CHAPTER 174

THERMAL DISCHARGES: PROTOTYPE vs. HYDRAULIC MODEL

Gary C. Parker*
C. S. Fang*
Albert Y. Kuo*

ABSTRACT

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

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

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

INTRODUCTION

The generation of electrical energy from a steam source results in an energy loss as described by the laws of thermodynamics. The thermal energy not utilized is rejected from the process in the form of heat transferred to the water circulating through the condensers of a power station. This heat is ultimately transferred to the atmosphere by conduction and evaporative cooling either in closed-cycle systems, e.g. cooling towers, or in once-through systems, from the surface of the receiving water body.

Decisions dealing with methods for transferring the rejected heat to the atmosphere must be based upon a thorough understanding of hydro-thermal dynamics and the effects of excess temperature on indigenous populations of aquatic life.

---

*Scientists, Virginia Institute of Marine Science, Gloucester Point, Virginia U.S.A.

The Virginia Institute of Marine Science has been conducting a hydrothermal monitoring program since 1971 at the site of the VEPCO Nuclear Power Plant on the James River (Fig. 1).

The objectives of this investigation have been:

1) Compare pre- and post-plant operation data to determine the physical effects of the thermal discharge on the survey area.

2) Compare field results with predictions of temperature distributions made with the James River hydraulic model to determine the applicability of the hydraulic model to field temperature predictions.

The Surry Nuclear Power Plant consists of two 788 MW nuclear reactors, the first of which began commercial operation in December 1972, the second in March 1973. The power plant uses the once-through cooling method. Water is drawn into the intake canal on the downstream side of Hog Point, pumped through the condensers and out through the discharge structure into the James River estuary, upstream from Hog Point. The shoreline distance between intake and discharge points is about 9.17 km and the intake canal is about 2.74 km long.

Each unit requires 52,987 liters/second of river water to supply condensing and service water needs. The maximum temperature rise through the condensers is 8.3°C.

FIELD STUDY RESULTS

A detailed description of the study sampling program was given by Parker and Fang (1975) and Fang and Parker (1976). A moving boat sampling scheme was used. The parameters measured were water temperature at depths of 0.15, 0.9 and 1.8 m, air temperature at 0.9 and 1.8 m above the water surface and dew point temperature. These data, along with salinity and dissolved oxygen samples taken at fixed stations and meteorological data from nearby Ft. Eustis, were deemed sufficient to identify natural variations in river conditions and to isolate thermal effects of the heated water discharge.

AREA WITHIN ISOTHERMS

After isothermal plots of a survey run were drawn, a planimeter was used to measure the area within the isotherms

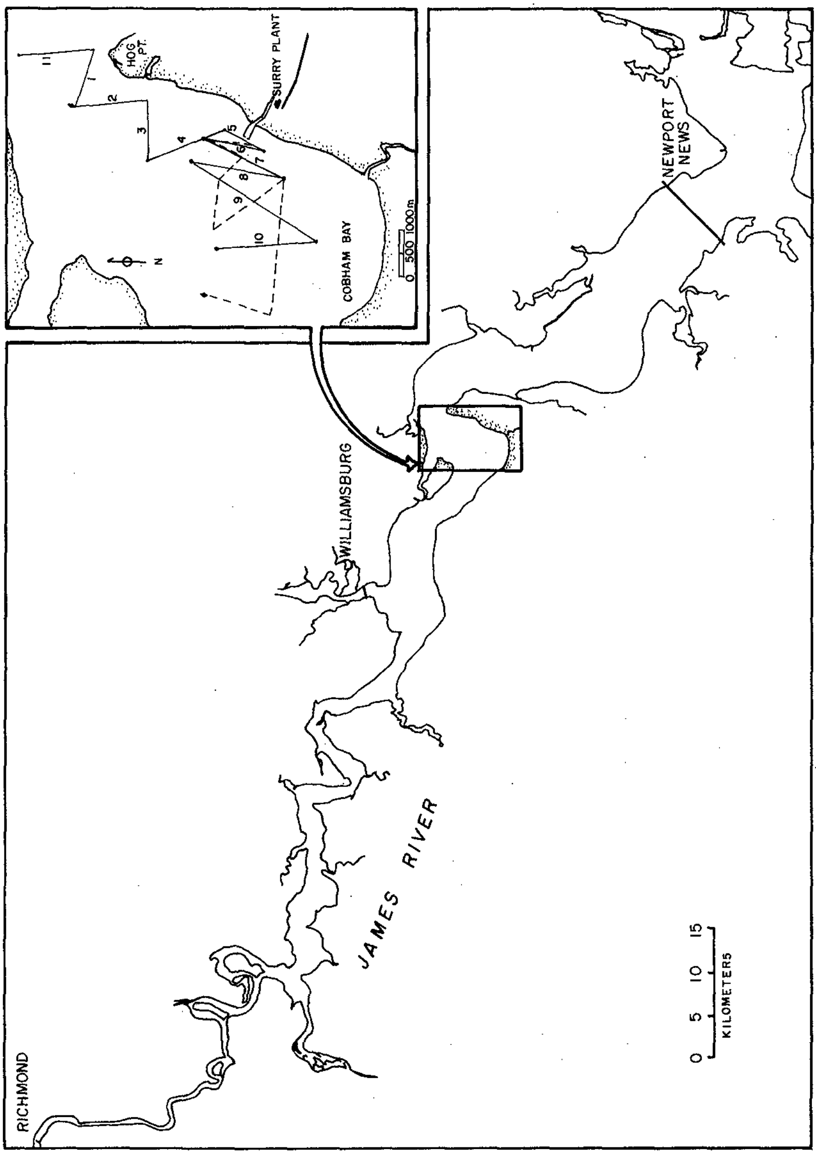


Figure 1. Location of the Surry Nuclear Power Station Site Inset: 1975 transects (solid), 1974 (dashed). Transects 11, 1, 2, 3, 4 same for both years.

which were "closed" around the outfall.

A graph of the area within excess temperature isotherms as a function of fractional excess temperature, Figure 2, indicates that the area (A) within the isotherms generally increases logarithmically with decreasing fractional excess temperature (θ/θ_o). An approximation to a straight line fit to the data is represented by the line:

$$A = (5.6 \times 10^6)e^{-6.8\ (\theta/\theta_o)}$$

The data plotted in Figure 2 represent data for plumes with plant operation at greater than 90% capacity. When the data are separated into low and high slack water plumes, as shown in Figure 2, it appears that the low slack water plumes were slightly larger than high slack plumes, although the differences were not significant.

The area data from 1975 indicate as a rough estimate that as the value of θ/θ_o approaches zero, the area within the excess temperature isotherm, θ, approaches $5.6 \times 10^6 m^2$, which represents the maximum surface area affected by the plume.

CENTERLINE TEMPERATURE DECAY

In 1975, plume centerline temperature decay was determined from isothermal plots for ten selected survey runs in August and September. The selection process was based upon the ease of determining plume centerlines from the isothermal plots. Plume centerlines were drawn subjectively, and distance and temperature along the centerline were recorded.

A graphical presentation of the data, Figure 3 indicates an exponential centerline temperature decay approximately represented by the equation:

$$\theta/\theta_o = e^{-.0002d}$$

where d is the distance along the plume centerline. Fractional excess temperatures at centerline distances less than 45 m from the outfall show much less variation than those at greater distances.

The graph indicates that generally θ/θ_o reaches a value of 0.5 within 1050 m of the outfall, indicating that a major portion of initial plume mixing with ambient water occurs within 1050 m from the outfall.

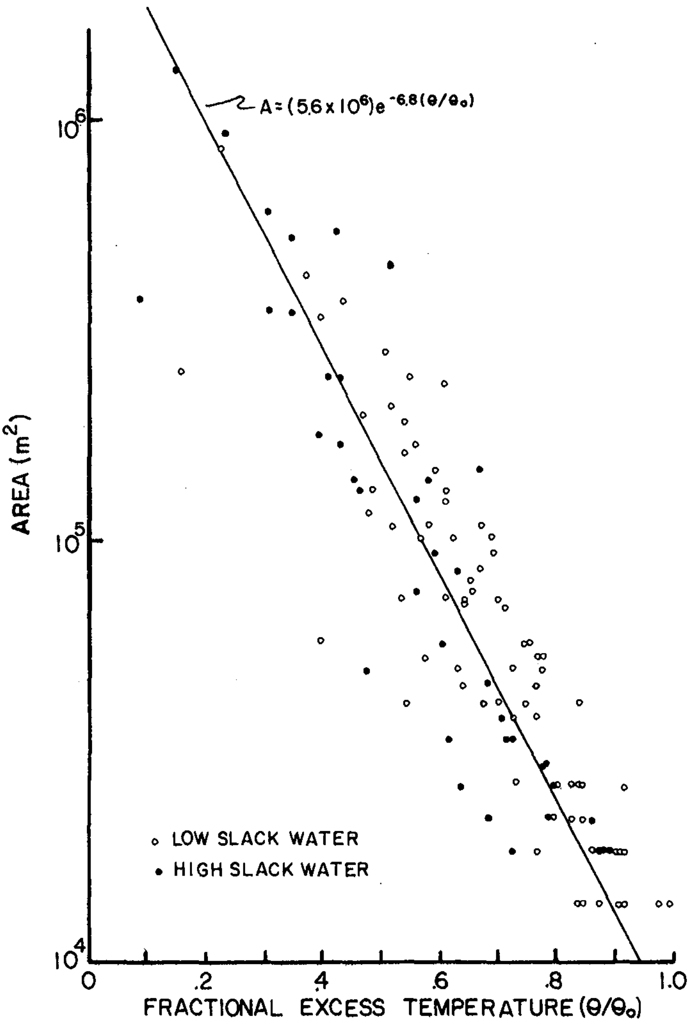


Figure 2. Area within excess temperature isotherm versus fractional excess temperature (θ/θ_o), 1975 data.

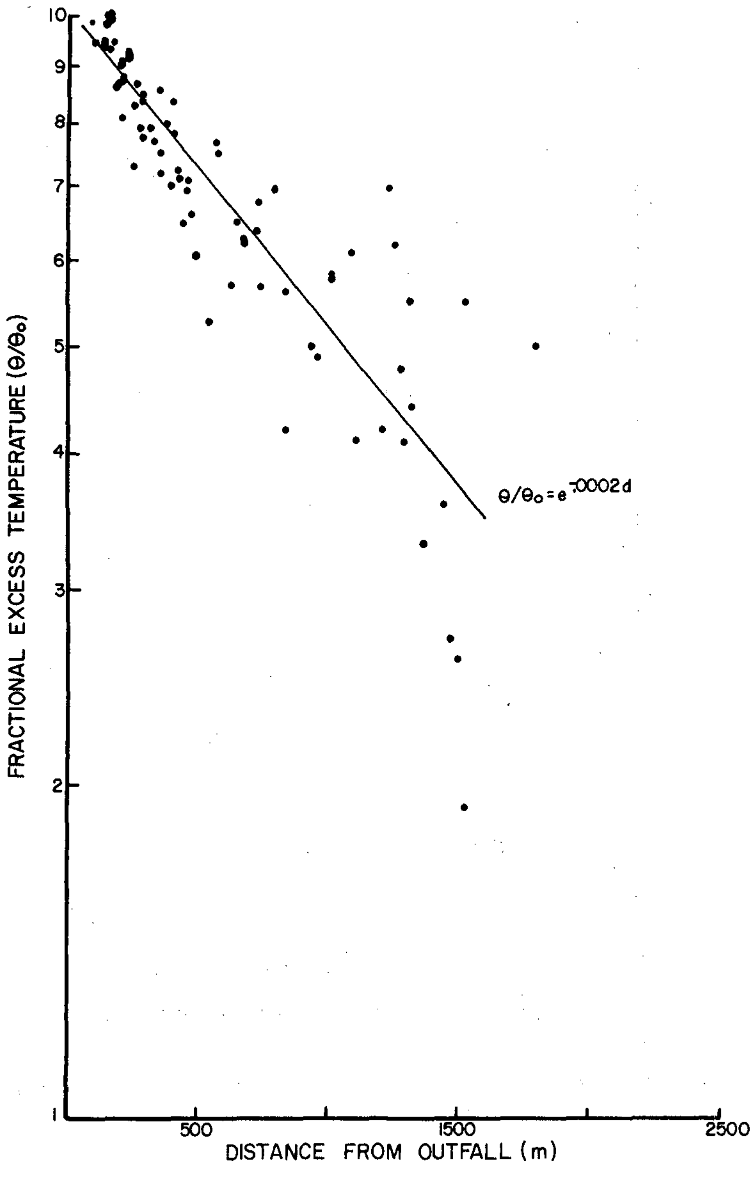


Figure 3. Plume centerline temperature decay, August and September 1975 data.

VERTICAL TEMPERATURE STRATIFICATION

Figure 4 shows a portion of the isothermal plot for August 21, 1975, at high slack water. On this date the plant power production was 1487 MW, winds were SE at 11-12.8 kph. Four transects, AA', BB', B'C, and DD', have been shown in vertical cross section to the maximum sample depth of 1.8 m in Figure 5.

Transects AA' and BB' show a maximum stratification of approximately 1.1°C over 1.8 m. Transect B'C, across the mouth of the outfall, shows a hot core of 37.8°C water at 0.9 m depth at the outfall. The maximum stratification along this transect is approximately 2.8°C over the 1.8 m depth. The plot of transect B'C also shows a sharp temperature gradient on the downstream (B') side of the plume, with a more gradual gradient on the upstream side. Transect DD', 365 m offshore and parallel to B'C, shows that plume temperatures at the centerline have dropped to 35°C. The strongest areas of stratification are on the extreme upstream (D') and downstream (D) ends of the transect. Figure 4 shows that these regions are near sharp temperature gradients at the surface. In these regions the temperature gradient is a maximum 3.3°C over 1.8 m of depth.

COMPARISON OF AREAS WITHIN ISOTHERMS

Areas within excess temperature isotherms for August 1974 and 1975 are compared in Figure 6. Water temperatures are generally at their peak during August, and as mentioned previously, August 1975 power production was continuously higher than 90% of capacity. These factors suggest that August 1975 data would represent conditions under maximum temperature loading for the river. The figure indicates that excess temperature isotherms enclosed larger areas during 1975 than during 1974 and that the differences were greater for low values of fractional excess temperature. The line drawn in Figure 6 shows an approximate best fit line for the 1975 area data; this line represents an approximation for the isotherm area versus fractional excess temperature relationship under equilibrium conditions at the Surry plant. The equation for the line shown in Figure 6 is given by:

$$A = (8.2 \times 10^6)\, e^{-7.2(\theta/\theta_o)}$$

where A is the area within fractional excess temperature θ/θ_o. This equation and the line representing it were not calculated mathematically and are given only as approximations. An exact equation for such a relationship obviously does not exist and for this reason, approximations were deemed

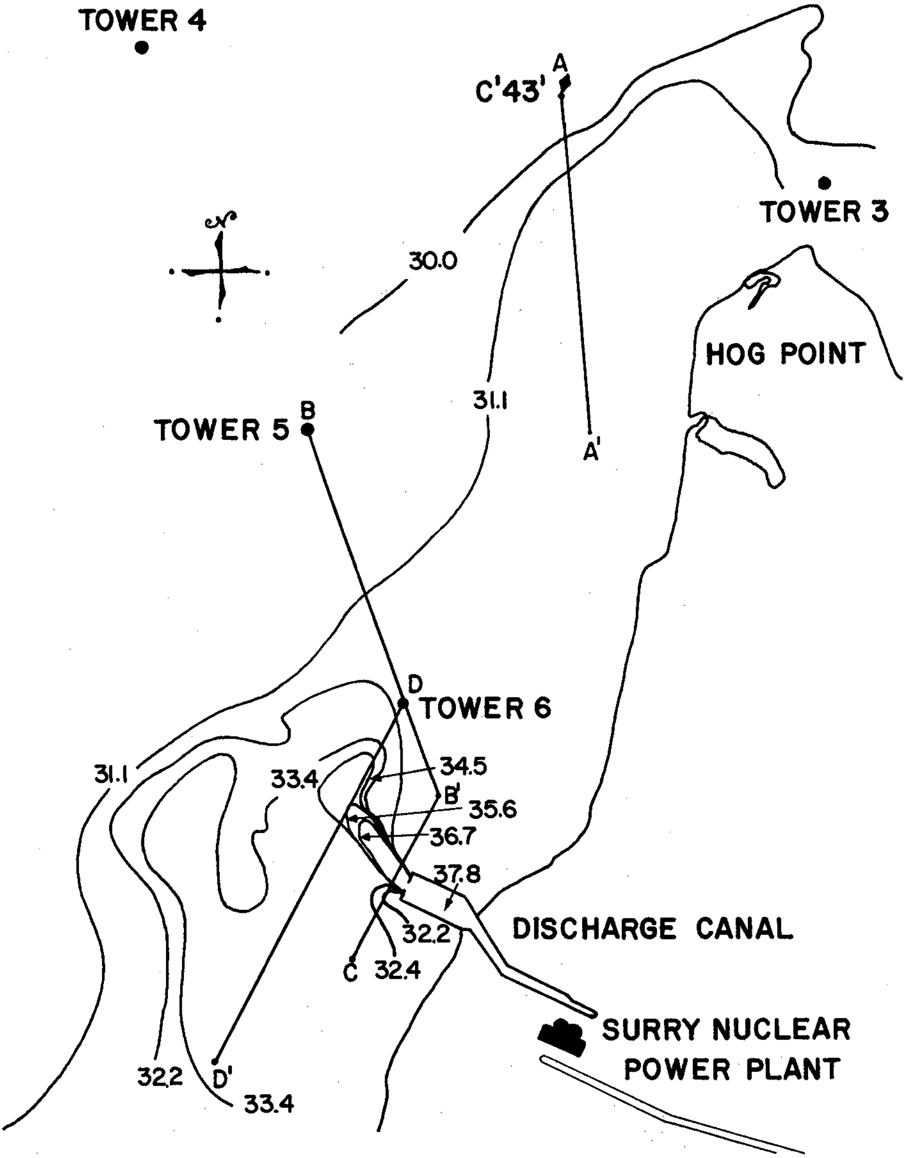


Figure 4. Thermal plume on August 21, 1975.

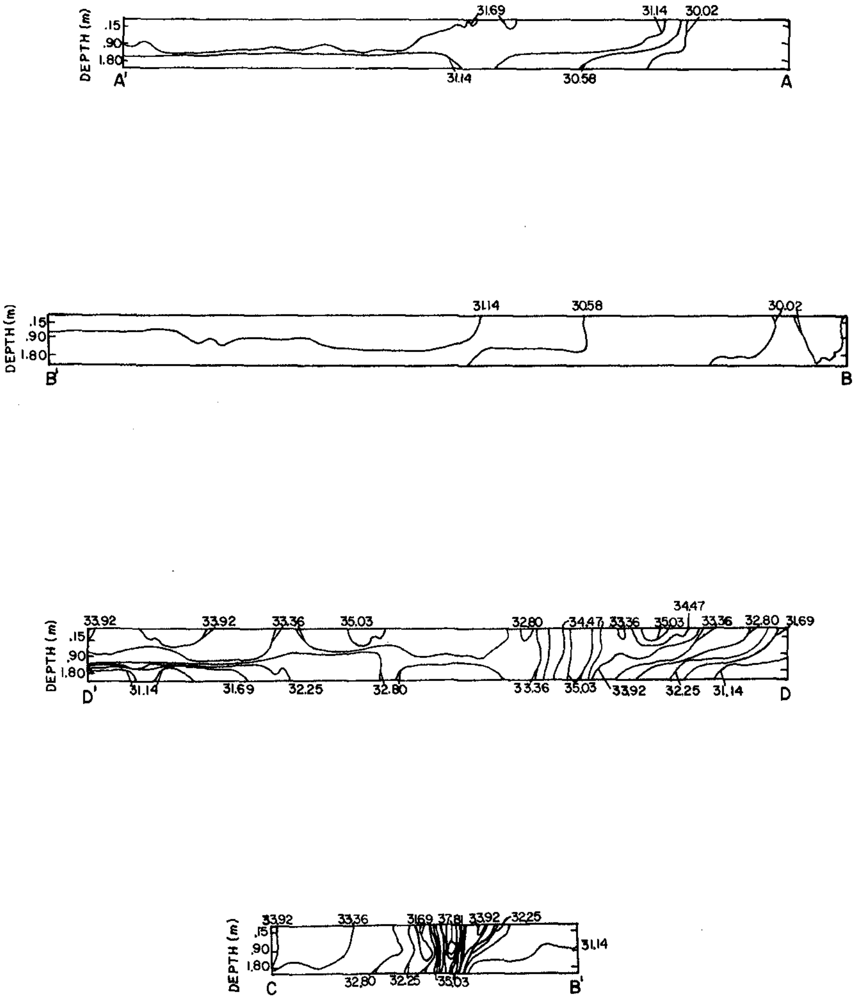


Figure 5. Vertical sections AA', BB', B'C, DD'.

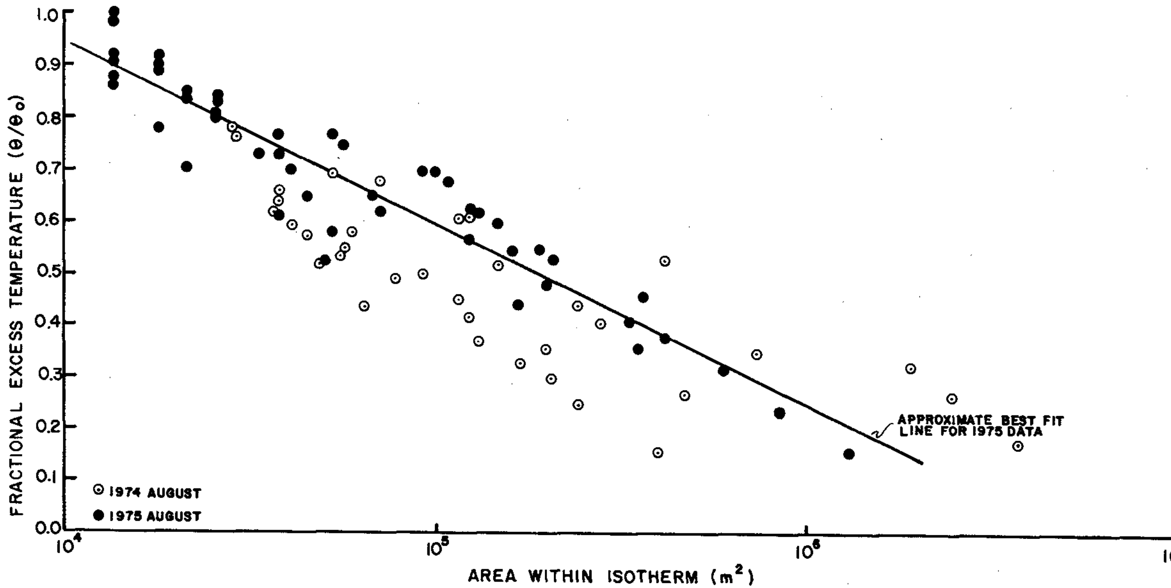


Figure 6. Comparison of areas within excess temperature isotherms for August 1974 and August 1975, power production greater than 1400 MW.

sufficient for the analysis. The equation indicates that as θ/θ_0 approaches zero, the area within the excess temperature approaches 8.2×10^6 square meters. This area represents the maximum area affected by the thermal discharge under equilibrium conditions, with close to maximum (>90%) power production.

HYDRAULIC MODEL PREDICTIONS

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

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

Two separate sets of experiments were run on the hydraulic model. In the first set the model was run for a total of 475 tidal cycles, corresponding to approximately 246 days of prototype time. During this set of experiments the river discharge at Richmond was at a simulated 56.6 cms. In the second set of experiments, river discharge at Richmond was at 169.9 cms and the model was run for a total of 784 tidal cycles.

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

Temperatures in the model were measured using a rapid response thermistor head mounted on a trolley which ran across the model on a 4.9 meter unit beam. The beam could be moved to the desired transect and the thermistor sensor run across the model to obtain a plot of temperature versus lateral distance made on a strip chart recorder.

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

The correction procedure used by Carpenter and Pritchard was:

$$(A_\theta)_p \;/\; (A_\theta)_m = 1, \quad \theta \geq 0.5\ \theta_o$$

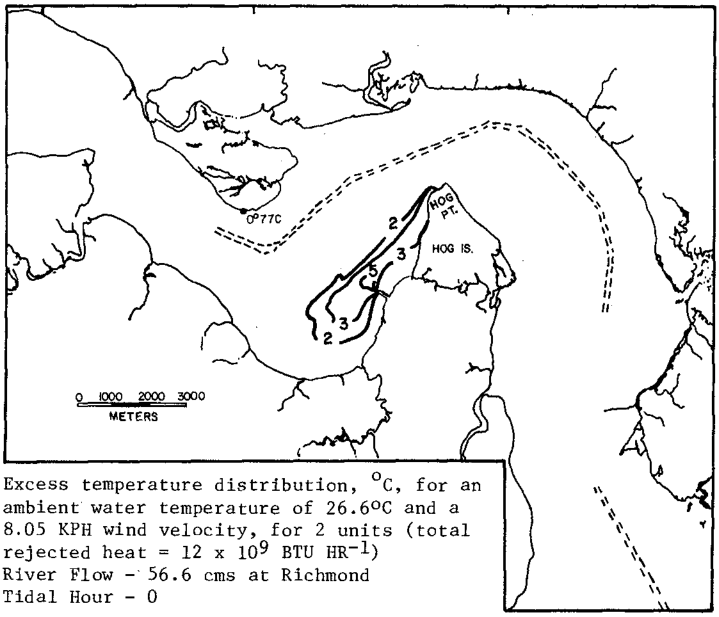
$$(A_\theta)_p \;/\; (A_\theta)_m = 0.9\ \frac{\gamma_m}{\gamma_p}, \quad \theta \leq 0.15\ \theta_o$$

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

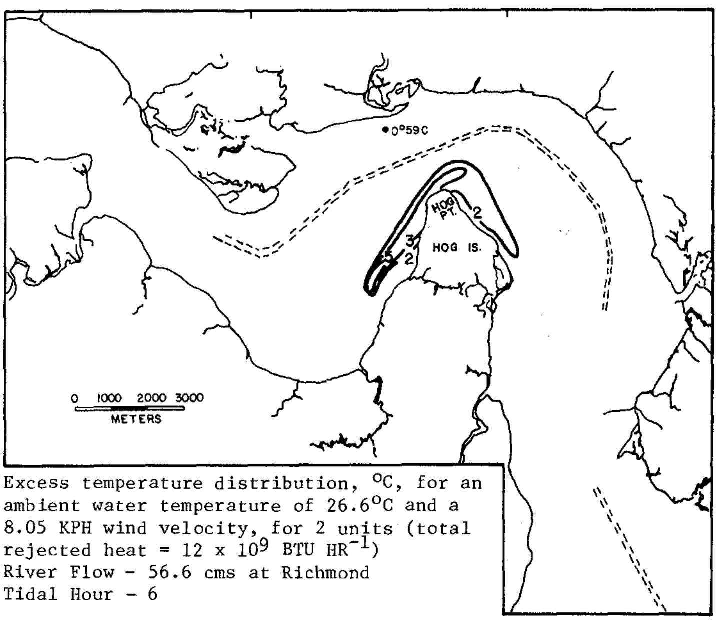
The results of these experiments were presented as a series of excess temperature isothermal plots. Figure 7 shows two of these plots, for high slack water (tidal hour 0), and for slack water (tidal hour 6).

For comparison purposes, prototype data had to be selected so that heat rejection was as close as possible to the modeled heat rejection. As mentioned previously, hydraulic model tests were run for 56.6 and 169.9 cms river discharges at Richmond. This factor should also be taken into account for the comparisons, but it was considered secondary when compared to heat rejection. The prototype data which had the maximum heat rejection also had river discharges in the range 56.6-198.2 cms so that differences between model and prototype due to river discharge differences were minimal. This conclusion is justified since it has been previously shown that river discharge has little direct effect on tidal currents and excess temperature except for periods of extreme river discharge.

The average values of ambient water temperature, wind speed, and heat rejection for the prototype data selected for comparison with the model were 27.6^{o}C, 9.8 kph, 11.2 x 10^9 BTU-hr^{-1} respectively. These values are relatively close to the modeled values of 26.7^{o}C, 8.0 kph, and 12.0 x 10^9 BTU-hr^{-1}. For the purposes of this investigation, the



Excess temperature distribution, °C, for an ambient water temperature of 26.6°C and a 8.05 KPH wind velocity, for 2 units (total rejected heat = 12 x 10^9 BTU HR^{-1})
River Flow - 56.6 cms at Richmond
Tidal Hour - 0



Excess temperature distribution, °C, for an ambient water temperature of 26.6°C and a 8.05 KPH wind velocity, for 2 units (total rejected heat = 12 x 10^9 BTU HR^{-1})
River Flow - 56.6 cms at Richmond
Tidal Hour - 6

Figure 7. Typical excess temperature isotherms as predicted by the hydraulic model (from Carpenter and Pritchard, 1967).

effects of the differences between ambient water temperature and wind speed for the model and the prototype are considered negligible when compared to the effects due to the difference in rejected heat.

Areas within each excess temperature isotherm were determined from isothermal plots of the appropriate survey runs in 1973 through 1975 using a compensating polar planimeter. These areas, along with the areas within the excess temperature isotherms presented in the results of Carpenter and Pritchard's report, were plotted and are shown in Figure 8.

The figure indicates that the lower limit of the model data approximately coincides with the upper limit of the prototype data. There are only a few data points which lie above the lower limit of the model data. To determine whether the difference between the model and prototype data was statistically significant, the means and 95 percent confidence intervals of the means were calculated for the area within the 2.0°C, 3.0°C, and 5°C excess temperature isotherms in both model and prototype. In the prototype the area within the 2°C and 3°C isotherms were obtained by linear interpolation between the area within next higher and next lower whole degree isotherms.

The means of the area and the 95 percent confidence interval of these means are presented in Figure 9. The fact that the confidence intervals do not overlap for any of the model and prototype data indicates that the differences between the data were significant. The model enclosed areas were significantly greater than the corresponding prototype enclosed areas in all three cases. For the 2°C excess temperature isotherm, the model predictions were greater than prototype data by a factor of five, while for the other two isotherms, model predictions were greater than prototype data by an order of magnitude or more.

The prototype data indicate that the excess heat dissipated more rapidly than was predicted by the hydraulic model. The model predictions for the area with the 2°C excess temperature isotherms were more accurate than those for the higher excess temperatures. Qualitatively, the temperature distributions in the field, as a function of tidal phase, were similar to those predicted by the model.

Lower heat rejection in the prototype was partially responsible for the smaller areas within each excess temperature isotherm. Heat rejection on the days compared with the hydraulic model predictions were from 8-14 percent lower than the modeled heat rejection. It is assumed that at full plant capacity the areas in the prototype would be

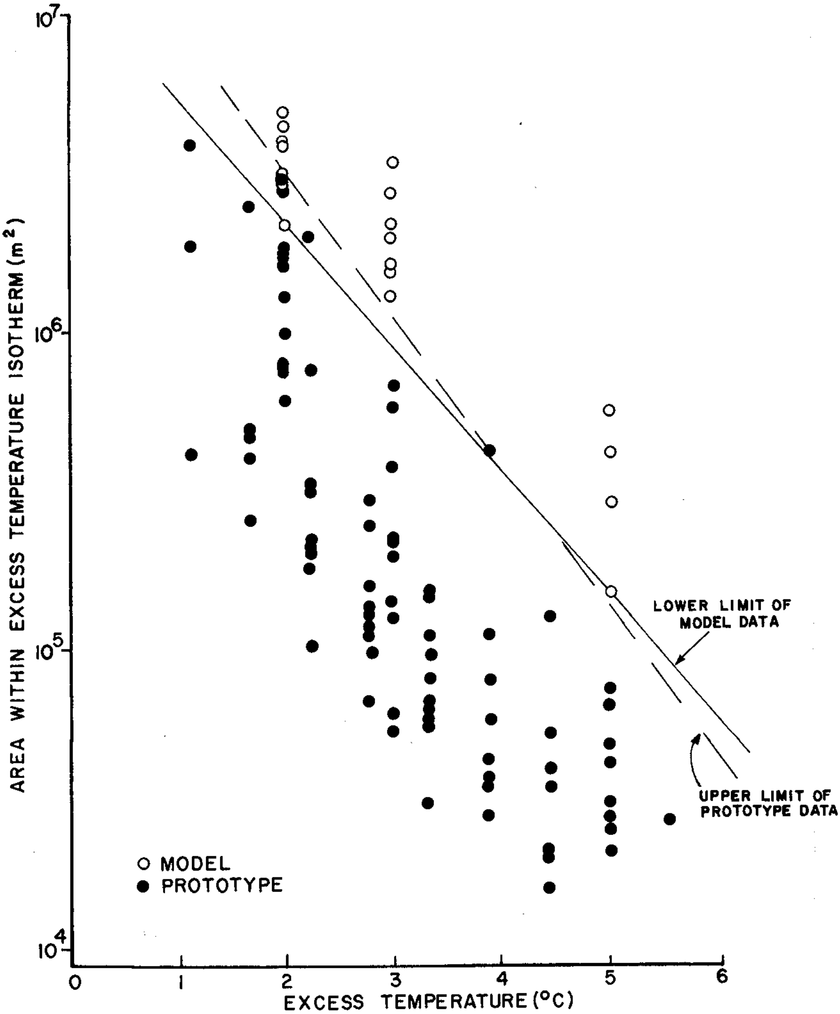


Figure 8. Comparison of areas within a given excess temperature isotherm for the hydraulic model and the prototype.

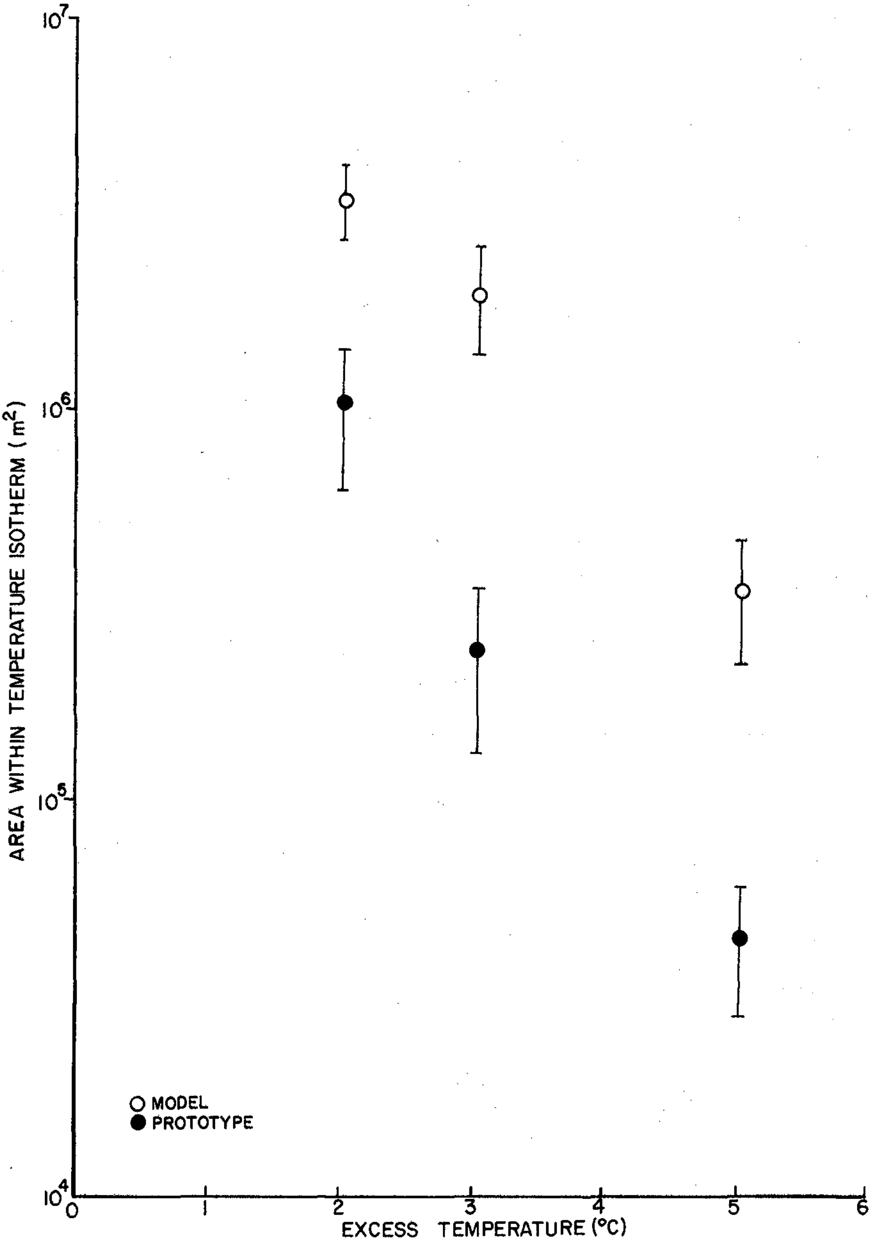


Figure 9. Comparison of mean areas and 95 percent confidence intervals for the hydraulic model and the prototype.

10-20 percent larger, which is probably an over-estimation, the differences between the model predictions and the prototype would still be significant.

Carpenter and Pritchard assumed that in the near field region, which they define as $\theta \geq 0.5\theta_o$, cooling has had little time to act. To reflect this, the correlation factor applied to this area, $(A_\theta)_p$ / $(A_\theta)_m$, had a value of unity. With an average value of θ_o of approximately 6.7^oC, the field data indicate that for values of $\theta > .50\theta_o$, the ratio $(A_\theta)_p/(A_\theta)_m$ had a value of approximately 0.1.

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

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

which reduces to

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

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

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

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

with a linear variation for intermediate values of θ.

The inability of the hydraulic model to predict the areas within the higher excess temperature isotherms to the same order of magnitude was most probably due to scale distortion. In a discussion of hydraulic modeling, Silberman and Stefan (1970) indicate that it is necessary to model three regions: near field, the joining region, and far field, in order to completely model a given plume. In the near field region near the outfall, entrainment of ambient fluid is the major process to be modeled. In the joining region, entrainment is still important, but buoyancy, surface cooling, and convection are also important. Surface cooling, dispersion, and convection are the most significant processes in the far field. The different physical phenomena involved within each region mean that in most situations these regions cannot be combined in one hydraulic model.

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

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

ACKNOWLEDGEMENTS

Funding for the study which was provided by the U. S. Energy Research and Development Administration is greatly appreciated.

REFERENCES

Fang, C. S. and G. C. Parker. 1976. Thermal Effects of the Surry Nuclear Power Plant on the James River, Va. Part VI. Results of Monitoring Physical Parameters. Special Rept. No. 109 in Applied Marine Science and Ocean Engineering of the Va. Inst. of Marine Science.

Parker, G. C. and C. S. Fang. 1975. Thermal Effects of the Surry Nuclear Power Plant on the James River, Va. Part V. Results of Monitoring Physical Parameters During the First Two Years of Plant Operation. Special Rept. No. 92 in Applied Marine Science and Ocean Engineering of the Va. Inst. of Marine Science.

Pritchard-Carpenter, Consultants. 1967. Temperature Distribution in the James River Estuary which will Result from the Discharge of Waste Heat from the Surry Nuclear Power Station. A report prepared for VEPCO, Richmond, Va. 79 p.

Silberman, E. and H. Stefan. 1970. Physical Modeling of Heat Dispersion in Large Lakes: A Review of the State of the Art. Argonne Nat. Lab. Special Rep. ANL/ES-2, 112 p.