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# BIOLOGICAL ASPECTS OF THERMAL POLLUTION I. ENTRAINMENT AND DISCHARGE CANAL EFFECTS\*

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## INTRODUCTION

Within the past five years, there has been vigorous expression of concern that waste heat from an expanding electricity generating industry has the potential for marked alteration of aquatic habitats important for fish and other aquatic organisms. Whether this concern is justified, whether it warrants large expenditures by the utility industry for cooling systems which avoid natural waters, and whether it should prompt us to reassess all energy use are all valid questions which society must now face.

These emotion-prone questions can be viewed with some perspective with available information. Thermal discharges from several operating power stations have been studied ecologically, and there is a large volume of biological and ecological literature pertinent to these problems. In short, the concern appears to be justified, although dire predictions of imminent catastrophe have perhaps underesti-

mated both biological and technological adaptability. An understanding of biological and technological capabilities and of their limitations should provide the basis for environmental control that will preserve or enhance desirable ecosystems. This review assesses that understanding as it relates to design and operation of thermal electric generating plants.

"Thermal pollution" problems resulting from condenser cooling operations are often more directly related to the manner of discharge than to the quantity of waste heat released. This is because discrete ecological processes are created or infringed upon by each step in the cooling process, from condenser flow to heat dispersion in the receiving water. Many water bodies would show few detrimental effects of added heat had sufficient thought been given to integrated planning of temperature rise, outlet structures, and the mechanics of dispersion, dilution, and cooling in the receiving water.<sup>1</sup> Because of the great importance of temperature for the survival and rates of ac-

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tivity of organisms, no cooling operation can be entirely free of effects upon biota. Critical for environmental control, however, is the recognition that some disposal methods produce greater effects than others at particular sites. These effects must be understood and the capability developed for predicting them quantitatively.

This article concentrates on two sites for ecological effects in the condenser cooling sequence; namely, (1) condensers and outlet piping, and (2) discharge canal. A subsequent article will cover other sites, e.g., mixing zones and mixed water bodies. Most previous reviews of the biological effects of "thermal pollution" have stressed fundamental biological responses to temperature without relating these responses to conditions actually encountered at power plant sites. The approach taken here is to emphasize the results of ecological field studies at power plants and to introduce only those laboratory data which appear directly pertinent to explaining or quantifying effects observed in the field.

Three philosophical points must preface this review. One concerns the use of the phrase "thermal pollution," another concerns legal "standards" for water temperature, and the last concerns the fuel used by the power plant.

"Pollution" implies degradation, although the entities degraded may differ according to the particular observer. Temperature, however, is an all-pervasive, dynamic, abiotic factor that influences aquatic life through variation in range and rate of change. Variations occur naturally and commonly subject organisms to levels and changes that are optimum at times but often are above or below optima for particular physiological, behavioral, and competitive functions. To label any thermal increase in a water body as pollution, regardless of season or other considerations, is to strike a misleading oversimplification. Rather, temperature exerts *effects*, which alone or in concert with most other environmental factors (including time), may yield results that are favorable or unfavorable to particular human interests. Only when they are clearly unfavorable are we justified in asserting pollution.

For purposes of this discussion, the water quality standards for temperature and the re-

lated factors adopted by the states and approved by the Department of Interior are considered secondary to the actual ecological effects. Establishment of standards, and particularly the selection of locations for temperature measurement by regulatory agencies, must be based on sound evaluation of ecological changes produced at specific locations. These changes, not the regulations concerning them, are our concern in this review.

Despite public concern principally over nuclear power plants, one must recognize that the problems of thermal effects are not unique to any fuel source. Nuclear power, however, must concern long-range environmental planners to a degree disproportionate to its present use if projections of its relative expansion are correct. A recent study has estimated that in 1980 nuclear plants will account for 44.2% of discharged heat compared to 1.2% in 1967.<sup>2</sup> In addition, the trend toward larger generating units combined with multireactor groupings and the less efficient conversion of energy to electricity in water moderated nuclear reactors compared to modern fossil-fueled plants amplify the ecological problems. This is largely because environmental capacities for dissipating large heat loads within small areas are limited.

### ONCE-THROUGH, OPEN CIRCUIT COOLING

The most economical system for cooling exhaust steam from the turbine of an electrical power plant involves a single passage of cooling water through a steam condenser. It is this system that has aroused the greatest concern for the environment. In the cooling sequence, a large volume of water is drawn from a convenient, cool source. Pumps then force it through one-inch diameter tubes that are surrounded by the hot exhaust steam. Heat is transferred from steam to the cooling water, and the warmed water is returned to the source. Recirculation of the inlet and outlet water is avoided through use of the natural flow patterns of the water body (river or tidal flow, stratification, etc.) or by engineering designs (discharge canals, barrier walls, etc.).

This cooling circuit is illustrated in Figure 1. Nuclear power plants planned or now operating average approximately 1.8 cfs, or about 3 m<sup>3</sup>/min, per megawatt (electrical).<sup>3</sup> Detailed reviews of the engineering aspects are available.<sup>1-5</sup>

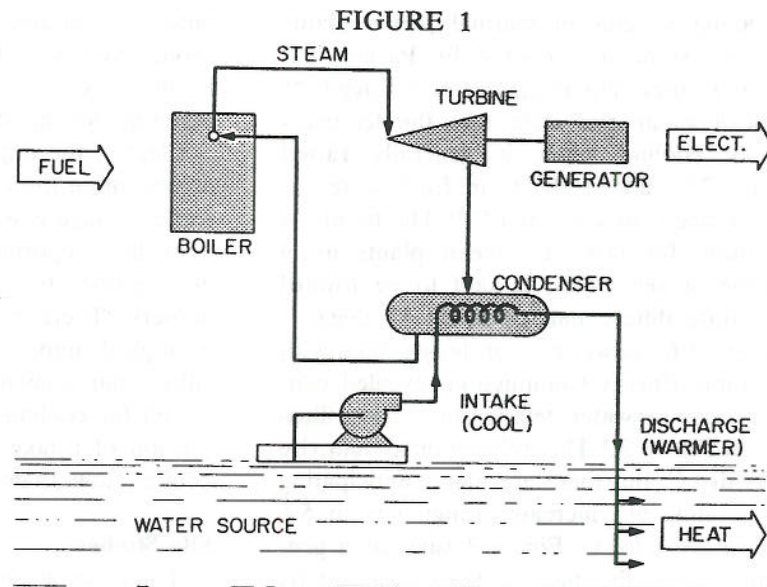
Ecological effects may be observed in five primary areas of this cooling system: (1) the intake, (2) in the condenser and outlet piping, (3) in a discharge canal (if used), (4) in a mixing zone or "plume," and (5) in the mixed body of water (if mixing is complete, as in a river). These effects can be most clearly identified and controlled when viewed according to this functional design. The general cooling sequence and its alternatives are similar whether the water body is fresh, marine, or estuarine. No two aquatic sites are ever ecologically identical, and detailed evaluation must include peculiarities of organisms at that site. Accumulated experience, however, has revealed general changes typical or particular discharge arrangements. Observed or potential problem areas can thus be readily defined and corrected (or avoided) at the points in the cooling sequence where they are likely to occur most significantly. Specific alternative discharge designs, e.g., diffusers for rapid effluent mixing or stratified plumes for most rapid heat radiation, can

be selected to match their characteristics with those that will minimize detrimental effects upon the biota at the specific site.

Intake problems will not be discussed, for they are rarely of a thermal nature. Assessment of the total impact of a plant on the environment must consider these effects, however, for available evidence suggests that they may be highly significant.<sup>6</sup>

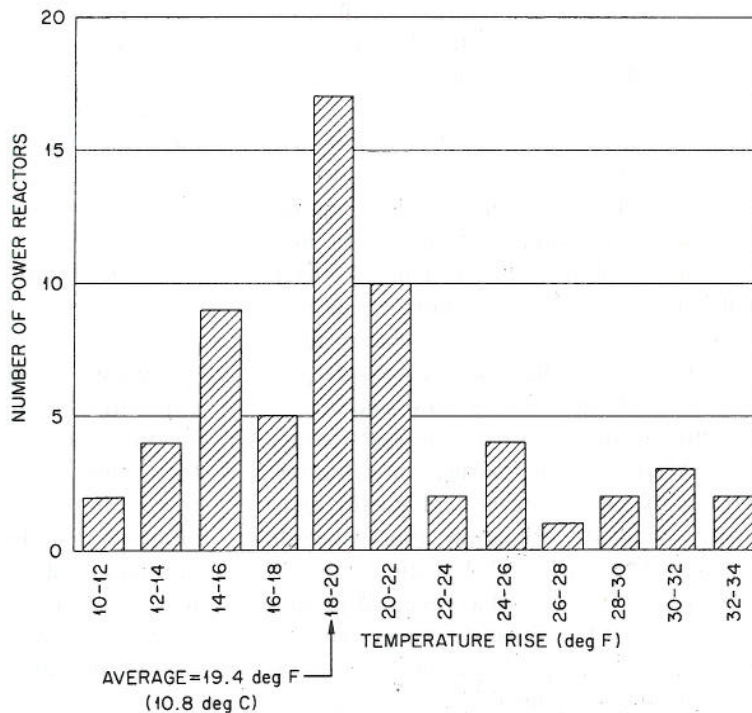
## ENTRAINMENT IN COOLING WATER

Passage through a condenser and subsequent exposures to elevated temperature in the discharge system (whatever the release scheme to the receiving water) is a physiological shock to certain types of organisms, including phytoplankton, zooplankton, and the planktonic eggs and larvae of fish and invertebrates. This thermal shock may lead to rapid thermal death, it may induce secondary effects that ultimately affect survival of the organism or its population, or there may be no identifiable response. In addition to temperature elevation, organisms experience pressure changes and possible mechanical disruption in passing through the extensive system of pumps and piping. Chemicals for fouling and corrosion control added in



The energy cycle of a thermal electric plant, using once-through, open circuit cooling.

FIGURE 2



Designed temperature rises through condensers of 61 nuclear power plants for which applications were made to the U.S. Atomic Energy Commission.<sup>3</sup>

batches or as continuous low concentrations may exert direct chemical toxicity.<sup>7, 8</sup>

Summaries of temperature elevations through the cooling systems of thermal power plants vary. One summary (quoted by Parker and Krenkel<sup>5</sup>) notes an average rise of 8.3 deg.C.\*<sup>9</sup> European summaries state that the temperatures of cooling water is generally raised between 7.5 and 11 deg.C in fresh water or 12 to 16 deg.C in salt water.<sup>10, 11</sup> The trend for the future, for large European plants using estuarine or sea water, is said to be toward temperature differentials of about 13 deg.C.<sup>10</sup> A survey of 61 power reactor designs filed with the Atomic Energy Commission revealed condenser cooling water temperature rises illustrated in Figure 2.<sup>3</sup> The average maximum rise is 10.8 deg.C, but there are plants anticipating (or operating at) increases ranging from 5.6 deg.C to 18.0 deg.C. Figure 3 suggests a general pattern of thermal shock experienced by entrained organisms (including two alternative

routes of disposal). The time scale is in minutes, although the details will be different for each power plant. Adams<sup>12</sup> has provided a detailed time-course for water flow through the cooling system of the Pittsburg Power Plant of Pacific Gas and Electric Co. and a total passage time for the Moro Bay Station.

Clearly, the impact of entraining suspended organisms in the cooling water flow (assuming some damage is incurred thereby) will depend upon the proportion of total volume of the receiving body that is diverted through the condensers. There is potential for more serious ecological implications at locations where a substantial portion of a total stream flow is diverted for cooling, or where a substantial proportion of a lake or estuary is recirculated in cooling flow, than where this percentage is low.

#### Site Studies

There are a number of studies that have attempted, with varying success and detail of ob-

\* deg. C = temperature change; °C = actual temperature.

servation, to assess the biological effects of entrainment at operating power stations. The principal criticism of most of this work is that broad generalizations regarding effects or lack thereof have often been made on scanty data obtained during a small portion of the seasonal variations in environmental temperature and plant operating conditions. There has been little attempt to develop predictability based on the temperature exposure or other factors encountered by the organisms.

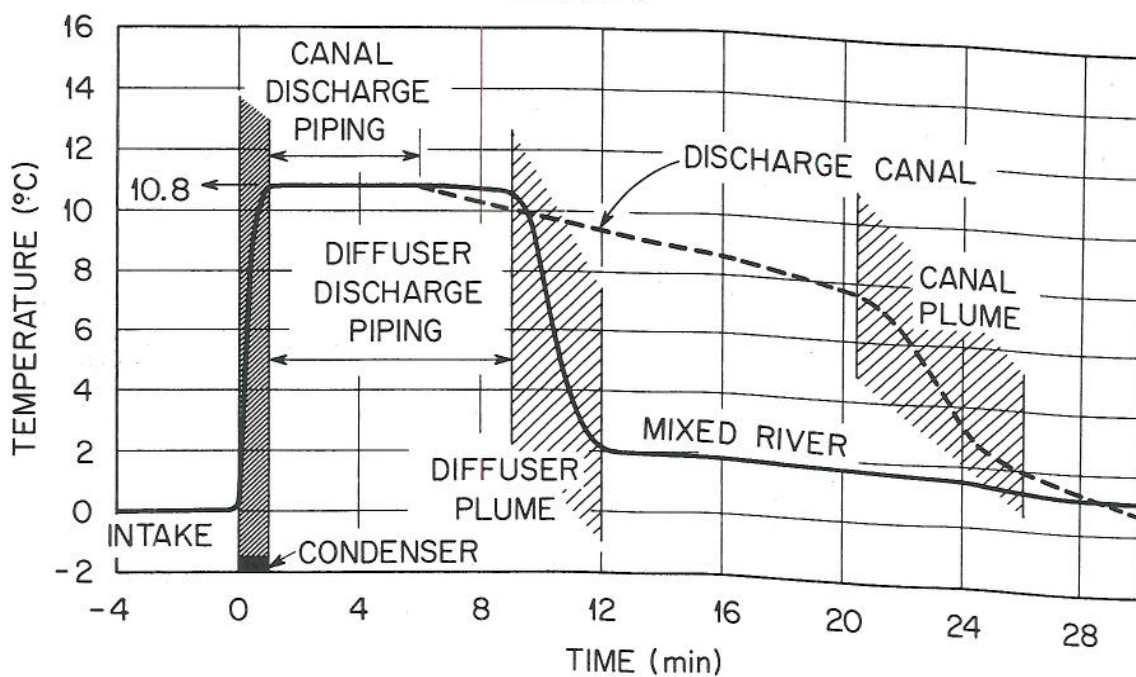
#### Fish

Kerr<sup>6</sup> passed live juvenile chinook salmon and juvenile striped bass through an actual operating condenser of the Contra Costa Steam Plant (Pacific Gas and Electric Co.) where the temperature rise was 16 deg.C. Immediate and latent (five- or ten-day) mortalities were observed. For this experiment, a condenser tube was brought out on each end through the water box walls and connected to hoses attached to disposing and receiving tanks for the fish. Length of exposure time (3.5 to 5 min) and travel conditions through the condenser were similar to the normal passage of entrained fish.

The duration of exposure did not, however, include the extended period between condenser and point of temperature drop through dilution in the receiving water. Generally high survival was claimed for both species, although data were not presented on such crucial points of the experiment as the base water temperature. While it was acknowledged that the small striped bass would "readily go into a state of shock," no consideration was given to increased susceptibility to predation that may occur due to this shock. Thus, while these experiments approach a practical problem in a potentially useful manner, the "results" are of little predictive value and may be misleading for periods of seasonal high temperatures.

On several occasions, several hundred minnows (mostly the western silvery minnow, *Hypognathus nuchalis*) were seen dead and dying along the banks of the effluent canal of the Indianapolis Power and Light Plant on the White River, Ind., by Proffitt<sup>13</sup> after they had passed through the condenser system. No details of thermal exposure were presented. Proffitt considers the mortalities insignificant

FIGURE 3



Hypothetical time-courses of acute thermal shock to organisms entrained in condenser cooling water and discharged by diffuser or via a discharge canal.



compared to normal seasonal deaths in drying sloughs in summer, although no investigation was made to substantiate the belief.

Tentative indications were obtained at the Connecticut Yankee Atomic Power Plant on the Connecticut River that larval river herring (*Alosa spp.*) were able to successfully pass through condensers in July in which the temperature was raised to 34°C.<sup>14</sup> All larvae were judged to be in good condition following the rapid thermal shock and collection by plankton net in the plant's discharge canal. These opportunistic observations are being followed by active investigations of the problem.

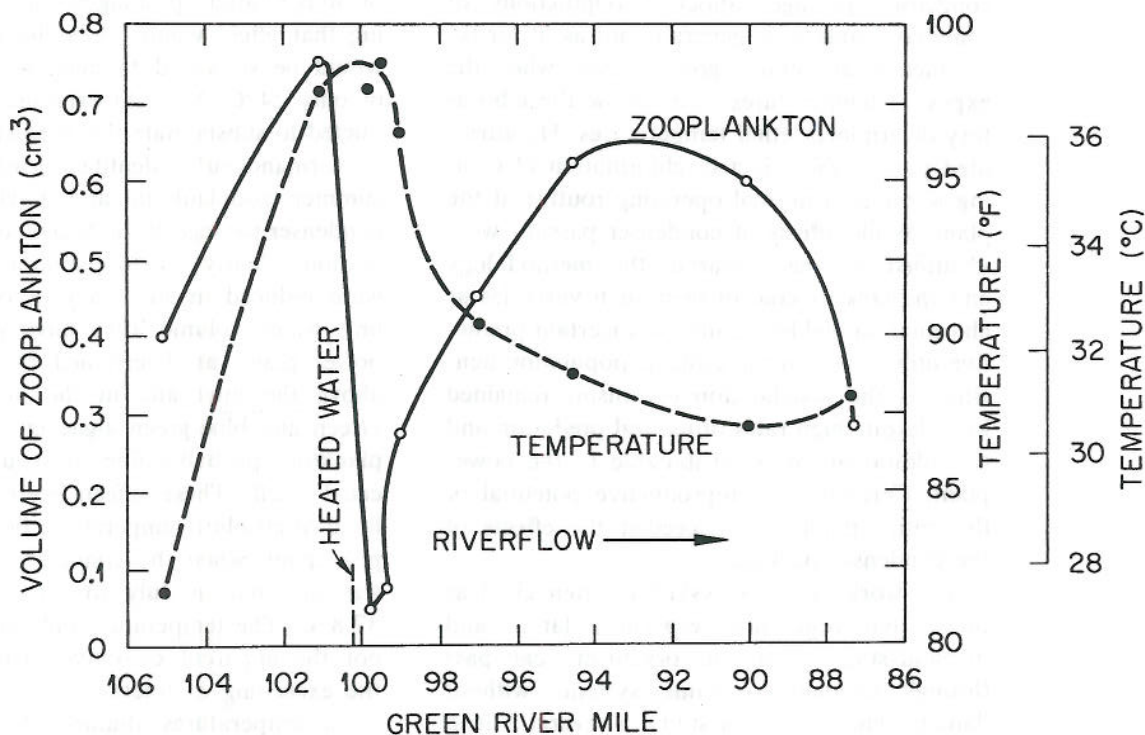
#### Zooplankton

In the Green River, Ky., Tennessee Valley Authority (TVA) biologists found zooplankton did not survive passage through the single pass cooling system of the Paradise Power Plant in May 1964.<sup>15</sup> The base temperature was about 27.8°C with a  $\Delta T$  of 8.9 deg.C. With these losses in May, one might suspect similar or more pronounced losses throughout

the summer and early fall. Observations may have been made, but no results have been published. Figure 4 illustrates the reduction in volume of zooplankton in the river below the plant and the subsequent recovery downstream. The recovery was attributed to seeding by organisms bypassing the plant followed by accelerated reproduction in the warmed, mixed river. There was similar high reproduction immediately upstream of the cooling water intake due to a surface layer of warmed water. Clearly, study of mortality in the cooling system must be balanced by study of potentially rapid recovery below the area of maximum temperature.

It is difficult to reconcile decreases in zooplankton populations with direct effects of thermal shock. While thermal shock may kill large numbers of organisms, it does not destroy the carcasses. An additional mechanism must be involved. This may be mechanical destruction in the condenser or piping system, predation upon carcasses and weakened individuals at or near the plant discharge, or other factors.

FIGURE 4



Zooplankton and water temperatures in the Green River, Ky., near the Paradise Steam Plant, May 26-27, 1964.<sup>15</sup>

The Green River reports shed no light on these processes.

A significant decrease in hatchability of eggs of zooplankton after passage through a power plant has been shown in studies of the Patuxent Estuary.<sup>16</sup> The species affected are major food items of fish in the estuary.

The effects of 8 and 15 deg.C rises in cooling water temperature at the Millikin Station on Cayuga Lake, N.Y., (from base temperatures of 11° and 10°C, respectively) were discussed by Youngs.<sup>17</sup> Sampling difficulties prevented an accurate assessment of mortalities through the cooling system, but 17 to 19% of the Copepods and Cladocera were dead in samples from the outfall. The duration of thermal exposure was not determined.

Heinle<sup>18</sup> conducted an extensive series of experiments in both field and laboratory to determine the effect of condenser passage on zooplankton in the brackish (12 ppt) Patuxent estuary. The power plant was the Chalk Point Station of Potomac Electric Power Co. Rather than examining survival alone, he observed the reproductive success in subsequent laboratory culture of populations that had experienced the thermal, mechanical, and chemical shocks of condenser passage. Shocked populations of some copepods were generally not as fit for reproduction as control groups, even when the exposure temperatures were below the laboratory-determined lethal temperatures. He attributed part of this effect to chlorination of cooling water as a normal operating routine at the plant. While effects of condenser passage were identified by this research, the methodology and the lack of control over such variables as chlorination yielded results of uncertain predictive utility. Within the estuary, population densities of the zooplankton organisms remained high despite high rates of natural predation and the additional losses attributable to the power plant. Certainly, the reproductive potential of the entire population exceeded the effects of the condenser passage.

The work of Markowski<sup>19</sup> is often cited as proof that organisms, especially larval and juvenile stages of marine organisms, can pass through condenser cooling systems without damage. He stated after study of several British power stations that "the faunistic composition

of the intake and outfall water is the same," and that "all the organisms listed were found alive." There are no data presented on temperature rise experienced, or of the duration of exposure, for the purely qualitative surveys. This omission severely limits the serious predictive utility of the results. In addition, at least half of the collections were made at times other than peak summer temperatures. The one quantitative series that yielded numbers of most taxa much higher in the outlet water than in the intake suggest that there were not similar initial populations prior to condenser exposure. While Markowski conceded that this paper offered only a "few sporadic observations,"<sup>20</sup> the conclusions have been repeated without critical examination of the amount of data in their support.

Barnett and Hardy<sup>21</sup> examined the possibility of mortality of planktonic larvae of the lamellibranch molluscs *Tellina tenuis* and *T. fabula* in passing through the cooling system of the Hunterston Generating Station on the Clyde coast of Scotland ( $\Delta T = 10$  deg.C). *Tellina* is the dominant invertebrate in the area. Larvae acclimated to the maximum ambient 14 to 15°C had a 50% death temperature of 36.6°C after "prolonged exposure," suggesting that effect would be unlikely since larvae would be subjected to maximum temperature of only 24°C. No field experiments were conducted to substantiate this prediction, however.

Normandeau<sup>22</sup> identified clear effects on summer zooplankton and phytoplankton of condenser passage at the Merrimack Generating Station. Nearly all zooplankton and diatoms were reduced in frequency of occurrence per unit water volume after passing through the power plant, as determined by samples from above the inlet and in the discharge canal. Green and blue-green algae increased in canal plankton, probably due to scouring from the canal itself. These effects were definitely related to absolute temperature, being discernible principally when the condenser cooling water was elevated in July to temperatures above 37.8°C. The temperature differential itself was not the apparent causative factor, but rather the exceeding of tolerance limits at the maximum temperatures attained. The zooplankton population depressions were also evident in the



mixing zone in the Merrimack River downstream of the plant, although cooling water was a small percentage of total river flow at that point. Survival of *Keratella*, a rotifer that is an important grazer on diatoms in aquatic habitats, was observed by Patrick<sup>23</sup> at a power plant on the Patuxent River. With a 6.7 deg.C temperature rise in the spring, no heat deaths could be identified. The result was offered in discussion, and further details of thermal exposure and methods of observation are not available.

Preliminary studies at the Turkey Point Plant of Biscayne Bay, Fla., indicated that 80% of the total zooplankton in a net haul were dead at discharge temperatures of 40°C in July 1969.<sup>24</sup> When the discharge temperature was 33°C percentages of 12 and 7 were found. Subsequent samples determined that a maximum accuracy of about 10% was achievable due to deaths during collection, transportation, and counting.

Adams<sup>12</sup> reported that the discharge canal of the Humboldt Bay Nuclear Plant on the California coast was a favorable site for natural setting of native oysters (*Ostrea lurida*), cockles (*Cardium corbis*), littleneck clams (*Protothaca staminea*), butter clams (*Saxidomus giganteus*), gaper clams (*Tresus nuttalli*), and about half a dozen other bivalves. The net flow in the canal was always outward because of domination by the cooling water flow, and complete evacuation of the canal, as revealed by dye studies, took place in less than three hours. Therefore, some of the free-swimming stages of these bivalves had to pass alive through the condenser system of the power plant in order to colonize the canal. Similar successful passage must have occurred at the Chalk Point Power Station on the Patuxent estuary to account for high densities of invertebrates found in the discharge canal by Cory and Nauman<sup>25</sup> and Nauman and Cory.<sup>26</sup>

#### *Phytoplankton*

Effect on phytoplankton as determined by ability of produce organic matter depended upon the ambient temperature of the stream as well as on the change in temperature imposed by the condensers in studies on the York River, Va., by Warinner and Brehmer.<sup>27</sup> At

low winter temperatures, 0 to 10°C, temperature rise increased production; with high summer temperatures, 15° to 20°C, slight increases increased production while large increases (greater than 5.6 deg.C) depressed it. The greater the temperature rise in summer, the greater was the depression of the affected plankton's ability to photosynthesize. This paper aptly demonstrated the seasonality of temperature effects, a point often lost by investigators conducting "one shot" surveys.

Similar results were shown by Morgan and Stross<sup>28</sup> for the Chalk Point Plant on the Patuxent estuary off Chesapeake Bay. In this study, temperature rises of about 8 deg.C stimulated photosynthesis when natural water temperatures were 16°C or cooler and inhibited photosynthesis when temperatures were 20°C or warmer. Passage through the condensers at times, however, contributed additional damage (perhaps mechanical or chemical) that nullified stimulation by temperature rise at cool temperatures and increased inhibition at warmer base levels. Return of phytoplankton to the cool temperatures of the mixed estuary at the end of the discharge canal did not allow recovery of photosynthetic ability. A daily synchrony in photosynthetic metabolism was identified that strongly influenced the severity of effects. For example, the daily maximum of stimulations occurred at about 0900. The data presented thus far from this series of experiments have been largely descriptive. Further research and data analysis should lead to data with predictive utility. In relating the observed changes in productivity to the entire estuary, the authors noted that real reduction in productivity is indicated only if the rate of photosynthesis is herbivore controlled and not nutrient limited. Since Stottlemeyer<sup>29</sup> concluded that nutrient limitation was only a sporadic occurrence, then herbivores must be the principal limiting factor. Reduction in photosynthesis by another factor (the power plant) must, therefore, reduce the amount of material available for passage through the food chain.

A few studies were made to determine the effect on phytoplankton of passing Potomac River water through the condenser of the Dickerson Plant (Potomac Electric Power Co.) when there was an 8 deg.C rise.<sup>23</sup> A few

algal cells showed morphological changes following condenser passage, but the numbers were not significant. There was no attempt to culture the cells to determine their resultant viability.

### Responses to Acute Thermal Shock in the Laboratory

In spite of the inadequacy of existing site studies to provide useful predictability for effects of passing organisms through cooling systems, there is a large amount of pertinent data from laboratory experiments. Some of these experiments closely approximate the thermal shocks that organisms may receive during condenser passage. Much of the experimental work used in formulating a general pattern of effect for thermal shock has been obtained for larger organisms, principally fish, than will pass through condensers. The principles, however, and the quantitative model that is being developed, seem directly applicable to predicting whether direct or secondary mortalities can occur in a proposed system. Use of these quantitative laboratory data (which are incompletely collated and tested in the field) to predict ecological effects offers the possibility of significantly reducing the time-consuming discretionary processes in evaluating power plant sites. The basic principles were described by Fry, Hart, and Walker,<sup>30</sup> and the applicability to present problems has been discussed in some detail.<sup>31-33</sup>

### Lethal Temperatures

Fry et al.<sup>30</sup> collated their accumulated data and that of earlier authors on thermal responses of fish and divided the total range of temperature experience of an organism into several zones. They discerned an upper and lower zone of *thermal resistance* and a central zone of *thermal tolerance*, bounded respectively above and below by an upper and lower *incipient lethal temperature*. The incipient lethal temperature is defined as that temperature which, when a fish is brought rapidly to it from a different temperature, will kill a stated fraction of the population (generally 50%) within an indefinitely prolonged exposure. In the zones of thermal resistance an organism can survive for a definite period of

time that becomes longer as the temperature approaches the incipient lethal temperature.

Previous thermal history profoundly affects the incipient lethal temperature, this history being referred to as *acclimation* or *acclimitization* temperature. In general, a history of cold temperatures results in a low incipient lethal temperature, while a history of warm temperatures produces an elevated lethal temperature. This effect of thermal history will be discussed further below. Despite prior conditions, however, a temperature will ultimately be reached which will be lethal to the species; this is called the *ultimate incipient lethal temperature*. These thermal relationships are illustrated in Figure 5. In discussing acute thermal shock to entrained organisms, we will be concerned only with the upper limits, although "cold shock" may occur due to other aspects of power plant operations.

The possibility of direct mortality of entrained organisms due to acute thermal shock may be very real during the warmer months when temperature increases in the condensers to above the incipient lethal level. As an example, Figure 6 illustrates the seasonal cycle of temperature in the Columbia River near Richland, Wash., and the cooling water temperature after an average 10.8 deg.C rise from a hypothetical nuclear power plant there. Juvenile chinook salmon are abundant in this region from April through August, although some may reside in that area throughout their first year. The incipient lethal temperatures for this species at the changing levels of acclimation are shown superimposed upon the water temperatures. The cooling water flow would be within the zone of resistance for chinook between about July 1 and the end of October. Similar comparisons could be made for other species perhaps more likely to be drawn into condenser cooling water than young salmon.

The diagram in Figure 5 has several limitations as a general description of thermal tolerance and resistance, even for fish, as has been pointed out by Fry in a later article.<sup>34</sup> The first is the sharpness of the boundary which the incipient lethal temperature forms for the zone of resistance. Cocking has objected to this sharpness, believing that there are slow deleterious effects of high temperature below the in-

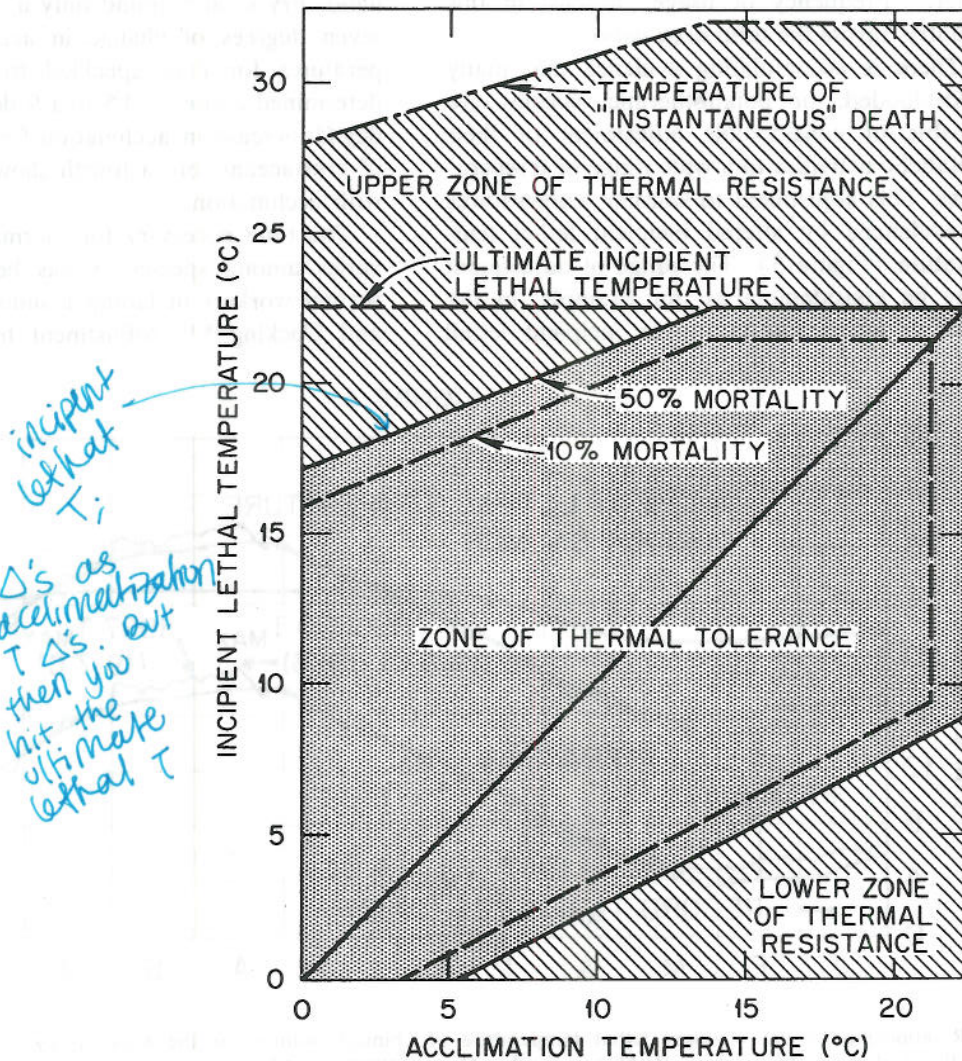
ultimate upper lethal was also defined as lowest T @ which 100% mortality occurred  
sublethal = highest test T where  $\phi$  mortality occurred

incipient lethal temperature which will result in death.<sup>35</sup> It is likely, however, in the light of even his own further work, that there were factors other than temperature causing harm to his fish.<sup>36, 37</sup> A second limitation is that the thermal response given is presented only in relation to thermal history. It is now well known that body size,<sup>38</sup> season,<sup>38, 39</sup> day length,<sup>40</sup> sex,<sup>41</sup> water chemistry,<sup>42-44</sup> diet,<sup>45, 46</sup> and hormonal variations<sup>47</sup> all influence to a certain extent the exact lethal temperature.

It was noted that incipient lethal temperature was defined in terms of survival of a certain fraction (50%) of a test population. Fry et al.<sup>30</sup> and Brett<sup>48</sup> have discussed the validity

of this procedure and affirmed that individual death responses of fish conform to a normal distribution. In such a distribution the mean, mode, and median coincide, giving the 50% survival datum evident descriptive utility. It is important, however, to recognize this additional limitation of the relationship as shown in Figure 5: that the upper incipient lethal temperature is a central statistic and that some fish will die at temperatures below this. This statistic is strictly applicable only to the population investigated; it is generally accepted that geographic races within some species will exhibit different lethal temperatures even when similarly acclimated.<sup>49</sup> Thus, data to be used for

FIGURE 5



Thermal tolerance of a hypothetical fish in relation to thermal acclimation.

predicting effects should be selected from as close as possible to the site in question.

### Acclimation

Further discussion of acclimation seems desirable. Understanding of this phenomenon, i.e., the effect of thermal history on the responses of an organism, is presently made more difficult by frequent use of two terms, *acclimation* and *acclimatization*. Most often they are used synonymously,<sup>50</sup> occasionally discrete definitions are given in which *acclimation* is used to indicate experimentally induced and relatively rapid thermal adaptation while *acclimatization* is reserved for slow, naturally occurring adaptation.<sup>51</sup> Some authors accept synonymy yet strongly prefer one term or the other.<sup>52</sup> Frequency of usage, at least in this country, favors the term *acclimation*.

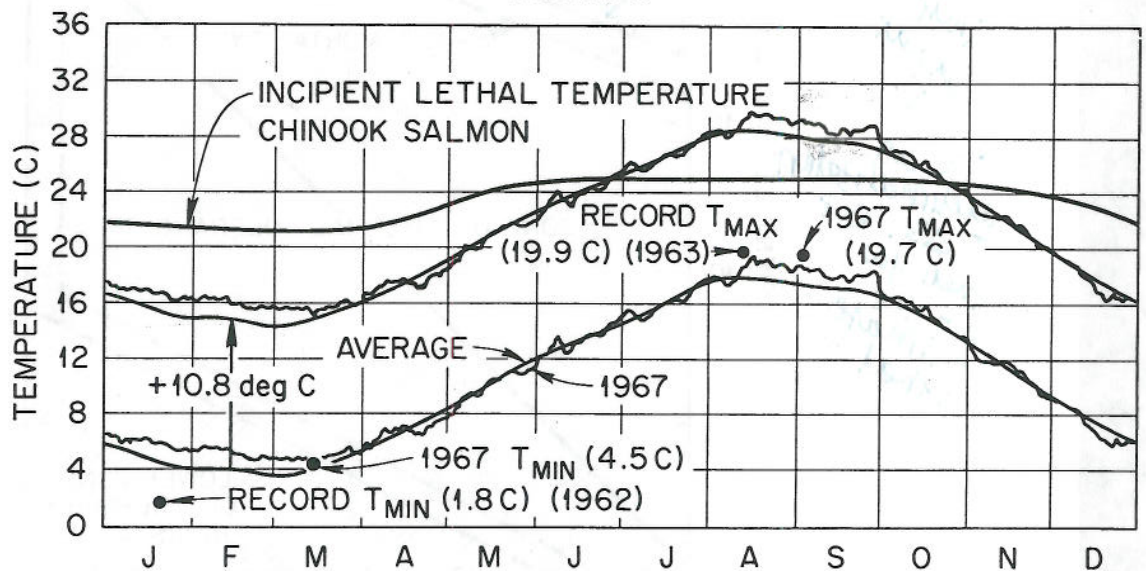
There is accumulating evidence that many cold-blooded, or poikilothermic, species are capable of considerable adjustment of their metabolic activities to a wide range of temperatures. This adjustment to warmer temperatures is evidenced by altered incipient lethal temperature (Figure 5). The range of adjustment may be considerable as, for example, in the goldfish which has an upper incipient lethal

temperature that varies from approximately 26°C to 40°C.<sup>34</sup> This hardy species may be one of the extreme cases in this respect.

Elevation of incipient lethal temperature is not directly proportional to elevation of acclimation temperature, but rather some fraction of it. The result is that acclimation temperature and upper incipient lethal temperature tend to converge upon the ultimate upper incipient temperature, at which both acclimation and incipient lethal temperatures are the same (Figure 5). Cocking<sup>36</sup> has determined a rise in upper incipient lethal temperature of about 1 deg.C for each 3 deg.C rise in acclimation of the roach, *Rutilus rutilus*, which agrees closely with data by Brett<sup>53 54</sup> on the goldfish, speckled trout, and *Ameiurus*. On the other hand, Fry et al.<sup>40</sup> found only a 1 deg. rise for seven degrees of change in acclimation temperatures for their speckled trout. Sprague<sup>38</sup> determined a rise of 0.5 to 1.9 deg.C for a 10 deg.C increase in acclimation for three species of crustaceans, but a fourth showed no change with acclimation.

The time necessary for thermal acclimation varies among species as has been shown by several workers including Doudoroff,<sup>55</sup> Brett,<sup>56</sup> and Cocking.<sup>36 37</sup> Adjustment to higher tem-

FIGURE 6



Relationship of the incipient lethal temperature of chinook salmon to the seasonal cycle of temperature in the Columbia River near Richland, Wash., (lower curves) and to river temperatures elevated by 10.8 deg. C, the average increase in condensers (upper curves).

peratures is generally fairly rapid; data of Alabaster and Downing<sup>57</sup> indicate an elevation of about 1 deg.C per day for the roach; Sprague<sup>38</sup> found that acclimation temperatures could be raised 2.5 to 5°C per day for several crustaceans; Dickie<sup>58</sup> reported 1.7 deg.C per day for the scallop. Several authors have shown that acclimation to cooler temperatures, at least by fish, is slower.<sup>54-59</sup> Brett,<sup>54</sup> for example, found that fathead minnows (*Pimephales promelas*) took over 20 days to become acclimated completely to 16°C after being held previously at 24°C; the upward acclimation from 20 to 28°C took only 24 hours. Sprague<sup>38</sup> reported rapid downward acclimation in *Ascellus intermedius* (a crustacean) of at least 1 to 2.5°C per day.

There are a number of reports of seasonal changes in lethal levels or metabolic rates in aquatic poikilotherms.<sup>60-61</sup> Generally, these can be explained by acclimation to the prevalent seasonal temperature, as in the fishes of Lake Opeongo, Ont., studied by Brett;<sup>54</sup> but some authors report persistence despite careful laboratory acclimation to particular temperatures. Greater heat-resistance in summer than in winter, independent of acclimation temperature, has been reported for *Planaria*,<sup>62</sup> an annelid,<sup>63</sup> rainbow trout,<sup>64</sup> and goldfish.<sup>39</sup> Some of these apparent seasonal effects may be due to different sizes of individuals at different times of the year. When Sprague<sup>38</sup> corrected his data on *Ascellus intermedius* for this size variation, he could detect no seasonal variation in resistance.

Some seasonal differences in thermal resistance may be due to changes in day length. Hoar and Robinson<sup>40</sup> maintained goldfish under controlled photoperiods for 6 weeks or longer and found that fish kept at long day length (16 hr) were relatively more resistant to sudden elevation in temperature than fish kept at short photoperiods (8 hr). Short photoperiod provided more resistance to cold death. The endocrine system, perhaps thyroid output, was suggested as the mediator between light and thermal resistance.<sup>47</sup>

#### Thermal Resistance Times

Perhaps the greatest present obstacle to the use of thermal resistance and "lethal level" data for aquatic organisms by designers and

operators of thermal power plants is the diversity of forms in which the data have been obtained and published. Many data were simply not in a useful form for practical application.

The most serious drawback to the summary figure (Figure 5) and to the whole concept of a single "lethal temperature" for an organism is that thermal death within the zone of resistance (above the incipient lethal level) is a function of *duration of exposure* (i.e., time) as well as the temperature, as noted above. Thermal death within the zone of resistance is a dose response, analogous to dose responses that are well known in pharmacy and radiation biology. Many discussions of thermal effects neglect to recognize this phenomenon and consider all organisms dead once the "lethal level" has been reached. That thermal death is a dose response in aquatic plants as well as in animals has been stressed by Ferguson-Wood and Zieman.<sup>65</sup>

The most comprehensive and useful method of presenting information on the thermal death relationships of organisms in the zone of resistance was originally a graphical one introduced by Fry et al.<sup>30</sup> as a means for illustrating the resistance time pattern for the speckled trout. The statistical methodology (if not the terminology) was adopted from the established fields of pharmacology and toxicology (citation of Bliss).<sup>66</sup> An ideally complete example is presented in Figure 7 and is described below. This figure takes into consideration work on invertebrates and is believed to be representative of all aquatic organisms.

It is important for understanding this summary figure to recall the following:

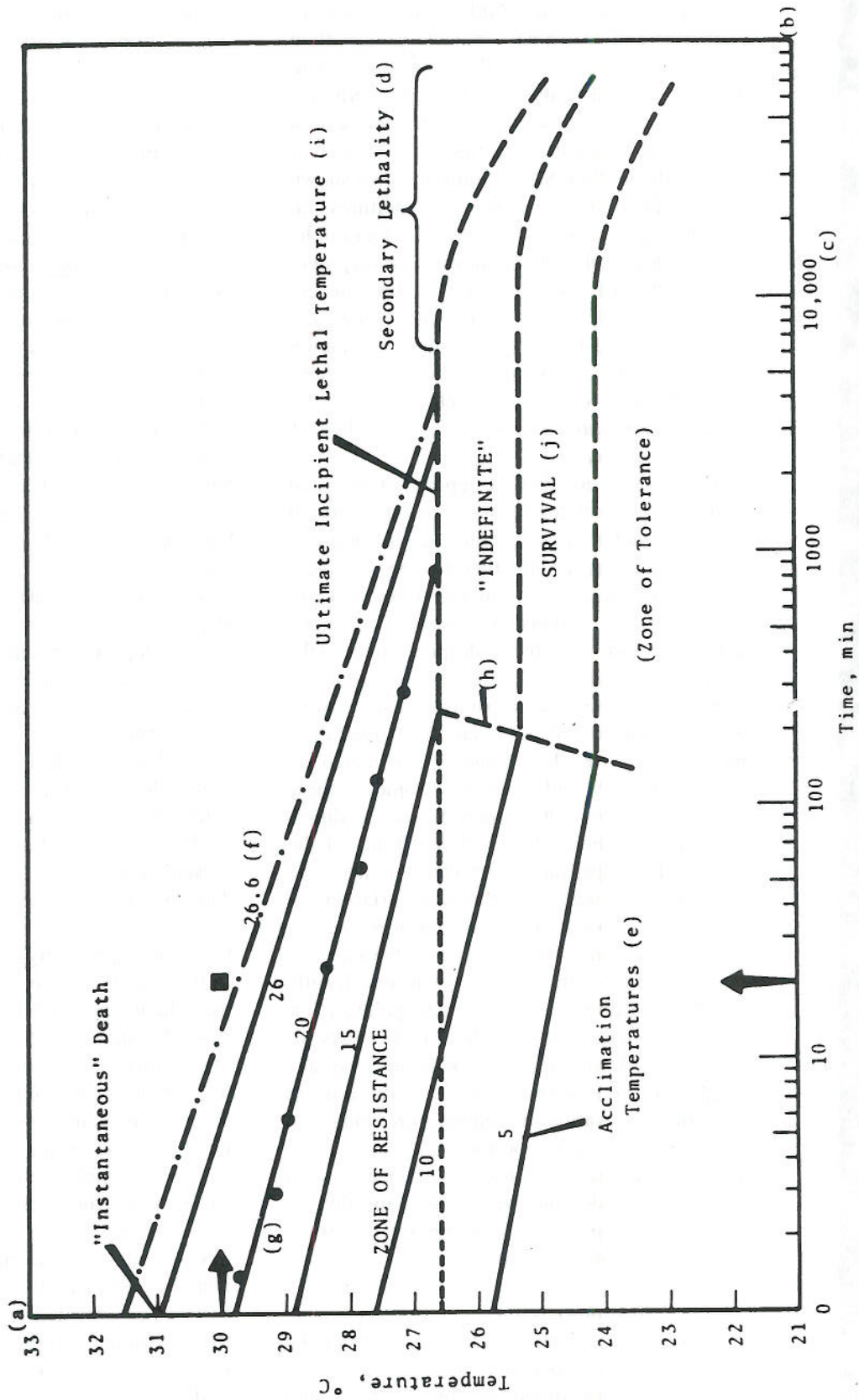
a) In the zone of resistance (at a temperature above the lowest upper incipient lethal temperature), the lethal effect of a high temperature is manifested at a discrete time interval after beginning of exposure.

b) The higher the new temperature the shorter the time interval between beginning of exposure and death.

c) Acclimation to higher temperatures both increases the length of time an organism can survive an elevated temperature and elevates the maximum temperature that the organism can survive for a given time period.

d) There is an ultimate incipient lethal tem-

FIGURE 7



Median resistance times to high temperatures by a hypothetical organism.<sup>21</sup>

perature below which an organism should survive indefinitely if unaffected by other factors but above which it cannot be acclimated successfully and it has only a discrete survival time.

The figure basically illustrates time-temperature relationships, as can be seen by the ordinate (a) and abscissa (b) which, incidentally, are reversed in most thermal death literature from the customary orientation of dependent and independent variables. For practical purposes one week (c) is taken as an arbitrary limit, for beyond this time secondary lethal effects (d) aggravated by high temperatures confuse the purely heat effects. Several acclimation temperatures (e) are represented, including a hypothetical one at the ultimate incipient lethal temperature (f). For each acclimation temperature, the median survival times at several experimental temperatures have most often been fitted by a straight line [e.g., (g)] that can be expressed mathematically. Recent studies on juvenile salmon suggest that this linear relationship may not be the most appropriate.<sup>67</sup>

It will be noted that the lower ends of the regression lines are abruptly terminated by two boundary lines, one roughly at right angles to the regression lines (h) and the other horizontal (i). The regression lines have no meaning beyond these boundaries because 50% mortality does not occur beyond them (j) no matter how long the exposure. The boundary lines thus separate the zone of resistance from the zone of tolerance and delineate the upper incipient lethal temperatures for the various levels of thermal acclimation. The rising boundary line represents the region where upper incipient lethal temperatures can be adjusted by thermal history; the horizontal portion is the ultimate upper incipient lethal temperatures.

This graph can be quite useful as a "survival monogram" for high temperature shock. For example, a school of small fish is drawn into the intake of a power plant. The temperature of the heated condenser water is 30°C, 10 deg.C above ambient. At the rate of water flow, it takes the fish 20 min to pass through the condenser, out the discharge piping, through a discharge canal, and finally into the

cooler river. We ask, "Will the fish survive?" (or more correctly, will half of them survive?). Knowing temperature and duration of exposure, lines can be drawn to a point on the resistance figure for this fish species. If the intersection of these lines lies above the acclimation temperature corresponding to the river temperature, half or more of the fish will perish (as they will in our example). However, had the maximum temperature been designed to be 28°C and the long discharge canal replaced by a rapid diffuser to cut the exposure time to five minutes, the intersection would fall well below the 20-degree acclimation line, and no direct mortalities would have occurred.

The thermal resistance pattern, which is available for many aquatic species, can thus be used as a simple, reasonably accurate tool for predicting the effects of proposed combinations of temperature rise at the condenser and travel time of the cooling water from condenser to the receiving water. The concept is relatively straightforward and one that would seem useful to both design engineers and to operators. For the sophisticated, who prefer to see data summarized in mathematical rather than graphical form, the entire pattern of resistance can be converted to simple regression equations with stated limits. With a tool no more refined than this, design engineers should be able to select safe temperature rises across condensers or safe combinations of temperature elevations and discharge times. If there is a seasonal period of critical high temperatures, power operators should be able to conduct periodic checks of temperature and exposure time for critical species and adjust plant operation accordingly. It is astonishing that such a simple technique has not found wide use. The responsibility probably lies partly with ecologists who have not clearly explained (or recognized?) the predictive utility of their quantitative data and then made that data readily available to the right people. To date, there is no single document which can serve as an adequate handbook of thermal resistance data. Such a text is sorely needed.

#### *Exposure to Fluctuating Lethal Temperatures*

While it is convenient to determine thermal resistance of organisms at constant tempera-





tures, such constant temperatures are not generally found in nature or in power plant cooling systems. Thermal death outside the laboratory almost always occurs under changing temperature conditions, even in passage through piping of condensers and discharge works (Figure 2). It is, therefore, necessary to know the relationship between the resistance times at constant temperatures and the time course of mortality over the range of fluctuation. It is also important to know whether any ill effects of brief, sublethal heating to potentially lethal levels can be accumulated and affect exposures later in life.

The relationship between time to death at constant temperatures and at changing levels appears not to be a terribly complex one but an integration of the brief thermal experiences at each level. This was first suggested by Jacobs<sup>68</sup> and was pursued in further detail by Fry et al.<sup>30</sup> The length of time a fish can exist at a given lethal level of temperature depends upon the rate at which "mortification,"<sup>30</sup> or dying, proceeds at that temperature. Fry et al. considered this rate to be essentially constant throughout the time necessary to bring about death.<sup>30</sup>

The resistance time pattern illustrated in Figure 7 defines, in effect, these *rates of dying*. Thus, if a fish could exist at a given temperature for 100 minutes, the rate of mortification or dying could be assumed to be 1% per minute; and it could be taken that 50% of the condition leading ultimately to the death of the organism would be brought about by the unfavorable temperature in the first 50 minutes, and the remaining 50% in the last 50 minutes. What Fry et al.<sup>30</sup> termed the "minute rate of mortification" at any lethal level of temperature is the reciprocal of the resistance time in minutes at that temperature, and the degree of mortification resulting from a given exposure to that temperature would be the minute rate of mortification multiplied by the exposure time in minutes. If the animal were exposed for known lengths of time to a series of temperatures for which the minute rates of mortification were also known, then the degree of mortification resulting from each exposure could be calculated and these fractions

summed. When the total of the fractions was unity, the animal would have received a lethal dosage. Two types of experiments were undertaken by Fry et al.<sup>30</sup> to confirm this relationship: one in which fish were subjected to a stepwise elevation in temperature, and the other in which temperature was continuously changed. In both cases the theoretical and observed times to death agreed within expected limits of experimental error.

An assumption inherent in the work of Fry et al., but one which cannot be accepted as entirely valid, is that of instantaneous attainment of the ambient temperature by the body of an organism. Data by Dean<sup>69</sup> indicate that it takes the muscle of a 1.35 kilogram rainbow trout nearly an hour to reach 20°C from 7°C. This would be considerably shorter, however, for a smaller organism, or for a fish's central nervous system that is closely connected to the "outside" by blood flow from the gills. Rapid fluctuations in exposure temperatures are certainly not reflected in equally rapid changes in body temperatures, the ones which are causing lethality. This problem of time lag between the temperature of surrounding water and the temperature of the thermally-sensitive tissue(s) must be recognized in the establishment of the thermal resistance times (Figure 7) and in using these times in summing mortification.

Some exposures to potentially lethal temperatures may be too brief to kill a fish. The question can be asked whether such sublethal exposures can also be accumulated throughout an organism's life, eventually resulting in premature death. Accumulation of sublethal experiences was found by Fry et al.<sup>30</sup> not to occur in the brook trout; indeed, a certain gain of acclimation was suggested as a result of previous sublethal time exposure to lethal temperature levels. Pearce<sup>70</sup> described thermal tolerance experiments with *Mytilus*, the marine mussel, in which temperatures of 30°C were experienced recurrently for 6 hr in a 24-hr period. The exposures were tolerated for over 1000 hr, whereas the mussels were killed in 9 to 12 hr of continuous exposure. In this instance, lethal effects were not accumulated when periods of recovery were allowed. It is apparent, however, that insufficient information is available on this subject, even for a

single species, to allow for quantitative predictions.

#### *Computer Simulation of Thermal Death*

In order to provide more accurate predictions of lethal thermal doses (temperature and duration of exposure) than is possible using a resistance time graph, the mortification concept of Fry et al.<sup>30</sup> has been extended by means of modeling on a hybrid computer.<sup>32</sup> The basic input information for this "thermal death model" is the resistance time pattern for the species (such as Figure 7) and the temperature exposure curve to be examined (such as Figure 2). In addition, the model includes considerations of the rate of temperature change of thermally-sensitive fish tissues in relation to the external water temperature, both during experience of the fluctuating thermal regime being tested and establishment of the input thermal resistance data. The model was tested favorably against several hypothetical temperature patterns to which groups of juvenile coho salmon were exposed experimentally.

With additional refinements and extension to include sublethal as well as directly lethal effects, the thermal death model should find considerable utility in initial planning stages of thermal power plants. The ability to predict with some accuracy whether conditions of a proposed cooling water system would be capable of causing direct or secondary mortality to entrained aquatic organisms should allow modifications to be made in early stages of plant siting and design so that the deleterious conditions modeled are not reached.

Unfortunately, resistance time data are not available for all organisms susceptible to being entrained in condenser discharge water. In many instances, there are no data available on portions of the life cycle that are susceptible to condenser passage although there may be data for other stages, perhaps adults. Pearce<sup>70</sup> found that the larvae and plantigrade spat of the marine mussel, *Mytilus edulis*, were far more tolerant of temperature increase than were adults. For example, spat survived four times as long as adults at 28°C.

#### *Other Ways to Determine Lethal Temperatures*

The biological literature is fraught with con-

siderably less useful methods of estimating temperatures too high to be tolerated by aquatic organisms subjected to acute thermal shocks. Those responsible for establishing or perpetuating such methods apparently gave little consideration to quantitative use of their data.

There is a sizable literature on the tolerance of organisms, principally fish, to slow rises in temperature.<sup>71-75</sup> The predictive utility of the accumulated data is questionable, however. Each tolerance experiment or observation is most likely a special instance of the summation of lethal effects just discussed and would bear careful examination in this context, perhaps through the use of a thermal death simulation model. Such an examination however, is beyond the scope of this review. In addition, the processes of acclimation were almost certainly working during the period of slowly rising temperatures prior to death. Since this acclimation was incomplete, it merely served as an uncontrolled variable in the resistance time experiment.

Particularly regrettable (for quantitative predictability) is the continued use of the "Routine Bioassay Method" in which the prescribed measure of toxicity (including high and low temperatures) is the median tolerance limit (TL<sub>m</sub>).<sup>76</sup> The TL<sub>m</sub> defines the concentration of the tested material (in this case, the degree of temperature) at which 50% of the test animals are able to survive for a specified period of exposure, generally 24, 48, or 96 hours. The TL<sub>m</sub> is comparable to the median lethal dose or 50% lethal dose (LD<sub>50</sub>) commonly reported in toxicological literature, a fact that makes one wonder why a new name was coined.

It becomes a frustrating challenge to try to predict mortality in a thermal regime such as Figure 2 from a 24-hour TL<sub>m</sub>. Even more difficult is an attempt to use a 96-hour TL<sub>m</sub> value for a total condenser water exposure of, perhaps, less than 10 minutes. Should TL<sub>m</sub> values be available for two time periods, e.g., 24 and 48 hr, then a straight line can be drawn on a graph between them yielding an approximation to a resistance time line. This line can be treated as any other resistance pattern, although with only two points with which to

establish the line, one sacrifices accuracy of the extrapolations.

Despite the drawbacks of this method for making quantitative predictions, it is easily standardized and readily conducted within normal 8-hr working shifts. Thus, it continues to have a great deal of popularity, and it is the procedure recommended by the U.S. Federal Water Pollution Control Administration (FWPCA).

### Indirect Mortality From Thermal Shock

#### *Equilibrium Loss and Predation*

Thermal death, with an endpoint such as (for fish) cessation of beating of the opercula, may not be the most pertinent ecological effect of acute thermal shock to organisms passing through condenser cooling systems. Heat death of cold-blooded organisms has been observed to follow a common pattern which includes, in sequence, loss of equilibrium, coma, and physiological death. These observations have been made with several species of fishes and with amphibians and reptiles. They probably hold, in essence, for lower forms as well. The early stages of heat death, while not "death" in themselves, may lead to death through (1) immobilization in the area of adverse temperature (which may prolong exposure until death results) or (2) stimulation of predatory activity upon the heat-injured organisms. Both results have been observed in the field and in laboratory experiments.

Heat death has been studied more extensively in fishes than in other taxa, but only a few authors have attributed much significance to the behavioral events preceding death. Huntsman<sup>77</sup> describes equilibrium losses in Atlantic salmon migrating into warm (<30°C) streams in Nova Scotia. Here, loss of equilibrium was soon followed by cessation of swimming and death, both in the field and in laboratory tests with small salmon. Doudoroff,<sup>78</sup> reporting on laboratory experiments with *Girella nigricans* at constant lethal temperatures, noted an initial stimulation, then loss of equilibrium, and finally a permanent cessation of swimming and respiration which he termed "heat coma." He also noted differences in the timing of equilibrium loss with tempera-

tures that were rapidly and slowly lethal. Brett,<sup>54</sup> also studying thermal resistance at constant lethal temperatures, noted loss of equilibrium control and a tendency to roll up on one side in six species of fish, including five Cyprinidae and one Ictaluridae from Ontario. He also described the symptoms referred to by Doudoroff as coma. Further field observations of equilibrium losses under thermal stress were reported by Bailey<sup>79</sup> and Threinen.<sup>80</sup> Tsukuda and Ohsawa<sup>73</sup> reported both "spasmodic activity" and heat coma as events preceding death of the guppy (*Lebistes reticulatus*) when temperatures were slowly raised to the lethal point. Onset of heat coma was used by these authors as a convenient end point in thermal resistance studies. Hoff and Westman<sup>81</sup> report "disturbances in equilibrium" as a principal feature of heat death at constant lethal temperatures in three species of marine fishes, the common silverside (*Menidia menidia*), the winter flounder (*Pseudopleuronectes americanus*), and the northern swellfish (*Spheroides maculatus*).

Working with desert reptiles independently of fisheries researchers, Cowles and Bogert introduced the concept of a "critical thermal maximum" and a "critical thermal minimum" to describe, for high and low limits of a species' tolerance, "the thermal point at which locomotory activity becomes disorganized and the animal loses its ability to escape from conditions that will promptly lead to its death".<sup>82</sup> The point was reached as the result of slow heating (or cooling) to the temperature of equilibrium loss. Lowe and Vance,<sup>83</sup> in further studies of reptile heat tolerances, have equated the critical thermal maximum (CTM) with the upper incipient lethal temperature of fishery researchers, stating that from the "ecological and evolutionary point of view" the CTM is the lethal point. Hutchison,<sup>84</sup> however, points out in his research with salamanders that despite the probable ecological significance of the CTM, it cannot be equated with the ultimate incipient lethal temperature since the behavioral response (CTM) must precede physiological death. He also recognizes that the CTM is experimentally derived in a very different manner, being a combined result of two variables, time and temperature, yet providing only temperature as an end point. Recently, the

CTM has been applied as a criterion of thermal tolerance in fishes by Lowe and Heath<sup>85</sup> for the desert pupfish, *Cyprinodon macularius*, and by Heath<sup>75</sup> for several species of inshore fishes in the northern Gulf of California.

A concept of a critical exposure to heat, which causes equilibrium loss, similar to that proposed by Cowles and Bogert,<sup>82</sup> would seem to be of paramount significance in understanding the relations of aquatic populations to thermal shock in condenser cooling water of a power station, as was noted by Mihursky and Kennedy.<sup>86</sup> It is increasingly recognized that the demise of animal populations is not absolutely dependent upon the physiological death limits of individuals, but upon broad ecological considerations such as breeding densities and predator-prey relationships. Equilibrium loss in the natural environment is a critical occurrence for an organism.

The conceptual contributions of Cowles and Bogert, Lowe and Vance, Hutchison, and others are very important to the practical problems of thermal waste, but the most commonly used technique and criterion of effect (CTM) is inadequate for quantitative assessment of potential thermal effects. The CTM is a temperature, yet its determination involves two variables, time and temperature, as noted by Hutchison. On the other hand, the experimental procedure of Fry, Hart, and Walker<sup>30</sup> and Brett<sup>48</sup> for determining thermal resistance of fishes involves only one variable, time, in experiments at constant temperatures. With a range of test temperatures, the lethal thermal doses for the species are identified concisely and thus have predictive utility for transient conditions normally found in nature, as was discussed in a previous section. To date, however, the thermal resistance methodology for fishes has not been used extensively for precise determinations of time to loss of equilibrium, and most fishery researchers have not embraced the ecological implications of equilibrium loss to the degree shown by investigators of reptiles and amphibians. Some determinations of equilibrium loss doses for salmonids have been reported by Dean and Coutant<sup>87</sup> and Coutant.<sup>87</sup> An attempt was made to relate the doses causing equilibrium loss and death in order that a universal "correction factor" might

be found for translating thermal death times found in the literature to equilibrium loss times that are more pertinent for power plant assessments. The results reported to date have not identified such a universal factor although further study may do so.

The effect of equilibrium loss in providing stimulatory cues to predators may be a particularly important feature in fishes and other animals shocked by condenser cooling water. Mossman<sup>88</sup> cites several points of evidence that suggest release of predator attack by any behavior associated with weakness. Coutant<sup>87, 89</sup> has specifically studied the effects of acute thermal shock on the vulnerability of juvenile salmonids to predation by larger fishes. Thermally shocked juvenile rainbow trout and chinook salmon were found to be selectively preyed upon by large fishes under controlled laboratory conditions when both shocked and control fish were offered simultaneously. Relative vulnerability of shocked fish to predation increased with duration of sublethal exposure to lethal temperatures. Effects were also shown well below doses causing equilibrium loss visible to the investigator. Significant increases in predation rates were found at thermal doses above 10% (chinook) and 20% (rainbow) of the doses showing visible equilibrium losses. Similar experiments are needed with zooplankton organisms, including immature forms of benthic fauna. It seems apparent that microscopic observations of thermally exposed organisms (such as done by Markowski<sup>19</sup> and others), or even techniques of culture after exposure, are not sufficient to predict survival in the predation situations of a natural environment.

Confirmation of the potential importance of predation on shocked organisms in the field situations of thermal discharges can be found in the many references to predators being attracted to points of thermal discharge.<sup>90, 91</sup> While preference for particular temperature range may be the predominant attractant for some organisms, it hardly would apply to concentrations of fish-eating gulls.<sup>91</sup> Neill<sup>92</sup> reported intensive feeding by fishes on entrained zooplankton in the outfall area of a power plant on Lake Monona. Young of the year bluegills congregated at the periphery of the

discharge plume and fed on zooplankton. Several large, long nose gar, their stomachs distended by an abundance of zooplankton, were taken in and near the discharge. Bigmouth buffalo, yellow bass, bluegills, black crappies, and brook silversides caught near the outfalls were suspected of feeding heavily on zooplankton, although confirming data were not collected. Abundant zooplankton was entrained by this plant in cooling water taken from 110 m offshore and 5.2 m below the water surface. The temperature rise of 10 deg.C may have killed or debilitated the zooplankton sufficiently that predation upon them was easier than it was in the unheated water of the lake.

Other indirect effects of thermal shock have been suggested. Increased susceptibility to disease, reduced reproduction potential,<sup>18</sup> and behavioral effects have been implicated as modes of action. Quantitative data on these responses from which to base prediction of power plant effects are not available, however.

#### Lowering Dissolved Oxygen Concentrations in the Condensers

Since warm water can hold less oxygen in solution than can cooler, an elevation of water temperatures by an average of about 11 deg.C in passing through the condensers will theoretically result in some loss of oxygen that may subsequently influence aquatic organisms. For example, the air-equilibrium oxygen concentration in water at 28°C is 7.9 mg/l, whereas at 44°C the saturation concentration is 6.1 mg/l. Another factor theoretically tending to lower dissolved oxygen concentrations in the water passing through a condenser is the partial vacuum existing at the discharge end of the condenser. This partial vacuum results from the fact that the discharge end of the condenser lies above the hydraulic gradient. This situation is common to all steam plants. Vacuum pumps are generally installed in the cooling circuit to remove any accumulated air.

These theoretical considerations have been examined in a number of studies at operating power stations. Alabaster and Downing,<sup>57</sup> after examining literature and conducting their own studies in Britain, acknowledged that the dissolved-oxygen content of water used for direct cooling may change slightly in its passage

through electricity generating stations. This appeared to be partly due to the turbulent flow in the effluent outfall causing water unsaturated with dissolved oxygen to *pick up* this gas, while supersaturated water lost it. If the initial concentration is near the air-saturation value, the increase in temperature in the condensers can cause supersaturation. Similar changes occur more readily in cooling towers because falling water droplets present a large surface area to the updraught of air. Thus cooling-water discharges tend to slightly *increase* the dissolved-oxygen content of river water where concentrations are low and to *reduce* it where they are above saturation.

Samples taken by Alabaster and Downing to determine dissolved-oxygen concentration showed that most unheated water was not saturated and that there was either a slight rise in concentration in the heated water or little difference from that in the normal river water. These authors made the further (very pertinent) observation that the changes were generally small compared with those which occur in rivers through plant photosynthesis and respiration, through aeration at weirs, and through the oxidation of organic effluents.

Adams has reported similar analyses on California power stations.<sup>12</sup> Measurements of dissolved oxygen at intake and outfall points showed that dissolved-oxygen concentrations were not decreased in passing through the cooling water system. Rather, the water merely became super-saturated with dissolved-oxygen. As temperatures of the effluent dropped in the mixing zone, saturation values dropped correspondingly, with little loss of dissolved-oxygen.

Despite abundant evidence to the contrary, the spectre of loss of dissolved oxygen in power stations is continually raised by speculative articles for the layman.

#### DISCHARGE CANALS

The simplest and least costly discharge scheme is an open canal leading from the immediate vicinity of the power station to the edge of the receiving water. Recent engineering studies have identified additional advantages of a canal for partial temperature equilibration of

warm effluent with the atmosphere. Two somewhat independent problems arise in this instance: one of the canal itself, and the other of the shoreline method by which a canal empties into a body of water. The following discussion is concerned with processes within the canal.

Concern for the biological effects of heated water in discharge canals stems not from a desire to maintain a balanced ecology there for its own sake; rather, it stems from the understanding that ecological events in the canal may have a direct or indirect effect on the ecology of the main receiving water body or on the suitability of the discharged water for other human uses. These points were discussed by Trembley.<sup>90</sup> The ecological processes in canals are not completely understood, but there is evidence from the field and from the laboratory to allow some predictions of the consequences of canal use. With these predictions we can compare the biological costs of a canal with the economic gain during construction. In general, it would appear that sufficient ecological problems can arise such that this discharge system should be avoided.

Planktonic (drifting) organisms spend only a few minutes (perhaps four or five) in passage through the condenser and outlet piping of a power plant. They can then be returned to temperature elevated only slightly from their normal habitat. A discharge canal may significantly prolong the exposure of entrained organisms to the highest temperatures unless cool dilution water is added close to the condenser outlets. The predictive models previously discussed can assess the significance of this additional exposure time. In the warmest seasons, the added duration of exposure may be critical to survival of the entrained species.

In addition to aggravating entrainment effects, a discharge canal provides habitats where a stationary community develops, and organisms may spend their entire life cycle under the influence of high temperatures. Fish, although mobile, may spend many months within the heated areas and exhibit selection or repulsion as temperatures rise and fall seasonally and with plant operation. Some of the ecological problems that are known to arise from discharge canals are discussed below.

### Productivity

Perhaps the most serious objection to a canal is its propensity for "*self pollution*," to use the phrase of Oksiyuk<sup>93</sup> who reviewed problems of canals throughout Europe and Asia.

Canals approximate natural streams in many respects; like streams they can be very productive of aquatic organisms. This production can lead to many of the more visible difficulties now known as "thermal pollution." High primary productivity of streams occurs in the bottom algal communities (periphyton) on hard substrates and in beds of rooted aquatic plants that thrive where the bottom is soft and current is gentle. Most streams—and discharge canals—are shallow and the bottom is usually well within the photic zone. Abundance of light, together with currents which replenish nutrients and dispose of metabolic wastes, ensures that production of organic matter occurs at a rapid rate.

A stream is generally abundantly supplied with animals to consume the organic matter produced as well as organic detritus from surrounding land. Stream animals efficiently consume both attached and drifting food. Their continual grazing and straining, together with predatory activities of other animals that in turn feed upon them, prevent a build-up of biological materials despite high rates of production.

This natural sequence is illustrated in Figure 8. This diagram of energy flow through a stream ecosystem was first published by Teal.<sup>94</sup> There are others of a similar structure in the ecological literature. The diverse community of algae (the primary producers) and herbivores, carnivores, and microorganisms studied by Teal in a cold spring assured that most of the energy entering the system was used biologically and was eventually wasted to the environment as heat. There was a small net increase in energy passing through the system as debris, but the imbalance was not great.

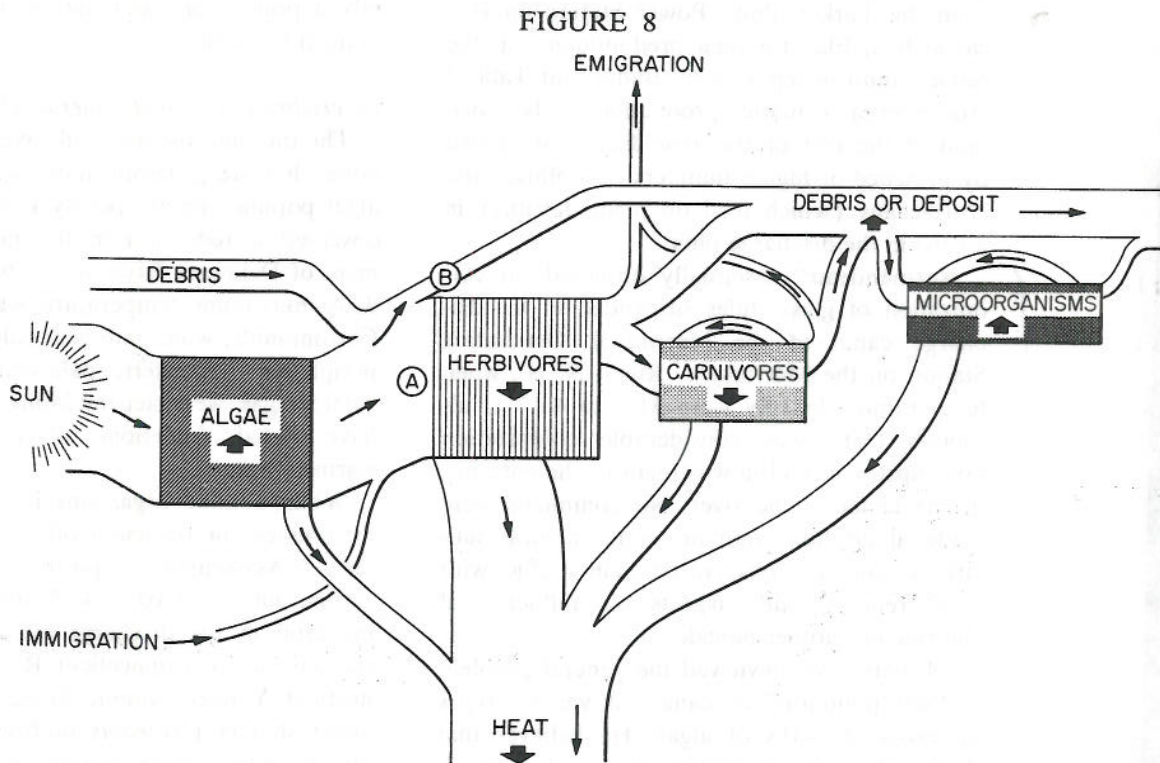
There is evidence from site studies of existing power plants that elevated temperatures in discharge canals can disrupt this efficient flow of organic matter (energy) through the biological community such that excessive accumulations do occur and fairly large quantities of de-

composable organic matter are washed out into the receiving water. The consequences of this washout of organic debris may be similar to other examples of organic loading such as untreated sewage. The organic matter added to the receiving water due to elevated temperature in combination with an extensive area of suitable substrate such as a shallow discharge canal may be equated with an untreated sewage load from a community.

This disruption of energy flow was evident at the Martin's Creek Steam Electric Station on the Delaware River at temperatures above about 30°C when heat-tolerant blue-green algae and some diatoms replaced the normal bottom-algae community<sup>90</sup> and most normal bottom animals were killed without replacement by hot-water species.<sup>95</sup> Algal photosynthesis proceeded very rapidly at the elevated temperatures while there were few animals surviving to utilize the products. In the absence of efficient grazing, dense algal mats developed which were periodically dislodged and washed downstream. The quantities of organic matter

thus delivered to the Delaware were not measured, yet the consequences were observed both in downstream zones of organic matter accumulation and in suspected additional food for filter-feeding bottom organisms located below the heated zone.

Beer and Pipes<sup>96</sup> observed a greater abundance of organic matter on the bottom of Lake Michigan off the 2000-foot discharge canal of the Waukegan Power Plant than at a similar station at another location. Invertebrates associated with organic enrichment were collected from the bottom materials. At the time of their April survey they observed significantly less algal material in the discharge canal than in the plant inlet. Water temperatures were about 15.6°C and 8.9°C, respectively. This reduction of algae in the heated zone was claimed a benefit to shoreline ecology. No surveys were conducted during other seasons, particularly the summer period of maximum lake temperatures, to see if the relative algal abundances remained consistent or whether the organic deposits were related to the discharge canal.



Pattern of energy flow through a stream ecosystem.<sup>94</sup> Small arrows indicate direction of energy flow; large arrows indicate increase (up) or decrease (down) of a component at abnormally high temperatures.

An increase in the standing crop of periphyton was observed in the heated water at the Paradise Plant of the Tennessee Valley Authority on the Green River, Ky., compared to accumulation in the unheated river.<sup>97</sup> This has also been seen at the Colbert and John Sevier Steam Plants of TVA.<sup>15</sup>

Attached algae were more prominent throughout the year in the effluent canal of the Indianapolis Power and Light Co. Plant on the White River, Ind., ( $\Delta T$  about 10.6 deg.C) than in the unheated river.<sup>13</sup> There was no evidence seen, however, of obvious organic loading of the river by these accumulations such as seen on the Delaware. There was complete disappearance of periphyton when the discharge temperature abruptly rose to 41.7°C.

Large quantities of algae, chiefly *Oscillatoria limosa*, developed on the bottom of the power station effluent channel flowing into Lake Lichen, Poland.<sup>10</sup> The algae formed large floating masses at the surface that presumably washed into the lake.

Mat-forming blue-green and green algae probably predominate in the discharge canal from the Turkey Point Power Station on Biscayne Bay, Fla., for their predominance at the canal mouth is reported by Bader and Tabb.<sup>24</sup> Higher organic matter production in the canal than in the rest of Biscayne Bay is suggested by presence of higher numbers of molluscs and crustaceans (which feed on plant detritus) in a zone in the discharge plume.

Normandeau<sup>22</sup> essentially observed no colonization of glass slides suspended in the discharge canal of the Merrimack Generating Station on the Merrimack River, N. H., when temperatures in July were 31.1 to 41.7°C although there was considerable colonization both upstream and downstream of the entrance of the canal to the river. No comments were made about the communities on natural substrates. Since this observation is in conflict with other reports, one suspects the influence of chlorine or another biocide.

Oksiyuk<sup>93</sup> has reviewed the general problem of "self pollution" of canals of various types by excess growths of algae. He believes that the problem is a general one of canals, regardless of their specific uses for irrigation, drainage, navigation, water supply, energy produc-

tion, or whatever and occurs wherever the water has an ample supply of biogenic nutrients.

As Figure 8 indicates, there are several processes that could be contributing to imbalances of production and consumption. A quantitative assessment must evaluate each of these and their relation to water temperature. Algae could be producing exceptionally high quantities of organic matter in the heated water, the herbivores may be eliminated or reduced in population size by the high or fluctuating temperatures (or biocides), or the prominent algal species may be inedible.

There is no unanimity of conclusions concerning the production of organic matter by algae at different temperatures. Reviews of recent literature on temperature effects have noted some papers indicating an increase in production with increased temperature, while others have noted the reverse.<sup>98-99</sup> A careful review of pertinent literature in this area is certainly needed. Specific attention must be made of a great deal of laboratory culture data, much of which, however, may not be relevant to the mixed populations and natural lighting conditions in the field.

#### *Invertebrate Thermal Tolerance*

The thermal tolerances of invertebrate herbivores that are generally most active in grazing algal populations are poorly known. Coutant<sup>95</sup> observed a reduction in the normal complement of Delaware River invertebrates when the daily maximum temperature was near 32°C. Chironomids, which are generally important as periphyton harvesters, persisted in the zone where algae were accumulating. Other studies have noted depletions of invertebrates in warmed water.

While benthic organisms may be destroyed in summer, the reverse is often the case in winter.<sup>90-95</sup> Massengill<sup>100</sup> reported not only colonization, but also a 10 to 40% increase in standing crop in the discharge canal compared to stations in the Connecticut River at the Connecticut Yankee Atomic Power Plant.<sup>14</sup> Spottailed shiners (*Notropis hudsonius*) were observed to feed more heavily on aquatic insects within the canal in winter than elsewhere in the river.<sup>14</sup>



One species of invertebrates, a Tendipedid, was unusually favored by summer conditions in the effluent canal of a power plant on the White River, Ind.<sup>3</sup> This result is comparable to that seen by Coutant on the Delaware River where Tendipedids were the dominant invertebrates in the warmest water in summer. Alteration of the seasonal cycle, principally lengthening the reproductive season into the fall, was also noted by both authors.

Organisms adapted to the warm water conditions of a discharge canal may suffer marked mortalities when the source of warmth ceases due to plant shutdown. Massengill<sup>100</sup> reported that under conditions of 10 deg.C elevation, large numbers of invertebrates populated the discharge canal of the Connecticut Yankee Atomic Power Plant in the winter of 1968. The plant shut down in March, and populations decreased to the lowest number found in the study to the date of reporting.

The poor habitat for marine animals that a heated discharge canal provides when at highest temperatures was recognized by Chadwick et al.<sup>101</sup> and Ritchie<sup>102</sup> with the suggestion that periodic flushing with hot water may be a useful method for controlling nuisance fouling of plant intakes. This process has been used successfully at the San Onofre Nuclear Power Station where 40.6°C water is flushed through the entire cooling-water system to rid it of encrusting barnacles and mussels.

Marine or estuarine discharge canals may respond differently than freshwater ones at moderately warm temperatures. Autotrophic forms were sparse or completely lacking in the canals of two coastal power stations, while solid surfaces were densely colonized with sessile invertebrates.<sup>25 26 103</sup> Invertebrate grazers were not common in one of the studies<sup>103</sup> (at Morro Bay on the Pacific Coast) although there may have been important herbivorous fishes. It is possible that carnivorous invertebrates were preying upon damaged entrained organisms, although this hypothesis was not investigated. Many of the invertebrates observed at Morro Bay contained symbiotic unicellular algae in the tissues.<sup>103</sup> Primary production could thus still be high without discrete plants being apparent. Another discharge canal along the Pacific Coast (Humboldt Bay, Calif.) has an

abundance of green algae.<sup>103</sup> Temperatures were said to be similar to Morro Bay.

Benthic production (determined as biomass accumulation per month) was considerably greater in the discharge canal of the Chalk Point Plant on the Patuxent estuary than in the intake canal.<sup>25 26</sup> This "production" included both plants and animals that attached to submerged substrates. For the months April through August, and November, the production was 2.8 times greater than the intake. This standing crop production may not have resulted in excess detrital transport to the estuary, however, since both producers (algae) and consumers (animals) were represented. The species diversity was actually greater in the effluent canal in all months except July and August when surface temperatures were maximum.<sup>26</sup> Similar high production of benthic organisms, largely invertebrates, was shown in brackish waters by Markowski.<sup>19 20 104</sup>

#### *Algal Successions*

Inherent in the question of availability of different algal groups as food for invertebrates is the succession of these algae with increasing temperature. As Patrick<sup>23</sup> noted in her review of the effects of temperature on freshwater algae, each species in nature has its own range of temperature tolerance and its range of optimum growth, photosynthesis, and reproduction. In general, the diatoms are represented by the largest number of species with relatively low temperature tolerances, i.e., below 30°C (86°F). The tolerances of the green algae cover a wide temperature span. The blue-green algae have more species that are tolerant of very high temperatures. There are some species in all groups, however, that tolerate the unusual extreme for their group. Under normal seasonal conditions, there is a succession of species on the same substrate. This succession is largely the result of changes in water temperature and light intensity through the optima for the various species. As the temperature increases or decreases, one species replaces another as the dominant organism. In nature, there are also many other pressures upon a species, including interspecies competition and predation so that the temperature of maximum development in a stream may not be exactly

the same as the optimum range for growth in the laboratory. Figure 9 summarizes some population shifts. The figure has been used repeatedly since introduced by Cairns,<sup>105</sup> and it needs critical examination in the light of new data such as that presented by Kullberg, Figure 10.<sup>106</sup>

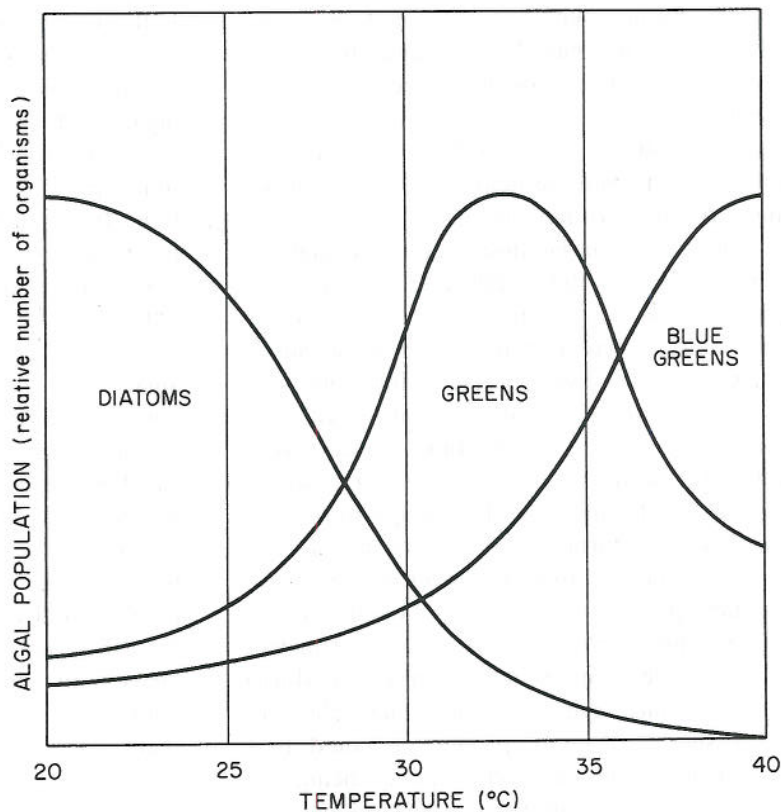
Reports of field studies of the discharge canals of power plants, where the water temperature is still essentially as high as it was when it left the condensers, have noted dominance of the periphyton community by heat-tolerant blue-green algae when water temperatures exceed about 30°C. Reports by Trembley<sup>90</sup> and <sup>107</sup> indicate an increase in the dominance of periphyton grown on glass slides by blue-green algal species in the discharge canal of the Martin's Creek Power Plant on the Delaware River when the temperature exceeded 34.5°C. There were fewer species on the slides than when the water was cooler, but those remaining were represented by a larger number of individuals.

This condition is generally recognized as an indication of an abnormal community structure. It is difficult to determine, however, how much of the alteration of community structure was due to chlorination of the cooling water.

Foerster<sup>108</sup> discussed the apparent early arrival of spring seasonal successions in periphyton of the discharge canal of the Yankee Atomic Power Plant on the Connecticut River. Buck<sup>109</sup> reported a noticeable shift to blue-green algae in plankton (from diatoms) in the area of thermal effluent. These planktonic forms were likely derived from the periphyton populations of the mile-long canal, although a detailed report of this study has not yet been published. Similar changes in plankton species composition of cooling water was reported by Beer and Pipes<sup>110</sup> who described a shift from diatom dominance in the inlet to dominance by unicellular green algae in the effluent canal of the Dresden Station on the Illinois River.

In a September survey, *Oscillatoria* (a blue-

FIGURE 9



Population changes among algal groups with change in temperature.<sup>105</sup>

green filamentous algae) covered all bottom materials in shallow water of the discharge canal and the river bed close to the confluence of the discharge from the John Sevier Steam Plant (Tennessee Valley Authority) with the Holston River, Tenn.<sup>111</sup> No large-scale replacement of cold-water marine algae by warm-water tolerant forms was found by North<sup>103</sup> at the Morro Bay discharge canal, however. The entire algal flora was simply depleted at the warmer temperatures.

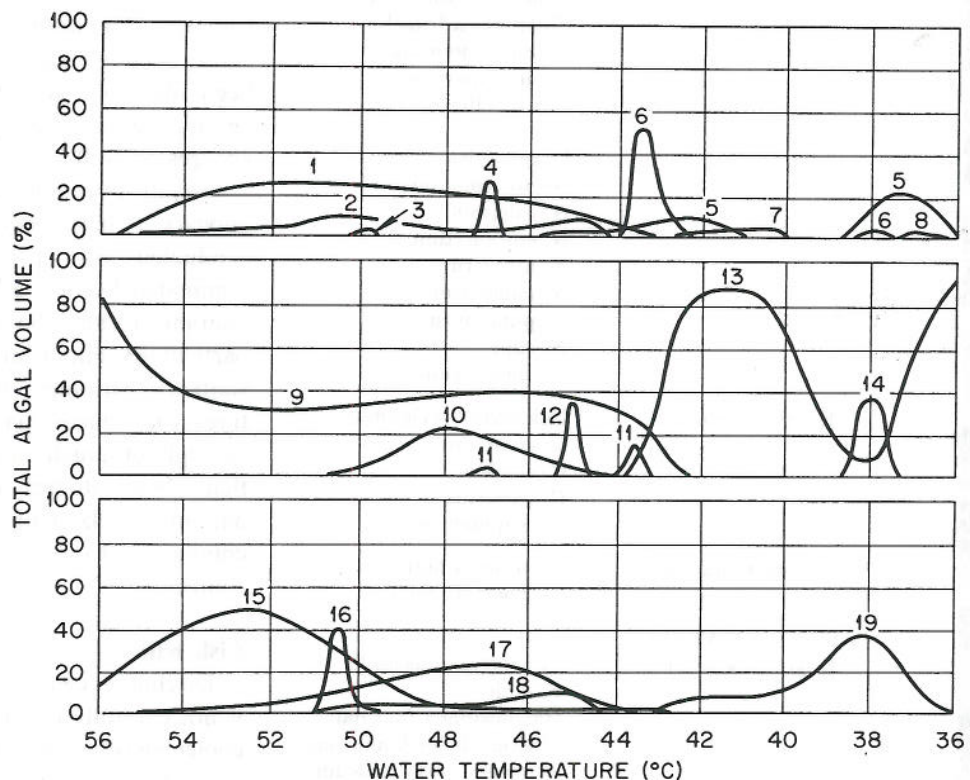
There is conflicting evidence on the food-chain availability of blue-green algae. Arnold<sup>112</sup> determined that planktonic blue-green algae are not usable as food by *Daphnia pulex*, a member of the zooplankton. Trembley<sup>90</sup> discussed the apparent poor suitability of blue-green algae of the periphyton as animal food. Some blue-greens are extremely toxic to animal life.<sup>113</sup> On the other hand, Prowse<sup>114</sup> found that *Tilapia mossambica* in Maylasia could digest and use blue-green algae much better than it

could *Euglena*, a green alga. Resolution of this question would seem very important for assessing possible perturbations of the food chains of a water body by replacing diatoms, green algae, and other cool water forms by communities dominated by species of blue-green algae. Suitability of blue-greens for food would largely determine the relative importance of energy transfer to herbivores or to deposit and microorganisms in Figure 8.

#### Nitrogen Fixation

Trembley,<sup>90</sup> and others subsequently, raised the question of possible nitrogen fixation by blue-green algae in discharge canals or shoreline areas where temperatures are high enough in summer to favor dominance of the periphyton by this algal group. Such fixation could enrich the water with nitrogen nutrients, perhaps leading to accelerated eutrophication. Stewart<sup>115, 116</sup> has reported that over 40 nitrogen-fixing species of blue-green algae are

FIGURE 10



Percent volume of the major species of algae (numbered 1 through 19) along a temperature gradient at Boulder Hot Springs, Mont.<sup>106</sup> Refer to original article for specific names.

known from pure culture studies in the laboratory (Table 1). All belong to the orders Nostocales or Stigonematales, filamentous forms that characteristically have large empty-

TABLE 1

Nitrogen-Fixing Blue-Green Algae  
(after Stewart<sup>115</sup>)

Order and Family	Species which fix nitrogen in pure culture
<b>NOSTOCALES</b>	
Nostocaceae	Anabaena ambigua A. azollae A. cycadaeae A. cylindrica A. fertilissima A. flos-aquae A. gelatinosa A. humicola A. naviculoides A. variabilis* A. spp* Anabaenopsis circularis Aulosira fertilissima Chlorogloea fritschii Cylindrospermum gorakhporensis C. licheniforme C. maius C. sphaerica Nostoc commune N. calcicola N. entophyllum N. muscorum N. paludosum N. punctiforme N. spp. N. sphaericum
Rivulariaceae	Calothrix brevissima C. crustacea C. elenkinii C. parietina C. scopulorum
Scytonemataceae	Scytonema hofmannii Tolypothrix tenuis
<b>STIGONEMATALES</b>	
Stigonemataceae	Fischerella muscicola F. major Hapalosiphon fontinalis Mastigocladus laminosus Stigonema dendroideum Westelliopsis prolifica

\* A non-nitrogen-fixing strain has been reported.

looking cells called heterocysts. Heterocysts thus may provide a "rapid-scan" method for identifying potential nitrogen-fixing blue-green algae in field populations. Many of the nitrogen-fixing species are largely planktonic.<sup>117</sup> The physiology and biochemistry of the fixation processes have been reviewed.<sup>118</sup>

In retrospect, the blue-green algae accumulations in periphyton reported by Trembley<sup>90</sup> were probably not fixing nitrogen, since the filamentous forms were classified as being in the Oscillatoriaceae. Fogg<sup>118</sup> notes that this is one family in the order Nostocales that seems to lack the ability to fix nitrogen. Many of the blue-greens commonly reported for the periphyton of thermal waters apparently do not have the ability, e.g., *Phormidium*, *Synechococcus*, *Oscillatoria*, and *Gloeocapsa*. Billaud<sup>117</sup> and Stewart<sup>116</sup> have reported fixation by the rock-surface *Mastigocladus* in thermal springs, but the species thrived only at temperatures above 35°C (somewhat high for most thermal discharges in the temperate zone).

Some nitrogen-fixing, free-living thermal bacteria (*Pseudomonas ambigua*, *Azotobacter chroococcum*, and *A. agilis*.) have recently been identified in hot springs, and these may be associated with the warmest thermal discharges as well.<sup>119, 120</sup>

Despite over ten years of speculation, there appears to have been no study of N<sub>2</sub> fixation conducted in a power plant discharge area dominated by blue-green algae and other heat-tolerant forms. Such a study would seem particularly important at thermal plants in the southern latitudes where discharge temperatures may encourage blue-green algal growth throughout much of the year. It is important that these studies be quantitative, for the amounts of fixed nitrogen may be insignificant compared to the background from other sources.

### Fish Kills

Discharge canals can lead to death of fish if not carefully constructed. Particularly during cooler seasons, but also at other times of the year, fish are attracted from the cooler receiving body to the warm temperatures of the canal and perhaps to the more rapidly growing

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food organisms thriving there. This attraction has been confirmed for many plants across the U.S. With onset of rising water temperatures both in the receiving water and in the discharge canal, the preferred temperatures of the fish species may be exceeded and the fish should return to their normal habitat. If they are prevented from doing so, either by barrier or by being diverted into a temporarily cooler blind channel, they may suffer heat death or death from crowding and starvation. Such a trap was created at the Martin's Creek Steam Electric Station owned by the Pennsylvania Power and Light Co. where the discharge canal crossed an old river channel, thus creating a cooler lagoon as an extension of the canal.<sup>90</sup>

Clark described similar fish kills.<sup>121</sup> In 1963, wintering striped bass were attracted to heated discharges from a plant on the Hudson River, became trapped near the discharge, and died by the thousands. Testing of a new power plant on Cape Cod Canal killed a large number of menhaden in 1968 when they were trapped in 33.9 to 35°C discharge water. Detailed analyses of these fish kills are not available in the literature to evaluate how they might have been prevented.

The Martin's Creek situation also indicated that spring migrating fish moved into the canal and its lagoon during the night when reduced power output created less of a rise in cooling water temperature. The fish were apparently unable to distinguish the canal from a channel of the river. As discharge temperatures increased in the morning, fish became blocked in the lagoon and perished.<sup>71</sup> This situation could occur whenever there are daily fluctuations in use of a plant. A similar case of a fish kill due to daily power changes was reported in Great Britain.<sup>57</sup> Deaths followed abrupt rises in summer time effluent temperatures well above 30°C.

#### *Temperature Selection in the Field*

Fish kills are an obviously extreme and relatively uncommon result of what is a remarkably common phenomenon, i.e., the attraction of fish to warmed water during cooler months and repulsion by thermal extremes in the peak of summer. There are other, less dramatic effects on fish populations that will be dis-

cussed following a review of our ability to predict temperature selection.

Few power plant studies offer data of predictive utility even though several report occasional temperatures at which fish were found.<sup>90</sup> Studies of the Connecticut Yankee Atomic Power Plant by Merriman and his staff<sup>122</sup> have documented fish attraction to the discharge canal and concentration there in large numbers. White catfish (*Ictalurus catus*) and brown bullheads (*I. nebulosus*) make up approximately 95% of the fish throughout the year. Tagging studies have indicated that the warm water randomly attracts a certain number of fish from the general area rather than the existence of a discrete fish population that moves into and out of the canal in response to changes in temperature or season. Based upon two years of postoperative study, an upper limit of preference was apparent for most adult fish entering or leaving the canal. This was estimated to be about 34°C. Fish driven from the canal by temperatures higher than this (35 to 39°C) returned with a drop of only 1°C in summer (35 to 34°C). Apparently healthy young fish were observed up to 37°C. The direct or indirect importance of temperature as an attractant to the canal was shown by plant shutdown in April 1969. Upon cessation of heating, almost all fish moved out of the discharge canal and began to range widely in the lower Connecticut River System (based upon tag returns). It might be speculated that this ranging was an instinctive attempt to locate the then-absent source of warmth.

Large numbers of threadfin shad (*Dorosoma petenense atchafaylae*) were reported to be attracted between January and March to a warm discharge harbor (82 acres) at the New Johnsonville Steam Plant of TVA.<sup>123</sup> The concentrations were identified by experimental gill and cast netting but were readily apparent as they hindered outboard motor operation and attracted large numbers of predatory gulls. Numbers of sauger (*Stizostedien caudense*) and skipjack (*Alosa chryso*) were related directly to numbers of threadfin on which they were feeding. Other species that concentrated in the discharge area were blue catfish (*Ictalurus furcatus*) and channel catfish (*Ictalurus lacustris*), between late February



and June. There was active commercial fishing for these two species in 1956, the year of the study. Threadfin were most abundant in the harbor when the receiving water was 7.2°C and the harbor was 12.8°C. Shad left the harbor when the temperature there was about 16.7°C, and the lake 11.1°C. Unfortunately, precise definition of the attracting temperature was not made. Studies of threadfin populations in Kentucky Lake before and after steam plant operation suggested to the authors that the discharge harbor provided a warm overwintering area allowing postoperation expansion of the population.

High abundance of roach has been noted in some British rivers receiving heated effluents where summer temperatures do not exceed 26°C and low abundance where they exceed 30°C.<sup>57</sup> Common carp, in particular, have congregated in heated effluent outfalls, and attempts have been made in USSR to rear them in floating cages in heated water reservoirs.<sup>10</sup>

Five winter fish inventories were made at the TVA Paradise Plant by TVA and State of Kentucky biologists (1962–1966). A much larger fish population was consistently found in the vicinity of the discharge canal than in the Green River above and below the plant.<sup>124</sup> No data on these inventories have been published.

The TVA Fish and Wildlife Branch reported on studies of fish and fishing in condenser discharge basins at the Kingston and John Sevier Steam Plants.<sup>125</sup> The discharge basins of these two TVA steam plants attract large concentrations of fish—and fishermen—in certain seasons. Heaviest fish concentrations usually occur during cold weather, when the basin water is 5.6 to 8.3 deg.C warmer than the adjacent reservoir water. Winter water temperatures in both basins range between 11.1 and 18.3°C; summer temperatures, between 20 and 30°C.

TVA studies in these basins between October 1960 and September 1962 showed the Kingston basin had a greater fish population per acre than adjacent Watts Bar Reservoir. Samples of John Sevier were about the same as in Cherokee Reservoir. The proportion of game fish was consistently higher in the basins. Both basins had fewest fish in summer when water temperatures were highest. Heaviest

concentration did not correlate well with times when basin water reached a specific temperature.

Two studies of relative fishing success in thermal plumes provide inferences of temperature selection. Although discharge canals were not involved in the study areas, the work is appropriately discussed here.

Test fishing in the spring in the thermal plume at the Humboldt Bay Nuclear Plant in California identified three categories of fish: those preferring warm plume water, those showing no preference, and those avoiding the outfall and remaining in cooler adjacent areas.<sup>126</sup> Table 2 summarizes the species and the percentages of catches taken at warm and cool locations.

During test fishing above and below a thermal plume in the Potomac River, heated water yielded substantially more fish throughout the year except during June to September when the heated station had temperatures above 26.7°C.<sup>127</sup> Channel catfish (*Ictalurus punctatus*) predominated. The relative catch performance of heated water declined throughout the spring and increased through the fall. Maximum relative catch performance was seen in winter. No fish were caught in the heated area in mid-August when the temperature was at a yearly peak of 37.8°C. There were no significant differences in fish length among stations.

Multiple factors operate to determine fish distributions in areas of thermally modified waters. Selection or avoidance of an outfall area by different fishes depends primarily upon their responses to temperature and food supply.<sup>91</sup> The response of a given fish at any instant may be altered by its condition and may vary diurnally and seasonally. Except for reasonably quantitative data on temperature selection by some species, we have a poor data base for accurate predictions of fish behavior in situations of thermal discharges. In general, however, fish kills need not occur if the planners of thermal discharges were to consult the biological literature on temperature selection by fishes, or to at least be aware of the limits to their plans set by these biological responses. These limits can be quite well defined for temperature selection in the laboratory, which

must provide a quantitative base from which further details for field situations can be derived.

#### Temperature Selection in the Laboratory

It has been well established for fish that, depending upon the prior acclimation temperature, individuals will choose particular temperatures in gradients set up in tanks. Bull<sup>128</sup> concluded that individual fish can perceive and react purposively to a temperature change of 0.03 deg.C, although Alabaster and Downing<sup>57</sup> found 0.5 deg.C the lowest effective for bream. The normal tendency is for the fish to move gradually or in stages to a final temperature (the final preferendum) which is characteristic of the species. The final preferendum for the species is not a sharp point on the temperature scale but rather a zone of normal distribution owing to individual variability. If the final preferendum is higher than the acclimation temperature, the fish will tend to initially select a higher temperature than the latter, and then after acclimating to the new value, will move on until the final preferendum is reached. Conversely, if the final preferendum is lower than the acclimation temperature, the fish will gradually move to lower temperatures until the preferendum is reached.

These tendencies are illustrated in Figure 11.<sup>34</sup> The relation of the thermal preferendum to the acclimation temperature as well as the final preferendum can be seen in the upper diagram to vary markedly from species to species. A proposed classification of types of response is shown in the lower diagram.<sup>129</sup> There may be seasonal fluctuation, however, in final preferred temperatures for a species as was shown by Sullivan and Fisher<sup>130</sup> for the brook trout and by Mantleman<sup>131</sup> for rainbow trout. While many similar experiments have been conducted on terrestrial insects, there is essentially no such information for aquatic invertebrates.

Laboratory determinations of final temperature preferendum are intended to indicate both the directions in a thermal gradient that an organism will migrate and the probable temperatures at which it will be found in the field. It is significant for thermal discharge design that the lowest final preferendum determined experimentally for temperate fresh-water species is about 12°C.<sup>34</sup> This is well above most natural winter water temperatures and accounts in large measure for winter accumulation of fish at outfalls. There is fairly close agreement between laboratory results and field observations for some species<sup>132</sup> although field records gen-

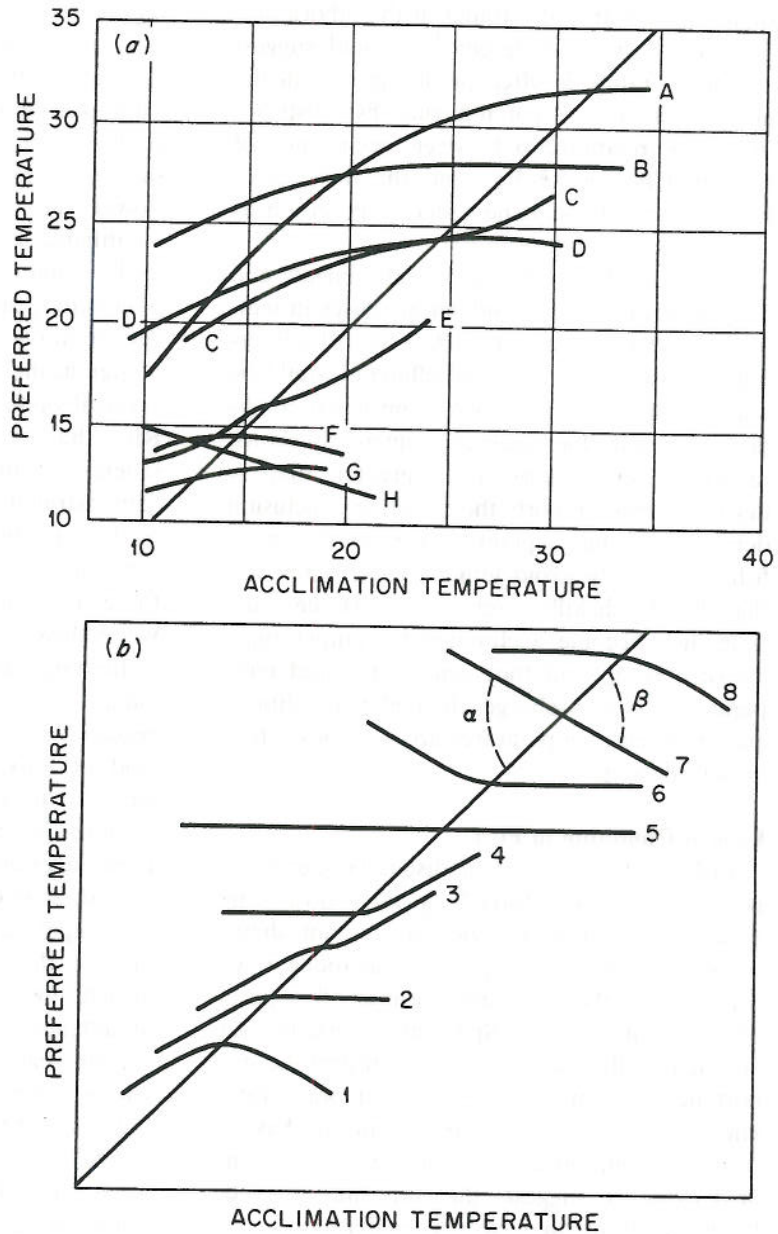
TABLE 2

Percentage of Fish Taken in Warm Water (52°F and above), and in Cold Water (51°F and below), by Hook and Line along the Rock Jetty Bordering a Coolant Water Discharge Canal, 1963-65.<sup>122</sup>

Apparent preference	Species	Percentage taken in cold water	Percentage taken in warm water	
			Away from outfall	At outfall
Warm water.....	Jacksmelt ( <i>Atherinopsis californiensis</i> )	0.0	12.5	87.5
	Silver surfperch ( <i>Hyperprosopon ellipticum</i> )	25.0	0.0	75.0
	Walleye surfperch ( <i>Hyperprosopon argenteum</i> )	28.5	33.5	38.0
	White seaperch ( <i>Phanerodon furcatus</i> )	36.0	45.5	18.5
	Pile perch ( <i>Rhacochilus vacca</i> )	40.5	54.0	5.5
None shown.....	Sand sole ( <i>Psettichthys melanostictus</i> )	52.0	32.0	16.0
	Striped seaperch ( <i>Embiotoca lateralis</i> )	53.0	30.0	17.0
	Redtail surfperch ( <i>Amphistichus rhodoterus</i> )	54.0	36.0	10.0
Cold water.....	Cabezon ( <i>Scorpaenichthys marmoratus</i> )	95.0	5.0	.0
	Staghorn sculpin	80.0	20.0	.0
	Speckled sanddab ( <i>Citharichthys stigmaeus</i> )	69.0	31.0	.0
	Kelp greenling ( <i>Hexagrammos decagrammus</i> )	62.0	38.0	.0



FIGURE 11



Thermal preferenda of fish in relation to thermal acclimation.<sup>34</sup> (a) Examples for the following species: A, *Cyprinus carpio*; B, *Carassius auratus*; C, *Perca flavescens*; D, *Girella nigricans*; E, *Salvelinus fontinalis*; F, *Oncorhynchus nerka*; G, *Oncorhynchus tshawytscha*; H, *Salmo gairdneri*. (b) Tentative classification of types of response (numbered 1 to 8) of thermal preferendum to thermal acclimation.<sup>129</sup> Responses for a species may be different on either side of the thermal preferendum ( $\alpha$  and  $\beta$  angles may differ). In both diagrams, the diagonal intersects the final preferendum.

erally indicate congregation at temperatures slightly less than those found in the laboratory. This relatively close agreement would suggest that temperature is often predominating in the many field factors that influence fish distribution. The relationship between occurrence of shad in Chesapeake Bay and the water temperature are of the same order of precision as is found in the laboratory.<sup>133</sup>

It appears from laboratory experiments and field observations that sudden increases in temperature less than about 10°C caused by intermittent discharges of heated effluents would be effective in driving fish away from lethal conditions. Juvenile shad were experimentally shown to avoid temperature rises greater than 4 deg.C.<sup>134</sup> This supports the tentative conclusion derived from many plant operations that most fish successfully avoid lethal temperatures and that direct fish kills rarely occur. At the same time, fish become acclimated to temperatures above normal, and they select preferred temperatures in a discharge channel if conditions are stable and temperatures are not above their preferred range.

#### Loss of Condition in Fish

Fish attracted to warm discharge canals of power plants, and forced by their own temperature selection behavior to remain there, subject themselves to speeded metabolic rates compared to their seasonal norm in other parts of the water body. Speculative articles on "thermal pollution" have often stressed the importance of this change in metabolic rate, known from fish physiology, without having truly pertinent field data for support. Recent field evidence suggests that this may, indeed, be an effect worth serious consideration.

At the Connecticut Yankee Atomic Power Company's plant on the Connecticut River, Merriman et al.<sup>122</sup> have identified "skinny fish" (non-technical, but descriptive) in the winter accumulations of brown bullheads (*Ictalurus nebulosus*) and white catfish (*I. catus*) in the discharge canal. The weight-length ratio, or "condition factor," exhibited significant declines throughout the winter months. Fish tagged early in the winter of 1968-1969 and recaptured four months later had lost an average of 20% of their weight, with some having

lost 60%. Comparisons of tagged and untagged fish in weekly collections indicated that this marked weight loss was not the result of the tagging but was indicative of the resident canal population as a whole. Populations in the cooler river water outside the canal also showed some condition loss, but at a much slower rate. The poorer condition was also identifiable in these two species of fishes caught in the canal in the summer. Channel catfish (*I. punctatus*), on the other hand, showed no such decline in condition at any season.

Significance of the weight losses for ultimate survival of the populations in the Connecticut River has yet to be established, but the persistence of the effect beyond the winter was demonstrated through tagging and recovery studies. Early fall returns from fish tagged in the canal the previous winter revealed that these fish had not made up their past winter's weight loss over the summer.

Benthic surveys conducted in the discharge canal simultaneously with fish studies have revealed abundant invertebrates during the period of maximum weight losses. Populations were 10 to 40% greater in the canal than at stations in the unheated river. Suitability of these invertebrate species as food was not discussed, however.

Temperature has often been shown to be one of the most influential factors affecting growth of fish. When food is present in abundance, an optimum temperature for growth can be determined. This optimum varies among species and may be significantly influenced by other environmental factors such as salinity.<sup>135</sup> Recent experiments by Brett et al.<sup>136</sup> have demonstrated the extent that this optimum, and indeed the entire pattern of growth response, is dependent upon interacting effects of ration and temperature. While the quantitative data obtained to date do not provide all of the necessary information for predicting or explaining effects in the field, a general pattern of response has emerged. This pattern and subsequent improvements in both form and supporting data should allow for future development of predictive capability.

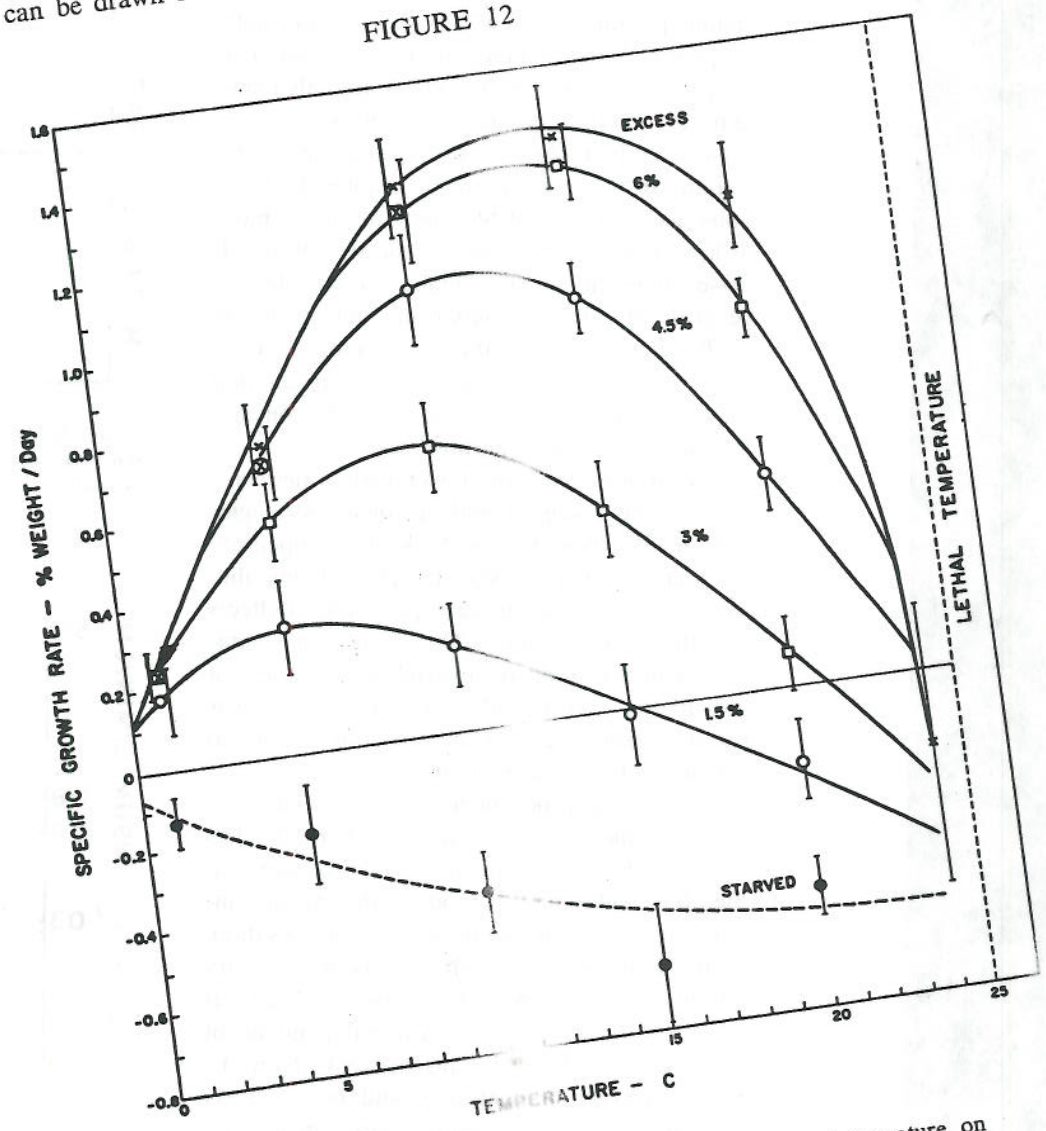
Figure 12 illustrates the general relationships among temperature, ration and specific growth rate (percent body weight added per

day) drawn from data on sockeye salmon.<sup>136</sup> Starved fish progressively lose weight at a rate that increases with temperature rise. At the opposite extreme, excess ration yields a growth response with a marked thermal optimum that decreases either side to low growth rate at low temperatures, and weight loss as temperature approaches the lethal level. Limitations in available food displaces toward lower temperatures both the optimum (or mode of the curve) and the temperature at which growth ceases and weight is lost. Isopeleths for predicting growth response from any combination of ration and temperature can be drawn from these data.<sup>136</sup>

### Oxygen Requirements

Having broached the subject of metabolic rates in the context of "skinny fish" in a discharge canal, it seems reasonable to further pursue the subject. It is an important topic, both for the organisms and because of the common argument advanced by speculative articles, which proceeds thus: thermal additions are bad because higher metabolic rates and greater O<sub>2</sub> consumption at elevated temperatures coincide with reduced capacity of water to hold oxygen at these temperatures. Most aquatic organisms are poikilotherms; that is, they cannot maintain a body tempera-

FIGURE 12



Combined effects of ration (% of body weight per day) and temperature on rates ( $\pm 2$  SE) of 7- to 12-month-old sockeye salmon.<sup>136</sup>

ture independent of their environment. Many uncritical reviews of "thermal pollution" have, therefore, ascribed to metabolic processes, particularly the respiratory uptake of oxygen, the laws of physical chemistry in which the rate of a reaction doubles for each ten degrees (C) rise in temperature. This is inconsistent with a large body of biological data and can lead to gross misestimations of ecological effects of temperature increases.

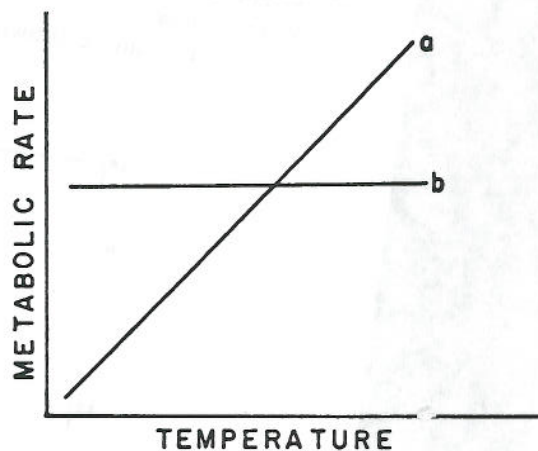
A major evolutionary trend in the development of metabolic processes has been for animals to become increasingly independent of fluctuations in any of the various environmental parameters to which they are normally subjected. Various behavioral and physiological ploys have evolved by which animals maintain an internal environment in which processes tend to be relatively constant. This stability in the internal milieu enables the functions necessary for life to continue under more or less optimal conditions irrespective of an adverse environment. The higher vertebrates, in general, have met the environmental challenge of fluctuating temperature by being able to control body temperature, with the result that their metabolic rate remains relatively constant over a wide ambient thermal range.

Invertebrates and the lower vertebrates have evolved physiological and ecological strategies that enable them to *metabolically* compensate for thermal changes even though their inability to thermo-regulate can have pronounced effects on their respiration. The topic of metabolic compensation of invertebrates in view of anticipated thermal additions of industry was recently reviewed.<sup>137</sup> The following discussion is adapted from that review.

Of particular pertinence to the problem of assessing the biological effect of thermal additions to the environment is the concept of metabolic adaptation of poikilotherms to temperature. Without temperature compensation, their metabolic rate should typically vary directly with temperature (Figure 13a). If their oxidative processes are independent of temperature (thermally insensitive), then the rate of oxygen utilization would be relatively constant over a wide temperature range (Figure 13b). Studies involving many species of invertebrates indicate that over certain parts of

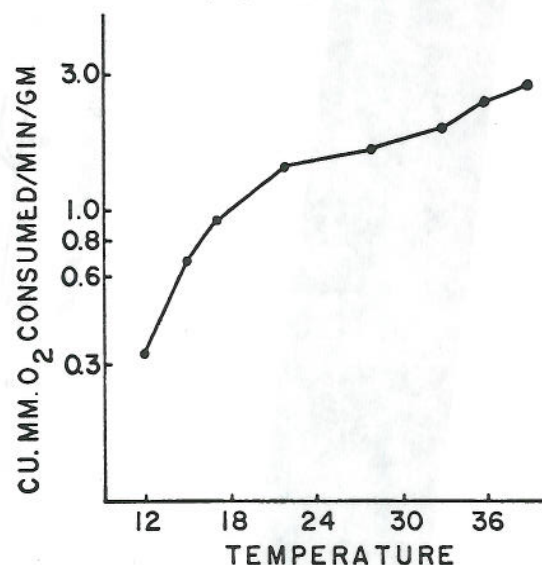
a temperature range in which they can be held for prolonged periods, animals tend to be metabolically independent. This kind of response is intermediate between the two extremes in Figure 13 and can be represented by the response of a tropical species of fiddler crab (Figure 14).<sup>138</sup> In general, this thermal range of metabolic insensitivity coincides with the temperature regime of the animal's habitat; i.e., for polar animals the temperature range is low, while it is high for tropical zone animals

FIGURE 13



Metabolic responses to temperature by thermally sensitive animals (a) and thermally insensitive animals (b).<sup>137</sup>

FIGURE 14



The metabolic response to temperature by *Uca rapax*, illustrating the relative metabolic insensitivity to temperatures approximating those of their habitat.<sup>138</sup>

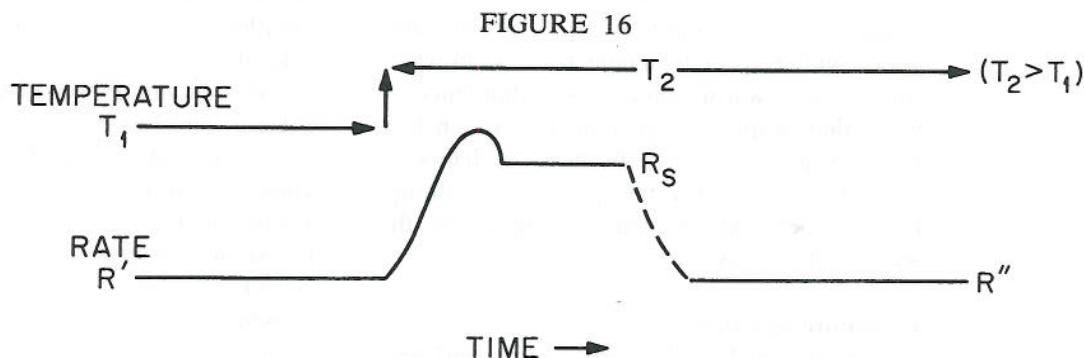
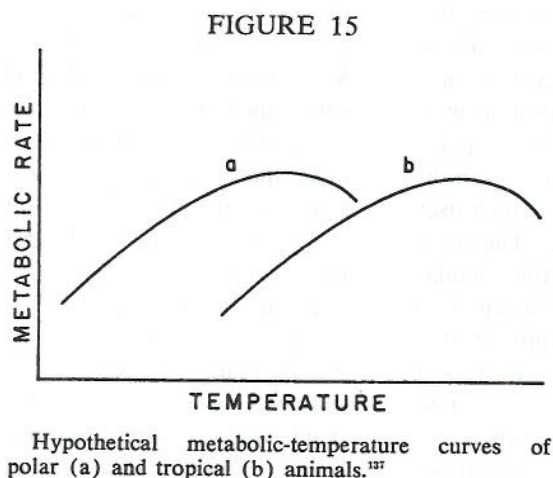
and variable for temperate zone species. Therefore, it is to be expected that the shape and the position of the metabolic-temperature curve (M-T curve) on a thermal gradient would not be similar for animals from different thermal environments (Figure 15). The different thermal environments may be on a global scale (e.g., latitudinal differences between or within species) or on a very local scale (e.g., populations occupying habitats such as intertidal and subtidal with very different thermal characteristics).

Animals may show the ability to metabolically acclimate to fluctuating temperatures. When comparing M-T curves, the previous thermal history of the animal must be known. This was also shown to be important in determining the lethal responses to elevated temperature. The respiration rate of an animal maintained at one temperature (e.g., 10°C) for a long period of time might be different

from that of the same animal kept at a higher temperature (e.g., 25°C) if both rates are determined at a common temperature. This is a variable response that reflects a genetic ability to maintain approximately constant metabolic rates within a range of fluctuating temperatures, provided the rate of temperature change does not exceed the rate of metabolic acclimation.

When an organism is subjected to a rapid temperature change, a characteristic sequence of acclimation usually occurs in any temperature-dependent function such as oxygen uptake. This pattern is illustrated in Figure 16.<sup>40</sup>  $R'$  represents the level of activity of the rate function prior to temperature increase to  $T_2$ . The level immediately rises, through a transient overshoot, then levels off at a value somewhat higher than  $R'$ . This level is termed the "stabilized level ( $R_s$ )". The overshoot period usually ends after a few minutes, whereas  $R_s$  may endure for several hours. With time, homeostatic processes tend to return the function to its original level ( $R'$ )—at which time the organism is said to be acclimated. Several days, or even several months, may pass before the fully acclimated state ( $R''$ ) is attained. Compensation may be complete (in which case  $R'' = R'$ ) but is often only partial. If the temperature were decreased rather than raised, the expected sequence of events would be the mirror image of the above diagram (time representing the axis of symmetry).

Not all organisms acclimate, however. Precht<sup>139</sup> has proposed a scheme to classify acclimation or "capacity adaptation" responses when only two temperature points are in-



volved. These patterns of response are determined by measuring the metabolic rate of an animal completely acclimated to one temperature ( $T_1$ ). Then the respiration rate is immediately determined (acutely) at a second temperature ( $T_2$ ). After the animal has become acclimated to this temperature the rate is redetermined at  $T_2$ . Five patterns may be observed: Type 4, no compensation—the rate is statistically similar to the acutely determined value; Type 2, complete compensation—the rate is the same as at  $T_1$ ; Type 1, supra-compensation—the rate is less than at  $T_1$ ; Type 3, partial compensation; and Type 5, inverse compensation. Considerable research has been conducted toward classifying organisms along these lines.

Vernberg and Vernberg<sup>137</sup> concluded that insufficient data are available to predict the capacity of organisms to metabolically compensate for man's manipulation of their thermal environment. Particularly complicating are effects of body size, stage in the life cycle, cyclic changes of short (min), intermediate, and long (seasonal) duration, and local habitat differences. Despite this lack of data necessary to predict changes in oxygen consumption with accuracy, ecologists involved in power plant analyses must realize that we are not ignorant in the subject. Basic data exist from which useful generalizations have been made. The basis exists for the beginning of quantitative simulation modeling of changes in respiration with temperature modification. It is doubtful that oxygen requirements would limit survival of organisms acclimated to warm-water conditions of a discharge canal. Sudden temperature changes, however, might prove detrimental before acclimation could occur.

Fish species are often divided into two categories with respect to temperature, cold-water species and warm-water ones. Mantleman<sup>131</sup> notes that despite the general assumption that more oxygen is required by fishes as temperature rises, the cold-water species, as a group, have higher oxygen demands than do the warm-water fishes.

#### Premature Spawning

Fish attracted to discharge canals and resident there for several months may be induced by higher temperatures to spawn earlier than

normal. Temperature is recognized as an important, if not always controlling, factor in initiation of spawning by many species of fish and invertebrates. Premature spawning can be speculated to have many repercussions in the receiving water, ranging from loss of progeny due to lack of proper food to species changes brought about the overly dominant large warm water fry. The problem is not unique to discharge canals but occurs in cooling ponds and mixed water bodies wherever the water temperature is elevated.

Few of the speculated changes have been studied at power plants, and observations are generally limited to evidence that premature spawning can and does occur.

White suckers (*Catostomus commersonni*) spawned prematurely in the discharge canal of the Martin's Creek Power Plant on the Delaware River.<sup>90</sup> Spawning activities were observed earlier there than elsewhere (times not given). Young of the year were active in the spring in the canal and apparently left the warmer water as temperature rose in summer. Very small fry of several other species (rearing determined them to be principally minnow species) were found in the canal prior to normal spawning times. They probably were spawned in the canal, rather than having passed through the condensers, although it was not certain.

Examination of gonads of sauger taken in the discharge harbor of the New Johnsonville Steam Plant (TVA) indicated that they had spawned at least one week earlier in the 5.6 deg C warmer water than in the main Kentucky lake.<sup>123</sup> Ovaries of white catfish and brown bullheads were also compared during winter months on a weekly basis in heated water inside the discharge canal of the Connecticut Yankee Atomic Power Plant.<sup>14</sup> Ovaries in both species were found to be developing earlier, or at a faster rate, in the heated water discharge canal than in those fish collected outside in the Connecticut River. Maximum temperature increase may have been 12.7°C (plant specifications) although no temperature data were presented.

The development of sexual maturity is accelerated by high temperature, and it is well known that differences in the time of maturation

tion within a species are associated with differences in climatic conditions linked with latitude. Earlier commencement of spawning by the southernmost populations of a species compared with the northernmost ones is also reflected in differences in gonad development. Predictability can likely be developed if literature on spawning times and temperatures for a variety of species is carefully surveyed and the data collated.

### SUMMARY

In summary, this review has attempted to critically evaluate some thermal effects seen at operating thermal power plants, to group these

into several "problems" associated with 1) entrainment and 2) discharge canals, and to indicate pertinent field and laboratory experiments that can assist in developing information of predictive utility. Most power plant surveys lack detail of observation and definition of goals sufficient to provide more than circumstantial evidence for ecological processes. On the other hand, laboratory experiments are often unrealistic simulations of complex phenomena. True predictability will require judicious application of data from both sources. Until complete information is available, certain laboratory tests provide conservative approximations that can guide power plant siting and design so that environments can be maintained safe for aquatic life.

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