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THE DISTRIBUTION OF
EXCESS TEMPERATURE
FROM THE VIENNA
GENERATING STATION ON
THE NANTICOKE RIVER

H. H. Carter
R. J. Regier

Reference 75 - 5
June 1975

Technical Report 90

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THE DISTRIBUTION OF EXCESS TEMPERATURE
FROM THE
VIENNA GENERATING STATION
ON THE
NANTICOKE RIVER

by

H.H. Carter

R.J. Regier

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EXECUTIVE SUMMARY

Temperature and dye tracer data, collected in the Nanticoke River in the vicinity of the Delmarva Power and Light Company Vienna, MD Generating Station (66MWe) between 12 and 26 April 1974, were analyzed and interpreted in terms of the distribution of excess temperature as a function of tidal phase. Cooling water flows and plant recirculation were also determined.

In general, the thermal plume tended to remain on the west bank; the maximum estimated excess temperature (6°C (10.8°F)) at our sampling sections occurred at Section 1F just after slack before ebb (Figures 20 and 23). At the same time and place, however, it is estimated that over 80% of the cross-section would have excess temperatures less than 1°C (1.8°F). Our analysis indicates that with all units running at rated power, no excess temperatures larger than 1.5°C (2.7°F) would occur at distances greater than 5100 feet downstream (between Sections 1E and 2E) or larger than 1°C (1.8°F) at distances greater than 5600 feet upstream (between Sections 1F and 2F) with the possible exception of the extensive marshlands on which sampling was not possible. As a matter of fact, the analysis showed that over most of the estuary, larger diurnally cycled lateral (cross estuary) temperature gradients resulted from differential solar heating than from the plant's heated water discharge.

Considerable recirculation was observed; the maximum occurring was 24% at approximately midway in the ebb cycle. Total cooling water flow for Units 5, 6, and 7 was estimated from the intake and discharge dye concentrations to be 50,000 GPM, somewhat lower than the rated pump capacities (57,400 GPM).

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LIST OF SYMBOLS

AM	ante meridiem,
C_d	dye tracer concentration,
$C_{d,i}$	dye tracer concentration at intake,
$C_{d,o}$	dye tracer concentration at discharge,
$C_d/C_{d,o}$	dilution ratio,
C	degrees Celsius,
E	section designator,
F	degrees Fahrenheit; also section designation,
GPM	gallons per minute,
K_y	lateral eddy coefficient of diffusion,
MWe	megawatts (electrical),
n	amount of "new" water which is considered to be mixed with 1 part of plant's heated effluent in computing a dilution ratio,
PM	post meridiem,
$Q_{c,i}$	cooling water intake flow to the condensers,
$Q_{c,o}$	cooling water discharge flow to the estuary (does not include cooling tower blowdown),
Q_s	service water flow,
Q_t	cooling tower makeup flow,
q_d	dry tracer injection rate,
SBE	slack water before ebb, a tidal current phase,
SBF	slack water before flood, a tidal current phase,
t	time,
ΔT	reference time,
ΔT_c	temperature rise across the condensers,
T_a	background or base temperature,

LIST OF SYMBOLS (continued)

$T_{a,i}$	background temperature at intake,
T_h	general designation of a temperature measurement,
$T_{h,i}$	temperature at intake,
$T_{h,o}$	temperature at discharge,
W	width of estuary,
θ	excess temperature, $T_h - T_a$,
θ_o	excess temperature at discharge, $T_{h,o} - T_a$,
$\mathcal{L}$	run for which cross-sectional distribution follows,
τ_M	time scale of mixing ,
τ_H	time scale of heating.

I. INTRODUCTION

Since the early 1960's, the Chesapeake Bay Institute has been engaged in studying the dissipation of waste heat to the marine environment from generating plants, both nuclear and conventional. These studies have been primarily¹ aimed at increasing our knowledge of the processes whereby waste heat is advected and dispersed within the marine environment and their dependence on intake and discharge design (the densimetric Froude number at discharge, the discharge orifice aspect ratio, etc.), and receiving water characteristics (velocity, temperature, and salinity gradients), with the goal of predicting the probable distribution of excess heat in the local marine environment resulting from a proposed nuclear power station. Here excess heat means the difference between the heat that a given parcel of water would contain under conditions of a heated discharge and the heat that it would contain under "natural" conditions.

We have approached this problem by studying these processes, which must be included in any predictive model, experimentally through field studies at existing generating stations and in a low velocity flume. Some of the more pertinent results have been reported in Pritchard and Carter (1965, 1972); Carter (1968, 1969, 1973); Carter, Schiemer, and Regier (1973); and Carter and Regier (1974). A numerical model for the prediction of the temperature distribution in the thermal plume from a condenser cooling water discharge has been developed known as the Pritchard model (see Pritchard, 1973). This model is essentially phenomenological or parametric and is being continuously refined by Pritchard as new field and/or flume data become available. In addition, field techniques for quantitating the distribution of excess heat from a generating station have been developed. See Carter, Pritchard, and Rives (1975).

This report describes the results of a field study designed to delineate the field of excess temperature resulting from the cooling water discharge of the Delmarva Power and Light Company Vienna, MD generating station into the Nanticoke River. Since the river is a major spawning area for striped bass, yellow and white perch, and shad, the study period was selected to coincide with the spawning season and an on site laboratory study of the effects of exposure to typical time-excess temperature histories on the hatching success of fish eggs. See Schubel (1973).

¹

Expressions have also been developed for estimating the excess heat transferred to the atmosphere at the air-sea interface by the processes of evaporation, eddy conduction, and long wave back radiation (unpublished).

II. THE NANTICOKE RIVER

The position of the Nanticoke River² in relation to the Chesapeake Bay region is shown in Figure 1; a more detailed view of the twelve mile (~ 22 km) section surveyed is shown in Figures 2 and 3. Although this portion of the river is surrounded by extensive marshland, the channel is relatively deep (of the order of 30 feet (~ 9 m)).

NOAA tide tables predict an average tidal range at Vienna, MD of 2.3 feet (20 cm), increasing to 2.8 feet (85 cm) in the spring. Observed salinities ranged from immeasurable sea salts to 0.10 ‰ at section 4F, the most upstream section monitored, and from 1.31 ‰ to 4.19 ‰ at section 5E, the most downstream section. In Figure 4, salinity values for 1973 at the route 50 bridge are compared to occasional records from the same point for the month of April between 1955 and 1968.

Air temperatures during the study ranged from freezing on 13 April, to 85°F (29.4°C) only nine days later. Figure 5 is an hourly plot of air temperature recorded at the Salisbury airport, twenty miles (~ 37 km) east of Vienna. Water temperature in the shoals and shallow creeks bordering the Nanticoke channel responded rapidly to fluctuations in air temperature, greatly complicating analysis and interpretation of the data.

² As is the case with numerous river names in Maryland, "Nanticoke," originally "Naitaquack" or "Nautaquack," stems from an Indian word describing a single spot along a river rather than a river per se. "Naitaquack," or "point of land on a tidewater stream," was but one of five Indian villages bordering the river reported by John Smith when he explored the area in 1608. See Bump (1907).

Figure 1. Chart of Chesapeake Bay showing the location of the study area.

Figure 2. Chart of the Nanticoke River showing the location of the downstream sampling sections.

Figure 3. Chart of the Nanticoke River showing the location of the upstream sampling sections and the tracer source.

DISTRIBUTION OF SALINITY
AT ROUTE 50 BRIDGE FOR
THE MONTH OF APRIL, 1955-1968

Figure 4.

Figure 5. Air temperatures in °F at the Salisbury, MD airport during the study period.

III. THE VIENNA GENERATING STATION

The Vienna Generating Station of the Delmarva Power and Light Co. is a conventional, fossil fuel burning plant. Four units, having the nominal ratings listed in Table I, were in operation during the study. The older units, #5, 6, and 7, draw river water through submerged ports into a single pass condenser

Table I. Design Operating Parameters for the Vienna Generating Station.

Unit	Rated Output (MWe)	Condenser Cooling Water Flow (GPM/m ³ s ⁻¹)	Design ΔT_c across condensers at Full Load, °F/°C
5	17	16000/1.009	18*/10
6	18	16000/1.009	18*/10
7	31	23600/1.489	24*/13.33
8	160	65000/4.100	25 /13.89

* Average ΔT_c , weighted by rated circulating pump capacities = 20.54°F or 11.41°C.

cooling system. Heated water is discharged through a canal 280 feet (~ 85 m) long, 17 feet (~ 5 m) wide, and, because of sedimentation, about half its original 10 foot (~ 3 m) depth (at low water). Depending upon the phase of the tide, discharge velocities range from 1.5 - 2.0 fs⁻¹ (46 - 61 cm s⁻¹). Waste heat from unit #8 is transferred to the atmosphere by a cooling tower whose 1400 GPM (~ 0.088 m³s⁻¹) makeup water flow is drawn from the discharge canal of the other three units. Figure 6 illustrates schematically the plant's condenser cooling water paths. Because of the season, cooling water was not chlorinated as it entered the plant.

The temperature rise across the condensers, ΔT_c , for April 1 - 26 is plotted in Figure 7. Values shown are based on records of hourly readings by plant personnel and are averages weighted by the rated condenser circulating water pump capacities. *Note the wide range of ΔT_c .* Except for the period between 0100 and 0500 on both 4/20 and 4/23, when pumps for units #5 and 7 were turned off, all condenser circulating water pumps were in operation during the study period, so that the changing ΔT_c values represent changing values of electrical generation rather than varying flows through the condensers. Only infrequently were units #5, 6, and 7 operating at rated capacity.

Note also in Figure 7 that the maximum values of ΔT_c are greater than 20.54°F (11.41°C), the rise one would expect from the *rated* capacities of the circulating water pumps. This discrepancy will be addressed in greater detail in a later section (see Section V-A).

Figure 6. Schematic of Vienna Generating Station Cooling Water System ($15,852 \text{ GPM} = 1 \text{ m}^3 \text{ s}^{-1}$).

Figure 7. Plant statistics during the study period (9 April - 26 April 1973).

IV. THE EXPERIMENT

In a tidal tributary, thermal plume characteristics, such as excess temperature, will have both spatial and temporal dependencies. To portray accurately such a situation, one would ideally use a very large number of sampling points, at each of which pertinent plume parameters would be identified and monitored continuously. Only two boats were available for this survey, however, so the three-dimensional, time-dependent plume was tracked using a time series of two-dimensional (lateral & vertical) realizations. By defining a number of cross sections perpendicular to the river axis and stationing both boats at the same section for an entire tidal cycle, with one boat sweeping back and forth making continuous measurements at a shallow depth, while the other boat was making vertical casts at discrete points over the width of the river, it was possible to define the plume at each cross section as a function of tidal phase. Cross sections upstream from the plant were sampled on days when the predicted SBF occurred as soon after daybreak as possible. Downstream sections were scheduled to coincide with an early morning SBE. This sampling schedule assured that, upstream or downstream of the source, inside or outside a tidal excursion, the day's record at any cross section would include the maximum anticipated value of excess temperature for that section.

The field program began on 9 April 1973. While dye dispensing equipment was being rigged at the plant and current meters moored, personnel aboard the R/V SCANNER, a 20' (~ 6 m) Penn Yan, measured the background fluorescence of Nanticoke water throughout the study area. The dye dispensing pump was started at 1828 hours that day. It continued pumping until 1310, 26 April 1973, discharging a 20% solution of Rhodamine WT at an average rate of 26.21 pounds day⁻¹ (0.1376 gs⁻¹).

Underway sampling began on 12 April, after allowing several days for the dye to approach equilibrium with the rejected heat in the river. Continuous samples were drawn through one half inch (1.27 cm) clear polyethylene (polyflo) tubing, to and through a Turner Model 111 fluorometer, a PTI temperature monitoring flow cell (Schiemer, 1962), a Jabsco water puppy pump, and back into the river. For near surface measurements, the intake was located at the bottom of a faired aluminum strut mounted about one foot (~ 30 cm) from the side of the SCANNER. Vertical samples were taken by lowering polyflo tubing to the desired depth and drawing water through a Model 111 Turner fluorometer, an ICTI flow cell (see Schiemer et al., 1961) and a pump in series. The SCANNER was used for surface lateral samples (probe depth of 18" (~ 46 cm)), and the R/V LYDIA LOUISE II, a 40' (~ 12 m) Chesapeake Bay Cabin Cruiser, for vertical profiling. Each section was sampled at least hourly both laterally and vertically with the frequency increased to half hourly during periods of most rapid change in temperature and dye concentration. Based on experience and the location of convenient navigational aids, nine cross sections were defined. See Figures 2 and 3. The distance of each section from the source and the sampling calendar are shown in Table II.

Table II. Distances from the Source of the Various Sampling Sections Together with Sampling Dates.

	<u>Section</u> <u>Section</u>	<u>Miles/km from</u> <u>Source</u>	<u>Date of</u> <u>Sampling</u>
upstream	4F	4.2/7.78	April 19
	3F	2.1/4.08	18
	2F	1.2/2.22	17
	1F	0.2/0.37	16
	Plant	0	
downstream	1E	0.7/ 1.30	12,26
	2E	1.5/ 2.78	20
	3E	3.3/ 6.11	23
	4E	5.8/10.75	24
	5E	8.0/14.82	25

River velocities immediately downstream from the plant intake were measured by Aanderaa Model 4 current meters. Meters were attached to a single cable at 1 foot (~ 30 cm) and 4 feet (~ 1.2 m) respectively, approximately 30 feet (~ 9 m) offshore from the pump house. The meters recorded instantaneous values of temperature, conductivity, and current direction, and a 10 minute average of current speed on magnetic tape at 10 minute intervals.

Dye concentrations were also intermittently measured at the plant, both at the intake screen to pump # 5B; and at the far downstream end of the discharge canal. The dye solution was located on a scale with a precision of ± 0.1 pounds ($\sim \pm 45$ g) and its weight determined frequently for purposes of determining the solution pumping rate.

V. RESULTS

A. Plant Cooling Water Flows and Recirculation.

From Figure 6 we have from continuity

$$Q_{c,i} + Q_s - Q_t = Q_{c,o} \quad (1)$$

where $Q_{c,i}$ is the condenser intake flow, Q_s the service water flow, Q_t the cooling tower make-up, and $Q_{c,o}$ the discharge to the canal. Conservation of dye requires that

$$C_{d,i} Q_{c,i} + C_{d,i} Q_s + q_d = C_{d,o} Q_{c,o} + C_{d,o} Q_t \quad (2)$$

where $C_{d,i}$ and $C_{d,o}$ are the dye tracer concentrations entering and leaving the plant cooling system and q_d is the rate at which dry dye is being injected. Combining (1) and (2) and dividing by q_d we have

$$Q_{c,i} + Q_s = \frac{1}{\frac{C_{d,o}}{q_d} - \frac{C_{d,i}}{q_d}} \quad (3)$$

which is the required relation for determining the cooling water flow to the river from the dye concentrations measured at the intake and discharge. See Figure 6. Assuming rated values of the pump flows from Table I and Figure 6 it follows that

$$\frac{C_{d,o}}{q_d} - \frac{C_{d,i}}{q_d} = \frac{1}{Q_{c,i} + Q_s} = 27.6 \times 10^{-8} \text{ s ml}^{-3}$$

From Figure 7 it may be seen that the average value of $\frac{C_{d,o}}{q_d} - \frac{C_{d,i}}{q_d}$ during the experiment was $31.7 \times 10^{-8} \text{ s ml}^{-3}$. We conclude that the total cooling water flow, $Q_{c,i} + Q_s$, is closer to 50,000 GPM ($\sim 3.15 \text{ m}^3 \text{ s}^{-1}$) than 57,400 GPM ($\sim 3.62 \text{ m}^3 \text{ s}^{-1}$) which accounts for the occasional higher than expected values of ΔT_c , referred to in Section III. Information is not at hand with which to partition this reduced flow between the various circulating and service water pumps.

Intuitively we know that if we "tag" each water molecule as it is drawn into the cooling water system, then after a time, a certain percentage of the water molecules entering the plant intake will be ones which were previously tagged. The amount of this recirculation depends, of course, on the intake and discharge arrangement and the dynamics of the receiving waters from which the cooling water is being withdrawn. With recirculation, the concentration of dye at intake, $C_{d,i}$ is from simple mixing

principles

$$C_{d,i} = \frac{1 \times C_{d,o} + n \times 0}{1 + n} \quad (4)$$

since the n parts of "new" water contain immeasurable tracer. Therefore, the fraction of the total flow, $Q_{c,i} + Q_s$, that is recirculated or "old" water is

$$\frac{1}{1 + n} = \frac{C_{d,i}}{C_{d,o}} \quad (5)$$

The remaining fraction, $n/n + 1$, which is "new" water, is from equations (2) and (5)

$$\frac{n}{n + 1} = \frac{q_d}{C_{d,o} (Q_{c,i} + Q_s)} \quad (6)$$

$C_{d,i}$ in units of $C_{d,i}/q_d$, i.e., the tracer concentration resulting from a unit mass emission rate, measured at the intake screen to pump # 5B is plotted in Figure 8. Since the length of time between consecutive slacks ranged from 4.5 to 7.5 hours, the time since SBE or SBF has been normalized for plotting these data by the length of the ebb or flood appropriate to the measurement (obtained from the current meter records). The data were then fitted by eye as follows:

$$\frac{10^8 \times C_{d,i}/q_d}{s \text{ ml}^{-3}} = 2.5 + 7.5 \sin \left(\pi \frac{t}{t_{SBF} - t_{SBE}} \right), \text{ for } t_{SBE} < t < t_{SBF}, \text{ and (7a)}$$

$$= 2.5 \quad \text{for } t_{SBF} < t < t_{SBE} \quad (7b)$$

Since $q_d/(Q_{c,i} + Q_s) = 31.7 \times 10^{-8} \text{ s ml}^{-3}$, the maximum recirculation is $10/41.7$ or approximately 24%; *it occurs midway in the ebb cycle.*

B. Current Speed and Direction and Temperature and Salinity in the Vicinity of the Plant.

It is not the intent of this report to analyze the Aanderaa records of current speed, current direction, temperature and salinity in any great amount of detail; a typical record commencing at 0100, 14 April 1973 and covering just over 6 days is shown in Figure 9. The record provided shows that the salinity ranged from 0.10 ‰ to 0.25 ‰ with the maximum occurring at slack before ebb and the minimum at slack before flood, that the maximum ebb and flood velocities were of the order of 40 cm s^{-1} (0.73 kts), with the net flow (by eye) apparently upstream due to the influence of the plant intake, that the ambient temperature ranged from 11.0°C to 16.0°C as the season advanced and that the maximum temperatures in the vicinity of the plant occur approximately midway in the ebb cycle as was previously shown in Figure 8.

Figure 8. Tracer concentrations at the intake, in units of concentration per unit mass emission rate, as a function of tidal phase.

Figure 9.

C. Distributions of Tracer and Excess Temperature (Scaled)

We are concerned here with the distribution of heat rejected by the plant; therefore, we must know what the water temperature would have been in the study area had the plant not been operating. This temperature is called the background or base temperature; it is designated T_a , and it is a function of both space and time.

One approach to this problem is to take a time series of temperatures, say at the intake, and to remove the plant effect by spectral analysis of the temperature record and recirculation data from a tracer experiment. This approach was utilized by Carter (1968) in quantitating the distribution of excess heat from the Chalk Point Generating Station on the Patuxent River (Potomac Electric Power Co.) and yielded useful results.

Another approach and the one used during this study is to dye the heated condenser discharge with a fluorescent tracer dye whose natural background is low and constant. After pumping the dye for a sufficiently long enough period of time for the heat and tracer to approach the same equilibrium state, the dye concentrations expressed as dilution ratios and receiving water temperatures will be related in a way that depends on the amount of dry dye discharged per unit of time, q_d , the temperature rise across the condensers, ΔT_c , the total cooling water flow, $Q_{c,i} + Q_s$, the amount of recirculation, $T_{h,i} - T_{a,i}$, where $T_{h,i}$ is the temperature of the water at the intake, the distribution of background temperature, T_a , in the receiving waters, and cooling at the air-sea interface. Conceptually, this relationship is shown in Figure 10. In Figure 10, a dilution ratio of zero corresponds to ambient conditions and a dilution ratio of 1, conditions at

Figure 10. Hypothetical $(T_h)(C_d/C_{d,o})$ diagram.

discharge. As drawn, the background temperature, T_a , varies from $(T_a)_{\text{MIN}}$ to $(T_a)_{\text{MAX}}$, either laterally or vertically or in combination, with the highest temperature in the system at discharge, $T_{h,o}$, given by

$$T_{h,o} = T_{h,i} + \Delta T_c \quad (8)$$

Obviously, all measurements of temperature and tracer concentration must fall within the triangle $(T_a)_{\text{MIN}} (T_a)_{\text{MAX}} T_{h,o}$. Furthermore, for the special case of isothermal receiving waters, i.e., T_a spatially constant, the triangle collapses to a straight line given by

$$T_h = T_a + (T_{h,o} - T_a)(C_d/C_{d,o}) \quad (9)$$

Designating the excess temperature as θ , equation (9) becomes

$$T_h - T_a = \theta = \theta_o (C_d/C_{d,o}) \quad (10)$$

which is the proper scaling relation between tracer concentration, C_d , and excess temperature, θ , for the *special case of T_a spatially constant*.

Even though the receiving waters were, in general, vertically homogeneous with respect to temperature during the study, three factors operated to complicate the analysis of the tracer and temperature data. They were (1) $T_{h,o}$ was highly variable since the Vienna generating station operates as a peaking station (see ΔT_c in Figure 7), (2) T_a was subject to larger and larger lateral variations as the day advanced due to the smaller heat capacity of the shallows and marshlands that border most sampling sections, see Figures 2 and 3, and (3) the range of dilution ratios measured at most sections was not sufficient to provide reliable regressions of T_h on $C_d/C_{d,o}$ for purposes of estimating T_a from the intercept and θ_o from the slope (equation (9)). In order to demonstrate the use of the $(T_h) (C_d/C_{d,o})$ diagram for estimating T_a and θ_o , we have plotted temperature, T_h , versus dilution ratio, $C_d/C_{d,o}$, for the 1727-1731 run of 16 April 1973 at Section 1F (one of the few occasions when the range in $C_d/C_{d,o}$ was adequate) in Figure 11. The estimate of θ_o is consistent with Figure 7 and the estimate of T_a agrees quite closely with an independent estimate of T_a from the quantity $T_h - \theta_o (C_d/C_{d,o})$ (see Figure 13 and the text immediately following).

In order to demonstrate the effect of differential solar heating, we have plotted in Figures 13 through 19, the quantity $T_h - \theta (C_d/C_{d,o})$ using an assumed value of θ_o of 12.0°C for the flood cycle (0% recirculation) and 14.4°C for the ebb cycle (~17% recirculation). To show that the quantity $T_h - \theta_o (C_d/C_{d,o})$ is a reasonable approximation of T_a , consider Figure 12. Figure 12 shows two curves, one for the AM with a uniform background temperature $(T_a)_{\text{AM}}$, and the second, labelled PM, showing a hypothetical $(T_h) (C_d/C_{d,o})$ curve with increased solar heating on the west bank (low tracer concentrations) and on the east bank (high tracer concentrations) over

Figure 11.

Figure 12. $(T_h)(C_d/C_{d,o})$ diagram showing effect of solar heating.

that at the intake. From Figure 12, it can be seen that for the AM

$$(T_h)_{AM} - \theta_o(C_d/C_{d,o}) = (T_a)_{AM} \quad , \quad (11)$$

and for the PM

$$(T_h)_{PM} - (T_a)_{AM} - \theta_o(C_d/C_{d,o}) = \Delta T_a \quad ,$$

or

$$(T_h)_{PM} - \theta_o(C_d/C_{d,o}) = (T_a)_{PM} \quad . \quad (12)$$

The figures (13 through 19) demonstrate quite clearly the lateral uniformity of T_h early in the AM, and the effect of increased solar heating in the shallows and marshes of both banks as the day advances.

The foregoing analysis whereby T_h is estimated from the quantity, $T_h - \theta_o(C_d/C_{d,o})$, depends on the mixing process being independent of the heating. That is, it was assumed, although not stated, in the analysis that the mixing involved only two temperature species, one at $T_{h,o}$ and one at $(T_a)_{AM}$, and that the solar heating was superimposed on the resulting temperature distribution without feedback to the mixing process. This assumption may only be justified if the time scale of mixing, τ_M , is large compared to the time scale of heating, τ_H . If $\tau_H \approx 10$ hours (see Figure 5) and if $\tau_M \approx W^2/K_y$ where W is the width of the estuary and K_y

Figure 13. Lateral distribution of $T_h - \theta_o(C_d/C_{d,0})$ at the surface as a function of time, Section 1F.

Figure 14. Lateral distribution of $T_h - \theta_o (C_d/C_{d,o})$ at the surface as a function of time, Section 2F.

Figure 15. Lateral distribution of $T_h - \theta_o(c_d/c_{d,o})$ at the surface as a function of time, Section 3F.

Figure 16. Lateral distribution of $T_h - \theta_o (C_d/C_{d,o})$ at the surface as a function of time, Section 4F.

Figure 17. Lateral distribution of $T_h - \theta_o(C_d/C_{d,o})$ at the surface as a function of time, Section 2E.

Figure 18. Lateral distribution of $T_h - \theta_o (C_d/C_{d,o})$ at the surface as a function of time, Section 3E.

Figure 19. Lateral distribution of $T_h - \theta_o (C_d/C_{d,o})$ at the surface as a function of time, Section 4E.

is the eddy diffusivity in the lateral direction, then if

$$W = 5 \times 10^4 \text{ cm}, \text{ and}$$

$$K_y = 10^3 \text{ cm}^2 \text{ s}^{-1}, \text{ then}$$

$$\tau_M \approx 25 \times 10^5 \text{ s}, \text{ and}$$

$$\tau_M / \tau_H \approx 100.$$

During the field study, 5 sections (1E, 2E, 3E, 4E, and 5E) were sampled downstream from the Vienna generating station and 4 sections upstream (1F, 2F, 3F, and 4F). The locations of these sections are shown on Figures 2 and 3. Our results are presented in two types of figures.

First of all, we have shown the time history of the *maximum* surface (0.5 meters) tracer concentrations scaled to excess temperature with equation (10) for assumed values of θ of 12.0°C (flood phase) and 14.4°C (ebb phase) at a particular section. In order to combine data taken at the same section but on different days, the actual times of observation were referred to a reference time which was arrived at as follows. At the upstream sections located at distances from the discharge canal greater than a tidal excursion, the reference time ($\Delta T = 0$) was taken as the time of slack water before ebb (SBE). At comparable distances downstream from the discharge canal, the reference time used was the time of slack water before flood (SBF). When the section was within a tidal excursion from the discharge canal, both up- and downstream, all times were referred to the time of arrival of the tracer front at the section. Having thus determined the reference time, individual scaled estimates of the maximum value of excess temperature were plotted as functions of time, ΔT , in accordance with the following relationship

$$\Delta T \equiv \text{real time of observation} - \text{reference time}.$$

Figures 20, 24, 27, 30, 33, 37, 41, 44, and 47 show the scaled surface excess temperature, θ , as a function of time (or tidal phase) referenced as described above for sections 1F, 2F, 3F, 4F, 1E, 2E, 3E, 4E and 5E, respectively.

A second set of figures was prepared (two or three figures for each section) showing the combined lateral and vertical distribution of excess temperature (scaled) at or near the time when maximum values were measured and at or near the time when minimum values were measured. All other realizations of the cross-sectional distribution of θ during this study lie within these envelopes. Figures 21, 22, 23, 25, 26, 28, 29, 31, 32, 34, 35, 36, 38, 39, 40, 42, 43, 45, 46, 48 and 49 show these maximum and minimum cross-sectional distributions of scaled excess temperature, θ . Also shown on these figures are the locations of the vertical casts.

Figure 20. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 1F upstream from the generating station.

Figure 21.

Figure 22.

Figure 23.

Figure 24. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 2F upstream from the generating station.

Figure 25.

Figure 24. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 2F upstream from the generating station.

Figure 25.

Figure 26.

Figure 27. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 3F upstream from the generating station.

Figure 28.

Figure 29.

Figure 30. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 4F upstream from the generating station.

Figure 31.

Figure 32.

Figure 33. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 1E downstream from the generating station.

Figure 34.

Figure 35.

Figure 36.

Figure 37. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 2E downstream from the generating station.

Figure 38.

Figure 39.

Figure 40.

Figure 41. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 3E downstream from the generating station.

Figure 42.

Figure 43.

Figure 44. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 4E downstream from the generating station.

Figure 45.

Figure 46.

Figure 47. Scaled excess temperature, θ , as a function of time during the tidal cycle at Section 5E downstream from the generating station.

Figure 48.

Figure 49.

REFERENCES

- Bump, Charles Weather. 1907. Indian place names in Maryland. *In* Maryland Historical Magazine, Vol. 2, p. 292. Dec. 1907.
- Carter, H.H. 1973. The distribution of excess temperature from the Morgantown generating station on the Potomac estuary. The Johns Hopkins Univ., Chesapeake Bay Institute Tech. Rept. 84, Ref. 73-10.
- Carter, H.H. 1969. A preliminary report on the characteristics of a heated jet discharged horizontally into a transverse current Part I - constant depth. The Johns Hopkins Univ., Chesapeake Bay Institute Tech. Rept. 61, Ref. 69-14.
- Carter, H.H. 1968. The distribution of excess temperature from a heated discharge in an estuary. The Johns Hopkins Univ., Chesapeake Bay Institute Tech. Rept. 44, Ref. 68-14.
- Carter, H.H., D.W. Pritchard, S.R. Rives. 1975. The analysis and interpretation of a heated jet. Paper presented at American Society of Civil Engrs., Ocean Engineering III Conference, 9-12 June 1975, Univ. of Delaware, Newark, Del.
- Carter, H.H., R. Regier. 1974. The three dimensional heated surface jet in a cross flow. The Johns Hopkins Univ., Chesapeake Bay Institute Tech. Rept. 88, Ref. 74-8.
- Carter, H.H., E.W. Schiemer, R. Regier. 1973. The buoyant surface jet discharging normal to an ambient flow of various depths. The Johns Hopkins Univ., Chesapeake Bay Institute Tech. Rept. 81, Ref. 73-7.
- Pritchard, D.W. 1973. Fate of and effect of excess heat discharged into Lake Michigan with specific application to the condenser cooling water discharge from the Zion Nuclear Power Station. Testimony at AEC Licensing Hearings for Zion Operating Permit, Chicago, Ill., June 1973.
- Pritchard, D.W., H.H. Carter. 1972. Design and siting criteria for once-through cooling systems based on a first-order thermal plume model. The Johns Hopkins Univ., Chesapeake Bay Institute Tech. Rept. 75, Ref. 72-6.
- Pritchard, D.W., H.H. Carter. 1965. On the prediction of the distribution of excess temperature from a heated discharge in an estuary. The Johns Hopkins Univ., Chesapeake Bay Institute Tech. Rept. 33, Ref. 65-1.
- Schiemer, E.W. 1962. A portable temperature indicator. The Johns Hopkins Univ., Chesapeake Bay Institute Tech. Rept. 27, Ref. 62-17.
- Schiemer, E.W., D.W. Pritchard. 1961. An induction conductivity temperature indicator. The Johns Hopkins Univ., Chesapeake Bay Institute Tech. Rept. 25, Ref. 61-4.

REFERENCES *(continued)*

Schubel, J.R. 1973. Effects of exposure to time-excess temperature histories typically experienced at power plants on the hatching success of fish eggs. The Johns Hopkins Univ., Chesapeake Bay Institute Spec. Rept. 32, Ref. 73-11.