (1.83 m)

^dIncluding two night runs

^eIncluding three extended runs

The distribution of runs for which WT.5 isotherm plots were made is shown in Table 2.6. The distribution is clearly biased toward the warmer months. No isotherm maps were ever prepared for December, January, or

Table 2.6. Surry -- Number of WT.5 isotherm maps for each month

Month	1971	1972	1973	1974	1975	Total
January	0	0	0	0	0	0
February	0	0	0	0	0	0
March	0	0	1	0	0	1
April	1	0	3	0	0	4
May	2	0	2	1	0	5
June	0	0	5	7	12	24
July	1	0	11	9	15	36
August	2	0	13	9	10	34
September	3	0	5	5	6	19
October	2	0	6	3	0	11
November	1	0	0	0	0	1
December	0	0	0	0	0	0
Total	12	0	46	34	43	135

February; March and November had only a single isotherm map drawn. This distribution of runs was planned so that most runs would be conducted during the time of greatest potential for biological impact and for operational reasons. Nevertheless, this scheme prevented the identification of seasonal trends and meant that no data could be gathered during the time of greatest predicted plume extent.

In the report covering the 1971 measurements,²⁵ a table is provided listing the tidal phase and water-level change during each boat run as well as values of air temperature, dew-point temperature, wind speed, wind direction, and percent sky cover. The meteorological data are the averages of 18 hourly observations made between 0600 and 2300 hr at the Ft. Eustis weather station, about 5 miles from the study area. Similar tables are included in the reports covering the 1972²⁶ and 1973²⁷ field years, but in the latter report different values for most of the meteorological variables are entered directly on the horizontal isotherm maps.

Presumably, these values were either measured by VIMS or at Ft. Eustis during the boat runs. The report covering 1974²⁸ gives meteorological data only on the horizontal isotherm maps, but the report covering 1975²⁸ has the same information in tables as well as on the isotherm maps. In these two reports, the meteorological data were measured at Ft. Eustis, but the time of these measurements is not clear.

Measurements made from the moving boat during 1971 and 1972 showed that the natural water temperature at the Surry site was quite homogeneous. Figure 2.29 shows three typical isotherm maps at the 0.5-ft level. In most of the runs, the 0.5-ft temperature varied by less than 1°F over the study area. The highest observed horizontal variation was 4°F, but this was an exceptional case. At 6 ft, horizontal variations were even smaller. During early spring and winter, water temperatures usually increased as the distance from shore increased, although exceptions did occur. No particular pattern was noticed during the summer months. This finding seems to conflict with the expectation that solar heating should be more important in shallow zones. Possible explanations are the high turbidity of the water (limiting the depth to which visible light can penetrate) and the fact that the boat could not sample in really shallow areas. There was no obvious relationship between tidal phase and isotherm pattern.

In order to investigate natural stratification, water temperatures at each depth were averaged over the entire boat path for each month during which data were collected in 1972. The highest stratification occurred

Fig. 2.29. Surry - Typical 0.5-ft (0.15-m) isotherms measured prior to plant operation; (a) April 15, 1971, flood, (b) August 12, 1971, flood, (c) November 4, 1971, ebb. Source: S. N. Chia, C. S. Fang, R. L. Bolus, and W. H. Hargis, Jr., *Thermal Effects of the Surry Nuclear Power Plant on the James River, Virginia. Part II*. Virginia Institute of Marine Sciences, Gloucester Point, SRAM30E No. 21, February 1972.

in June, July, and August, when the water temperature at 0.5 ft exceeded the 6-ft temperature by about 1°F. The 1971 data exhibited the same trend.

Once Surry began producing power, its effect was very obvious in the horizontal isotherm maps. Figure 2.30 shows the 0.5-ft plume measured at low slack water on August 21, 1975. A number of comments can be made about this typical map. First, the heated discharge obviously extends around Hog Point and out of the survey area. This occurred during most of the runs, particularly those made at low slack. However, it would have been impractical to extend the boat path since tidal distortion is already evident, as shown by the upstream bend of the plume near the outfall. Apparently, an appreciable flood current has started before the boat reached this area. Examples of such distortions occurring during the boat run are the rule rather than the exception. The path of the boat has been superimposed to illustrate the degree of judgment needed in drawing the isotherms. The extent of the isotherms between transects 8 and 9 is almost wholly arbitrary, making the measurement of areas within isotherms a somewhat dubious proposition.

The ambient water temperature listed on this figure is the average of the temperatures measured at the same depth at the start (Tower 2) and end of the boat path and at Tower 4. In 1974, VIMS defined ambient to be the average of the temperature at Tower 2, Tower 4, and buoy C51. It is not clear how VIMS defined ambient temperature in 1973. The "Plant Operation" listed on this figure is the daily average electrical output, as reported by Vepco.

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Fig. 2.30. Surry - Isotherms at 0.5 ft (0.15 m) for August 21, 1975, at low-slack water with boat path superimposed. Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part VI*. Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 109, May 1976.

Figure 2.31 shows the plume about 5 hr later at high-slack water. Although the general shape is greatly changed, some similarities remain. The heated water still extends around Hog Point, and tidal distortion due to the start of the ebb phase is now seen in the downstream inclination of the plume at the discharge. The heated water seems to extend farther out from the shoreline than during low slack.

Some insight into the vertical structure of the plume is given by Fig. 2.32, which shows vertical cross sections to 6 ft through the lines indicated in Fig. 2.31. Section CB', which cuts directly across the discharge, shows a submerged core of 100°F water. The entrainment of cooler water (89°F) from along the south side of the discharge structure can be seen, and stratification of 5°F can be noticed on the northern side of the discharge. Sharper horizontal gradients and less stratification occur on the southern side due to the apparent start of the ebb current. Section D'D, which is parallel to CB' but is 1200 ft farther offshore, shows that the maximum temperature has dropped to 95°F but that this core now extends over the entire depth of the section. Stratification of up to 6°F occurs on both sides of Section D'D in regions of high horizontal temperature gradient at the 0.5-ft level. Sections B'B and A'A show that cooler water from the offshore region is underrunning the plume. A maximum stratification of about 2°F is indicated in this region. Vertical cross sections such as these were prepared for only one other plume.

Fig. 2.31. Surry - Isotherms at 0.5 ft (0.15 m) for August 21, 1975, at high-slack water. Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part VI*. Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 109, May 1976.

Fig. 2.32. Surry -- Vertical cross sections for August 21, 1975, at high-slack water showing isotherms (Fig. 2.31). Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part VI.* Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 109, May 1976.

A very different vertical structure was observed on October 18, 1973. At this time, the regular temperature profiler was out of order, and temperature profiles were taken manually with an ARA thermistor at the beginning, middle, and end of each transect. Readings were made at the surface and every 3 ft to the bottom. The surface isotherm map (Fig. 2.33) shows a very small plume, even allowing for the fact that only one reactor was operating. The reason becomes apparent when the vertical profiles in Fig. 2.34 are examined. At Station A, 300 ft in front of the outfall, a normal profile with a stratification of about 1.3°F was observed; but at Station B, 900 ft from the outfall, the plume has begun to sink, and the temperature at 12 ft is about 5°F hotter than the surface temperature. At Station D, 2400 ft from the outfall, the first 6 ft of the water column are unaffected by the plume, yet the bottom temperature is 3°F hotter. In this case, the normal temperature profiler would have missed most of the plume. These facts are extremely significant. This sinking plume occurred because the salinity of the discharge water (4.82 ppt) was so much greater than the ambient salinity (3.6 ppt at the surface at Tower 6) that it overcame the effect of higher discharge temperature. In most once-through power plants, the salinity of the effluent is the same as that of the ambient into which it is discharged. In the case of the Surry Power Plant, the fact that the intake lies farther down the estuary than the discharge means that unless the entire reach is fresh, the effluent will be more saline than its surroundings. The higher salinity tends to make the effluent more dense, while the higher temperature has the opposite effect. Whether the plume sinks or

Fig. 2.33. Surry - Isotherms at 0.5 ft (0.15 m) for October 18, 1973, at low-slack water. Triangles refer to locations of vertical temperature profile measurements (see Fig. 2.34). Source: G. C. Parker, E. A. Shearls, and C. S. Fang, *Thermal Effects of the Surry Nuclear Power Plant on the James River, Virginia. Part IV.* Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 51, February 1974.

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Fig. 2.34. Surry - Vertical temperature profiles on October 18, 1973, at low-slack water for positions noted in Fig. 2.33. Source: G. C. Parker, E. A. Shearls, and C. S. Fang, *Thermal Effects of the Surry Nuclear Power Plant on the James River, Virginia. Part IV.* Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 51, February 1974.

floats depends on the particular relative values of salinity and temperature. Special studies during 1974 indicated that sinking plumes tended to occur whenever the intake salinity exceeded the Cobscook Bay salinity by 1 ppt. Unfortunately, there is no continuous record of the data needed to determine the frequency with which the plume sinks.

There is a more common mechanism which produces sinking plumes that may also occur at Surry. In fresh water, density is a maximum at 39°F. When ambient waters are colder than 39°F and the discharge temperature is warmer, the plume will eventually sink when its density exceeds that of the ambient. This density maximum persists throughout the range of salinities observed at Surry, although it is most pronounced in fresh water. As shown in Fig. 2.23, intake salinities do tend to go to zero during the winter months when the river temperature may go as low as 32°F during periods of ice formation. Once again, the frequency of this phenomenon cannot be accurately assessed due to the lack of adequate continuous monitoring data.

During 1973, three extended boat runs were made to observe how far beyond Hog Point the Surry plume could go. Figure 2.35 shows the 0.5-ft isotherms observed at low-slack water on June 22, 1973. The 4°F excess temperature isotherm extended more than 1 mile past Hog Point to the limit of the sampled region. Although this was the longest plume ever observed by VIMS, the maximum length that occurs is certainly longer.

Fig. 2.35. Surry Isotherms at 0.5 ft (0.15 m) for extended boat survey of June 22, 1973, at low-slack water. Source: G. C. Parker, E. A. Shearls, and C. S. Fang, *Journal of Great Lakes Research*, Vol. 1, No. 1, 1975, Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 51, February 1974.

The early flood plume of August 27, 1975, shown in Fig. 2.36, is quite interesting since the plume proceeded upstream for about 1 mile and then turned sharply out from shore into lower Cobham Bay. In this instance, the plume is apparently following the depth contours shown in Fig. 2.3 and is avoiding very shallow regions.

As noted above, the program of infra-red imaging did not turn out to be a major thrust of the VIMS study. Nevertheless, the images provided by EG&G on March 15, 1974, (shown in Fig. 2.37) give some excellent insight into the instantaneous behavior of the plume. On this day, Unit 1 was not operating and Unit 2 was at 96% capacity. The discharge was about 8°F hotter than ambient. In Fig. 2.37a, the pool of hot water that formed off the outfall during high slack has begun to drift toward Hog Point. The entrainment of large masses of cool water into this pool is apparent. Figure 2.37b, taken one-half hour later, is difficult to interpret. In Fig. 2.37c, at maximum ebb, the plume has been forced close to shore and an interesting striated pattern has formed downstream of the outfall. Figure 2.37d, at late ebb, shows the plume hugging the shore and extending around Hog Point. A large separated eddy of hot water has apparently formed in the lee of the outfall. In Fig. 2.37e, a hot pool that has formed off the discharge has begun to move upstream. A plume of hot water returning from around Hog Point seems to have separated from the shoreline and is flowing out toward the channel. Figure 2.37f, taken at maximum flood, shows the same I-shaped plume noted by the boat survey of Fig. 2.36 on a different date. This sequence suggests that large-scale instabilities tend to disrupt the plume within about 2000 ft of the outfall.

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Fig. 2.36. Surry - Isotherms at 0.5 ft (0.15 m) for August 27, 1975, during early flood. Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part VI.* Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 109, May 1976.

(a)

ORNL PHOTO 2960-76

(b)

(c)

2-83

Fig. 2.37. Surry — Sequence of infra-red images taken on March 15, 1974. Lighter areas represent warmer water (a) high-slack-early ebb, (b) early ebb, (c) Maximum ebb, (d) late ebb, (e) low-slack-early ebb, (f) early-maximum flood.

ORNL PHOTO 2959-74

(a)

2-84

(c)

Fig. 2.37 (continued)

ORNL PHOTO 2958-76

Fig. 2.37 (cont. inced)

A comparison of the plumes measured by VIMS and those predicted by the Vepco physical model (Sect. IV.A.1.a) shows a strong qualitative similarity. Attempts to relate these studies in a quantitative manner were made in the VIMS reports covering the postoperational period.²⁷ In the report covering the 1973 field year,²⁷ comparisons between the model and two groups of measurements were offered. As stated previously, model predictions were for constant Richmond freshwater flows of 2000 and 6000 cfs, a heat rejection rate of 3516 MW(t), an ambient water temperature of 80°F, and a wind speed of 5 mph. The first group of six plumes were all measured during August and September 1973. The average freshwater flow at Richmond on the days surveyed was 2296 cfs, and the monthly average flows were 3700 cfs and 2200 cfs. The average ambient water temperature for the days surveyed was 82.6°F, with an average wind speed of 4.2 mph. The average of the daily heat rejection rates was 3252 MW(t), 92% of the model heat rejection rate. The prototype areas within 0.5-ft isotherms were reported to be consistently much smaller than predicted by the model for 2000 cfs conditions. The areas within the 3.6, 5.4, and 9°F isotherms were smaller by factors of 2.9, 14.4, and 13.1 respectively.

The second group of five plumes were measured in June 1973 when the monthly average freshwater flow at Richmond was 8000 cfs. The average for the days surveyed was 6733 cfs. The average ambient water temperature was 80.5°F, the average wind speed was 7.0 mph, and the average heat rejection rate was 3047 MW(t) on the days surveyed. This is 87% of the model heat rejection rate. Once again, the prototype plume was reported

to be much smaller than the model plume. The areas within the 3.6 and 5.4°F isotherms were smaller by factors of 2.4 and 4.8 respectively. The differences in plume size were attributed to the distortion of the Vepco model, which apparently underestimated near-field dilution. The present author views this comparison with some skepticism since in a total of 11 cases, the 3.6°F isotherm extended out of the survey region in 10 cases and the 5.4°F isotherm did so in 8 cases. Consequently, the total areas within these isotherms could not be known. Moreover, the conditions in the model were held constant over long periods of time, something which never occurred in the prototype. Figure 2.8 shows that the monthly average heat rejection rates for the months compared were only 62, 73, and 66% of the model heat rejection rate. Finally, there is the question of whether the model results are comparable to the 0.5-ft prototype data.

In the report covering the 1974 field year,¹² Vepco model data were compared with an unspecified set of 1973 and 1974 isotherm areas. The mean conditions for these dates were: ambient water temperature 81.7°F, wind speed 6.1 mph, and heat rejection rate 3281 Mw(t) (93% of the model rate). Freshwater flows at Richmond on the days surveyed ranged from 2000 to 7000 cfs.

Figure 2.38 illustrates that the upper limit of the prototype areas barely overlap the lower limit of the model areas. (It is not clear which set of model data is presented.) For the 3.6°F isotherm the mean

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Fig. 2.38. Surry - Comparison of areas within a given excess temperature isotherm for the Veeco hydraulic model, ORNL mathematical model, and 1974 field data. Source: G. C. Parker and C. S. Fang, *Thermal Effects of the Surry Nuclear Power Plant on the James River, Virginia. Part V.* Virginia Institute of Marine Sciences, Gloucester Point, SRAMSOE No. 92, June 1975.

of the prototype areas was smaller than the model areas by a factor of 5. The 5.4 and 9°F prototype areas were smaller by an order of magnitude.

On the basis of this comparison, VIMS proposed that the following formula should have been used to correct the model areas:

$$\frac{(A_{\theta})_r}{(A_{\theta})_m} = \begin{cases} 0.1, & \theta \geq 0.5 \theta_o \\ 0.18 (K_m/K_p), & \theta \leq 0.33 \theta_o \end{cases}$$

with a linear variation for intermediate values of θ . This formula should be compared with the one actually used by Vepco, given in Sect. IV.A.1.a. The most striking difference is in the near-field correction, which has been reduced by a factor of 10. VIMS once again attributed this to the vertical distortion of the Vepco model.

Also included in Fig. 2.38 are the ORNL summer predictions for the 3 and 5°F isotherm areas. These are also higher than the observed areas.

Figure 2.39 shows the relation between isotherm area and fractional excess temperature for those 1975 boat surveys during which daily plant power output was 1400 MW(e) or greater. In this case, only closed isotherms were measured. The line through the data is a subjective best-fit line. The low-slack water plumes tend to be larger than the high-slack plumes, although it is reported that this difference is not significant. A table of these isotherm areas was provided.²⁹

Fig. 2.39. Surry — Area within excess temperature isotherm vs fractional excess temperature (θ/θ_0), 1975 data. Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia*. Part VI. Virginia Institute of Marine Sciences, Gloucester Point, SRANISOE No. 109, May 1976.

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Fig. 2.40. Surry - Area within excess temperature isotherm θ , 1975 data. Triangle shows ORNL prediction. Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part VI. Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 109 May 1976.*

Figure 2.40 compares the 1975 isotherm areas on days with power production of 1400 MW(e) or greater with the lower limit of the Vepco model predictions. As in 1974, the upper limit of the prototype data just overlaps the model predictions. Nevertheless, the 1975 plumes tended to be larger than the 1974 plumes. Figure 2.41 compares the August isotherm areas from these years. The 1975 areas are seen to be larger, especially at the higher excess temperatures. This was attributed primarily to the higher average heat rejection rate during August 1975. The approximate best fit line to the August 1975 data is represented by the equation:

$$A = 8.8 \times 10^7 \exp[-7.2 (\theta/\theta_0)] ,$$

where A is the area in square ft, and θ is the excess temperature in degrees Fahrenheit.

Figure 2.42 shows that the 1974 Surry isotherm areas generally fell below the phenomenological correlation recommended by Asbury and Frigo.³⁰ This was expected and indicates that mixing in the James River estuary is more vigorous than at the lake sites for which the Asbury-Frigo relation was derived. The straight line on Fig. 2.42 is a least squares best fit to the 1974 data.

Using a multiple regression screening procedure, VIMS derived from the 1974 isotherm area data an empirical model that relates isotherm areas

Fig. 2.41. Surry - Comparison of areas within excess temperature isotherms for August 1974 and August 1975 for days with power production greater than 1400 MW(e). Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part VI.* Virginia Institute of Marine Sciences, Gloucester Point, SRAMSOE No. 109, May 1976.

Fig. 2.42. Surry -- Comparison of 1974 VIMS data for areas within excess temperature isotherms with Asbury-Frigo correlation. Source: C. S. Fang and G. C. Parker, *Thermal Effects of Pump Recirculation Piping on the Core Reactor, Virginia. Part VI.* Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 109, May 1976.

to fractional excess temperature, wind speed, and plant operating level.

The relation is:

$$\log (A) = -5.886 - 3.428 \log (\bar{t}/\bar{t}_0) - 0.047 (WS) + 0.008 (PO) ,$$

where WS is wind speed and PO is plant operation. The units of these variables were not specified. The comparison of this model to the 1974 data from which it was derived is shown in Fig. 2.43. The multiple correlation coefficient is 0.94, and the standard error is 0.19. The correlation is best for areas less than $4 \times 10^5 \text{ ft}^2$, corresponding to excess temperatures of 5°F or greater.

As demonstrated in Fig. 2.44, this model was inadequate to predict 1975 data. Order of magnitude agreement was the best that was obtained. This failure was attributed to higher power levels, wind speeds, and ambient temperatures in 1975.

The moving boat temperature measurements were analyzed in a number of other ways, which will not be described in detail here because they were not particularly informative. Among these analyses were the calculations of monthly and yearly average temperatures for each transect and for the entire boat course. Monthly average water and air temperature profiles were also drawn and studies were made of the centerline temperature decay of the plume. On two occasions in 1974, drogues were released at the outfall and tracked for about an hour. As expected during an ebb tide, they tended to follow the shoreline toward Hog Point. An intensive

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Fig. 2.43. Surry -- Comparison of VIMS multiple regression model with the 1974 excess temperature isotherm area data from which it was derived. Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part VI*. Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 109, May 1976.

Fig. 2.44. Surry - Comparison of VIMS multiple regression model and 1975 excess temperature isotherm area data. Source: C. S. Fang and G. C. Parker, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part VI*. Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 109, May 1976.

hydrographic survey of the Hog Point transect was conducted in 1971. This included the measurement of salinity, temperature, and 100 hr of current velocity and direction data. These data were never reported, but they are supposed to be available in the VIMS data bank.

Beginning in 1972, grab samples of water were taken at three stations (Fig. 2.27) in the Surry area during nearly every boat run and on some additional occasions. Water was sampled at station 1 before the run began and at station 2 immediately after the run ended. The boat was then driven to station 3, where another sample was taken. Sampling consisted of using a 1-liter Frautschy bottle to obtain water samples at the desired depths. The samples were transferred to 130-ml bottles and the portions to be used for the dissolved oxygen (DO) measurement were chemically treated at that time. These samples were then brought back to the lab and analyzed. Salinity was determined with a Beckman salinometer (RS-7), and DO was determined by standard Winkler titration.

During 1972, samples were obtained at the surface, middle, and bottom of the water column. Only the surface and bottom were sampled in succeeding years. During 1974 and 1975, salinity samples were also taken at surface level of the outfall. The results were reported in tables for each year except 1974. Salinity was listed to the nearest 0.001 ppt and DO was listed to the nearest 0.01 mg/liter. A summary of the monthly tabular data is reported in Table 2.7. Graphs of monthly averages were also reported. Figure 2.45 depicts the monthly average results for 1974. During the preoperational year (1972), salinity

Table 2.7. Summary - Number of VIMS salinity and DO measurements reported in tabular form for each month

Month	1972	1973	1974	1975	Total
January	0	0	0	0	0
February	0	0	0	0	0
March	3	0	0	0	3
April	8	1	0	0	9
May	8	1	0	0	9
June	9	5	0	12	26
July	8	8	0	15	31
August	9	12	0	10	31
September	7	3	0	6	16
October	5	5	0	0	10
November	8	0	0	0	8
December	3	2	0	0	5
Total	68	37	0	43	148

decreased monotonically up the estuary. Figure 2.45 also shows that the plant discharge has altered this pattern. At both surface and bottom, station 3, near the outfall, usually has the highest salinity due to the discharge of more saline water by the plant. At all stations, the salinities are slightly higher near the bottom. Comparison with Fig. 2.6 again demonstrates the inverse correlation between freshwater flow and salinity. The results presented in Fig. 2.45 are typical of the post-operational years.

Individual DO measurements showed a great deal of variability, but the monthly averages were well behaved. DO is seen to attain minimum values during the warmer months; however, no plant-induced effect on DO was identified.

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Fig. 2.45. Surry - Monthly average salinity and dissolved oxygen at the VIMS sampling stations and outfall during 1974; (a) surface salinity and DO and (b) bottom salinity and DO. Source: G. C. Parker and C. S. Fang, *Thermal Effects of Surry Nuclear Power Plant on the James River, Virginia. Part V.* Virginia Institute of Marine Sciences, Gloucester Point, SRMSOE No. 92, June 1975.

The following are the conclusions arrived at by VIMS at the conclusion of their five-year study:²⁹

1. During the three year period of operation of Surry Nuclear Power Plant water temperatures in the immediate vicinity of the outfall were monitored closely to determine the thermal plume. The plume usually stayed close to the southern shoreline of the James River and excess surface temperatures covered less than 30 percent of the river in the survey area adjacent to the discharge point.
2. Maximum excess temperatures of 12°F (6.7°C) were recorded in the immediate vicinity of the outfall in 1973 and 1974. In 1975 primarily due to a combination of mechanical problems at the station, maximum excess temperatures as high as 16.7°F (9.3°C) were measured in the immediate vicinity of the outfall. The highest surface temperature ever recorded near the outfall was 99.9°F (37.7°C) on August 21, 1975. All excess temperatures decreased rapidly as distance from the outfall increased, and temperatures outside a distance of 1000 yards (914 m) were rarely greater than 5°F (2.8°C) above ambient temperatures.
3. Because cooling water is drawn from downstream of Hog Point and discharged upstream, the salinity was higher near the outfall than for the ambient water in this area. On several occasions this resulted in a "sinking" plume particularly when the salinity of discharge water was over 1 ppt higher than the ambient salinity.
4. During ebb tide, the thermal plume tended to stay close to shore and extended around Hog Point, while on flood tide the thermal plume headed upstream and away from shore.
5. In some instances, there was vertical thermal stratification along the monitoring transects which had a maximum gradient of approximately 4°F (2.2°C) over 6 feet (1.8 m) of depth.
6. The minimum value of dissolved oxygen measured during the 1975 sampling period was 3.72 mg/liter which was measured twice during August 1975. August monthly averages for the three stations had a maximum of 5.11 mg/liter and a minimum of 4.61 mg/liter.
7. The major cause of differences between the hydraulic model and prototype excess temperature areas was probably the scale distortion of 10:1, vertical to horizontal, in the model. As a result of this distortion, the model

did not properly reproduce entrainment in the near field, which is the major process affecting the plume in this area. This resulted in a larger predicted excess temperature area than has been observed in the river.

8. A statistical multiple regression analysis was used to predict the plume temperature distribution. The results were variable, probably due to the complexity of circulation in the tidal James. Predictions were somewhat better with higher loading. More reliable predictions probably would be obtained by this method in a lake environment.
9. The hydrothermal data taken over the past five years at the Surry site indicate that the thermal discharge was rapidly assimilated in the river. Outside the 'mixing zone' for the discharge, in this case the area within approximately 1000 yards (914 m) of the discharge opening, water temperatures were not higher than those which could occur naturally in the area.
10. During the survey years water with excess temperatures of 1°F (0.6°C) never crossed the width of the river at its narrowest point. This excess temperature was rarely found to cover half of the width.

The VIMS report covering the 1974 field year²³ made the following recommendation:

It is our opinion that self monitoring by the electric utilities is undesirable. We suggest that government regulatory agencies should require that environmental monitoring be performed by an independent organization.

d. Oak Ridge National Laboratory (ORNL) analysis of VIMS hydrothermal data

After reviewing the VIMS hydrothermal study, it was felt that further analysis would lead to an improved understanding of the Surry plume and that the VIMS data base would allow the development and demonstration of techniques of plume analysis that might prove to be generally useful. In interpreting this section, one must constantly be aware that these

results cannot transcend the limitations of the data base from which they are derived. The VIMS program consisted of a limited number of boat runs that were biased in their timing. Nearly all were made during daylight, and the annual distribution emphasized the summer months heavily. If these limitations are not dismissed, the results of this section should shed valuable new light on the Surry plume behavior.

The most fundamental question in the consideration of a thermal plume is to define its location. The VIMS postoperational reports answered this question directly, by plotting isotherm maps for individual boat runs, and indirectly, by computing the average temperatures along each transect. The first technique provides easily understandable information about the extent of the plume during the time of a given run, but one must pore over many such maps before an intuition for the typical behavior of the plume emerges. Mapping individual plumes simply provides more detail than can be readily assimilated. The technique of computing transect-averaged temperatures seems to err on the side of excessive abstraction. Consequently, a new method of analysis was sought.

For the field years 1973 to 1974, the only data available to the writer were contained in the VIMS reports^{27,28} and described in Sect. IV.A.2.c. Since it was not feasible to put the 1973 tabular data on computer cards within the constraints of this program, the analysis was limited to the horizontal isotherm maps at the 0.5-ft depth. These were overlaid, and the bounding envelope of the 3 and 5°F excess temperature isotherms was drawn. On the original maps, isotherms for integral values of actual

temperature were given. Excess temperatures were estimated by subtracting the VIMS ambient temperature and rounding to the nearest integer. The result for the 1973 VIMS surveys is shown in Fig. 2.46. The isotherms in this figure bound the maximum extent of these excess temperatures, which were observed in 43 runs between March 27 and October 18, 1973. The 3°F excess temperature isotherm runs about 4000 ft offshore along the entire western side of the Hog Point peninsula and extends out of the survey area around Hog Point and into lower Cobham Bay. The 5°F excess temperature isotherm extends out of the survey area on the west but does not appear to go around Hog Point. The behavior of the plume very near the shoreline has not been measured.

Figure 2.47 presents the results of a similar overlay analysis for the 34 surveys conducted between May 30 and October 24, 1974. The pattern of these 0.5-ft envelopes is similar to that of 1973 except that the 5°F envelope did reach around Hog Point and a small region of 10°F water was observed near the outfall.

Through the cooperation of Dr. George L. Sherwood of ERDA, Dr. C. S. Fang of VIMS, and Dr. John P. Jacobson of VIMS, computer tapes containing the temperature data from the 1975 boat surveys were supplied to the author. This made possible a more complete analysis of the 1975 data. These tapes contained the air and water temperatures measured by the VIMS temperature profiler (usually every 3 or 10 sec) during each 1975 boat run. There were 43 runs made between June 3 and September 15, and the plant and environmental parameters pertaining to them are listed in Table 2.8.

Fig. 2.46. Surry - Maximum observed extent of 0.5-ft (0.15-m) isotherms, VIMS 1973 data.

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Fig. 2.47. Surry - Maximum observed extent of 0.5-ft (0.15-m) isotherms, VIMS 1974 data.

Table 2.8. Sarry - Basic environmental and plant data for 1975 VIMS surveys

Month	Day	Tide	Power produced (MW)	Wind speed (MPH) (km/hr)	Wind direction	Ambient water temperature (F)(C)	Discharge temperature (F)(C)	Air temperature (F)(C)	Dew point temperature (F)(C)
June	3	L	749	6.7 (19.7-11.3)	SSW	79.0 (26.1)	90.5 (32.5)	81.0 (27.2)	64.0 (17.8)
	5	H	746	10 (16.1)	SSW	78.6 (25.9)	87.5 (30.8)	80.0 (26.7)	67.0 (19.4)
	6	E	751	12.16 (19.3-25.7)	W	78.7 (25.9)	88.2 (31.2)	77.3 (25.2)	67.0 (19.4)
	9	H	741	5 (8.0)	S-SW	77.5 (25.3)	84.2 (29.0)	72.0 (22.2)	54.0 (12.2)
	10	H	751	10 (16.1)	SE	76.6 (24.8)	84.3 (29.1)	76.0 (24.4)	55.0 (12.8)
	12	L	751	12 (19.3)	S	75.0 (23.9)	81.7 (27.6)	73.0 (22.8)	67.0 (19.4)
	16	L	741	10 (16.1)	SE	80.0 (26.7)	87.0 (30.6)	86.0 (30.0)	69.3 (20.7)
	18	H	973	0		80.8 (27.1)	90.1 (32.3)	80.0 (26.7)	72.0 (22.2)
	19	H	1287	8 (12.9)	NNW	80.7 (27.1)	92.4 (33.6)	84.0 (28.9)	72.3 (22.4)
	23	H	1505	5 (8.0)	SW	82.9 (28.3)	94.0 (34.4)	80.3 (26.8)	60.6 (15.9)
	25	L	749	5 (8.0)	SW	81.6 (27.6)	88.3 (31.3)	79.0 (26.1)	67.0 (19.4)
	26	F	750	10 (16.1)	NE	82.1 (27.8)	88.0 (31.7)	81.3 (27.4)	64.0 (17.8)
Average			872	7.9 (12.6)		79.5 (26.4)	88.1 (31.2)	79.2 (26.2)	65.8 (18.8)
July	1	L	1518	5.10 (8.0-16.1)	NE	80.2 (26.8)	92.0 (33.3)	76.7 (24.8)	54.7 (12.6)
	2	F	1497	5.10 (8.0-16.1)	W	80.0 (26.7)	95.3 (35.2)	82.0 (27.8)	72.0 (22.2)
	3 ^a	H	1509	5.10 (8.0-16.1)	W	78.9 (26.1)	91.6 (33.1)	74.6 (23.7)	62.6 (17.0)
	8	H	735	0		82.0 (27.8)	87.7 (30.9)	81.7 (27.6)	68.7 (20.4)
	9	H	730	5.10 (8.0-16.1)	SW	81.7 (27.6)	88.7 (32.1)	85.4 (29.7)	72.4 (22.4)
	10	H	735	5 (8.0)	SW	82.1 (27.8)	90.4 (32.4)	84.3 (29.1)	71.0 (21.7)
	15	L	1485	5.10 (8.0-16.1)	NNE	80.0 (26.7)	95.2 (35.2)	79.7 (26.5)	73.7 (23.2)
	17	L	1485	10.15 (16.1-24.1)	S	80.6 (27.0)	97.3 (36.3)	82.3 (27.9)	72.0 (22.2)
	18	H	1491	0-5 (8.0)	SW	80.6 (27.0)	94.2 (34.6)	75.0 (23.9)	71.2 (21.8)
	21 ^a	H	1484	7.10 (11.3-16.1)	W	83.7 (28.7)	95.8 (35.4)	85.3 (28.5)	70.9 (21.6)
	22	H	1491	0-5 (8.0)	SW	84.8 (29.3)	97.7 (36.5)	85.7 (29.8)	73.5 (23.1)
	25	L	745	15.20 (24.1-32.2)	S	82.9 (28.3)	91.2 (32.9)	81.0 (27.2)	76.4 (24.7)
	28	L	745	0-5 (8.0)	S	83.1 (28.4)	88.6 (31.4)	81.7 (27.6)	72.5 (22.5)
	29	L	736	10 (16.1)	E	83.7 (28.7)	92.0 (33.3)	82.7 (28.2)	73.5 (23.1)
	31	L	730	5 (8.0)	E	86.0 (30.0)	91.4 (33.0)	83.6 (28.7)	59.2 (15.1)
Average			1141	6.9 (11.1)		82.0 (27.8)	92.7 (33.7)	81.3 (27.4)	69.6 (20.9)
August	5 ^a	H	1482	10 (16.1)	WNW	86.1 (30.1)	98.3 (36.8)	84.0 (28.9)	74.0 (23.3)
	6	E	1467	10 (16.1)	SW	85.7 (29.8)	98.6 (37.0)	84.3 (29.1)	74.0 (23.3)
	7	H	1504	8 (12.9)	NW	83.8 (28.8)	95.6 (35.3)	72.0 (22.2)	63.0 (17.2)
	12	L	1507	6.10 (9.7-16.1)	NW	82.9 (28.3)	96.0 (35.6)	80.5 (26.9)	65.0 (18.3)
	21	L	1467	5 (8.0)	E	85.4 (29.7)	99.2 (37.3)	79.7 (26.5)	73.0 (22.8)
	21	H	1487	7.8 (11.3-12.9)	SE	86.3 (30.2)	99.9 (37.7)	83.3 (28.5)	70.7 (21.5)
	22	L	1468	10-12 (16.1-19.3)	SW	84.3 (29.1)	97.6 (36.4)	79.6 (26.4)	72.6 (22.6)
	26	L	1420	0-5 (8.0)	NW	85.9 (29.3)	99.3 (37.4)	86.3 (30.7)	71.1 (21.7)
	27	F	1416	10-15 (16.1-24.1)	NNE	85.6 (29.8)	99.1 (37.3)	83.0 (28.3)	67.0 (19.4)
	29	F	1428	8 (12.9)	E	86.2 (30.1)	99.6 (37.6)	83.3 (28.5)	64.0 (17.8)
Average			1485	8.3 (13.4)		85.2 (29.6)	98.4 (36.9)	81.6 (27.6)	69.4 (20.8)
September	3	H	1432	10-15 (16.1-24.1)	NNE	79.3 (26.3)	92.8 (33.8)	77.7 (25.4)	63.7 (17.6)
	4	H	1442	5 (8.0)	E	79.9 (26.6)	93.3 (34.1)	78.0 (25.6)	66.0 (18.9)
	5	H	1432	0		80.8 (27.1)	94.7 (34.8)	78.3 (25.7)	60.7 (15.9)
	10	F	1424	5-10 (8.0-16.1)	NE	78.9 (26.1)	92.9 (33.8)	74.3 (23.5)	54.3 (12.4)
	11	L	1456	10-15 (16.1-24.1)	S	77.9 (25.5)	92.2 (33.4)	80.7 (27.1)	68.7 (20.4)
Average			1440	7.9 (12.7)		78.4 (25.8)	91.9 (33.3)	75.9 (24.3)	61.3 (16.3)

^aNot used in ORNL analysis.

The records of three boat runs (July 3, July 21, and August 5) could not be correctly read from the tape and were not used in the analyses presented here.

When trying to assess the ecological impact of a thermal plume, areas which are significantly affected by the plume must be separated from those which are not. The definition of "significantly affected" varies, depending on actual temperature, deviation from natural temperature, time of exposure, and species. For example, it is well known that boiling water results in instant death to the common crab. Fortunately, such extreme conditions do not occur in environmental contexts. For this reason, merely knowing the extreme extent of certain isotherms does not answer all possible questions. The more typical problem involves determining the implications to a given species of exposure to a 5°F elevated temperature for 75% of the time. With this in mind, it was decided to apply a probability analysis to the 1975 VINS data.

In order to reduce the amount of computation, data were read only for six equally spaced positions on each transect (except transect 10, from which the final location was inadvertently omitted). This meant that calculations were performed at 55 horizontal positions. To combine the measurements from different runs, an ambient temperature (whose definition will be discussed below) was computed for each level of each run and subtracted from the 55 readings. At each location, the excess temperature from each run was tabulated.

In the first phase of this analysis, the data from all 40 runs were combined without respect to tidal phase, plant operating level, or any other qualifying parameter. The range of excess temperatures measured at each location was divided into 0.2°F intervals, and the number of observations in each interval was counted. Summing all observations lower than a specified excess temperature and normalizing by the total number of observations yields an estimate of the cumulative distribution function (CDF).³¹ Figure 2.48 is a graph of the CDF estimate prepared from the 40 measurements of excess temperature at the first position on transect 11 at the 0.5-ft depth. The graph indicates that 5% of the observations (two observations) were in the -0.2 to 0°F interval, 52.5% of the observations were less than 1.0°F , and that 100% of the observations were less than 2.6°F . To obtain a visual presentation of the spatial and temporal extent of the plume, similar CDF estimates were calculated for all 55 locations mentioned earlier. The excess temperatures corresponding to a certain frequency of occurrence were plotted on a map of the Surry area, and contours of constant excess temperature were drawn in by hand. The result of this operation for the 100% level of occurrence at the 0.5-ft depth is shown in Fig. 2.49. The contours represent the maximum observed extent of each excess temperature. Their relation to the 55 numbers indicates the degree of judgment involved in this process. Figure 2.49 may be compared with Figs. 2.46 and 2.47. The observed plume obviously covered more area in 1975.

Plots similar to Fig. 2.49 were prepared for the 90%, 75%, 50%, 25%, and 0% levels of occurrence. These were overlayed, and the positions

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Fig. 2.48. Surry - Cumulative distribution function estimate for excess temperature at 0.5 ft (0.15 m), transect 11, station 1, derived from 40 VIMS 1975 boat runs.

Fig. 2.49. Surry — Maximum extent of 0.5-ft (0.15-m) isotherms based on 100% CDF estimate for VIMS 1975 data (40 boat runs).

of particular isotherms at these levels of occurrence were traced. This process led to the creation of Fig. 2.50. Figure 2.50d shows the percentage of runs for which the 7°F isotherm was bounded by the various contours. This isotherm was observed within the outermost contour 100% of the time, was within the innermost contour during 75% of the observations, and extended into the area between these contours during 25% of the boat runs. This type of plot conveys the maximum amount of information about the spatial and temporal extent of the plume, and so a large number of them were prepared. Table 2.9 classifies these plots for easy reference.

Because the VIMS ambient temperatures were available only at the 0.5-ft level, a new definition based on the temperature profiler data was needed. For the purpose of this study, ambient temperature was defined to be the average of the five lowest temperatures recorded on the VIMS tape during each run. All locations were scanned, not just the 55 used for CDF analysis. According to this definition, there is a different ambient temperature for each level of each boat run. This definition is more natural (although less simple) than the definition used by VIMS because it references all temperatures to the coolest water available for entrainment into the plume. Five readings were averaged to ensure that there was a substantial quantity of water at this temperature. The location of this ambient varies from run to run.

OML DWS 76-12005

Fig. 2.50. Surry - WT.5 excess temperature (θ) extent contours, 40 VIMS 1975 boat runs (a) $\theta = 1^\circ\text{F}$ (0.6°C), (b) $\theta = 3^\circ\text{F}$ (1.7°C), (c) $\theta = 5^\circ\text{F}$ (2.8°C), (d) $\theta = 7^\circ\text{F}$ (3.9°C).

ORNL DWG 76-12445

Fig. 2.50b

Fig. 2.50c

ORNL DWG 70-12448

Fig. 2.50d

Table 2.9. Surry - Key to excess temperature extent maps

Figure number	Condition	Number runs	Depth (ft) (m)	Excess temperature					
				1°F (0.56°C)	3°F (1.67°C)	5°F (2.78°C)	7°F (3.89°C)	9°F (5.0°C)	10°F (5.56°C)
50	All	40	0.5 (0.15)	a	b	c	d		
51	All	40	6 (1.83)	a	b	c	d		
52	Low slack ^a	21	0.5 (0.15)	a	b	c	d		e
53	Low slack ^a	21	6 (1.83)	a	b	c	d		e
54	High slack ^b	19	0.5 (0.15)	a	b	c	d		
55	High slack ^b	19	6 (1.83)	a	b	c	d		
56	One unit	16	0.5 (0.15)	a	b	c	d		
57	One unit	16	6 (1.83)	a	b	c	d		
58	Two units	21	0.5 (0.15)	a	b	c	d	e	
59	Two units	21	6 (1.83)	a	b	c	d	e	

^aIncludes seven flood or early flood cases: 6-26, 7-2, 7-25, 7-29, 8-27, 8-29, and 9-10.

^bIncludes two ebb or early ebb cases: 6-6 and 8-6.

Table 2.10 compares the VIMS and ORNL ambient temperatures at the 0.5-ft depth for the 40 runs analyzed by ORNL. The ORNL ambient is always lower, the mean difference being 0.9°F; the maximum difference was 2.2°F, and the minimum difference was 0.2°F. To determine if these definitions lead to significant differences in the value of ambient temperatures, a t-test for the differences of the ambient temperatures was applied.³ The t-statistic for the hypothesis that the VIMS and ORNL definitions have the same mean is 14.2, a value that is significant at the 0.01 level. Consequently, it is concluded that a significant difference does exist. The magnitude of the difference is not large, however, and the more conservative ORNL definition is used in this study.

Returning to a consideration of the plume probability plots, Fig. 2.50a shows that the 1°F excess temperature isotherm extends past Tower 5 in 50% of the observations and goes around Hog Point more than 75% of the

**Table 2.10. Serry - Comparison of VIMS and ORNL definitions
of ambient temperature at 0.5-ft depth**

Number	Date	VIMS ambient (°F) (°C)	ORNL ambient (°F) (°C)	Δ = VIMS - ORNL (°F) (°C)
1	6-3-75	79.0 (26.1)	78.5 (25.8)	0.5 (0.3)
2	6-5-75	78.6 (25.9)	78.2 (25.7)	0.4 (0.2)
3	6-6-75	78.7 (25.9)	78.0 (25.6)	0.7 (0.3)
4	6-9-75	77.5 (25.3)	76.9 (24.9)	0.6 (0.4)
5	6-10-75	76.6 (24.8)	76.4 (24.7)	0.2 (0.1)
6	6-12-75	75.0 (23.9)	74.5 (23.6)	0.5 (0.3)
7	6-16-75	80.0 (26.7)	79.0 (26.1)	1.0 (0.6)
8	6-18-75	80.8 (27.1)	79.8 (26.6)	1.0 (0.5)
9	6-19-75	80.7 (27.1)	80.4 (26.9)	0.3 (0.2)
10	6-23-75	82.9 (28.3)	81.4 (27.4)	1.5 (0.9)
11	6-25-75	81.6 (27.6)	80.7 (27.1)	0.9 (0.5)
12	6-26-75	82.1 (27.8)	81.8 (27.7)	0.3 (0.1)
13	7-1-75	90.2 (26.8)	79.7 (26.5)	0.5 (0.3)
14	7-2-75	80.0 (26.7)	79.5 (26.4)	0.5 (0.3)
15	7-8-75	82.0 (27.8)	80.4 (26.9)	1.6 (0.9)
16	7-9-75	81.7 (27.6)	80.8 (27.1)	0.9 (0.5)
17	7-10-75	82.1 (27.8)	81.4 (27.4)	0.7 (0.4)
18	7-15-75	80.0 (26.7)	79.2 (26.2)	0.8 (0.5)
19	7-17-75	80.6 (27.0)	79.7 (26.5)	0.9 (0.5)
20	7-18-75	80.6 (27.0)	79.6 (26.4)	1.0 (0.6)
21	7-22-75	84.8 (29.3)	84.5 (29.2)	0.3 (0.1)
22	7-25-75	82.9 (28.3)	82.0 (27.8)	0.9 (0.4)
23	7-28-75	83.1 (28.4)	82.0 (27.8)	1.1 (0.6)
24	7-29-75	83.7 (28.7)	82.7 (28.2)	1.0 (0.5)
25	7-31-75	86.0 (30.0)	84.5 (29.2)	1.5 (0.8)
26	8-6-75	85.7 (29.8)	84.8 (29.3)	0.9 (0.5)
27	8-7-75	83.8 (28.8)	81.6 (27.6)	2.2 (1.2)
28	8-12-75	82.9 (28.3)	82.5 (28.1)	0.4 (0.2)
29	8-21-75A	85.4 (29.7)	84.4 (29.1)	1.0 (0.6)
30	8-21-75B	86.3 (30.2)	85.4 (29.7)	0.9 (0.5)
31	8-22-75	84.3 (29.1)	83.4 (28.6)	0.9 (0.5)
32	8-26-75	85.9 (29.9)	85.3 (29.6)	0.6 (0.3)
33	8-27-75	85.6 (29.8)	84.9 (29.4)	0.7 (0.4)
34	8-29-75	86.2 (30.1)	85.5 (29.7)	0.7 (0.4)
35	9-3-75	79.3 (26.3)	77.7 (25.4)	1.6 (0.9)
36	9-4-75	79.9 (26.6)	79.3 (26.3)	0.6 (0.3)
37	9-5-75	80.5 (27.1)	79.8 (26.6)	1.0 (0.5)
38	9-10-75	78.8 (26.0)	77.8 (25.4)	1.0 (0.6)
39	9-11-75	77.9 (25.5)	77.1 (25.1)	0.8 (0.4)
40	9-15-75	73.6 (23.1)	71.6 (22.0)	2.0 (1.1)
Mean		81.4 (27.4)	80.6 (27.0)	0.9 (0.4)
Standard deviation		3.1 (1.7)	3.1 (1.7)	0.4 (0.2)
Maximum		86.3 (30.2)	85.5 (29.7)	2.2 (1.2)
Minimum		73.6 (23.1)	71.6 (22.0)	0.2 (0.1)

time. From Fig. 2.50b it can be seen that the 3°F excess temperature isotherm extends around Hog Point in more than 25% of the observations but has not extended across stream beyond Tower 2. Figure 2.50c reveals that the 5°F excess temperature isotherm has stayed within about 4000 ft of the western shore of the Hog Point peninsula and has extended around Hog Point in more than 10% of the boat runs.

Figure 2.51 shows the behavior of the plume at the 6-ft depth during 40 runs at all tidal phases and levels of operation. Even at this depth, 5°F excess temperatures have been observed to go around Hog Point as Fig. 2.51c shows. Comparing these plots with the corresponding parts of Fig. 2.50 shows that the 0.5-ft plume is usually larger. In the 3°F excess temperature plots, for example, the 90% contour at 0.5 ft roughly follows the 100% contour at 6 ft. This indicates that during these runs the stratification of the upper 6 ft of the water column was usually positive. An exception occurs in the 7°F figures, where the 100% contour extends farther into lower Cobham Bay at the 6-ft level.

Figures 2.52 and 2.53 present plots generated using only those runs made at low-slack water at 0.5-ft and 6-ft depths. Figures 2.54 and 2.55 show the same cases at high-slack water. Actually, this is not exactly true. The division was made on the basis of the designation of "high" or "low" written on the computer tape for each run. As Table 2.8 shows, 7 of the 21 cases analyzed as low-slack runs were actually made during flood or early flood stages. Two of the 19 high-slack cases were actually

Fig. 2.51. Surry - WT6 excess temperature (Δ) extent contours, 40 VIMS 1975 boat runs (a) $\Delta = 1^\circ\text{F}$ (0.6°C), (b) $\Delta = 3^\circ\text{F}$ (1.7°C), (c) $\Delta = 5^\circ\text{F}$ (2.8°C), (d) $\Delta = 7^\circ\text{F}$ (3.9°C).

ORNL DWG 76-12430

Fig. 2.51b

ORNL DWG 70-1243

Fig. 2.51c

ORNL DWG 76-12432

Fig. 2.51d

Fig. 2.52. Surry - WT.5 excess temperature (θ) extent contours, 21 VIMS 1975 low-slack boat runs (a) $\theta = 1^{\circ}\text{F}$ (0.6°C), (b) $\theta = 3^{\circ}\text{F}$ (1.7°C), (c) $\theta = 5^{\circ}\text{F}$ (2.8°C), (d) $\theta = 7^{\circ}\text{F}$ (3.9°C), (e) $\theta = 10^{\circ}\text{F}$ (5.6°C).

Fig. 2.52b

Fig. 2.52c

Fig. 2.52d

Fig. 2.52e

Fig. 2.53. Surry - WT6 excess temperature (θ) extent contours, 21 VIMS 1975 low-slack boat runs (a) $\theta = 1^{\circ}\text{F}$ (0.6°C), (b) $\theta = 3^{\circ}\text{F}$ (1.7°C), (c) $\theta = 5^{\circ}\text{F}$ (2.8°C), (d) $\theta = 7^{\circ}\text{F}$ (3.9°C), (e) $\theta = 10^{\circ}\text{F}$ (5.6°C).

Fig. 2.53b

Fig. 2.53c

Fig. 2.53d

Fig. 2.53e

Fig. 2.54. Surry - WT.5 excess temperature (θ) extent contours, 19 VIMS 1975 high-slack boat runs (a) $\theta = 1^{\circ}\text{F}$ (0.6°C), (b) $\theta = 3^{\circ}\text{F}$ (1.7°C), (c) $\theta = 5^{\circ}\text{F}$ (2.8°C), (d) $\theta = 7^{\circ}\text{F}$ (3.9°C).

Fig. 2.54b

Fig. 2.54c

Fig. 2.54d

Fig. 2.55. Surry - WT6 excess temperature (θ) extent contours, 19 VIMS 1975 high-slack boat runs (a) $\theta = 1^\circ\text{F}$ (0.6°C), (b) $\theta = 3^\circ\text{F}$ (1.7°C), (c) $\theta = 5^\circ\text{F}$ (2.8°C), (d) $\theta = 7^\circ\text{F}$ (3.9°C).

Fig. 2.55b

Fig. 2.55c

Fig. 2.55d

measured at ebb or early-ebb flow. However, these errors are not believed to be seriously misleading.

Comparison of the low-slack 0.5-ft results of Fig. 2.52 with the low-slack 6-ft results of Fig. 2.53 indicates complex three-dimensional behavior. The 1 and 10°F contours are usually larger at the 0.5-ft level, but the 6-ft contours are usually larger at the 3, 5, and 7°F values. In all cases, a considerable upstream bend of the contours is apparent near the outfall. This is due partially to the nonsynoptic nature of the boat runs and partially to the inclusion of the flood cases mentioned above. At both depths, 3°F excess temperature water extended beyond Hog Point in more than half of the cases studied.

A different picture in regard to vertical stratification emerges from comparing the high-slack 0.5-ft plots of Fig. 2.54 with the high-slack 6-ft plots of Fig. 2.55. In virtually every instance, the 0.5-ft contours are more extensive than their 6-ft counterparts. Relatively little downstream distortion of the near-field contours is observed. The high-slack plumes appear to bring 3°F excess temperatures at both depths into the lower Cobham Bay region in more than 25% of the runs analyzed.

Comparing the low-slack cases with their high-slack counterparts shows that the low-slack cases tended to be larger. No significant 10°F areas were measured in the high-slack cases. In addition to the expected tendency of the low-slack plumes to extend farther toward Hog Point,

a tendency exists for the low-slack plumes to be closer to shore and for the high-slack plumes to move out from shore into Cobham Bay. Combined with the observations on vertical stratification, this is suggestive of a tendency toward an onshore subsurface component and an offshore surface component to the flood currents on the western shore of the Hog Point peninsula. The opposite trend seems to exist during ebb currents.

In order to examine the effect of heat rejection rates on the plume structure, a CDF analysis was run for subsets corresponding to one and two reactors operating near capacity. The results for 16 cases with a net electric power production of from 700 to 800 MW(e) are presented in Figs. 2.56 and 2.57. The results for 21 cases having a net electric power generation of more than 1400 MW(e) are shown in Figs. 2.58 and 2.59.

Comparing the one reactor 0.5-ft and 6-ft plots shows that the 0.5-ft contours are nearly always more extensive, the notable exceptions being the 90 and 75% occurrence contours of the 5°F excess temperature region. The 5°F excess temperature regions never extended out of the survey area, but 3°F excess temperature water did so in at least 25% of the runs at the 0.5-ft level and in at least 10% of those runs at the 6-ft level.

When two reactors were operating, negative stratification was rarely observed. In the 5°F excess temperature case, the 25 and 50% contours are comparable at 0.5 ft and 6 ft, but the 75 and 90% envelopes are much larger at 0.5 ft. The 100% envelope is slightly larger at the upper

Fig. 2.56. Surry - WT.5 excess temperature (θ) extent contours, 16 VIMS 1975 1-reactor boat runs (a) $\theta = 1^{\circ}\text{F}$ (0.6°C), (b) $\theta = 3^{\circ}\text{F}$ (1.7°C), (c) $\theta = 5^{\circ}\text{F}$ (2.8°C), (d) $\theta = 7^{\circ}\text{F}$ (3.9°C).

Fig. 2.56b

Fig. 2.56c

Fig. 2.56d

Fig. 2.57. Surry - WT6 excess temperature (θ) extent contours, 16 VIMS 1975 1-reactor boat runs (a) $\theta = 1^{\circ}\text{F}$ (0.6°C), (b) $\theta = 3^{\circ}\text{F}$ (1.7°C), (c) $\theta = 5^{\circ}\text{F}$ (2.8°C), (d) $\theta = 7^{\circ}\text{F}$ (3.9°C).

Fig. 2.57b

Fig. 2.57c

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Fig. 2.37d

Fig. 2.58. Surry - WT.5 excess temperature (θ) extent contours, 21 VIMS 1975 2-reactor boat runs (a) $\theta = 1^\circ\text{F}$ (0.6°C), (b) $\theta = 3^\circ\text{F}$ (1.7°C), (c) $\theta = 5^\circ\text{F}$ (2.8°C), (d) $\theta = 7^\circ\text{F}$ (3.9°C), (e) $\theta = 9^\circ\text{F}$ (5.0°C).

Fig. 2.58b

Fig. 2.58c

Fig. 2.58d

Fig. 2.58e

Fig. 2.59. Surry -- WT6 excess temperature (θ) extent contours, 21 VIMS 1975 2-reactor heat runs (a) $\theta = 1^\circ\text{F}$ (0.6°C), (b) $\theta = 3^\circ\text{F}$ (1.7°C), (c) $\theta = 5^\circ\text{F}$ (2.8°C), (d) $\theta = 7^\circ\text{F}$ (3.9°C), (e) $\theta = 9^\circ\text{F}$ (5.0°C).

Fig. 2.59b

Fig. 2.59c

Fig. 2.59d

Fig. 2.59e

level. The 7°F excess temperature water never left the survey area, but 5°F excess temperature water went around Hog Point in more than 10% of the cases at both depths.

The plumes generated by two reactors are much larger than when only one reactor is operating. The most obvious manifestation of this is the fact that measurable 9°F excess temperature areas are only seen in the two-reactor case. A comparison of the corresponding plots shows that at both depths the two-reactor plumes are larger. The only contours that are comparable in extent are the 25 and 50% envelopes for 1°F excess temperature at 0.5 ft. In the 6-ft, 7°F excess temperature plots, the two-reactor 50% contour is comparable to the one-reactor 100% line.

A direct investigation of stratification was made by computing CDF estimates for the difference of the water temperature at 0.5 and 6 ft. This was done at the 55 locations mentioned earlier, using the 1975 VIMS boat data. When 40 runs were analyzed as a group, negative stratification had been measured at least once at each location and negative stratification had been measured in at least 25% of the runs at 40 out of the 55 locations. Performing this analysis for high-slack and low-slack cases separately (using the previously mentioned definitions) confirmed that negative stratification occurred more frequently in the low-slack cases. In order to determine how much of this could be attributed to the plant, a comparison with the data collected during the Vepco monthly boat cruises (see Sect. IV.A.2.a) was made, since no evidence of the plume was

apparent in that data. Figure 2.60 compares the mean CDF estimate for the VIMS 1975 low-slack runs with the mean CDF estimate for the Vepco summer monthly cruises. The Vepco cruises are from July through September of 1973 and from June through September of 1974 and 1975. The Vepco temperature difference is the 15-cm (0.49-ft) temperature minus the 2-m (6.6-ft) temperature, but this discrepancy compared to the VIMS difference is not expected to be of much importance. The mean temperature differences of the two data sets are similar; negative stratification was found in more than 25% of the Vepco measurements, but more extreme values of stratification — positive and negative — are found in the VIMS data. Both effects can plausibly be attributed to the plume, which sometimes sinks and sometimes floats.

B. ECOLOGICAL EVALUATION

1. Thermal effects

The analysis of the effects of heated effluent additions from Surry Units 1 and 2 on the biota of the James River estuary (centered at Hog Point) has been performed within the following framework. The preoperational monitoring program (prior to 1973) for Surry is characterized by infrequent and irregular sampling intervals that are concentrated within the summer months (June through September) and by only a small number of stations that are consistently sampled. Due to the inadequacy of the preoperational monitoring program, only data from 1973 to 1975 were

Fig. 2.60. Surry - Mean CDF estimates for stratification in top 6 ft (1.8 m) of water column.

included in this analysis, and thus, no comparison of a preoperational and an operational condition is possible. This analysis will also concentrate on near-field effects of thermal additions within a designated discharge area, which was defined in the hydrothermal plume analysis (see Sect. IV.A). Far-field effects cannot be assessed for two reasons: (1) there are great physical and chemical variations in stations located on the south bank of the James River (Surry site) as compared with those in the channel and on the north bank; and (2) the south bank stations within the discharge and control areas are the only areas that are consistently sampled over the three operational years.

a. Assessment of monitoring methods

(i) Phytoplankton

Phytoplankton were collected monthly using a nonmetallic 2-liter Van Dorn bottle, and samples were preserved with Lugol's iodine solution. The identification and counting of cells were performed using the inverted microscope method. In most cases, identification of phytoplankton was made to genera, although some common estuarine forms were identified to species. Phytoplankton data were reported as the total number of cells per milliliter, and only the three or four most predominant genera at each station were identified. Because no quantitative information was reported as to the abundance (number of cells per milliliter) of any genera, no diversity indices could be employed in

this analysis, and no quantitative evaluation of shifts in the dominant phytoplankters could be assessed.

Monthly phytoplankton samples were collected at 9 stations in 1973 and 1974 and at 12 stations in 1975; however, over all years, only 6 stations were consistently monitored (Fig. 2.61). Beginning in 1975, duplicate samples were collected at all stations. The Surry phytoplankton monitoring program illustrates the evolution of a sampling design. Stations Hog Point West A (HPWA), Hog Point West B (HPWB), and Cobham Bay East (CBE) were added in 1975 to sample more intensively within the discharge area, while Hog Point East A (HPEA), Hog Point East B (HPEB), and Hog Point North (HPN) were added in the control area.

The phytoplankton community at Surry was predominated during most months by the diatoms (*Skeletonema*, *Cyclotella*, *Melosira*, or *Nitzschia*) and by the dinoflagellates (*Pyramimonas* and *Chroomonas*). In addition, phytoplankton assemblages of these major genera were highly similar in both the thermally stressed (discharge) area and the unstressed (control) area (Tables 2.11 and 2.12). In the Surry FES, it was predicted that the dominance of diatoms would be decreased, and heat-tolerant green and blue-green species would increase in abundance in the plume area. Unfortunately, because quantitative taxonomic information on the abundance of all genera occurring at each station is lacking, this prediction cannot be validated.

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Fig. 2.61. Surry - Phytoplankton sampling program.

Table 2.11: Surry - Major phytoplankton genera at control area^a in the James River estuary

Genus	1973												1974												1975													
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D		
<i>Nitzschia</i>		X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
<i>Chroomonas</i>								X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
<i>Micraster</i>	X			X	X	X							X	X	X	X									X	X	X	X	X							X	X	X
<i>Skatzenoma</i>	X	X						X	X		X	X	X						X	X	X										X	X	X					
<i>Cyclotella</i>				X	X	X	X	X					X			X	X	X											X									
<i>Gyrodinium</i>								X	X	X								X	X	X												X	X	X				
<i>Pyramnomas</i>																	X	X								X				X								
<i>Cryptomonas</i>																														X								
<i>Katodinium</i>																									X			X			X							
<i>Coscinodiscus</i>																														X								
<i>Antrodinellus</i>		X																																				
<i>Asterionella</i>			X																																			

^aControl composed of INT (1973-1974) INT and HPEA (1975).Table 2.12: Surry - Major phytoplankton genera at discharge area^a in the James River estuary

Genus	1973												1974												1975												
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	
<i>Nitzschia</i>		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Chroomonas</i>								X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Micraster</i>	X	X		X	X	X							X	X	X	X									X	X	X	X	X	X	X	X	X	X	X	X	X
<i>Skatzenella</i>	X	X						X	X		X	X	X						X	X	X	X								X	X	X					
<i>Cyclotella</i>				X	X	X	X	X	X				X	X	X	X	X	X											X								
<i>Gyrodinium</i>									X	X	X							X	X	X	X									X				X		X	
<i>Pyramomonas</i>								X											X						X	X	X		X								
<i>Cryptomonas</i>													X	X															X								
<i>Katodinium</i>																									X			X									
<i>Coscinodiscus</i>																														X							
<i>Antrodinellus</i>	X	X																																			
<i>Asterionella</i>	X	X	X	X																																	

^aDischarge composed of DHS, HPS, CBC (1973-1975).

Temporal changes in the phytoplankton populations exposed to Surry thermal discharges were compared with those populations monitored in the unstressed control area (Fig. 2.62). Phytoplankton densities were generally greatest from April through August during all operational years. In the first half of 1973, control phytoplankton densities were higher than those found at the discharge. This was the period when the Surry plant was slowly increasing its energy production and the ΔT was gradually increasing (Fig. 2.63). After July 1973, the discharge populations increased, reaching densities comparable to the control, and by

Fig. 2.62. Surry - Temporal variations in phytoplankton densities in the control and discharge areas (1973-1975).

Fig. 2.63. Surry — Temporal variations in ΔT ($^{\circ}F$) for discharge station (DIS) and discharge areas (DIS, HPS, CBC) from 1973 to 1975.

December, discharge populations were four times greater than the control, suggesting that thermal enhancement of growth rates may have occurred. Early in 1974, phytoplankton concentrations at the discharge were higher than at the intake; however, as the summer approached and a higher ambient temperature regime was established, discharge densities declined, suggesting inhibition of phytoplankton production. In 1975, the year when the highest ΔT s were attained over all months, control population densities were consistently greater than those in the discharge. This further suggests the inhibitory effect of the thermal discharge on phytoplankton densities.

The temporal changes in phytoplankton densities during a seasonal growth cycle direct attention toward specific critical periods when maximum stress may be exerted on the population; however, an overall view of the mean annual phytoplankton densities can also be used to view possible impacts. In Fig. 2.64, the mean annual phytoplankton density for the intake (INT) station (control) is compared to stations discharge (DIS), Cobham Bay Central (CBC), and Hog Point South (HPS) in the thermal plume. In 1973, phytoplankton densities were highest in the INT, declining by 53% in 1974. Phytoplankton densities in 1975 increased, but only to 68% of 1973 values. Overall, discharge phytoplankton densities declined by 34%, 42%, and 45% for DIS, CBC, and HPS, respectively; however, populations at station DIS continued to decline in 1975 to 44% of 1973 densities, CBC concentrations remained unchanged, and only at station HPS did densities show a recovery in 1975 (still remaining 38% below 1973 concentrations). Although some enhancement of primary productivity

Fig. 2.64. Surry — Comparison of mean annual phytoplankton densities for control and discharge areas (1973-1975).

may have occurred during the cooler months, a net reduction in the phytoplankton standing crop occurred at all discharge stations on a yearly basis. While control phytoplankton populations began to recover in 1975 toward concentrations present in 1973 (the lowest energy production year for Surry 1 and 2), no such recovery was exhibited by stations DIS and CBC, although some recovery of the phytoplankters occurred at station HPS, the station farthest from the discharge.

The effect of thermal discharge on phytoplankton densities in the York River (a river similar to the James, which empties into Chesapeake Bay) was studied by Warinner and Brehmer.³³ This study reported that primary production in the winter was enhanced with a temperature increase of 9 to 18°F above ambient. If the temperature increase exceeded 18°F, however, primary production was depressed. In addition, during warmer months when ambient temperatures reached 77°F, thermal additions generally depressed phytoplankton populations. In a similar site study³⁴ at a power plant on the Indian River (Delaware) estuary, primary production was stimulated by thermal elevations of 10.3 to 12.6°F for eight months of the year when ambient temperatures remained below 71.6°F; however, during warmer months, thermal additions depressed primary productivity. During the warmer months at Surry, the DIS station is characterized by having consistently higher water temperatures than the control area (Fig. 2.65). From June to September, ambient mean monthly temperatures were greater than 77°F and discharge temperatures were 7.7 to 10.0°F, 7.4 to 10.7°F, and 9.2 to 14°F higher than at the intake station during 1973, 1974, and 1975 respectively. With reference to certain studies,^{33,34}

Fig. 2.65. Surry — Comparison of mean monthly water temperature in the intake area (INT), discharge areas (DIS, CBC, HPS), and at the discharge station (DIS).

enhancement of phytoplankton could occur from October to May; however, during summer months (June to September), ambient temperatures increase and heat additions (ranging from 7.4 to 14°F) would create elevated temperatures unfavorable to phytoplankton growth.

The magnitude of the ΔT superimposed on the ambient temperature, as opposed to the overall temperature attained, may stress phytoplankton beyond their physiological abilities for recovery. In plume-simulated tests conducted in the laboratory,³⁵ no change was reported in surface photosynthetic activity in phytoplankton assemblages collected at an ambient temperature of 78.8 to 80.6°F and exposed to a changing ΔT with a maximum of 8.1°F. However, when phytoplankton assemblages were collected at ambient temperatures of 74.3 to 75.2°F and were exposed to a changing ΔT with a maximum of 10.8°F, decreased photosynthetic activity was reported.

In summary, the data from the Surry phytoplankton monitoring program indicate that thermal additions have an adverse effect on the phytoplankton in the discharge area. Therefore, a statistical model needs to be developed to describe the behavior of phytoplankton in the discharge area. The models developed for the phytoplankton, zooplankton, and benthic analysis will be discussed in Sect. IV.B.1.b.

Chlorophyll *a*. Chlorophyll *a* samples were collected monthly at the surface (coincidentally with phytoplankton samples) using a nonmetallic 2-liter Van Dorn bottle. Samples were preserved with mercuric chloride

(40 mg/liter), stored in opaque bottles on ice until returned to the laboratory, subsequently filtered (using glass filters), and ground in 90% acetone to extract the chlorophyll a . Chlorophyll a concentrations were measured using a Turner Fluorometer (Model 111), and the resulting data were reported as milligrams of chlorophyll a per liter. Monitoring of chlorophyll a should be pursued further, as this method is a good indicator of biomass.

Chlorophyll a sampling was conducted at 6 stations during 1973 and at 12 stations during 1975; however, only 6 stations were consistently sampled over both years (Fig. 2.66). No chlorophyll a data were available for operating year 1974, although the Technical Specifications require sampling of this parameter. In addition, although monthly sampling was generally performed (Table 2.13), the months of August, September, October, and December were omitted from sampling in 1975. Because chlorophyll a data are not available for the entire year of 1974 or for four months in 1975, no further statistical analysis of this parameter was performed. The deficiency in this portion of the monitoring program, however, should be noted.

^{14}C calculations of primary productivity. Primary productivity measurements were conducted using two light and two dark bottles per station. Each 107-ml sample received 1.0 μCi ^{14}C in a solution of sodium carbonate and was incubated in the James River at a depth of 5 cm for a minimum of 2 hr. Following incubation, samples were filtered through 0.45 μ pore-size membrane filters, placed in scintillation vials containing

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Fig. 2.66. Saray - Chlorophyll *a* sampling program.

dioxane scintillation cocktail, and counted on a Beckman LS-150 liquid scintillation counter. Results were reported as milligrams of carbon per cubic meter per hour.

Primary production determinations using ^{14}C were a new addition to the ecological monitoring program as of 1975. Because only one year of data is available and no comparison to other operational years can be made, ^{14}C data were not analyzed statistically to assess potential power plant induced changes. The ^{14}C technique employed (Steeman Nielsen ^{14}C

Table 2.13. Surry - Sampling frequency of the chlorophyll *a* monitoring program

1973	1974	1975 ^a
January		January
February		February
March		March
April		April
May		May
June	No data	June
July	collected	July
August	for 1974	
September		
October		
November		November
December		

^aDuplicate samples collected at all stations.

method) is widely thought to give the most accurate estimates for potential primary production of any method commonly in use today³⁶ and should be continued in the monitoring program.

(11) Zooplankton

Zooplankton samples were collected monthly using a 12.5-cm diam Clarke-Bumpus quantitative sampler equipped with a #20 mesh net. The zooplankton nets were towed at the surface for a period of 1 to 5 min, depending on the water turbidity encountered. Samples were preserved with 5% buffered formalin, and counts and identifications were made using a dissecting microscope. Monitoring data were reported as the number of organisms per 100 liters. Identification of zooplankters was made to genus in some cases, but primarily individuals were grouped as gastropod

larvae, barnacle nauplii, polychaete larvae, ostracods, rotifers, and copepods; thus, no species diversity indices could be calculated.

Monthly zooplankton samples were collected at 7 stations during 1973 and 1974 and at 12 stations during 1975 (duplicates); however, only 6 stations were sampled consistently during all three operational years (Fig. 2.67). The Surry zooplankton monitoring program clearly illustrates the evolution of a sampling design. In 1975, stations HPWA, HPWB, and CBE were added to sample more intensively within the discharge area, while HPEA, HPEB, and HPN were added in control areas.

The zooplankton community at Surry was predominated by copepods and their nauplii throughout the year, while the meroplankton (gastropod larvae, barnacle nauplii, and polychaete larvae) became an important portion of the plankton community from early summer through the winter during the major benthic spawning periods (Fig. 2.68) but were absent from the plankton during other months. In addition to differences in zooplankton densities due to seasonal factors, there is a tidal factor influencing species composition in the Hog Point area. The zooplankton communities upstream from Hog Point have greater relative densities of freshwater species (i.e., *Bosmina*, *Daphnia*, and rotifers), while stations downstream of Hog Point are predominated by more euryhaline fauna (i.e., *Acartia*, *Eurytemora*, polychaetes, and barnacles). Depending on the amount of freshwater flow into the James River, salt water intrusion can move up or downstream from the plant over at least a 10-mile range (see Sect. IV.A). The tidal movement of saline waters can thus mediate

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Fig. 2.67. Surry - Zooplankton sampling program.

changes in zooplankton populations within the estuary since zooplankton movements are determined in part by mass water movements.

Temporal changes in the zooplankton populations exposed to the thermal effluent at Surry were compared to populations in the unstressed control areas (Fig. 2.69). Generally, zooplankton concentrations in the two

Fig. 2.68. Surry -- Temporal variations in copepod and meroplankton densities in the control and discharge areas.

Fig. 2.69. Surry - Temporal variations in zooplankton densities in the control and discharge areas (1973-1975).

areas differed to a greater extent than phytoplankton densities within the same areas. In 1973, zooplankton densities were higher in the control area until June, when zooplankton densities declined sharply and remained depressed until June 1974. After June 1974, densities increased, but remained below those exhibited by the discharge stations. The increased densities in the discharge area during 1974 may be a response to increased thermal input by the Surry facility. Both control and discharge populations of zooplankton declined in the fall of 1974 after the reactor had been nonoperational (November and December 1974). During 1975, control zooplankton densities were generally higher than those in discharge areas, although standing crops in the control and discharge areas were more similar than in previous years. Discharge station densities lagged behind increases in densities occurring at the control area.

Temporal changes in zooplankton dynamics can be compared using mean annual densities as an indicator of long-term trends in the system (Fig. 2.70). The control area densities were the lowest annual densities recorded in both 1973 and 1974; however, in 1975, the control attained the highest zooplankton densities of all stations. The discharge area stations generally exhibited a decline in densities from 1973 to 1974 paralleling the control decline; however, no recovery in the discharge populations occurred in 1975. When compared individually, station DIS exhibited a sharp decline (55%) in zooplankton densities in 1974, but in 1975 no increase occurred. At station CBC, densities declined by 48% in 1974 and in 1975 continued to decline to 58% of the 1973 values.

Fig. 2.70. Surry - Comparison of mean annual zooplankton densities for control and discharge areas (1973-1975).

At station HPS, farthest from the discharge, the lowest decline (31%) occurred from 1973 to 1974 and densities remained unchanged in 1975. On an annual basis, zooplankton densities were reduced for stations affected by thermal additions; the degree of the inhibitory effect seems to be directly related to the distance of the station from the discharge canal. Only zooplankton densities at the control station exhibited a recovery from 1974 to 1975.

(iii) Benthos

The benthic sampling program at Surry included monitoring of both the epibenthic fauna and the fouling organism community.

Epibenthos were sampled with a 0.05-m² Ponar grab. The samples were then sieved through a 1.0-mm mesh screen and preserved in formalin for subsequent identification. Benthic data were reported in two ways: as total numbers of individuals per 0.1 m² and as total wet weight (grams) per 0.1 m². Unfortunately, however, the biomass data were not usable for inter-year comparisons because total wet weights in 1973 included meat and shell weights combined, while in 1974 and 1975, total wet weight included only meat weights. The biomass data, therefore, were only useful for comparisons of benthic population changes among stations within any given year.

During the three operational years (1973 through 1975), epibenthic samples were consistently collected at 16 stations in the vicinity of

the plant (Fig. 2.71) approximately six times annually; however, the sampling frequency was not consistent among years. Few samples were collected in the winter or early spring (Table 2.14), while the majority of samples were collected from April through September. Although epibenthic sampling was conducted at more stations than plankton and fish sampling, the irregularity of the sampling program makes assessment of plant-induced changes very difficult.

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Fig. 2.71. Surry - Benthic sampling program.

Table 2.14. Surry -- Sampling frequency of the
epibenthic monitoring program

1973	1974	1975
February	February	February
—	—	—
—	—	April
May	May	—
June	June	June
July	July	July
August	August	August
September	—	September
—	—	—
—	November	—
December	—	—

The benthic estuarine community at Surry was predominated by the mollusks (*Rangia cuneata* and *Hydrobia* sp.), polychaetes (*Scolecoplepides viridis* and *Nereis succinea*), amphipods (*Gammarus* sp.), and several species of dipteran larvae. In the Surry FES, concern is raised over the possible reduction in the commercial blue crab (*Callinectes sapidus*) fishery; however, the Ponar grab is an inadequate sampling device for this species, which is best captured in a benthic trawl. The epibenthos sampling at Surry reflects collection of only the nonmobile members of the benthic community.

In order to assess the effects of thermal effluents on benthic populations, a control area (stations 13 and 15) was compared to the discharge area composed of stations 4, 8, and 11. These station locations were chosen to correspond to stations selected for analysis in the phytoplankton and zooplankton analysis. Stations 5 and 9 within the plume were not used since no corresponding plankton sampling station was available for comparison.

Temporal changes in the density of epibenthic populations exposed to thermal additions (stations 4, 8, and 11) from the discharge were compared to control populations at stations 13 and 15 (Fig. 2.72). These specific stations were selected to correspond to plankton sampling stations so that comparisons of thermal effects could be made for all ecological communities within the same area. During a season cycle, benthic densities were generally lowest during winter months and maximum densities were attained between June and August. During 1973, benthic populations in both control and discharge areas displayed low densities, although the discharge density was slightly higher than the control for most of the year. In 1974, benthic densities increased 200 to 600% over the previous year in both control and discharge areas. During the first six months, the control populations were higher than those in the discharge, despite the increased heat input during the same period (January through June). After August, discharge densities increased; by November, densities were 200% of those at the control, even though the power plant had decreased the total thermal additions during this period. Throughout 1973, discharge densities were 200 to 300% higher than control densities. Beginning in January 1975, heat rejection was consistently the highest observed during the three operational years of this study. Enhancement of benthic growth that occurred during the winter of 1974 attained the highest densities observed during any period, and these densities were maintained during the 1975 season.

The temporal changes in benthos induced in both discharge and control areas were compared using the mean annual benthic densities as an

Fig. 2.72. Surry — Comparison of benthic population densities in the discharge and control areas (1973-1975).

indicator of long term trends in the population (Fig. 2.73). During the three operational years, control densities increased by 198% in 1974 (from a low in 1973), but declined again in 1975 to densities comparable to 1973. The three discharge stations generally exhibited an increase in densities from 1973 to 1974, which remained high through 1975. When compared individually, station DIS exhibited the greatest change in benthic densities, increasing by 500% for 1974 (from a low in 1973). In 1975, these densities declined slightly to 328% of the 1973 values. Station CBC exhibited moderate increases in density from 1973 to 1974 (188%), and values remained high in 1975. Station HPS was affected least of all as densities increased by 222% in 1974, but declined in 1975 to densities 145% greater than 1973. On an annual basis, the density of benthos was clearly enhanced for stations affected by thermal additions, and the degree of enhancement was related to the magnitude of the heat input at various distances from the discharge. Control stations did not exhibit this enhancement in benthic densities.

Fouling community. Fouling organisms were collected on 125 by 75 mm asbestos plates suspended 1 m above the bottom at three locations in the James River estuary. Two pair of horizontal fouling plates and two pair of vertical fouling plates were suspended at each of three stations (Fig. 2.74); one horizontal plate and one vertical plate were replaced bimonthly, while the other of the pair was replaced annually. The fouling community data were reported as the number of individuals per 0.1 m².

ORNL DWG 76-12502 R1

Fig. 2.73. Surry - Comparison of mean annual benthic densities for control and discharge areas (1973-1975).

ORNL DWG. 76 - 12498

Fig. 2.74. Surry - Fouling plate sampling program.

The three stations used in the monitoring program represented one discharge area (station 8) and two control areas (stations 6 and 16); however, their placement in the estuary should have been considered more carefully. Station 8, in the discharge area, was continually exposed to thermal effluent. The two control areas, however, were located on the north bank of the James River and were positioned at the mouths of creeks entering the river. A sewage treatment plant and brewery located on the north bank of the river may have enhanced conditions for growth as a result of nutrient enrichment from these facilities. Fouling plates were generally removed five times annually (Table 2.15). However, two major problems make utilization of the information difficult to evaluate: (1) there was heavy loss of plates over the three-year period, and no replicates were available to substitute missing values; and (2) although the plates should have been removed at equal bimonthly intervals, this sampling frequency was not consistently maintained, resulting in the inter-year comparison of numbers of fouling organisms colonizing the plates over variable time intervals. Because of the inadequacy of the fouling data, no statistical analysis was performed.

Despite the scarcity of sampling dates and stations, temporal variations in the densities of the fouling community were compared during the three operational years (Fig. 2.75). For the purpose of this study, the density of individuals on both the vertical and horizontal plates was combined. One station was not sampled in October 1973, and all the horizontal plates for the first six months of 1974 were lost; therefore, these months show only the density of the vertical plates.

Table 2.15. Surry - Sampling frequency of the fouling plate study

1973	1974	1975
Horizontal plates		
-	-	-
-	-	-
March	-	-
-	-	-
-	-	May-June
June	-	-
-	July-August	July-August
August	-	-
-	September-October	September-October
October	-	-
-	November-December	November-December
December	-	-
Annual data lost	Annual data	Annual sampled differently
Vertical plates		
-	January-February	January-February
-	-	-
March	March-April	-
-	-	-
-	May-June	May-June
June	-	-
-	July-August	July-August
August	-	-
-	September-October	September-October
October	-	-
-	November-December	November-December
December	-	-
Annual data lost	Annual data	Annual sampled differently

The latter problem is not considered critical, however, since the settlement of fouling organisms was usually very low during the spring.

During all three years, the density of fouling organisms was generally highest on the August or September plate, which had been exposed to the environment for at least two months prior to collection. This abundance would be expected since many of the adult benthic and fouling organisms would be reproducing during the summer. In addition, there was a trend

Fig. 2.75. Surry - Density of fouling organisms collected (after about two months immersion) on both the horizontal and vertical tiles combined (1973-1975).

over the three years toward an increase in the total density of fouling organisms (Fig. 2.75); this trend may or may not correspond to the increased power production at Surry.

The fouling study data did not illustrate any clear or consistent trends with regard to the densities at the three stations. During 1973 and 1974, station 6 on the north shore of the James River had the highest density of fouling organisms, while densities at stations 8 (discharge) and 16 remained low. In 1975, this pattern changed, and the discharge station had twice the density of fouling organisms of the other two stations. This increase may have been a result of an increase in larval additions at station 8 from organisms surviving passage through the condenser or from an unusually heavy spawn of adult fouling organisms in the general area of the discharge. However, since sampling size was extremely small, the observed increase in densities may also have been a result of sampling variability in the three areas.

The FES for Surry predicted that attached fouling organisms might be killed at temperatures above 90°F. Data from the monitoring program are not adequate to validate this prediction since the limited data for 1975 suggest that densities of fouling organisms at the discharge were not inhibited by 90°F or greater. This temperature was maintained and exceeded from July through mid-August (the same period when settlement of fouling organisms was greatest).

Fouling plates at all stations were predominated by barnacles (*Balanus* sp.) and an amphipod (*Corophium lacustre*). These two organisms together often accounted for 90% of the fouling community. In the fall and winter, another amphipod (*Gammarus* sp.) and a bivalve (*Congeria leucophaeta*) also appeared in moderate numbers. Again, due to sample size and periods of missing data, no species diversity indices were applied to the fouling data. Generally, no more than eight genera were present at any station during any sampling period.

At a similar power plant site located on the Patuxent River estuary (Chalk Point, Maryland), the following differences between fouling plates located at the intake as compared to the discharge ($\Delta T = 11.4^{\circ}\text{F}$) were reported.³⁷ First, species composition was generally similar at both locations. Secondly, a higher production occurred at the discharge during all months even though fewer species were present at the discharge (dry weight at the discharge was nearly three times greater than intake). Thirdly, differences in species, biomass production, and total number of individuals appear to be temperature dependent with other factors exerting minor influence. The fouling study at Surry might well use methods employed by these authors to upgrade the fouling plate study.

(iv) Fish

Fish populations in the James River were monitored using haul seines and otter trawls.

Haul seines. Two haul seine sampling programs were in use at Surry; one program was performed at regular monthly intervals to monitor shore zone fish populations, while the other program was performed periodically to estimate the total population of shore zone fishes in the James River estuary in the vicinity of the site. The seine used in both programs was a 6.4-mm-bar mesh seine that was 15.2 m long and 1.8 m deep.

In the first shore zone sampling program, the seine was hauled along a 100-m stretch of beach parallel to the shoreline. In 1970, this beach seining was performed in June, August, October, and December. Monthly samples were consistently taken beginning in 1971, except when ice formation prevented effective seining. Seven stations have been sampled since 1970, and all are located between Jamestown Island and the power plant (Fig. 2.76). However, data from this monitoring program were not analyzed for this report.

For population estimates, replicate seine hauls at three stations were made along the shore between the intake and discharge (Fig. 2.76). The seine was stretched 15 m perpendicular to the shore, and the offshore end was swept toward the shoreline inscribing an arc. The bottom area sampled by the seine could thus be calculated, and the numbers of fish caught per unit area were extrapolated to estimate the total population of each species of shore zone fish in the vicinity of the plant.

It is recommended that this phase of the haul seine monitoring program be discontinued for the following reasons: (1) The shore zone is a

Fig. 2.76. Surry - Fish sampling program.

dynamic and unstable habitat characterized by wide fluctuations in water temperature. Fish continuously move in and out of this habitat in response to changing temperature regimes, food availability, and shelter.

(2) Some of the fish that frequent the shore zone are schoolers; therefore, sophisticated sampling techniques would have to be employed to properly sample the nonhomogenous distribution of the population. As presently conducted, the seining program associated with inshore fishes is inadequate for obtaining realistic population estimates in the area of Hog Point. Thus, extrapolation from sampling three small areas was

insufficient to obtain realistic population estimates for shore zone fishes in the vicinity of the power plant.

Fish trawls. Fish trawl sampling surveys were performed monthly using a 5.5-m long by 3.05-m wide otter trawl with 6.4-mm bar mesh. At all stations, trawls were made perpendicular to the shoreline and not along the main river channel. In the discharge area, three transects were made radiating off the discharge groin, and these are identified as transects DA, DB, and DC (Fig. 2.76). For the purpose of this study, the control transects sampled were Hog Point South-to-North (HPS-N), INT, and Jamestown Island (JI). Transect HPS-N was considered a control rather than a discharge (as in the plankton and benthic sampling programs) because the transect extended into deeper waters not affected by the thermal additions of the plant. All catch data were reported as the number of fish caught per unit effort during a 10-min trawl.

Trawl data were available from 1971 through 1975. The preoperational years were considered to be 1971 through 1973, and the operational years were 1974 and 1975. Assignment of 1973 as a preoperational year was made because thermal additions were minimal during the first six months of operations in that year. During 1971 and 1972, from two to six stations were sampled, although several monthly trawls were not performed and all stations were not sampled during each survey. From 1973 through 1975, trawl data were collected more consistently at the six transects.

Temporal variations in the monthly catch per unit effort (CPE) over both the preoperational and operational years were compared for stations in the discharge and control areas (Fig. 2.77). In preoperational years (1971 through 1973), fish CPE in control areas was highest in April and July 1971 and March and October 1972. In the discharge areas (prior to startup of the power plant), fish catches were highest in April, September, and December 1971 and in February and April 1972. During the latter part of 1972 and early 1973, fish catches in discharge areas were greatly reduced, possibly as a result of fluctuations in power plant testing operations. In periods of plant operations (1973 through 1975), fish catches in the discharge increased greatly from November 1973 through February 1974, November 1974 through December 1974, and again in April 1975. These increases may coincide with the presence of large numbers of fish during the spring and fall spawning runs. During the warmer months (May through September) in both operation years, the CPE was lowest in the discharge and often highest in the control areas. The fish trawl data indicate that fish were avoiding the plume area during the warm summer months but concentrated in the plume area in the early spring and winter months, when temperatures were close to their preferred range. The Surry FES prediction that fish might congregate in the plume during winter months and avoid the plume during summer months is validated by this analysis.

The fish CPE data collected at six trawl stations during the preoperational and operational years are summarized in Table 2.16. The ratio of the mean CPE in the operational years (O) to the mean CPE in the

Fig. 2.77. Surry - Comparison of the mean monthly fish catch per unit effort for discharge and control areas (1971-1975).

Table 2.16. Survey - Total and mean annual fish catch per unit effort (CPE) for all stations during the preoperational period (1971-1973) and the operational period (1974-1975)

Preoperational years (1971-1973)						Operational years (1974-1975)					
Station	Total CPE	Total number of trawls	Mean CPE	Standard deviation	Coefficient of variation	Total CPE	Total number of trawls	Mean CPE	Standard deviation	Coefficient of variation	Operational preoperative
Control											
HPSN	1573	33	47.7	51.8	108.7	872	24	36.3	40.8	112.2	0.8
Intake	1585	32	49.0	37.6	80.1	1152	24	48.0	65.0	135.4	1.0
J1	1565	33	47.1	50.3	125.9	792	24	33.0	30.7	92.9	0.7
Discharge											
DA	576	22	26.2	30.6	116.8	1065	24	44.4	44.7	100.7	1.7
DB	1021	34	30.0	31.1	103.5	1824	24	76.0	80.0	106.1	2.5
DC	688	22	29.5	37.0	129.1	2117	24	88.2	94.0	106.5	3.0

preoperational years (P) is given for each station. The three stations (HPS-N, INT, and J1) form one group (controls), while stations DA, DB, and DC form a second group (discharge). The ratios for the former group varied from 0.7 to 1.0 and for the latter group varied from 1.7 to 3.0. The stations were combined as indicated above to form the control and stressed (discharge) area (Table 2.17). The mean CPE in 1975 at the discharge areas shows a two-fold increase over the mean in 1974.

The mean CPE was assumed to follow a Poisson process with some rate λ_t at time t . The transformation $x = 0.5 (\sqrt{N} + \sqrt{N+1})$ (where N is the CPE) was used to obtain normality, and the ratios of the means for the transformed variables are presented in Table 2.18. The ratio of the transformed mean CPE in the discharge to the transformed mean CPE in the control is defined by θ . In Fig. 2.78, the ratios are plotted with the confidence interval for each year. The ratio $\hat{\theta}$ shows an upward trend. From 1971 through 1974, the confidence interval includes one, indicating

Table 2.17. Surry - Mean and total annual fish catch per unit effort (CPE) for control areas (HPS-N, INT, JI) and the discharge area (DA, DB, DC)

Year	Total CPE	Number of traw's	Mean CPE	Standard deviation	Coefficient of variation
Control stations					
1971	1581	29	54.5	42.1	77.3
1972	1494	33	45.3	48.8	107.7
1973	1558	36	43.3	57.2	132.2
1974	1359	36	37.8	38.1	100.8
1975	1457	36	40.5	55.8	138.0
Discharge stations					
1971	459	11	39.1	38.8	99.3
1972	889	31	28.7	33.1	115.3
1973	926	36	25.7	30.6	118.8
1974	1597	36	44.4	48.9	110.2
1975	3409	36	94.7	91.6	96.7

Table 2.18. Surry - Comparison of annual θ values^a for fish catch per unit effort (CPE) for both preoperational and operational years

Year	Observed θ	95% Confidence limits		Δt [°F (°C)]
		Upper limit	Lower limit	
1971	0.83	1.0	0.6	
1972	0.80	1.2	0.55	
1973	0.82	1.1	0.6	2.1 (1.2)
1974	1.1	1.5	0.85	2.4 (1.3)
1975	1.6	2.4	1.1	4.5 (2.5)

$$\theta = \frac{\bar{X}}{\bar{Y}}$$

$$\text{where } \bar{X} = \frac{1}{n} \sum X_i = \frac{1}{n} \sum [0.5 (\sqrt{N_i} + \sqrt{N_i+1})]$$

= mean at discharge;

$$\bar{Y} = \frac{1}{n} \sum Y_i = \frac{1}{n} \sum 0.5 (\sqrt{N_i} + \sqrt{N_i+1})$$

= mean at control.

Fig. 2.78. Surry - Yearly variation in the ratio of catch per unit effort (θ) at the discharge compared to the ratio of catch per unit effort at the control area.

that the mean CPE at the two stations are not significantly different.

In 1975, the interval does not include one, indicating a significantly large CPE in the discharge.

The preference of fish for the thermally affected area of the James River can be explained on the basis of both physiological and ecological processes. Neill and Magnuson³⁸ reported that fishes exposed to a power plant discharge plume during summer months either avoided or concentrated in the area, and the fishes distributed themselves in the plume primarily in accordance with species-specific thermoregulatory preferences. Different species tended to maximize their exposure to temperatures within a species-specific temperature range. Strawn³⁹ found that young channel catfish (a species that is prevalent at Surry) grow fastest and have their greatest ecological efficiency (net growth efficiency) at 84 to 86°F. The optimal environment for growth for each species varies, but is related to the preferred temperature and the availability of food. If food organisms are abundant in the discharge area and the water temperature is within the preferred temperature range for a species, the species will remain in the area. However, if food is scarce, then fish may move out of the plume to search for food. In Neill and Magnuson's study,³⁸ fish that were living in the outfall area at their preferred temperature also encountered abundant food supplies. This also seems to be the case at Surry, since the discharge area generally had higher densities of benthos than control areas. In addition, the mean monthly temperatures in the discharge area were generally below 90°F, which is within the preferred temperature range for most species in the area. The combination of an abundant food supply (benthic density) and preferred temperatures could explain the preference of fish for the discharge area. Many of the species in the Surry area are primarily

bottom feeders (e.g., spot, croaker, bullhead, and channel catfish), and these species could take advantage of the increased benthic production in the discharge area.

In summary, results of the fish monitoring data from 1971 through 1975 illustrate that the CPE increased directly as the mean annual ΔT increased. This increase may be due to the establishment of a preferred temperature regime and the coinciding increase in benthic organisms in the discharge area. Although fish catches in the discharge area increased during operational years, this does not indicate that increases in the standing crop or growth rates of fish in the James River also occurred; however, it does indicate that some changes in fish distribution may have resulted in response to thermal discharges.

b. Statistical models for impact assessment

In the previous sections, the thermal discharge (ΔT) was shown to increase from 1973 through 1975. The behavior of the four major trophic levels was discussed in detail in relation to possible thermal effects. In this section, some simple models to assess the effect of the thermal stress will be developed.

In most impact assessment models, it is customary to compare the discharge area (or a few stressed areas) with a 'control' area. In nature, there is no control area; however, if one uses 'control' to indicate a nonstressed area or reference area, one can obtain reasonable results.

Some investigators have suggested using the ratio of the responses in the two areas as the variable of interest. The ratio can be written as

$$R_S \propto R_C \rightarrow R_S = KR_C,$$

where R_C and R_S are the responses at the control and stressed areas.

One can generalize this model to obtain

$$R_S \propto (R_C)^\alpha \rightarrow R_S = K(R_C)^\alpha,$$

where α is some constant. Clearly when $\alpha = 1$, a simple ratio is obtained.

There will exist a correlation between the two patterns. This correlation does not represent any cause and effect however; rather, it represents the natural variations on the environment. The response of interest is not R_C , but R_S . Suppose factors $f_1, f_2, f, \dots, f_p$ are p stress factors that can be measured and are suspected to affect the organisms in an aquatic system. The general model of the form

$$R_S = K(R_C)^\alpha \prod_{j=1}^p (f_j)^{B_j}$$

can then be formulated.

This model is a hypothesis and is not based on any theoretical considerations. One can formulate other models just as easily. The advantage of a model of this form is that the parameters can be estimated easily using ordinary least-square methods by using a logarithmic transformation. Suppose, for example, only one factor (f_1) is important. Then the model can be written as

$$\ln R_S = \ln k + \alpha \ln R_C + B_1 \ln f_1 .$$

The model can be interpreted as follows: By introducing the term $\ln R_C$ the natural variation is accounted for in the system. The hypothesis to be tested is that B is equal to zero; that is, after removing any natural (temporal) variation, one observes only pure noise. If B_1 is significantly different from zero, then one would be led to suspect a significant (in the logical sense) effect due to f_1 . In Table 2.19, the results of some simple models for phytoplankton, zooplankton, and benthos are summarized. In these models, the stress that is being investigated is thermal stress, and the thermal stress was measured as a ratio of the temperature in the discharge to the temperature at the intake structure. Also, additional terms were included to allow for lagged effects. For example, the model for phytoplankton is given by

$$R_S = \alpha_0 + \alpha \ln R_C + B_1 \delta_0 + B_2 \delta_2 ,$$

Table 2.19. Surry - Linear models for thermal effects on phytoplankton, zooplankton, and benthos

I. Phytoplankton	$y = 3.10 + 0.62 C - 1.28 \delta_0 - 0.81 \delta_2$ (0.07) ^a (0.50) (0.37)	R^2 0.91	S.D. 0.32	C.V. 4.7	N 33
II. Zooplankton	$y = 3.90 + 0.46 C - 2.50 \delta_0 + 1.40 \delta_2$ (0.13) (1.06) (0.82)	0.63	0.64	10.3	26
III. Benthos	$y = 1.20 + 0.60 C + 2.00 \delta_2$ (0.12) (0.56)	0.75	0.27	7.7	13
IV. Zooplankton-phytoplankton	$y = 3.18 + 0.26 C + 0.60 \ln (P_0 + 1) - 0.35 \ln (P_2 + 1)$ (0.12) (0.14) (0.11)	0.66	0.63	9.8	29

where $y = \ln (x + 1)$ where x is the density of phytoplankton, zooplankton, etc., in discharge;

$c = \ln (x + 1)$ where x is the density of phytoplankton, zooplankton, etc., in control;

$\delta_1 = \ln (T_S/T_C)$ at lag i ;

P_0 = phytoplankton in the discharge at lag 0;

P_2 = phytoplankton in the discharge at lag 2.

^aValues in parenthesis are standard errors.

where

$$\delta_0 = \ln \frac{T_S}{T_C} \text{ at lag zero,}$$

$$\delta_2 = \ln \frac{T_S}{T_C} \text{ at lag 2,}$$

$$R_S = \ln(P_S + 1),$$

$$R_C = \ln(P_C + 1).$$

The temperatures at the discharge and control areas are T_S and T_C , respectively, measured in degree centigrade. The phytoplankton concentrations in the discharge and control areas are P_S and P_C respectively.

(i) Phytoplankton

In the model for phytoplankton (Model I, Table 2.19), the coefficients of the temperature differentials δ_0 and δ_2 are negative, indicating a deleterious effect of discharge temperature on the density of phytoplankton. Increased temperatures have been reported to have inhibitory effects on phytoplankton populations.^{33,35,40} Other factors that may be responsible for lowering phytoplankton concentrations are: (1) the prolonged residence times of cells at the discharge area during low river flow periods, which subject phytoplankton to additional heat stress, (2) the synergistic effects of temperature and mechanical damage induced by entrainment of organisms in the condenser, (3) the synergistic effects of changes in water temperature and salinity, and (4) the intense grazing pressures on phytoplankton by localized dense concentrations of zooplankton.

(ii) Zooplankton

In the zooplankton equation (Model II, Table 2.19), the density of zooplankton in the discharge is modeled as a function of thermal stress. The coefficient of δ_0 is negative (-2.5), and the coefficient of δ_2 is positive (1.4). The model for phytoplankton also included the δ_2 term. Given the signs on the coefficients and the known predator-prey relationships between zooplankton and phytoplankton, a better model for describing the behavior of zooplankton in the discharge would be Model IV (Table 2.19). The coefficient for phytoplankton in the discharge at lag 0 is 0.6, and at lag 2 it is -0.35. The signs on these coefficients

are in keeping with the predator-prey concept. If at time $t-2$ the density of phytoplankton is very low, then the zooplankton have a limited amount of food, and therefore, the population starts declining. The rate at which zooplankton densities decrease would be a function of the density of phytoplankton. As zooplankton decline, the phytoplankton have an opportunity to recover and grow. Over time, one should observe a growth and decay pattern with zooplankton population peaks and phytoplankton population peaks displaying lag periods. This behavior can be observed in Fig. 2.79, where peak zooplankton densities usually fall a few weeks behind the peaks in phytoplankton densities. If the model for phytoplankton is valid and the power plant continues to operate at a high level of thermal discharge, the concentration of zooplankton may continue to decline over time.

Models I and IV together constitute a set of simple-transfer function models. These types of models can be developed for all the trophic levels (phytoplankton, zooplankton, benthos, fish) in an aquatic system. Development of such models is necessary for a sound understanding of the impact of nuclear power plant operations on the aquatic environment. Simple regression models as these indicate only the short-term behavior of individual ecological parameters.

One of the objectives of a monitoring program should be to calibrate the mathematical models that have been developed to study the stability of the ecosystem.¹¹ With proper monitoring programs, one can develop a series of predictive curves for various operating conditions using the mathematical models.

Fig. 2.79. Surry - Comparison in temporal variations in phytoplankton and zooplankton populations in the discharge area (stations CBC, DIS, and HPS).

(111) Benthos

The coefficient of α_2 in the benthos model (Model III) in Table 2.19 is greater than zero. A lag of two appears in all the models discussed previously. The appearance of the lag-two term in the equations for phytoplankton and zooplankton is not surprising because of the characteristic populations dynamics of these two groups. The lag-two term is probably related to the population densities of phytoplankton and zooplankton through some nonlinear relationship. However, since benthos were sampled only a few times each year (usually bimonthly), it is not possible to develop a further relationship to describe the behavior of benthos in the discharge area. The turnover rates of benthos in general have been observed to be relatively constant, about 2.5 to 5 with a mean of 3.5.⁴² Since benthic organisms have relatively slower turnover rates than plankton, the lag of two is not as important in explaining the behavior of benthos in the discharge area.

In summarizing the results discussed in the preceeding paragraphs, one observes that while the phytoplankton and zooplankton densities decrease in the thermally affected area, benthic and fish concentrations have increased. Whether these conditions are less stable, more stable, or the same as those prior to plant operations cannot be answered on the basis of the monitoring data collected. Power plant operation perturbs the immediate environment. The question of interest is whether the system will return to its original state, achieve stability at a new level, or continue a trend toward ecological instability. Future

monitoring programs should be formulated to answer these questions and determine what measurable parameters are most important for analyzing ecosystem stability.

The values of the parameters discussed in the preceding paragraphs were estimated using ordinary least squares (OLS) techniques. The assumption was made that these estimators have all the properties generally associated with OLS estimators. In the models discussed above,⁴³ this is not strictly true. However, given the scope of this report, such first approximations are considered sufficiently accurate.

2. Impingement

From the period of initial operation through May 1974, impingement was monitored on the conventional traveling screens of the high-level canal near the entrance to the power plant. Impingement monitoring during this time consisted of four 5-min samples per unit, collected five times per week during daylight and three times per week during the night. In May and June 1974, the high-level screens were replaced by modified lower-level continuous traveling screens at the river intake. Fish encountering these screens drop into a water filled trough, are removed from the trough by a low pressure wash, and are then dropped into a running water sluiceway, which empties back into the James River. Monitoring was conducted five days a week with two 5-min replicates per day. Data collected during the ten 5-min samples per week are extrapolated to weekly estimates (seven-day period) to total fish impinged.

A total of 152 weeks of impingement data was available for analysis and evaluation. From January 1973 through December 1975, 12.7 million fish representing 66 species were impinged. Of the 66 species impinged from 1973 through 1975, species comprised 94% of the total catch (Table 2.20). The total numbers impinged in 1973, 1974, and 1975 were 2.7, 3.9, and 6.1 million fish respectively. Clearly, fish impingement increased by 154% in 1974 and by 236% in 1975. This increase may be a result of two factors: an increase in the total number of juvenile fish present in the estuary (particularly young-of-the-year, threadfin shad, Atlantic menhaden, and spot) or a result of reimpingement of fish injured (but not killed) by the traveling screens. If injured fish are being reimpinged after their return to the James River, a mark-and-recapture study could be initiated to determine the magnitude of the reimpingement and the long-term survival of impinged individuals. Trawl samples collected in front of the intake screens and fish collected in the impingement study could be monitored for recapture of marked individuals.

In the following discussion, a dominant species refers to one that represents at least 2% or more of the total fish impinged during the three-year period. The 12 dominant species were classified by salinity preference, location in the water column, and feeding habit (Table 2.21). In terms of salinity preference, 34% of the species impinged were marine (spending most of their life in the ocean), 28% were anadromous, 24% were considered typical freshwater species, and only 8% were entirely estuarine. The 12 species were found to be distributed fairly equally over the water column; however, according to feeding habit, 61% were

Table 2.20. Surry -- Species list showing percent composition by year and for the total three-year study period

Species common name	Scientific name	1973 number (%)	1974 number (%)	1975 number (%)	Total -- three years number (%)
Blueback Herring	<i>Alosa aestivalis</i>	849,912 (34)	1,487,462 (38)	625,704 (10)	2,963,078 (23)
Threadfin Shad	<i>Dorosoma petenense</i>	31,704 (1)	128,537 (3)	1,660,104 (27)	1,820,345 (14)
Atlantic Menhaden	<i>Brevoortia tyrannus</i>	268,728 (11)	286,436 (7)	1,056,552 (17)	1,611,716 (13)
Spot	<i>Leiostomus xanthurus</i>	372,752 (15)	254,295 (7)	902,883 (15)	1,529,927 (12)
Atlantic Croaker	<i>Micropogon undulatus</i>	61,512 (2)	545,195 (14)	239,496 (4)	846,203 (7)
Bay Anchovy	<i>Anchoa mitchilli</i>	59,112 (2)	374,060 (10)	276,120 (5)	709,292 (6)
Gizzard Shad	<i>Dorosoma cepedianum</i>	306,782 (12)	190,592 (5)	188,640 (3)	686,014 (5)
Alewife	<i>Alosa pseudoharengus</i>	201,360 (8)	127,440 (3)	277,956 (5)	606,760 (5)
Spottail Shiner	<i>Notropis hudsonius</i>	112,608 (5)	96,140 (3)	202,032 (3)	410,780 (3)
White Perch	<i>Morone americana</i>	44,784 (2)	103,616 (3)	118,656 (2)	267,056 (2)
White Catfish	<i>Ictalurus catus</i>	24,504 (1)	120,037 (3)	105,120 (2)	249,661 (2)
Atlantic Silverside	<i>Menidia menidia</i>	106,776 (4)	37,647 (1)	83,060 (1)	227,483 (2)
Total		2,440,534 (97)	3,751,457 (97)	5,736,320 (94)	11,928,316 (94)

filter feeders (planktonic), 24% were omnivores, 7% were scavengers, and 2% were carnivores. In addition, it must be noted that of the 12 major species being impinged, five were clupeids which comprised 60% of the total fish impinged for the three-year study period (Table 2.21).

The impingement data will be discussed in two ways. First, the discussion will identify the six most commonly impinged fish at the Surry site and relate the major periods of impingement to life history information and spawning behavior. Secondly, a statistical analysis of the impingement data will be made identifying and assessing both physical factors in the environment and biological characteristics that contribute to impingement.

Table 2.21. Surry – Grouping of dominant fish species by salinity preference, location in water column, and feeding habit

Salinity preference (%)					
Freshwater			Marine		
Gizzard shad	5		Atlantic menhaden	13	
White catfish	2		Atlantic silverside	2	
Threadfin shad	14		Atlantic croaker	7	
Spottail shiner	3		Spot	12	
Total	24		Total	34	
Estuarine			Anadromous		
White perch	2		Blueback herring	23	
Bay anchovy	6		Alewife	5	
Total	8		Total	28	
Location in water column (%)					
Bottom		Midwater		Surface	
Croaker	7	Alewife	5	Atlantic menhaden	13
White catfish	2	Blueback herring	23	Atlantic silverside	2
Spot	12	White perch	2	Bay anchovy	6
		Gizzard shad	5	Spottail shiner	3
				Threadfin	14
Total	21	Total	35	Total	38
Feeding habit (%)					
Carnivorous			Planktonic (filter-feeder)		
White perch	2		Atlantic menhaden	13	
			Threadfin	14	
			Bay anchovy	6	
			Blueback herring	23	
			Alewife	5	
Total	2		Total	61	
Scavengers			Omnivorous		
Gizzard shad	5		Spot	12	
White catfish	2		Croaker	7	
			Spottail	3	
			Atlantic silverside	2	
Total	7		Total	24	

a. Species evaluation

Six dominant species at the Surry site composed 75% of all species impinged from 1973 through 1975. These species were blueback herring (*Alosa restivalis*), threadfin shad (*Dorosoma petense*), Atlantic menhaden (*Brevoortia tyrannus*), spot (*Leiostomus xanthurus*), Atlantic croaker (*Micropogon undulatus*), and bay anchovy (*Anchoa mitchilli*).

(i) Blueback herring

This species predominated the fish impingement catches during 1973 and 1974, but declined in importance in 1975 (Table 2.20). The temporal variations in numbers of bluebacks impinged from 1973 through 1975 are shown in Fig. 2.80. In addition, the seasonal water temperature, spawning temperature, and spawning period are identified. Two major periods of impingement occurred annually from January through May and from September through December (Fig. 2.80). Both peaks consisted primarily of young-of-the-year, and few (if any) adults were impinged. Spawning of this species occurs in April through May (Fig. 2.80) in freshwater areas upriver of the plant. Beginning in September, young-of-the-year (spawned during the spring) are impinged during their seaward migratory runs into Chesapeake Bay; however, a portion of the young-of-the-year appear to overwinter in the estuary, accounting for the winter impingement (December through March). Bluebacks typically exhibit peaks in population density in the Chesapeake during the fall and winter.⁴⁴ These peak population periods are composed of individuals six months old measuring 60 to 80 mm in total length.

ORNL DWG 78-12509 R1

Fig. 2.80. Surry — Impingement of Blueback Herring (*Alosa aestivalis*) from 1973 to 1975.

(ii) Threadfin shad

Threadfin shad were the second most abundant fish impinged during 1973 through 1975, and impingement occurred during all months except May, June, and July (Fig. 2.81). This period of low impingement occurs after the shad spawning period (March through early May),⁴⁵ and due to the slow developmental rate of the young, fish are too small to be impinged. Juvenile fishes that were impinged were less than one year old and ranged from 60 to 100 mm in total length. According to Griffith and Tomljanovich,⁴⁶ threadfin shad are very susceptible to impingement at temperatures below 10°C. This accounts for the high impingement mortality of this species in the winter and early spring months.

(iii) Atlantic menhaden

This species ranked third in total number of fish impinged during 1973 through 1975. Menhaden spawn at sea in the late fall, and the young spend most of their first year in estuaries such as Chesapeake Bay. Most of the fish impinged ranged from 40 to 120 mm in total length, and according to Mansueti and Hardy,⁴⁷ fish of this size range are less than one year old. The majority of menhaden impingement occurred from mid-February to October and consisted of two separate age classes (Fig. 2.82).

ORNL DWG 76-12511R1

Fig. 2.81. Surry — Impingement of Threadfin Shad (*Dorosoma petenense*) from 1973 to 1975.

ORNL DWG 76-12507 R1

Fig. 2.82. Surry - Impingement of Atlantic Menhaden (*Brevoortia tyrannus*) from 1973 to 1975.

(iv) Spot

The spot (*Leiostomus xanthurus*) was the fourth most abundant fish impinged at the Surry Power Station for the period January 1973 through December 1975. Most of the fish impinged were 40 to 120 mm total length (young-of-the-year), and impingement was greatest from March through November (Fig. 2.83). Spot spawn at sea in the late autumn through early winter, and larvae and young enter the estuaries shortly thereafter. Only young-of-the-year are vulnerable to impingement because this age class of fish prefer shallow low salinity waters.⁴⁴

(v) Atlantic croaker

Croakers comprised 7% of all fish impinged from 1973 through 1975 and were the fifth most numerous fish collected on the screens. This species spawns at sea from late summer through the winter and even into early spring.⁴⁸ During the first year of life, young croakers prefer low salinity water and remain near the bottom. Impingement of croakers was greatest soon after their spawning period from February through May (Fig. 2.84). As shown in Fig. 2.84, impingement occurred in four fairly large peaks during the first half of the year (1973). In 1974 and 1975, two larger peaks are present instead of four, and again these occurred during the first half of the year. These peaks consisted of impinged individuals of young-of-the-year fish ranging from 20 to 100 mm total length.

Fig. 2.83. Surry - Impingement of the Spot (*Leiostomus xanthurus*) from 1973 to 1975.

Fig. 2.84. Surry - Impingement of Atlantic Croaker (*Micropogon undulatus*) from 1973 to 1975.

(vi) Bay anchovy

This species accounted for 6% of all fish impinged during the three-year study, being the least abundant in 1973 and most abundant in 1974.

Anchovies were impinged rather randomly throughout the year (Fig. 2.85), the 40 to 100 mm (total length) size range of fish accounting for the majority of those impinged. According to Mansueti and Hardy,⁴⁷ this size range represents first-year mature fish. Young-of-the-year anchovy prefer shallow, low-salinity waters similar to the area adjacent to the power plant intakes.

(vii) Statistical analysis

The impingement data have been analyzed to determine and evaluate those factors, acting independently or in combination, that contribute to impingement.

(viii) Total impingement analysis

The total number of fish impinged over the three-year period was analyzed as a function of temperature, river flow, and salinity. The correlation coefficients for the main effects and the interaction effects, with their significance levels, are shown in Table 2.22. All effects are significantly different from zero except the temperature x salinity interaction. Even though the correlations are significantly different from zero, each of the effects may only explain a small percentage of the variation in impingement.

CRNL DWG 76-12508 RI

Fig. 2.85. Surry - Impingement of the Bay Anchovy (*Anchoa mitchilli*) from 1973 to 1975.

The linear regression equation estimating the total number of fish impinged as a function of salinity (S), temperature (T), and river flow (RF) is

$$\text{Total fish impinged} = 175,553 - 15,167 (S) - 1.920 (T) - 0.3 (RF) .$$

Table 2.22. Surry - Correlation of the main and interaction effects with total number of fish impinged

	Correlation coefficient (Pearson)	Number of samples	Level of significance
Total X temperature	-0.31	150	0.001
Total X salinity	-0.53	75	0.001
Total X river flow	0.21	151	0.004
Temperature X salinity	0.12	74	0.161
Temperature X river flow	-0.35	149	0.001
Salinity X river flow	-0.42	74	0.001

The multiple R correlation of 0.57 is significant at the 0.05 level, but only 32% of the variation in total impingement can be explained by a linear relationship among these three independent factors.

The average number of fish impinged per week was greatest in the temperature range of 10 to 20°C and the salinity range of 0.0 to 0.4 parts per thousand, but tapered off at either extreme for temperature and at the higher extreme for salinity.

(ix) Species analysis

An analysis was performed to identify the species most often impinged, characteristics influencing impingement (mean length, and height:length ratio), and other environmental factors (time of year and temperature) that contribute to impingement. Over the three-year period, those species which accounted for more than 2% of the total numbers impinged were: blueback herring (23%), threadfin shad (14%), Atlantic menhaden (13%), spot (12%), croaker (7%), bay anchovy (6%), gizzard shad (5%),

alewife (5%), spottail shiner (3%), white perch (2%), white catfish (2%), and Atlantic silverside (2%). For all three years, five species accounted for about 70% of all fish impinged; however, if considered on a yearly basis, at least 75% of the impingement could be explained by only five species.

Temperature vs species. A chi-square contingency table was constructed to determine if temperature had a differential effect on impingement of various species. Six categories of temperature (at 5°C increments) were compared against frequency of species impinged. The calculated chi-square value was 349.7 with 280 degrees of freedom. There was a significant correlation ($S = 0.0025$) between frequency of species impinged and various temperatures, indicating that temperature affects the propensity of a species to be impinged differently for different species. This relationship can be seen in Table 2.23 where the mean maximum number of fish impinged (during the peak periods of impingement) is given for various temperature ranges. Atlantic menhaden, for example, are more susceptible to impingement at colder temperatures than the other species.

Length vs impingement. Over 80% of the fish impinged had a mean modal length of less than 100 mm; only 2% had a mean modal length greater than 200 mm; and 65% of those impinged were 60 to 100 mm total length.

The relationship between the height:length ratio and number impinged was determined using linear regression. The four height/length ratio categories were: 0.15-0.25, 0.25-0.35, 0.35-0.45, and >0.45. The

Table 2.23. Surry - Variation in impingement at different temperature ranges for the five dominant species impinged

Species	Number impinged per week (at peaks)	Percent of time at peak	Temperature range (°C)
Blueback herring	8,770	15	15-20
Threadfin shad	10,210	12	10-15
Atlantic menhaden	3,290	21	5-10
Spot	50,060	16	10-15
Atlantic croaker	13,115	15	10-15

percent impinged that fell into each category were 17, 61, 21, and <0.5% respectively. The regression equation is

$$\text{total impinged} = 1609 + 950 (\text{height/length ratio}) .$$

This relationship is statistically significant, but the linear correlation is only 0.08.

The effect of length and temperature on the impingement of blueback herring, threadfin shad, Atlantic menhaden, and spot was determined by multiple linear regression. For blueback herring, the correlation of impingement with temperature alone was -0.39, increasing to -0.40 with the inclusion of length (Table 2.24). When the total impinged was transformed to $\log_{10}$, the correlation coefficient increased to -0.73. Transforming to logs improved the correlation coefficient for all four species. Temperature was more important in explaining impingement than was length for bluebacks and Atlantic menhaden; however, length was important for threadfin and spot (Table 2.24).

Table 2.24. Surry - Correlation (R) of temperature (T) and length (L)
on the impingement of the four dominant species

Species	R(T)	R(T+L)	R(T) ^a	R ² (T+L) ^a
Blueback herring	-0.39	-0.40	-0.73	0.54
Threadfin shad	-0.25	-0.30	-0.20	0.20
Atlantic menhaden			0.44	0.19
Spot			0.38	0.33

^aTotal impinged transformed to log₁₀.

For all species combined, correlations were not significant between log₁₀ total impinged, temperature, and length. Although linear correlations between total impinged and length did not appear to be significant, it was believed that length does have an effect on the number impinged. Thus, a two-way chi-square contingency correlation was performed that relaxed the requirement of a linear relationship. Ten categories of lengths (20-mm increments starting at 20 mm) were compared against the number of fish impinged for each species. For croaker, alewife, white perch, and spot, there were significant differences between lengths and the number impinged.

b. Summary

Of the 12 dominant species at the Surry site, the first five species represented approximately 70% of the total catch. These five species also all have similar life histories, which require migration of the young fish past the intake structure; most fish were less than 100 mm in total length. Therefore, the probability of being impinged seems to be a function of the increase in numbers of fish available for impingement and small body size.

A satisfactory linear relationship (i.e., number impinged as a function of temperature) did not exist for the top four species until $\log_{10}$ transformation of the impinged data was investigated. For blueback herring (the most commonly impinged fish, 23%), a multiple-linear correlation coefficient was found to be 0.73 between temperature (and length) and impinged fish. For interpretation purposes, 53% of the variation in impingement can be explained by variation in temperature and length, with length adding very little to the correlation. For the other species analyzed, however, temperature and length were not as significant. For example, for spot, length accounted for more variation in impingement than did temperature. This would imply that other factors are causing the variations observed in impingement.

Most of the individuals being impinged at Surry are young-of-the-year, and the variation in total number impinged is quite variable from week to week and among years. Salinity, temperature, and river flow all indicate statistically significant (i.e., different from 0.0) linear correlations with total number of fish impinged. A majority (over 70%) of the variation in the total fish impinged was unexplained by a linear relationship of these three key factors. Certainly, temperature and the seasons of the year have an important impact, but they cannot be explained satisfactorily by a linear functional relationship. Transforming the number impinged by $\log_{10}$ did increase correlations of the four major species with temperature.

c. Recommendations

The following recommendations are given to improve the present Technical Specifications monitoring program for the evaluation of impingement impacts.

1. Sampling should be conducted on a regular basis at night (in addition to daytime samples) because diurnal variations in impingement may exist and could bias the estimated total number of fish impinged.
2. At least four 24-hr samples should be taken each year. Each 24-hr sample should consist of six day and six night samples.
3. Turbidity measurements should be taken every two days immediately in front of the trash racks so that the effects of turbidity on impingement can be assessed.
4. A mark and recapture study should be conducted to determine if fish are being reimpinged by the power plant. Marked fish reimpinged on the screens or recaptured in the trawling program will provide information on the long-term survival ability of fish that have been impinged (predator survival, disease, etc.) and quantitative data on the number of fish that are reimpinged by the power plant.
5. Age classes of impinged fish should be determined so that these can be related to the age class structure of the fish populations in the James River in the vicinity of the plant.

3. Entrainment

Entrainment studies at Surry were initiated in April 1975 and involved monitoring of zooplankton.

a. Zooplankton

Zooplankton samples were collected using a stepped-dolique tow technique from the intake and discharge with an 18.5-cm diam Bongo sampler using 202 Nitex net. All samples were collected from April through June 1975. Live samples were stained with neutral red stain. The preliminary zooplankton entrainment studies investigated various techniques for staining organisms and estimating mortalities and evaluated some of the variables influencing mortality estimates, such as diurnal variations in species composition and abundance in replicate tows. Estimates of mortality were calculated using three different methods:

1. By differentiation of stained and unstained organisms (using neutral red) in the intake and discharge.
2. By determination of the number of live organisms per cubic meter in the discharge developed by the number of live organisms per cubic meter at the intake, which results in calculation of percent survivorship.
3. By calculation of the ratio of the number of live organisms per cubic meter in the discharge as compared to the number of live organisms per cubic meter at the intake (with correction for the number of dead organisms at the intake), which results in a corrected percent survivorship.

Estimates of the percent survivorship based on the three methods varied considerably. The percent survivorship calculation based on method 1 resulted in the most variable estimates; method 2 resulted in low estimates because this method assumed that the total number of dead and live organisms in the intake are equal in density; and estimates based on method 3 (ref. 49) resulted in the most consistent values. This method was judged to be the most reasonable of the three techniques employed. However, problems associated with net avoidance, net mortality, and net extrusion and their effect on the calculation were not discussed in depth.

No evaluation of the Surry zooplankton entrainment monitoring program can be made for the following reasons. First, no data for the percent of live and dead organisms are given for the intake and discharge, even though the absolute densities are given. Secondly, the methods used in estimating mortality are not discussed in detail; therefore, intrinsic problems associated with each of the methods are not resolved.

D. CHEMICAL EFFLUENTS

Although chlorine use (limited to 0.5 ppm residual chlorine for 30 min each 8-hr period) is provided for in the Technical Specifications, chlorine has never been employed as a biocide. A mechanical method of cleaning (Amertap) has been employed on several occasions.

E. AVIAN MORTALITY

1. Cooling towers

This is not applicable because the condenser heat is dissipated by once-through cooling.

2. Transmission lines

The applicant proposed that 11 miles of new transmission lines are needed to connect Surry Nuclear Power Plant to various substations. A portion of the adjacent lands (Hog Island State Waterfowl Refuge) is drained and seeded to increase waterfowl utilization. Both resident and migrating populations are supported in the refuge with peak populations exceeding 25,000 birds. The presence of two endangered species, the bald eagle and peregrine falcon, have been observed at the Surry site.

No monitoring data on bird populations were collected; therefore, the impact of transmission lines on bird populations cannot be assessed.

F. SALT DRIFT

This is not applicable because the condenser heat is dissipated by once-through cooling.

G. HERBICIDES

The applicant cleared 3543 acres of timber and bush in the transmission right-of-ways. The corridors were to be maintained free of woody growth

either through seeding or with chemical treatment every three years.

The following herbicides were to be used: Tordon 101 for pines (resistant species), Silnex for oaks (intermediate species), and 2,4,5,T for broadleaf species.

No monitoring data were available from the Technical Specifications program for assessment of impacts related to herbicide use.

V. FINAL ASSESSMENT OF SURRY TECHNICAL SPECIFICATIONS

A. HYDROTHERMAL

1. Conclusions

These general conclusions follow from the staff's review of the Surry hydrothermal monitoring programs.

- (1) In numerous instances, the application of the hydrothermal portions of the Surry Technical Specifications is deficient.
- (2) Even if faithfully executed, the Surry Technical Specifications are inadequate to characterize the operation of the plant, much less its plume.
- (3) The VIMS study yielded much information about the behavior of the Surry plume, but it was too limited in the area covered and too biased in time to yield a definitive characterization of the plume.
- (4) There are no existing data adequate to verify or disprove the validity of the various Surry plume predictions.
- (5) On the basis of the available information, the Vepco physical model study may have been conservative.
- (6) The plume sinks to the bottom an appreciable fraction of the time.

2. Recommendations

The following major recommendations are offered to improve the hydrothermal monitoring carried out by Vepco under Technical Specifications.

1. Plant operating data should be recorded every 15 min and should be available on magnetic tape. These data should include shoreline intake temperature and salinity, high-level intake temperature, condenser outlet temperature, discharge temperature and velocity, condenser flow rate, and heat rejection rate. Summaries should be included in the annual operating reports.
2. The utility should use these data to resolve the time lag problem affecting the ΔT limitation of TS 4.14.A.2.
3. The utility should determine the time lag between fresh-water flows at Richmond and at Hog Point.
4. The present system of thermographs should be expanded. Particular emphasis should be placed on an improved resolution of the horizontal and vertical temperature, salinity, and velocity structure. This information, together with onsite meteorological data, should be available on magnetic tapes on an hourly basis. Analyses of these data, intended to describe the plume in a probability sense and in its relation to ambient and operating parameters, should be included in the annual operating reports.
5. The present series of monthly boat cruises conducted by Vepco under TS 4.13.A.3 should be discontinued.

6. If TS 4.14.A.1 is to be retained, the utility should develop a method to forecast episodes of high intake water temperature and a plan to accommodate such episodes.

B. ECOLOGICAL

1. Summary

The following summary is made from the staff's evaluation of the Surry ecological data.

1. Phytoplankton densities in the discharge during the colder months were higher than those in control areas; however, on an annual basis, thermal additions depressed phytoplankton densities.
2. Over the years, the density of zooplankton was reduced in the discharge area; this reduction, however, was due in part to low phytoplankton concentrations.
3. Densities of benthic organisms were higher in the discharge areas than control areas, especially in 1975, the year of the highest heat rejection by the plant.
4. Overall, fish catches in the discharge area increased from 1973 through 1975, being highest in the plume areas in winter and lowest in the summer.
5. The highest fish impingement occurred during the fall when young-of-the-year migrate seaward past the plant.

Temperature was the main factor investigated that influenced impingement.

6. In the entrainment studies, no justifications were given for the various methods used to estimate mortalities, and intrinsic problems associated with each method were not resolved.

2. Validation and comparison with Technical Specifications

In Table 2.25, a summary is presented comparing the predictions of impact at the Surry site made in the FES with the results of the ORNL staff's analysis of the monitoring data. In addition, a comparison of the required Technical Specifications monitoring is made with the applicant's actual program (Table 2.26).

3. Conclusions and recommendations

a. Monitoring stations

Selection of monitoring stations at Surry should have been made within the following framework. All stations should have comparable physical characteristics (velocity of water, depth of water, bottom sediment type) and comparable chemical characteristics (salinity, pH, NO_3 , PO_4 , O_2). Stations should not be placed at the mouths of creeks or in close proximity to areas affected by sewage effluents or toxic industrial effluents. Therefore, monitoring stations on the north shore of the James River (CBN, H2H, DWS) should be deleted from the monitoring

Table 2.25. Surry - Comparison of impacts predicted in FES with observed impacts

Predicted impacts	Observations from monitoring data
Phytoplankton	
1. The phytoplankton community may change toward a heat tolerant community. Dominance of diatoms may decrease and green and blue-green species may increase in abundance in the plume during summer months.	1. No quantitative data on phytoplankton species changes are available, although diatom genera are generally most predominant at all stations during all months.
2. During the winter, phytoplankton standing crops may increase in the discharge area.	2. Phytoplankton densities in the discharge during colder months were higher than those in control areas, however, on an annual basis, thermal additions depressed phytoplankton standing crop.
Zooplankton	
3. Zooplankton losses will be greatest during the summer months and may have an impact on larval fish growth.	3. Significant reduction of zooplankton densities in the discharge area did not occur during the summer months, although on an annual basis zooplankton standing crops were reduced. Although development of larval fishes may be affected, no data are available to assess this problem.
Benthos	
4. Benthos will probably be eliminated at the discharge groin.	4. Benthos were not sampled in the discharge groin area.
5. Maximum summer temperatures may eliminate benthic species over a considerable area in contact with the plume.	5. Benthic standing crops were highest in stations located in the discharge area as compared to controls, particularly in 1975, the year of highest heat rejection.
6. Attached benthos will be killed at temperatures above 90°F (38°C).	6. No adequate data were sampled to validate this statement, however, densities of fouling organisms were highest at the discharge station during 1975 (ΔT of 14°F (8°C)).
7. Blue crab migration out of the discharge area may occur and this industry may be reduced.	7. No proper sampling gear for collecting blue crabs was employed, thus no assessment of this prediction can be made.
8. Larval clams and oysters will be killed by combined salinity and temperature changes.	8. No data are available for assessing this problem.
Fish	
9. During the summer, adults of most species may avoid the discharge area; however, during the winter, fish may congregate in the plume.	9. During summer months the catch per unit effort (CPE) in the discharge is less than control areas, but during winter months CPE is higher in the plume area.
10. The overall impact of the Surry plant effluents will be to stress fish populations in the Hog Point area. Standing crops and recruitment may be reduced.	10. Overall, fish densities in the discharge increased from 1973 to 1975. Reduction in recruitment and standing crops cannot be assessed with present data.
Impingement	
11. Impingement of adult fishes on travelling screens during spawning runs would be expected.	11. A strong correlation exists between the number of adult fish impinged and the time of the spawning migration. The highest fish impingement occurs during the fall when young of the year migrate out of the estuarine nursery areas.
Entrainment	
12. Larval and egg stages of marine fishes will be entrained since estuarine areas are used as spawning and nursery grounds.	12. The densities of ichthyoplankton passing through the plant were monitored; however, no assessment of mortality of the entrained individuals was made.

Table 2.26. Summary - Comparison of utility monitoring programs with Technical Specifications requirements

Technical Specifications requirement	Utility program	Comments
A. Phytoplankton		
1. Sampled at six stations and at intake and discharge	Adequate	Additional stations added in 1975
2. Analysis of dominant genera and chlorophyll <i>a</i> performed monthly	Dominant genera not adequate; no chlorophyll <i>a</i> for 1974 and four months of 1975 missing	Dominant were identified but not quantitatively enumerated
B. Zooplankton		
1. Sampled at six stations and at intake and discharge	Adequate	Additional stations added in 1975
2. Analysis includes monthly identification of generic composition, life history stage, and species	Adequate	Stations poorly chosen
C. Benthos (settled)		
1. Sampled at three locations and analysis of two vertical and two horizontal plates	Adequate	Stations poorly chosen
2. One pair of plates removed and replaced quarterly	Not performed consistently at quarterly intervals	Many plates lost
3. One pair of plates left for one year	Only 1973 data usable	Annual plates lost for 1972 and 1973
4. Analyzed for species composition and diversity	Adequate	
D. Benthos		
1. Sampled at 16 locations	Adequate	
2. Replicate samples	Adequate	Data presented as if single sample should be presented as replicates
3. Samples quarterly except monthly in June-August	Adequate	
4. Data analyzed to detect change in specific components of community	Inadequate	Data not analyzed in such a manner as to detect these changes
E. Nekton		
1. Trawl samples taken monthly at six locations	Adequate	
2. Seining monthly at three to five locations	Adequate	Method inadequate for estimation of population of inshore fishes
3. Samples analyzed for species composition, size, and life history stage	Inadequate (occasionally)	Trawl data not presented in semiannual reports. Analysis not performed each six months
F. Impingement		
1. Impinged fish identified by species, size, and quantity	Adequate	Better breakdown of age classes needed
2. Recorded in tabular form	Adequate	
G. Entrapment		
1. Planktonic organisms sampled periodically in intake and discharge canals	Adequate	Began in April 1975
2. Data analyzed to determine cooling system passage and entrapment of feces	Inadequate	Intrinsic problems associated with various methods not resolved
H. Chlorine		
1. Residual chlorine at discharge not to exceed 0.1 mg/liter	No chlorine used	Mechanical device
I. Data analysis and evaluation		
1. Monitoring data compared with model and analytical predictions and also with preoperational data	Inadequate (occasionally)	Data in most cases simply reported and no analysis and comparisons made. Exception: annual semioperational report number 4 (fish and benthos)
2. Monitoring program designed to evaluate influence of seasonal pattern salinity and "turbidity zones" on biological populations	Inadequate	See Sect. related to sampling policy

program. If stations are properly selected during the preoperational period, there would be no need to eliminate or add stations at a later time, and a degree of consistency in monitoring would have been maintained from the preoperational to the operational period.

b. Phytoplankton

Qualitative taxonomic identification of phytoplankton genera is inadequate. The total number of cells and a breakdown of the number of cells in each genera is necessary to determine whether major shifts in phytoplankton composition have occurred. However, the FES prediction of major shifts in the community structure from diatoms to blue-greens is probably in error since most blue-green algae blooms associated with thermal effluent occur in freshwater. Most estuarine blue-green algae species do not "bloom" and seldom attain dominance in the estuarine environment.⁵⁰

All data should be consistently collected throughout all years in order to be useful in an analysis of the trends that may be occurring over the years. Because chlorophyll *a* data were not collected in 1974, this parameter cannot be used to assess long-term changes in the system. Primary production should be continued to be monitored using ¹⁴C technique because this method measures net system effects and gives a relatively good indication of long-term changes in productivity.

c. Zooplankton

All data should be reported using consistent units and units that are generally employed in the scientific literature. The Surry zooplankton data were reported in two different units in several of the semiannual reports. Reporting in a standardized set of units should be consistent in all Technical Specification documents.

Monitoring of zooplankton should be increased to biweekly sampling during periods of highest densities (April through October). Major genera should be enumerated, and identification to the species level should be performed for macroplankton.

d. Benthos

Sampling and data analysis should be performed in a consistent manner in all years. The wet weights of benthos reported in 1972 included both meat and shell weight; however, from 1973 through 1975, benthic weights included only meat weights. No inter-year comparison of these units can be made; thus, biomass data for Surry is only useful for intra-year comparisons. If a sampling and analytical technique must be changed, then a transitional period using both techniques should be employed so that some correlation between the two methods can be made.

The frequency of benthic monitoring should be increased to monthly sampling from April through October during periods of highest densities.

The fouling plate study is inadequate in its present form to be of any value, and it is recommended that the study be dropped. The stations were poorly chosen; two of the three stations are located at the mouths of creeks, one of which receives sewage effluents. Sample size is too small, and too many of the plates were lost to accurately show changes in seasonal patterns in the fouling community.

e. Fish populations

The beach seining method used to estimate the total population of the inshore fishes in the James River estuary is inadequate in its present form and should probably be eliminated from the Technical Specifications requirements. The sample size employed for these calculations as well as the dynamic movement of fishes in this area make population estimates too variable for interpretation and evaluation.

The frequency of fish trawling should be increased to biweekly samples during periods of major fish activity during migrations (i.e., April through June and September through November).

f. Entrainment

The methods used for calculating entrainment mortality contain several intrinsic problems that need to be resolved. One good method for estimating entrainment mortalities should be used, and problems associated with net avoidance, net mortality, and net extrusion should be quantified and discussed.

It is recommended that the entrainment program be redesigned and continued for a period of not less than one year with the condition that both Units 1 and 2 be operating at peak commercial capacity during the test period. The program will involve collection of plankton in the intake and discharge areas. Through the use of neutral red or other appropriate vital stains, live organisms will be counted and the percent entrainment mortality should be calculated using the equation:

$$M_e = \frac{L_i - L_d}{L_i} \times 100 ,$$

where

L_i = percent live at the intake

L_d = percent live at the discharge.

g. Impingement

The present impingement monitoring methods are generally adequate for determining the magnitude of fish impingement, and the traveling screen design employed at Surry greatly reduces impingement mortalities. However, the following additions to the present program are recommended:

- (1) night sampling should be initiated to determine whether the magnitude of nocturnal impingement is equivalent to that during daylight hours,
- (2) a mark and recapture study of fishes discharged back into the James River should be performed to validate the long-term survival ability of impinged individuals, and (3) age class determinations of impinged fish should be made to assess the age classes of each species most vulnerable

to impingement. These studies could be conducted on a short-term basis (one year), after which time results could be evaluated to determine whether they should be extended or terminated.

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APPENDIX A

MICROMETEOROLOGICAL EFFECTS OF THE SURRY PLUME

Although it has long been realized that the artificial heating of water bodies must somehow affect the overlying air, this phenomenon has received little study in the field. The moving boat surveys of the Surry plume conducted by the Virginia Institute of Marine Sciences (VIMS) included the measurement of air temperature at two heights. These data are insufficient to define the process of heated water - air interaction, but they do contain some information. Because such data are rarely collected, these should not be ignored.

The VIMS moving boat program is described in Sect. IV.A.2.c. The major limitations on using the moving boat data to describe the aquatic plume are the changes in the plume which occur during the 100-min sampling time and the lack of knowledge of the velocity field. These limitations are even more important for the air temperature measurements. Wind speeds are much higher and more variable than are water velocities. During the 100-min travel time of the boat, a steady 5-mph wind can transport a parcel of air completely across the study area. Moreover, the air is not confined to the riverbed, nor is it subject to the regularities of tidal motion. Furthermore, the lack of simultaneous humidity measurements during 1975 prevents any good estimation of the amount of heat transferred to the air by evaporation. These limitations are very serious. Were it not for the extremely primitive state of knowledge about the micrometeorological effects of thermal plumes, the analysis of these data would probably be unwarranted.

According to Table 2.8, there were three boat surveys during 1975 with calm conditions prevailing, all of which were during high-slack water. It was felt that these would offer the best opportunity to see the manner in which heat was transferred to the air. (See Figs. A.1, A.2, and A.3, showing how superimposed WT.5 and AT3 isotherms were prepared.) At each level, an ambient temperature equal to the average of the five lowest readings at the level was subtracted from the temperatures measured at the 55 locations shown in Fig. 2.49. These values were plotted, and isotherms were drawn in by hand.

Inspection of Figs. A.1, A.2, and A.3 reveals that the relationship of the AT3 isotherms to the WT.5 isotherms is rather weak. Closer examination indicates that the air temperatures may be distorted by natural daily trends. The runs of June 18 (Fig. A.1) and July 8 (Fig. A.2) were conducted from 0830 to 1018 and from 1157 to 1329 respectively. The normal increase in air temperature during these hours may explain why relatively high air temperatures were measured in lower Cotham Bay. The run of September 5 (Fig. A.3) was conducted from 1237 to 1405, but in this case, higher air temperatures were detected near Hog Point. The reason for this is not clear.

The higher excess air temperatures observed on June 18 may be due to the fact that the ambient relative humidity was higher on that date than on any others. Higher humidity would be expected to reduce the proportion of heat transferred by evaporation and hence increase the importance of sensible heat transfer.

Fig. A.1. Surry - Excess temperature isotherms ($^{\circ}\text{F}$) at 3 ft above water (—) and 0.5 ft below the surface (---). VIMS boat run of June 18, 1975, conducted at high-slack water from 0830 to 1018. For further information, see Table 2.8.

Fig. A.2. Surry - Excess temperature isotherms ($^{\circ}\text{F}$) at 3 ft above water (—) and 0.5 ft below the surface (---). VIMS boat run of July 8, 1975, conducted at high-slow water from 1157 to 1329. For further information, see Table 2.8.

Fig. A.3. Surry - Excess temperature isotherms ($^{\circ}\text{F}$) at 3 ft above water (—) and 0.5 ft below the surface (---). VIMS boat run of September 5, 1975, conducted at high-slack water from 1237 to 1405. For further information, see Table 2.8.

The most surprising observation that can be drawn from these figures is that the warmest air lies offshore of the discharge rather than over the warmest water. This suggests that cooler air, originally over the land, drifts offshore and grows warmer as its time of contact with the heated water (and hence its distance from shore) increases. There are at least two mechanisms that might induce such an offshore drift under calm conditions. The first is that the air may simply be dragged along by the offshore discharge current. Put more precisely, there may be a transfer of offshore momentum from the water to the air. The second mechanism is that a weak "land breeze" may be induced by the artificially warmed water.

Data from surveys conducted under windy conditions were also examined, and the tendency for the highest air temperatures to occur offshore of the discharge and over lower Cobham Bay was found to persist, regardless of wind speed.

APPENDIX B

THREE-DIMENSIONAL REPRESENTATION OF THERMAL PLUME DATA

J. G. Clark*

One of the most difficult aspects of interpreting thermal plume data is visualizing the three-dimensional structure of the plume. One method explored in connection with this report is that of stereographic projection. When viewing a real three-dimensional object, the separation of the eyes presents the brain with two slightly different images, which are interpreted by the brain to judge the depth of the object. In stereographic projection, three-dimensional information is used to produce two flat drawings showing how the object would look from slightly different viewpoints. If each eye sees only one of these drawings, the brain will interpret these images as a single three-dimensional object.

Figures B.1 and B.2 are representative of the stereographic projections that were produced. To view them, the eyes should be positioned about 4.5 in. from the paper with one eye over each drawing and the line connecting the eyes directly over the tick mark on the dividing line. A card should be held perpendicular to the page with its edge on the dividing line so that each eye sees only one image. After about 10 sec (depending on the observer), the images will seem to come together and will finally unite to form a single three-dimensional object. In order to obtain a sharp focus, it is best to try to relax the eyes and see

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Fig. B.1. Surry - Stereographic projection of 75% CDF contours of Surry plume at depths of 0.5 ft, 3 ft, and 6 ft for high-slack-water boat runs. Numbers near each contour denote excess temperature ($^{\circ}\text{F}$). For viewing instructions, read the text.

Fig. B.2. Surry - Stereographic projection of 75% CDF contours of Surry plume at 3 ft above water and depths of 0.5 ft and 3 ft for high-slack-water boat runs. Numbers near each contour denote excess temperature ($^{\circ}\text{F}$). For viewing instructions, read the text.

beyond the page because the apparent object is located 11 in. from the eyes. Perceiving the object is a learned response that becomes easier with practice.

Each figure represents contours within which certain excess temperatures were observed to occur for 75% of the time. The excess temperature values ($^{\circ}\text{F}$) are indicated by the numbers near each contour. North is to the top of the drawings, and the Surry outfall is to the right. The shoreline of the Hog Point Peninsula has not been included in these drawings. The contours were obtained from data collected during 19 high-slack-water VIMS boat runs in 1975 according to the methods explained in Sect. IV.A.2.d. Figure B.1 shows the contours at depths of 0.5 ft, 3 ft, and 6 ft. The existence of positive stratification at nearly all locations is evident, as is the fact that too much detail has been included near the outfall. Figure B.2 shows the air temperature contours 3 ft above the water surface, as well as the water temperature contours at 0.5 ft and 3 ft. The tendency for warmer air temperatures to occur above the warmer parts of the plume can readily be seen. Although these plots are relatively crude, it is believed that with further improvements, stereographic projections of plume data may be of value in many instances.