A Rationale For Evaluating Thermally Induced Biological Effects Due To Once-Through Cooling Systems

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SUMMARY AND RECOMMENDATIONS

Summary

In this report we show how the thermally induced biological effects of power plants
with once-through cooling systems can be evaluated in a logical, scientifically defensible
manner. First, we used existing models to predict the fields of excess temperature and
velocity associated with a power plant sited on a river and an estuary, and to establish
the time-excess temperature exposure histories resulting from the interaction of an
assumed distribution of organisms with these fields. Next, we developed a new thermal
response model to assess the thermal effects of these exposures on these organisms.

We combined a near-field integral model (the Shirazi-Davis model) with a far-field
model (the Okubo-Pritchard model) to describe the combined (complete) excess temperature
and velocity fields. The Shirazi-Davis model is a steady state three dimensional model
containing seven adjustable parameters: jet entrainment (mechanical mixing), ambient
entrainment (turbulent diffusion), buoyant spreading, interfacial shear between the jet
and the ambient fluid, cross flow drag, and surface heat exchange. It assumes similar
velocity and excess temperature profiles in the lateral and vertical directions. We esti-
mated the far-field excess temperature and velocity fields by superimposing a large number
of small diffusing patches, each from an infinitesimal instantaneous source, and all mov-
ing with a velocity $v(t)$. To estimate the diffusion relative to the center of mass of
these elementary patches we used the Okubo-Pritchard diffusion model -- a radially symmet-
rical solution for horizontal diffusion from a vertical line source characterized by a
"diffusion velocity".

Our near- and far-field superposition consists of combining velocity fields by vector
addition and excess temperature fields by invoking a simple mixing concept. We described
the complete field for a "typical" plant sited on a river (unidirectional flow), and for a
plant sited on an estuary (oscillating flow). The hypothetical plant had a full load gen-
erating capacity of 375 MWe, a ΔT of 10C, and a cooling water flow of 10.6 m^3s^{-1} (375
cfs). Since there was no provision in our analysis for an intake, the effects of pump
entrainment have not been considered.

Using the complete (combined) velocity and excess temperature fields for the river
and the estuary cases, we computed the time-excess temperature exposure histories experi-
enced by each of 100 organisms with an assumed spatial distribution. The associated
thermal doses -- the integrals of the time-excess temperature histories -- were also
determined for the organisms and were sorted by maximum excess temperature.

The next task was to assess the biological effects of exposure of Representative
Important Species to the frequency distribution of thermal doses calculated for our hypo-
thetical power plant. We developed a simple thermal response model that combines in
graphical form: (a) the distribution of thermal doses computed from the physical models
for an assumed distribution of organisms in the receiving waters with (b) the distribution
of thermal doses calculated from laboratory-determined thermal resistance curves which
have been demonstrated to produce mortality at a particular level, usually 50%, for Repre-
sentative Important Species. From the relative positions of these two curves, predictions
can be made of the mortality rate expected from thermal stresses at a particular site.

Our thermal response model can be used with data from existing and proposed power
plants to estimate what fraction of plankton in waters contiguous to the plant will be
exposed to thermal doses greater than that for mortality at any stated level, usually 50%.
The model can also be used to aid in the design of once-through cooling systems to keep
the mortality rate caused by thermal stresses below any designated threshold. The inputs

to the model are the frequency distribution of time-excess temperature histories experienced by the plankton of particular concern (the Representative Important Species), thermal resistance curves for those organisms, and the spatial and temporal variations of the natural temperature of the receiving waters.

We took Long Island Sound, the lower Hudson River, and Lake Ontario as examples to demonstrate the types of data input required to apply our thermal response model to important aquatic environments of New York State. Serial observations of ambient water temperature for daily, monthly and annual changes were obtained for numbers of years at various long-term observation stations in the three environments. We identified Representative Important Species for each environment and the present availability of thermal resistance data for their early (entrainable) life-stages was reviewed. From *all* of the thermal resistance data available for *any* of the entrainable species composing these three communities, we constructed "community thermal resistance curves". For each community it appeared that the most sensitive organisms were the ichthyoplankton and juvenile fish; therefore, protection of these organisms from thermal stress should protect the entrainable populations as a whole.

We discussed the problems involved in attempting to assess the effects of power plant induced mortality on fish populations. Detailed site studies of entrainment mortalities can not provide a basis for assessing possible population effects unless they are related to the whole (water body wide) population or organisms -- of which the local group of organisms maybe only a small part. Natural mortalities of early life stages of most finfish and shellfish are extremely high, but it does not necessarily follow that power plant induced mortalities could not be manifested in reductions in the recruit populations of those organisms. Daily plant induced mortalities may be cumulative in effect and may be of a relatively large magnitude. They should be considered as additive to other mortalities (natural, or man-induced). The net effects of plant mortalities on the population may not be additive, however, because of compensatory responses, but they will remove some of the ability of the stock to successfully withstand unpredictable environmental changes, their impact being more severe on populations already being heavily fished by man. Until the interactions of such factors which regulate fish populations are better understood, prudence should be exercised in choosing sites for power plants, and in designing and operating the plants to minimize the total numbers of organisms killed by entrainment.

Recommendations for Research

The physical models we used to compute time-excess temperature histories and associated thermal doses should be refined to include: (a) an intake to simulate pump entrainment, and (b) interactions of the thermal plume with the bottom and with the far shore. If the Shirazi-Davis/Okubo-Pritchard complete-field model used in the present analysis can not be so modified, other models should be investigated.

There is a dearth of diagnostic thermal data for the Representative Important Species of New York's riverine, estuarine, and coastal environments. Thermal resistance curves should be determined for these organisms. Until such data are available, the diagnostic value of our thermal response model, or of any other biological model, will be severely limited. We strongly recommend that appropriate laboratory experiments be conducted for construction of thermal resistance curves for New York's Representative Important Species. Initially the emphasis should be put on ichthyoplankton. A relatively modest research effort could produce data for the most important and sensitive organisms within 3-5 years.

During the course of the laboratory studies to determine thermal resistance curves for important species, the study should include a detailed consideration of the

relationship of maximum excess temperature (T_{max}) to thermal dose in inducing mortality. Attention should also be directed at determining the sublethal effects of excess temperature on egg and larval stages, which may disturb normal development of sensory-nervous systems, or morphogenesis and which could lead to behavior or anatomy detrimental to survival in subsequent life stages. The apparent onset of debilitation (and susceptibility to predation) at 2C lower than temperatures necessary for death at the same exposure time, should be critically assessed.

We recommend that more emphasis be placed on water body wide studies with appropriate sampling techniques. This information is required if we are to assess the effects of an existing plant on a water body, or if we are to rank potential sites for proposed plants. Once a site for a plant with a once-through cooling system has been selected, the plant should be designed and operated to minimize the total number of organisms killed by entrainment.

Finally, we recommend that the refined physical and thermal response models be applied to an existing electric generating station with a once-through cooling system sited in New York State waters. The station should be selected jointly by representatives of the NYSERDA and the MSRC. One site that may be appropriate is the Rochester Gas and Electric Company's Ginna station located on Lake Ontario.

TABLE OF CONTENTS

LIST OF FIGURES

v

LIST OF FIGURES cont'd.

LIST OF TABLES

ACKNOWLEDGMENTS

I. INTRODUCTION

H. H. Carter

A. *Background*

In the simplest terms, a steam electric generating station consists of a heat source and boiler to generate steam, a turbine which is driven by the steam, a generator which in turn is driven by the turbine and, for purposes of economy, a system for condensing the steam after it has been exhausted from the turbine. In the event the condenser cooling water is withdrawn from and returned at an elevated temperature to the water body on which the plant is sited, the system is termed once-through or open-cycle. Typically, a 1000 MWe nuclear steam electric generating station with once-through cooling must discharge to the aquatic environment approximately 48 m^3s^{-1} (28 m^3s^{-1} if fossil fueled) if the elevated temperature is 10C.

According to Schubel and Marcy (in press), there were 493 generating stations using once-through cooling as of 1973, the latest year for which data were available. In the late 1950's and early 1960's, as generating stations grew larger and more numerous, it was perceived by scientists that there was significant *potential* for thermal stress on planktonic organisms which were entrained in a thermal plume by turbulent diffusion or jet mixing (plume entrainment) or drawn into the plant intake and passed through the condensers and discharge system (pump entrainment), and on benthic organisms on whose habitats a thermal plume impinged either occasionally or continuously. Early on, the distribution of excess temperature[1] from once-through cooling systems was labelled "thermal pollution", a term connoting significant degradation of the natural state of affairs. Faced with an apparent environmental crisis of large proportions, the federal and most state governments adopted, in short order, stringent

criteria and standards regulating the discharge of excess heat associated with once-through cooling systems. Two major pieces of federal legislation which regulated thermal discharges soon followed. The first, the National Environmental Policy Act of 1969 (Public Law 91-190; hereafter referred to as NEPA), was a major attempt to focus and coordinate all federal actions that were "significantly affecting the quality of the human environment" (NEPA, 1969) toward the need for detailed environmental analyses. The Council of Environmental Quality (CEQ) under Title II of NEPA, is the administrator, reviewer and clearinghouse for the impact statements from the involved federal agencies. NEPA guidelines were published in the Code of Federal Regulations, Title 90, Chapter V, Part 1500, and appeared in the Federal Register, August 1, 1973, pp. 20549-20562. The NEPA guidelines provide a mechanism whereby federal agencies must fully assess the potential environmental impact as early as possible. In all cases, the assessment must be made prior to agency decision concerning legislative actions which may significantly affect the environment.

The second and most important legislation affecting thermal discharges was the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500; hereafter referred to as the Act) which proclaimed as a national goal "...that wherever attainable, an interim goal of water quality which provides for the protection and propagation of fish, shellfish, and wildlife and provides for recreation in and on the water be achieved by July 1, 1983." The Act further states that it is a national goal to eliminate all pollutant discharges into navigable water by 1985.

With the passage of the Act, a national program was implemented which required a permit for every point source discharge of pollutants -- including waste heat -- into the navigable waters of the

1

United States. This program is known as the National Pollutant Discharge Elimination System (NPDES), Section 402. A state may administer the NPDES program pursuant to compliance with "State Program Elements Necessary for Participation in the National Pollutant Discharge Elimination System" (40CFR Part 124). If a state does not meet the requirements of 40CFR Part 124, then the Environmental Protection Agency (EPA) retains the permit authorization. Section 301(b)(1)(A) of the Act requires for all point sources, other than publicly owned treatment works, the "best practicable control technology currently available" by 1 July 1977 and the most stringent best available technology economically achievable by no later than 1 July 1983 {Section 301 (b) (2) (A)}.

Section 316(a) of the Act, however, provides an *opportunity* for the owner or operator of a steam electric generating station to demonstrate that the *thermal* effluent limitations imposed by the Administrator of the EPA, (or if appropriate, the State) pursuant to Section 301 of the Act are more stringent than necessary to, "...assure the protection and propagation of a balanced, indigenous population of shell fish, fish, and wildlife in and on the body of water into which the discharge is to be made,...". In the event a successful demonstration is made, the Administrator (or, if appropriate, the State) may impose alternate, or less stringent, limitations.

Final effluent guidelines and limitations for steam electric generating units were promulgated on 8 October 1974 (40 CFR 423, 39 Fed. Reg. 36186). After evaluation of all factors, *EPA selected closed-cycle cooling (cooling towers) as the best technology*, in general, but deemed it proper to exempt from this technology requirement "old units" with once-through cooling systems (40 CFR 423.30). An "old unit" is any generating unit which was first placed in service on or before 1 January 1970 and any generating unit of less than 500 megawatts

rated net generating capacity which was first placed in service on or before 1 January 1974. The applicable thermal limitations for these "old units," therefore, are contained in appropriate State standards. In the event of non-compliance with appropriate State standards, a variance can be granted, however, in accordance with Section 316(a) of the Act.

Section 301(d) of the Act also requires a review every five years of all effluent limitations established pursuant to the Act. This is interpreted as requiring a "second round" of Section 316(a) determinations when the first permit expires.

The thermal effluent limitations referred to are implemented by the EPA (or, if appropriate, the State) through the NPDES described earlier. Those States which have been delegated the administration of the NPDES permit program by EPA have the lead role for making 316(a) decisions within the State. EPA, however, retains what amounts to a veto power since they must sign all permits before they are issued.

In addition to the foregoing, the Nuclear Regulatory Commission (NRC) requires applicants for licenses or permits for nuclear fueled generating stations to submit information in order that NRC might evaluate the environmental impacts of any action it might take pursuant to NEPA.

This recent legislation, i.e., the Act and NEPA, seems certain to increase the use of cooling towers over once-through cooling unless the owner or operator can provide a satisfactory demonstration in accordance with Section 316 of the Act. In fact, as the law stands some existing plants with open-cycle cooling may be required to back fit for cooling towers.

It is clear that in evaluating open-cycle thermal effects, both the EPA and the appropriate states are continuing to place heavy reliance on protecting aquatic

2

life by prescribing some combination of maximum receiving water temperature, maximum temperature rise across the condensers, and the maximum size of a mixing zone. As pointed out by Stolzenbach (1976), this strategy is probably due to the relative ease with which these limits can be predicted and monitored for a given location and design of plant. It is naive to suppose that these somewhat arbitrarily established limits of maximum temperatures and "critical" areas and/or volumes are *a priori* an acceptable substitute for scientifically based regulations for controlling thermally induced biological effects associated with once-through cooling systems. There is considerable evidence to suggest that the present standards and criteria are not only unduly restrictive with respect to temperature, but may result in greater impact than necessary from physical stresses because of the tendency to impose relatively low ΔT's across the condensers, a practice that requires large volumes of cooling water. There is also considerable evidence to suggest that once-through cooling systems can be used at many sites without demonstrable and persistent damage to the environment, and at far less cost than cooling towers. Cooling towers can have undesirable environmental and aesthetic effects, as well as economic drawbacks.

It is the goal of this report to describe a scientifically defensible procedure or rationale for evaluating *thermally* induced biological effects due to once-through cooling systems of steam electric generating stations. Details will be provided where the state of the art permits; where not, concepts will be outlined. Our analysis considers only the effects of thermal stresses, it does not consider the effects of other stresses associated with once-through cooling -- chemical stresses associated with biocides used to prevent fouling of the cooling system, and physical stresses associated with pressure changes, shear forces, impact, and

abrasion. In addition, guidance for meeting the objectives of Section 316(b) of the Act is not provided; that section requires that the location, design, construction, and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impact.

B. *The Evaluation Process*

When a heated effluent is discharged into a water body, its fate depends upon many physical processes which, for purposes of analysis, may be categorized as either *near* or *far field*. The near-field processes are governed primarily by the characteristics of the discharge whereas the far-field processes depend on larger scale ambient conditions. Conditions in the near-field are heavily dependent on the thermal emission rate, the initial temperature of the effluent, and the type of discharge. Conditions in the far-field depend on the thermal emission rate, the receiving water characteristics, and surface cooling. Thermal mixing zones must be considered on a case-by-case basis, therefore.

According to EPA (1973), however, "..., the following general recommendation can be established for the purpose of protecting aquatic life in areas where effluents are mixing with receiving waters:

> The total time-toxicity exposure history must not cause deleterious effects in affected populations of important species, including the post-exposure effects."

If we substitute excess temperature for toxicity in the foregoing statement, we arrive at the concept of thermal dose or the integral of excess temperature over the time of exposure. Probably more important, in our view, are the maximum temperature and the maximum temperature rise (ΔT) to which an organism is exposed.

3

In any event, a determination of whether or not a given site for a power plant with a once-through cooling system is biologically acceptable requires a step-by-step evaluation. We propose the following:

    (a)   a procedure to determine the temporal and spatial distribution of excess temperature and velocity in the receiving waters off the plant. These data are necessary to calculate thermal dose statistics, i.e., time-temperature histories, for both benthic and planktonic species;

    (b)   a procedure to calculate for a given distribution of benthic and planktonic organisms, the fractions of that total distribution that have been exposed to various thermal doses ordered with respect to maximum temperature. The procedure should be applicable to riverine, lacustrine, and estuarine/coastal situations;

    (c)   a procedure to determine the most probable levels of mortality of the given distributions of the various Representative Important Species (R.I.S.). That is, the fraction of a given distribution that has been exposed to a combination of thermal dose and maximum temperature equal to or greater than some critical combination must be estimated from items 1 and 2, above. Critical thermal dose-maximum temperature data for the various RIS must be obtained from either the published literature on thermal tolerances or established by experiment; and

    (d)   a procedure to determine whether such mortality levels are permissible, that is, are not manifested in reductions in the recruit population.

II. A THERMAL DOSE MODEL
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A. Modelling The Fields Of Velocity And Excess Temperature

In Section I.B. we broadly categorized the regions of a thermal plume from a power plant into near- and far-field according to the physical processes which were dominant, Figure 1. One should not, however, assume from this that these two fields are independent; under certain circumstances they interact with important consequences. For example, in a lake or an estuary where the current reverses periodically due to either wind or astronomical tides, heat discharged at some earlier time (the far-field) may be re-entrained into the jet region (near-field) or directly recirculated into the intake. Periodic interactions of this type can result in variations in the areas enclosed within specific isotherms of several orders of magnitude. Whether or not existing near-field thermal plume models are truly predictive is, therefore, moot other than in a statistical sense, since such models assume that heat leaves the near-field, enters the far-field, and never returns. On the other hand, a far-field model is inadequate to describe conditions in the near-field since it can not account for the effect of the discharge on near-field mixing and flows.

4

NEAR FIELD ◄——————►◄—— FAR FIELD ——————————►

JET DISCHARGE   SURFACE HEAT LOSS ↑ ▼

VERTICAL
JET
ENTRAINMENT   DIFFUSION
          BUOYANT FORCES INHIBIT ENTRAINMENT   DUE TO AMBIENT
                                               TURBULENCE

VERTICAL SECTION

JET DISCHARGE   ↑↑ CROSS FLOW ↑↑
                       ↓↓ INTERACTION ↓↓

                       BUOYANT
LATERAL   SPREADING
JET   PLUME DRIFTING
ENTRAINMENT   WITH AMBIENT
                                 CURRENT

PLAN VIEW
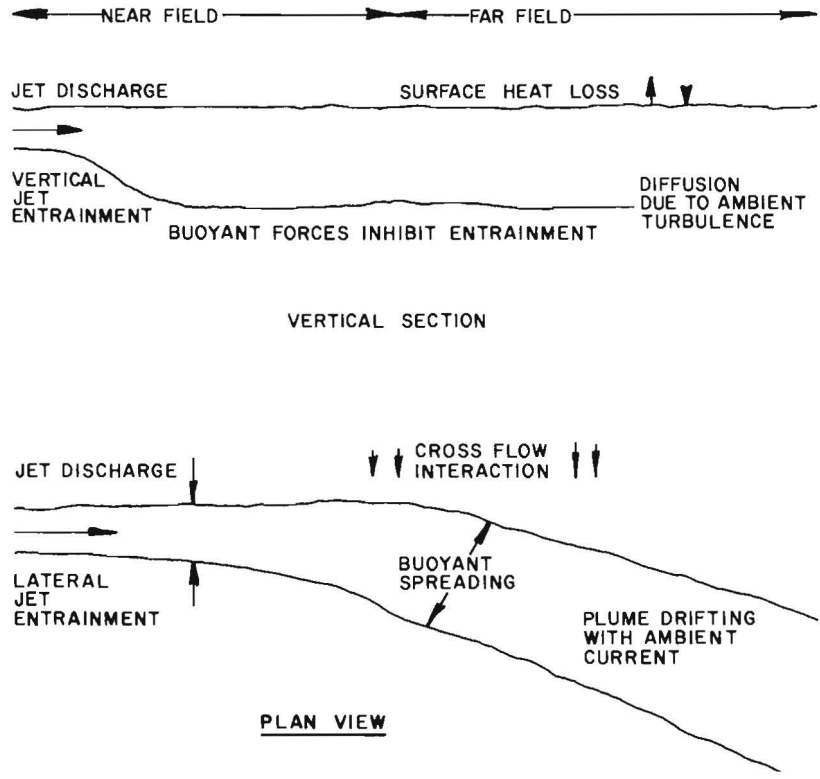
Figure 1. Schematic categorization of plume geometry according to physical processes.

In our view, therefore, a combined or complete-field model is required for even a first order estimate of the distribution of excess temperature.

Leaving open for the moment the precise form of the near- and far-field models which we will use for our analysis, we have chosen to produce a complete-field model by superimposing the predicted near- and far-field velocities and excess temperatures. Velocity fields will be combined by simple vector addition since our near-field model predicts the velocity that is excess to ambient. The two temperature fields, one from our near-field model and one from our far-field model, will be superimposed in accordance with the following simple mixing concept.

Let θ_n (x,y,z,t) be the excess temperature resulting from the near-field model,

θ_f (x,y,z,t) be the excess

temperature resulting from the far-field model,

θ_c (x,y,z,t) be the excess temperature resulting from the combined fields, and

θ_o be the excess temperature at the point of discharge,

then, for the case where $\theta_f > 0$, the combined excess temperature at any point x, y, z, and time t is given by

$$\theta_c(x,y,z,t) = \frac{1 \cdot \theta_o + N \cdot \theta_f(x,y,z,t)}{1 + N} \quad (1)$$

if we neglect surface cooling. In equation (1), N is the volume into which a unit volume at temperature θ_o is considered to be mixed. Similarly, for the case where $\theta_f = 0$,

5

$$\theta_n(x,y,z,t) = \frac{1 \cdot \theta_o}{1 + N} \qquad (2)$$

Rearranging equation (2), we have

$$N = \frac{\theta_o}{\theta_n} - 1 . \qquad (3)$$

Finally, substituting equation (3) into (1) results in

$$\frac{\theta_c}{\theta_o} = \frac{\theta_n}{\theta_o} + (1 - \frac{\theta_n}{\theta_o}) \frac{\theta_f}{\theta_o} \qquad (4)$$

which is the desired superposition scheme for excess temperature.

1. The Near-Field Model

Excellent reviews of the state of the art of hydrothermal modeling are provided in Dunn *et al.* (1975, 1975a) and Jirka *et al.* (1975). Included in those references are detailed discussions of the important physical processes, the governing equations, and the various types of models, i.e., analytical, integral[1], and finite difference[1]. According to Dunn *et al.* (1975), over 40 near-field models have been formulated, none of which has been sufficiently validated to ensure reasonably accurate predictions over a practical range of prototype situations; they provide details of 11 of these. Based on Dunn *et al.* (1975), verbal communications with A. J. Policastro, and the fact that a computer code was readily available[2], we selected the near-field model known as the Shirazi-Davis model (Shirazi and Davis, 1974, 1976).

For their model, Shirazi and Davis collected available laboratory and field data and then used these data to calibrate an existing model known as the Prych model (Prych, 1972). The model is a steady state three-dimensional scheme containing seven adjustable parameters. It includes jet entrainment (mechanical mixing), ambient entrainment (turbulent diffusion), buoyant spreading, interfacial shear between the jet and the ambient fluid, cross flow drag, and surface heat exchange. It does not include bottom topography, boundary effects (either nearshore or farshore), a time varying current, and a variable density, i.e., stratification. Since it assumes similar velocity and excess temperature profiles in the lateral and vertical directions, it is an integral model. For details concerning the model, the reader is referred to Shirazi and Davis (1974, 1976).

2. The Far-Field Model

We have chosen to treat the far-field by superimposing a large number of small diffusing patches, each from an infinitesimal, instantaneous source and all moving with a velocity, U(t). For the diffusion relative to the center of mass for these elementary patches, we have chosen the Okubo-Pritchard (O-P) diffusion model (Okubo and Pritchard, unpublished note in Pritchard {1960}). This model is one of a class of radially symmetric solutions for horizontal diffusion from an instantaneous vertical line source characterized by a "diffusion velocity." The O-P model is based on the intuitive concept that the rate of change of local variance, i.e., the diffusivity, depends on a characteristic velocity, ω, and the time of diffusion. We recognize that in a turbulent environment the shape of an instantaneous release of material is seldom if ever circular and that by characterizing the velocity field as spatially uniform we cannot account for the highly variable trajectories taken by the various patches. Nevertheless, radially symmetric models have achieved considerable success in predicting the diffusion of introduced substances.

For horizontal diffusion from an instantaneous vertical line source, Okubo and Pritchard proposed the relationship

6

$$S_i(x,y,t) = \frac{m}{\pi\omega^2 Dt^2} \exp\left\{\frac{-(x - \int_0^t U dt')^2 - y^2}{\omega^2 t^2}\right\}$$

(5)

where $S_i(x,y,t)$ is the concentration of material at distance x from the source and y from the centerline, at time t since the single instantaneous release of mass m, distributed uniformly within a layer of thickness D; ω is the diffusion velocity, and $U(t)$ the ambient velocity -- assumed to be vertically uniform and directed parallel to the x-axis.

Assuming that a continuous source can be considered as a superposition of a large number of instantaneous releases (N per unit time), we have at time t after initiation of discharge

$$\int_0^t S_i N dt = S_c(x,y,t) = \frac{q}{\pi\omega^2 D} \int_0^t \frac{1}{t^2} \exp\left\{\frac{-(x - \int_0^t U[t']dt')^2 - y^2}{\omega^2 t^2}\right\} dt$$

(6)

where $S_c(x,y,t)$ is now the concentration from a continuous release of material at the rate q = Nm.

For the simple case where U is constant, equation (6) may be integrated analytically with the result that

$$S_c(x,y,t) = \frac{q}{2\sqrt{\pi}\ \omega D\ \sqrt{x^2+y^2}} \exp\left\{-\frac{U^2 y^2}{\omega^2(x^2+y^2)}\right\}\left\{1-\text{erf}\left(\frac{\sqrt{x^2+y^2}}{\omega}[\frac{1}{t} - \frac{xU}{x^2+y^2}]\right)\right\}$$

(7)

For the more general estuarine/coastal situation, however, where U is a function of t, the integration was performed numerically.

3. The Complete-Fields By Superposition

Our near- and far-field superposition scheme which was described earlier, consists simply of combining velocity fields by vector addition and excess temperature fields by the simple mixing relation given by equation (4). For a unidirectional flow, such as in a river, there can be no complicating interaction similar to that described above for an oscillating flow. Therefore, since the Shirazi-Davis model includes ambient turbulence, i.e., far-field mixing, no superposition is required. We first show in Figures 2 and 3, therefore, the velocity field and the excess temperature field as a result of exercising the Shirazi-Davis model alone for a typical fossil fuel generating station sited on a river. We have assumed that the plant generates approximately 375 MWe at full load, rejecting 1.53 x 10^9 BTU per hour (4.484 x 10^3 joules per second) at a temperature rise across the condens-

ers of 18F (10C) in a cooling water flow of 375 cfs (10.62 m³s⁻¹). The cooling water has been discharged normal to the naarshore at a velocity of 3.75 fs⁻¹ (114.3 cms⁻¹) and at an initial densimetric Froude number of 4. The discharge channel is 10 feet by 10 feet (3.05 m by 3.05 m). The receiving waters were assumed to flow past the plant at a spatially uniform and steady velocity of 0.315 fs⁻¹ (9.61 cms⁻¹) for Figure 2[3] and 0.375 fs⁻¹ (11.43 cms⁻¹) for Figure 3[3]. Implicit in the model is a bottom slope in the offshore direction of infinity, i.e., no bottom and a vertical nearshore, and no farshore boundary, i.e., we are constrained to place any farshore just beyond the offshore boundary of the jet discharge as defined by some arbitrary isotherm. The following values were assumed for the dimensionless free parameters in the model (see Shirazi and Davis [1974,1976] for their definitions).
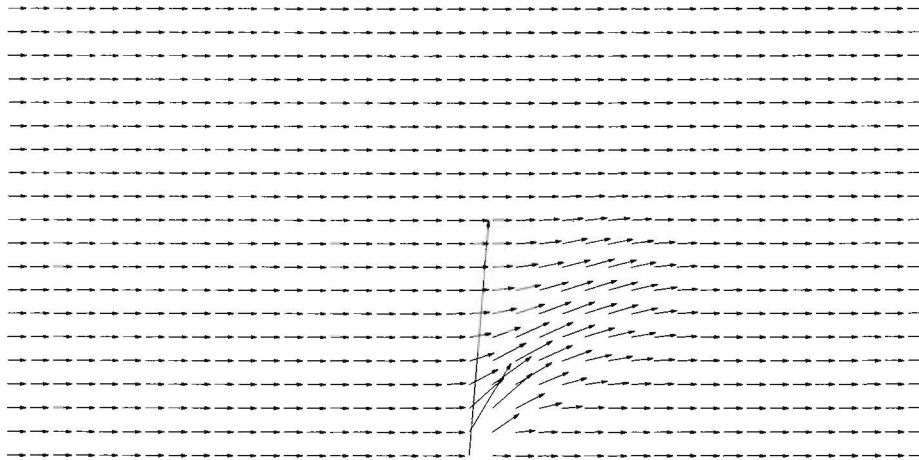
Figure 2.   The velocity field resulting from the discharge of heated cooling
water (375 cfs) into a river. See text for details.

Entrainment coefficient, E_o 0.05

Horizontal eddy diffusion, E_h 0.02
    coefficient

Vertical eddy diffusion, E_v ..... $0.2E_h$
    coefficient

Spreading coefficient, C_s 1.4

Interfacial shear drag, C_f 0.0
    coefficient

Drag coefficient, C_D 1.0

Surface cooling, K 0.0
    coefficient

Figures 4, 5, 6, and 7 show the fields of excess temperature for the same generating station but now sited on an estuary or coast. As a result of the superposition, the near-field jet plume (as predicted by the Shirazi-Davis model) can now be seen to be embedded in the far-field distribution (as predicted by the Okubo-Pritchard diffusion model). We have assumed here that the flow in the receiving waters is uniform but time varying in accordance with the following relation:

$$u(t) = u_o + u_{max} \sin(2\pi t/T) \qquad (8)$$

where u_o, the non-tidal velocity, was

assumed to be 1.905 cms^{-1}, u_{max}, the tidal velocity amplitude, was assumed to be 9.525 cms^{-1}, and T was assumed to be 12 hours. In preparing these figures, we first ran the O-P model to steady state (approximately 5 tidal cycles) and then superposed the near- and far-field distributions in accordance with equation (4) but did not count any heat discharged from the far-field source after slack before flood (SBF) for SBF < t < SBE (flood tide) and after slack before ebb (SBE) for SBE < t < SBF (ebb tide).

Figures 8[4] and 9 show the velocity fields at maximum ebb (approximately) and maximum flood, respectively.

B. Sample Thermal Dose Calculations

In order to assess the response to a thermal discharge of the biota that inhabit the receiving waters and the underlying substratum, a method of relating response in "biological units" to stimulus in physical units must be found. For this purpose, we shall use the maximum temperature and maximum temperature rise to which the organism is exposed, as well

8

KEY: ☉ = 9 C ,   ▲ = 6 C , + = 4 C , ✕ = 3 C , ◆ = 2 C , ⬆ = 1 C , ✕ = 0.04 C
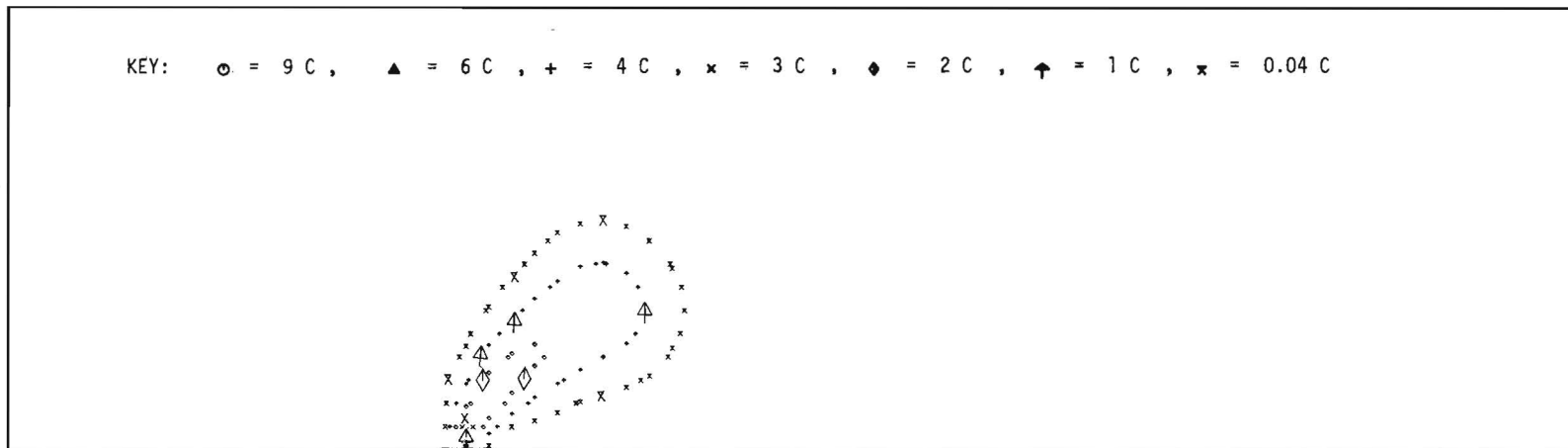
Figure 3.   The excess temperature field resulting from the discharge of heated cooling water
(375 cfs) at an excess temperature of 10 C into a river.   See text for details.
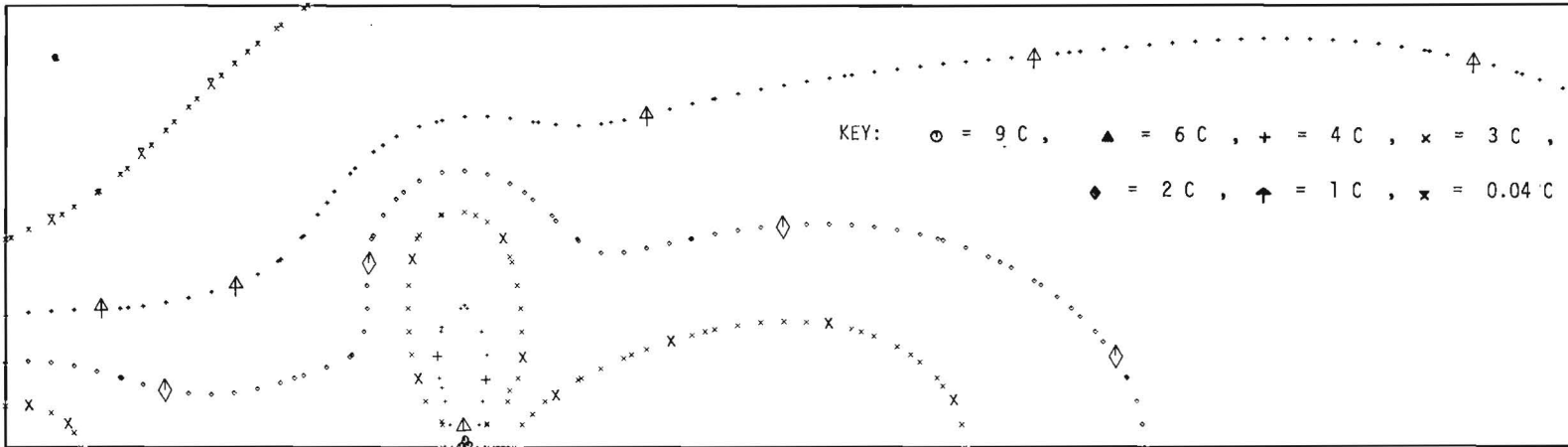
Figure 4.   The excess temperature field at (approximately) slack before ebb resulting from the discharge of cooling water (375 cfs) into estuarine or coastal receiving waters (tidal).   See text for details.
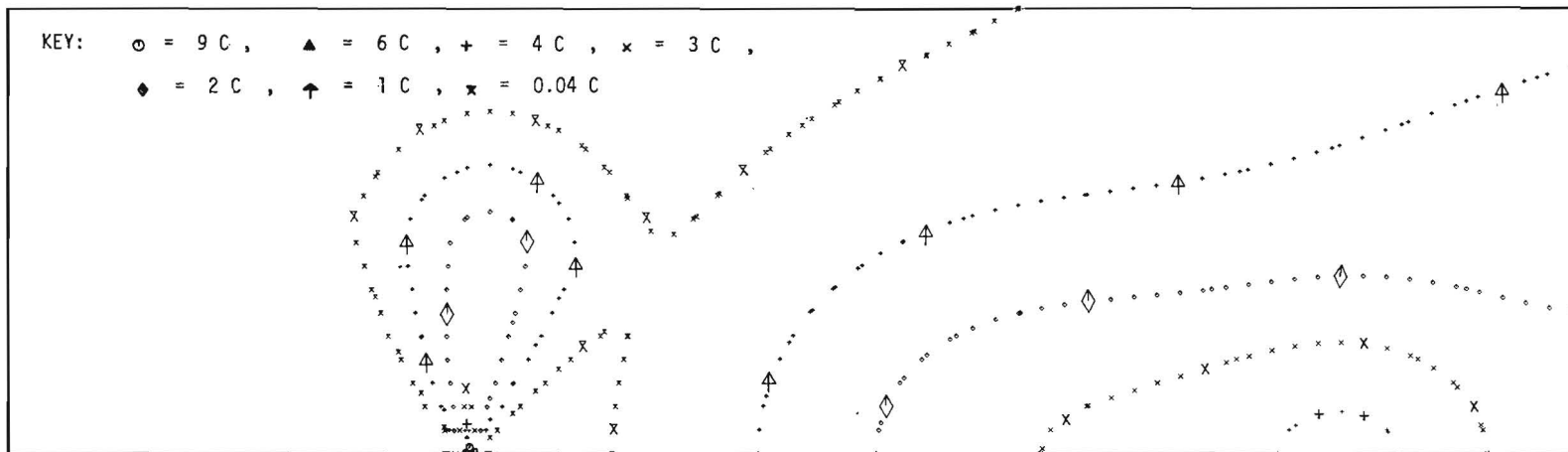
Figure 5.   The excess temperature field at (approximately) slack before flood resulting from the discharge of cooling water (375 cfs) into estuarine or coastal receiving waters (tidal).   See text for details.

KEY: ⊙ = 9 C ,   ▲ = 6 C , + = 4 C ,

x = 3 C ,   ◆ = 2 C ,

↑ = 1 C ,   ⋈ = 0.04 C
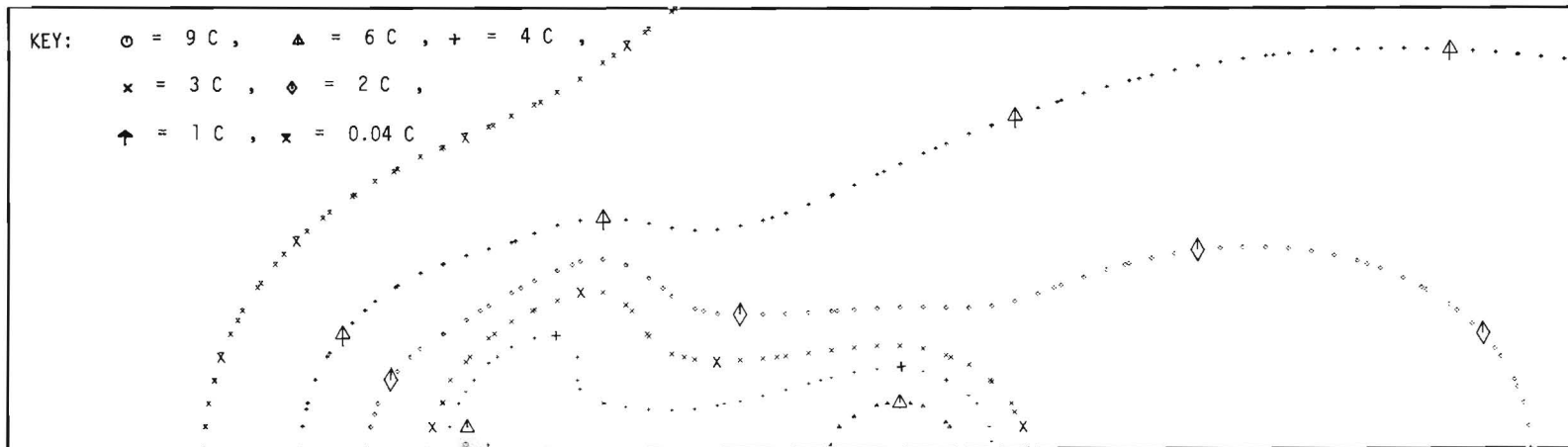
Figure 6.   The excess temperature field at (approximately) maximum ebb resulting from the discharge of cooling water (375 cfs) into estuarine or coastal receiving waters (tidal). See text for details.

KEY: ⊙ = 9 C ,   ▲ = 6 C , + = 4 C

x = 3 C ,   ◆ = 2 C ,

↑ = 1 C ,   ⋈ = 0.04 C
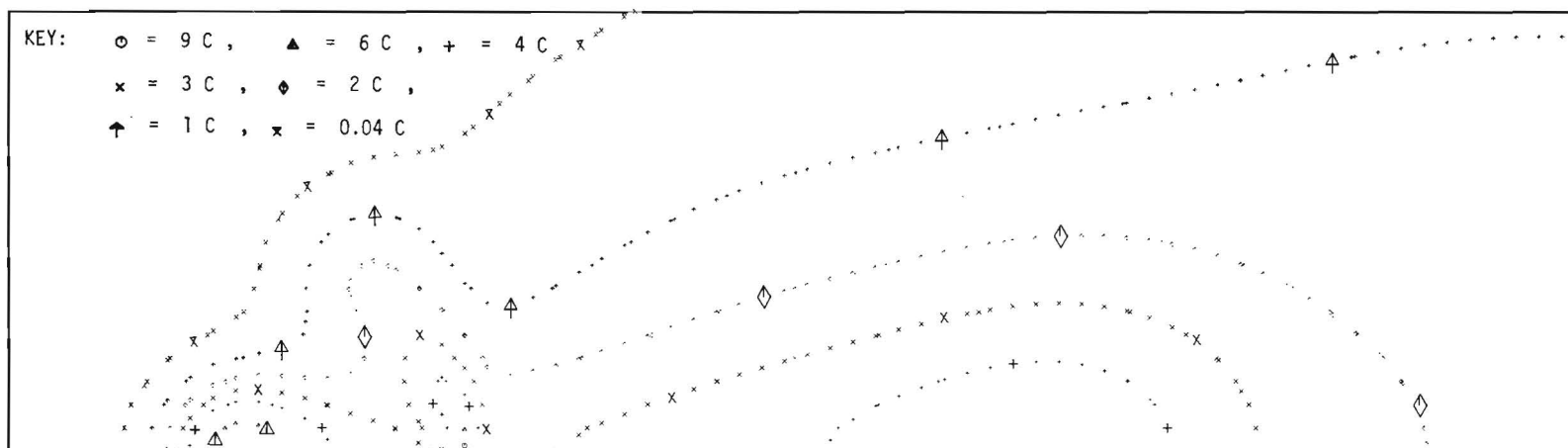
Figure 7.   The excess temperature field at (approximately) maximum flood resulting from the discharge of cooling water (375 cfs) into estuarine or coastal receiving waters (tidal). See text for details.
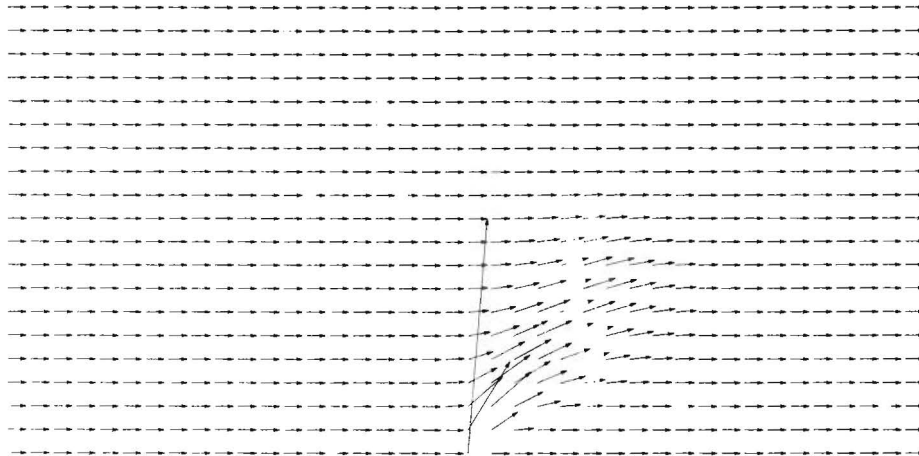
Figure 8. The velocity field at maximum ebb (approximately) resulting from the discharge of heated cooling water (375 cfs) into estuarine or coastal receiving waters (tidal). See text for details.
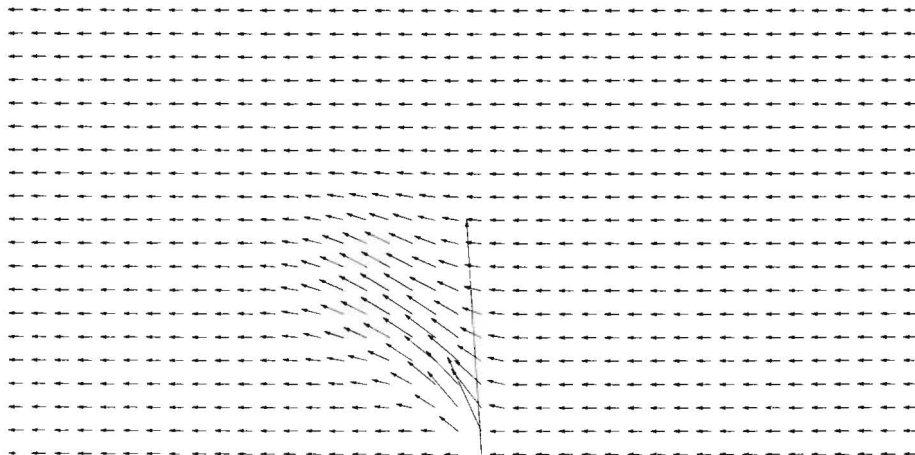
Figure 9. The velocity field at maximum flood (approximately) resulting from the discharge of heated cooling water (375 cfs) into estuarine or coastal receiving waters (tidal). See text for details.

12

as the thermal dose by which we mean

$$\text{Thermal dose} \equiv \int_0^t \theta \, dt' \qquad (9)$$

where θ is the excess temperature and t is the time of exposure. The thermal dose to which an organism is exposed is calculated from the fields of velocity and excess temperature arrived at as described above and which may be considered as known from this point on. That is, the path or trajectory of an organism being carried passively in the flow and starting at an initial position (x_o, y_o) is calculated from

$$x = x_o + u \, dt, \text{ and}$$

$$y = y_o + v \, dt \qquad \text{10b)}$$

where dt is small interval of time. At each time step, dt, along the path, the excess temperature is noted and the integration indicated in equation (9) is carried out by the trapezoidal rule. The highest excess temperature to which the organism was exposed during its travel is noted for future input to the thermal response model; for the estuarine cases doses received at excess temperatures less than some minimum excess temperature are excluded from the sum or integration. See Section III.B.2. All organisms contained in an assumed initial distribution are followed in this manner until such time as they are no longer in the region influenced by the cooling water discharge. The result is a list containing a dose and its associated maximum excess temperature for each organism followed which now may be plotted or tabulated in some suitable format.

To demonstrate and, in addition, to provide input to the thermal response model described in a later section, we show on Figures 10 and 11 the results from two such sets of calculations. Figure 10 shows, for a riverine situation, thermal dose plotted as a function of the highest excess temperature experienced for 100 organisms uniformly distributed along the surface,

864 m in the lateral or offshore direction. Figure 11 is a similar presentation of the thermal dose/maximum excess temperature data for an estuarine/coastal situation. The characteristics of the hypothetical generating station and receiving waters, (riverine and estuarine/coastal, respectively) used in the calculations are identical to those used previously in this chapter, Section II.A.3., to calculate the appropriate fields of velocity and excess temperature.

It should be noted that these data include only thermal dose as a result of plume entrainment. Inclusion of plant (pump) entrainment effects, i.e., the passage of organisms through the plant via the intake channel, would require modification of the near-field model. Such modifications could presumably be achieved with modest effort, and have been proposed as an extension of this research. The goal of this essay is restricted to demonstrating a new conceptual model that can be used to evaluate the biological effects of power plants with once-through cooling systems.

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[1] The distinction here is that integral models use a profile assumption for velocity and excess temperature which allow the governing equations to be integrated over the jet cross-section and then solved numerically; the second type solves the governing equations directly using finite-difference or finite-element techniques.

[2] A. J. Policastro kindly furnished us with complete documentation.

[3] A slightly lower ambient velocity was used for Figure 2 so that the velocity vectors would not merge.

[4] An ambient velocity slightly lower than maximum ebb (11.43 cms^{-1}) was used in Figure 8 so that the velocity vectors would not merge.
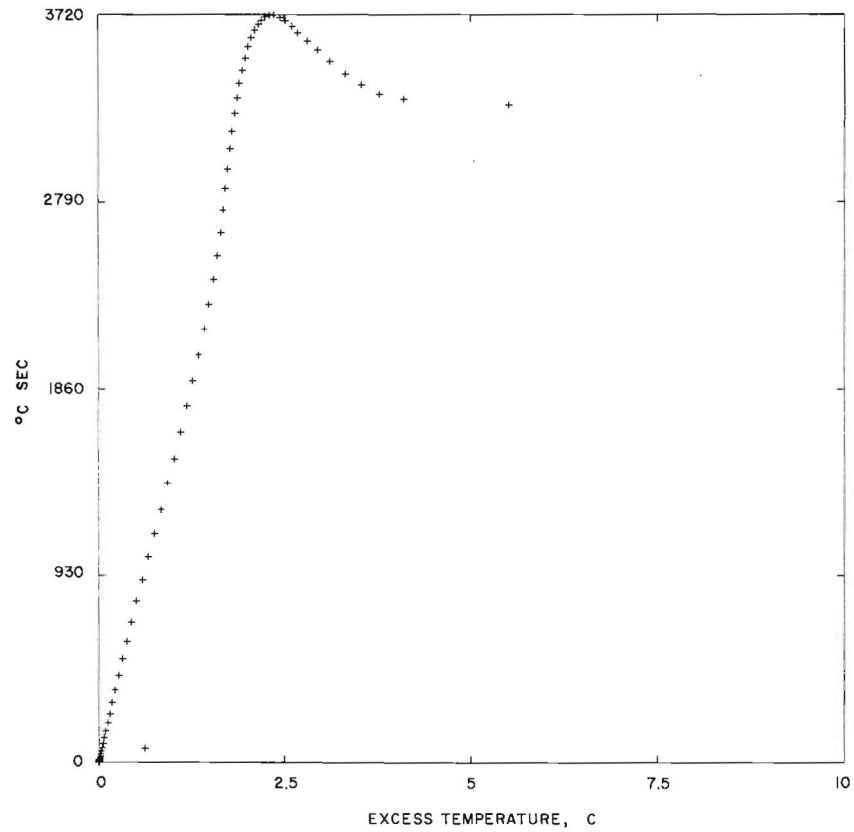
Figure 10. Calculated thermal dose as a function of maximum excess temperature experienced for 100 organisms for a riverine situation. See text for details. Each point represents the integral of the time-temperature history experienced by a single organism. Examples of time-temperature histories are shown in Figures 20-25.
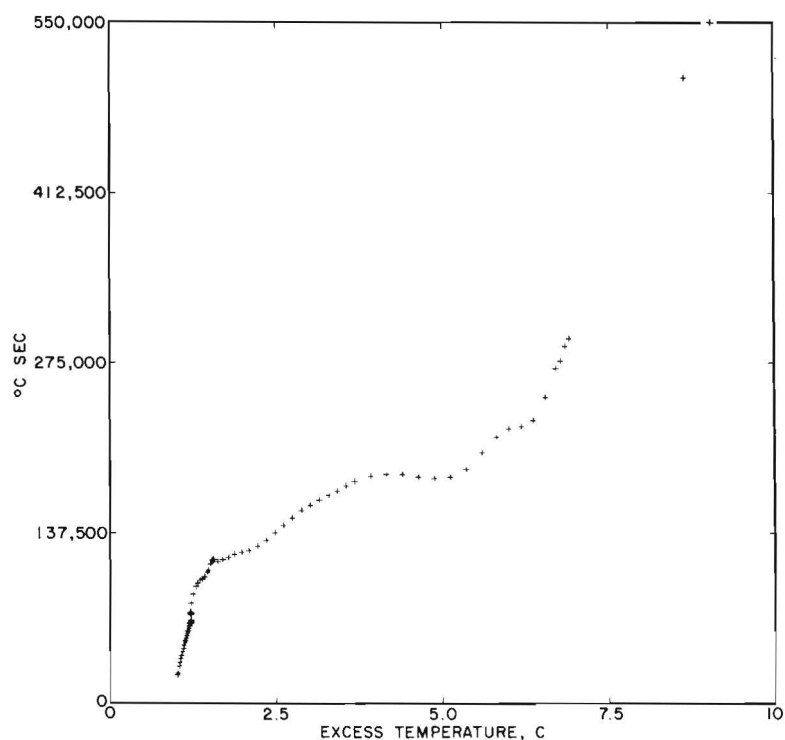
Figure 11. Calculated thermal dose as a function of maximum excess temperature experienced for 100 organisms for an estuarine/coastal situation. See text for details. Each point represents the integral of the time-temperature history experienced by a single organism. Examples of time-temperature histories are shown in Figures 26-32. Calculations were truncated at an excess temperature of 1C.

III. A THERMAL RESPONSE MODEL

J. R. Schubel

R. E. Wilson

A. *Introduction*

In Section II methods were developed to calculate time-excess temperature histories experienced by organisms in the receiving waters of a power plant, and to integrate these curves to determine the thermal dose (°C sec) associated with each time-excess temperature exposure history. In this section we establish a method for combining thermal dose statistics with thermal resistance (tolerance) data to assess the biological effects of these thermal exposures.

Thermal resistance curves, Figure 12, can provide a basis for assessing and predicting the thermal effects of exposure of organisms to different time-temperature histories. Figure 12 summarizes the thermal resistance (tolerance) of individuals of a single species to different combinations of temperature and time. The data are for 50% mortality and are shown for different acclimation temperatures. For each acclimation temperature, the length of time an organism can withstand exposure to an elevated temperature decreases with increasing temperature demonstrating that thermal death is a dose response. With increasing acclimation temperature, an organism's tolerance to elevated temperature increases. The data in Figure 12 indicate that individuals of this species which have been acclimated to 10C can withstand exposure to 26C for about 100 minutes while individuals acclimated to 20C
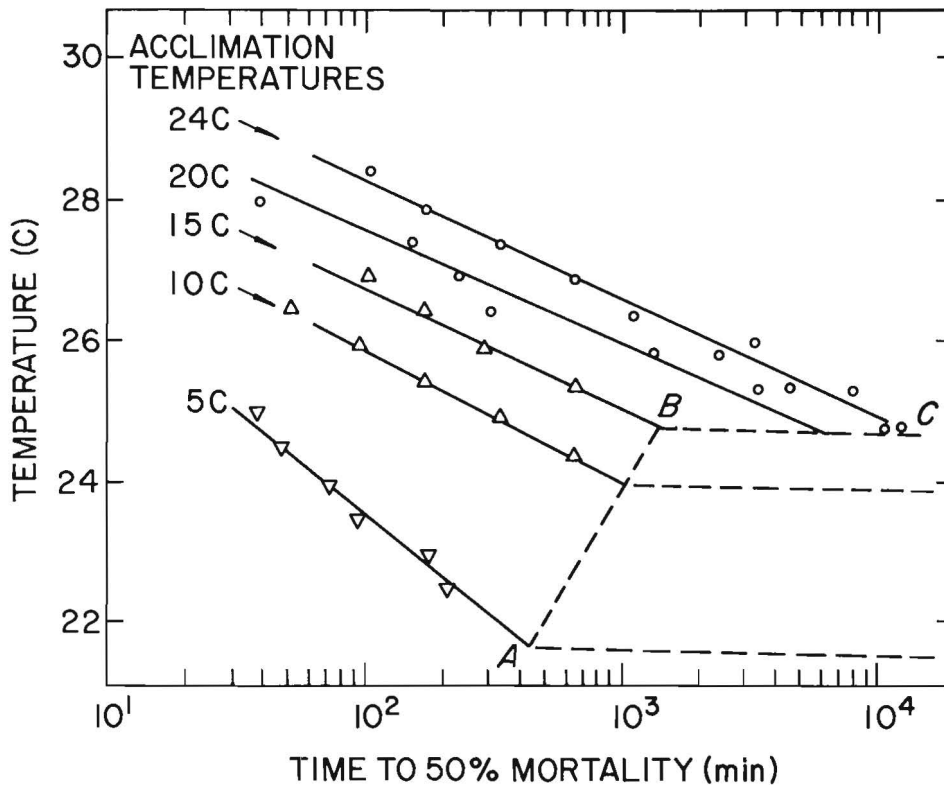
Figure 12. Median resistance times to high temperature of organisms acclimated to different temperatures. For each acclimation temperature there is an incipient lethal temperature -- the highest temperature to which an organism can be continuously exposed for an indefinite period without increasing the mortality rate. Line A-B denotes rising lethal threshold temperatures with increasing acclimation temperature. This rise in threshold eventually ceases at B-C, the ultimate incipient lethal temperature. (Adapted from Brett, 1952).

can withstand exposure to 26C for 1000 minutes with the same expected mortality rate -- 50%. The maximum temperature that the organism can tolerate also increases with acclimation temperature up to some limit.

For each acclimation temperature, there is some upper temperature to which organisms can be subjected continuously for an indefinite period without increasing the mortality rate. This temperature is defined as the incipient lethal temperature and is indicated in Figure 12 by the horizontal lines extending out from AB. The incipient lethal temperature increases with acclimation temperature up to some limit; this limit is called the *ultimate* incipient lethal temperature. It is the maximum temperature to which an organism can be acclimated.

The validity of the thermal

resistance model is well established; application and interpretation are straightforward, at least conceptually. The usefulness of the model in any particular situation, however, depends upon the availability of thermal tolerance data for the important entrainable organisms in an appropriate form -- a form that permits construction of thermal resistance curves. Unfortunately, this is rarely the case. There is no shortage of data; only of appropriate data. Many of the thermal stress studies that have been made and continue to be made for power plant applications have little or no predictive value. All too frequently they provide answers in search of questions.

Let's assume we have a thermal resistance curve such as that shown in Figure 13 and consider a very simple example of how we can use it to assess whether, or not,

16

organisms entrained by a power plant would survive the thermal stresses. Consider a power station with a once-through cooling system that has a five minute transit time through the plant and a ΔT of 10C across the condensers. Further, assume that the plant discharges the cooling water through a multi-port diffuser which reduces the temperature back to ambient almost instantaneously. Assume the ambient temperature is 20C. With a ΔT of 10C the temperature in the plant to the point of discharge is 30C. Compare this time-temperature exposure pattern directly with the thermal resistance curve for the species to be protected (Figure 13) to assess the chances for survival. This figure indicates that 20C-acclimated representatives of this species (50% mortality data) will survive at 30C for seven minutes. Data may also be available which indicate 10% of the sample tested died after six minutes and 90% died after eight minutes. Thus, the thermal exposure BY ITSELF would not be expected to cause mortality. A data set for equilibrium loss or susceptibility to predation could have been used for the species if it were available, or the data set for 50% mortality could have been adjusted downward by about 2C to estimate a predation threshold (Coutant, 1973).

It has been established that under high temperature stress, organisms exhibit progressive debilitation prior to actual death. Such debilitation may have important consequences for survival of organisms because their susceptibility to predation may be increased significantly. In laboratory studies (Coutant, 1973) of predator-prey relationships, it was found that equilibrium loss and susceptibility to increased predation followed a dose response pattern; the effects occurred sooner at higher temperature. Debilitation sufficient to increase susceptibility to predation occurred at temperatures about 2C lower than the incipient lethal threshold. At an actual plant the rate of cooling is, of course, not instantaneous

and therefore organisms experience a greater thermal dose than we have considered in our simple example.

For convenience in summarizing large amounts of time-temperature data, tables of coefficients for semi-logarithmic regression equations have replaced graphs (EPA, 1973), but the comparisons remain equally straightforward. The basic equation,

$$\log \text{TIME}_{(min)} = a + b \ (\text{TEMP}_{(C)}) \quad (11)$$

is used to calculate corresponding times and temperatures for 50% mortality. By rearrangement, the equation can also be used to define conditions for survival by setting the right-side of the equation to less than or equal to 1. This gives:

$$1 \geq \frac{\text{TIME}_{(min)}}{10^{a + b \ (\text{TEMP}_{(C)})}} \quad (12)$$

and by incorporating the 2C "correction factor" for debilitory effects prior to death we have:

$$1 \geq \frac{\text{TIME}_{(min)}}{10^{a + b \ (\text{TEMP}_{(C)} + 2C)}} \quad (13)$$

Thermal exposures during entrainment are generally not as simple as just described, however. While heating is generally abrupt, and a portion of the exposure is at reasonably constant temperatures in pipes and conduits, there is often a period of changing temperatures in a discharge canal or effluent mixing zone before temperatures cool below the upper tolerance level for entrained organisms (Figures 14a and 14b). To evaluate such exposures, one must rely upon the additivity of thermal damages first explored by Fry, Hart and Walker (1946) and subsequently confirmed by others.

Exposures to changing temperatures during entrainment can be viewed as a sequence of discrete temperature exposures each having a known duration (Figure 15). Rearrangement of the basic semi-logarithmic equation, equation (11), in the form of equation (12) or equation (13) is particularly useful now, for the increments can be
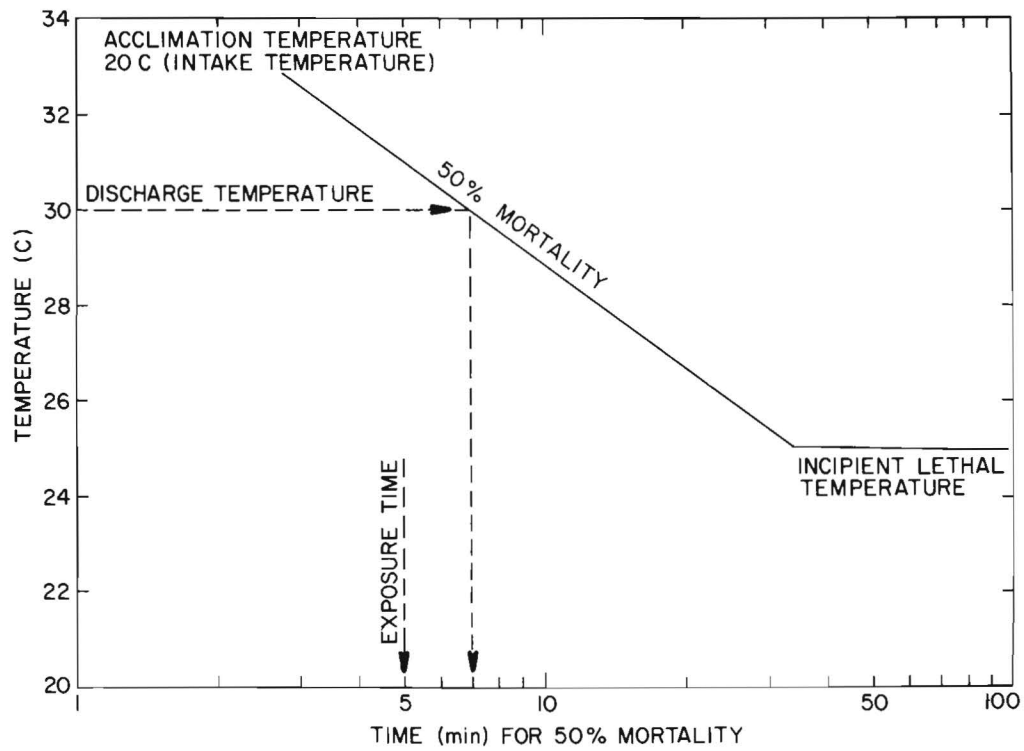
Figure 13. Example of how a Thermal Resistance Curve can be used to predict whether or not mortality from thermal stresses will be expected for entrained organisms. Consider a plant with an intake temperature of 20C, a ΔT of 10C, and a transit time of 5 min. Assume the organisms are acclimated to 20C and that cooling takes place instantaneously.
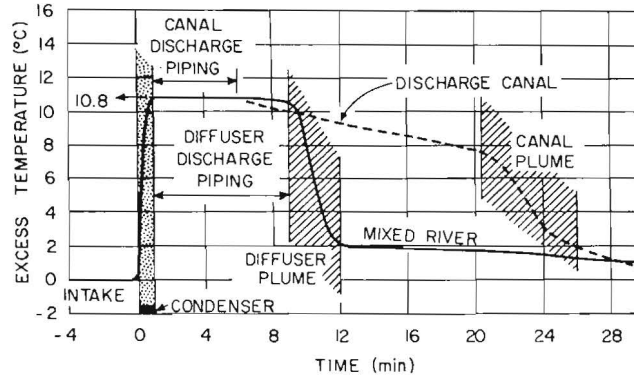
Figure 14a. Hypothetical time-courses of acute thermal shock to organisms entrained in condenser cooling water and discharged by diffuser or via a discharge canal (after Coutant, 1970b).
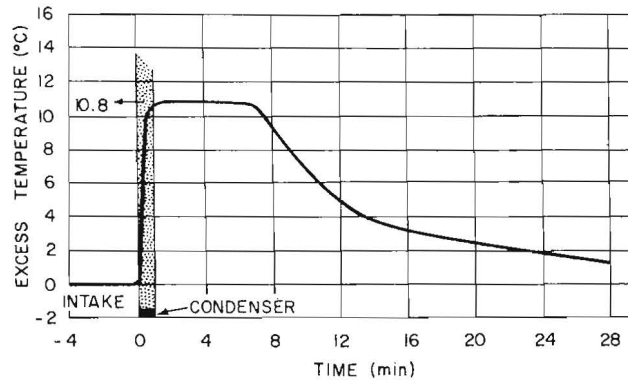
Figure 14b. Hypothetical time-course of acute thermal shock to organisms entrained in condenser cooling water and discharged as a jet.

added until the temperature falls below the lethal threshold (the incipient lethal temperature):

$$1 \geq \frac{TIME_{(min)}}{10^{a\,+\,b\,(TEMP_{(C)})}} + \frac{TIME_{(min)}}{10^{a\,+\,b\,(TEMP_{(C)})}}$$

$$+ \frac{TIME_{(min)}}{10^{\,\cdot\,\cdot\,\cdot}} + \frac{TIME}{10^{\,\cdot\,\cdot\,\cdot}}$$

$$\frac{TIME}{10^{\,\cdot\,\cdot\,\cdot}} + \text{etc.} \qquad (14)$$

The computation is readily handled by a programmable desk calculator. As with equation (12), survival is indicated if the right-side of the equation remains at or below unity. These methods have been introduced previously (EPA, 1973) and they have been used in Environmental Impact Statements for the U. S. Atomic Energy Commission (the Nuclear Regulatory Commission). A recent compilation of time-temperature relationships and lethal threshold temperatures for a variety of aquatic organisms, particularly fish, is contained in Appendix 11-C of the EPA 1973 report entitled "Water Quality Criteria 1972."

These data and calculation methods can be helpful in setting power plant design criteria as well as methods to evaluate already selected designs. With the known time-temperature responses of key species as boundary conditions to ensure survival, the engineer can select among ΔT's and exposure times in discharge structures and mixing zones to find safe combinations that will suit his particular plant site. As pointed out elsewhere (Schubel and Marcy, in press), power plants should be operated at least at the highest ΔT that is biologically acceptable.

This report describes a model for combining thermal dose statistics calculated for the population of organisms in the receiving waters of a power plant with thermal resistance data to assess the
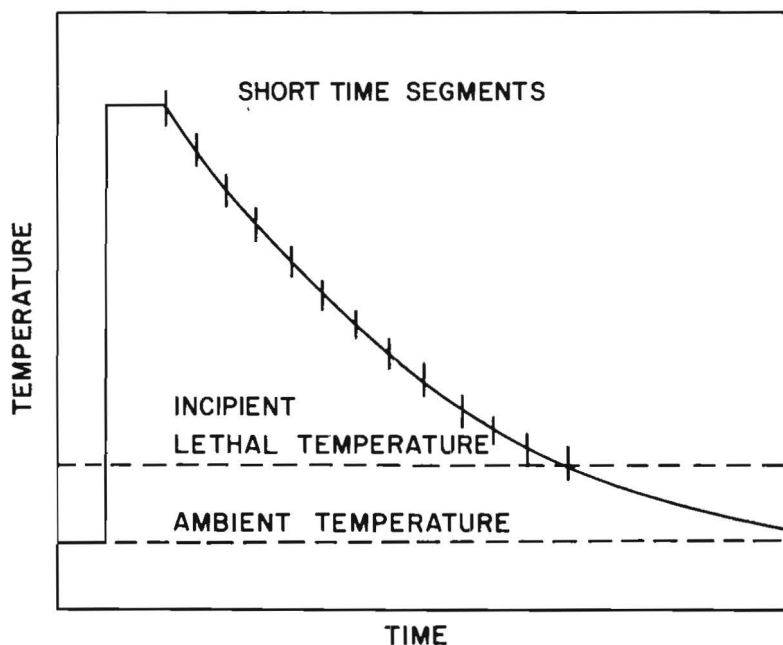
Figure 15. Hypothetical time-temperature exposure history experienced by entrained organisms. The curve has been segmented into short time intervals for calculation of additive thermal doses.

biological effects of those exposures. Application of the model involves several steps:

    (1) Determination of the tolerances of Representative Important Species to thermal dose as a function of temperature. (These can be determined from standard hermal resistance curves and are usually expressed for a mortality of 50%.)

    (2) Determination of the frequency distribution of thermal doses experienced by organisms in the receiving waters of a power plant. (These doses should be sorted by maximum excess temperature.

    (3) Presentation of both of these curves on a single graph to make a "Thermal Dose-Excess Temperature Diagram;" thermal dose in °C sec on the ordinate and temperature, both actual and excess, on the abscissa. The relative positions of the two curves indicates -- at some probability level, usually 0.5 -- what fraction of the organisms exposed to excess temperature would be expected to be killed by thermal stress.

Some organisms will be pump entrained (carried through the plant's once-through cooling system) where they will be exposed to the maximum excess temperature -- the temperature rise across the condensers. Other organisms will be entrained into the discharge plume without passing through the plant and will be subjected to somewhat lower excess temperatures. Still others will experience only the far-field excess temperature. Organisms then, experience a range of maximum excess temperatures, and thermal doses -- the integral of the time-excess temperature exposure history. We have developed a conceptual model to calculate the thermal dose associated with a variety of time-excess temperature

histories experienced at a power plant, and to use these doses along with doses calculated from thermal resistance curves to assess the effects of various exposures on mortality.

    B. Assessing Biological Effects Of Different Doses

1. Calculation of doses from thermal resistance curves

We constructed a "community" thermal resistance curve for Representative Important Species for summer for a New York estuarine-coastal case, Figure 16. The organisms we selected for the *summer* thermal resistance curve were: silverside (*Menidia menidia*) juveniles acclimated to 21 and 28C (Hoss *et al.*, 1974), hard clam (*Mercenaria mercenaria*) larvae in cleavage and trocophore stages of development with no acclimation temperature stipulated (Kennedy *et al.*, 1974), and winter flounder (*Pseudopleuronectes americanus*) juveniles acclimated to 21 and 28C (Hoff and Westman, 1966). We had relatively little choice in the data we could use; there is a dearth of data suitable for construction of thermal resistance curves for Representative Important Species of New York's coastal waters. The dashed line in Figure 16 is our conservative estimate of a community thermal resistance curve. The placement of this curve should ensure protection of most species.

For construction of a *winter* thermal resistance curve for a New York estuarine-coastal case study, we had even less choice. The most suitable data we could find were for winter flounder (*Pseudopleuronectes americanus*) juveniles acclimated to 7C (Hoff and Westman, 1966), Figure 17.

For each thermal resistance curve in Figures 16 and 17, we have included an excess temperature scale on the ordinate. The excess temperatures were obtained by subtracting the acclimation temperature of the test organisms from the experimental
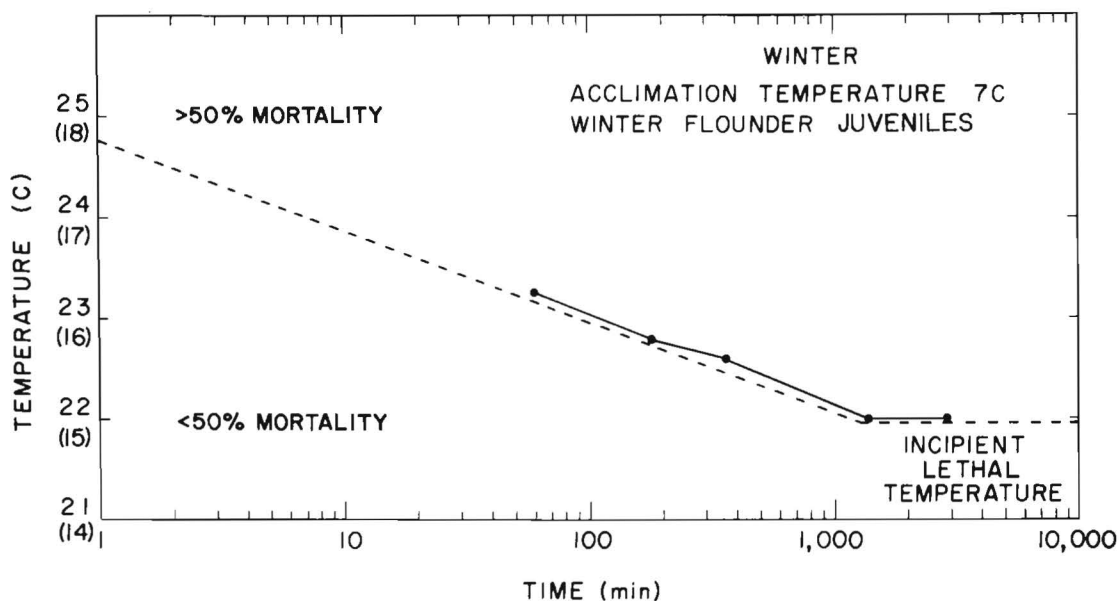
Figure 16. Thermal resistance curves for several Representative Important Species of New York's estuarine/coastal environment in summer and our estimate of a community thermal resistance curve (dashed line). All data are for 50% mortality. Base temperature is 21C; excess temperatures are indicated in parenthesis on the ordinate.
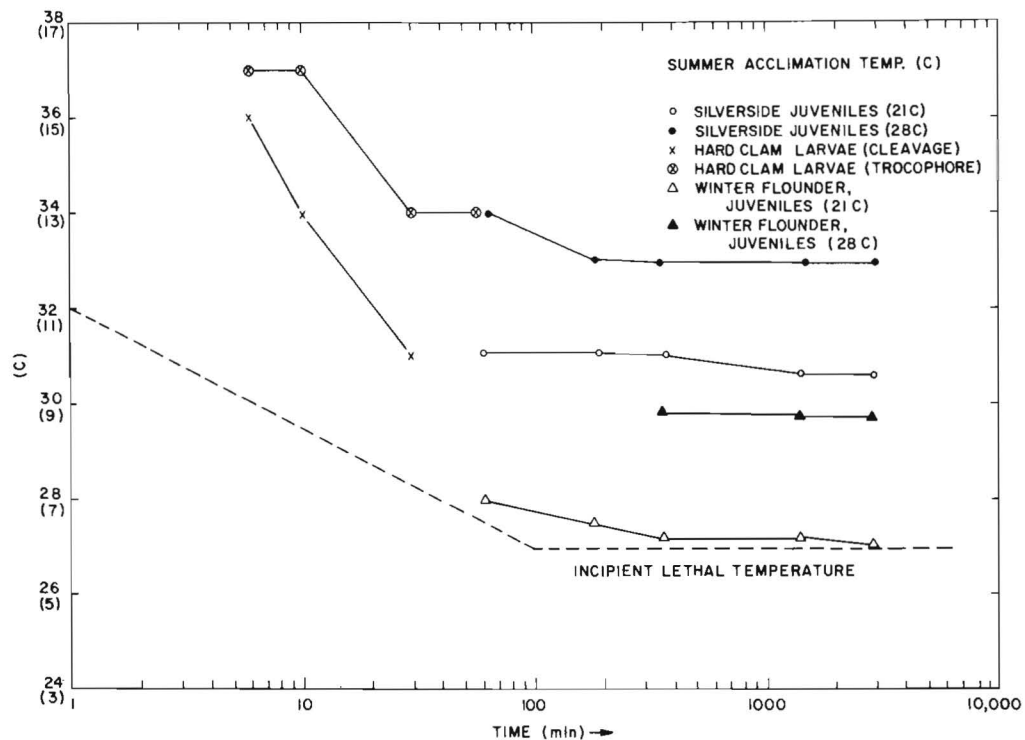
Figure 17. Thermal resistance curve for juvenile winter flounder and our estimate of a community thermal resistence curve (dashed line). Data are for 50% mortality. Base temperature is 7C; excess temperatures are indicated in parenthesis on the ordinate.

22

temperature. The acclimation temperature we selected for the two seasons -- winter and summer -- are 7 and 23C respectively. The mean winter temperature of 7C may be too high, but we were unable to find any thermal resistance data for organisms acclimated to a lower temperature. For the *summer* "community" thermal resistance curve we used data for organisms acclimated to both 21 and 28C. In our calculations of excess temperature we selected 21C as the base temperature.

From these thermal resistance data, we calculated the thermal doses associated with a variety of constant excess temperature-time combinations, each of which would produce a mortality of 50%[1]. In accordance with the EPA's 1973 report on Water Quality Criteria (1972), doses associated with temperatures below the incipient lethal temperature have been ignored. Thermal doses for the *summer* thermal resistance community curve for a New York estuarine-coastal environment are summarized in Table 1. Thermal doses for the winter case are summarized in Table 2.

Next, we used the data from Tables 1 and 2 and Figures 16 and 17 to construct Thermal Dose-Excess Temperature, or D-T,

Diagrams, Figures 18 and 19. These figures show for each of a series of excess temperatures (and actual temperatures) the thermal dose that would be expected to produce a mortality of 50%. Exposure of a group of organisms to any excess temperature-dose combination that falls to the left of the curve would be expected to produce a mortality of < 50%. For exposures to the right of the curve, the probability of mortality would be expected to be > 0.5 (mortality > 50%). At some temperature, instantaneous death would be expected for 50% of the exposed organisms; for the summer case, this temperature is 32C (excess temperature 11C), for winter, 25C (excess temperature 18C).

To apply the D-T Curve to any particular power plant, one needs the frequency distribution of doses experienced by organisms sorted by maximum excess temperature. These were calculated for our hypothetical power plant for both the riverine and estuarine cases using procedures described in Section II. For the sake of completeness, these procedures are briefly reviewed here.

2. Computing dose statistics for a plant[2]

For the riverine and estuarine cases

TABLE 1

Summary of Thermal Doses (°C sec) associated with selected temperature-time combinations for 50% mortality for the summer New York estuarine-coastal case. The base temperature is 21C, and the doses associated with temperatures below the incipient lethal temperature have been disregarded. The basic data were taken from Figure 16.

Temp. (C)	ΔT (C)	Time (sec)	Dose (°C sec)
31.5	10.5	96	1,008
31.0	10.0	150	1,500
30.0	9.0	360	3,240
29.0	8.0	900	7,200
28.0	7.0	2400	16,800
27.0	6.0	6000	36,000

TABLE 2

Summary of Thermal Doses (°C sec) associated with selected temperature-time combinations for 50% mortality for the winter estuarine-coastal case. The base temperature is 7C, and the doses associated with temperatures below the incipient lethal temperature have been disregarded. The basic data were taken from Figure 17.

Temp. (C)	ΔT (C)	Time (sec)	Dose (°C sec)
24.5	17.5	120	2,100
24.0	17.0	420	7,140
23.5	16.5	1,500	24,750
23.0	16.0	5,400	86,400
22.5	15.5	19,200	297,600
22.0	15.0	72,000	1,080,000
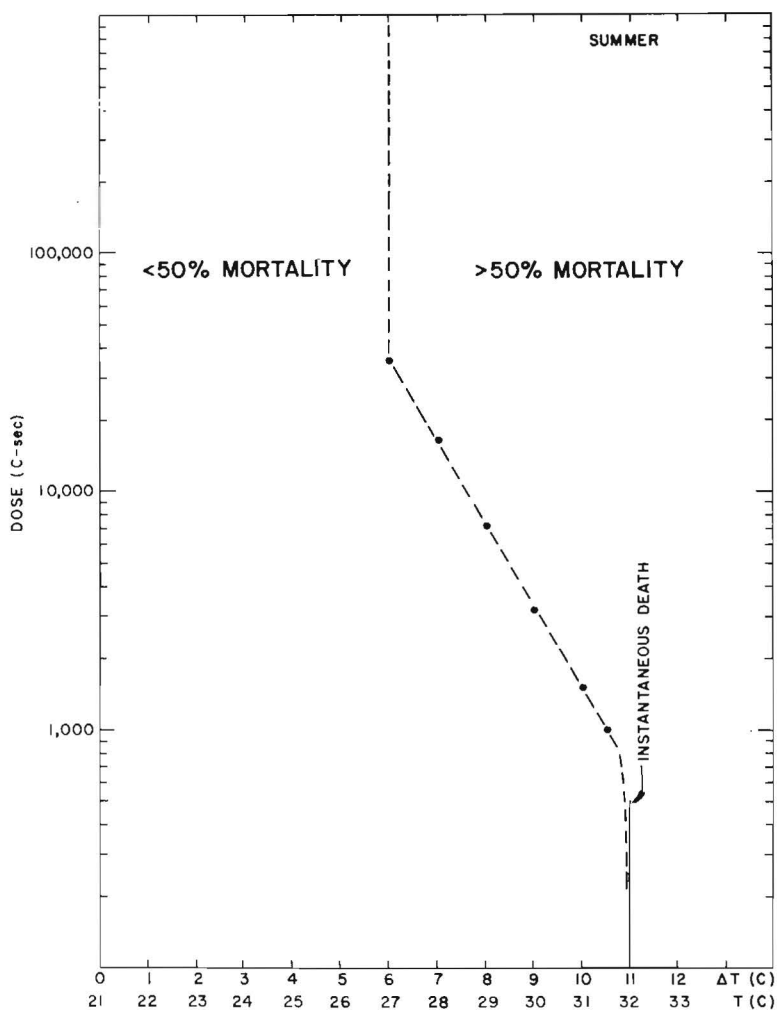
Figure 18. Thermal Dose-Excess Temperature Diagram for the summer estuarine/coastal case described in the text. The curve is for 50% mortality and was constructed from combined data for: silverside (*Menidia menidia*) juveniles acclimated to 21 and 28C; hard clam (*Mercenaria mercenaria*) larvae; and winter flounder (*Pseudopleuronectes americanus*) juveniles acclimated to 21 and 28C. Excess temperatures are relative to a base temperature of 21C. For exposures to the left of the curve, mortalities of less than 50% are expected; for exposures to the right of the curve, greater than 50%. At 32C (excess temperature 11C), instantaneous death is expected for 50% of the organisms. At temperatures below 27C (excess temperature 6C), increased thermal dose does not affect the position of the 50% mortality curve.

24
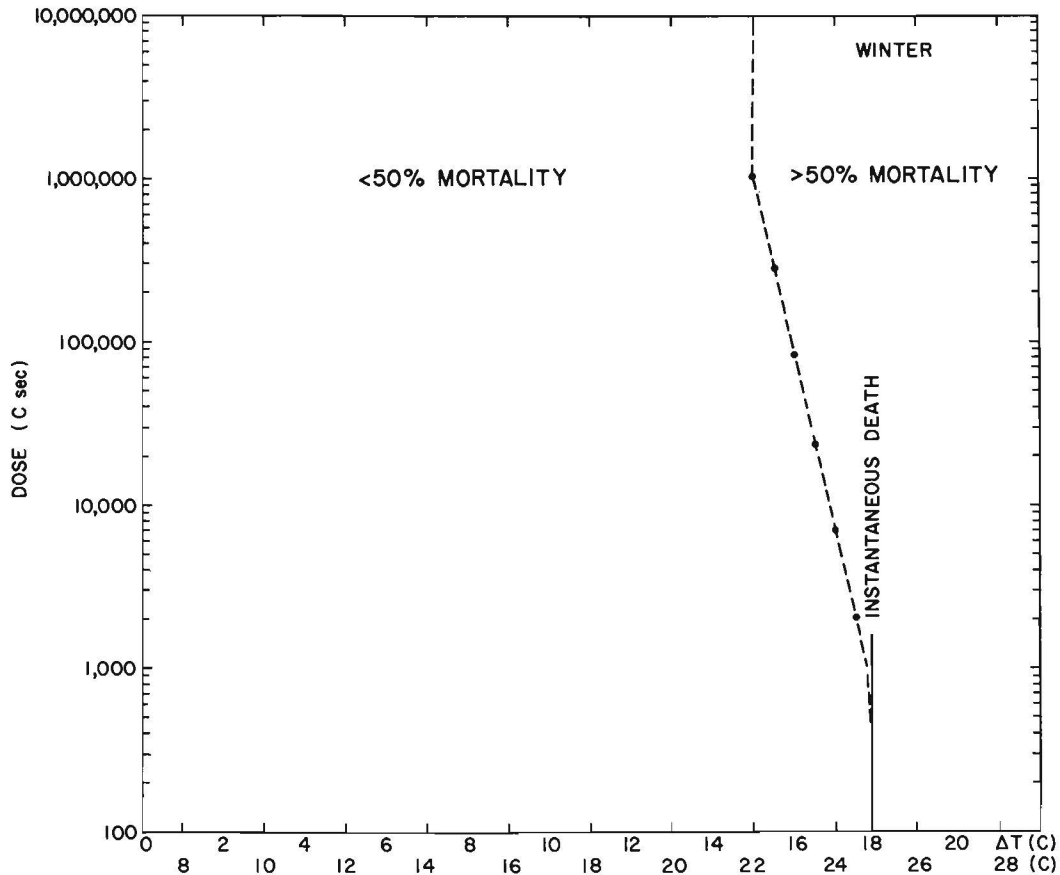
Figure 19. Thermal Dose-Excess Temperature Diagram for the winter estuarine/coastal case described in the text. The curve is for 50% mortality and was constructed from data for juvenile winter flounder (*Pseudopleuronectes americanus*) acclimated to a temperature of 7C. Excess temperatures are relative to 7C. For exposures to the left of the curve, mortalities of less than 50% are expected; for exposures to the right, mortalities of greater than 50% are expected. At 25C (excess temperature 18C) instantaneous death is expected for 50% of the exposed organisms. At temperatures below 22C (excess temperature 15C), increased thermal dose does not affect position of the 50% mortality curve.

described earlier in this report, we calculated the thermal dose experienced by each of 100 hypothetical planktonic organisms distributed uniformly along a line at the water surface extending from shore out for a distance of 864 m. This is approximately the offshore limit of the 0.5C excess temperature isotherm. The first organism (Number 1) was placed at the shore; the 100th organism at the offshore limit. The others were equally spaced between these two extremes. The line of organisms was placed approximately 1 km upstream from the

hypothetical power plant.

For the riverine case, as each organism is carried past the plant, the excess temperature to which it is exposed increases to some maximum value and then decreases monotonically as the organism is carried downstream. Figures 20 through 25 depict time-excess temperature exposure histories calculated for each of a number of organisms. We calculated the *total* thermal dose experienced by each of the 100 organisms. The thermal dose is the integral of the time-excess temperature

25

Figure 20. Time-excess temperature exposure history for a hypothetical planktonic organism in the riverine case. The organism was started approximately 1 km upstream from the "plant" and approximately 9 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.

Figure 21. Time-excess temperature exposure history for a hypothetical planktonic organism in the riverine case. The organism was started approximately 1 km upstream from the "plant" and approximately 35 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.

Figure 22. Time-excess temperature exposure history for a hypothetical planktonic organism in the riverine case. The organism was started approximately 1 km upstream from the "plant" and approximately 79 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.

Figure 23. Time-excess temperature exposure history for a hypothetical planktonic organism in the riverine case. The organism was started approximately 1 km upstream from the "plant" and approximately 122 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.

Figure 24. Time-excess temperature exposure history for a hypothetical planktonic organism in the riverine case. The organism was started approximately 1 km upstream from the "plant" and approximately 340 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.

Figure 25. Time-excess temperature exposure history for a hypothetical planktonic organism in the riverine case. The organism was started approximately 1 km upstream from the "plant" and approximately 428 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.

history and is expressed in °C sec; integrations were continued until the excess temperature was reduced to zero. The integration could, of course, have been stopped at some excess temperature > 0C at which no adverse biological effects would be expected. Since *total* doses for the riverine case are relatively small, we decided to extend the integrations until the excess temperature approached zero. For the riverine case, the computation and interpretation of thermal dose are straightforward.

The estuarine case is somewhat more complicated because of the oscillatory tidal motion. As in the riverine case, an organism's thermal *dose* continues to increase until it is carried out of the excess-temperature field, but for the estuary the exposure time may be extended considerably because of the oscillatory tidal motion. Several time-excess temperature exposure histories are shown in Figures 26 through 32. We have calculated the thermal dose experienced by each of the 100 estuarine organisms *for excess temperatures greater than 1C*. This is the threshold below which we have assumed there is no dose response to temperature. In other words, we assume that organisms could be exposed to an excess temperature of $\leq$ 1C for an infinitely long period (greater than several hundreds of hours, at least) regardless of the base (ambient) temperature without increasing the probability of mortality. We believe that biologically, this is a very conservative threshold; the actual value is probably higher and, of course, varies with ambient water temperature since the excess temperature is superimposed upon ambient. Spatial variations of the ambient temperature of the receiving waters of a power plant probably exceed 1C at any time, and temporal variations on even a diurnal cycle probably exceed 1C. When an organism was carried out of the excess temperature field delimited by the 1C isotherm -- either upstream or downstream -- the integration

was interrupted. If the organism was carried back into the excess temperature field, the integration was resumed. This process was continued until the organism was carried far enough downstream so that on the subsequent flood it did not re-enter the excess temperature field as defined by the 1 C-isotherm. All doses were calculated using excess temperatures. Because of the tidal motion, the excess temperature field built up to appreciable values (> 4C) within approximately 150 m of the shore for more than 1 km upstream. Had we started the organisms and the integrations farther upstream, the thermal doses calculated for organisms within approximately 250 m of shore would have been greater than our calculations indicate, but the formulation and mode of application of our conceptual model would not be affected.

We partitioned the total dose experienced by each organism for the estuarine case into the doses associated with excess temperatures of $\geq$ 1, $\geq$ 2, $\geq$ 3, $\geq$ 4, and $\geq$ 5C. This partitioning permits us to subtract that fraction of the total dose accounted for by exposures to excess temperatures below any of these values. These results are summarized in Figures 33 to 37. It is apparent from this partitioning that the contribution of different excess temperatures to the total thermal dose is a function of the starting position of the organism along the line source. For organisms closer to the bank, higher excess temperatures contribute more to the total dose than they do farther offshore.

C. *Coupling The Physics To The Biology*

Our next task was to develop a model to couple the physics to the biology. The objective was to combine dose statistics calculated from time-temperature exposure histories at a power plant with laboratory-determined thermal resistance curves to assess the biological significance of exposure to those time-excess temperature
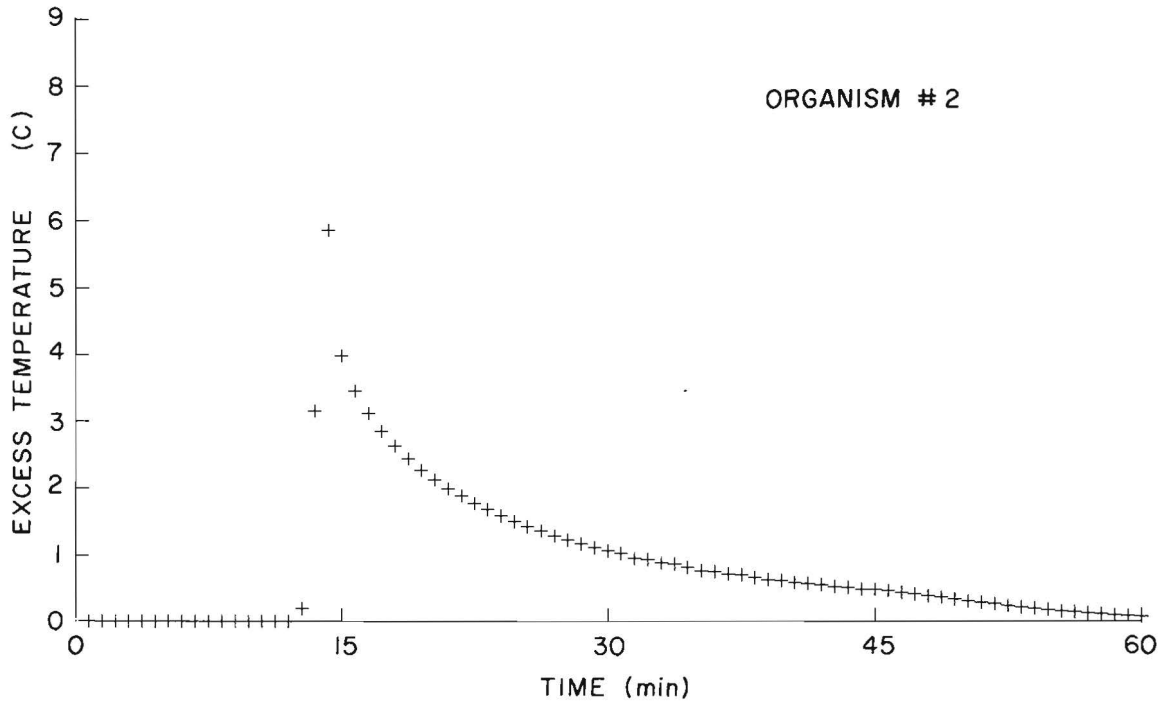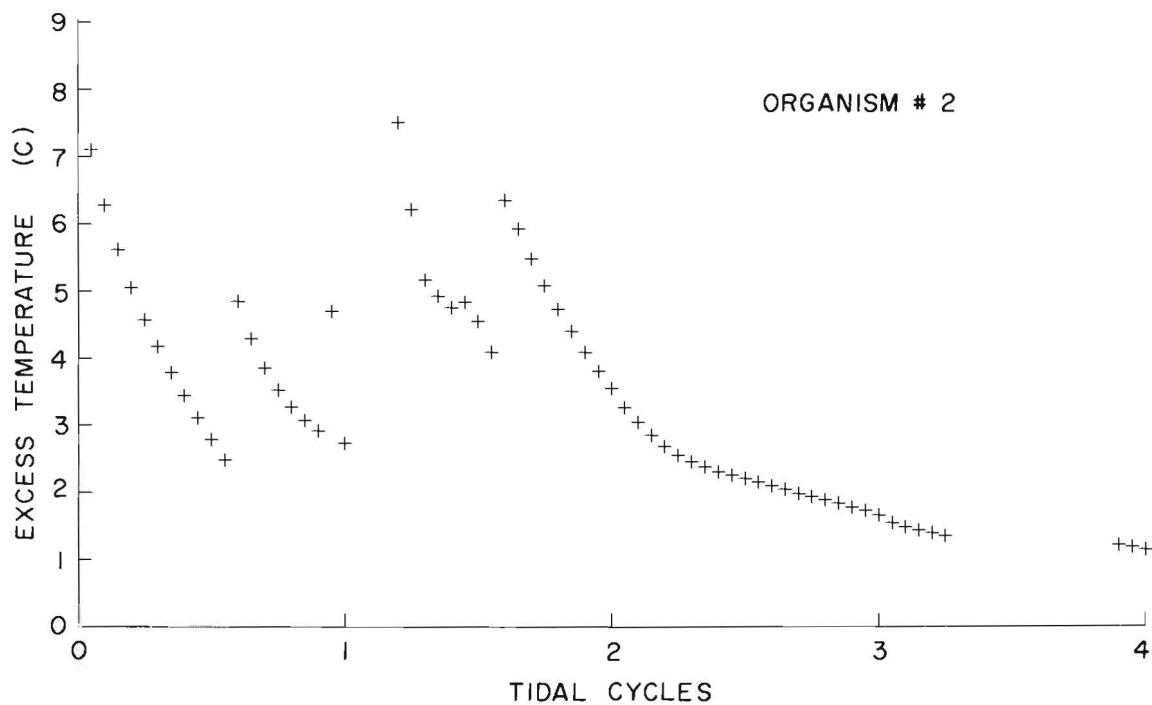
Figure 26. Time-excess temperature exposure history for a hypothetical planktonic organism in the estuarine case. The organism was started approximately 1 km upstream from the "plant" and approximately 9 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.
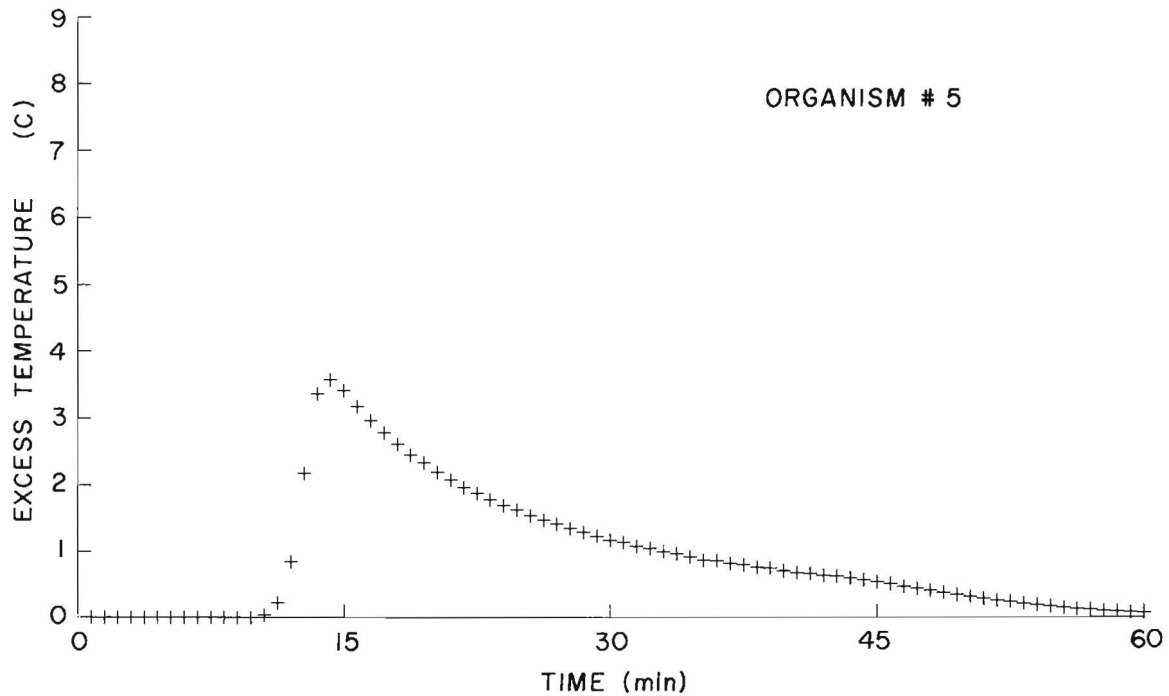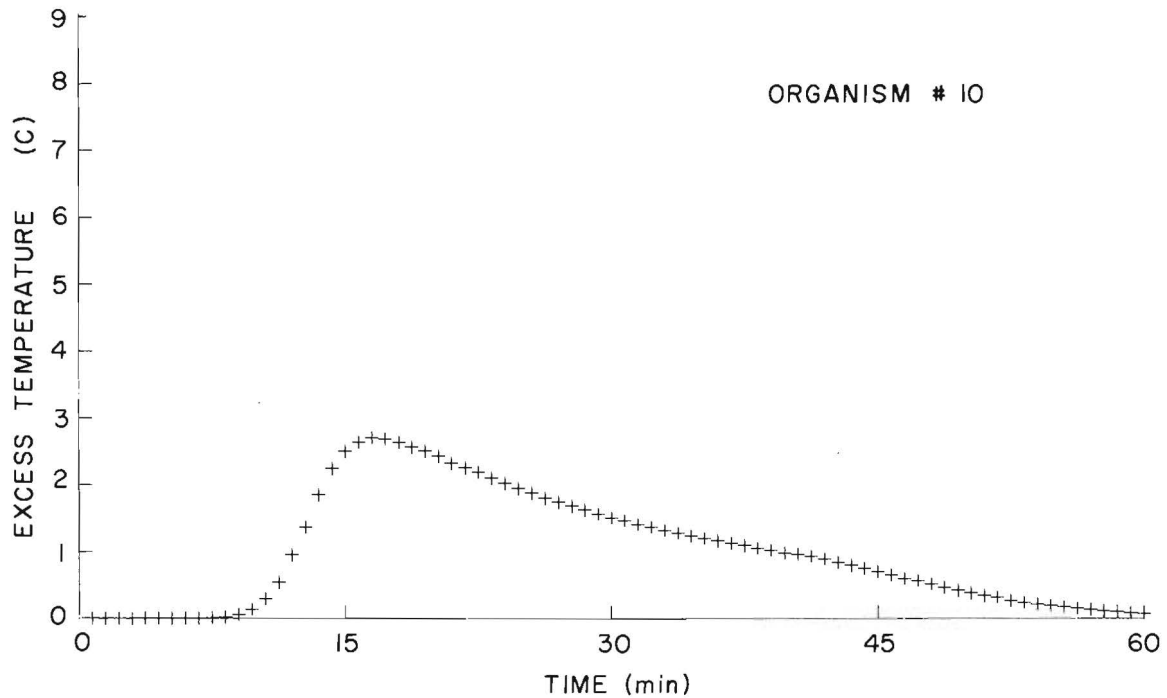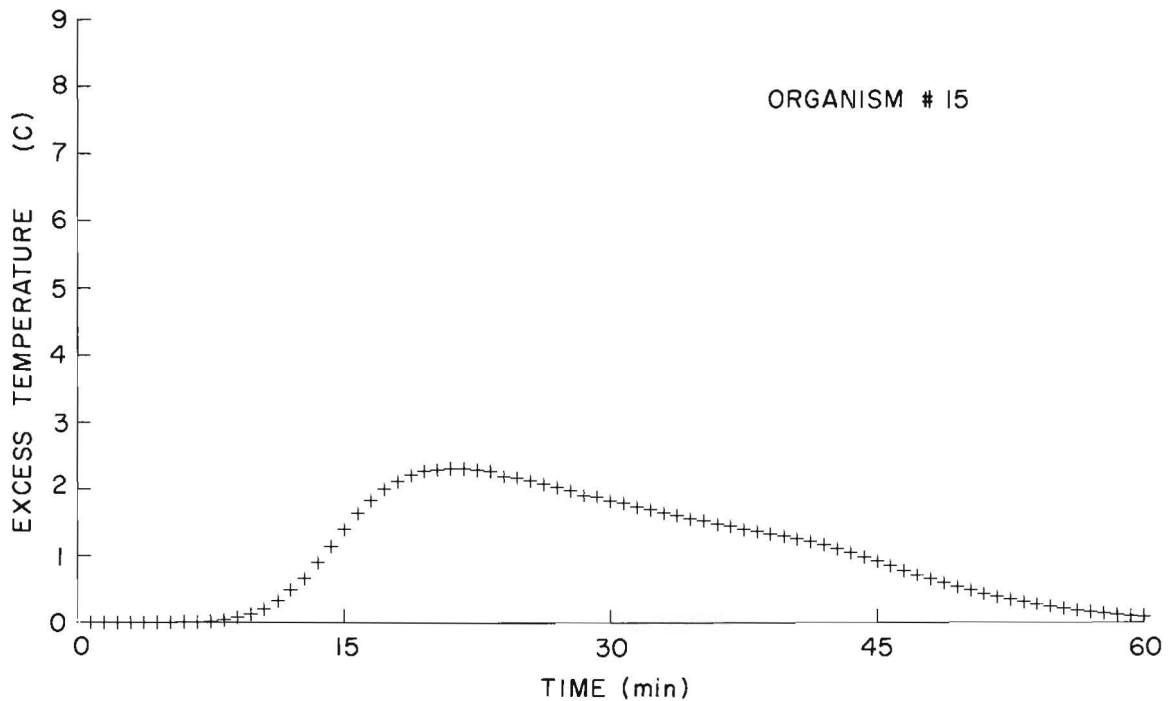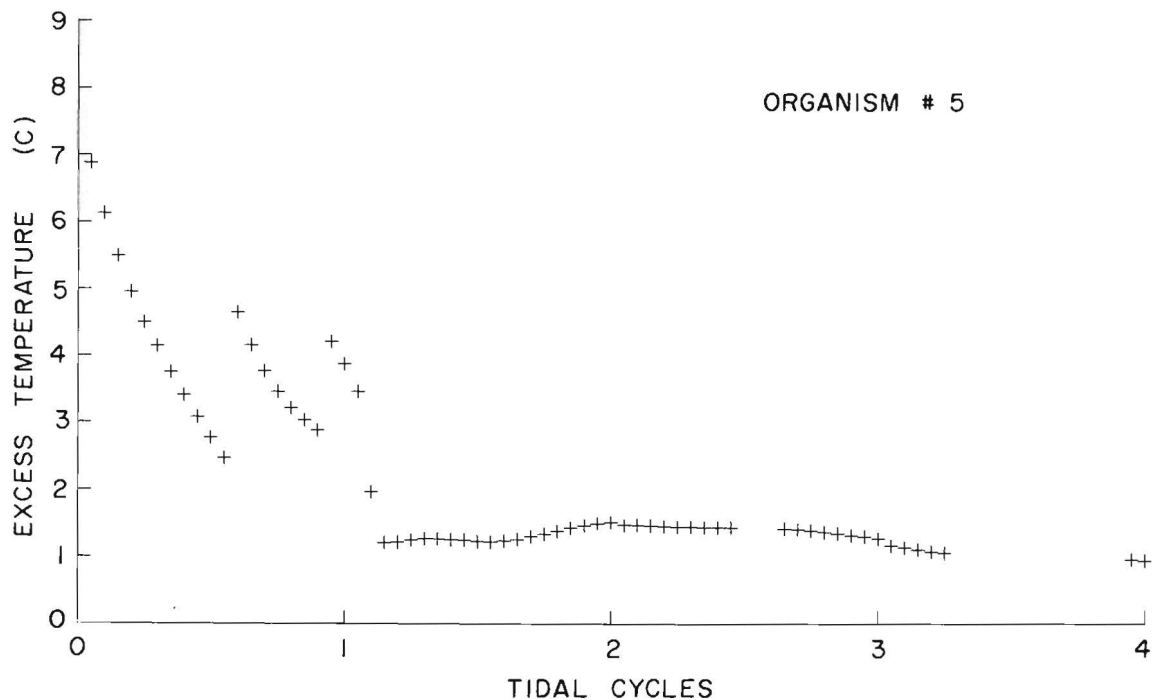

Figure 27. Time-excess temperature exposure history for a hypothetical planktonic organism in the estuarine case. The organism was started approximately 1 km upstream from the "plant" and approximately 35 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.
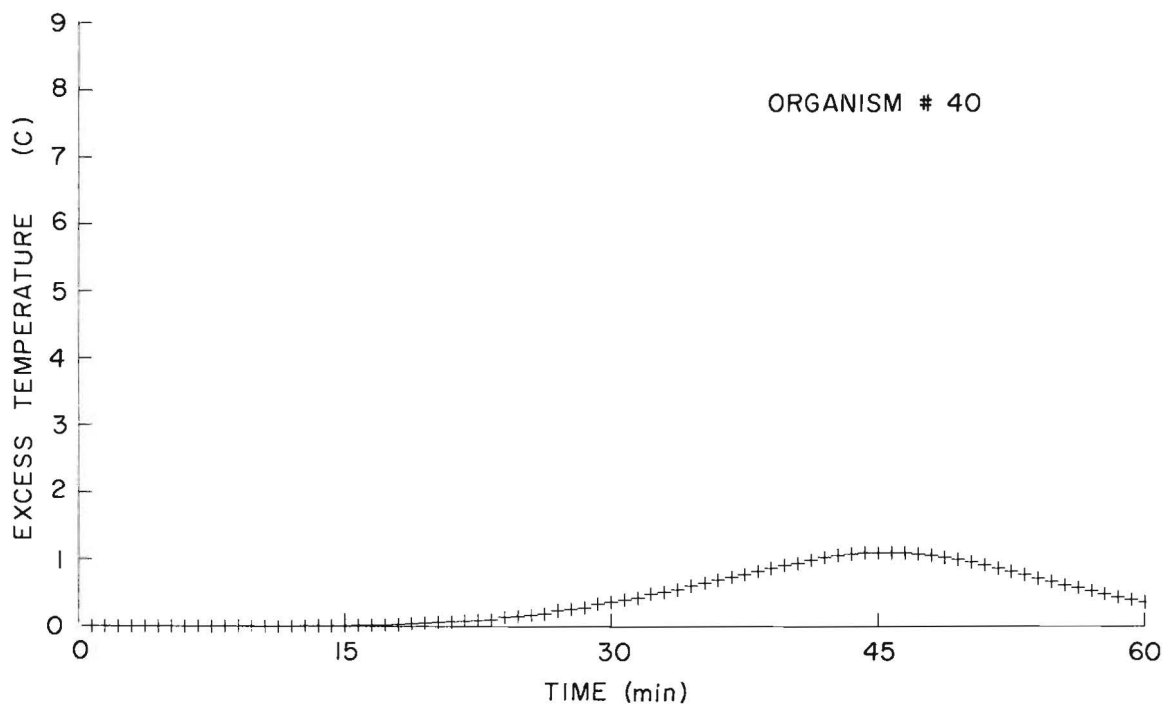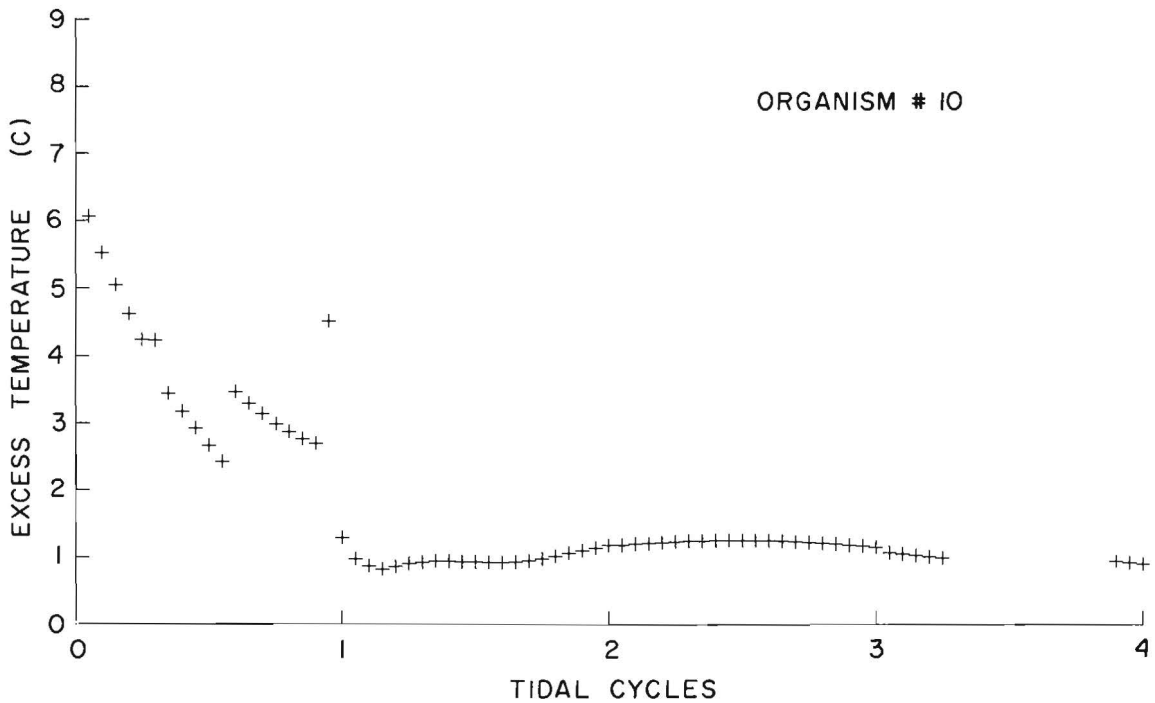
Figure 28. Time-excess temperature exposure history for a hypothetical planktonic organism in the estuarine case. The organism was started approximately 1 km upstream from the "plant" and approximately 79 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.
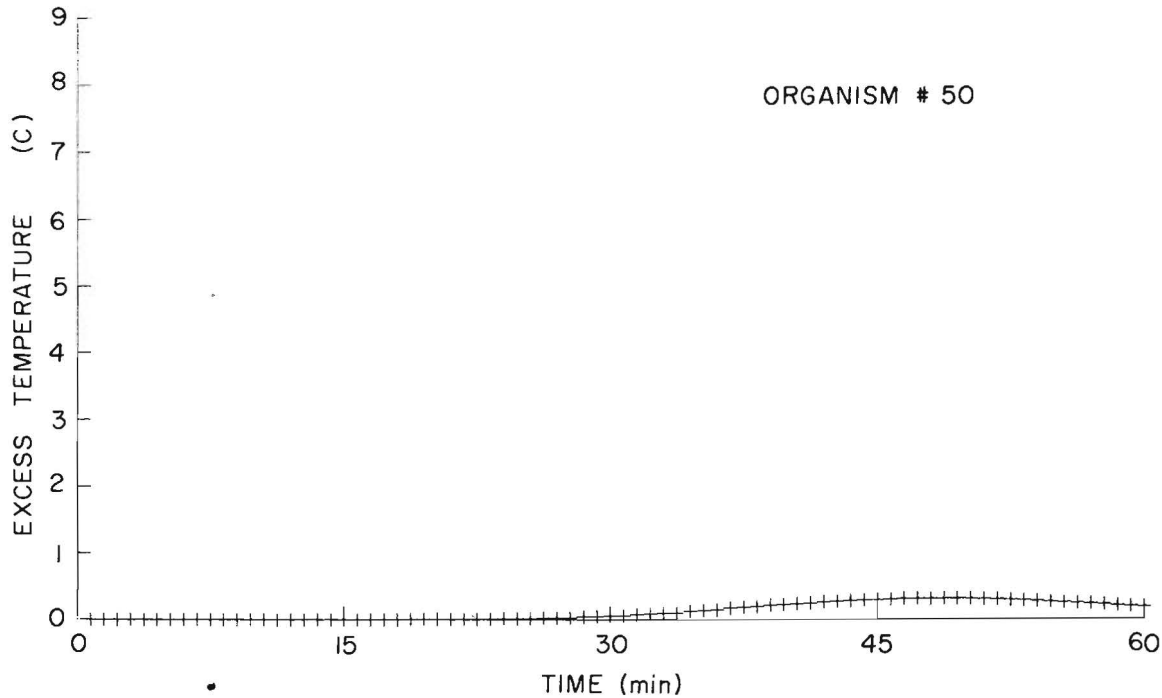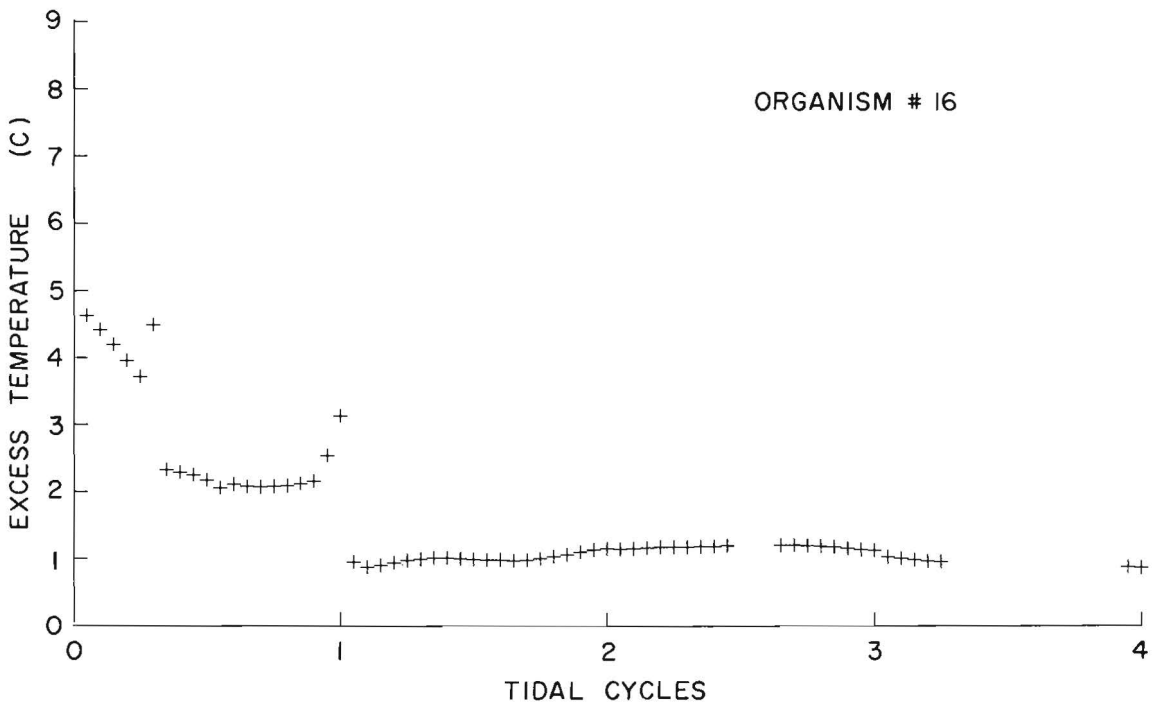

Figure 29. Time-excess temperature exposure history for a hypothetical planktonic organism in the estuarine case. The organism was started approximately 1 km upstream from the "plant" and approximately 131 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.
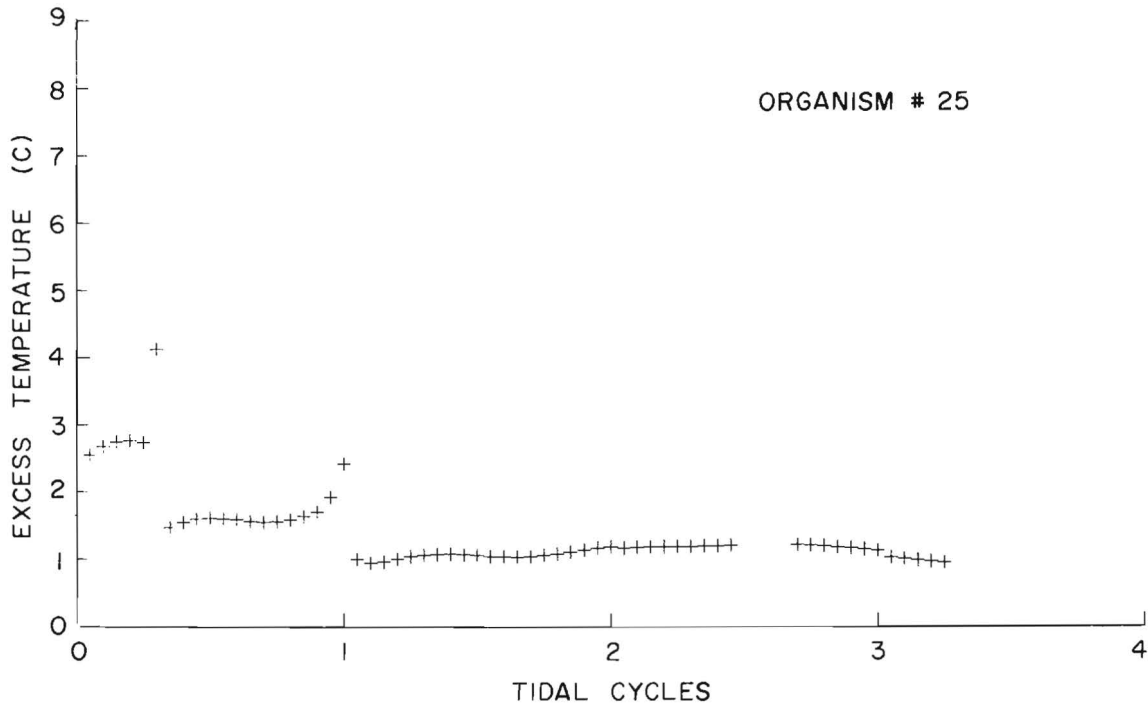
Figure 30. Time-excess temperature exposure history for a hypothetical planktonic organism in the estuarine case. The organism was started approximately 1 km upstream from the "plant" and approximately 209 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.
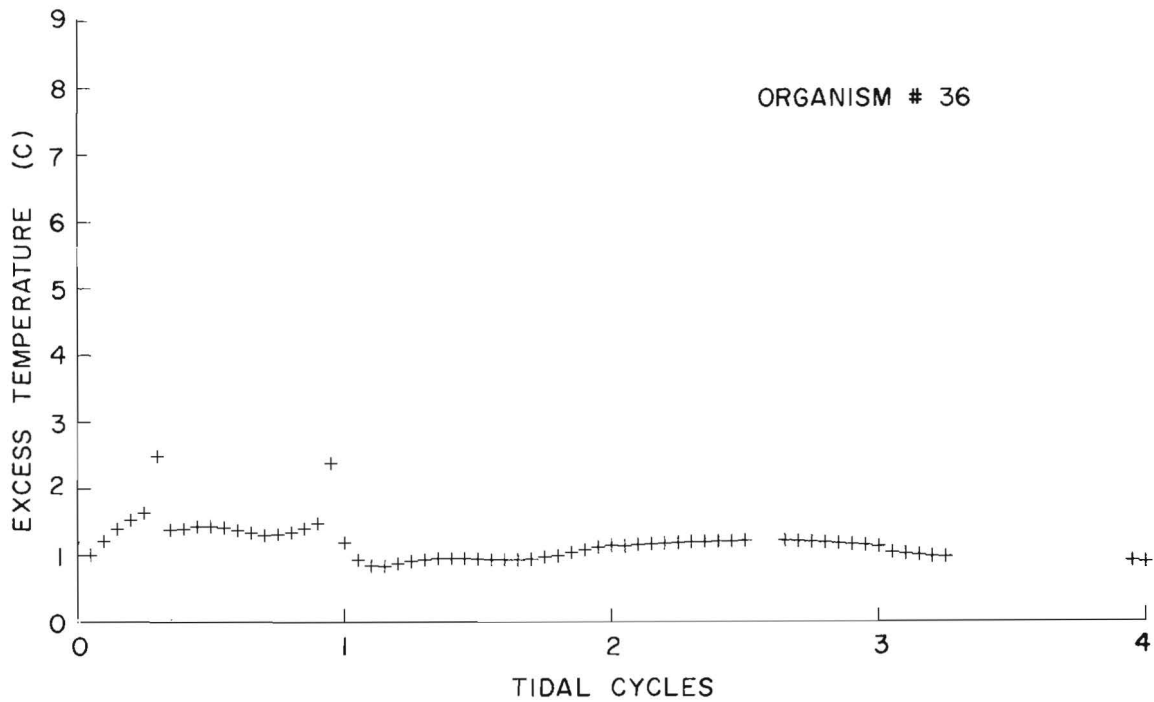
Figure 31. Time-excess temperature exposure history for a hypothetical planktonic organism in the estuarine case. The organism was started approximately 1 km upstream from the "plant" and approximately 305 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.
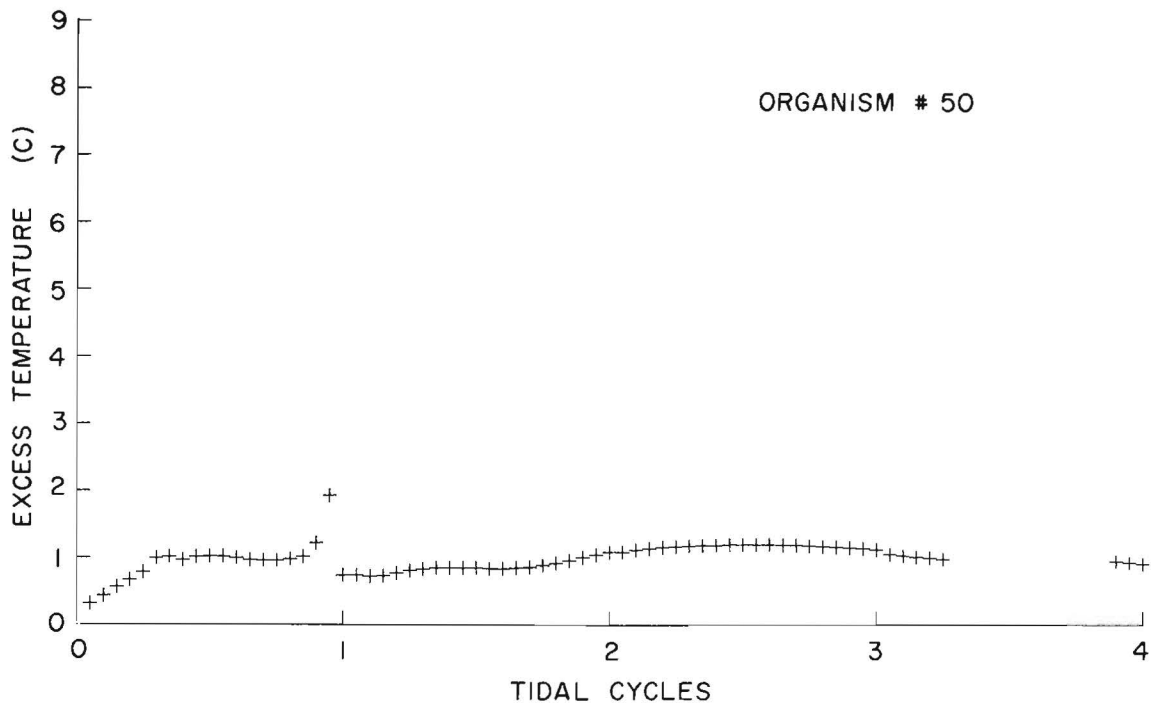
Figure 32. Time-excess temperature exposure history for a hypothetical planktonic organism in the estuarine case. The organism was started approximately 1 km upstream from the "plant" and approximately 428 m offshore. The maximum excess temperature possible -- the ΔT across the condensers -- was 10C.
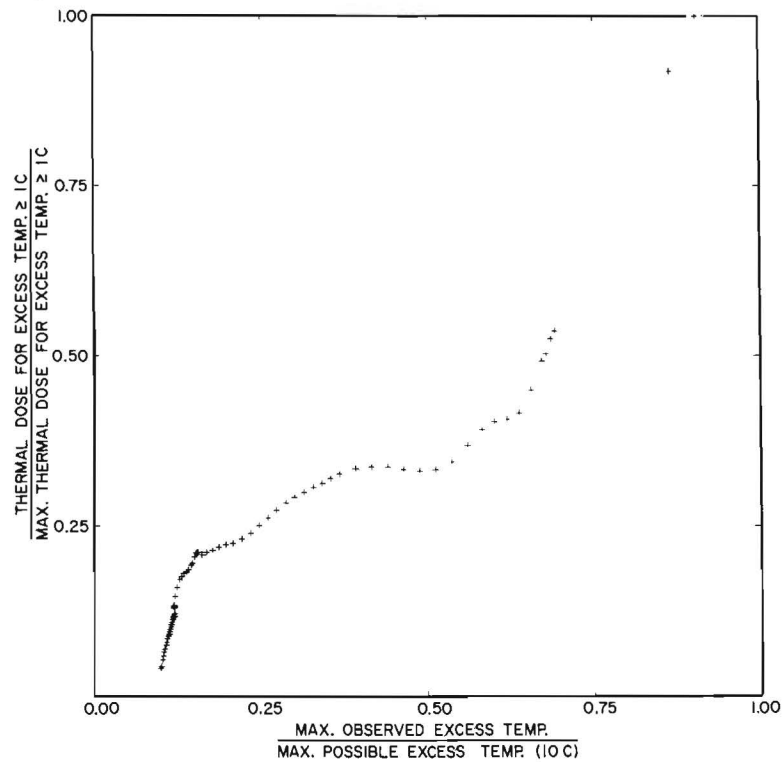
Figure 33. Thermal Dose for excess temperatures ≥ 1C as a function of maximum excess temperature experienced by each of the appropriate organisms. The thermal doses (°C-sec) have been normalized to the maximum dose calculated and are plotted on the ordinate. The excess temperatures have been normalized to the maximum possible excess temperature -- the ΔT across the condensers -- 10C, and are plotted on the abscissa. See Figure 11 for the un-normalized case.

33
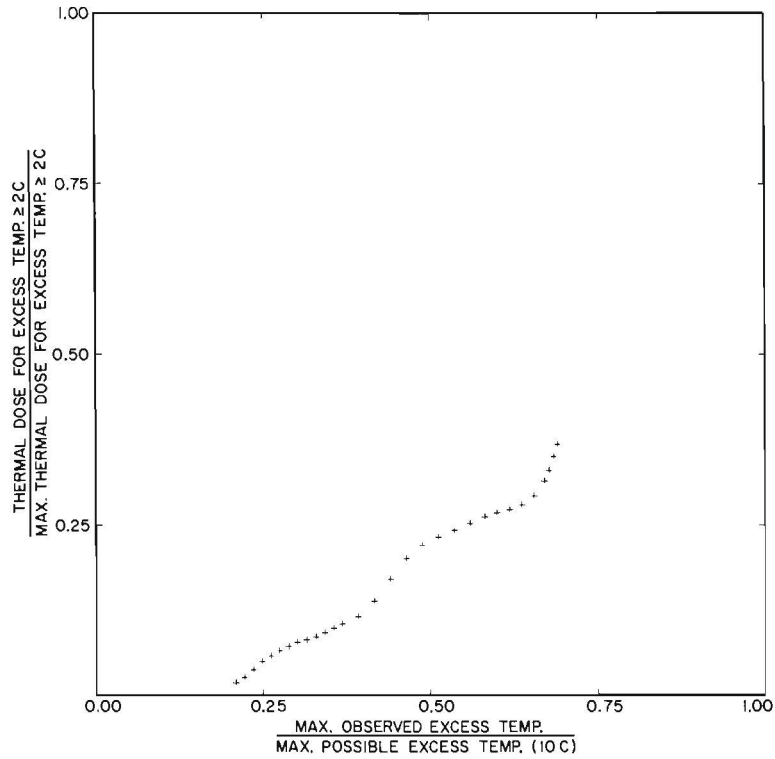
Figure 34. Thermal Dose for excess temperatures $\geq$ 2C as a function of maximum excess temperature experienced by each of the appropriate organisms. The thermal doses (°C-sec) have been normalized to the maximum dose calculated and are plotted on the ordinate. The excess temperatures have been normalized to the maximum possible excess temperature -- the ΔT across the condensers -- 10C, and are plotted on the abscissa.
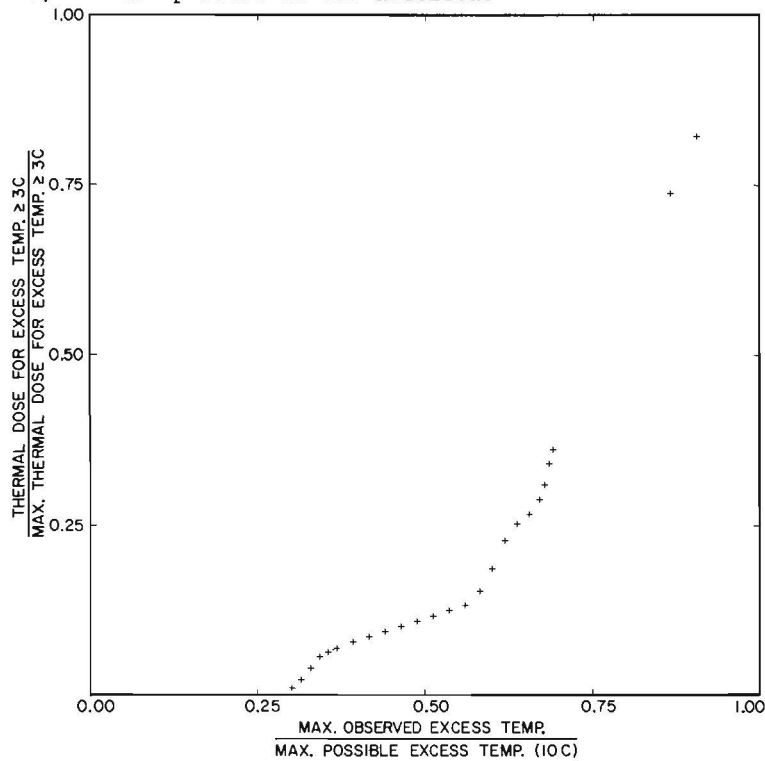
Figure 35. Thermal Dose for excess temperatures $\geq$ 3C as a function of maximum excess temperature experienced by each of the appropriate organisms. The thermal doses (°C-sec) have been normalized to the maximum dose calculated and are plotted on the ordinate. The excess temperatures have been normalized to the maximum possible excess temperature -- the ΔT across the condensers -- 10C, and are plotted on the abscissa.

34
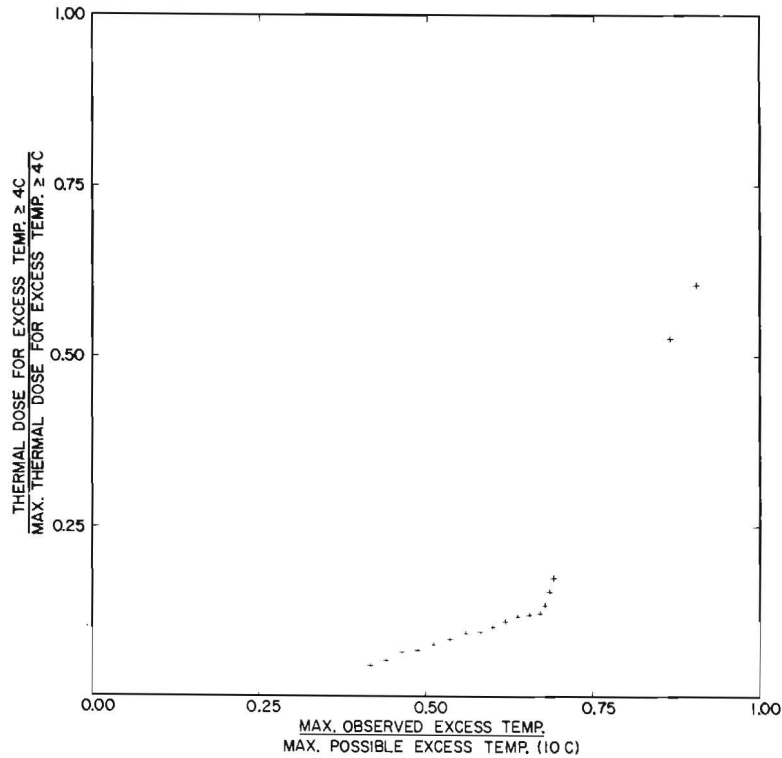
Figure 36. Thermal Dose for excess temperatures > 4C as a function of maximum excess temperature experienced by each of the appropriate organisms. The thermal doses (°C-sec) have been normalized to the maximum dose calculated and are plotted on the ordinate. The excess temperature have been normalized to the maximum possible excess temperature -- the ΔT across the condensers -- 10C, and are plotted on the abscissa.
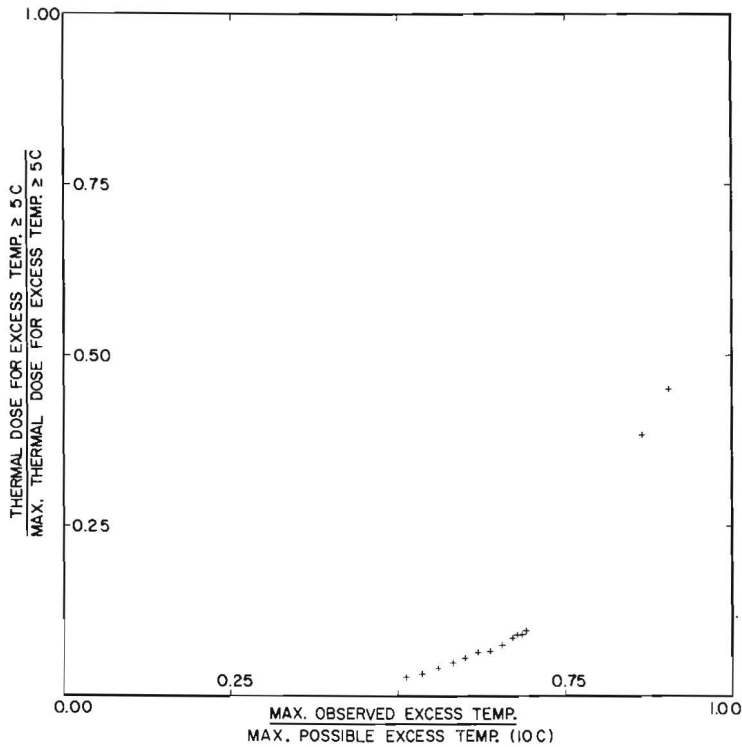
Figure 37. Thermal Dose for excess temperatures > 5C as a function of maximum excess temperature experienced by each of the appropriate organisms. The thermal doses (°C-sec) have been normalized to the maximum dose calculated and are plotted on the ordinate. The excess temperatures have been normalized to the maximum possible excess temperature -- the ΔT across the condensers -- 10C, and are plotted on the abscissa.

35

exposure histories and associated thermal doses. We combined our calculated thermal doses for an estuarine-coastal power plant with the appropriate experimentally determined *summer* thermal resistance dose curve and have plotted this information on a single graph. We did the same for the winter case. The doses experienced by our hypothetical organisms which are associated with temperatures below the incipient lethal temperature should be eliminated from the dose calculations since organisms can be subjected to this temperature indefinitely without increasing the probability of death.[3] For this discussion, we have chosen not to do this. Instead, we have developed environmentally conservative cases by extending the calculations of excess temperature to 1C for the estuarine cases and to 0C for the riverine cases. Our calculations of doses for our hypothetical plant are all in terms of excess temperatures. To convert these to actual temperatures, one needs to select a base temperature. The appropriate base is set by the choice of acclimation (base) temperature used in developing our thermal resistance curves -- the acclimation temperature representative of ambient water temperature.

We have plotted in Figures 38 and 39 our calculated thermal dose-maximum excess temperature data for the 100 organisms in the estuarine case on the Thermal Dose-Excess Temperature Diagrams presented earlier (Figures 18 and 19). We have also plotted similar data on these figures for the riverine case for comparison. Thermal dose in °C sec is plotted along the ordinate and actual temperature and excess temperature along the abscissa. It is apparent that for the riverine case for both summer and winter the doses for all 100 organisms fall to the left of the 50% mortality curve[4] and therefore the probability of mortality is less than 0.5. For the estuarine case doses are, as expected, considerably larger. For the winter case, none of the doses experienced

by any of the 100 organisms exceeded the threshold associated with 50% mortality. For the summer estuarine case, 9 of the 100 organisms, or 9%, experienced doses in excess of that expected to produce 50% mortality.

With an increase in base temperature, all three curves in Figure 38 and in Figure 39 would be displaced up and to the right, although not necessarily by the same amount. The calculation of thermal doses for different base temperatures is straightforward; however the assessment of the biological significance of those changes may, and probably would, require laboratory experiments to establish thermal resistance curves. Thermal tolerance data that are appropriate for construction of thermal resistance curves are unavailable for most of New York's Representative Important Species for freshwater, estuarine, and marine environments. This simple conceptual thermal response model should be useful in assessing the thermal effects of power plants with once-through cooling systems on organisms in the receiving waters.

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[1] A mortality of 10 or perhaps 25% would be more desirable, but thermal resistance data are rarely available for mortalities other than 50%. This is a deficiency of most studies. Mortalities should be determined for 10 to 90% at 10% intervals.

[2] See Section II. A. 3. for the characteristics of the hypothetical plant and receiving waters used in the calculations.

[3] In our examples, the probability of death is 0.5 (mortality rate 50%). Incipient lethal temperatures could, of course, be defined for mortalities other than 50%.

[4] The Thermal Dose-Excess Temperature mortality curve is for estuarine-coastal organisms. For the purposes of this discussion, we are assuming that the riverine case would not be significantly different.
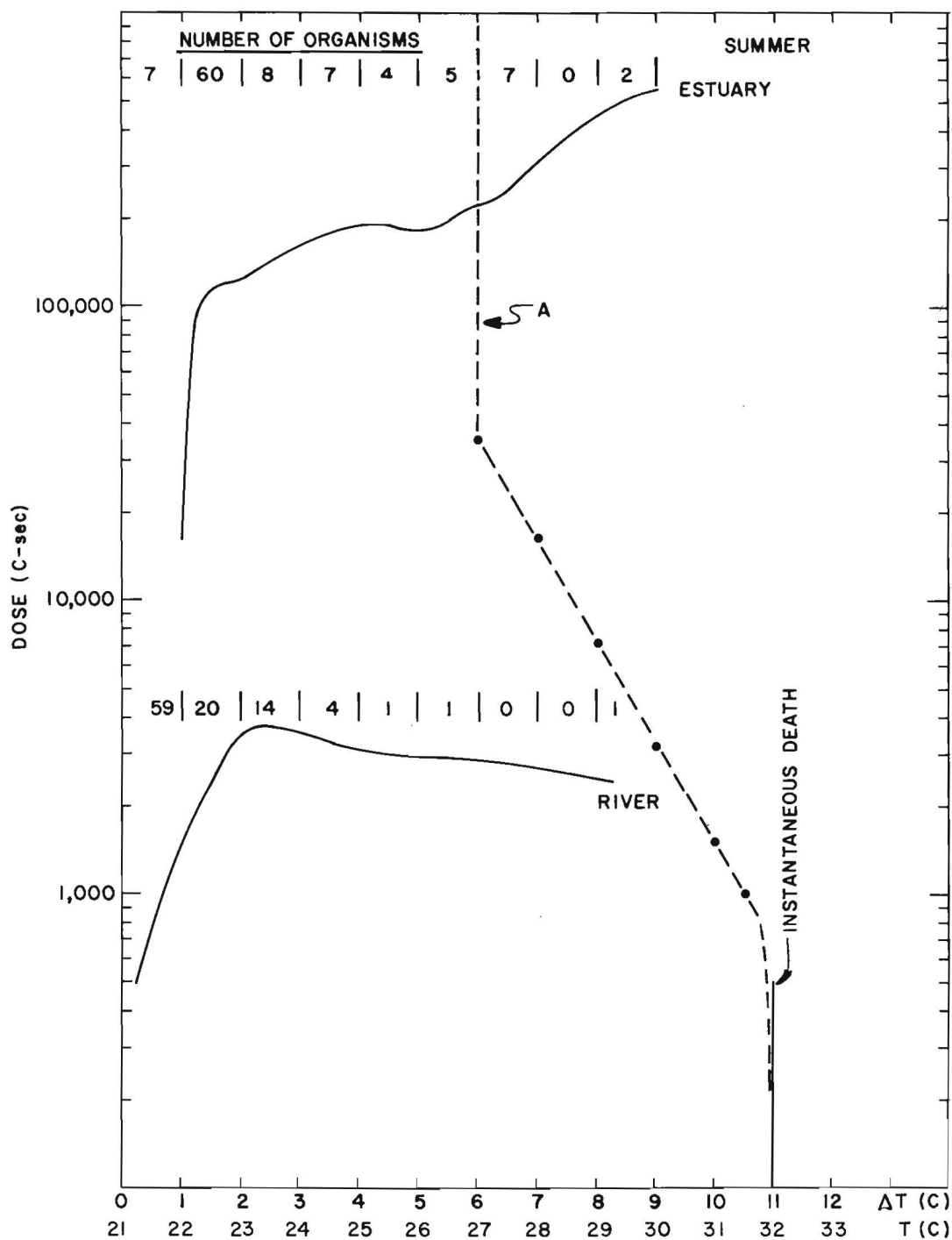
Figure 38. Graphical representation of the Thermal Response Model applied to a New York estuarine/coastal case in summer. The Thermal Dose-Excess Temperature mortality curve (A) was calculated from Thermal Resistance Data and is for a mortality of 50%. The thermal doses experienced by each of the 100 hypothetical organisms are presented for the estuarine and the river cases. The numbers above these curves indicate the number of organisms exposed to the indicated excess temperatures. The probability of mortalities is greater than 0.5 when the thermal dose-maximum excess temperature exposure curve crosses the Thermal Dose-Excess Temperature mortality curve (A). For the riverine case none of the 100 organisms experienced dose-temperature combinations in excess of those associated with a mortality of 50%. For the estuarine case 9 organisms experienced doses in excess of those expected to produce 50% mortality.

37
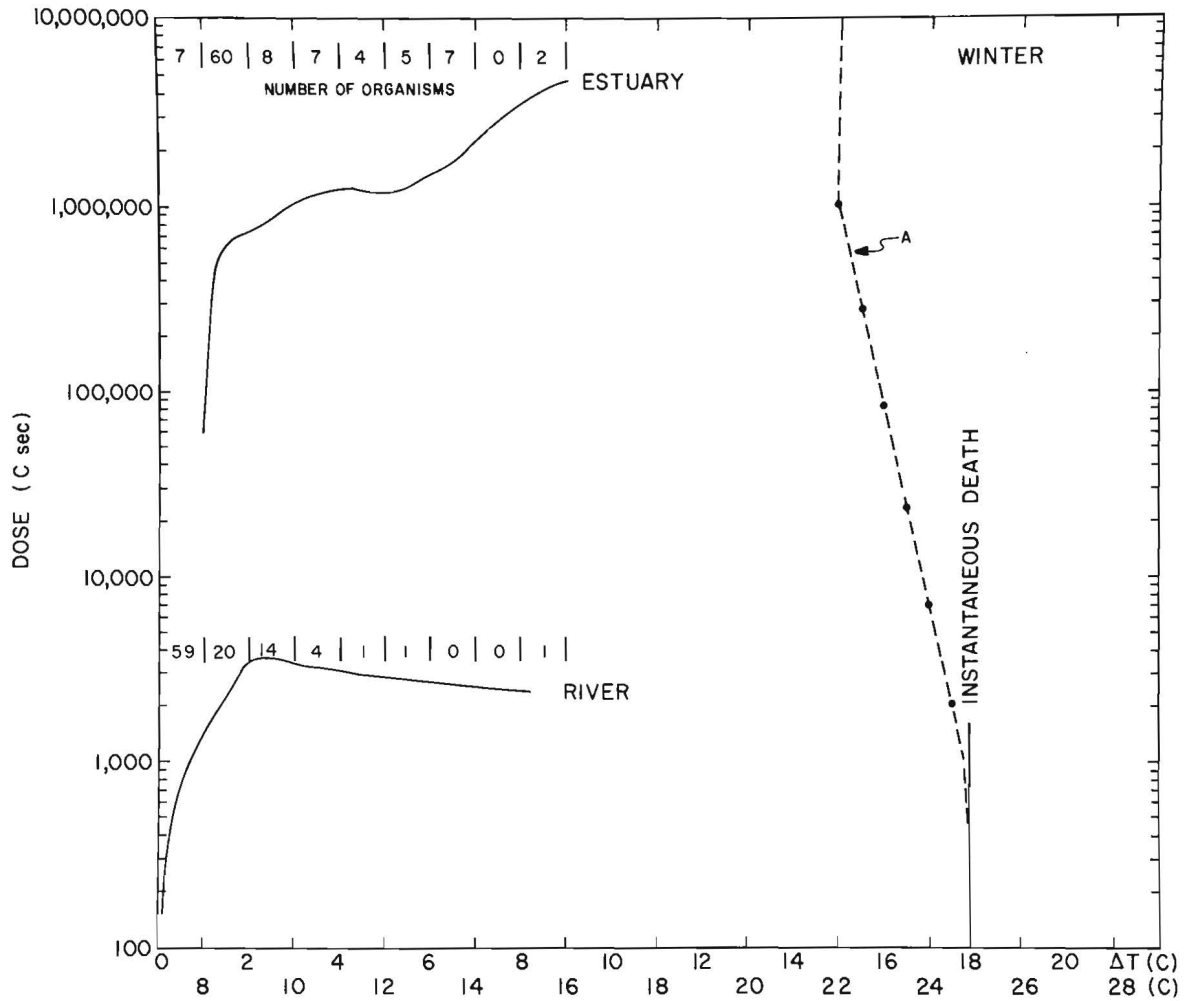
Figure 39. Graphical representation of the Thermal Response Model applied to a New York estuarine/coastal case in winter. The Thermal Dose-Excess Temperature mortality curve (A) was calculated from Thermal Resistance Data and is for a mortality of 50%. The thermal doses experienced by each of the 100 hypothetical organisms are presented for the estuarine and the river cases. The numbers above these curves indicate the number of organisms exposed to the indicated excess temperatures. The probability of mortalities is greater than 0.5 when the thermal dose-maximum excess temperature exposure curve crosses the Thermal Dose-Excess Temperature mortality curve (A). None of the 100 organisms for either the riverine or estuarine case experienced dose-temperature combinations in excess of those associated with a mortality of 50%.

IV. INPUTS TO THE THERMAL RESPONSE MODEL
(P. M. J. Woodhead)

A. Natural Temperature Variations
Of New York State Waters

1. Introduction

Aquatic organisms usually have body temperatures that conform to the water temperature, and any water temperature change will have effects upon the organisms in that water body. The biological effects of temperature, and of temperature change are complex, fundamentally effecting growth, metabolism, reproduction, behavior and distribution of organisms and communities. The ambient temperatures of surface waters vary widely with latitude, altitude, season, climatic change, flow and many other variables. Nevertheless any consideration of thermal effects of power plants operating in an aquatic environment and circulating the water for condenser cooling, necessarily requires data on the natural temperature variations in that environment, i.e., their amplitudes and periods.

There are two basic requirements for detailed information on the natural variations in water temperatures in the vicinity of a power plant. First, the thermal effects induced by heat introduction from the power plant to the cooling water will vary according to the ambient temperature, and will be represented as increments to the ambient temperature of the water. Secondly, it has long been established that fish and other aquatic organisms each have a discrete temperature tolerance range (Kinne, 1970). Exposure to temperatures in excess of the tolerance limits may lead to mortalities which are time dependent -- the higher the temperature above the tolerance limit, the more rapid is death. The recent thermal experience profoundly affects the lethal

temperature of an organism, thus a recent history of warm temperatures produces an elevated lethal temperature, while a history of cold temperatures results in a low lethal temperature. Therefore, in order to make an assessment of the thermal tolerance of an organism in relation to temperature increments induced by a power plant, it is essential to know the ambient water temperature to which the organism is acclimated before it encounters the heated effluent.

2. Sources of temperature data

In order to describe the natural variations of water temperature in a particular environment, the most useful data for analysis are consistent historical records for individual sites at which water temperatures have been measured frequently -- if possible on a daily basis. For the coastal and estuarine regions of New York State, such historical data are available at a few tide recording stations operated originally by the U. S. Coast and Geodetic Survey, and more recently incorporated into the National Ocean Survey (Coast and Geodetic Survey, 1955, 1965; National Ocean Survey, 1976). The positions of these tidal stations are shown in Figure 40.

The longest water temperature data series available in the New York region was for surface temperatures at the Battery, N.Y. from 1927 to 1976. Other data series collected were for Sandy Hook, N.J. from 1946 to 1976, Montauk Pond, Long Island, N.Y. from 1948 to 1971 and New London, Conn., from 1948 to 1976. These series have all been analysed in some
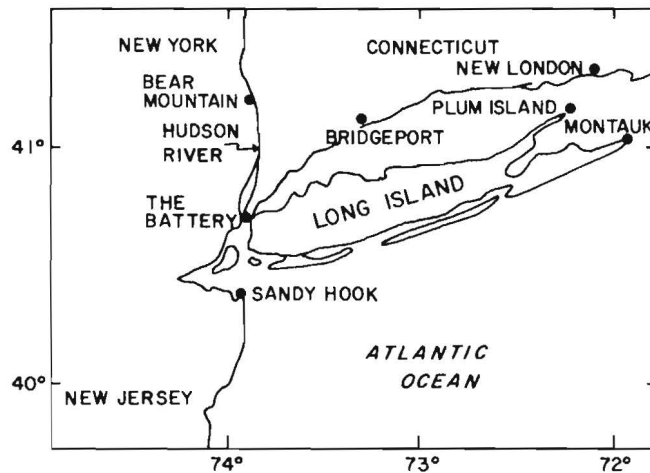
Figure 40. Positions of stations at which surface
water temperature series were recorded
(Lake Ontario stations are not shown).

detail; the results are rather similar for all four series. Therefore, for purposes of this report, the discussion and illustrations will be largely restricted to the long series at the Battery, N.Y. For convenience of analysis of examples in this report, monthly mean temperature data have been used, but we stress that we have the daily observations which could be used in exactly the same ways should finer levels of analysis be required.

Supplementary temperature data for Long Island Sound are also available as short series of surface observations for tidal stations at Bridgeport, Conn., New Rochelle, N.Y., and Plum Island, N.Y. A series of observations for the Hudson River, at Bear Mountain in the vicinity of the important spawning grounds, was obtained for the period 1958 to 1962.

Data that have been obtained to show

the annual changes of surface temperature in Lake Ontario show complex patterns of temperature distribution across the lake, especially during the warmer months (Gächter, Vollenweider and Glooschenko, 1973). The precise description of natural temperature changes occurring in the waters of Lake Ontario depends very much upon the particular coastal site which is involved. Therefore, to illustrate the general seasonal cycle of surface temperature change in Lake Ontario, we have chosen data from water temperature monitoring stations at the inflow to the lake on the lower Niagara River, and at the outflow at Cape Vincent, N.Y.

3. Seasonal cycles of surface temperature

The seasonal cycles of surface water temperatures at the Battery, N.Y. and Bear Mountain on the Hudson River are given in the form of mean monthly temperatures in

40
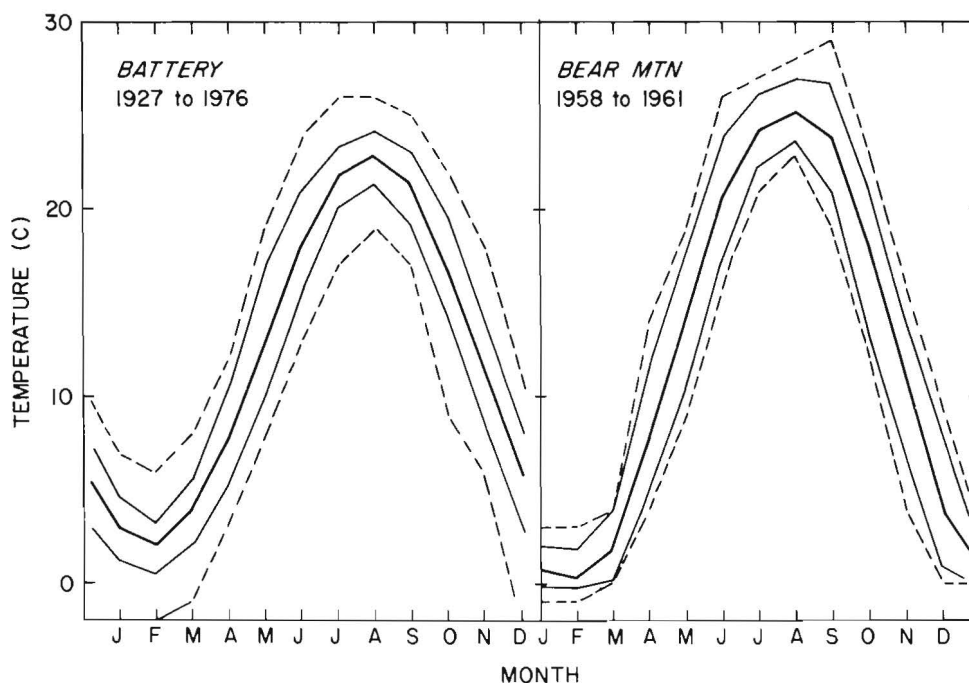
Figure 41a,b.   Seasonal cycles of monthly surface water temperatures at
(a) Battery, N.Y., 1927-1976; (b) Bear Mountain, Hudson
River, N.Y., 1958-1961.
The thick center line indicates the *mean* monthly temper-
atures for the observation series. The thin lines
indicate the *mean* monthly maximum and minimum tempera-
tures. The dashed lines represent the single monthly
maximum and minimum temperatures for the series.

Figure 41a and 41b. Seasonal surface tem-
peratures associated with Long Island Sound
are given for New London, Conn., and
Montauk Pond, N.Y. in Figure 41c and 41d.
In addition to the monthly means in Figure
41, the mean maximum and mean minimum tem-
peratures for each month are shown (during
each year of observation a single maximum
and a single minimum temperature is
recorded for each month, the mean monthly
maximum (or minimum) is derived from the
sum of the series of maxima (or minima) for
that month, divided by the number of years
in the observed series). Finally, the
extreme maximum and extreme minimum temper-
atures recorded over the whole data series
for each month, are also shown in the
figure.

Water temperature changes recorded at
the surface inflow and outflow from Lake
Ontario are shown in Figure 42a and 42b.

The mean monthly temperature data are for
eight months of 1972 and for all of 1973.
Considering annual surface temperature
data for Lake Ontario over the period 1966
to 1973, Grumblatt (1976) noted that 1972
was an unusually cold year, whereas 1973
was warmer than average, so that the sea-
sonal changes for 1972 and 1973 shown in
Figure 42 probably represent an approxima-
tion to the range of annual variations
anticipated in the inflow and outflow
regions of the lake.

4. Long series temperature data

The longest series of records of
surface water temperatures of the New York
region (as noted earlier) was for the
Battery, from 1927 to 1976. The annual
mean temperatures for this 50-year period
are shown in Figure 43; in the same figure
annual mean temperatures are also shown
for New London in eastern Long Island
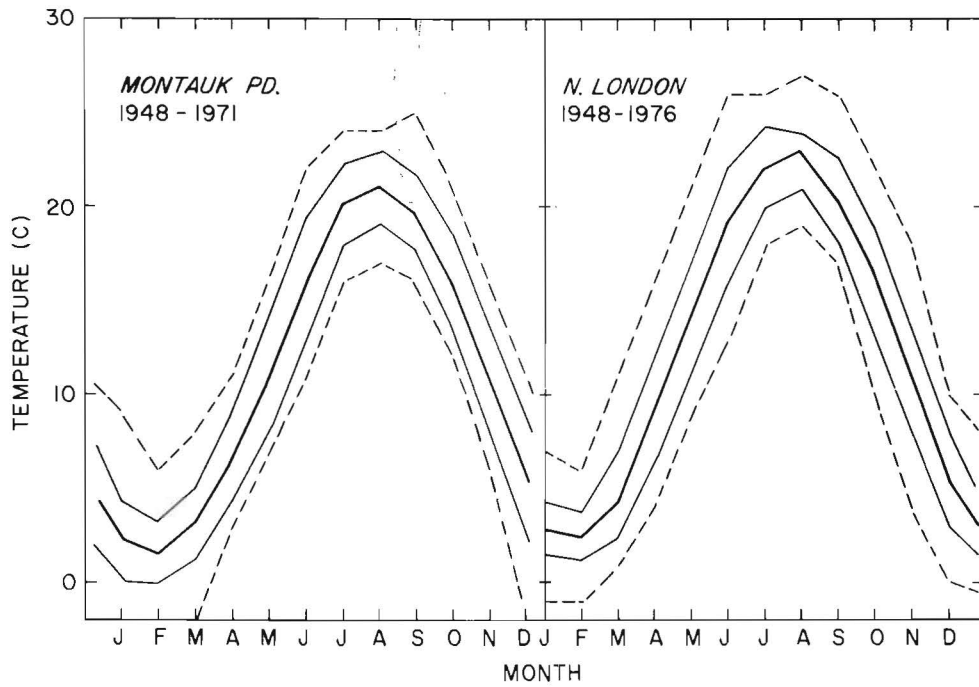
Figure 41c,d.   Seasonal cycles of monthly surface water temperatures at
                (c) Montauk Pond, Long Island, N.Y., 1948-1971; (d) New
                London, Conn., 1948-1976.
                The thick center line indicates the *mean* monthly temper-
                ature for the observation series.   The thin lines
                indicate the *mean* monthly maximum and minimum tempera-
                tures.   The dashed lines represent the single monthly
                maximum and minimum temperatures for the series.
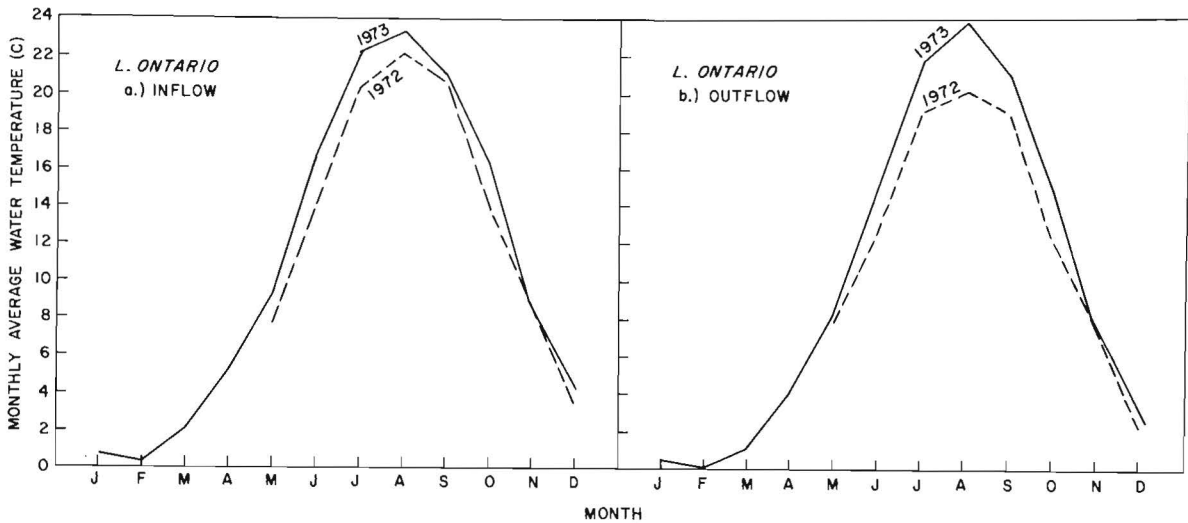
Figure 42.   Seasonal cycles of monthly surface water temperatures for 1972-1973 at Lake Ontario
             (a) inflow at lower Niagara River; (b) outflow at Cape Vincent, N.Y.
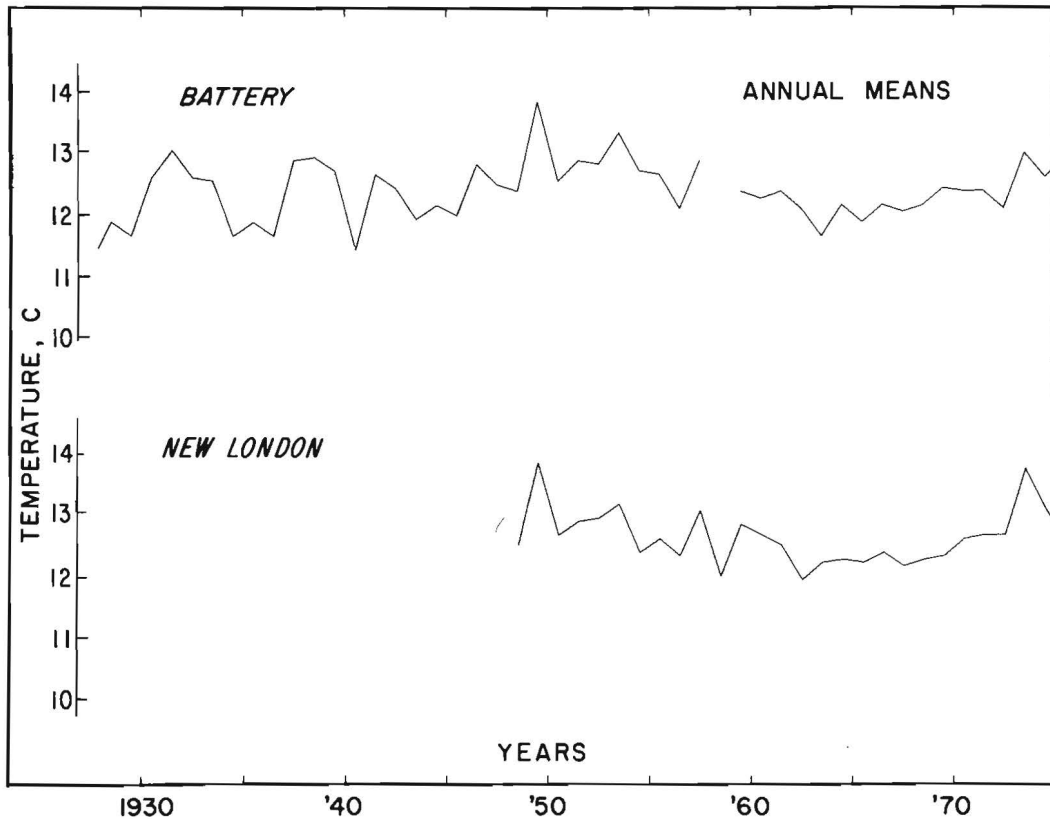
Figure 43. Mean annual surface water temperatures at Battery, N.Y., 1927-1976; (b) New London, Conn., 1948-1976.

Sound, from 1948 to 1976. Observations from the other coastal temperature recording stations (not included in this report) showed very similar annual changes.

The monthly temperature data for the Battery were also separated for the quarters of the year -- 1st, January to March; 2nd, April to June; 3rd, July to September; and 4th, October to December. These quarterly temperature data were then analyzed to show their cumulative percentage distribution with respect to temperature, over the whole 50-year observation period, Figure 44a, b, c and d.

These figures allow ready estimation of the frequency with which ambient water temperatures are likely to occur in any season. In this respect Figure 44c, for the period of summer or maximum tempera-

tures, is particularly interesting in that the range of temperatures observed is small, fully 65% of all mean monthly temperatures falling within 1C of 22C during July to September. Examination of similar quarterly temperature distributions for the other coastal recording stations also showed only a small range of temperatures during the summer. Because summer is the time of maximum ambient temperatures, when organisms might be especially susceptible to thermal inputs from power plants, it facilitates these analyses that the summer appears also to be a time of thermal stability, enabling prediction of the possible consequences of thermal increments to the aquatic environment to be made with some confidence.

43
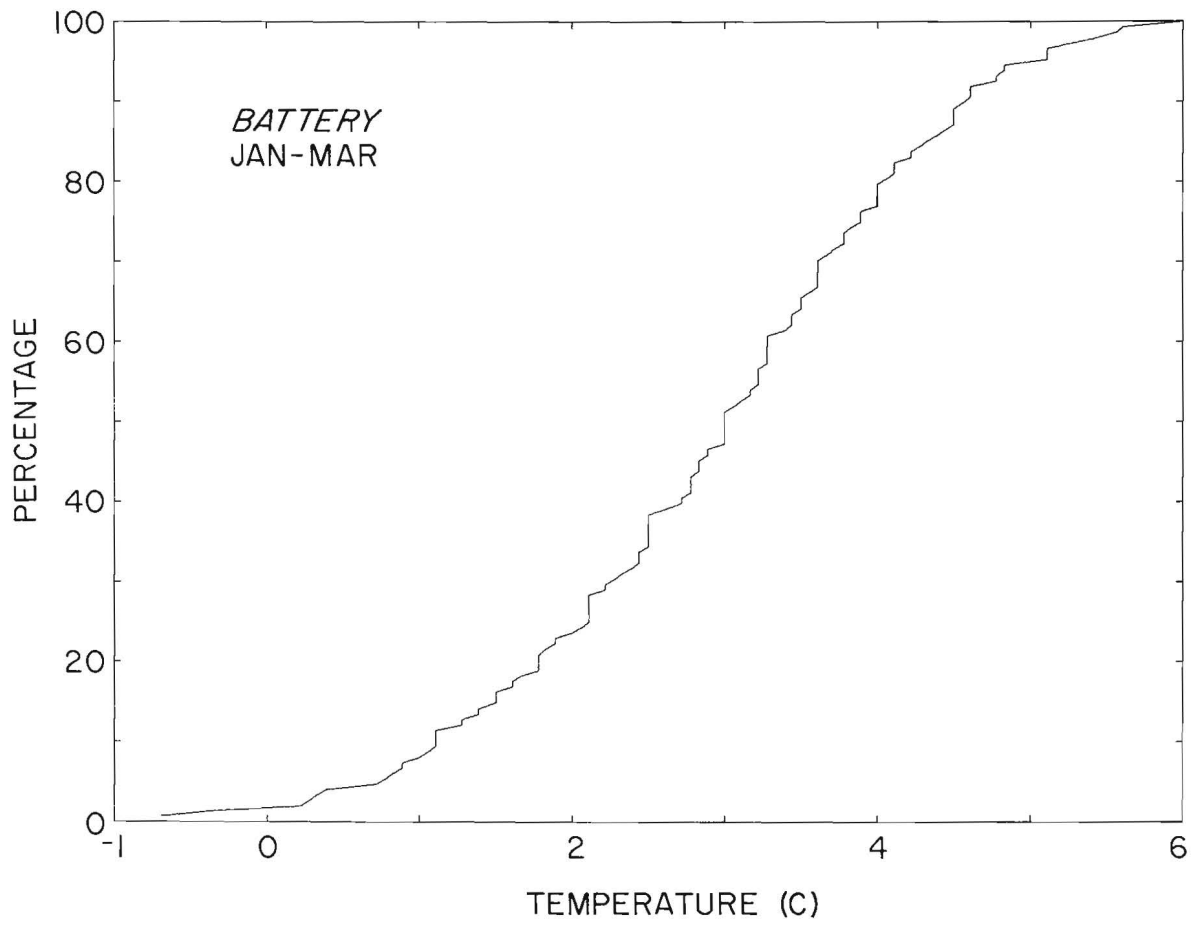
Figure 44a. Monthly mean surface temperatures at Battery, N.Y., 1927 to 1976, plotted as cumulative percentages for January to March.
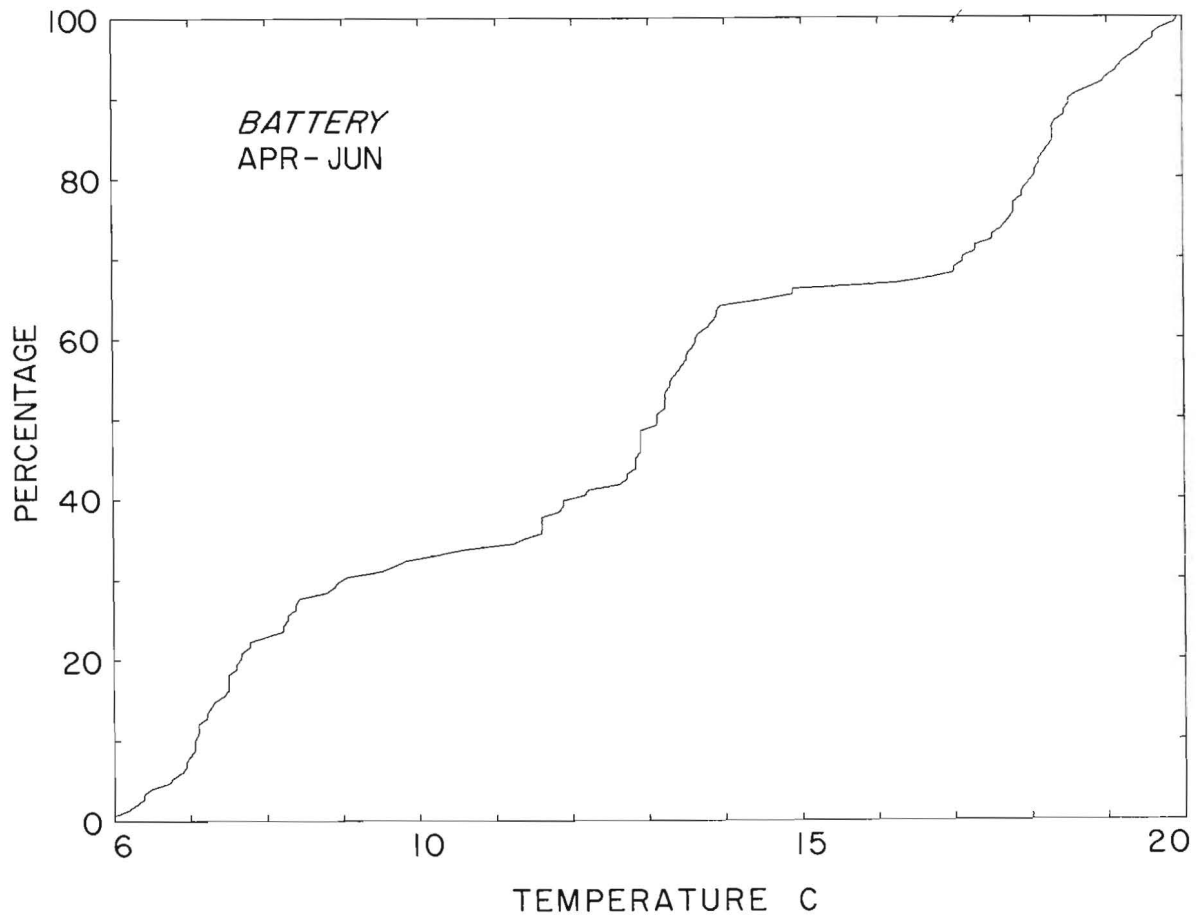
Figure 44b. Monthly mean surface temperatures at Battery, N.Y., 1927 to 1976, plotted as cumulative percentages for April to June.
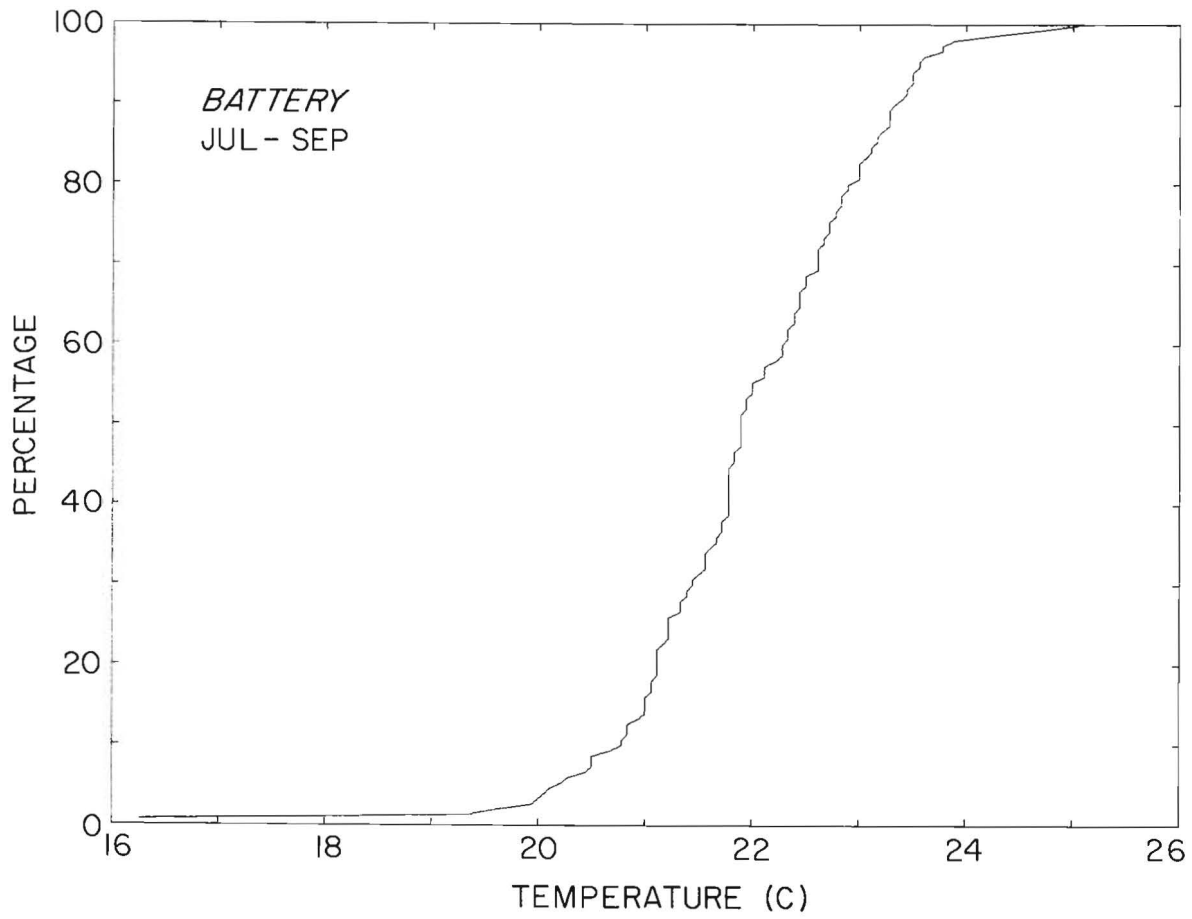
Figure 44c. Monthly mean surface temperatures at Battery, N.Y., 1927 to 1976, plotted as cumulative percentages for July to September.
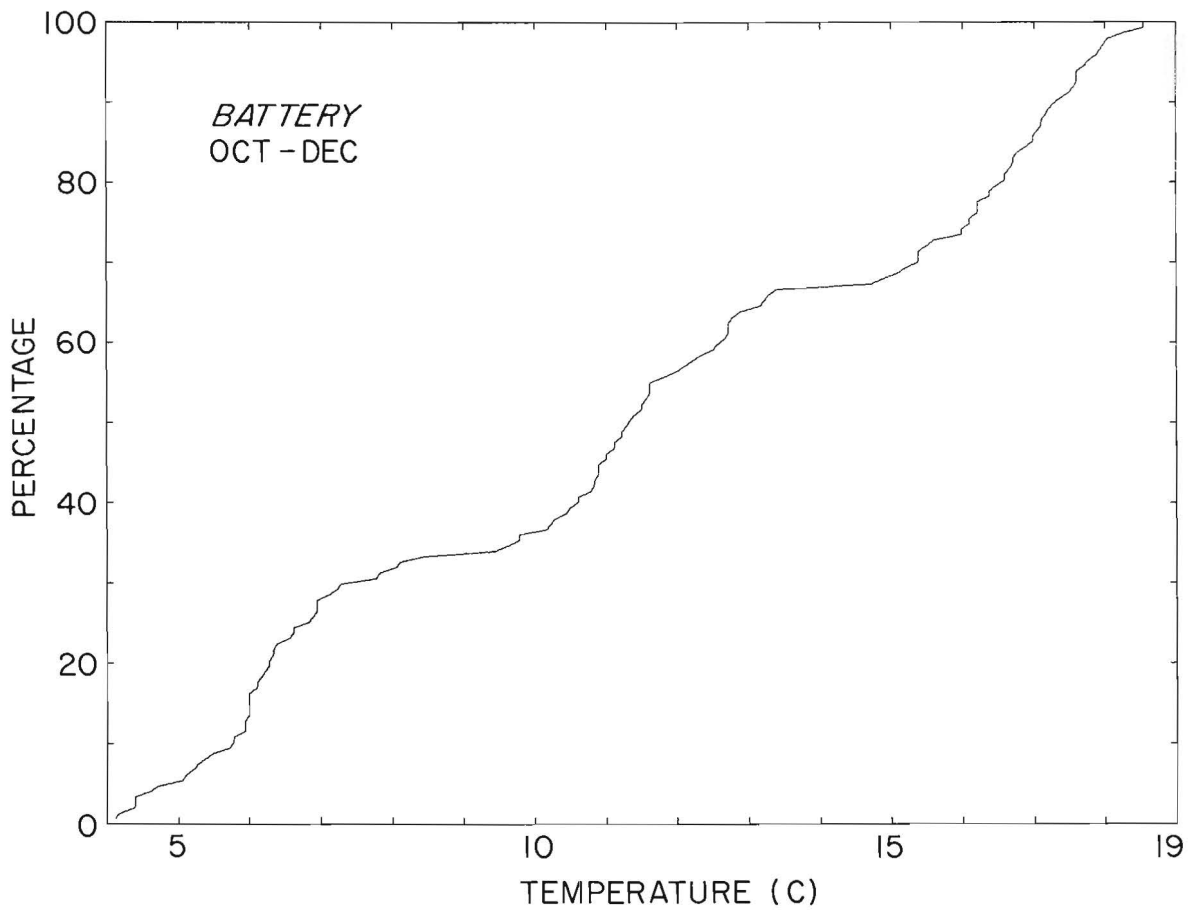
Figure 44d. Monthly mean surface temperatures at Battery, N.Y., 1927 to 1976, plotted as cumulative percentages for October to December.

1. R.I.S. selected

Representative Important Species (R.I.S.) have been chosen for Long Island Sound, the Hudson River and Lake Ontario. The criteria used for selection of R.I.S. were, (1) that the species spawned in that environment, (2) that they were of importance to the commercial or sport fisheries of the region either as desirable fish to catch, or as important links in the food chains.

We have not considered phytoplankton. Regeneration times of phytoplankton are so short relative to those of zooplankton, and particularly ichthyoplankton, that protection of these groups of organisms should ensure adequate protection of phytoplankton. Similarly, the invertebrates components of the zooplankton have been largely ignored in the selection of R.I.S. because they are generally more tolerant of abrupt temperature increases than are members of the ichthyoplankton (this is discussed further in Section C. of this chapter), thermal protection of representative important fish species should, therefore, protect the invertebrate planktonic community.

Long Island Sound

Fish

Winter flounder, *Pseudopleuronectes americanus*
Blackfish, *Tautoga onitis*
Weakfish, *Cynoscion regalis*
Scup, *Stenotomus chrysops*

Of less importance but present in large numbers and pursued as forage or bait fish fish.

Menhaden, *Brevoortia tyrannus*
Bay anchovy, *Anchoa mitchilli*
Silversides, *Menidia menidia*

Shellfish

Lobsters, *Homarus americanus*
Oysters, *Crassostrea virginica*
Hard Clams, *Mercenaria mercenaria*

Lobster eggs are carried attached to the body of the female until the free-swimming larvae hatch. The eggs are therefore provided with a considerable degree of protection according to the behavior of the female. Similarly, oyster husbandry practices in which the spat are collected upon old shells in certain areas of the Sound (largely off the Connecticut shores), and then later transported to particular *growing grounds*, provides special protection for this species (which can also be propagated in large numbers at Long Island hatcheries).

The eastern population of menhaden is presently greatly reduced in size due to fishing, but menhaden have been a dominant species in the Sound until recently.

Hudson River

Striped bass, *Morone saxatilis*
American shad, *Alosa sapidissima*
White perch, *Morone americana*
Tomcod, *Microgadus tomcod*
Short nosed sturgeon, *Acipenser brevirostris*

The short nosed sturgeon is listed as an *endangered species* and is now fairly rare. Because it is a year-round resident of the river and legally protected against destruction, it may pose special problems. Herrings occur seasonally in the Hudson River in large numbers, but they are presently of little commercial interest and are unexploited, although their juveniles are important as forage fish.

Lake Ontario

Alewives, *Alosa pseudoharengus*
White perch, *Morone americana*
Yellow perch, *Perca flavescens*

The fish fauna of Lake Ontario has changed radically over the past century. The lake originally supported stocks of Atlantic salmon, lake trout, whitefish and lesser coregonid stocks but at present all of these valuable species are virtually extinct. The changes in the Lake Ontario fisheries have been reviewed by Christie (1973), who attributes the decline of the former stocks to overfishing, followed by the proliferation of colonizing alewives,

smelt, perch, etc., which then prevented the return of the premium species.

2. Spawning seasons of R.I.S.

Typically, the annual reproduction of aquatic organisms in temperate regions is circumscribed in time and space; spawning only takes place over a short period of the year in particular environments. In the Hudson River, the major spawning activity of the R.I.S. occurs in the spring with striped bass and American shad; blueback herring and white perch also begin their spawning in springtime. In Long Island Sound the greater part of fish spawning occurs during the summer, both in terms of numbers of eggs and as the number of different species spawning at that time of year; by area the spawning is most intense in the western and central areas of the Sound.

In Table 3 are listed the times of spawning of the R.I.S. in the three environments being considered in this report.

TABLE 3

Spawning Times of the R.I.S.

Species	Spawning	Species	Spawning
Long Island Sound		Hudson River	
Winter flounder	February-April	Striped bass	April-June
Blackfish	May-August	American shad	May-June
Weakfish	May-August	White perch	May-July
Scup	May-July	Shortnose sturgeon	Spring
Menhaden	May-September	Tomcod	December-February
Bay Anchovy	June-September		
Silversides	June-July	Lake Ontario	
Lobster	June-August	Alewives	May-July
Oyster	July-August	White perch	May-July
Hard clam	May-July	Yellow perch	May-July

C. Thermal Tolerance Data For R.I.S.

1. Introduction

There is a large literature on the effects of high temperatures upon aquatic organisms (see, for example, the bibliographies of Kennedy and Mihursky, 1967; Kennedy et al., 1974; Raney et al., 1972; Beltz et al., 1974; Coutant and Pfuderer, 1973, 1974; Coutant and Talmadge, 1975, 1976), but relatively little of this research is of *direct* use in predicting the effects of exposure to time-temperature histories typically experienced during entrainment at power plants with once-through-cooling systems. In most of the published laboratory studies of thermal tolerance, the organisms have been subjected to a constant temperature for all, or nearly all, of the experimental periods; in other studies organisms have been subjected to changing temperatures but at rates of change too slow (1C per 5 min to 1C per 2 hr) for approximate power plant comparisons. Finally, studies have frequently been made on adult or large juvenile stages in the life history -- organisms too large to be subjected to pump entrainment through a power plant. Data from field studies at operating power plants are usually equivocal due to the combinations of thermal, physical and

chemical stressors experienced, which may also have synergistic effects. For these reasons there is only a small and incomplete body of data available concerning thermal tolerances of the R.I.S., which is in a form applicable to possible predictions of effects of exposure to typical power plant thermal histories.

2. Thermal tolerance data

Data were sought concerning the thermal tolerances for early life stages of the R.I.S., in forms appropriate to prediction of thermal effects of power plants. The most useful data are in a form that permits construction of thermal resistance curves for the different species (see Chapter VI. B. 1.). The criteria for acceptability of such data were: (1) that exposure to the full temperature rise was almost instantaneous so that no thermal adaptation would occur, (2) that mortalities were reported as functions of both temperature and exposure time, (3) that mortalities were reported within a range of exposure times of from a few minutes up to about two hours, and (4) that the life-stages studied were of a size small enough to be unable to avoid the thermal influences of an operating power plant.

A second form of thermal tolerance data for aquatic organisms has been assembled as tables of coefficients for semilogarithmic regression equations (EPA, 1973). With these coefficients used in equation (11) of Chapter III. A., the corresponding times and temperatures to 50% mortality can be calculated for a number of organisms, largely fish.

The third form of thermal tolerance information which can be used is from experiments with appropriate time-temperature designs, but in which the organisms did *not* die; such results are of little value in constructing thermal resistance curves but are still valuable in indicating "safe" time-temperature exposures.

Using thermal tolerance information from these three categories of study, the available data for the early life-stages of the R.I.S. are listed in Table 4 for three environments, Long Island Sound, Hudson River and Lake Ontario.

From Table 4 it is clear that much more information is required concerning the tolerances of these R.I.S. to abrupt, short-term, thermal increments equivalent to those experienced during power plant entrainment. Complete data for all of the early life stages are not yet available for any single species listed, and for four (4) common species of fish listed, no thermal tolerance information exists for any of their early life-stages.

3. Community thermal resistance

Because there is a limited amount of suitable thermal data for the R.I.S. noted, it is informative to consider the results of thermal resistance studies for other organisms living in the three environments. For single species the data are usually few and so we have aggregated the information into "community thermal resistance" figures for Long Island Sound, the Hudson River, and Lake Ontario, using all of the results available. These figures combine the data for fish eggs, larvae and juveniles, zooplankton and macrobenthos. For the Long Island Sound and for the Hudson River (for which we had the largest bodies of data), the points for ichthyoplankton and juvenile fish were plotted on a separate figure from the zooplankton and macroinvertebrates. The points are for time to 50% mortality in relation to maximum temperature experienced during abrupt thermal increment experiments. Each figure has been plotted without regard for acclimation temperature (Figures 45a, b, c, d, e). There is some duplication in the Sound and the Hudson River figures because several animals, especially invertebrates, are common to both coastal marine and estuarine environments. A list of the species used to draw up the "community resistance" figures for the Sound, the Hudson River and Lake Ontario is given in Table 6 and the data sources are listed in Table 7.

TABLE 4

Data For R.I.S. Thermal Resistances

Species	Eggs	Larvae	Post-larvae	Juveniles
Long Island Sound				
Winter Flounder	--	C	--	A
Blackfish	--	--	--	--
Weakfish	--	--	--	--
Scup	--	--	--	--
Menhaden	--	A B	--	B
Bay Anchovy	--	--	--	--
Silversides	--	C	--	A
Lobster	--	C	--	--
Oyster	--	--	--	--
Hard Clam	A	A	--	--
Hudson River				
Striped Bass	A C	A C	C	--
American Shad	A C	A	--	--
White Perch	C	--	C	--
Tomcod	--	C	C	--
Lake Ontario				
Alewives	A C	--	--	C
Yellow Perch	--	--	--	B
White Perch	C	--	--	--

A = Thermal resistance curve data

B = Coefficients from EPA, 1973

C = Experiments with no significant mortality

(The data sources are listed in Table 5.)

TABLE 5

Sources of the Thermal Resistance Data in Table 4

Austin, H. N., A. D. Sosnow, and C. R. Hickey. 1975.

Coutant, C. C. and R. J. Kedl. 1975.

Hoff, J. H. and J. R. Westman. 1966.

Hoss, D. E., W. F. Hettler, and L. C. Coston. 1974.

Kennedy, V. S., W. H. Roosenburg, M. Castagna, and J. A. Mihursky. 1974.

Lauer, G. J., W. T. Waller, D. W. Bath, W. Meeks, R. Heffner, T. Ginn,
        L. Zubarik, P. Bibko, and P. C. Storm. 1974.

National Academy of Sciences. 1973.

Otto, K. G., M. A. Kitchel, and J. O. Rice. 1976.

Schubel, J. R. S. 1974.

Schubel, J. R. S. and A. H. Auld, 1972a.

Schubel, J. R. S. and A. H. Auld, 1972b.

Schubel, J. R. S. and A. H. Auld, 1974.

Schubel, J. R. S. and T. S. Y. Koo, 1976.

Schubel, J. R. S., T. S. Y. Koo and C. F. Smith, 1976.

Valenti, R. J. 1974.

Although this approach enables consideration of a greater body of information representative of more organisms from the local community, some of its value is lost by combining results derived from experiments using different acclimation temperatures. Nevertheless, a number of conclusions can be drawn. First of all, after an initial period of about 20 minutes, mortality is a function of maximum temperature of exposure and is independent of time. Less clearly in these figures, there is a slope to the initial portions of the thermal resistance data, for up to about 20 minutes, indicating that death is a dose response for relatively short exposure times. (The initial slope of thermal resistance curves is clear in studies of single species, as in Figures 12 and 13, but is somewhat obscured in the "community resistance" figures because data for different species and acclimation temperatures have been used.)

The limit of median lethal temperatures for exposure times of up to 20 - 30 minutes appears to be about 27C for both estuarine and coastal marine fish eggs, larvae and juveniles. For lacustrine organisms the limit may be higher at about 30C. The figures also indicate that fish eggs and larvae are usually significantly more sensitive to temperature stress than the zooplankton and macroinvertebrates. Therefore, if thermal criteria are set to protect the ichthyoplankton of a community, most invertebrate zooplanktonic organisms will be adequately safeguarded against thermally induced mortalities.

V. FISH POPULATION CONSIDERATIONS
(P. M. J. Woodhead)

A. Introduction

In terms of its impact on a fish population, a power plant operates much like an additional predator upon the early life stages of fish, consuming a part of the young populations. In a number of field studies estimates have been made of the percentage of fish eggs, larvae and juveniles killed at operating power plants. Unfortunately, it is not easy to relate these early losses to their impacts upon a population of fish, in terms of recruitment and the long-term health of the

Figure 45a. Community thermal sensitivity. Time to 50% mortality after abrupt exposure to high temperature, T_{max}. (T_{max} is the actual temperature experienced by the organisms.) Long Island Sound Ichthyoplankton. (o) = fish larvae.
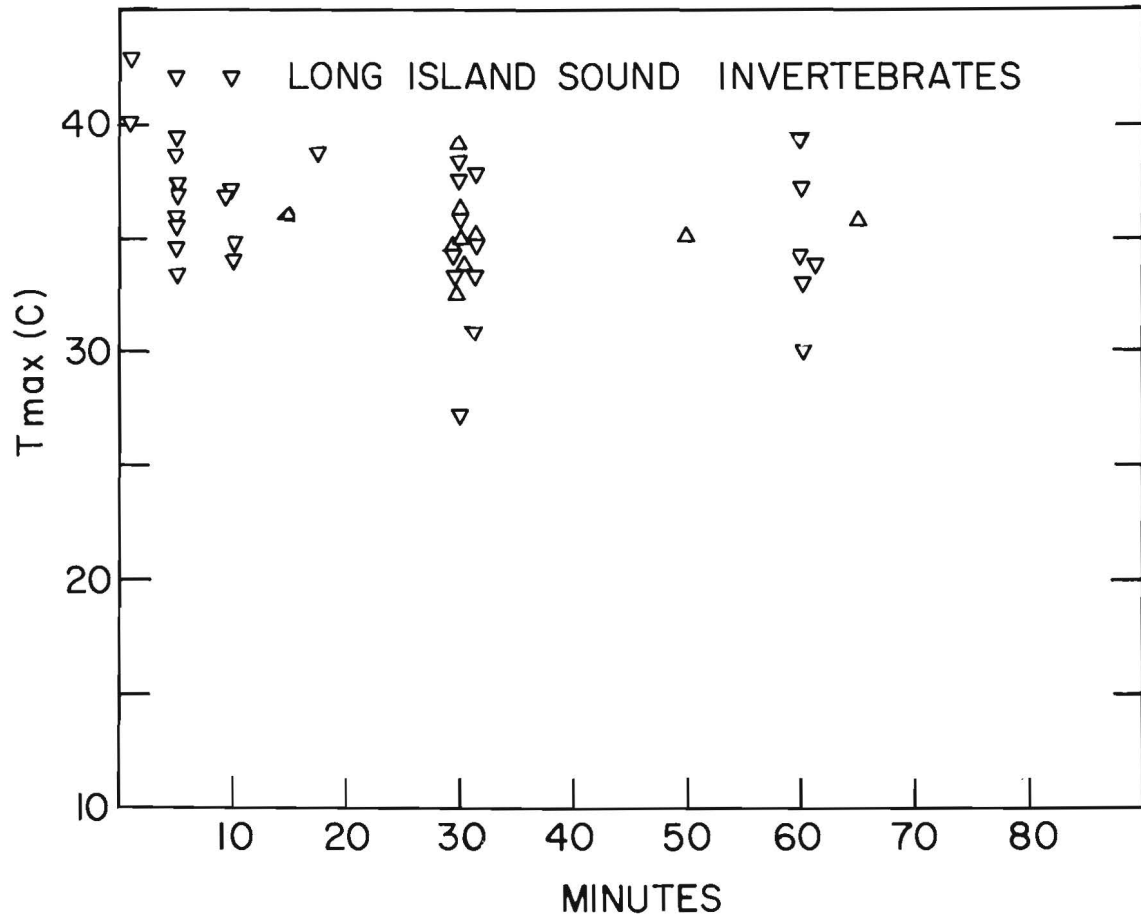
Figure 45b. Community thermal sensitivity. Time to 50% mortality after abrupt exposure to high temperature, T_{max}. (T_{max} is the actual temperature experienced by the organisms.) Long Island Sound Invertebrates. (Δ) = microzooplankton; (∇) = macroinvertebrate larvae.

Figure 45c. Community thermal sensitivity. Time to 50% mortality after abrupt exposure to high temperature, T_{max}. (T_{max} is the actual temperature experienced by the organisms.) Hudson River Ichthyoplankton. (o) = fish larvae; (□) = fish eggs.
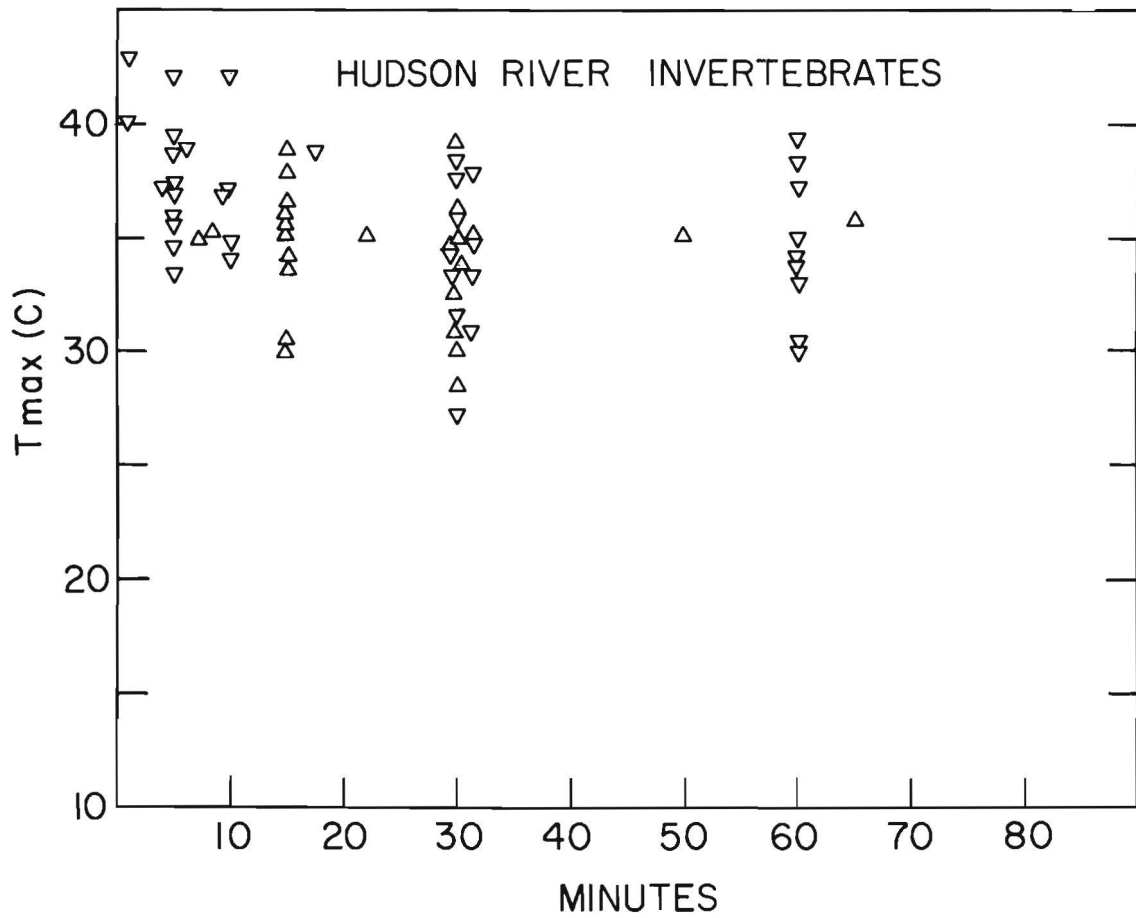
Figure 45d. Community thermal sensitivity. Time to 50% mortality after abrupt exposure to high temperature, Tmax. (Tmax is the actual temperature experienced by the organisms.) Hudson River Invertebrates. (Δ) = microzooplankton; (∇) = macroinvertebrate larvae.
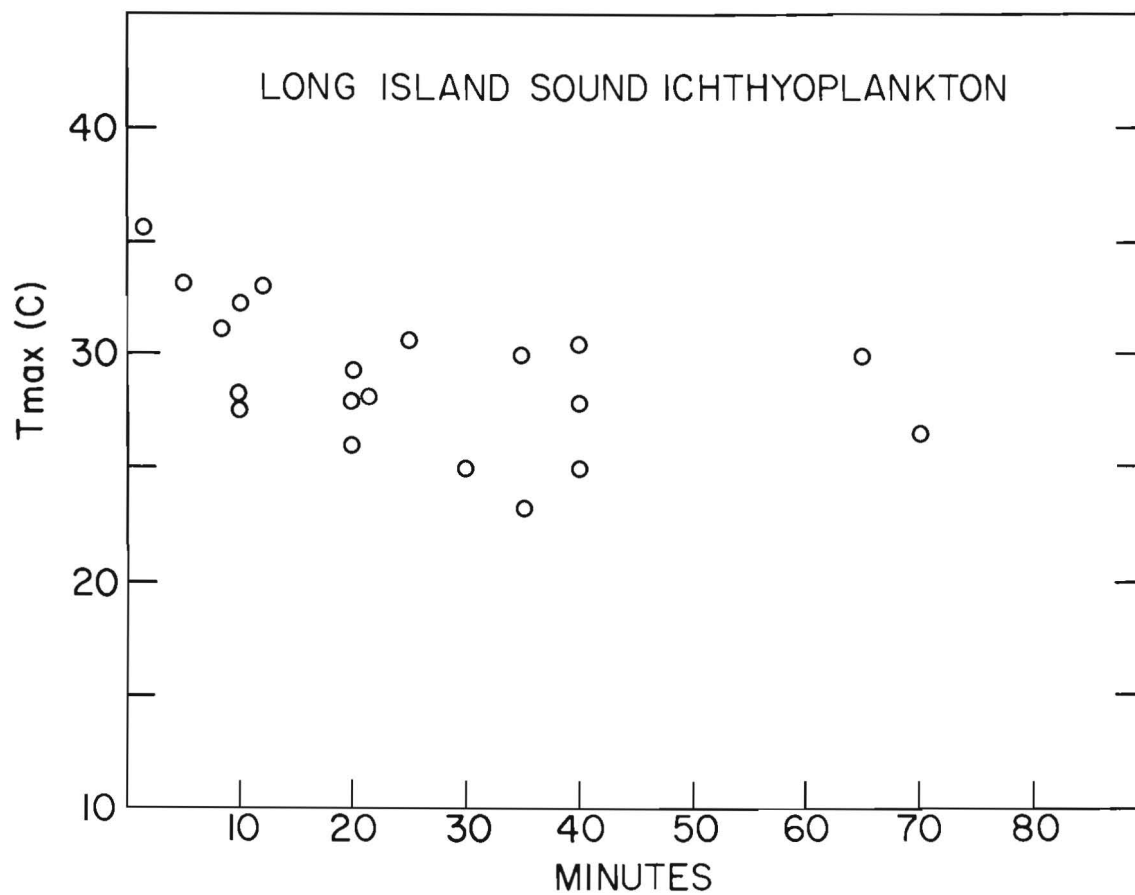
Figure 45e. Community thermal sensitivity. Time to 50% mortality after abrupt exposure to high temperature, T_{max}. (T_{max} is the actual temperature experienced by the organisms.) Lake Ontario Ichthyoplankton and Invertebrates. (●) = fish juveniles; (∇) = macroinvertebrate larvae; (□) = fish eggs.

TABLE 6

Species Used in Compiling Figure 45a, b, c, d, e

<table>
<tr><td>Long Island Sound</td><td>Hudson River</td></tr>
<tr><td>FISH</td><td>FISH</td></tr>
<tr><td>Flounder, Paralichtys, sp.</td><td>Striped bass, Morone saxatilis</td></tr>
<tr><td>Spot, Leiostomus xanthurus</td><td>American shad, Alosa sapidissima</td></tr>
<tr><td>Pinfish, Lagodon rhomboides</td><td>Blueback herring, Alosa aestivalis</td></tr>
<tr><td>Menhaden, Brevoortia tyrannus</td><td>INVERTEBRATES</td></tr>
<tr><td>Silversides, Menidia menidia</td><td>Hard clam, Mercenaria mercenaria</td></tr>
<tr><td>INVERTEBRATES</td><td>Coot clam, Mullina lateralis</td></tr>
<tr><td>Hard clam, Mercenaria mercenaria</td><td>Copepods, Acartia tonsa</td></tr>
<tr><td>Coot clam, Mullina laberalis</td><td>Eurytemora affinis</td></tr>
<tr><td>Copepod, Acartia tonsa</td><td>Halicyclops sp.</td></tr>
<tr><td>Mysid shrimp, Neomysis americana</td><td>Amphipods, Gammarus sp.</td></tr>
<tr><td></td><td>Monoculodes edwardsi</td></tr>
<tr><td>Lake Ontario</td><td>Mysid shrimp, Neomysis americana</td></tr>
<tr><td>FISH</td><td>Cladocera, Bosmina longirostris</td></tr>
<tr><td>Cisco, Coregonus artedii</td><td></td></tr>
<tr><td>Bloater, Coregonus hoyi</td><td></td></tr>
<tr><td>Carp, Cyprinus carpio</td><td></td></tr>
<tr><td>Minnows, Chrosomus eos</td><td></td></tr>
<tr><td>Chrosomus neogaeus</td><td></td></tr>
<tr><td>INVERTEBRATES</td><td></td></tr>
<tr><td>Isopod, Asellus intermedius</td><td></td></tr>
<tr><td>Amphipods, Hyallela azteca</td><td></td></tr>
<tr><td>Gammarus fasciatus</td><td></td></tr>
</table>

N.B. The species listed above represent all the thermal tolerance data which we have found for the three environments, but they do *not* proportionately represent the composition of the communities in those environments.

population. This is due to the lack of a complete understanding of the mechanisms that control population change in fish stocks. The problem of estimating the responses of a population to changes in mortality is one of fundamental importance to fishery research and management (Cushing, 1975; Hunter, 1976), and is not restricted to estimating the impact of power plant mortalities.

The size of recruitment to fish stocks, as new year-classes, is very variable. Reviewing species of temperate water fish for which recruitment statistics covered several years, we found year-class sizes varying over 1.0 to 2.2 orders of magnitude for single fish stocks. Most species of fish of commercial importance have very high fecundities, a single female spawning

TABLE 7

Sources of the Thermal Resistance Data
Plotted in Figures 45a, b, c, d, e

Austin, H. M., A. D. Sosnow, and C. R. Hickey. 1975

Coutant, C. C. and R. J. Kedl. 1975.

Edsall, T. A. and P. J. Colby. 1970.

Frank, M. L. 1974.

Heinle, D. R. 1969.

Hoss, D. E., W. F. Hettler, and L. C. Coston. 1974.

Kennedy, V. S., W. H. Roosenburg, H. H. Zion, and M. Castagna. 1974.

Kennedy, V. S., W. H. Roosenburg, M. Castagna, and J. A. Mihursky. 1974.

Lauer, G. J., W. T. Waller, D. W. Bath, W. Meeks, R. Heffner, T. Ginn,
     L. Zubarik, P. Bibko, and P. C. Storm. 1974.

Otto, K. G., M. A. Kitchel, and J. O. Rice. 1976.

Schubel, J. R., T. S. Y. Koo, and C. F. Smith. 1976.

Sprague, J. B. 1963.

Tyler, A. A. 1966.

thousands or millions of eggs each year; it follows that mortalities must be correspondingly high in the juvenile stages to maintain the fish population in approximate balance. The loss in numbers between spawning and recruitment is much more widely variable, being over 4 or 5 orders of magnitude.

Tow net surveys of the abundance of fish eggs and larvae have been made by many laboratories since the beginning of this century, principal objectives have been to determine the distribution of spawning areas and to measure the size of the parent fish stocks from survey estimates of the total number of eggs spawned. Particular attention has been directed to the possibilities for improved management policies by understanding the processes contributing to year-class survival and future successful recruitment to the fisheries. But, despite many studies of different species, both with pelagic eggs and demersal eggs, it has only been established that there does *not* appear to be a convincing empirical relationship between size of the spawning stock and subsequent recruitment for many species. That is, there does *not* appear to be a direct relationship between the total number of eggs spawned and the number of survivors from that spawning which later appear in the fishery as young fish. This is illustrated in Figure 46 for North Sea haddock, *Melanogrammus aeglefinus*, which had been sampled from 1926 to 1967 (Jones, 1973), comprising one of the largest series available for such a comparison.

Despite the lack of an apparent relationship between the size of the spawning stock to subsequent recruitment in general, a possible exception of particular importance is that when some fish stocks have been heavily overfished and reduced in size, recruitment to the adult stock may continue to remain very low with poor spawning success (e.g. Burd, 1974). The reasons for such catastrophic failures in recruitment are obscure at the present time.

For a few species of fish, surveys of *larval* populations have demonstrated positive correlations between numbers of larvae and year-class success (or

59
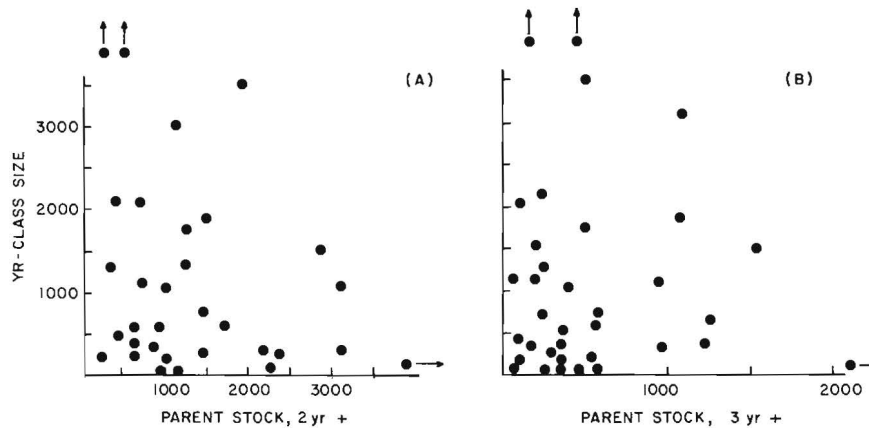
Figure 46.   Lack of an apparent relationship between size of spawning
             stock and subsequent recruitment for haddock, 1926 to 1967.
             Haddock first mature at 2 to 3 years old, therefore the
             spawning stock has been represented as both the numbers of
             2yr and older fish, and also as the numbers of 3yr and
             older fish, for each year in which the corresponding year
             class was spawned.   The numbers on the axes of the figures
             are relative, and derived from research vessel trawl
             surveys.   (After Jones, 1973).

subsequent recruitment to the adult stock),
although the relationships may still be
very variable. As might be expected, bet-
ter correlations are generally found with
older stages of larvae, or with post
larvae, and subsequent recruitment to the
population.

B. Fish Egg And Larval Mortalities

The very high fecundities of fish
imply massive mortalities, greater than
99%, prior to recruitment. It is generally
known that the highest mortalities occur
during the first year of life, the main
regulation of population numbers perhaps
taking place during the *larval* stages
whilst drifting in the plankton (Hunter,
1976; Cushing, 1975; May, 1974). Reviewing

mortalities during the early life stages
of fish, May (1974) demonstrated consider-
able differences in early mortalities
between stocks and between species,
casting doubt upon the validity of gener-
alizations. Nevertheless starvation
appeared to be an important cause of
larval mortality.

Synchronization of factors control-
ling production of plankton (light,
temperature, vertical stability and nutri-
ent supply) is not perfect in nature, nor
is the timing of fish spawning controlled
by such factors in the same way as is
plankton production; some mismatch should,
therefore, be expected and will be accom-
panied by larval mortalities. When the
timing of spawning does coincide with
plankton production, horizontal and

60

vertical patchiness may also cause some mismatch in space, again accompanied by mortality. Density-dependent intraspecific larval competition, as well as interspecific competition, for food resources is a principal cause of starvation. A second principal source of egg and larval mortality is predation, although this has received much less attention until recent years (Hunter, 1976).

Examples of natural mortality rates are given in Table 8 which is based upon surveys of eggs and larvae made on a flatfish, the plaice, *Pleuronectes platessa*.

TABLE 8

Egg and Larval Mortality Rates for Plaice

	Mortality (%)		
Year	Eggs	Larvae	Eggs+Larvae
1962	74.18	94.75	99.97
1963	49.93		
1968	69.97	99.63	99.97
1969	70.60	60.93	92.66
1971	81.27	98.57	99.89

The example was chosen because the surveys were particularly accurate, they covered the complete spawning area and season, and were made with high-speed tow-nets (which avoid a number of sampling problems). The surveys allow mortality rates during the first few weeks of life to be compared for a number of years (Harding & Talbot, 1973).

Natural mortality rates for fish eggs and larvae have been estimated for a one or two fish species in Long Island Sound. For the winter flounder, *Pseudopleuronectes americanus*, Pearcy (1962) calculated mortality rates of 99.98% for the larvae and 99.99% for larvae plus juveniles over the period 0.7 to 22.4 months old -- figures much the same as for the plaice in preceding table. The winter flounder had demersal eggs which could not be sampled and egg mortalities were therefore not estimated. Mortalities of planktonic fish eggs in Long Island Sound were studied by

Williams *et al.* (1973); for eggs of the cunner, *Tautogolabrus adspersus*, mortality up to hatching was estimated to be about 95%. Other species were examined, including fourbeard rockling, *Enchelyopus cimbrius*, windowpane flounder, *Scophthalmus aquosus*, and bay anchovy, *Anchoa mitchilli*. Williams *et al.* believed that their calculations of egg mortality for these species were not as reliable as those for cunner, due to problems of variability and dispersal, but in general their estimates for all of these species showed low egg survival in the Sound - in agreement with the low value for the cunner; predation was considered probably the most important cause of death.

C. *Power Plant Mortality Impacts Upon Fish Populations*

In general there does *not* appear to be a direct relationship between the size of a spawning stock (that is, the total numbers of eggs spawned) and the subsequent size of year-class surviving from that spawning; it is therefore difficult to predict the effect of egg mortalities at a power station in terms of recruitment to the adult fish stock. On the other hand, because fish larval populations have been related to the size of subsequent recruitment for some species, it may be possible to make estimates of the impact of larval mortalities upon year-class strength and recruitment to the population. But to begin to make such predictions it is necessary to know the distribution and size of the larval population as a whole, not solely in the local area of entrainment. For example, large numbers of both the Atlantic mackerel, *Scomber scomber*, and the menhaden, *Brevoortia tyrannus*, may spawn pelagically in Long Island Sound, but the egg populations from such spawnings are parts of the more extensive spawning of the bulk of these fish stocks in the New York Bight and elsewhere along the U. S. eastern seaboard. On the other hand some species may have very localized

populations, for example, winter flounder, *P. americanus*, populations appear to be relatively isolated as a number of sub-stocks making only limited seasonal inshore-offshore migrations. The eggs of the winter flounder are demersal and are laid in shallow inshore or estuarine regions, the larvae also tend to aggregate in the same zones (Pearcy, 1962) and it seems likely that they would be particularly susceptible to continuous "cropping mortality" by coastal sited power plants.

The populations of yet other species lie between these extremes of single, huge, wide-ranging stocks, and such small, discrete local populations. In order to assess the effects of the local daily "cropping mortalities," due to the once-through-cooling systems of a power plant upon such fish populations, it is essential to relate the estimated total mortalities of the early life stages to the wider populations of which they are a part. This must be done by surveys of the water body involved, and not only in the immediate locality of the plant, as has frequently been the case.

The mean daily mortality rates are very high for the early stages in the life of fish; the continuous daily "cropping mortality" induced by a power plant will be additional to these high natural mortalities. Because the effects of the daily mortalities are *cumulative*, small increases in the daily rates of mortality will tend to produce relatively large effects upon ultimate survival.

Goodyear (1977) has developed a technique to quantify the concept of compensatory reserve in fish populations, compensation being the sum of all density-dependent phenomena (e.g. density-dependent starvation, cannibalism, predation, growth, etc.) that serve to stabilize the size of a population. Compensation allows a fish stock to successfully withstand the unpredictable changes of the temperate aquatic

environment, including commercial exploitation by fishing, conferring an apparent resilience upon fish stocks. But there is a limit to the degree that the mechanisms of compensation can offset additional mortality. Each additional source of mortality will remove some of the compensatory reserve of a stock, until ultimately it can sustain no more mortality. When that point is passed the stock will rapidly decline and may *not* be able to recover (Goodyear, 1977; Burd, 1974). It is in such ways that the impact of continued, power plant-induced daily mortalities upon a fish population must be considered. Removal of compensatory reserve reduces the ability of a fish stock to successfully withstand unpredictable mortalities and increases the vulnerability of the stock to destruction. Assessment of the effects of power plant mortalities must therefore also consider the other sources of mortality to which a fish stock is being subjected. Thus, Goodyear (1977) has shown that a power plant would be likely to have a more severe impact on the compensatory reserve of a fished stock than upon an unexploited fish stock.

In view of such considerations, great care is required in interpreting the impact of mortalities from power plants, at least until the interactions of the factors which regulate population size and stability are better understood, and until adequate population parameters have been determined for the stocks affected. Leggett (1977) has suggested that even when an extensive data base is available for a population which has been well studied, as for the Connecticut River American shad, *Alosa sapidissima*, the potential for error in interpretation of the effects of increased levels of early mortality is still considerable, although the biologically acceptable range for error may be small. Power plant mortalities should, therefore, be minimized by first making rational choices between available sites, based

upon assessment of their relative biolog-
ical values, and on the thermal sensitivity
of the local organisms, particularly
ichthyoplankton and juvenile fishes.
Entrainment losses will be less if plants
are located in areas where plankton,
particularly meroplankton, is relatively
scarce or thermally tolerant. After an
appropriate site has been selected for a
plant, the cooling system should be
designed and operated in such a way as to
minimize the total number of organisms
killed by entrainment. Flexible operation
of the number of pumps, for example, could

allow protection of organisms during
critical times of year to take advantage of
seasonal changes in ambient and discharge
temperatures. Thermal damage to organisms
should be considered in conjunction with
probable damages from physical and chemi-
cal stresses of entrainment. The problems
of minimizing such mortalities have been
considered in detail by the Committee on
Entrainment (Schubel and Marcy, in press)
which discusses a variety of recommenda-
tions for their resolution, or their
amelioration.

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DUE DATE