*see next
page for
reference*

TEMPERATURE CRITERIA FOR FRESHWATER FISH:

PROTOCOL AND PROCEDURES

by

William A. Brungs
Bernard R. Jones
Environmental Research Laboratory-Duluth
Duluth, Minnesota 55804

APPENDIX A*

HEAT AND TEMPERATURE

Living organisms do not respond to the quantity of heat but to degrees of temperature or to temperature changes caused by transfer of heat. The importance of temperature to aquatic organisms is well known, and the composition of aquatic communities depends largely on the temperature characteristics of their environment. Organisms have upper and lower thermal tolerance limits, optimum temperatures for growth, preferred temperatures in thermal gradients, and temperature limitations for migration, spawning, and egg incubation. Temperature also affects the physical environment of the aquatic medium, (e.g., viscosity, degree of ice cover, and oxygen capacity. Therefore, the composition of aquatic communities depends largely on temperature characteristics of the environment. In recent years there has been an accelerated demand for cooling waters for power stations that release large quantities of heat, causing, or threatening to cause, either a warming of rivers, lakes, and coastal waters, or a rapid cooling when the artificial sources of heat are abruptly terminated. For these reasons, the environmental consequences of temperature changes must be considered in assessments of water quality requirements of aquatic organisms.

The "natural" temperatures of surface waters of the United States vary from 0 C to over 40 C as a function of latitude, altitude, season, time of day, duration of flow, depth, and many other variables. The agents that affect the natural temperature are so numerous that it is unlikely that two bodies of water, even in the same latitude, would have exactly the same thermal characteristics. Moreover, a single aquatic habitat typically does not have uniform or consistent thermal characteristics. Since all aquatic organisms (with the exception of aquatic mammals and a few large, fast-swimming fish) have body temperatures that conform to the water temperature, these natural variations create conditions that are optimum at times, but are generally above or below optima for particular physiological, behavioral, and competitive functions of the species present.

Because significant temperature changes may affect the composition of an aquatic or wildlife community, an induced change in the thermal characteristics of an eco-system may be detrimental. On the other hand, altered thermal characteristics may be beneficial, as evidenced in most fish hatchery practices and at other aquacultural facilities. (See the discussion of Aquaculture in Section IV.)

The general difficulty in developing suitable criteria for temperature (which would limit the addition of heat) lies in determining the deviation from "natural" temperature a particular body of water can experience without suffering adverse effects on its biota. Whatever requirements are suggested, a "natural" seasonal cycle must be retained, annual spring and fall changes in temperature must be gradual, and large unnatural day-to-day fluctuations should be avoided. In view of the many variables, it seems obvious that no single temperature requirement can be applied uniformly to continental or large regional areas; the requirements must be closely related to each body of water and to its particular community of organisms, especially the important species found in it. These should include invertebrates, plankton, or other plant and animal life that may be of importance to food chains or otherwise interact with species of direct interest to man. Since thermal requirements of various species differ, the social choice of the species to be protected allows for different "levels of protection" among water bodies as suggested by Doudoroff and Shumway (1970)[272] for dissolved oxygen criteria. (See Dissolved Oxygen, p. 131.) Although such decisions clearly transcend the scientific judgments needed in establishing thermal criteria for protecting selected species, biologists can aid in making them. Some measures useful in assigning levels of importance to species are: (1) high yield to commercial or sport fisheries, (2) large biomass in the existing ecosystem (if desirable), (3) important links in food chains of other species judged important for other reasons, and (4) "endangered" or unique status. If it is desirable to attempt strict preservation of an existing ecosystem, the most sensitive species or life stage may dictate the criteria selected.

Criteria for making recommendations for water temperature to protect desirable aquatic life cannot be simply a maximum allowed change from "natural temperatures." This is principally because a change of even one degree from

an ambient temperature has varying significance for an organism, depending upon where the ambient level lies within the tolerance range. In addition, historic temperature records or, alternatively, the existing ambient temperature prior to any thermal alterations by man are not always reliable indicators of desirable conditions for aquatic populations. Multiple developments of water resources also change water temperatures both upward (e.g., upstream power plants or shallow reservoirs) and downward (e.g., deepwater releases from large reservoirs), so that "ambient" and "natural" are exceedingly difficult to define at a given point over periods of several years.

Criteria for temperature should consider both the multiple thermal requirements of aquatic species and requirements for balanced communities. The number of distance requirements and the necessary values for each require periodic reexamination as knowledge of thermal effects on aquatic species and communities increases. Currently definable requirements include:

- maximum sustained temperatures that are consistent with maintaining desirable levels of productivity;
- maximum levels of metabolic acclimation to warm temperatures that will permit return to ambient winter temperatures should artificial sources of heat cease;
- temperature limitations for survival of brief exposures to temperature extremes, both upper and lower;
- restricted temperature ranges for various stages of reproduction, including (for fish) gonad growth and gamete maturation, spawning migration, release of gametes, development of the embryo, commencement of independent feeding (and other activities) by juveniles; and temperatures required for metamorphosis, emergence, and other activities of lower forms;
- thermal limits for diverse compositions of species of aquatic communities, particularly where reduction in diversity creates nuisance growths of certain organisms, or where important food sources or chains are altered;
- thermal requirements of downstream aquatic life where upstream warming of a cold-water source will adversely affect downstream temperature requirements.

Thermal criteria must also be formulated with knowledge of how man alters temperatures, the hydrodynamics of the changes, and how the biota can reasonably be expected to interact with the thermal regimes produced. It is not sufficient, for example, to define only the thermal criteria for sustained production of a species in open waters, because large numbers of organisms may also be exposed to thermal changes by being pumped through the condensers and mixing zone of a power plant. Design engineers need particularly to know the biological limitations to their design options in such instances. Such considerations may reveal nonthermal impacts of cooling processes that may outweigh temperature effects, such as impingement of fish upon intake screens, mechanical or chemical damage to zooplankton in condensers, or effects of altered current patterns on bottom fauna in a discharge area. The environmental situations of aquatic organisms (e.g., where they are, when they are there, in what numbers) must also be understood. Thermal criteria for migratory species should be applied to a certain area only when the species is actually there. Although thermal effects of power stations are currently of great interest, other less dramatic causes of temperature change including deforestation, stream channelization, and impoundment of flowing water must be recognized.

DEVELOPMENT OF CRITERIA

Thermal criteria necessary for the protection of species or communities are discussed separately below. The order of presentation of the different criteria does not imply priority for any one body of water. The descriptions define preferred methods and procedures for judging thermal requirements, and generally do not give numerical values (except in Appendix II-C). Specific values for all limitations would require a biological handbook that is far beyond the scope of this Section. The criteria may seem complex, but they represent an extensively developed framework of knowledge about biological responses. (A sample application of these criteria begins on page 166, Use of Temperature Criteria.)

TERMINOLOGY DEFINED

Some basic thermal responses of aquatic organisms will be referred to repeatedly and are defined and reviewed briefly here. Effects of heat on organisms and aquatic communities have been reviewed periodically (e.g., Bullock 1955,[259] Brett 1956;[253] Fry 1947,[276] 1964,[278] 1967;[279] Kinne 1970[296]). Some effects have been analyzed in the context of thermal modification by power plants (Parker and Krenkel 1969;[308] Krenkel and Parker 1969;[298] Cairns 1968;[261] Clark 1969;[263] and Coutant 1970c[269]). Bibliographic information is available from Kennedy and Mihursky (1967),[294] Raney and Menzel (1969),[313] and from annual reviews published by the Water Pollution Control Federation (Coutant 1968,[265] 1969,[266] 1970a,[267] 1971[270]).

Each species (and often each distinct life-stage of a species) has a characteristic tolerance range of temperature as a consequence of acclimations (internal biochemical adjustments) made while at previous holding temperature (Figure III-2; Brett 1956[253]). Ordinarily, the ends of this range, or the lethal thresholds, are defined by survival of 50 per cent of a sample of individuals. Lethal thresholds typically are referred to as "incipient lethal temperatures," and temperature beyond these ranges would be considered "ex-

treme." The tolerance range is adjusted upward by acclimation to warmer water and downward to cooler water, although there is a limit to such accommodation. The lower end of the range usually is at zero degrees centigrade (32 F) for species in temperate latitudes (somewhat less for saline waters), while the upper end terminates in an "ultimate incipient lethal temperature" (Fry et al. 1946[281]). This ultimate threshold temperature represents the "breaking point" between the highest temperatures to which an animal can be acclimated and the lowest of the extreme temperatures that will kill the warm-acclimated organism. Any rate of temperature change over a period of minutes

After Brett 1952 [252]

FIGURE III-3—Median resistance times to high temperatures among young chinook (Oncorhynchus tshawytscha) acclimated to temperatures indicated. Line A-B denotes rising lethal threshold (incipient lethal temperatures) with increasing acclimation temperature. This rise eventually ceases at the ultimate lethal threshold (ultimate upper incipient lethal temperature), line B-C.

After Brett 1960 [254]

FIGURE III-2—Upper and lower lethal temperatures for young sockeye salmon (Oncorhynchus nerka) plotted to show the zone of tolerance. Within this zone two other zones are represented to illustrate (1) an area beyond which growth would be poor to none-at-all under the influence of the loading effect of metabolic demand, and (2) an area beyond which temperature is likely to inhibit normal reproduction.

to a few hours will not greatly affect the thermal tolerance limits, since acclimation to changing temperatures requires several days (Brett 1941).[251]

At the temperatures above and below the incipient lethal temperatures, survival depends not only on the temperature but also on the duration of exposure, with mortality occurring more rapidly the farther the temperature is from the threshold (Figure III-3). (See Coutant 1970a[267] and 1970b[268] for further discussion based on both field and laboratory studies.) Thus, organisms respond to extreme high and low temperatures in a manner similar to the dosage-response pattern which is common to toxicants, pharmaceuticals, and radiation (Bliss 1937).[249] Such tests seldom extend beyond one week in duration.

MAXIMUM ACCEPTABLE TEMPERATURES FOR PROLONGED EXPOSURES

Specific criteria for prolonged exposure (1 week or longer) must be defined for warm and for cold seasons. Additional criteria for gradual temperature (and life cycle) changes during reproduction and development periods are discussed on pp. 162–165.

SPRING, SUMMER, AND FALL MAXIMA FOR PROLONGED EXPOSURE

Occupancy of habitats by most aquatic organisms is often limited within the thermal tolerance range to temperatures somewhat below the ultimate upper incipient lethal temperature. This is the result of poor physiological performance at near lethal levels (e.g., growth, metabolic scope for activities, appetite, food conversion efficiency), interspecies competition, disease, predation, and other subtle ecological factors (Fry 1951;[277] Brett 1971[256]). This complex limitation is evidenced by restricted southern and altitudinal distributions of many species. On the other hand, optimum temperatures (such as those producing fastest growth rates) are not generally necessary at all times to maintain thriving populations and are often exceeded in nature during summer months (Fry 1951;[277] Cooper 1953;[264] Beyerle and Cooper 1960;[246] Kramer and Smith 1960[297]). Moderate temperature fluctuations can generally be tolerated as long as a maximum upper limit is not exceeded for long periods.

A true temperature limit for exposures long enough to reflect metabolic acclimation and optimum ecological performance must lie somewhere between the physiological optimum and the ultimate upper incipient lethal temperatures. Brett (1960)[254] suggested that a provisional long-term exposure limit be the temperature greater than optimum that allowed 75 per cent of optimum performance. His suggestion has not been tested by definitive studies.

Examination of literature on performance, metabolic rate, temperature preference, growth, natural distribution, and tolerance of several species has yielded an apparently sound theoretical basis for estimating an upper temperature limit for long term exposure and a method for doing this with a minimum of additional research. New data will provide refinement, but this method forms a useful guide for the present time. The method is based on the general observations summarized here and in Figure III-4(a, b, c).

1. Performances of organisms over a range of temperatures are available in the scientific literature for a variety of functions. Figures III-4a and b show three characteristic types of responses numbered 1 through 3, of which types 1 and 2 have coinciding optimum peaks. These optimum temperatures are characteristic for a species (or life stage).

2. Degrees of impairment from optimum levels of various performance functions are not uniform with increasing temperature above the optimum for a single species. The most sensitive function appears to be growth rate, for which a temperature of zero growth (with abundant food) can be determined for important species and life stages. Growth rate of organisms appears to be an integrator of all factors acting on an organism. Growth rate should probably be expressed as net biomass gain or net growth (McCormick et al. 1971)[302] of the population, to account for deaths.

3. The maximum temperature at which several species are consistently found in nature (Fry 1951;[277] Narver 1970)[306] lies near the average of the optimum temperature and the temperature of zero net growth.

4. Comparison of patterns in Figures III-4a and b among different species indicates that while the trends are similar, the optimum is closer to the lethal level in some species than it is in sockeye salmon. Invertebrates exhibit a pattern of temperature effects on growth rate that is very similar to that of fish (Figure III-4c).

The optimum temperature may be influenced by rate of feeding. Brett et al. (1969)[257] demonstrated a shift in optimum toward cooler temperatures for sockeye salmon when ration was restricted. In a similar experiment with channel catfish, Andrews and Stickney (1972)[242] could see no such shift. Lack of a general shift in optimum may be due to compensating changes in activity of the fish (Fry *personal observation*).[326]

These observations suggest that an average of the optimum temperature and the temperature of zero net growth [(opt. temp. + z.n.g. temp.)/2] would be a useful estimate of a limiting weekly mean temperature for resident organisms, providing the peak temperatures do not exceed values recommended for short-term exposures. Optimum growth rate would generally be reduced to no lower than 80 per cent of the maximum if the limiting temperature is as averaged above (Table III-11). This range of reduction from optimum appears acceptable, although there are no quantitative studies available that would allow the criterion to be based upon a specific level of impairment.

The criteria for maximum upper temperature must allow for seasonal changes, because different life stages of many species will have different thermal requirements for the average of their optimum and zero net growths. Thus a juvenile fish in May will be likely to have a lower maximum acceptable temperature than will the same fish in July, and this must be reflected in the thermal criteria for a waterbody.

TABLE III-11—*Summary of Some Upper Limiting Temperatures in C, (for periods longer than one week) Based Upon Optimum Temperatures and Temperatures of Zero Net Growth.*

Species	Optimum	Zero net growth	Reference	$\frac{opt+z.n.g.}{2}$	% of optimum
Catostomus commersoni (white sucker)	27	29.6	*	28.3	86
Coregonus artedii (cisco or lake herring)	16	21.2	McCormick et al. 1971[302]	18.6	82
Ictalurus punctatus (channel catfish)	30	35.7	Strawn 1970[290]	32.8	94
"	30	35.7	Andrews and Stickney 1972[242]	32.8	88
Lepomis macrochirus (bluegill) (year II)	22	28.5	McComish 1971[301]	25.3	82
Micropterus salmoides (largemouth bass)	27.5	34	Strawn 1961[319]	30.8	83
Notropis atherinoides (emerald shiner)	27	33	*	30.5	83
Salvelinus fontinalis (brook trout)	15.4	18.8	*	17.1	80

*National Water Quality Laboratory, Duluth, Minn., unpublished data.[326]
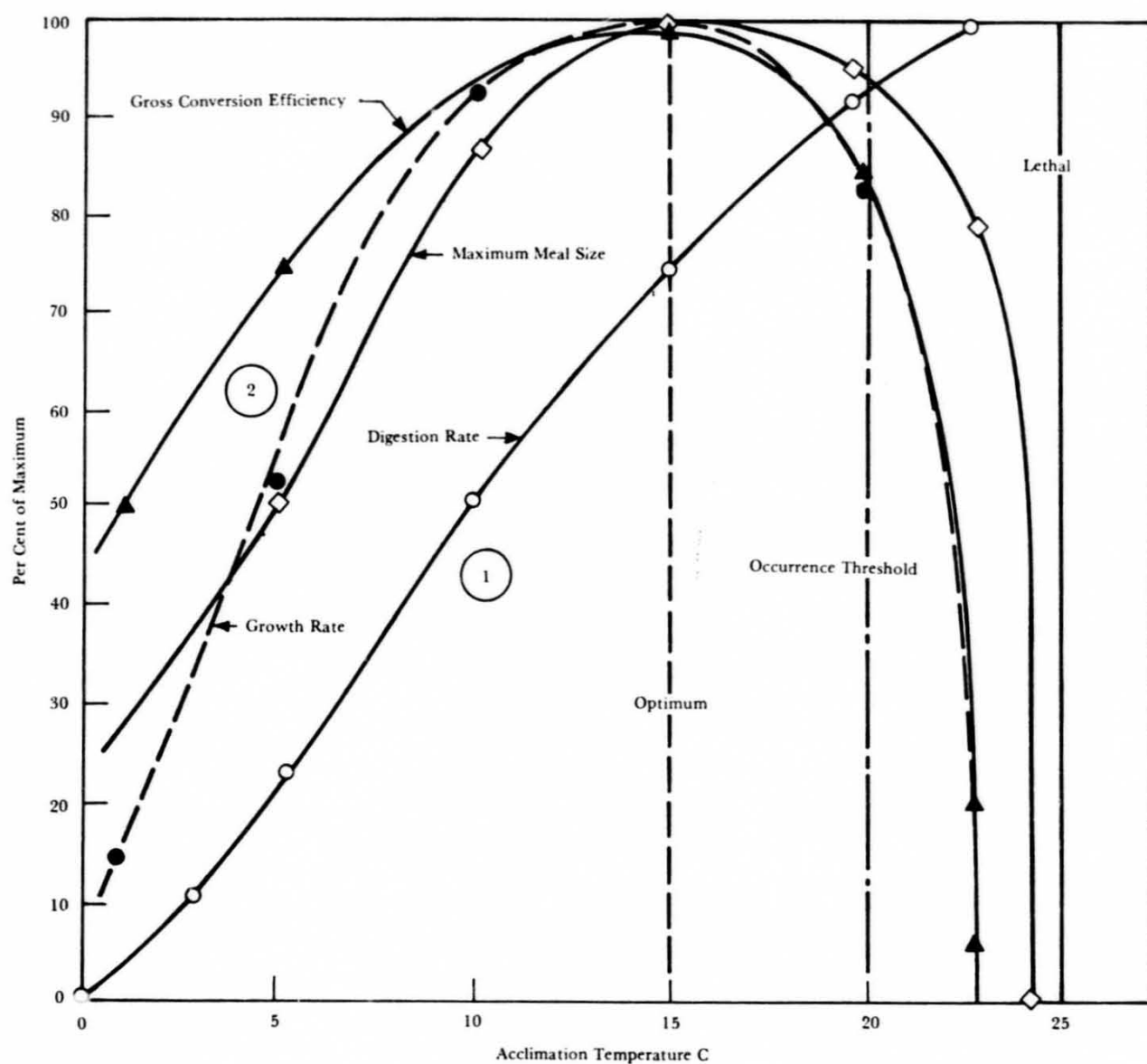
After Brett 1971[256]

FIGURE III–4a—*Performance of Sockeye Salmon* (Oncorhynchus nerka) *in Relation to Acclimation Temperature*

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While this approach to developing the maximum sustained temperature appears justified on the basis of available knowledge, few limits can be derived from existing data in the literature on zero growth. On the other hand, there is a sizeable body of data on the ultimate incipient lethal temperature that could serve as a substitute for the data on temperature of zero net growth. A practical consideration in recommending criteria is the time required to conduct
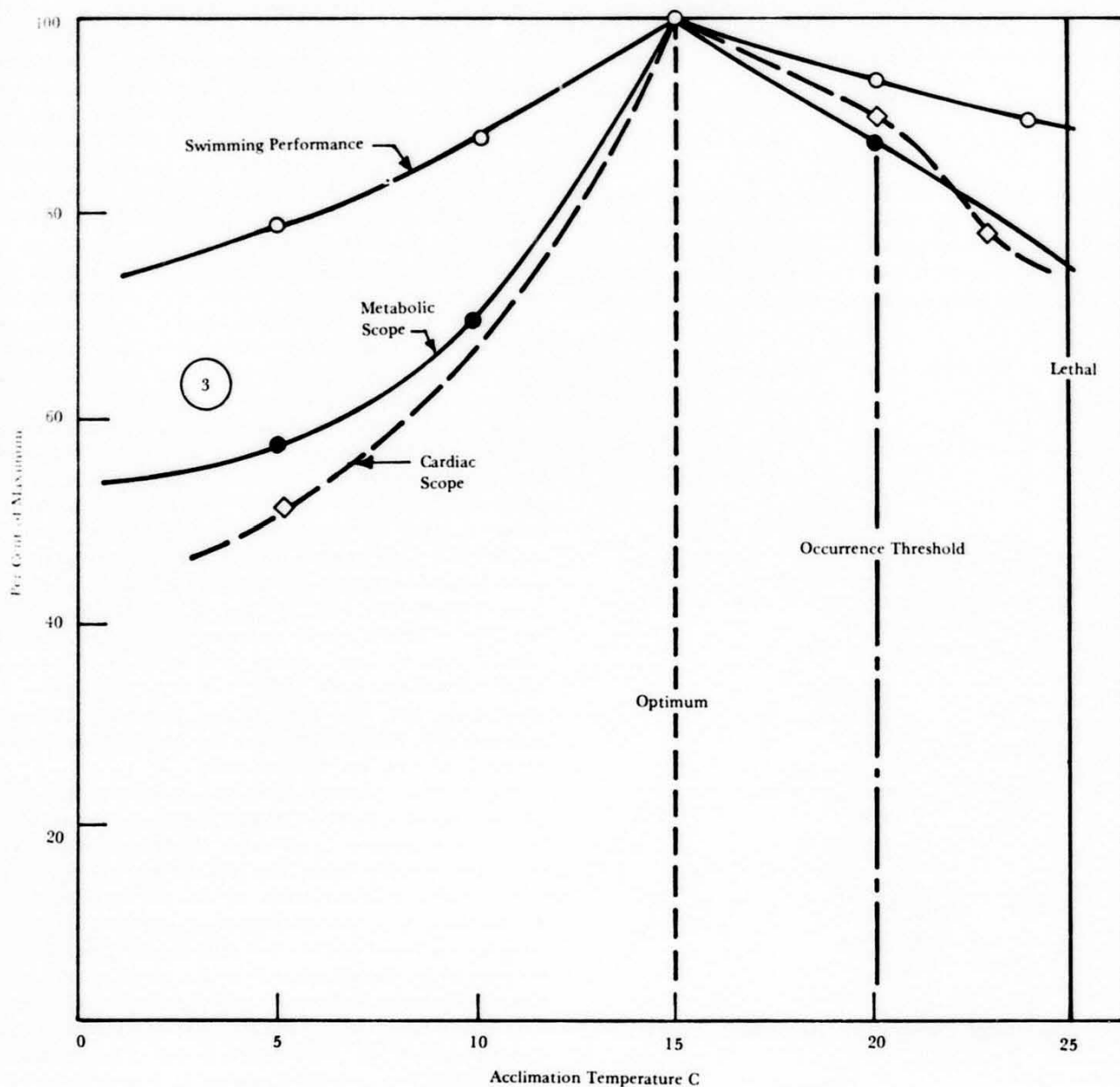
After Brett 1971[256]

FIGURE III-4b—Performance of Sockeye Salmon (Oncorhynchus nerka) in Relation to Acclimation Temperature

research necessary to provide missing data. Techniques for determining incipient lethal temperatures are standardized (Brett 1952)[252] whereas those for zero growth are not.

A temperature that is one-third of the range between the optimum temperature and the ultimate incipient lethal temperature that can be calculated by the formula

$$\text{optimum temp.} + \frac{\text{ultimate incipient lethal temp.} - \text{optimum temp.}}{3}$$

(Equation I)

yields values that are very close to (optimum temp. + z.n.g. temp.)/2. For example, the values are, respectively, 32.7 and 32.8 C for channel catfish and 30.6 and 30.8 for largemouth bass (data from Table III-8 and Appendix II). This formula offers a practical method for obtaining allowable limits, while retaining as its scientific basis the requirements of preserving adequate rates of growth. Some limits obtained from data in the literature are given in Table III-12. A hypothetical example of the effect of this limit on growth of largemouth bass is illustrated in Figure III-5.

Figure III-5 shows a hypothetical example of the effects of the limit on maximum weekly average temperature on growth rates of juvenile largemouth bass. Growth data as a function of temperature are from Strawn 1961[319]; the ambient temperature is an averaged curve for Lake Norman, N. C., adapted from data supplied by Duke Power Company. A general temperature elevation of 10 F is used to provide an extreme example. Incremental growth rates (mm/wk) are plotted on the main figure, while annual accumulated growth is plotted in the inset. Simplifying assumptions were that growth rates and the relationship of growth rate to temperature were constant throughout the year, and that there would be sufficient food to sustain maximum attainable growth rates at all times.

The criterion for a specific location would be determined by the most sensitive life stage of an important species likely to be present in that location at that time. Since many fishes have restricted habitats (e.g., specific depth zones) at many life stages, the thermal criterion must be applied to the proper zone. There is field evidence that fish avoid localized areas of unfavorably warm water. This has been demonstrated both in lakes where coldwater fish normally evacuate warm shallows in summer (Smith 1964)[318] and at power station mixing zones (Gammon 1970;[282] Merriman et al. 1965).[304] In most large bodies of water there are both vertical and horizontal thermal gradients that mobile organisms can follow to avoid unfavorable high (or low) temperatures.

The summer maxima need not, therefore, apply to mixing zones that occupy a small percentage of the suitable habitat or necessarily to all zones where organisms have free egress to cooler water. The maxima must apply, however, to restricted local habitats, such as lake hypolimnia or thermoclines, that provide important summer sanctuary areas for cold-water species. Any avoidance of a warm area not part of the normal seasonal habitat of the species will mean that less area of the water body is available to support the population and that production may be reduced. Such reduction should not interfere with biological communities or populations of important species to a degree that is damaging to the ecosystem or other beneficial uses. Non-mobile organisms that must remain in the warm zone will probably be the limiting organisms for that location. Any recommendation for upper limiting temperatures must be applied carefully with understanding of the population dynamics of the species in question in order to establish both local and regional requirements.
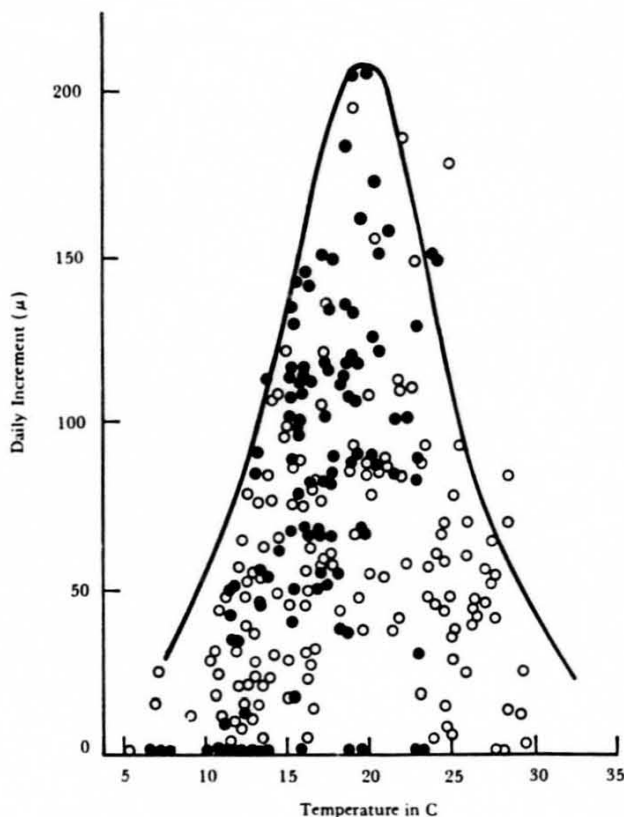
Ansell 1968 [243]

FIGURE III-4c—M. mercenaria: *The general relationship between temperature and the rate of shell growth, based on field measurements of growth and temperature.*

●: *sites in Poole Harbor, England;* ○: *North American sites.*

Annual Accumulated Growth

Elevated (with limit)

Elevated (without limit)

Ambient

Accumulated growth (mm)

250

200

150

60

50

2 4 6 8 10 12

Weeks

Ambient + 10 F

Average Ambient
(Lake Norman, N.C.)

Weekly Growth Rate
(Ambient + 10 F)

Weekly Growth Rate
(Ambient)

Growth (mm/wk)

10

9

8

7

6

5

4

3

2

0 7 14 21 28 4 11 18 25 4 11 18 25 1 8 15 22 29 6 13 20 27 3 10 17 24 1

JAN.   FEB.   MAR.   APR.   MAY   JUNE

35
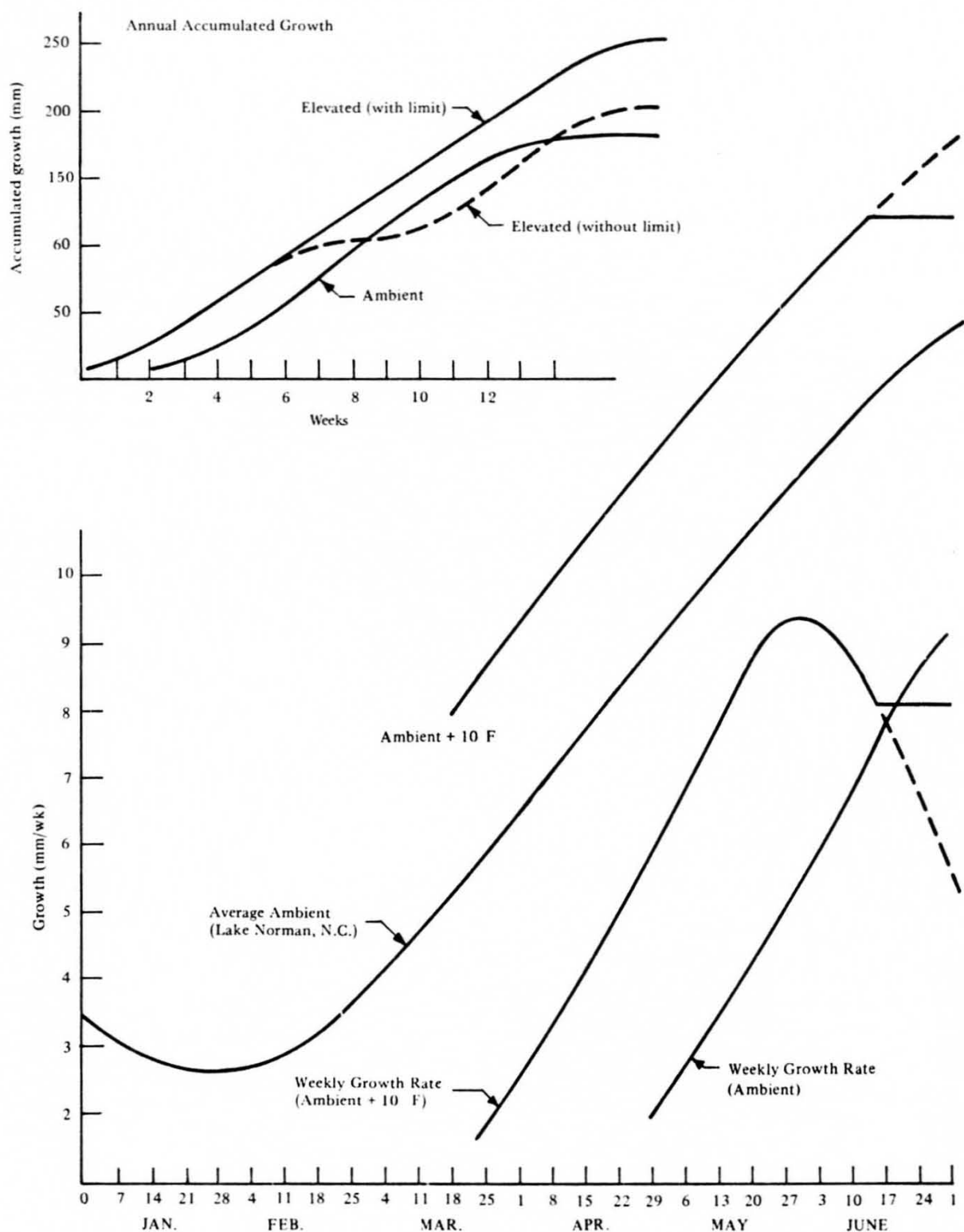
FIGURE III-5—*A hypothetical example of the effects of the limit on maximum weekly average temperature on growth rates of juvenile largemouth bass. Growth data as a function of temperature are from Strawn 1961; the ambient temperature is an averaged curve for Lake Norman, N.C., adapted from data supplied by Duke Power Company. A general temperature elevation of 10 F is used to provide an extreme example. Incremental growth rates (mm/wk) are plotted on the main figure, while annual accumulated growth is plotted in the inset. Simplifying assumptions were that growth rates and the relationship of growth rate to temperature were constant throughout the year, and that there would be sufficient food to sustain maximum attainable growth rates at all times.*

Max. Weekly Avg., largemouth bass

with limit

Incremental
Growth Rates
(mm/wk)

without limit

Temperature (C)

38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4

3 15 22 29 5 12 19 26 2 9 16 23 30 7 14 21 28 4 11 18 25 2 9 16 23 30

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TABLE III-12—*Summary of Some Upper Limiting Temperatures for Prolonged Exposures of Fishes Based on Optimum Temperatures and Ultimate Upper Incipient Lethal Temperatures (Equation 1).*

Species	Optimum		Function	Reference	Ultimate upper incipient lethal temperature		Reference	Maximum weekly average temperature (Eq. 1)	
	C	F			C	F		C	F
Catostomus commersoni (white sucker)	27	80.6	growth	unpubl., NWQL[328]	29.3	84.7	Hart 1947[285]	27.8	82
Coregonus artedii (Cisco or lake herring)	16	60.8	growth	McCormick et al. 1971[308]	25.7	78.3	Edsall and Colby 1970[274]	19.2	66.6
Ictalurus punctatus (channel catfish)	30	86	growth	Strawn 1970;[320] Andrews and Stickney 1971[242]	38.0	100.4	Allen and Strawn 1968[240]	32.7	90.9
Lepomis macrochirus (bluegill) (yr II)	22	71.6	growth	McComish 1971[301] Anderson 1959[241]	33.8	92.8	Hart 1952[286]	25.9	78.6
Micropterus dolomieu (smallmouth bass)	26.3	83	growth	Horning and Pearson 1972[291]	35.0	95.0	Horning and Pearson 1972[291]	29.9	85.8
	28.3	83	growth	Peek 1965[309]					
	ave 27.3	81.1							
Micropterus salmoides (largemouth bass)(fry)	27.5	81.5	growth	Strawn 1961[319]	36.4	97.5	Hart 1952[286]	30.5	86.7
Notropis atherinoides (emerald shiner)	27	80.6	growth	unpubl., NWQL[328]	30.7	87.3	Hart 1952[286]	28.2	82.8
Oncorhynchus nerka (sockeye salmon)	15.0	59.0	growth	Brett et al. 1969[267]	25.0	77.0	Brett 1952[252]	18.3	64.9
	15.0	59.0	other functions	Brett 1971[256]					
(juveniles)	15.0		max. swimming						
Pseudopleuronectes Americanus (winter flounder)	18.0	64.4	growth	Brett 1970[255]	29.1	84.4	Hoff and Westman 1966[289]	21.8	71.2
Salmo trutta (brown trout)	8 to 17	54.5	growth	Brett 1970[255]	23.5	74.3	Bishai 1960[247]	16.2	61.2
	ave 12.5								
Salvelinus fontinalis (brook trout)	15.4	59.7	growth	unpubl., NWQL[328]	25.5	77.9	Fry, Hart and Walker, 1946[281]	18.2	64.8
	13.0	55.4	growth	Baldwin 1957[244]					
	15	59	metabolic	Graham 1949[284]					
	ave 14.5	58.1	scope						
Salvelinus namaycush (lake trout)	16	60.8	scope for activity (2 metabolism)	Gibson and Fry 1954[283]	23.5		Gibson and Fry 1954[283]	18.8	65.8
	17	62.6	swimming speed						
	ave 16.5	61.7							

Heat added to upper reaches of some cold rivers can be retained throughout the river's remaining length (Jaske and Synoground 1970).[292] This factor adds to the natural trend of warming at distances from headwaters. Thermal additions in headwaters, therefore, may contribute substantially to reduction of cold-water species in downstream areas (Mount 1970).[305] Upstream thermal additions should be evaluated for their effects on summer maxima at downstream locations, as well as in the immediate vicinity of the heat source.

Recommendation

Growth of aquatic organisms would be maintained at levels necessary for sustaining actively growing and reproducing populations if the maximum weekly average temperature in the zone inhabited by the species at that time does not exceed one-third of the range between the optimum temperature and the ultimate upper incipient lethal temperature of the species (Equation 1, page 157), and the temperatur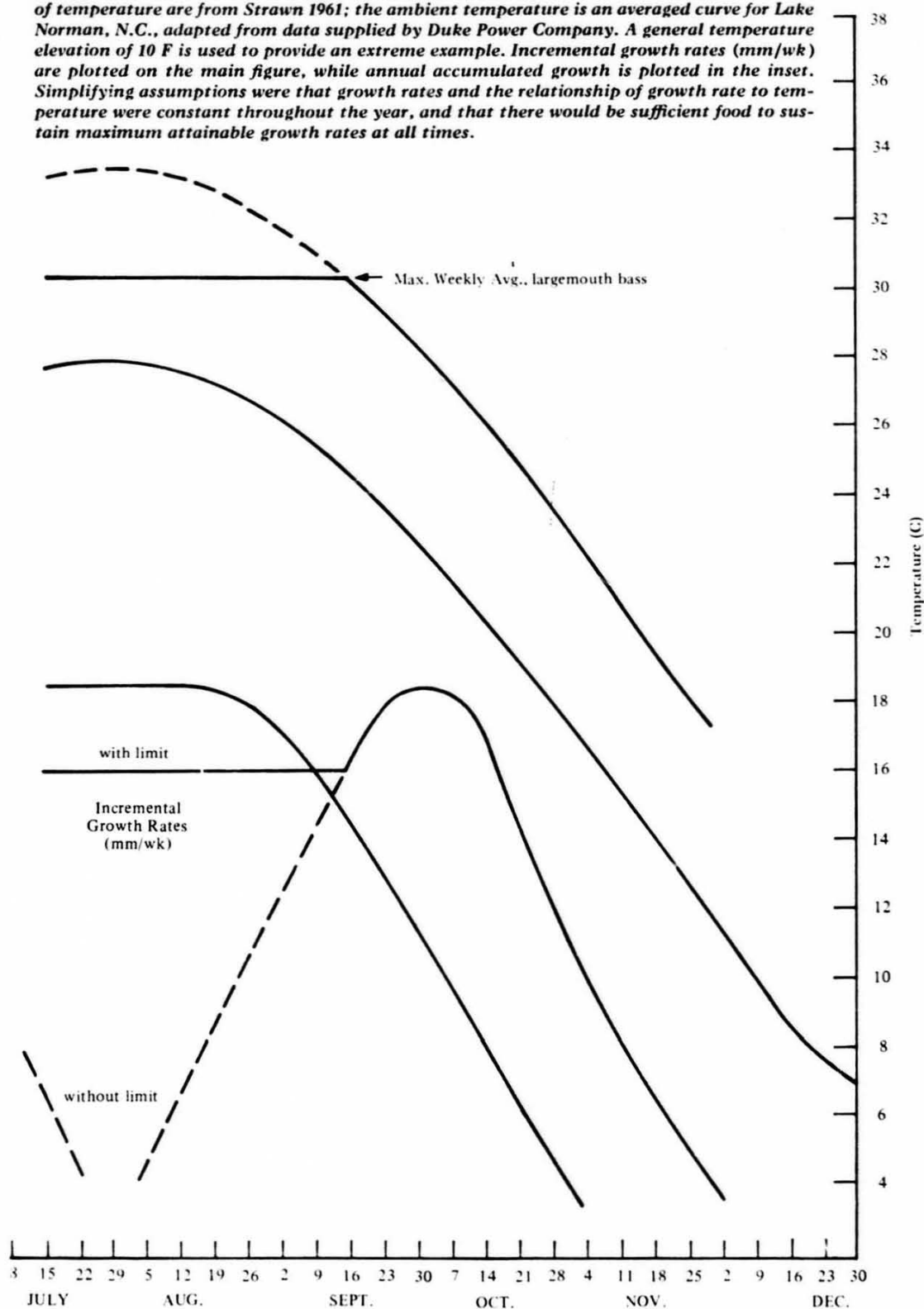es above the weekly average do not exceed the criterion for short-term exposures. This maximum need not apply to acceptable mixing zones (see proportional relationships of mixing zones to receiving systems, p. 114), and must be applied with adequate understanding of the normal seasonal distribution of the important species.

WINTER MAXIMA

Although artificially produced temperature elevations during winter months may actually bring the temperature closer to optimum or preferred temperature for important species and attract fish (Trembley 1965),[321] metabolic acclimation to these higher levels can preclude safe return of the organism to ambient temperatures should the artificial heating suddenly cease (Pennsylvania Fish Commission 1971;[310] Robinson 1970)[316] or the organism be driven from the heat area. For example, sockeye salmon (*Oncorhynchus nerka*) acclimated to 20 C suffered 50 percent mortality in the laboratory when their temperature was dropped suddenly to 5 C (Brett 1971:[256] see Figure III-3). The same population of fish withstood a drop to zero when acclimated to 5 C. The lower limit of the range of thermal tolerance of important species must, therefore, be maintained at the normal seasonal ambient temperatures throughout cold seasons, unless special provisions are made to assure that rapid temperature drop will not occur or that organisms cannot become acclimated to elevated temperatures. This can be accomplished by limitations on temperature elevations in such areas as discharge canals and mixing zones where organisms may reside, or by insuring that maximum temperatures occur only in areas not accessible to important aquatic life for lengths of time sufficient to allow metabolic acclimation. Such inaccessible areas would include the high-velocity zones of diffusers or screened dis-

charge channels. This reduction of maximum temperatures would not preclude use of slightly warmed areas as sites for intense winter fisheries.

This consideration may be important in some regions at times other than in winter. The Great Lakes, for example, are susceptible to rapid changes in elevation of the thermocline in summer which may induce rapid decreases in shoreline temperatures. Fish acclimated to exceptionally high temperatures in discharge canals may be killed or severely stressed without changes in power plant operations (Robinson 1968).[314] Such regions should take special note of this possibility.

Some numerical values for acclimation temperatures and lower limits of tolerance ranges (lower incipient lethal temperatures) are given in Appendix II-C. Other data must be provided by further research. There are no adequate data available with which to estimate a safety factor for no stress from cold shocks. Experiments currently in progress, however, suggest that channel catfish fingerlings are more susceptible to predation after being cooled more than 5 to 6 C (Coutant, *unpublished data*).[324]

The effects of limiting ice formation in lakes and rivers should be carefully observed. This aspect of maximum winter temperatures is apparent, although there is insufficient evidence to estimate its importance.

Recommendation

Important species should be protected if the maximum weekly average temperature during winter months in any area to which they have access does not exceed the acclimation temperature (minus a 2 C safety factor) that raises the lower lethal threshold temperature of such species above the normal ambient water temperatures for that season, and the criterion for short-term exposures is not exceeded. This recommendation applies especially to locations where organisms may be attracted from the receiving water and subjected to rapid thermal drop, as in the low velocity areas of water diversions (intake or discharge), canals, and mixing zones.

SHORT-TERM EXPOSURE TO EXTREME TEMPERATURE

To protect aquatic life and yet allow other uses of the water, it is essential to know the lengths of time organisms can survive extreme temperatures (i.e., temperatures that exceed the 7-day incipient lethal temperature). Both natural environments and power plant cooling systems can briefly reach temperature extremes (both upper and lower) without apparent detrimental effect to the aquatic life (Fry 1951;[277] Becker et al. 1971).[245]

The length of time that 50 per cent of a population will survive temperature above the incipient lethal temperature

can be calculated from a regression equation of experimental data (such as those in Figure III-3) as follows:

$$\log (time) = a + b (temp.) \qquad (Equation\ 2)$$

where time is expressed in minutes, temperature in degrees centigrade and where a and b are intercept and slope, respectively, which are characteristics of each acclimation temperature for each species. In some cases the time-temperature relationship is more complex than the semilogarithmic model given above. Equation 2, however, is the most applicable, and is generally accepted by the scientific 'community (Fry 1967).[279] Caution is recommended in extrapolating beyond the data limits of the original research (Appendix II-C). The rate of temperature change does not appear to alter this equation, as long as the change occurs more rapidly than over several days (Brett 1941;[251] Lemke 1970).[300] Thermal resistance may be diminished by the simultaneous presence of toxicants or other debilitating factors (Ebel et al. 1970,[273] and summary by Coutant 1970c).[269] The most accurate predictability can be derived from data collected using water from the site under evaluation.

Because the equations based on research on thermal tolerance predict 50 per cent mortality, a safety factor is needed to assure no mortality. Several studies have indicated that a 2 C reduction of an upper stress temperature results in no mortalities within an equivalent exposure duration (Fry et al. 1942;[250] Black 1953).[248] The validity of a two degree safety factor was strengthened by the results of Coutant (1970a).[267] He showed that about 15 to 20 per cent of the exposure time, for median mortality at a given high temperature, induced selective predation on thermally shocked salmon and trout. (This also amounted to reduction of the effective stress temperature by about 2 C.) Unpublished data from subsequent predation experiments showed that this reduction of about 2 C also applied to the incipient lethal temperature. The level at which there is no increased vulnerability to predation is the best estimate of a no-stress exposure that is currently available. No similar safety factor has been explored for tolerance of low temperatures. Further research may determine that safety factors, as well as tolerance limits, have to be decided independently for each species, life stage, and water quality situation.

Information needed for predicting survival of a number of species of fish and invertebrates under short-term conditions of heat extremes is presented in Appendix II-C. This information includes (for each acclimation temperature) upper and lower incipient lethal temperatures: coefficients a and b for the thermal resistance equation; and information on size, life stage, and geographic source of the species. It is clear that adequate data are available for only a small percentage of aquatic species, and additional research is necessary. Thermal resistance information should be obtained locally for critical areas to account for simul-

taneous presence of toxicants or other debilitating factors, a consideration not reflected in Appendix II-C data. More data are available for upper lethal temperatures than for lower.

The resistance time equation, Equation 2, can be rearranged to incorporate the 2 C margin of safety and also to define conditions for survival (right side of the equation less than or equal to 1) as follows:

$$1 \geq \frac{time}{10^{[a+b(temp.+2)]}} \qquad (Equation\ 3)$$

Low levels of mortality of some aquatic organisms are not necessarily detrimental to ecosystems, because permissible mortality levels can be established. This is how fishing or shellfishing activities are managed. Many states and international agencies have established elaborate systems for setting an allowable rate of mortality (for sport and commercial fish) in order to assure needed reproduction and survival. (This should not imply, however, that a form of pollution should be allowed to take the entire harvestable yield.) Warm discharge water from a power plant may sufficiently stimulate reproduction of some organisms (e.g., zooplankton), such that those killed during passage through the maximally heated areas are replaced within a few hours, and no impact of the mortalities can be found in the open water (Churchill and Wojtalik 1969:[262] Heinle 1969).[288] On the other hand, Jensen (1971)[293] calculated that even five percent additional mortality of 0-age brook trout (Salvelinus fontinalis) decreased the yield of the trout fishery, and 50 per cent additional mortality would, theoretically, cause extinction of the population. Obviously, there can be no adequate generalization concerning the impact of short-term effects on entire ecosystems, for each case will be somewhat different. Future research must be directed toward determining the effects of local temperature stresses on population dynamics. A complete discussion will not be attempted here. Criteria for complete short-term protection may not always be necessary and should be applied with an adequate understanding of local conditions.

Recommendation

Unless there is justifiable reason to believe it unnecessary for maintenance of populations of a species, the right side of Equation 3 for that species should not be allowed to increase above unity when the temperature exceeds the incipient lethal temperature minus 2 C:

$$1 \geq \frac{time}{10^{[a+b(temp.+2)]}}$$

Values for *a* and *b* at the appropriate acclimation temperature for some species can be obtained from Appendix II–C or through additional research if necessary data are not available. This recommen-

dation applies to all locations where organisms to be protected are exposed, including areas within mixing zones and water diversions such as power station cooling water.

REPRODUCTION AND DEVELOPMENT

The sequence of events relating to gonad growth and gamete maturation, spawning migration, release of gametes, development of the egg and embryo, and commencement of independent feeding represents one of the most complex phenomena in nature, both for fish (Brett 1970)[255] and invertebrates (Kinne 1970).[296] These events are generally the most thermally sensitive of all life stages. Other environmental factors, such as light and salinity, often seasonal in nature, can also profoundly affect the response to temperature (Wiebe 1968).[323] The general physiological state of the organisms (e.g., energy reserves), which is an integration of previous history, has a strong effect on reproductive potential (Kinne 1970).[296] The erratic sequence of failures and successes of different year classes of lake fish attests to the unreliability of natural conditions for providing optimum reproduction.

Abnormal, short-term temperature fluctuations appear to be of greatest significance in reduced production of juvenile fish and invertebrates (Kinne, 1963).[295] Such thermal fluctuations can be a prominent consequence of water use as in hydroelectric power (rapid changes in river flow rates), thermal electric power (thermal discharges at fluctuating power levels), navigation (irregular lock releases), and irrigation (irregular water diversions and wasteway releases). Jaske and Synoground (1970)[292] have documented such temperature changes due to interacting thermal and hydroelectric discharges on the Columbia River.

Tolerable limits or variations of temperature change throughout development, and particularly at the most sensitive life stages, differ among species. There is no adequate summary of data on such thermal requirements for successful reproduction. The data are scattered through many years of natural history observations (however, see Breder and Rosen 1966[250] for a recent compilation of some data; also see Table III–13). High priority must be assigned to summarizing existing information and obtaining that which is lacking.

Uniform elevations of temperature by a few degrees during the spawning period, while maintaining short-term temperature cycles and seasonal thermal patterns, appear to have little overall effect on the reproductive cycle of resident aquatic species, other than to advance the timing for spring spawners or delay it for fall spawners. Such shifts are often seen in nature, although no quantitative measurements of reproductive success have been made in this connection. For example, thriving populations of many fishes occur in diverse streams of the Tennessee Valley in which the date of the spawning temperature may vary in a

TABLE III–13—Spawning Requirements of Some Fish, Arranged in Ascending Order of Spawning Temperatures
(Adapted from Wojtalik, T. A., unpublished manuscript)*

Fishes	Temp. (C)	Spawning site	Range in spawning depth	Daily spawning time	Egg site	Incubation period days (Temp. C)
Sauger						
Stizostedion canadense	5.0	Shallow gravel bars	2–4 feet	Night	Bottom	25 (5.0)
Walleye						
S. vitreum vitreum	7.0	Gravel, rubble, boulders on bar	3–10 feet	Day, night	Bottom	....
Longnose gar						
Lepisosteus osseus	10.8	Flooded shallows	Flooded shallows	Day	Weeds	6 (20.0)
White bass						
Morone chrysops	11.7	Sand & rock shores	2–12 feet	Day, long but esp. night	Surface	2 (15.6)
Least darter						
Etheostoma microperca	12.0			'		
Spotted sucker						
Minytrema melanops	12.8					
White sucker						
Catostomus commersoni	12.0–13.0	Streams or bars	....	Day, night	Bottom	....
Silvery minnow						
Hybognathus nuchalis	13.0	Coves	....	Day	Bottom	....
Banded pygmo sunfish						
Elassoma zonatum	13.9–16.7					
White crappie						
Pomoxis annularis	14.0–16.0	Submerged materials in shallows	....	Day	Bottom	1 (21.1–23.2)
Fathead minnow	14.4					
Pimephales promelas	25.0	Shallows	Nr. surface	Day	Underside floating objects	....
Bigmouth buffalo						
Ictiobus cyprinellus	15.6–18.3	Shallows	....	Day	Bottom	9–10 (18.7)
Largemouth bass						
Micropterus salmoides	15.6	Shallows near bank	30 inches	Day	Bottom	5 (18.9)
Common shiner						
Notropis cornutus	15.6–18.3	Small gravel streams	....	Day	Bottom	
Golden shiner						
Notemigonus crysoleucas	15.6	Bays & shoals, weeds	....	Day	Weeds	4 (15.6+)
Green sunfish						
Lepomis cyanellus	15.6	Bank, shallows	Inches to 1½ feet	Day	Bottom	....
Paddlefish						
Polyodon spathula	16.0	Over gravel bars	Nr. surface	Night, day	Bottom	....
Blackside darter						
Percina maculata	16.5					
Gizzard shad						
Dorosoma cepedianum	16.7					
Smallmouth bass						
Micropterus dolomieui	18.7	Gravel rock shore	3–20 feet	Day	Bottom	7 (15.0)
Spotted bass						
Micropterus punctulatus	17.8	Small streams, bar	....	Day	Bottom	4–5 (20.0)
Johnny darter						
Etheostoma nigrum	18.0					
Orange spotted sunfish						
Lepomis humilis	18.3					
Smallmouth buffalo						
Ictiobus bubalus	18.9					
Black buffalo						
I. niger	18.9					
Carp						
Cyprinus carpio	19.0	Flooded shallows	Nr. surface	Day night	Bottom	4–8 (16.7)
Bluegill						
Lepomis macrochirus	19.4	Weeds, shallows	2–6 feet	Day	Bottom	1½–3 (22.2)
Redbreast sunfish						
L. auritis	20.0					
Channel catfish	20.0					
Ictalurus punctatus	26.7	Bank cavity	<10 feet	Day, night	Bottom	9–10 (15.0)
White catfish						
I. catus	20.0	Sand gravel bar	<10 feet	Day	Bottom	6–7 (23.9–29.4)
Pumpkinseed						
Lepomis gibbosus	20.0	Bank shallows	<5 feet	Day	Bottom	3 (27.8)
Black crappie						
Pomoxis nigromaculatus	20.0					
Brook silverside						
Labidesthes sicculus	20.0	Over gravel	Surface	Day	Weeds, bottom	....
Brown bullhead						
Ictalurus nebulosus	21.1	Shallows, weeds	Inches to 6 feet	....	Weeds, bottom	5 (25.0)
Threadfin shad						
Dorosoma petenense	21.1	Shallow and open water	Surface	Day	Bottom	3 (26.7)
Warmouth						
Lepomis gulosus	21.0	Bank shallows	<5 feet	Day	Bottom	1½ (25.0–26.7)
River redhorse						
Moxostoma carinatum	21.7–24.4	Riffles, streams	....	Day	Bottom	....

TABLE III-13—Spawning Requirements of Some Fish, Arranged in Ascending Order of Spawning Temperatures—Continued

Fishes	Temp. (C)	Spawning site	Range in spawning depth	Daily spawning time	Egg site	Incubation period days (Temp. C)
Blue catfish						
Ictalurus furcatus	22.2					
Flathead catfish						
Pylodictis olivaris	22.2					
Redear sunfish						
Lepomis microlophus	23.0	Quiet, various	Inches to 10 feet			
Longear sunfish						
L. megalotis	23.3					
Freshwater drum						
Aplodinotus grunniens	23.0					
River carpsucker						
Carpoides carpio	23.9					
Spotted bullhead						
Ictalurus serracanthus	26.7					
Yellow bullhead						
I. natalis		Quiet, shallows	1' -4 feet		Bottom	5-10 (18.9)

T. A. Wojtalik, Tennessee Valley Authority, Muscle Shoals, Alabama.[329]

given year by 22 to 65 days. Examination of the literature shows that shifts in spawning dates by nearly one month are common in natural waters throughout the U.S. Populations of some species at the southern limits of their distribution are exceptions, e.g., the lake whitefish (*Coregonus clupeaformis*) in Lake Erie that require a prolonged, cold incubation period (Lawler 1965)[299] and species such as yellow perch (*Perca flavescens*) that require a long chill period for egg maturation prior to spawning (Jones, *unpublished data*).[327]

This biological plasticity suggests that the annual spring rise, or fall drop, in temperature might safely be advanced (or delayed) by nearly one month in many regions, as long as the thermal requirements that are necessary for migration, spawning, and other activities are not eliminated and the necessary chill periods, maturation times, or incubation periods are preserved for important species. Production of food organisms may advance in a similar way, with little disruption of food chains, although there is little evidence to support this assumption (but see Coutant 1968;[265] Coutant and Steele 1968;[271] and Nebeker 1971).[307] The process is similar to the latitudinal differences within the range of a given species.

Highly mobile species that depend upon temperature synchrony among widely different regions or environments for various phases of the reproductive or rearing cycle (e.g., anadromous salmonids or aquatic insects) could be faced with dangers of dis-synchrony if one area is warmed, but another is not. Poor long-term success of one year class of Fraser River (British Columbia) sockeye salmon (*Oncorhynchus nerka*) was attributed to early (and highly successful) fry production and emigration during an abnormally warm summer followed by unsuccessful, premature feeding activity in the cold and still unproductive estuary (Vernon 1958).[322] Anadromous species are able, in some cases, (see studies of eulachon (*Thaleichthys pacificus*) by Smith and

Saalfeld 1955)[317] to modify their migrations and spawning to coincide with the proper temperatures whenever and wherever they occur.

Rates of embryonic development that could lead to premature hatching are determined by temperatures of the microhabitat of the embryo. Temperatures of the microhabitat may be quite different from those of the remainder of the waterbody. For example, a thermal effluent at the temperature of maximum water density (approximately 4 C) can sink in a lake whose surface water temperature is colder (Hoglund and Spigarelli, 1972).[290] Incubating eggs of such species as lake trout (*Salvelinus namaycush*) and various coregonids on the lake bottom may be intermittently exposed to temperatures warmer than normal. Hatching may be advanced to dates that are too early for survival of the fry in their nursery areas. Hoglund and Spigarelli 1972,[290] using temperature data from a sinking plume in Lake Michigan, theorized that if lake herring (*Coregonus artedii*) eggs had been incubated at the location of one of their temperature sensors, the fry would have hatched seven days early. Thermal limitations must, therefore, apply at the proper location for the particular species or life stage to be protected.

Recommendations

After their specific limiting temperatures and exposure times have been determined by studies tailored to local conditions, the reproductive activity of selected species will be protected in areas where:

- **periods required for gonad growth and gamete maturation are preserved;**
- **no temperature differentials are created that block spawning migrations, although some delay or advancement of timing based upon local conditions may be tolerated;**

- temperatures are not raised to a level at which necessary spawning or incubation temperatures of winter-spawning species cannot occur;
- sharp temperature changes are not induced in spawning areas, either in mixing zones or in mixed water bodies (the thermal and geographic limits to such changes will be dependent upon local requirements of species, including the spawning microhabitat, e.g., bottom gravels, littoral zone, and surface strata);
- timing of reproductive events is not altered to the extent that synchrony is broken where reproduction or rearing of certain life stages is shown to be dependent upon cyclic food sources or other factors at remote locations.
- normal patterns of gradual temperature changes throughout the year are maintained.

These requirements should supersede all others during times when they apply.

CHANGES IN STRUCTURE OF AQUATIC COMMUNITIES

Significant change in temperature or in thermal patterns over a period of time may cause some change in the composition of aquatic communities (i.e., the species represented and the numbers of individuals in each species). This has been documented by field studies at power plants (Trembley 1956–1960)[321] and by laboratory investigations (McIntyre 1968).[303] Allowing temperature changes to alter significantly the community structure in natural waters may be detrimental, even though species of direct importance to man are not eliminated.

The limits of allowable change in species diversity due to temperature changes should not differ from those applicable to any other pollutant. This general topic is treated in detail. in reviews by others (Brookhaven National Lab. 1969)[258] and is discussed in Appendix II–B, Community Structure and Diversity Indices, p. 408.

NUISANCE ORGANISMS

Alteration of aquatic communities by the addition of heat may occasionally result in growths of nuisance organisms provided that other environmental conditions essential to such growths (e.g., nutrients) exist. Poltoracka (1968)[311] documented the growth stimulation of plankton in an artificially heated small lake; Trembley (1965[321]) reported dense growths of attached algae in the discharge canal and shallow discharge plume of a power station (where the algae broke loose periodically releasing decomposing organic matter to the receiving water). Other instances of algal growths in effluent channels of power stations were reviewed by Coutant (1970c).[269]

Changed thermal patterns (e.g., in stratified lakes) may greatly alter the seasonal appearances of nuisance algal growths even though the temperature changes are induced by altered circulation patterns (e.g., artificial destratification). Dense growths of plankton have been retarded in some instances and stimulated in others (Fast 1968;[275] and *unpublished data* 1971).[325]

Data on temperature limits or thermal distributions in which nuisance growths will be produced are not presently available due in part to the complex interactions with other growth stimulants. There is not sufficient evidence to say that any temperature increase will necessarily result in increased nuisance organisms. Careful evaluation of local conditions is required for any reasonable prediction of effect.

Recommendation

Nuisance growths of organisms may develop where there are increases in temperature or alterations of the temporal or spatial distribution of heat in water. There should be careful evaluation of all factors contributing to nuisance growths at any site before establishment of thermal limits based upon this response, and temperature limits should be set in conjunction with restrictions on other factors (see the discussion of Eutrophication and Nutrients in Section I).

CONCLUSIONS

Recommendations for temperature limits to protect aquatic life consist of the following two upper limits for any time of the year (Figure III–6).

1. One limit consists of a maximum weekly average temperature that:
   (a) in the warmer months (e.g., April through October in the North, and March through November in the South) is one third of the range between the optimum temperature and the ultimate upper incipient lethal temperature for the most sensitive important species (or appropriate life stage) that is normally found at that location at that time; or
   (b) in the cooler months (e.g., mid-October to mid-April in the North, and December to February in the South) is that elevated temperature from which important species die when that elevated temperature is suddenly dropped to the normal ambient temperature, with the limit being the acclimation temperature (minus a 2 C safety factor), when the lower incipient lethal temperature equals the normal ambient water temperature (in some regions this limit may also be applicable in summer); or
   (c) during reproduction seasons (generally April-June and September-October in the North, and March-May and October-November in the South) is that

temperature that meets specific site requirements for successful migration, spawning, egg incubation, fry rearing, and other reproductive functions of important species; or

(d) at a specific site is found necessary to preserve normal species diversity or prevent undesirable growths of nuisance organisms.

2. The second limit is the time-dependent maximum temperature for short exposures as given by the species-specific equation:

$$1 \geq \frac{time}{10^{[a+b(temp.+2)]}}$$

Local requirements for reproduction should supersede all other requirements when they are applicable. Detailed ecological analysis of both natural and man-modified aquatic environments is necessary to ascertain when these requirements should apply.

USE OF TEMPERATURE CRITERIA

A hypothetical electric power station using lake water for cooling is illustrated as a typical example in Figure III-7. This discussion concerns the application of thermal criteria to this typical situation.

The size of the power station is 1,000 megawatts electric (MW$_e$) if nuclear, or 1,700 MW$_e$ if fossil-fueled (oil, coal, gas); and it releases 6.8 billion British Thermal Units (BTU) per hour to the aquatic environment. This size is representative of power stations currently being installed. Temperature rise at the condensers would be 20 F with cooling water flowing at the rate of 1,520 cubic feet/second (ft³/sec) or 682,000 gallons/minute. Flow could be increased to reduce temperature rise.

The schematic Figure III-7 is drawn with two alternative discharge arrangements to illustrate the extent to which design features affect thermal impacts upon aquatic life
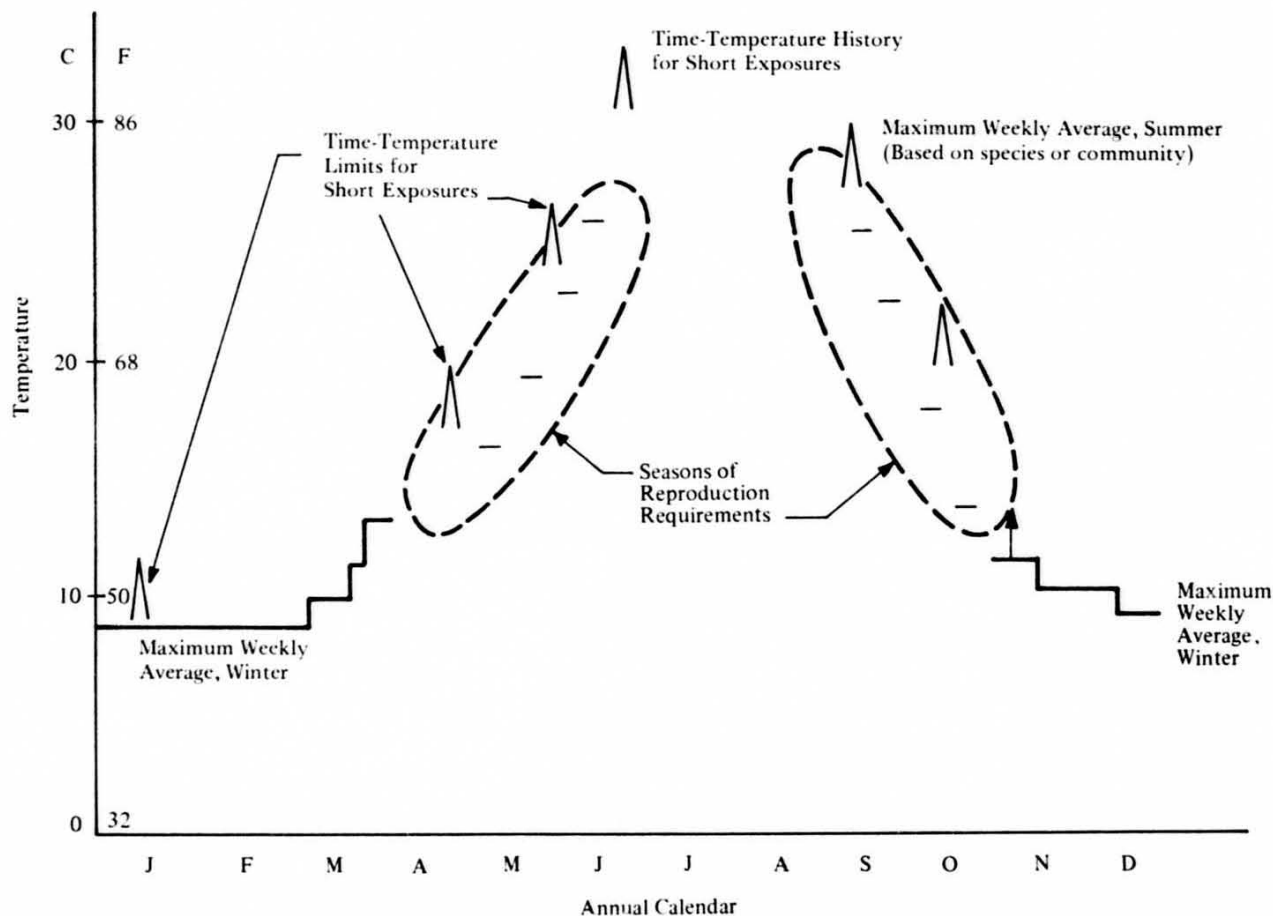
FIGURE III-6—Schematic Summary of Thermal Criteria
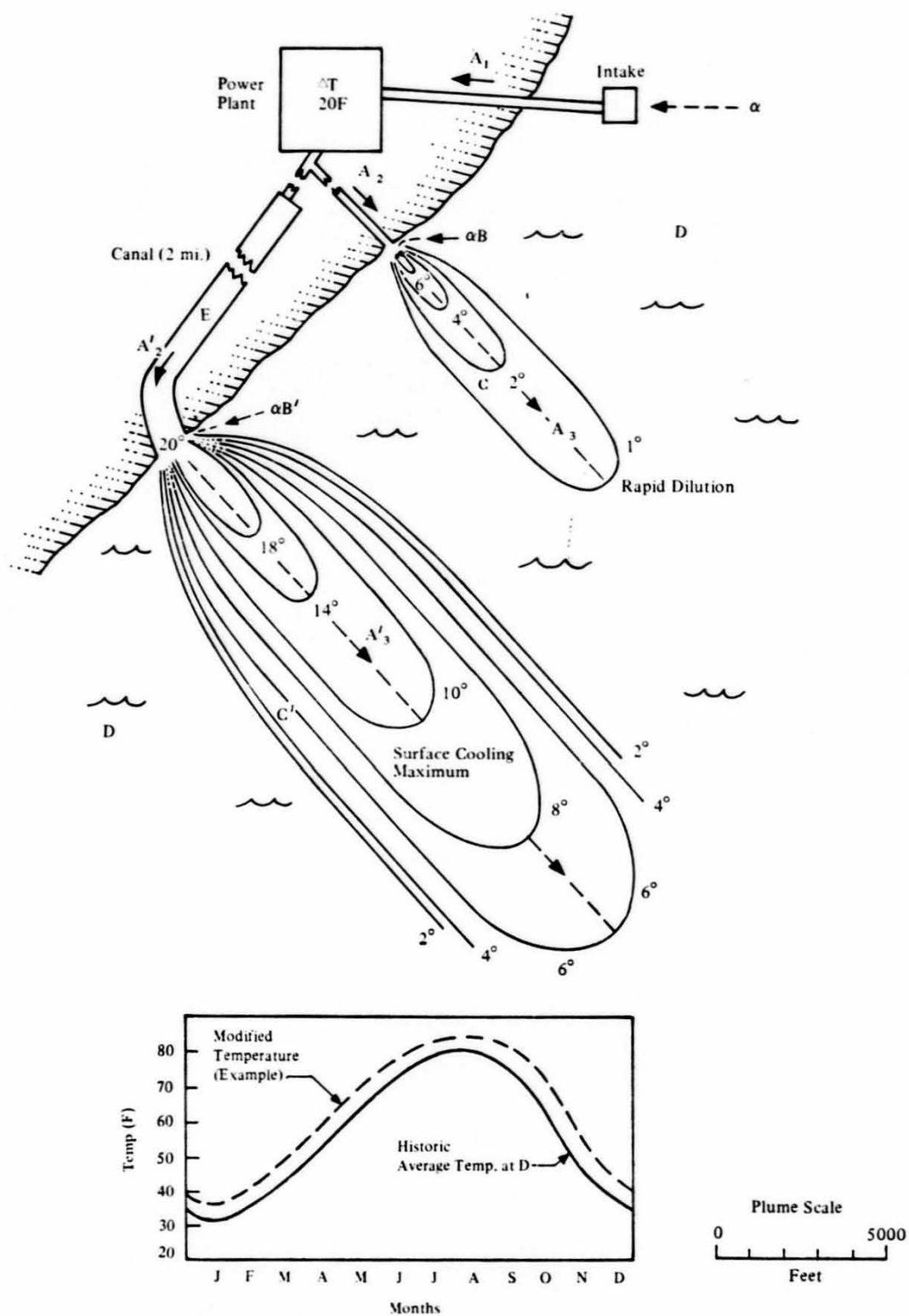
FIGURE III-7—Hypothetical Power Plant Site For Application of Water Temperature Criteria

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Warm condenser water can be carried from the station to the lake by (a) a pipe carrying water at a high flow velocity or (b) a canal in which the warm water flows slowly. There is little cooling in a canal, as measurements at several existing power stations have shown. Water can be released to the lake by using any of several combinations of water velocity and volume (i.e., number of outlets) or outlet dimensions and locations. These design features largely determine the configuration of the thermal plumes illustrated in Figure III-7 resulting from either rapid dilution with lake water or from slow release as a surface layer. The isotherms were placed according to computer simulation of thermal discharges (Pritchard 1971)[312] and represent a condition without lake currents to aid mixing.

Exact configuration of an actual plume depends upon many factors (some of which change seasonally or even hourly) such as local patterns of currents, wind, and bottom and shore topography.

Analytical Steps

Perspective of the organisms in the water body and of the pertinent non-biological considerations (chemical, hydrological, hydraulic) is an essential beginning. This perspective requires a certain amount of literature survey or on site study if the information is not well known. Two steps are particularly important:

1. identification of the important species and community (primary production, species diversity, etc.) that are relevant to this site; and

2. determination of life patterns of the important species (seasonal distribution, migrations, spawning areas, nursery and rearing areas, sites of commercial or sport fisheries). This information should include as much specific information on thermal requirements as it is possible to obtain from the literature.

Other steps relate the life patterns and environmental requirements of the biota to the sources of potential thermal damage from the power plant. These steps can be identified with specific areas in Figure III-7.

Aquatic Areas Sensitive to Temperature Change

Five principal areas offer potential for biological damage from thermal changes, labeled A-E on Figure III-7. (There are other areas associated with mechanical or chemical effects that cannot be treated here; see the index.)

Area A The cooling water as it passes through the intake, intake piping (A_1), condensers, discharge piping (A_2) or canal (A'_2), and thermal plume (A_3 or A'_3), carrying with it small organisms (such as phytoplankton, zooplankton, invertebrate larvae, and fish eggs or larvae). Organisms receive a thermal shock to the full 20 F above ambient temperature with a duration that depends upon the rate of water flow and the temperature drop in the plume.

Area B Water of the plume alone that entrains both small and larger organisms (including small fish) as it is diluted (B or B'). Organisms receive thermal shocks from temperatures ranging from the discharge to the ambient temperature, depending upon where they are entrained.

Area C Benthic environment where bottom organisms (including fish eggs) can be heated chronically or periodically by the thermal plume (C or C').

Area D The slightly warmed mixed water body (or large segment of it) where all organisms experience a slightly warmer average temperature (D).

Area E The discharge canal in which resident or seasonal populations reside at abnormally high temperatures (E).

Cooling Water Entrainment

It is not adequate to consider only thermal criteria for water bodies alone when large numbers of aquatic organisms may be pumped through a power plant. The probability of an organism being pumped through will depend upon the ratio of the volume of cooling water in the plant to the volume in the lake (or to the volume passing the plant in a river or tidal fresh water). Tidal environments (both freshwater and saline) offer greater potential for entrainment than is apparent, since the same water mass will move back and forth past the plant many times during the lifetime of pelagic residence time of most organisms. Thermal shocks that could be experienced by organisms entrained at the hypothetical power station are shown in Figure III-8.

Detrimental effects of thermal exposures received during entrainment can be judged by using the following equation for short-term exposures to extreme temperatures:

$$\text{General criterion: } 1 \geq \frac{time}{10^{[a+b(temp.+2)]}}$$

Values for a and b in the equation for the species of aquatic organisms that are likely to be pumped with cooling water may be obtained from Appendix II, or the data may be obtained using the methods of Brett (1952).[252] The prevailing intake temperature would determine the acclimation temperature to be selected from the table.

For example, juvenile largemouth bass may frequent the near-shore waters of this lake and be drawn into the intake. To determine whether the hypothetical thermal discharges (Figure III-7) would be detrimental for juvenile bass, the following analysis can be made (assuming, for example, that the lake is in Wisconsin where these basic data for bass are available):

Criterion for juvenile bass (Wisconsin) when intake
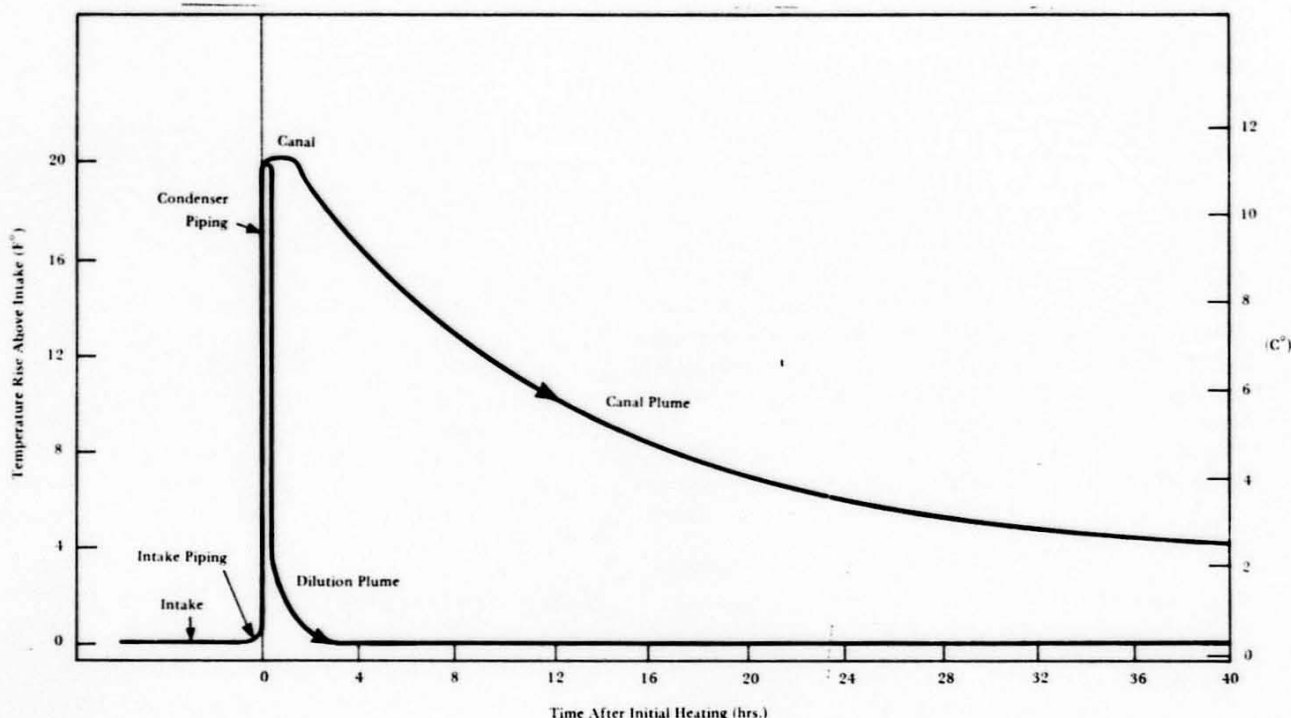
Modified after Coutant 1970c[269]

FIGURE III-8—*Time Course of Temperature Change in Cooling Water Passing Through the Example Power Station with Two Alternate Discharges. The Canal Is Assumed to Flow at a Rate of 3 Ft. Per Sec.*

temperature (acclimation) is 70 F (21.11 C). (Data from Appendix II-C).

$$1 \geq \frac{time}{10^{[34.3649-0.9789(temp.+2)]}}$$

Canal

Criterion applied to entrainment to end of discharge canal (discharge temperature is 70 F plus the 20 degree rise in the condensers or 90 F (32.22 C). The thermal plume would provide additional exposure above the lethal threshold, minus 2 C (29.5 C or 85.1 F) of more than four hours.

$$1 \geq \frac{60}{10^{[34.3649-0.9789(32.22+2)]}}$$

$$1 \geq 8.15$$

Conclusion:

Juvenile bass would not survive to the end of the discharge canal.

Dilution

Criterion applied to entrainment in the system em-

ploying rapid dilution.

$$1 \geq \frac{1.2}{10^{[34.3649-0.9789(32.22+2.0)]}}$$

$$1 \geq \frac{1.2}{7.36}$$

Travel time in piping to discharge is assumed to be 1 min., and temperature drop to below the lethal threshold minus 2 C (29.5 C or 85.1 F) is about 10 sec. (Pritchard, 1971).[312]

Conclusion

Juvenile bass would survive this thermal exposure:

$$1 \geq 0.1630$$

By using the equation in the following form,

$$\log (time) = a + b (temp.+2)$$

the length of time that bass could barely survive the expected temperature rise could be calculated, thus allowing selection of an appropriate discharge system. For example:

$$\log (time) = 34.3649 - 0.9789 (34.22)$$
$$\log (time) = 0.8669$$
$$time = 7.36$$

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This would be about 1,325 feet of canal flowing at 3 ft/sec.

It is apparent that a long discharge canal, a nonrecirculating cooling pond, a very long offshore pipe, or delayed dilution in a mixing zone (such as the one promoting surface cooling) could prolong the duration of exposure of pumped organisms and thereby increase the likelihood of damage to them. Precise information on the travel times of the cooling water in the discharge system is needed to conduct this analysis.

The calculations have ignored changing temperatures in the thermal plume, because the canal alone was lethal, and cooling in the plume with rapid dilution was so rapid that the additional exposure was only for 10 seconds (assumed to be at the discharge temperature the whole time). There may be other circumstances under which the effect of decreasing exposure temperature in the plume may be of interest.

Effects of changing temperatures in the plume can be estimated by summing the effects of incremental exposures for short time periods (Fry et al. 1946[251]). For example, the surface cooling plume of Figures III–7 and III–8 could be considered to be composed of several short time spans, each with an average temperature, until the temperature had dropped to the upper lethal threshold minus 2 C for the juvenile bass. Each time period would be calculated as if it were a single exposure, and the calculated values for all time periods would be summed and compared with unity, as follows:

$$\frac{time_1}{10^{[a+b(temp._1+2)]}} + \frac{time_2}{10^{[a+b(temp._2+2)]}} + \cdots \frac{time_n}{10^{[a+b(temp._n+2)]}}$$

The surface cooling plume of Figure III–6 (exclusive of the canal) could be considered to consist of 15 min at 89.7 F (32.06 C), 15 min at 89.2 F (31.78 C), 15 min at 88.7 F (31.4 C), 15 min at 88.2 F (31.22 C), 15 min at 87.8 F (31.00 C), until the lethal threshold for 70 F acclimation minus 2 C (85.1 F) was reached. The calculation would proceed as follows:

$$1 \geq \frac{15}{10^{[34.3649-0.9789(32.06+2)]}}$$

$$+ \frac{15}{10^{[34.3649-0.9789(31.78+2)]}} + \cdots$$

In this case, the bass would not survive through the first 15-minute period. In other such calculations, several steps would have to be summed before unity was reached (if not reached, the plume would not be detrimental).

Entrainment in the Plume

Organisms mixed with the thermal plume during dilution will also receive thermal shocks, although the maximum temperatures will generally be less than the discharge temperature. The number of organisms affected to some degree may be significantly greater than the numbers actually pumped through the plant. The route of maximum thermal exposure for each plume is indicated in Figure III–7 by a dashed line. This route should be analyzed to determine the maximum reproducible effect.

Detrimental effects of these exposures can also be judged by using the criterion for short-term exposures to extreme temperatures. The analytical steps were outlined above for estimating the effects on organisms that pass through the thermal plume portions of the entrainment thermal pattern. There would have been no mortalities of the largemouth bass from entrainment in the plume with rapid dilution, due to the short duration of exposure (about 10 seconds). Any bass that were entrained in the near-shore portions of the larger plume, and remained in it, would have died in less than 15 minutes.

Bottom Organisms Impacted by the Plume

Bottom communities of invertebrates, algae, rooted aquatic plants, and many incubating fish eggs can be exposed to warm plume water, particularly in shallow environments. In some circumstances the warming can be continuous, in others it can be intermittent due to changes in plume configuration with changes in currents, winds, or other factors. Clearly a thermal plume that stratifies and occupies only the upper part of the water column will have least effect on bottom biota.

Several approaches are useful in evaluating effects on the community. Some have predictive capability, while others are suitable largely for identifying effects after they have occurred. The criterion for short-term exposures identified relatively brief periods of detrimental high temperatures. Instead of the organism passing through zones of elevated temperatures, as in the previous examples, the organism is sedentary, and the thermal pulse passes over it. Developing fish eggs may be very sensitive to such changes. A brief pulse of high temperature that kills large numbers of organisms may affect a bottom area for time periods far longer than the immediate exposure time. Repeated sublethal exposures may also be detrimental, although the process is more complex than straight-forward summation. Analysis of single exposures proceeds exactly as described for plume entrainment.

The criterion for prolonged exposures is more generally applicable. The maximum tolerable weekly average temperature may be determined by the organisms present and the phase of their life cycle. In May, for example, the maximum heat tolerance temperature for the community may be determined by incubating fish eggs or fish fry on the bottom. In July it may be determined by the important resident invertebrate species. A well-designed thermal discharge should not require an extensive mixing zone where these criteria are exempted. Special criteria for reproductive processes may have to be applied, although thermal dis-

charges should be located so that zones important for reproduction—migration, spawning, incubation—are not used.

Criteria for species diversity provide a useful tool for identifying effects of thermal changes after they have occurred, particularly the effects of subtle changes that are a result of community interactions rather than physiological responses by one or more major species. Further research may identify critical temperatures or sequences of temperature changes that cannot be exceeded and may thereby provide a predictive capability as well. (See Appendix II–B.)

Mixed Water Body (or major region thereof)

This is the region most commonly considered in establishing water quality standards, for it generally includes the major area of the water body. Here the results of thermal additions are observed as small temperature increases over a large area (instead of high temperatures locally at the discharge point), and all heat sources become integrated into the normal annual temperature cycle (Figure III–6 and Figure III–7 insert).

Detrimental high temperatures in this area (or parts of it) are defined by the criteria for maximum temperatures for prolonged exposure (warm and cool months) for the most sensitive species or life stage occurring there, at each time of year, and by the criteria for reproduction.

For example, in the lake with the hypothetical power station, there may be 40 principal fish species, of which half are considered important. These species have spawning temperatures ranging from 5 to 6 C for the sauger (*Stizostedion canadense*) to 26.7 C for the spotted bullhead (*Ictalurus serracanthus*). They also have a similar range of temperatures required for egg incubation, and a range of maximum temperatures for prolonged exposures of juveniles and adults. The requirements, however, may be met any time within normal time spans, such as January 1 to 24 for sauger spawning, and March 25 to April 29 for smallmouth bass spawning. Maximum temperatures for prolonged exposures

may increase steadily throughout a spring period. To predict effects of thermal discharges the pertinent temperatures for reproductive activities and maximum temperatures for each life stage can be plotted over a 12-month period such as shown in Fig. III–6. A maximum annual temperature curve can become apparent when sufficient biological data are available. Mount (1970)[305] gives an example of this type of analysis.

Discharge Canal

Canals or embayments that carry nearly undiluted condenser cooling water can develop biological communities that are atypical of normal seasonal communities. Interest in these areas does not generally derive from concern for a balanced ecosystem, but rather from effects that the altered communities can have on the entire aquatic ecosystem.

The general criteria for nuisance organisms may be applicable. In the discharge canals of some existing power stations, extensive mats of temperature-tolerant blue-green algae grow and periodically break away, adding a decomposing organic matter to the nearby shorelines.

The winter criterion for maximum temperatures for prolonged exposures identifies the potential for fish kills due to rapid decreases in temperature. During cold seasons particularly, fish are attracted to warmer water of an enclosed area, such as a discharge canal. Large numbers may reside there for sufficiently long periods to become metabolically acclimated to the warm water. For any acclimation temperature there is a minimum temperature to which the species can be cooled rapidly and still survive (lower incipient lethal temperature). These numerical combinations, where data are available, are found in Appendix II–C. There would be 50 per cent mortality, for example, if largemouth bass acclimated in a discharge canal to 20 C, were cooled to 5.5 C or below. If normal winter ambient temperature is less than 5.5 C, then the winter maximum should be below 20 C, perhaps nearer 15 C. If it is difficult to maintain the lower temperatures, fish should be excluded from the area.

HEAT AND TEMPERATURE

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APPENDIX B*

THERMAL TABLES

THERMAL TABLES—Time-temperature relationships and lethal threshold temperatures for resistance of aquatic organisms (principally fish) to extreme temperatures (from Coutant, in press[75] 1972). Column headings, where not self-explanatory, are identified in footnotes. LD50 data obtained for single times only were included only when they amplified temperature-time information.

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation Temp[a]	Acclimation Time	log time=a+b (temp.) a	b	N[b]	r[c]	Data limits (°C) upper	Data limits (°C) lower	LD50	Lethal threshold[d] (°C)
Abudefduf saxa-tilis (Sargent major)	Adult				Northern Gulf of California	Heath, W. G. (1967)[89]	Upper	32		42.9005	−0.0934	3	−0.9945	37.0	36.0		
Adinia xenica (diamond Killi-fish)	Adult				Jefferson Co., Texas	Strawn and Dunn (1967)[99]	Upper	35	(0 o/oo)[e]	21.9337	−0.4866	6	−0.9930	43.0	40.5		
							Upper	35	(5 o/oo)[e]	27.7919	−0.6159	6	−0.9841	43.5	41.0		
							Upper	35	(10 o/oo)[e]	26.8121	−0.5899	6	−0.9829	43.5	41.0		
							Upper	35	(20 o/oo)[e]	28.3930	−0.6290	6	−0.9734	43.5	41.0		
Atherinops affinis (topsmelt)	Juvenile	6.0-6.2 cm			LaJolla, Calif.	Doudoroff (1945)[79]	Upper	18.0								30.5(24)	
								20		42.2531	−1.2215	9	−0.9836	33.5	31.5		31.0
							Lower	14.5								7.6(24)	
								18.0								8.8(24)	
								20		−0.4667	0.3926	7	0.9765	11.0	5.0		10.5
								25.5								13.5(24)	
Brevoortia tyrannus (Atlantic menhaden)	Larval	17-34 mm		Mixed	Beaufort Harbor, North Carolina (36°N)	Lewis (1965)[91]	Lower	7.0		0.9611[f]	0.2564	9	0.9607	4.0			5.0
							"	10.0		0.7572	0.2526	12	0.9452	5.0	−1.0		6.0
							"	12.5		0.6602	0.2786	12	0.9852	5.5			>7.0
							"	15.0		0.5675	0.2321	14	0.9306	7.0			>8.0
							"	20.0		0.2620	0.1817	3	0.9612	4.0			
Brevoortia tyrannus (Atlantic menhaden)	Young-of-the-year				Beaufort; N.C.	Lewis and Hettler (1968)[92]	Upper	21	(5 o/oo)	57.9980	−0.1643	2		35.0	34.0		
								27	(5 o/oo)	85.1837	−2.3521	2		35.0	34.5		
							Lower	16	(26-30 o/oo)					7.0	3.0		6.5
								18	(10 o/oo)					7.0	3.0		6.5
Brevoortia tyrannus (Atlantic menhaden)	Yearling				Beaufort, N.C.	Lewis and Hettler (1968)[92]	Upper	21	(5 o/oo)	35.7158	−1.0468	3	−0.9174	34	33		
								22-23	(4-6 o/oo)	21.8083	−0.6342	10	−0.9216	35	31		32.5
Crassius auratus (goldfish)	Juvenile		2g ave.	Mixed	Commercial dealer (Toronto)	Fry, Brett, & Clawson (1942)[81] (and Fry, Hart, & Walker, 1946)[83]	Upper	1-2								28 (14)	
								10								31 (14)	
								17								34 (14)	
								24								36 (14)	
								32		20.0213	−0.4523	2		41.0	39.0	39.2(14)	
								38		21.9234	−0.4773	2		43.0	41.0	41.0(14)	41.0
							Lower	19								1.0(14)	
								24								5.0(14)	
								38								15.5(14)	
Catostomus com-mersonni (white sucker)	Adult (1-2 yr)		10-19.9 (mode)	Mixed	Don River, Thornhill, Ontario	Hart (1947)[87]	Upper	5		33.6957	−1.1797	2		27.5	27.0		26.3
								10		19.9890	−0.6410	3	−0.6857	29	28		27.7
								15		31.9007	−1.0034	2		30	29.5		29.3
								20		27.0023	−0.8068	4	−0.9606	31.5	30		29.3
								25		22.2209	−0.6277	7	−0.9888	32.5	29.5		29.3
							Lower	20									2.5
								25									6.0

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett (1952).[74]

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line=1.0).

[d] = Incipient lethal temperature of Fry, et al., (1946).[83]

[e] Salinity.

[f] Log time in hours to 50% mortality. Includes 2-3 hr. required for test bath to reach the test temperature.

THERMAL TABLES—Continued

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation Temp[a]	Acclimation Time	a	b	N[b]	r[c]	Data limits (°C) upper	Data limits (°C) lower	LD50	Lethal threshold[d] (°C)
Coregonus astedii (cisco)	Juvenile	....	....	Mixed	Pickerel Lake,[e] Washtenaw Co., Mich.	Edsall and Colby, 1970[102]	Upper	2	8 wks	16.5135	−0.6689	4	−0.9789	23.0	19.0	....	19.7
								5	4 wks	10.2799	−0.3645	3	−0.9264	24.0	20.0	....	21.7
								10	>2 wks	12.4993	−0.4098	6	−0.9734	28.0	24.0	....	24.2
								20	2 wks	17.2967	−0.5333	8	−0.9487	30.0	26.0	....	26.2
								25	3 wks	15.1204	−0.4493	7	−0.9764	30.0	25.5	....	25.7(u)
							Lower	2	8 wks	....	....	.....	....	1.5	0.3	....	<0.3
								5	4 wks	....	....	.....	....	1.0	0.5	....	<0.5
								10	>2 wks	2.7355	0.3381	5	0.9021	3.0	0.5	....	3.0
								20	2 wks	2.5090	0.2685	6	0.9637	4.5	0.5	....	4.7
								25	3 wks	1.7154	0.1652	9	0.9175	9.5	0.5	....	9.7
Coregonus hoyi (bloater)	Juvenile (age 1)	60.0 mm 5.0 5.8	....	Mixed	Lake Michigan at Kenosha, Wisc.	Edsall, Rottiers & Brown, 1970[80]	Upper	5	11 da	15.8243	−0.5831	5	−0.9095	26.0	22.0	....	22.2
								10	5 da	9.0700	−0.2896	6	−0.9516	30.0	23.0	....	23.6
								15	5 da	17.1908	−0.5707	4	−0.9960	28.0	24.5	....	24.8
								20	5 da	28.6392	−0.9458	4	−0.9692	29.0	25.5	....	26.2
								25	5 da	21.3511	−0.6594	5	−0.9958	30.0	26.5	....	26.7
Cyprinodon variegatus (sheepshead minnow)	Adult	....	....		Jefferson County, Texas	Strawn and Dunn (1967)[99]	Upper	35	(0 °/oo)	27.9021	−0.6217	6	−0.9783	43.0	40.5		
								35	(5 °/oo)	35.3415	−0.7858	6	−0.9787	43.5	41.0		40.5
								35	(10 °/oo)	30.0910	−0.6629	6	−0.9950	43.5	41.5		
								35	(20 °/oo)	30.0394	−0.6594	4	−0.9982	43.5	41.5		
Cyprinodon variegatus variegatus (sheepshead minnow)	Adult	....			Galveston Island, Galveston, Texas	Simmons (1971)[97]	Upper	30 : :	700 hrs.[h] (from 21.3 C)	35.0420	−0.8025	2	....	41.4	40.8		....
Dorosoma cepedianum (gizzard shad)	Underyearling	....			Put-in-Bay, Ohio	Hart (1952)[55]	Upper	25	field & 3-4 da	47.1163	−1.3010	3	−0.9975	35.5	34.5	....	34.0
								30	"	38.0658	−0.9694	4	−0.9921	38.0	36.5	....	36.0
								35	"	31.5434	−0.7710	5	−9.9642	39.0	37.0	....	36.5(u)
							Lower	25	....	....	....	.....	....	.....	.....	....	10.8
								30	....	....	....	.....	....	.....	.....	....	14.5
								35	....	....	....	.....	....	.....	.....	....	20.0
Dorosoma cepedianum (gizzard shad)	Underyearling	....			Knoxville, Tenn.	Hart (1952)[55]	Upper	25	....	32.1348	−0.8698	2	....	35.5	35.0	....	34.5
								30	....	41.1030	−0.0547	4	−0.9991	38.0	36.5	....	36.0
								35	....	33.2846	−0.8176	6	−0.9896	39	36.5	....	36.5
Esox lucius (Northern Pike)	Juvenile	Minimum 5.0 cm	....		Maple, Ontario, Canada	Scott (1964)[96]	Upper	25.0	....	17.3066	−0.4523	5	−0.9999	34.5	32.5	....	32.25
								27.5	....	17.4439	−0.4490	5	−0.9985	35.0	33.0	....	32.75
								30.0	....	17.0961	−0.4319	5	−0.9971	35.5	33.5	....	33.25(u)
Esox masquinongy (Muskellunge)	Juvenile	Minimum 5.0 cm	....		Deerlake Hatchery Ontario, Canada	Scott (1964)[96]	Upper	25.0	....	18.8879	−0.5035	5	−0.9742	34.5	32.5	....	32.25
								27.5	....	20.0817	−0.5283	5	−0.9911	35.0	33.0	....	32.75
								30.0	....	18.9506	−0.4851	5	−0.9972	35.5	33.5	....	33.25 (u)
Esox hybrid (lucius× masquinongy)	Juvenile	5.0 cm minimum	....		Maple, Ontario, Canada	Scott (1964)[96]	Upper	25.0	....	18.6533	−0.4926	4	−0.9941	34.5	33.0	....	32.5
								27.5	....	20.7834	−0.5460	5	−0.9995	35.0	33.0	....	32.75
								30.0	....	19.6126	−0.5032	5	−0.9951	35.5	33.5	....	33.25 (u)
Fundulus chrysotus (golden topminnow	Adult	....			Jefferson County, Texas	Strawn & Dunn (1967)[99]	Upper	35	(0 °/oo)−	23.7284	−0.5219	9	−0.9968	43.0	39.0	....	38.5
								35	(5 °/oo)−	21.2575	−0.4601	7	−0.9969	43.5	40.0	....	....
								35	(20 °/oo)−	21.8635	−0.4759	8	−0.9905	43.5	40.0	....	....
Fundulus diaphanus (banded killifish)	Adult	....			Halifax Co. and Annapolis Co., Nova Scotia	Garside and Jordan (1968)[54]	Upper	15	(0 °/oo)[e]	....	....	.....	....	.....	.....	....	27.5
								15	(14 °/oo)	....	....	.....	....	.....	.....	....	33.5
								15	(32 °/oo)	....	....	.....	....	.....	.....	....	27.5
Fundulus grandis (gulf killifish)	Adult	....			Jefferson County, Texas	Strawn & Dunn (1967)[99]	Upper	35	(0 °/oo)	22.9809	−0.5179	8	−0.9782	42.0	38.5	....	....
								35	(5 °/oo)	27.6447	−0.6220	7	−0.9967	42.5	39.5	....	....
								35	(10 °/oo)	24.9072	−0.5535	9	−0.9926	43.0	39.0	....	....
								35	(20 °/oo)	23.4251	−0.5169	8	−0.9970	43.0	39.5	....	....
Fundulus heteroclitus (mummichog)	Adult	....			Halifax Co. and Annapolis Co., Nova Scotia	Garside and Jordan (1968)[54]	Upper	15	(0 °/oo)[i]	....	....	.....	....	.....	.....	....	28.0
								15	(14 °/oo)	....	....	.....	....	.....	.....	....	34.0
								15	(32 °/oo)	....	....	.....	....	.....	.....	....	31.5

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett (1952).[74]

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line = 1.0).

[d] = Incipient lethal temperature of Fry, et al., (1946).[53]

[e] Experimental fish were hatched from eggs obtained from adults from this location.

[f] Experimental fish were reared from eggs taken from adults from this location.

[g] These times after holding at 8 C for >1 mo.

[h] Acclimated and tested at 10 °/oo salinity.

[i] Tested in three salinities.

[j] Tested at 3 levels of salinity.

THERMAL TABLES—Continued

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation Temp[a]	Acclimation Time	log time=a+b (temp.) a	b	N[b]	r[c]	Data limits (°C) upper	Data limits (°C) lower	LD50	Lethal threshold[d] (°C)
Fundulus par- vipinnis (Cali- fornia killifish) (tested in seawater except as noted)	Adult	6–7 cm	....	Mixed	Mission Bay, Calif. (sea- water)	Doudoroff (1945)[79]	Upper	14	....	23.3781	−0.6439	4	−0.9845	34.0	32.0	....	32.3
								20	....	50.6021	−1.3457	11	−0.9236	37.0	34.0		34.4
								28	....	24.5427	−0.5801	7	−0.9960	40.0	36.0		36.5
							Lower	14	....	2.1908	1.0751	3	0.9449	1.6	0.4		1.2
								20	....	2.7381	0.2169	6	0.9469	7.0	2.0		5.6
								20	....	2.5635	0.3481	4	0.8291	4.0	2.0		3.6
								20 (into 45‰ sea water 1 day before testing)		2.6552	0.4014	8	0.7348	4.0	2.0		3.8
Fundulus pul- verevus (bayou killifish)	Adult				Jefferson County, Texas	Strawn and Dunn (1967)[79]	Upper	35	(0 ‰)	28.1418	−0.6304	8	−0.9741	43.0	39.0	....	38.5
								35	(5 ‰)	29.3774	−0.6514	7	−0.9931	43.5	40.0		....
								35	(10 ‰)	25.0890	−0.5477	5	−0.9956	43.5	41.5		....
								35	(20 ‰)	30.4702	−0.6745	8	−0.9849	43.5	40.0		....
Fundulus similis (longnose killi- fish)	Adult	....			Jefferson County, Texas	Strawn and Dunn (1967)[99]	Upper	35	(0 ‰)[e]	22.9485	−0.5113	6	−0.9892	43.0	40.5	....	....
								35	(5 ‰)	25.6165	−0.5690	6	−0.9984	43.5	41.0		....
								35	(10 ‰)	26.4675	−0.5863	6	−0.9925	43.5	41.0		....
								35	(20 ‰)	26.5612	−0.5879	6	−0.9953	43.0	40.5		....
Gambusia affinis affinis (mosquito- fish)	Adult	....	....	Mixed	Knoxville, Tenn.	Hart (1952)[58]	Upper	25	....	39.0004	−0.9771	2	....	39	38	....	37.0
								30	....	30.1523	−0.7143	6	−0.9928	40	37.5	....	37.0
								35	....	23.8110	−0.5408	6	−0.9978	41.5	39	....	37.0(u)
Gambusia affinis (mosquitofish) (freshwater)	Adult	....			Jefferson Co.. Texas	Strawn & Dunn (1967)[99]	Upper	35	(0 ‰)[e]	22.4434	−0.5108	5	−0.9600	42.0	40.0	....	....
								35	(5 ‰)	23.1338	−0.5214	5	−0.9825	42.5	40.5		....
								35	(10 ‰)	23.4977	−0.5304	8	−0.9852	42.5	40.0		....
								35	(20 ‰)	22.1994	−0.5001	6	−0.9881	42.5	40.0		....
Gambusia affinis (mosquitofish) (saltwater)	Adult	....			Jefferson Co., Texas	Strawn and Dunn (1967)[99]	Upper	35	(0 ‰)[e]	17.6144	−0.3909	5	−0.9822	42.5	40.5	....	....
								35	(5 ‰)	18.9339	−0.4182	5	−0.9990	42.5	40.5		....
								35	(10 ‰)	23.0784	−0.5165	7	−0.9982	42.5	39.5		....
								35	(20 ‰)	22.8663	−0.5124	6	−0.9957	42.5	40.0		....
Gambusia affinis holbrooki (mosquitofish)	Adult	....		Mixed	Welaka, Florida	Hart (1952)[58]	Upper	15	....	32.4692	−0.8507	3	−0.9813	37	36	....	35.5
								20	....	38.3139	−0.9673	3	−0.9843	38.5	37.5	....	37.0
								30	....	31.4312	−0.7477	5	−0.9995	40	38	....	37.0
								35	....	28.1212	−0.6564	5	−0.9909	40	38.5	....	37.0(u)
							Lower	15	....							....	1.5
								20	....							....	5.5
								35	....							....	14.5
Garmannia chiquita (goby)	Adult	....	....	....	Northern Gulf of California Coast	Heath (1967)[89]	Upper	32	....	21.7179	−0.5166	3	−0.9905	37.0	36.0	....	....
Gasterosteus acu- leatus (three- spine stickle- back)	Adult	37 mm ave.	0.50 g ave.	Mixed	Columbia River near Prescott, Oregon	Blahm and Parente (1970)[101] un- published data	Upper	19	....	19.3491	−9.5940	3	−0.9998	32	26	....	25.8
Girella nigricans (opaleye)	Juvenile	7.1–8.0 cm	....	Mixed	LaJolla, Cali- fornia (33°N)	Doudoroff (1942)[78]	Upper	12	....	21.1277	−0.6339	6	−0.9138	31.0	27.0	....	28.7
								20	....	19.2641	−0.5080	7	−0.9930	35.0	31.0	....	31.4
								28	....	24.7273	−0.6740	4	−0.9822	33.0	31.0	....	31.4
							Lower	12	....	1.4851	0.4886	8	0.9550	5.0	1.0	....	5.5
								20	....	−1.3878	0.6248	6	0.9895	8.0	5.0	....	8.5
								28	....	−0.1238	0.2614	6	0.9720	13.0	6.0	....	13.5
Ictalurus (Amicurus) neb- ulosus (brown bullhead)	....	....	....	....	Florida to On- tario (4 lo- cations) com- bined	Hart (1952)[58]	Upper	5	....	14.6802	−0.4539	4	−0.9782	29.5	28.0	....	27.8
								10	....	16.4227	−0.4842	10	−0.9526	31.5	29.5	....	29.0
								15	....	20.3281	−0.8239	3	−0.9881	33.0	32.5	....	31.0
								20	....	23.9586	−0.6473	11	−0.9712	35.0	32.5	....	32.5
								25	....	22.4970	−0.5732	12	−0.9794	37.0	34.0	....	33.8
								30	....	24.2203	−0.5917	19	−0.9938	38.5	35.5	....	34.8
								34	....	19.3194	−0.4500	5	−0.9912	37.5	36.0	....	34.8
							Lower	20	....							....	0.5
								25	....							....	4.0
								30	....							....	6.8
Ictalurus puncta- tus (channel catfish)	Juvenile (44–5.' da old)	....	....	Mixed	Centerton, Ark. (hatchery)	Allen & Strawn (1968)[72]	Upper	26	....	34.7119	−0.8816	13	−0.9793	39.0	36.6	....	36.6
								30	....	32.1736	−0.7811	17	−0.9510	40.6	37.4	....	37.8
								34	....	26.4204	−0.6149	20	−0.9638	42.0	38.0	....	38.0

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett (1952).[74]

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line=1.0).

[d] = Incipient lethal temperature of Fry, et al., (1946).[43]

[e] Salinity.

THERMAL TABLES—Continued

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation Temp[a]	Acclimation Time	a	b	N[b]	r[c]	Data limits (°C) upper	Data limits (°C) lower	LD50	Lethal threshold[d] (°C)
Ictalurus punctatus (channel catfish)	Juvenile (11.5 mo)				Joe Hogan State Fish Hatchery, Lonoke, Arkansas	Allen & Strawn (1968)[72]	Upper	25		34.5554	0.8854	5	−0.9746	37.5	35.5		35.5
							Upper	30		17.7125	−0.4058	4	−0.9834	40.0	37.5		37.0
							Upper	35		28.3031	−0.6554	4	−0.9906	41.0	38.0		38
Ictalurus punctatus (I. lacustris) (channel catfish)	Adult			Mixed	Welaka, Fla. and Put-in-Bay, Ohio	Hart (1952)[88]	Upper	15		34.7829	−1.0637	3	−0.9999	31.5	30.5		30.4
							Upper	20		39.4967	−1.1234	4	−0.9980	34.0	33.0		32.8
							Upper	25		46.2155	−1.2899	5	−0.9925	35.0	34.0		33.5
							Lower	15									0.0
							Lower	20									0.0
							Lower	25									0.0
Lepomis macrochirus purpurescens (bluegill)	Adult			Mixed	Welaka, Florida	Hart (1952)[88]	Upper	15		25.2708	−0.7348	5	−0.9946	33.0	31.0		30.5
							Upper	20		28.0663	−0.7826	6	−0.9978	34.5	32.5		32.0
							Upper	25		23.8733	−0.6320	10	−0.9750	36.0	33.0		33.0
							Upper	30		25.7732	−0.6581	5	−0.9965	38	34.5		33.8
							Lower	15									2.5
							Lower	20									5.0
							Lower	25									7.5
							Lower	30									11.0
Lepomis macrochirus (bluegill)	Adult			Mixed	Lake Mendota, Wisconsin	Hart (1952)[88]	Upper	20–23		38.6247	−1.0581	4	−0.8892	35.5	34.0		
							Upper	30		30.1009	−0.7657	4	−0.9401	38.0	36.0		
Lepomis megalotis (longear sunfish)	Juvenile	>12 mm		Mixed	Middle Fork, White River, Arkansas	Neill, Strawn & Dunn (1966)[95]	Upper	25		35.4953	−0.9331	14	−0.9827	36.9	35.4		25.6
							Upper	30		20.5981	−0.4978	22	−0.9625	39.0	36.5		36.8
							Upper	35		30.7245	−9.7257	43	−0.9664	41.5	37.3		37.5
Lepomis symmetricus (bantam sunfish)	Adult				Jefferson Co., Texas	Strawn & Dunn (1967)[99]	Upper	35	(0 o/oo)[e]	20.7487	−0.4686	7	−0.9747	42.0	39.5		
							Upper	35	(5 o/oo)	23.5649	−0.5354	6	−0.9975	42.0	39.0		
							Upper	35	(20 o/oo)	10.4421	−0.2243	5	−0.9873	41.5	39.5		
Lucania parva (rainwater killifish)	Adult				Jefferson Co., Texas	Strawn and Dunn (1967)[99]	Upper	35	(0 o/oo)[e]	21.2616	−0.4762	9	−0.9844	42.5	38.5		
							Upper	35	(5 o/oo)	24.3076	−0.5460	8	−0.9846	42.5	39.0		
							Upper	35	(10 o/oo)	24.3118	−0.5467	8	−0.9904	42.5	39.0		
							Upper	35	(20 o/oo)	21.1302	−0.4697	7	−0.9940	42.5	39.5		
Menidia menidia (common silverside)		8.3–9.2 cm (average for test groups)	4.3–5.2 gm (average for test groups)	Mixed	New Jersey (40°N)	Hoff & Westman (1966)[90]	Upper	7		19.8801	−0.7391	5	−0.9398	24.0	20		22.0
							Upper	14		18.7499	−0.6001	6	−0.9616	27.0	23.0		25.0
							Upper	21		65.7350	−2.0387	6	−0.9626	32.0	28.0		30.4
							Upper	28		37.6032	−1.0582	5	−0.8872	34.0	30		32.5
							Lower	7		−9.8144	8.9079	5	0.8274	2	1		1.5
							Lower	14		−1.2884	2.5597	6	0.8594	5	1		2.0
							Lower	21		−1.4801	1.1484	6	0.9531	7	2		4.3
							Lower	28		−8.2366	1.3586	5	0.9830	15	7		8.7
Micropterus salmoides floridanus (largemouth bass)	9–11 mo. age				Welaka, Florida	Hart (1952)[88]	Upper	20		35.5107	−1.0112	5	−0.9787	34	32		32
							Upper	25		19.9918	−0.5123	8	−0.9972	36.5	33		33
							Upper	30		17.5645	−0.4200	8	−0.9920	38	34.5		33.7(u)
							Lower	20									5.2
							Lower	25									7.0
							Lower	30									10.5
Micropterus salmoides (largemouth bass)					Put-in-Bay, Ohio	Hart (1952)[88]	Upper	20		50.8091	−1.4638	2		34	33		32.5
							Upper	25		26.3169	−0.6846	3	−0.9973	36.5	35		34.5
							Upper	30		29.0213	−0.7150	4	−0.9959	38.5	37		36.4(u)
							Lower	20									5.5
							Lower	30									11.8
Micropterus salmoides (largemouth bass)	Under yearling				Knoxville, Tenn.	Hart (1952)[88]	Upper	30		36.0620	−0.9055	4	−0.9788	38.5	37		36.4
							Upper	35		23.9185	−0.5632	6	−0.9958	40	37.5		36.4(u)
Micropterus salmoides (largemouth bass)					Lake Mendota, Wisconsin	Hart (1952)[88]	Upper	22		34.3649	−0.9789	4	−0.9789	33.8	32.0		31.5
							Upper	30		35.2777	−0.9084	4	−0.9845	37.5	35.5		
Mysis relicta (Opossum shrimp)	Adult			Mixed	Trout Lake, Cook County, Minnesota	Smith (1970)[98]	Upper	7.5C	>1 wk	6.1302	−0.1170	3	0.9245	26	16		16

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett (1952).[74]

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line = 1.0).

[d] = Incipient lethal temperature of Fry, et al., (1946).[83]

[e] Salinity.

THERMAL TABLES—Continued

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation		log time=a+b (temp.)				Data limits (°C)		LD50	Lethal threshold (°C)
								Temp[a]	Time	a	b	N[b]	r[c]	upper	lower		
Neomysis awatschensis (opossum shrimp)	Adult	>7 mm		Mixed	Sacramento-San Joaquin delta, California	Hair (1971)[94]	Upper	10.3								73 (48)	
								11.0								72.5(48)	
								15.1								73.8(48)	
								18.3								76.1(48)	
								19.0								74.0(48)	
								19.0		8.4694	−0.2150	2					24.2–25.4[d]
								21.7								77.0(48)	
								22.0								77.5(48)	
								22.4								76.0(48)	
Notemigonus crysoleucas (golden shiner)	Adult				Composite[g] of 1. Welaka, Fla. 2. Put-in-Bay, Ohio 3. Algonquin Park, Ontario	Hart (1952)[88]	Upper	10		42.7095	−1.3507	3	−0.9998	30.5	29.5		29.5
								15		30.2861	−0.8933	4	−0.9844	32.5	31.0		30.5
								20		31.0275	−0.8722	15	−0.9869	34.5	32.0		32.0
								25		34.2505	−0.9226	9	−0.9665	36.0	34		33.5
								30		26.3829	−0.6615	10	−0.9940	37.5	35		34.5
							Lower	15									1.5
								20									4.0
								25									7.0
								30									11.2
Notropis atherinoides (emerald shiner)	Juvenile (<1yr)		0–1.9 g.mode	Mixed	Chippewa Creek, Welland, Ontario	Hart (1947)[87]	Upper	5		20.9532	−0.7959	3	−0.9519	24.5	23.5		23.3
								10		36.5023	−1.2736			27.5	27.0		26.7
								15		47.4849	−1.5441	3	−0.9803	30.5	29.5		28.9
								20		33.4714	−0.9858	3	−0.9805	32.5	31.5		30.7
								25		26.7096	−0.7337	6	−0.9753	34.0	31.5		30.7
							Lower	15									1.6
								20									5.2
								25									8.0
Notropis cornutus (common shiner)	Adult				Toronto, Ontario	Hart (1952)[88]	Upper	10				1		29.0	29.0		29.0
								15		45.4331	−1.3979			31.5	31.0		30.5
								20		34.5324	−1.0116	4	−0.9560	33.0	31.5		31.0
								25(winter)		24.9620	−0.6878	5	−0.9915	34.0	32.0		31.0
								25		28.5059	−0.7741	8	−0.9973	35.5	32.0		31.0
								30		28.1261	−0.7316	6	−0.9946	36.5	34.0		31.0(u)
Notropis cornutus (common shiner)	Adult (mostly 2 yr)		4.0–5.9 g (mode)	Mixed	Don River, Thornhill, Ontario	Hart (1947)[87]	Upper	5									26.7
								10		40.7738	−1.3522	3	−0.9729	30.0	29.0		28.6
								15		45.0972	−1.3874	3	−0.9999	32.0	31.0		30.3
								20		34.5324	−1.0116	4	−0.9560	33.0	31.5		31.0
								25		24.9620	−0.6878	5	−0.9915	34.0	32.0		31.0
							Lower	20									3.7
								25									7.8
Notropis cornutus (common shiner)	Adult				Knoxville, Tenn.	Hart (1952)[88]	Upper	25		25.5152	−0.6794	5	−0.9938	35.5	33.0		33.0
								30		24.9660	−0.6297	10	−0.9978	38.0	34.5		33.5(u)
Oncorhynchus gorbuscha (pink salmon)	Juvenile freshwater fry (3.8 mo.)	3.81±0.29 cm	0.30±0.15g	Mixed	Dungeness, Wash. (hatchery)	Brett (1952)[74]	Upper	5		11.1827	−0.4215	4	−0.9573	24.0	22.0		21.3±0.3
								10		11.9021	−0.3865	8	−0.9840	26.5	23.0		22.5±0.3
								15		12.8937	−0.4074	8	−0.9884	27.0	23.5		23.1±0.3
								20		16.2444	−0.4074	7	−0.9681	27.5	24.0		23.9±0.6
								24		14.7111	−0.4459	6	−0.9690	27.5	24.5		23.9
Oncorhynchus keta (chum salmon)	Juvenile freshwater fry (4.9 mo.)	5.44±0.89 cm	1.62±1.03g	Mixed	Nile Creek, B.C. (hatchery)	Brett (1952)[74]	Upper	5		14.3829	−0.5320	4	−0.9839	24.0	22.0		21.8
								10		14.1773	−0.4766	9	−0.8665	26.5	22.5		22.6
								15		15.8911	−0.5252	8	−0.9070	27.0	23.0		23.1±0.4
								20		16.1894	−0.5168	9	−0.9750	27.5	23.5		23.7
								23		15.3825	−0.4721	4	−0.9652	27.0	24.0		23.8±0.4
							Lower	5									0.5
								10								1	0.5
								15								5	4.7
								20								7	6.5
								23								8	7.3
Oncorhynchus keta (chum salmon)	Juvenile				Big Creek Hatchery, Hoodsport, Wash.[h]	Blahm and Parente (1970)[101] unpublished data	Upper	9	10%	16.9245	−0.5995	6	−0.9927	29	17		22.0
									50%	15.9272	−0.5575	4	−0.9972	29	17		23.2
									90%	16.8763	−0.5881	4	−0.3995	29	17		23.6

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett (1952).[74]

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line=1.0).

[d] — Incipient lethal temperature of Fry, et al., (1946).[63]

[e] All temperatures estimated from a graph.

[f] For maximum of 48 hr exposure. The lower temperature is uncorrected for heavy mortality of control animals at "acclimation" temperatures above about 21.6.

[g] The author concluded that there were no geographic differences. The Welaka, Florida subspecies was N.c. bosii, the others N.c. auratus, based on morphology.

[h] Tested in Columbia River Water at Prescott, Oregon.

[*] Mortality Value.

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation Temp[a]	Acclimation Time	a	b	N[b]	r[c]	Data limits (°C) upper	Data limits (°C) lower	LD50	Lethal threshold[d] (°C)
Oncorhynchus Kisutch (coho salmon)	Juvenile fresh-water fry (5.2 mo.)	4.78±0.6 cm	1.37±0.62g	Mixed	Nile Creek. B.C. (hatchery)	Brett (1952)[74]	Upper	5	....	21.3050	−0.7970	2	....	24.0	23.0	....	22.9±0.3
								10	....	19.5721	−0.6820	4	−0.9847	26.0	24.5	....	23.7
								15	....	20.4066	−0.6858	6	−0.9681	27.0	24.5	....	24.3±0.3
								20	....	20.4022	−0.6713	4	−0.9985	27.5	25.5	....	25.0±0.2
								23	....	18.9736	−0.6013	5	−0.9956	27.5	25.0	....	25.0±0.2
							Lower	5	....	....	....	....	....	....	....	....	0.2
								10	....	....	....	....	....	1	....	....	1.7
								15	....	....	....	....	....	3	....	....	3.5
								20	....	....	....	....	....	5	....	....	4.5
								23	....	....	....	....	....	7	1.0	....	6.4
Oncorhynchus kisutch (coho salmon)	Juvenile				Kalama Falls. Wash. (hatchery)[e]	Blahm & McConnell (1970)[100] unpublished data	Upper	10	(10%)[f]	15.4616	−0.5522	6	−0.8533	29	1.7	....	23.2
									(50%)	18.4136	−0.6410	6	−0.9705	29	17.0	....	23.5
									(90%)	15.9026	−0.5423	4	−0.9720	29	17.0	....	23.7
								14[g]	(10%)	8.5307	−0.2969	10	−0.9063	29	14.0	....	14.0
									(50%)	8.5195	−0.2433	10	−0.8483	29	0.14	....	17.0
									(90%)	....	....	....	....	....	....	....	22.0
Oncorhynchus kisutch (coho salmon)	Adult	a 570 mm ave.	a 2500 g ave.	Mixed	Columbia River at Priest Rapids Dam	Coutant (1970)[76]	Upper	17[h]	....	5.9068	−0.1630	5	−0.9767	30	26	....	?
Oncorhynchus nerka (sockeye salmon)	Juvenile fresh-water fry (4.7 mo)	4.49±0.84 cm	0.87±0.45g	Mixed	Issaquah. Wash. (hatchery)	Brett (1952)[74]	Upper	5	....	17.7887	−0.6623	4	−0.9383	24.0	22.5	....	22.2±0.3
								10	....	14.7319	−0.4988	8	−0.9833	26.5	23.5	....	23.4±0.3
								15	....	15.8799	−0.5210	7	−0.9126	27.5	24.5	....	24.4±0.3
								20	....	19.3821	−0.6378	5	−0.9602	27.5	24.5	....	24.8±0.3
								23	....	20.0020	−0.6496	4	−0.9981	26.5	24.5	....	24.8±0.3
							Lower	5	....	....	....	....	....	0	0	....	0
								10	....	....	....	....	....	4	0	....	3.1
								15	....	....	....	....	....	5	0	....	4.1
								20	....	....	....	....	....	5	0	....	4.7
								23	....	....	....	....	....	7	1.0	....	6.7
Oncorhynchus nerka (sockeye salmon)	Juvenile (under yearling)	67 mm ave.	....	Mixed	National Fish Hatchery[i] Leaven-worth. Wash.	McConnell & Blahm (1970)[103] unpublished data	Upper	10	10%[j]	18.4771	−0.6458	6	−0.9671	29	17	....	21.5
									50%	18.5833	−0.6437	6	−0.9750	29	17	....	22.5
									90%	20.6289	−0.7166	6	−0.9553	29	17	....	23.0
								20	10%	17.5227	−0.5861	6	−0.9739	29	21	....	23.5
									50%	16.7328	−0.5473	6	−0.9552	29	21	....	23.5
									90%	15.7823	−0.5061	6	−0.9539	29	21	....	23.5
Oncorhynchus nerka (sockeye salmon)	Juvenile (yearling)	100–105 mm are for test groups		Mixed	National Fish Hatchery Leaven-worth. Wash.[i]	McConnell & Blahm (1970)[103] unpublished data	Upper	10 1°C per day rise to accl. temp.	(10%)[j]	6.4771	−0.2118	4	−0.9887	32	14		
									(50%)	9.0438	−0.2922	4	−0.9392	32	14	....	23.5
									(90%)	9.0628	−0.2859	4	−0.9534	32	14	....	....
								12"	(10%)	13.2412	−0.4475	4	−0.9355	29	17	....	....
									(50%)	18.1322	−0.6178	4	−0.9598	29	17	....	23.5
									(90%)	17.5427	−0.5900	4	−0.9533	29	17	....	....
								15.5"	(10%)	12.1763	−0.4004	5	−0.9443	32	17	....	....
									(50%)	13.6666	−0.4432	5	−0.9720	32	17	....	22.5
									(90%)	12.7165	−0.4057	4	−0.9748	32	17	....	....
								17"	(10%)	17.4210	−0.6114	5	−0.9549	29	20	....	....
									(50%)	17.2432	−0.5885	4	−0.9450	29	20	....	23.5
									(90%)	17.2393	−0.5769	4	−0.9364	29	20	....	....
Oncorhynchus tshawytscha (Chinook salmon)	Juvenile fresh-water fry (3.6 mo.)	4.44±0.40 cm	1.03±0.27g	Mixed	Dungeness. Wash. (hatchery)	Brett (1952)[74]	Upper	5	....	9.3155	−0.3107	6	−0.9847	25.0	22.5	....	21.5
								10	....	16.4595	−0.5575	5	−0.9996	26.5	24.5	....	24.3±0.1
								15	....	16.4454	−0.5364	6	−0.9906	27.0	25.5	....	25.0±0.1
								20	....	22.9065	−0.7611	7	−0.9850	27.5	25.0	....	25.1±0.1
								24	....	18.9940	−0.5992	9	−0.9923	27.5	25.0	....	25.1±0.1
							Lower	10	....	....	....	....	....	1.0	0	....	0.8
								15	....	....	....	....	....	3.0	0.5	....	2.5
								20	....	....	....	....	....	5.0	0.5	....	4.5
								23	....	....	....	....	....	8.0	1.0	....	7.4

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett (1952).[74]

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line = 1.0).

[d] = Incipient lethal temperature of Fry, et al. (1946).[83]

[e] 10 C—acclimated fish came directly from the hatchery.

[f] Data were presented allowing calculation of 10% and 90% mortality.

[g] 14 C—acclimated fish were collected from the Columbia River 4–6 wks following release from the hatchery (and may have included a few fish from other upstream sources). River water was supersaturated with Nitrogen, and 14-C fish showed signs of gas-bubble disease during tests.

[h] River temp. during fall migration.

[i] Tested in Columbia River water at Prescott, Oregon.

[j] Per cent mortalities.

Appendix II—Freshwater Aquatic Life and Wildlife

THERMAL TABLES—Continued

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation		log time = a + b (temp.)				Data limits (°C)		LD50	Lethal threshold[d] (°C)
								Temp[a]	Time	a	b	N[b]	r[c]	upper	lower		
Oncorhynchus tshawytscha (chinook salmon)	Juvenile	39–124 mm averages for various test groups		Mixed	Columbia River at Prescott, Oregon	Snyder & Blahm (1970)[105] unpublished data	Upper	10[e]		16.8109	−0.5787	3	−0.9998	29	25		24.5
									(10%)[f]	18.9770	−0.6621	5	−0.9918	29	23		22.9
									(90%)	17.0278	−0.5845	3	−0.9997	29	25		24.5
								10[g]		15.7101	−0.5403	8	−0.9255	29	20		23.5
									(10%)	15.1583	−0.5312	8[h]	−0.9439	29	20		20.5
									(90%)	15.2525	−0.5130	8	−0.9360	29	20		23.5
								12		18.2574	−0.6149	5[h]	−0.9821	29	23		20.5
								13		12.4058	−0.3974	6	−0.9608	32	17		20.0
									(10%)	10.1410	−0.3218	7	−0.9496	32	17		19.5
									(90%)	12.7368	−0.4040	6	−0.9753	32	17		23.0
								18[g]		13.3175	−0.4240	11	−0.9550	30	20		20.5
									(10%)	11.5122	−0.3745	12	−0.9413	30	20		20.0
									(90%)	14.2456	−0.4434	10	−0.9620	30	20		23.5
Oncorhynchus tshawytscha (chinook salmon spring run)	Juvenile	84 mm ave.	6.3g ave.	Mixed	Little White Salmon River Hatchery, Cook, Washington	Blahm & McConnell (1970) unpublished data	Upper	11	2–3-wks 10%[k]	13.3696	−0.4691	4	−0.9504	29	17		23.0
									50%	14.6268	−0.5066	4	−0.9843	29	17		23.5
									90%	19.2211	−0.6679	4	−0.9295	29	17		23.8
								20	1C/day rise from 10C								
									10%	22.6664	−0.7797	4	−0.9747	29	21		23.8
									50%	21.3981	−0.7253	3	−0.9579	29	21		24.7
									90%	20.9294	−0.7024	3	−0.9463	29	21		24.8
Oncorhynchus tshawytscha (chinook salmon)	Juvenile	40 mm. ave.		Mixed	Eggs from Seattle, Wash. raised from yolk-sac stage in Columbia River water at Prescott, Oregon	Snyder & Blahm (1970)[105] unpublished data	Upper	4		13.5019	−0.4874	4	−0.9845	29	8		20
									(10%)[j]	8.9126	−0.3198	6	−0.9618	29	8		13.5
									(90%)[j]	10.6491	−0.3771	6	−0.9997	29	8		?
Oncorhynchus tshawytscha (chinook salmon fall run)	Juvenile	90.6 mm ave.	7.8 g ave.	Mixed	Little White Salmon Riverhatchery, Cook, Washington	Blahm & McConnell (1970)[100] unpublished data	Upper	11	2–3 wks 10%[k]	18.6889	−0.6569	5	−0.9618	29	17		23.5
									50%	20.5471	−0.7147	4	−0.9283	29	17		24.2
									90%	20.8960	−0.7231	4	−0.9249	29	17		24.5
								Upper	20	1C/day rise from 10C							
									10%	21.6756	−0.7428	4	−0.9550	29	21		24.5
									50%	22.2124	−0.7526	4	−0.9738	29	21		24.5
									90%	20.5162	−0.6860	3	−0.9475	29	21		24.5
Oncorhynchus tshawytscha (chinook salmon)	"Jacks" 1–2 yrs old	2500 mm ave.	2000 g. ave.	Males	Columbia River at Grand Rapids Dam	Coutant (1970)[76]	Upper	17[l]		13.2502	−0.4121	4	−0.8206	30	26		?
								19[l]		9.4683	−0.2504	4	−0.9952	26	22		22
Perca flavescens (yellow perch)	Juvenile	49 mm ave.	1.2 g ave.	Mixed	Columbia River near Prescott, Ore.	Blahm and Parente (1970)[101] unpublished data	Upper	19	field plus 4 da.	15.3601	−0.4126	2		38	32		?
Perca flavescens (yellow perch)	Adult (4 yr mode)		8.0–9.9 g mode	Mixed	Black Creek, Lake Simcoe, Ontario	Hart (1947)[87]	Upper	5		7.0095	−0.2214	9	−0.9904	26.5	22.0		21.3
								11		17.6536	−0.6021	2		26.5	26.0		25.0
								15		12.4149	−0.3641	5	−0.9994	30.5	28.5		27.7
								25		21.2718	−0.5909	6	−0.9698	33.0	30.0		29.7
							Lower	25									3.7
Petromyzon marinus (sea lamprey, land-locked)	Prolarvae				Great Lakes	McCauley (1963)[94]	Upper	15 and 20[m]		17.5642	−0.4680	18	−0.9683	34	29		28.5

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett 1952[14].

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line = 1.0).

[d] = Incipient lethal temperature or Fry, et al., (1946).[83]

[e] Fish tested shortly after capture by beach seine.

[f] Data were also available for calculation of 10% and 90% mortality of June test groups.

[g] These were likely synergistic effects of high N2 supersaturation in these tests.

[h] Excluding apparent long-term secondary mortality.

[i] Data were available for 10% and 90% mortality as well as 50%.

[j] Data also available on 10% and 90% mortality.

[k] Data available for 10% and 90% mortality as well as 50%.

[l] River temperatures during fall migrations two different years.

[m] No difference was shown so data are lumped.

THERMAL TABLES—*Continued*

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation Temp[a]	Acclimation Time	a	b	N[b]	r[c]	Data limits (°C) upper	Data limits (°C) lower	LD50	Lethal threshold[d] (°C)
Pimephales (Hyborhynchus) notatus (blunt-nose minnow)	Adult (mostly 1 yr)	....	mostly 0-2 g	Mixed	Etobicoke Cr., Ontario	Hart (1947)[87]	Upper	5	....	24.6417	−0.8602	2	....	27.0	26.5	....	26.0
								10	....	55.8357	−1.8588	2	....	29.5	29.0	....	28.3
								15	....	28.0377	−0.8337	3	−0.9974	32.0	31.0	....	30.6
								20	....	34.3240	−0.9682	4	−0.9329	34.0	32.5	....	31.7
								25	....	50.8212	−1.4181	3	−0.9490	35.0	34.0	....	33.3
							Lower	15	....	....	....	....	....	....	....	....	10
								20	....	....	....	....	....	....	....	....	4.2
								25	....	....	....	....	....	....	....	....	7.5
Pimephales promelas (fat-head minnow)	Adult (1 yr)	....	2.0-3.9 g mode	Mixed	Don River, Thornhill, Ontario	Hart (1947)[87]	Upper	10	....	60.7782	−2.0000	2	....	30.0	29.5	....	28.2
								20	....	6.9970	−0.1560	4	−0.7448	33.0	28.5	....	31.7
								30	....	41.3696	−1.1317	5	−0.9670	36.0	34.0	....	33.2
							Lower	20	....	....	....	....	....	....	....	....	1.5
								30	....	....	....	....	....	....	....	....	10.5
Poecilia latipinna (Sailfin molly)	Adult	....			Jefferson Co., Texas	Strawn and Dunn (1967)[99]	Upper	35	(0 °/oo)[e]	27.4296	−0.6279	6	−0.9902	42.5	38.5	....	....
								35	(5 °/oo)	25.6936	−0.5753	6	−0.9835	42.5	39.0	....	....
								35	(10 °/oo)	28.8808	−0.6535	7	−0.9949	42.0	39.0	....	....
								35	(20 °/oo)	27.1988	−0.6146	3	−0.9791	42.5	39.5	....	....
Pontoporeia affinis	Adult	....		Mixed	Lake Superior near Two Harbors, Minn.	Smith (1971)[104] unpublished data	Upper	6	....	9.1790	−0.5017	2	....	12	10.8	....	10.5
								9	....							10.4 (30 da)	
Pseudopleuro-nectes ameri-canus (winter flounder)		6.0-7.1 cm (averages for test groups)	3.4-4.2 g (averages for test groups)	Mixed	New Jersey (40°N)	Hoff & West-man (1966)[90]	Upper	7	....	28.2986	−1.1405	4	−0.9852	24.0	20.0	....	22.0
								14	....	24.3020	−0.8762	6	−0.9507	26.0	23.0	....	23.7
								21	....	49.0231	−1.6915	5	−0.9237	29.0	26.0	....	27.0
								28	....	60.8070	−1.9610	4	−0.9181	30.0	29.0	....	29.1
							Lower	7	....	....	....	....	....	1.0	1.0	....	1.0
								14	....	....	....	....	....	2.0	1.0	....	1.0
								21	....	2.4924	0.8165	3	0.7816	6.0	1.0	....	14
								28	....	2.2145	0.2244	3	0.9970	7.0	4.0	....	6.0
Rhinichthys atratulus (blacknose dace)	Adult	....			Knoxville, Tenn.	Hart (1952)[88]	Upper	20	....	21.2115	−0.5958	7	−0.9935	33	30	....	29.3
								25	....	19.6451	−0.5224	10	−0.9979	35	30.5	....	29.3
								28	....	21.3360	−0.5651	7	−0.9946	35.5	32.5	....	29.3
Rhinichthys atratulus (black-nose dace)	Adult (?)	....		Mixed	Toronto, Ontario	Hart (1952)[88]	Upper	5	....	....	....	....	....	27	27	27(1 hr)	....
								15	....	19.8158	−0.5771	4	−0.9632	31.5	30.0	....	29.3
								20	....	24.5749	−0.7061	7	−0.9926	33	30.0	....	29.3
								25	....	20.1840	−0.5389	8	−0.9968	35	32.0	....	29.3
Rhinichthys atratulus (Black-nose dace)	Adult	....	2.0-3.9 (mode)	Mixed	Don River, Thornhill, Ontario	Hart (1947)[87]	Upper	5	....	77.1877	−2.7959	2	....	27.5	27.0	....	26.5
								10	....	49.1469	−1.6021	3	−0.8521	30.5	29.5	....	28.8
								15	....	19.6975	−0.5734	4	−0.9571	31.5	30.0	....	29.6
								20	....	26.5952	−0.7719	8	−0.9897	33.5	29.5	....	29.3
								25	....	23.5765	−0.6629	9	−0.9937	34.0	30.0	....	29.3
							Lower	20	....	....	....	....	....	....	....	....	2.2
								25	....	....	....	....	....	....	....	....	5.0
Salmo gairdnerii (Rainbow trout)	Juvenile	4.5±0.4 cm	....	Mixed	Britain	Alabaster & Welcomme (1962)[70]	Upper	18[f]	....	18.4654	−0.5801	5	−0.9787	29.6	26.3	....	26.5
								18[g]	....	13.6531	−0.4264	5	−0.9742	29.1	26.3	....	26.5
Salmo gairdnerii (rainbow trout)	Yearling	....	....	....	East end of Lake Superior	Craigie, D.E. (1963)[77]	Upper	Raised in soft water									
								20 (tested in soft water)		14.6405	−0.4470	3	−0.9787	29	27	....	....
								20 (tested in hard water)		15.0392	−0.4561	3	−0.9917	29	27	....	....
								Raised in hard water									
								20 (tested in soft water)		15.1473	−0.4683	3	−0.9781	29	27	....	....
								20 (tested in hard water)		12.8718	−0.3837	3	−0.9841	29	27	....	....
Salmo gairdnerii (rainbow trout)	Juvenile	9.4±6.0 cm and 15.5± 1.8 cm	....	Mixed	London, England (Hatchery)	Alabaster & Downing (1966)[69]	Upper	15	....	15.6500	−0.500	2[h]	....	....	....	....	....
								20	....	19.6250	−0.6250	2	....	....	....	....	....

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett (1952).[74]

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line=1.0).

[d] = Incipient lethal temperature of Fry, et al., (1946).[63]

[e] Salinity.

[f] Dissolved oxygen Conc. 7.4 mg/l.

[g] Dissolved oxygen Conc. 3.8 mg/l.

[h] See note (under Salmo salar) about Alabaster 1967.[66]

THERMAL TABLES—Continued

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation Temp[a]	Acclimation Time	log time = a + b (temp.) a	b	N[b]	r[c]	Data limits (°C) upper	Data limits (°C) lower	LD50	Lethal threshold[d] (°C)
Salmo gairdnerii (anadromous) (Steelhead trout)	Adult	2650 mm ave.	4000 g ave.	Mixed	Columbia River at Priest Rapids Dam	Coutant (1970)[76]	Upper	19[e]	....	10.9677	−0.3329	7	−0.9910	29	21	....	21
Salmo salar (Atlantic salmon)	Smolts (1–2 yrs)	About 16 cm ave.	....	Mixed	River Axe, Devon, England	Alabaster (1967)[68]	Upper	9.2 (field)	....	43.6667	−1.6667	2[f]	....	(f)	(f)	....	....
								9.3 "		23.7273	−0.9091	2	....	....	....	....	....
								10.9 "		126.5000	−5.000		....	....	....	....	....
								Tested in 30% seawater 9.2 (field)		44.6667	−1.6667	2	....	....	....	....	....
								Tested in 100% seawater 9.2 (field)		14.7368	−0.5263	2	....	....	....	....	....
								Acclimated 7 hr in seawater; tested in seawater 9.2 (field)		36.9999	−1.4286	2	....	....	....	....	....
Salmo salar (Atlantic salmon)	Newly hatched larvae	....	....	Mixed	Cullercoats, North Shields, England (hatchery)	Bishai (1960)[73]	Upper	6 (brought up to test temp. in 6 hours)		13.59	−0.4287	6	−0.9678	28.0	20.0	....	22.0
Salmo salar (Atlantic salmon)	30 da after hatching	....	....	Mixed	Cullercoats, North Shields, England (hatchery)	Bishai (1960)[73]	Upper	5	....	8.9631	−0.2877	4	−0.9791	25.0	22	....	22.2
								10	....	15.7280	−0.5396	3	−0.9689	26.0	22	....	23.3
								20	....	11.5471	−0.3406	3	−0.9143	26.0	22	....	23.5
Salmo salar (Atlantic salmon)	Parr (1 yr)	10 cm ave.	....	Mixed	River Axe, Devon, England	Alabaster (1967)[68]	Upper	9.3 (field)		33.3750	−1.2500	2[g]	....	....	....	....	....
								10.9 (field)		28.0000	−1.0000	2	....	....	....	....	....
Salmo salar (Atlantic salmon)	Smolts (1–2 yrs)	11.7±1.5 cm	....	Mixed	River North Esk, Scotland	Alabaster (1967)[68]	Upper	11.7	....	25.9091	−0.9091	2[g]	....	....	....	....	....
Salmo salar (Atlantic salmon)	Smolts (1–2 yrs)	14.6±1.3 cm	....	Mixed	River Severn Gloucester, England	Alabaster (1967)[68]	Upper	16.7	....	14.5909	−0.4545	2[g]	....	....	....	....	....
Salmo trutta (brown trout)	Newly hatched fry	....	....	Mixed	Cullercoats, North Shields, England (hatchery)	Bishai (1960)[73]	Upper	6 (raised to test temp. over 6 hr period)		12.7756	−0.4010	6	−0.9747	28.0	20.0	....	22.0
Salmo trutta (Brown trout, searun)	30 da after hatching	....	....	Mixed	Cullercoats, North Shields, England (hatchery)	Bishai (1960)[73]	Upper	5	....	15.2944	−0.5299	4	−0.8783	25.0	22.0	....	22.2
								10	....	23.5131	−0.8406	3	−0.9702	26.0	22.0	....	23.4
								20	....	14.6978	−0.4665	3	−0.9797	26.0	22.0	....	23.5
Salmo trutta (brown trout, searun)	Juvenile	10.1±0.8 cm 7.4±4.5 cm	....	Mixed	London, England (hatchery)	Alabaster & Downing (1966)[69]	Upper	6	....	36.1429	−1.4286	2[g]	....	....	....	....	....
								15	....	21.5714	−0.7143	2	....	....	....	....	....
								20	....	17.6667	−0.5556	2	....	....	....	....	....
Salmo trutta (brown trout, searun)	Smolts (2 yr.)	About 21 cm ave.	....	Mixed	River Axe, Devon, England	Alabaster (1967)[68]	Upper	9.3 (field)		18.4667	−0.6667	2[g]	....	....	....	....	....
								10.9 "		33.6000	−1.2500	2	....	....	....	....	....
Salvelinus fontinalis (Brook trout)	Juvenile	....	....	....	Pleasant Mount Hatchery, Wayne Co., Penna. and Chatsworth Hatchery, Ontario[h]	McCauley (1958)[83]	Upper	10	....	17.5260	−0.6033	6	−0.9254	25.5	24.5	....	....
								20	....	20.2457	−0.6671	7	−0.9723	27.0	25.0	....	....

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett (1952).[74]

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line = 1.0).

[d] = Incipient lethal temperature of Fry, et al., (1946).[43]

[e] River temp. during fall migration

[f] Alabaster fitted by eye, a straight line to median death times plotted on semilog paper (log time), then reported only the 100 and 1000 min intercepts. These intercepts are the basis for the equation presented here.

[g] See note for Alabaster 1967.[68]

[h] Results did not differ so data were combined.

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THERMAL TABLES—Continued

Species	Stage/age	Length	Weight	Sex	Location	Reference	Extreme	Acclimation		log time=a+b (temp.)				Data limits (°C)		LD50	Lethal threshold[d] (°C)
								Temp[a]	Time	a	b	N[b]	r[c]	upper	lower		
Salvelinus fontinalis (brook trout)	Yearling		$\bar{X}=7.88$ g range 2-25 g	Mixed	Codrington, Ont. (hatchery	Fry, Hart & Walker (1946)[83]	Upper	3	....	13.4325	−0.4556	3	−0.9997	26.0	23.5	....	23.5
								11	....	14.6256	−0.4728	6	....	28.0	25.0	....	24.6
								15	....	15.1846	−0.4833	9	....	28.5	25.5	....	25.0
								20	....	15.0331	−0.4661	7	....	29.0	25.5	....	25.3
								22	....	17.1967	−0.5367	6	....	29.0	26.5	....	25.5
								24	....	17.8467	−0.5567	10	....	30.0	25.5	....	25.5
								25	....	17.8467	−0.5567	3	....	29.0	26.0	....	25.5
Salvelinus fontinalis (namaycush hybrid)	Juvenile				Ontario, Canada	Fry and Gibson (1953)[82]	Upper	10	....	13.2634	−0.4381	6	−0.9852	26.5	24.0	....	23.5-24.0
								15	....	16.9596	−0.5540	8	−0.9652	28.0	24.5	....	?
								20	....	19.4449	−0.6342	9	−0.9744	28.0	24.5	....	24.0-24.5
Salvelinus namaycush (Lake trout)	1-2 yr. old		27.7 gm ave. (1 yr) 82.8 gm ave. (2 yr)	Mixed	Hatcheries in Ontario	Gibson and Fry (1954)[85]	Upper	8	1 wk	14.4820	−0.5142	4	−0.9936	26	23	....	22.7
								15	"	14.5123	−0.4866	5	−0.9989	27	24	....	23.5
								20	"	17.3684	−0.5818	5	−0.9951	27	24	....	23.5
Scardinius erythrophthalmus (rudd)	Adult	10 cm		Mixed	Britain (field)	Alabaster & Downing (1966)[69]	Upper	20	....	26.9999	−0.7692	2[e]					
Semotilus atromaculatus (Creek chub)	Adult		2.0-3.9 gm mode	Mixed	Don River, Thornhill, Ontario	Hart (1947)[87]	Upper	5	....	42.1859	−1.6021	3	−0.9408	26.0	25.0	....	24.7
								10	....	31.0755	−1.0414	3	−0.8628	29.0	28.0	....	27.3
								15	....	20.8055	−0.6226	3	−0.9969	31.0	30.0	....	29.3
								20	....	21.0274	−0.5933	7	−0.9944	33.5	30.5	....	30.3
								25	....	16.8951	−0.4499	9	−0.9911	35.0	31.0	....	30.3
							Lower	20	....								0.7
								25	....								4.5
Semotilus atromaculatus (Creek chub)	Adult				Toronto, Ontario Knoxville, Tenn.	Hart (1952)[88]	Upper	10 (Toronto only)	....					29	28	....	27.5
								15 (Toronto only)	....	20.8055	−0.6226	3	−0.9969	31	30	....	29
								20 (Toronto only)	....	19.1315	−0.5328	6	−0.9856	33	30.5	....	30.5
								25	....	19.3186	−0.4717	18	−0.9921	36	32	....	31.5
								30	....	22.8982	−0.5844	19	−0.9961	37	33	....	31.5
Sphaeroides annulatus (Puffer)	Adult				Northern Gulf of Calif. Coast	Heath (1967)[89]	Upper	32.0	....	25.4649	−0.6088	3	−0.9716	37.0	36.0	....	....
Sphaeroides maculatus (Northern puffer)		13.8-15.9 cm (average)	62.3-79.3 gm (average)	Mixed	New Jersey (40 N)	Hoff and Westman (1966)[90]	Upper	10	....	11.3499	−0.2821	3	−0.9988	30.0	25.0	....	27.5
								14	....	35.5191	−1.0751	3	−0.9449	32.0	27.0	....	30.2
								21	....	21.5353	−0.5746	3	−0.9914	32.0	30.0	....	31.2
								28	....	23.7582	−0.6183	3	−0.9239	33.5	31.1	....	32.5
							Lower	14	....	−1.7104	0.6141	4	0.9760	10.0	6.0	....	8.8
								21	....	−3.9939	0.7300	6	0.9310	12.0	8.0	....	10.7
								28	....	−7.4513	0.8498	5	0.9738	16.0	10.0	....	13.0
Thaleichthys pacificus (Eulachon or Columbia River Smelt)	Sexually Mature	161 mm ave.	31 gm ave.	Mixed	Cowlitz River, Wash.	Blahm & McConnell (1970)[100] unpublished data	Upper	5	river temp.	7.7440	−0.2740	7	−0.9142	29.0	8.0	....	10.5
Tilapia mossambica (Mozambique mouthbreeder)	4 months	8.0-12.0 cm	10.0-17.0 gm		Transvaal Africa	Allanson & Noble (1964)[71]	Upper	22	....	313.3830	−8.3878	4	−0.8898	37.10	36.5	....	36.94
								26	....	14.0458	−0.2800	5	−0.2140	37.92	37.5	....	37.7
								28	....	41.1610	−0.9950	4	−0.3107	38.09	37.9	....	37.89
								29	....	94.8243	−2.4125	5	−0.7781	38.10	37.0	....	37.91
								30	....	41.3233	−1.0018	6	−0.9724	38.50	37.6	....	37.59
								32	....	34.0769	−0.8123	4	−0.9209	38.4	37.6	....	37.6
								34	....	123.1504	−3.1223	3	−0.9938	38.4	38.2	....	38.25
								36	....	68.6764	−1.7094	6	−0.9053	38.77	37.9	....	38.2
Tinca tinca (tench)	Juvenile	4.6±0.4 cm		Mixed	England	Alabaster & Downing (1966)[69]	Upper	15	....	33.2000	1.0000	2[e]				....	....
								20	....	29.6667	0.8333	3				....	....
								25	....	27.1429	0.7143	2				....	....

[a] It is assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett (1952).[74]

[b] Number of median resistance times used for calculating regression equation.

[c] Correlation coefficient (perfect fit of all data points to the regression line=1.0).

[d] =Incipient lethal temperature of Fry, et al., (1946).[83]

[e] See previous note for Alabaster 1967.[?]

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APPENDIX II-C

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FISH TEMPERATURE DATA

Species: Coho salmon, *Oncorhynchus kisutch*

I. Lethal threshold:

acclimation temperature	larvae	juvenile	adult	reference[1]
Upper				
5		23		1
10		24(1)	21*(3)	1,3
15		24		1
20		25		1
23		25		1

*Accl. temp. unknown

acclimation temperature	larvae	juvenile	adult	reference[1]
Lower				
5		0.2		1
10		2		1
15		3		1
20		5		1
23		6		1

II. Growth:

	larvae	juvenile	adult	
Optimum and [range]		15*		2
		(5-17)**		6

*unlimited food
**depending upon season

III. Reproduction:

	optimum	range	month(s)	
Migration		7-16		5
Spawning		7-13	Fall	3
Incubation and hatch	8(2)	?-11(7)		2,7

IV. Preferred:

acclimation temperature	larvae	juvenile	adult	
Winter			13	4

[1] References on following page.

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Coho salmon

References

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FISH TEMPERATURE DATA

Species: Lake trout, *Salvelinus namaycush*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper					
Lower					

II. Growth:

	larvae	juvenile	adult	
Optimum and [range]				

III. Reproduction:

	optimum	range	month(s)	
Migration				
Spawning		3-14(3)	Aug-Dec(2)	2,3
Incubation and hatch	8(1)	0.3-10(3)		1,3

IV. Preferred:

	acclimation temperature	larvae	juvenile	adult	
			12*		4
			8-15**		5

*yearling
**age unknown

Lake trout

References

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FISH TEMPERATURE DATA

Species: _Lake whitefish, Coregonus clupeaformis_

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	___	___	___	___	___
	___	___	___	___	___
	___	___	___	___	___
	___	___	___	___	___
Lower	___	___	___	___	___
	___	___	___	___	___
	___	___	___	___	___
	___	___	___	___	___

II. Growth:	larvae	juvenile	adult	
Optimum and [range]	___	___	___	___
	___	___	___	___
	___	___	___	___
	___	___	___	___

III. Reproduction:	optimum	range	month(s)	reference[1]
Migration	___	___		
Spawning	___	0.5-10	Sept-Dec	2
Incubation and hatch	3-8	___	___	1

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference[1]
	___	___	___	13*	3
	___	___	___	___	___
	___	___	___	___	___

*2 year old

[1] References on following page.

Lake whitefish

References

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FISH TEMPERATURE DATA

Species: Northern pike, *Esox lucius*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	18	25,28*			2
	25		32		1
	27		33		1
	30		33**		1

*At hatch and free swimming, respectively
**Ultimate incipient level

	acclimation temperature	larvae	juvenile	adult	reference
Lower	18	3*			2

*At hatch and free swimming

II. Growth:

	larvae	juvenile	adult	reference
Optimum and [range]	21	26		2
	(18-26)			2

III. Reproduction:

	optimum	range	month(s)	reference
Migration				
Spawning		4(4)-18(3)	Feb-June(5)	3,4,5
Incubation and hatch	12	7-19		2

IV. Preferred:

	acclimation temperature	larvae	juvenile	adult	reference
			24,26*		6

*Grass pickerel and musky, respectively

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Northern Pike

References

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FISH TEMPERATURE DATA

Species: Rainbow trout, *Salmo gairdneri*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	18		27		1
	19			21	2
Lower					

II. Growth:

	larvae	juvenile	adult	
Optimum and		17-19		5
[range]	[3(8)-20(11)]			8,11

III. Reproduction:

	optimum	range	month(s)	
Migration				
Spawning	9(10)	5-13(6)	Nov-Feb(7) Feb-June(7)	6,7,10
Incubation and hatch	5-7(9)	5-13(4)		4,9

IV. Preferred:

	acclimation temperature	larvae	juvenile	adult	
	Not given		14		3
		13-20	13-19		11
	18&24		18&22, resp.		12

[1] References on following page.

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Rainbow trout

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FISH TEMPERATURE DATA

Species: Sockeye salmon, *Oncorhynchus nerka*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	5		22		1
	10		23		1
	15		24		1
	20		25		1
Lower	5		0		1
	10		3		1
	15		4		1
	20		5		1
	23		7		1

II. Growth:

	larvae	juvenile	adult	
Optimum and [range]	15(5)	15(2)*		2,5
		(10-15)		4
		(11-17)		7

*Max. with excess food

III. Reproduction:

	optimum	range	month(s)	
Migration		7-16		4
Spawning		7-13	Fall	6
Incubation and hatch				

IV. Preferred:

	acclimation temperature	larvae	juvenile	adult	
	Summer		15		3

[1] References on following page.

Sockeye salmon

References

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

The evolution of freshwater temperature criteria is discussed as it relates to standards development by regulatory agencies. The present, generally accepted philosophical approach to criteria development is explained in detail and its use to protect various life stages of fish is demonstrated by selected examples. Numerical criteria for survival, spawning, embryo development, growth, and gamete maturation of fish species were calculated and tabulated.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Temperature Fresh Water Fishes Growth Reproduction (biology) Mortality Water Pollution	Water Quality Criteria Water Quality Standards Temperature Requirements Thermal Pollution	06 S 06 F 06 C

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