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TEMPERATURE CRITERIA FOR FRESHWATER FISH:

PROTOCOL AND PROCEDURES

by

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FOREWORD

Our nation's fresh waters are vital for all animals and plants, yet our diverse uses of water — for recreation, food, energy, transportation, and industry — physically and chemically alter lakes, rivers, and streams. Such alterations threaten terrestrial organisms, as well as those living in water. The Environmental Research Laboratory in Duluth, Minnesota, develops methods, conducts laboratory and field studies, and extrapolates research findings

--to determine how physical and chemical pollution affects aquatic life;

--to assess the effects of ecosystems on pollutants;

--to predict effects of pollutants on large lakes through use of models; and

--to measure bioaccumulation of pollutants in aquatic organisms that are consumed by other animals, including man.

This report discusses the history, procedures, and derivation of temperature criteria to protect freshwater fishes and presents numerical criteria for 34 species. It follows the general philosophical approach of the National Academy of Sciences and National Academy of Engineering in their Water Quality Criteria 1972 and is intended to make that philosophy practically useful.

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ABSTRACT

Temperature criteria for freshwater fish are expressed as mean and maximum temperatures; means control functions such as embryogenesis, growth, maturation, and reproductivity, and maxima provide protection for all life stages against lethal conditions. These criteria for 34 fish species are based on numerous field and laboratory studies, and yet for some important species the data are still insufficient to develop all the necessary criteria. Fishery managers, power-plant designers, and regulatory agencies will find these criteria useful in their efforts to protect fishery resources.

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SECTION 1

SUMMARY AND CONCLUSIONS

The evolution of freshwater temperature criteria has advanced from the search for a single "magic number" to the generally accepted protocol for determining mean and maximum numerical criteria based on the protection of appropriate desirable or important fish species, or both. The philosophy and protocol of the National Academy of Sciences and National Academy of Engineering (1973) were used to determine criteria for survival, spawning, embryo development, growth, and gamete maturation for species of freshwater fish, both warmwater and coldwater species.

The influence that management objectives and selection of species have on the application of temperature criteria is extremely important, especially if an inappropriate, but very temperature-sensitive, species is included. In such a case, unnecessarily restrictive criteria will be derived. Conversely, if the most sensitive important species is not considered, the resultant criteria will not be protective.

SECTION 2

INTRODUCTION

This report is intended to be a guide for derivation of temperature criteria for freshwater fish based on the philosophy and protocol presented by the National Academy of Sciences and National Academy of Engineering (1973). It is not an attempt to gather and summarize the literature on thermal effects.

Methods for determination of temperature criteria have evolved and developed rapidly during the past 20 years, making possible a vast increase in basic data on the relationship of temperature to various life stages.

One of the earliest published temperature criteria for freshwater life was prepared by the Aquatic Life Advisory Committee of the Ohio River Valley Water Sanitation Commission (ORSANCO) in 1956. These criteria were based on conditions necessary to maintain a well-rounded fish population and to sustain production of a harvestable crop in the Ohio River watershed. The committee recommended that the temperature of the receiving water:

1) Should not be raised above 34° C (93°F) at any place or at any time;

2) should not be raised above 23° C (73° F) at any place or at any time during the months of December through April; and

3) should not be raised in streams suitable for trout propagation.

McKee and Wolf (1963) in their discussion of temperature criteria for the propagation of fish and other aquatic and marine life refer only to the progress report of ORSANCO's Aquatic Life Advisory Committee (1956).

In 1967 the Aquatic Life Advisory Committee of ORSANCO evaluated and further modified their recommendations for temperature in the Ohio River watershed. At this time the committee expanded their recommendation of a 93° F (33.9° C) instantaneous temperature at any time or any place to include a daily mean of 90° F (32.2° C). This, we believe, was one of the first efforts to recognize the importance of both mean and maximum temperatures to describe temperature requirements of fishes. The 1967 recommedations also included:

1) Maximum temperature during December, January, and February should be 55° F (12.8° C);

2) during the transition months of March, April, October and November the temperature can be changed gradually by not more than 7° F (3.9° C);

3) to maintain trout habitats, stream temperatures should not exceed 55° F (12.8° C) during the months of October through May, or exceed 68° F (20.0° C) during the months of June through September; and

4) insofar as possible the temperature should not be raised in streams used for natural propagation of trout.

The National Technical Advisory Committee of the Federal Water Pollution Control Administration presented a report on water quality criteria in 1968 that was to become known as the "Green Book." This large committee included many of the members of ORSANCO's Aquatic Life Advisory Committee. The committee members recognized that aquatic organisms might be able to endure a high temperature for a few hours that could not be endured for a period of days. They also acknowledged that no single temperature requirement could be applied to the United States as a whole, or even to one state, and that the requirements must be closely related to each body of water and its fish populations. Other important conditions for temperature requirements were that (1) a seasonal cycle must be retained, (2) the changes in temperature must be gradual, and (3) the temperature reached must not be so high or so low as to damage or alter the composition of the desired population. These conditions led to an approach to criteria development different from earlier ones. A temperature increment based on the natural water temperature was believed to be more appropriate than an unvarying number. The use of an increment requires a knowledge of the natural temperature conditions of the water in question, and the size of the increment that can be tolerated by the desirable species.

The National Technical Advisory Committee (1968, p. 42) recommended:

> "To maintain a well-rounded population of warmwater fishes .... heat should not be added to a stream in excess of the amount that will raise the temperature of the water (at the expected minimum daily flow for that month) more than 5° F."

A casual reading of this requirement resulted in the unintended generalization that the acceptable temperature rise in warmwater fish streams was 5° F (2.8° C). This generalization was incorrect! Upon more careful reading the key word "amount" of heat and the key phrase "minimum daily flow for that month" clarify the erroneousness of the generalization. In fact, a 5° F (2.8° C) rise in temperature could only be acceptable under low flow conditions for a particular month and any increase in flow would result in a reduced increment of temperature rise since the amount of heat added could not be increased. For lakes and reservoirs the temperature rise limitation was 3° F (1.7° C) based "on the monthly average of the maximum daily temperature."

In trout and salmon waters the recommendations were that "inland trout streams, headwaters of salmon streams, trout and salmon lakes, and reservoirs containing salmonids should not be warmed," that "no heated effluents should be discharged in the vicinity of spawning areas," and that "in lakes and reservoirs, the temperature of the hypolimnion should not be raised more than 3° F (1.7° C)." For other locations the recommended incremental rise was 5° F (2.8° C) again based on the minimum expected flow for that month.

An important additional recommendation is summarized in the following table in which provisional maximum temperatures were recommended for various fish species and their associated biota (from FWPCA National Technical Advisory Committee, 1968).

PROVISIONAL MAXIMUM TEMPERATURES RECOMMENDED AS

COMPATIBLE WITH THE WELL-BEING OF VARIOUS SPECIES

OF FISH AND THEIR ASSOCIATED BIOTA

93 F:	Growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad, and gizzard shad.
90 F:	Growth of largemouth bass, drum, bluegill, and crappie.
84 F:	Growth of pike, perch, walleye, smallmouth bass, and sauger.
80 F:	Spawning and egg development of catfish, buffalo, threadfin shad, and gizzard shad.
75 F:	Spawning and egg development of largemouth bass, white, yellow, and spotted bass.
68 F:	Growth or migration routes of salmonids and for egg development of perch and smallmouth bass.
55 F:	Spawning and egg development of salmon and trout (other than lake trout).
48 F:	Spawning and egg development of lake trout, walleye, northern pike, sauger, and Atlantic salmon.

NOTE: Recommended temperatures for other species, not listed above, may be established if and when necessary information becomes available.

These recommendations represent one of the significant early efforts to base temperature criteria on the realistic approach of species and community requirements and take into account the significant biological factors of spawning, embryo development, growth, and survival.

The Federal Water Pollution Control Administration (1969a) recommended revisions in water quality criteria for aquatic life relative to the Main Stem of the Ohio River. These recommendations were presented to ORSANCO's Engineering Committee and were based on the temperature requirements of important Ohio River fishes including largemouth bass, smallmouth bass, white bass, sauger, channel catfish, emerald shiner, freshwater drum, golden redhorse, white sucker, and buffalo (species was not indicated). Temperature requirements for survival, activity, final preferred temperature, reproduction, and growth were considered. The recommended criteria were:

1. "The water temperatures shall not exceed 90° F (32.2° C) at any time or any place, and a maximum hourly average value of 86° F (30° C) shall not be exceeded."

2. "The temperature shall not exceed the temperature values expressed on the following table:"

AQUATIC LIFE TABLE[a]

	Daily mean (° F)	Hourly maximum (° F)
December-February	48	55
Early March	50	56
Late March	52	58
Early April	55	60
Late April	58	62
Early May	62	64
Late May	68	72
Early June	75	79
Late June	78	82
July-September	82	86
October	75	82
November	65	72

[a]From: Federal Water Pollution Control Administration (1969a).

The principal limiting fish species considered in developing these criteria was the sauger, the most temperature sensitive of the important Ohio River fishes. A second set of criteria (Federal Water Pollution Control Administration, 1969b) considered less temperature-sensitive species, and the criteria for mean temperatures were higher. The daily mean in July and September was 84° F (28.9° C). In addition, a third set of criteria was developed that was not designed to protect the smallmouth bass, emerald shiner, golden redhorse, or the white sucker. The July-to-September daily mean temperature criterion was 86° F (30° C).

The significance of the 1969 Ohio River criteria was that they were species dependent and that subsequently the criteria would probably be based upon a single species or a related group of species. Therefore, it is extremely important to select properly the species that are important otherwise the criteria will be unnecessarily restrictive. For example, if yellow perch is an extremely rare species in a water body and is the most temperature-sensitive species, it probably would be unreasonable to establish temperature criteria for this species as part of the regulatory mechanism.

In 1970 ORSANCO established new temperature standards that incorporated the recommendations for temperature criteria of the Federal Water Pollution Control Administration (1969a, 1969b) and the concept of limiting the amount of heat that would be added (National Technical Advisory Committee, 1968). The following is the complete text of that standard:

> " All cooling water from municipalities or political subdivisions, public or private institutions, or installations, or corporations discharged or permitted to flow into the Ohio River from the point of confluence of the Allegheny and Monongahela Rivers at Pittsburgh, Pennsylvania, designated as Ohio River mile point 0.0 to Cairo Point, Illinois, located at the confluence of the Ohio and Mississippi Rivers, and being 981.0 miles downstream from Pittsburgh, Pennsylvania, shall be so regulated or controlled as to provide for reduction of heat content to such degree that the aggregate heat-discharge rate from the municipality, subdivision, institution, installation or corporation, as calculated on the basis of discharge volume and temperature differential (temperature of discharge minus upstream river temperature) does not exceed the amount calculated by the following formula, provided, however, that in no case shall the aggregate heat-discharge rate be of such magnitude as will result in a calculated increase in river temperature of more than 5 degrees F:
>
> Allowable heat-discharge rate (Btu/sec) = 62.4 X river flow (CFS) X $(T_a - T_r)$ X 90%

Where:

T_a = Allowable maximum temperature (deg. F.) in the river as specified in the following table:

	T_a		T_a
January	50	July	89
February	50	August	89
March	60	September	87
April	70	October	78
May	80	November	70
June	87	December	57

T_r = River temperature (daily average in deg. F.) upstream from the discharge

River flow = measured flow but not less than critical flow values specified in the following table:

River reach		Critical flow in cfs[a]
From	To	
Pittsburgh, Penn. (mi. 0.0)	Willow Is. Dam (161.7)	6,500
Willow Is. Dam (161.7)	Gallipolis Dam (279.2)	7,400
Gallipolis Dam (279.2)	Meldahl Dam (436.2)	9,700
Meldahl Dam (436.2)	McAlpine Dam (605.8)	11,900
McAlpine Dam (605.8)	Uniontown Dam (846.0)	14,200
Uniontown Dam (846.0)	Smithland Dam (918.5)	19,500
Smithland Dam (918.5)	Cairo Point (981.0)	48,100

[a]Minimum daily flow once in ten years.

Although the numerical criteria for January through December are higher than those recommended by the Federal Water Pollution Control Administration, they are only used to calculate the amount of heat that can be added at the "minimum daily flow once in ten years." Additional flow would result in lower maxima since no additional heat could be added. There was also the increase of 5° F (2.8° C) limit that could be more stringent than the maximum temperature limit.

The next important step in the evolution of thought on temperature criteria was Water Quality Criteria 1972 (NAS/NAE, 1973), which is becoming known as the "Blue Book," because of its comparability to the Green Book (FWPCA National Technical Advisory Committee, 1968). The Blue Book is the report of the Committee on Water Quality Criteria of the National Academy of Sciences at the request of and funded by the U.S. Environmental Protection Agency (EPA). The heat and temperature section, with its recommendations and appendix data, was authored by Dr. Charles Coutant of the Oak Ridge National Laboratory. These materials are reproduced in full in Appendix A and Appendix B in this report. A discussion and description of the Blue Book temperature criteria will be found later in this report.

The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) contain a section [304 (a) (1)] that requires that the administrator of the EPA "after consultation with appropriate Federal and State agencies and other interested persons, shall develop and publish, within one year after enactment of this title (and from time to time thereafter revise) criteria for water quality accurately reflecting the latest scientific knowledge (A) on the kind and extent of all identifiable effects on health and welfare including, but not limited to, plankton, fish, shellfish, wildlife, plant life, shorelines, beaches, esthetics, and recreation which may be expected from the presence of pollutants in any body of water, including ground water; (B) on the concentration and dispersal of pollutants or their byproducts, through biological, physical, and chemical processes; and (C) on the effects of pollutants on biological community diversity, productivity, and stability, including information on the factors affecting rates of eutrophication and rates of organic and inorganic sedimentation for varying types of receiving waters."

The U.S. Environmental Protection Agency (1976) has published Quality Criteria for Water as a response to the Section 304(a)(1) requirements of PL 92-500. That approach to the determination of temperature criteria for freshwater fish is essentially the same as the approach recommended in the Blue Book (NAS/NAE, 1973). The EPA criteria report on temperature included numerical criteria for freshwater fish species and a nomograph for winter temperature criteria. These detailed criteria were developed according to the protocol in the Blue Book, and the procedures used to develop those criteria will be discussed in detail in this report.

The Great Lakes Water Quality Agreement (1972) between the United States of America and Canada was signed in 1972 and contained a specific water quality objective for temperature. It states that "There should be no change that would adversely affect any local or general use of these waters." The

International Joint Commission was designated to assist in the implementation of this agreement and to give advice and recommendations to both countries on specific water quality objectives. The International Joint Commission committees assigned the responsibility of developing these objectives have recommended temperature objectives for the Great Lakes based on the "Blue Book" approach and are in the process of refining and completing those objectives for consideration by the commission before submission to the two countries for implementation.

SECTION 3

THE PROTOCOL FOR TEMPERATURE CRITERIA

This section is a synthesis of concepts and definitions from Fry et al. (1942, 1946), Brett (1952, 1956), and the NAS/NAE (1973).

The lethal threshold temperatures are those temperatures at which 50 percent of a sample of individuals would survive indefinitely after acclimation at some other temperature. The majority of the published literature (Appendix B) is calculated on the basis of 50 percent survival. These lethal thresholds are commonly referred to as incipient lethal temperatures. Since organisms can be lethally stressed by both rising and falling temperatures, there are upper incipient lethal temperatures and lower incipient lethal temperatures. These are determined by removing the organisms from a temperature to which they are acclimated and instantly placing them in a series of other temperatures that will typically result in a range in survival from 100 to 0 percent. Acclimation can require up to 4 weeks, depending upon the magnitude of the difference between the temperature when the fish were obtained and the desired acclimation temperature. In general, experiments to determine incipient lethal temperatures should extend until all the organisms in any test chamber are dead or sufficient time has elapsed for death to have occurred. The ultimate upper incipient lethal temperature is that beyond which no increase in lethal temperature is accomplished by further increase in acclimation temperature. For most freshwater fish species in temperate latitudes the lower incipient lethal temperatures will usually end at 0° C, being limited by the freezing point of water. However, for some important species, such as threadfish shad in freshwater and menhaden in seawater, the lower incipient lethal temperature is higher than 0° C.

As indicated earlier, the heat and temperature section of the Blue Book and its associated appendix data and references have been reproduced in this report as Appendix A and Appendix B. The following discussion will briefly summarize the various types of criteria and provide some additional insight into the development of numerical criteria. The Blue Book (Appendix A) also describes in detail the use of the criteria in relation to entrainment.

MAXIMUM WEEKLY AVERAGE TEMPERATURE

For practical reasons the maximum weekly average temperature (MWAT) is the mathematical mean of multiple, equally spaced, daily temperatures over a 7-day consecutive period.

For Growth

To maintain growth of aquatic organisms at rates necessary for sustaining actively growing and reproducing populations, the MWAT in the zone normally inhabited by the species at the season should not exceed the optimum temperature plus one-third of the range between the optimum temperature and the ultimate upper incipient lethal temperature of the species:

$$\text{MWAT for growth} = \text{optimum temperature} + \frac{\text{ultimate upper incipient lethal temperature} - \text{optimum temperature}}{3}$$

The optimum temperature is assumed to be the optimum for growth, but other physiological optima may be used in the absence of growth data. The MWAT need not apply to accepted mixing zones and must be applied with adequate understanding of the normal seasonal distribution of the important species.

For Reproduction

The MWAT for reproduction must consider several factors such as gonad growth and gamete maturation, potential blocking of spawning migrations, spawning itself, timing and synchrony with cyclic food sources, and normal patterns of gradual temperature changes throughout the year. The protection of reproductive activity must take into account months during which these processes normally occur in specific water bodies for which criteria are being developed.

For Winter Survival

The MWAT for fish survival during winter will apply in any area in which fish could congregate and would include areas such as unscreened discharge channels. This temperature limit should not exceed the acclimation, or plume, temperature (minus a 3.6° F (2.0° C) safety factor) that raises the lower lethal threshold temperature above the normal ambient water temperature for that season. This criterion will provide protection from fish kills caused by rapid changes in temperature due to plant shutdown or movement of fish from a heated plume to ambient temperature.

SHORT-TERM EXPOSURE TO EXTREME TEMPERATURE

It is well established that fish can withstand short exposure to temperatures higher than those acceptable for reproduction and growth without significiant adverse effects. These exposures should not be too lengthy or frequent or the species could be adversely affected. The length of time that 50 percent of a population will survive temperature above the incipient lethal temperature can be calculated from the following regression equation:

$$\log \text{time (min)} = a + b\ (\text{temperature in °C});$$

or

$$\text{temperature (°C)} = (\log \text{time (min)} - a)/b.$$

The constants "a" and "b" are for intercept and slope and will be discussed later. Since this equation is based on 50 percent survival, a 3.6° F (2.0° C) reduction in the upper incipient lethal temperature will provide the safety factor to assure no deaths.

For those interested in more detail or the rationale for these general criteria, Appendices A and B should be read thoroughly. In addition, Appendix A contains a fine discussion of a procedure to evaluate the potential thermal impact of aquatic organisms entrained in cooling water or the discharge plume, or both.

SECTION 4

THE PROCEDURES FOR CALCULATING NUMERICAL TEMPERATURE CRITERIA FOR FRESHWATER FISH

MAXIMUM WEEKLY AVERAGE TEMPERATURE

The necessary minimum data for the determination of this criterion are the physiological optimum temperature and the ultimate upper incipient lethal temperature. The latter temperature represents the "breaking point" between the highest temperatures to which an animal can be acclimated and the lowest of the extreme upper temperatures that will kill the warm-acclimated organism. Physiological optima can be based on performance, metabolic rate, temperature preference, growth, natural distribution, or tolerance. However, the most sensitive function seems to be growth rate, which appears to be an integrator of all physiological responses of an organism. In the absence of data on optimum growth, the use of an optimum for a more specific function related to activity and metabolism may be more desirable than not developing any growth criterion at all.

The MWAT's for growth were calculated for fish species for which appropriate data were available (Table 1). These data were obtained from the fish temperature data in Appendix C. These data sheets contain the majority of thermal effects data for about 34 species of freshwater fish and the sources of the data. Some subjectivity is inevitable and necessary because of variability in published data resulting from differences in age, day length, feeding regime, or methodology. For example, the data sheet for channel catfish (Appendix C) includes four temperature ranges for optimum growth based on three published papers. It would be more appropriate to use data for growth of juveniles and adults rather than larvae. The middle of each range for juvenile channel catfish growth is 29° and 30° C. In this instance 29° C is judged the best estimate of the optimum. The highest incipient lethal temperature (that would approximate the ultimate incipient lethal temperature) appearing in Appendix C is 38° C. By using the previous formula for the MWAT for growth, we obtain

$$29^\circ\ C + \frac{(38-29^\circ\ C)}{3} = 32^\circ\ C.$$

The temperature criterion for the MWAT for growth of channel catfish would be 32° C (as appears in Table 1).

TABLE 1. TEMPERATURE CRITERIA FOR GROWTH AND SURVIVAL OF SHORT EXPOSURES (24 HR) OF JUVENILE AND ADULT FISH DURING THE SUMMER (° C (° F))

Species	Maximum weekly average temperature for growth[a]	Maximum temperature for survival of short exposure[b]
Alewife	--	--
Atlantic salmon	20 (68)	23 (73)
Bigmouth buffalo	--	--
Black crappie	27 (81)	--
Bluegill	32 (90)	35 (95)
Brook trout	19 (66)	24 (75)
Brown bullhead	--	--
Brown trout	17 (63)	24 (75)
Carp	--	--
Channel catfish	32 (90)	35 (95)
Coho salmon	18 (64)	24 (75)
Emerald shiner	30 (86)	--
Fathead minnow	--	--
Freshwater drum	--	--
Lake herring (cisco)	17 (63)[c]	25 (77)
Lake whitefish	--	--
Lake trout	--	--
Largemouth bass	32 (90)	34 (93)
Northern pike	28 (82)	30 (86)
Pumpkinseed	--	--
Rainbow smelt	--	--
Rainbow trout	19 (66)	24 (75)
Sauger	25 (77)	--
Smallmouth bass	29 (84)	--
Smallmouth buffalo	--	--
Sockeye salmon	18 (64)	22 (72)
Striped bass	--	--
Threadfin shad	--	--
Walleye	25 (77)	--
White bass	--	--
White crappie	28 (82)	--
White perch	--	--
White sucker	28 (82)[c]	--
Yellow perch	29 (84)	--

[a]Calculated according to equation:
maximum weekly average temperature for growth = optimum for growth + (1/3) (ultimate incipient lethal temperature - optimum for growth).

[b]Based on: temperature (° C) = (log time (min) - a)/b - 2° C, acclimation at the maximum weekly average temperature for summer growth, and data in Appendix B.

[c]Based on data for larvae.

SHORT-TERM MAXIMUM DURING GROWTH SEASON

In addition to the MWAT, maximum temperature for short exposure will protect against potential lethal effects. We have to assume that the incipient lethal temperature data reflecting 50 percent survival necessary for this calculation would be based on an acclimation temperature near the MWAT for growth. Therefore, using the data in Appendix B for the channel catfish, we find four possible data choices near the MWAT of 32° C (again it is preferable to use data on juveniles or adults):

Acclimation temperature (° C)	a	b
30	32.1736	-0.7811
34	26.4204	-0.6149
30	17.7125	-0.4058
35	28.3031	-0.6554

The formula for calculating the maximum for short exposure is:

$$\text{temperature (°C)} = (\log \text{time (min)} - a)/b$$

To solve the equation we must select a maximum time limitation on this maximum for short exposure. Since the MWAT is a weekly mean temperature an appropriate length of time for this limitation for short exposure would be 24 hr without risking violation of the MWAT.

Since the time is fixed at 24 hr (1,440 min), we need to solve for temperature by using, for example, the above acclimation temperature of 30° C for which a = 32.1736 and b = -0.7811.

$$\text{temperature (° C)} = \frac{\log 1{,}440 - a}{b}$$

$$\text{temperature (° C)} = \frac{3.1584 \quad -32.1736}{-0.7811} = \frac{-29.0152}{-0.7811} = 37.146$$

Upon solving for each of the four data points we obtain 37.1°, 37.8°, 35.9°, and 38.4° C. The average would be 37.3° C, and after subtracting the 2° C safety factor to provide 100 percent survival, the short-term maximum for channel catfish would be 35° C as appears in Table 1.

MAXIMUM WEEKLY AVERAGE TEMPERATURE FOR SPAWNING

From the data sheets in Apendix C one would use either the optimum temperature for spawning or, if that is not available, the middle of the range of temperatures for spawning. Again, if we use the channel catfish as an example, the MWAT for spawning would be 27° C (Table 2). Since spawning may occur over a period of a few weeks or months in a particular water body and only a MWAT for optimum spawning is estimated, it would be logical to use that optimum for the median time of the spawning season. The MWAT for the next earlier month

TABLE 2. TEMPERATURE CRITERIA FOR SPAWNING AND EMBRYO SURVIVAL OF SHORT EXPOSURES DURING THE SPAWNING SEASON (° C (° F))

Species	Maximum weekly average temperature for spawning[a]	Maximum temperature for embryo survival[b]
Alewife	22 (72)	28 (82)[c]
Atlantic salmon	5 (41)	11 (52)
Bigmouth buffalo	17 (63)	27 (81)[c]
Black crappie	17 (63)	20 (68)[c]
Bluegill	25 (77)	34 (93)
Brook trout	9 (48)	13 (55)
Brown bullhead	24 (75)	27 (81)
Brown trout	8 (46)	15 (59)
Carp	21 (70)	33 (91)
Channel catfish	27 (81)	29 (84)[c]
Coho salmon	10 (50)	13 (55)[c]
Emerald shiner	24 (75)	28 (82)[c]
Fathead minnow	24 (75)	30 (86)
Freshwater drum	21 (70)	26 (79)
Lake herring (cisco)	3 (37)	8 (46)
Lake whitefish	5 (41)	10 (50)[c]
Lake trout	9 (48)	14 (57)
Largemouth bass	21 (70)	27 (81)[c]
Northern pike	11 (52)	19 (66)
Pumpkinseed	25 (77)	29 (84)[c]
Rainbow smelt	8 (46)	15 (59)
Rainbow trout	9 (48)	13 (55)
Sauger	12 (54)	18 (64)
Smallmouth bass	17 (63)	23 (73)[c]
Smallmouth buffalo	21 (70)	28 (82)[c]
Sockeye salmon	10 (50)	13 (55)
Striped bass	18 (64)	24 (75)
Threadfin shad	19 (66)	34 (93)
Walleye	8 (46)	17 (63)[c]
White bass	17 (63)	26 (79)
White crappie	18 (64)	23 (73)
White perch	15 (59)	20 (68)[c]
White sucker	10 (50)	20 (68)
Yellow perch	12 (54)	20 (68)

[a] The optimum or mean of the range of spawning temperatures reported for the species.

[b] The upper temperature for successful incubation and hatching reported for the species.

[c] Upper temperature for spawning.

could approximate the lower temperature of the range in spawning temperature, and the MWAT for the last month of a 3-month spawning season could approximate the upper temperature for the range. For example, if the channel catfish spawned from April to June the MWAT's for the 3 months would be approximately 21°, 27°, and 29° C. For fall spawning fish species the pattern or sequence of temperatures would be reversed because of naturally declining temperatures during their spawning season.

SHORT-TERM MAXIMUM DURING SPAWNING SEASON

If spawning season maxima could be determined in the same manner as those for the growing season, we would be using the time-temperature equation and the Appendix B data as before. However, growing season data are based usually on survival of juvenile and adult individuals. Egg-incubation temperature requirements are more restrictive (lower), and this biological process would not be protected by maxima based on data for juvenile and adult fish. Also, spawning itself could be prematurely stopped if those maxima were achieved. For most species the maximum spawning temperature approximates the maximum successful incubation temperature. Consequently, the short-term maximum temperature should preferably be based on maximum incubation temperature for successful embryo survival, but the maximum temperature for spawning is an acceptable alternative. In fact, the higher of the two is probably the preferred choice as variability in available data has shown discrepancies in this relationship for some species.

For the channel catfish (Appendix C) the maximum reported incubation temperature is 28° C, and the maximum reported spawning temperature is 29° C. Therefore, the best estimate of the short-term survival of embryos would be 29° C (Table 2).

MAXIMUM WEEKLY AVERAGE TEMPERATURE FOR WINTER

As discussed earlier the MWAT for winter is designed usually to prevent fish deaths in the event the water temperature drops rapidly to an ambient condition. Such a temperature drop could occur as the result of a power-plant shutdown or a movement of the fish itself. These MWAT's are meant to apply wherever fish can congregate, even if that is within the mixing zone.

Yellow perch require a long chill period during the winter for optimum egg maturation and spawning (Appendix A). However, protection of this species would be outside the mixing zone. In addition, the embryos of fall spawning fish such as trout, salmon, and other related species such as cisco require low incubation temperatures. For these species also the MWAT during winter would have to consider embryo survival, but again, this would be outside the mixing zone. The mixing zone, as used in this report, is that area adjacent to the discharge in which receiving system water quality standards do not apply; a thermal plume therefore is not a mixing zone.

With these exceptions in mind, it is unlikely that any signficant effects on fish populations would occur as long as death was prevented.

In many instances growth could be enhanced by controlled winter heat addition, but inadequate food may result in poor condition of the fish.

There are fewer data for lower incipient lethal temperatures than for the previously discussed upper incipient lethal temperatures. Appendix B contains lower incipient lethal temperature data for only about 20 freshwater fish species, less than half of which are listed in Tables 1 and 2. Consequently, the available data were combined to calculate a regression line (Figure 1) which gives a generalized MWAT for winter survival instead of the species specific approach used in the other types of criteria.

All the lower incipient lethal temperature data from Appendix C for freshwater fish species were used to calculate the regression line, which had a slope of 0.50 and a correlation coefficient of 0.75. This regression line was then displaced by approximately 2.5° C since it passed through the middle of the data and did not represent the more sensitive species. This new line on the edge of the data array was then displaced by a 2° C safety factor, the same factor discussed earlier, to account for the fact that the original data points were for 50 percent survival and the 2° C safety factor would result in 100 percent survival. These two adjustments in the original regression line therefore result in a line (Figure 1) that should insure no more than negligible mortality of any fish species. At lower acclimation temperatures the coldwater species were different from the warmwater species, and the resultant criterion takes this into account.

If fish can congregate in an area close to the discharge point, this criterion could be a limit on the degree rise permissible at a particular site. Obviously, if there is a screened discharge channel in which some cooling occurs, a higher initial discharge temperature could be permissible to fish.

An example of the use of this criterion (as plotted in the nomograph, Figure 1) would be a situation in which the ambient water temperature is 10° C, and the MWAT, where fish could congregate, is 25° C, a difference of 15° C. At a lower ambient temperature of about 2.5° C, the MWAT would be 10° C, a 7.5° C difference.

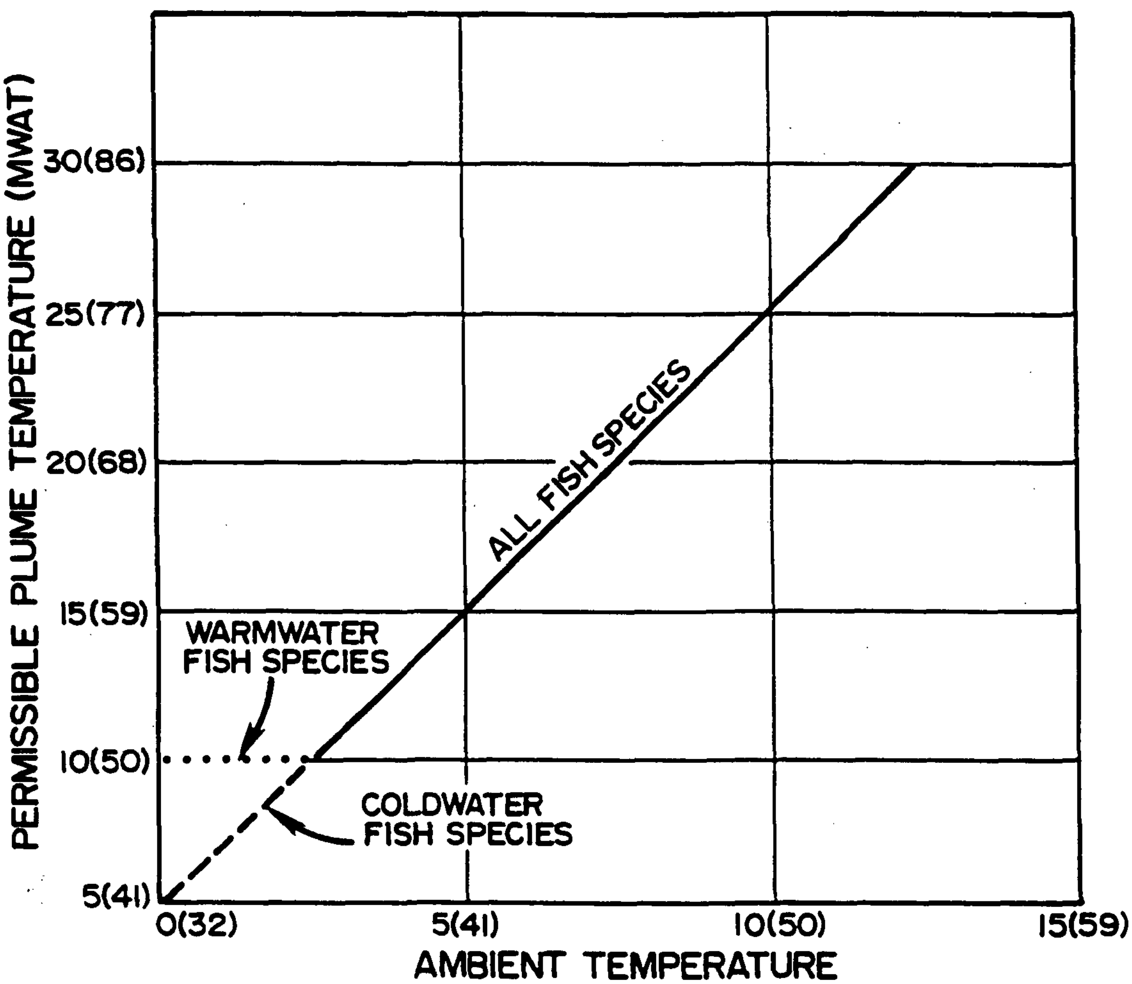

Figure 1. Nomograph to determine the maximum weekly average temperature of plumes for various ambient temperatures, °C (°F).

SECTION 5

EXAMPLES

Again, because precise thermal-effects data are not available for all species, we would like to emphasize the necessity for subjective decisions based on common-sense knowledge of existing aquatic systems. For some fish species for which few or only relatively poor data are available, subjectivity becomes important. If several qualified people were to calculate various temperature criteria for species for which several sets of high quality data were available, it is unlikely that they would be in agreement in all instances.

The following examples for warmwater and coldwater species are presented only as examples and are not at all intended to be water-body-specific recommendations. Local extenuating circumstances may warrant differences, or the basic conditions of the examples may be slightly unrealistic. More precise estimates of principal spawning and growth seasons should be available from the local state fish departments.

EXAMPLE 1

Tables 1 and 2, Figure 1, and Appendix C are the principal data sources for the criteria derived for this example. The following water-body-specific data are necessary and in this example are hypothetical:

1. Species to be protected by the criteria: channel catfish, largemouth bass, bluegill, white crappie, freshwater drum, and bigmouth buffalo.

2. Local spawning seasons for these species: April to June for the white crappie and the bigmouth buffalo; other species, May to July.

3. Normal ambient winter temperature: 5° C in December and January; 10° C in November, February, and March.

4. The principal growing season for these fish species: July through September.

5. Any local extenuating circumstances should be incorporated into the criteria as appropriate. Some examples would be yellow perch gamete maturation in the winter, very temperature-sensitive endangered species, or important fish-food organisms that are very temperature sensitive. For the example we will have no extenuating circumstances.

In some instances the data will be insufficient to determine each necessary criterion for each species. Estimates must be made based on available species-specific data or by extrapolation from data for species with similar requirements for which adequate data are available. For instance, this example includes the bigmouth buffalo and freshwater drum for which no growth or short-term summer maxima are available (Table 1). One would of necessity have to estimate that the summer criteria would not be lower than that for the white crappie, which has a spawning requirement as low as the other two species.

The choice of important fish species is very critical. Since in this example the white crappie is as temperature sensitive as any of the species, the maximum weekly average temperature for summer growth is based on the white crappie. Consequently, this criterion would result in lower than optimal conditions for the channel catfish, bluegill, and largemouth bass. An alternate approach would be to develop criteria for the single most important species even if the most sensitive is not well protected. The choice is a socioeconomic one.

Before developing a set of criteria such as those in Table 3, the material material in Tables 1 and 2 should be studied for the species of concern. It is evident that the lowest optimum temperature for summer growth for the species for which data are available would be for the white crappie (28° C). However, there is no maximum for short exposure since the data are not available (Appendix C). For the species for which there are data, the lowest maximum for short exposure is for the largemouth bass (34° C). In this example we have all the necessary data for spawning and maximum for short exposure for embryo survival for all species of concern (Table 2).

During the winter, criteria may be necessary both for the mixing zone as well as for the receiving water. Receiving-water criteria would be necessary if an important fish species were known to have gamete-maturation requirements like the yellow perch, or embryo-incubation requirements like trout, salmon, cisco, etc. In this example there is no need for receiving-system water criteria.

At this point, we are ready to complete Table 3 for Example 1.

EXAMPLE 2

All of the general concerns and data sources presented throughout the discussion and derivation of Example 1 will apply here.

1. Species to be protected by the criteria: rainbow and brown trout and the coho salmon.

2. Local spawning seasons for these species: November through January for rainbow trout; and November through December for the brown trout and coho salmon.

3. Normal ambient winter temperature: 2° C in November through February; 5° C in October, March, and April.

TABLE 3. TEMPERATURE CRITERIA FOR EXAMPLE 1

Month	Maximum weekly average temperature, (° C (° F)) Receiving water	Heated plume	Decision basis
January	--[a]	15(59)	Figure 1
February	--[a]	25(77)	Figure 1
March	--[a]	25(77)	Figure 1
April	18(64)[b]	--	White crappie spawning
May	21(70)	--	Largemouth bass spawning
June	25(77)	--	Bluegill spawning and white crappie growth
July	28(82)	--	White crappie growth
August	28(82)	--	White crappie growth
September	28(82)	--	White crappie growth
October	21(70)	--	Normal gradual seasonal decline
November	--[a]	25(77)	Figure 1
December	--[a]	15(59)	Figure 1

Month	Short-term maximum	Decision basis
January	None needed	Control by MWAT in plume
February	None needed	Control by MWAT in plume
March	None needed	Control by MWAT in plume
April	26(79)	Largemouth bass[b] survival (estimated)
May	29(84)	Largemouth bass[b] survival (estimated)
June	34(93)	Largemouth bass[b] survival
July	34(93)	Largemouth bass[b] survival
August	34(93)	Largemouth bass[b] survival
September	34(93)	Largemouth bass[b] survival
October	29(84)	Largemouth bass[b] survival (estimated)
November	None needed	Control by MWAT in plume
December	None needed	Control by MWAT in plume

[a] If a species had required a winter chill period for gamete maturation or egg incubation, receiving-water criteria would also be required.

[b] No data available for the slightly more sensitive white crappie.

4. The principal growing season for these fish species: June through September.

5. Consider any local extenuating circumstances: There are none in this example.

At this point, we are ready to complete Table 4 for Example 2.

TABLE 4. TEMPERATURE CRITERIA FOR EXAMPLE 2

Month	Maximum weekly average temperature, (° C (° F)) Receiving water	Heated plume	Decision basis
January	9(48)	10(50)	Rainbow trout spawning and Figure 1
February	13(55)	10(50)	Normal gradual seasonal rise and Figure 1
March	13(55)	15(59)	Normal gradual seasonal rise and Figure 1
April	14(57)	15(59)	Normal gradual seasonal rise and Figure 1
May	16(61)	--	Normal gradual seasonal rise
June	17(63)	--	Brown trout growth
July	17(63)	--	Brown trout growth
August	17(63)	--	Brown trout growth
September	17(63)	--	Brown trout growth
October	12(54)	15(59)	Normal gradual seasonal decline
November	8(46)	10(50)	Brook trout spawning and Figure 1
December	8(46)	10(50)	Brown trout spawning and Figure 1

Month	Short-term maximum	Decision basis
January	13(55)	Embryo survival for rainbow trout and coho salmon
February	13(55)	Embryo survival for rainbow trout and coho salmon
March	13(55)	Embryo survival for rainbow trout and coho salmon
April	--	
May	--	
June	24(75)	Short-term maximum for survival of all species
July	24(75)	Short-term maximum for survival of all species
August	24(75)	Short-term maximum for survival of all species
September	24(75)	Short-term maximum for survival of all species
October	--	
November	13(55)	Embryo survival for rainbow trout and coho salmon
December	13(55)	Embryo survival for rainbow trout and coho salmon

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May 1977

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May 1977

TEMPERATURE CRITERIA FOR FRESHWATER FISH:

PROTOCOL AND PROCEDURES

by

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DISCLAIMER

FOREWORD

Our nation's fresh waters are vital for all animals and plants, yet our diverse uses of water — for recreation, food, energy, transportation, and industry — physically and chemically alter lakes, rivers, and streams. Such alterations threaten terrestrial organisms, as well as those living in water. The Environmental Research Laboratory in Duluth, Minnesota, develops methods, conducts laboratory and field studies, and extrapolates research findings

--to determine how physical and chemical pollution affects aquatic life;

--to assess the effects of ecosystems on pollutants;

--to predict effects of pollutants on large lakes through use of models; and

--to measure bioaccumulation of pollutants in aquatic organisms that are consumed by other animals, including man.

This report discusses the history, procedures, and derivation of temperature criteria to protect freshwater fishes and presents numerical criteria for 34 species. It follows the general philosophical approach of the National Academy of Sciences and National Academy of Engineering in their Water Quality Criteria 1972 and is intended to make that philosophy practically useful.

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ABSTRACT

Temperature criteria for freshwater fish are expressed as mean and maximum temperatures; means control functions such as embryogenesis, growth, maturation, and reproductivity, and maxima provide protection for all life stages against lethal conditions. These criteria for 34 fish species are based on numerous field and laboratory studies, and yet for some important species the data are still insufficient to develop all the necessary criteria. Fishery managers, power-plant designers, and regulatory agencies will find these criteria useful in their efforts to protect fishery resources.

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CONTENTS

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SECTION 1

SUMMARY AND CONCLUSIONS

The evolution of freshwater temperature criteria has advanced from the search for a single "magic number" to the generally accepted protocol for determining mean and maximum numerical criteria based on the protection of appropriate desirable or important fish species, or both. The philosophy and protocol of the National Academy of Sciences and National Academy of Engineering (1973) were used to determine criteria for survival, spawning, embryo development, growth, and gamete maturation for species of freshwater fish, both warmwater and coldwater species.

The influence that management objectives and selection of species have on the application of temperature criteria is extremely important, especially if an inappropriate, but very temperature-sensitive, species is included. In such a case, unnecessarily restrictive criteria will be derived. Conversely, if the most sensitive important species is not considered, the resultant criteria will not be protective.

SECTION 2

INTRODUCTION

This report is intended to be a guide for derivation of temperature criteria for freshwater fish based on the philosophy and protocol presented by the National Academy of Sciences and National Academy of Engineering (1973). It is not an attempt to gather and summarize the literature on thermal effects.

Methods for determination of temperature criteria have evolved and developed rapidly during the past 20 years, making possible a vast increase in basic data on the relationship of temperature to various life stages.

One of the earliest published temperature criteria for freshwater life was prepared by the Aquatic Life Advisory Committee of the Ohio River Valley Water Sanitation Commission (ORSANCO) in 1956. These criteria were based on conditions necessary to maintain a well-rounded fish population and to sustain production of a harvestable crop in the Ohio River watershed. The committee recommended that the temperature of the receiving water:

1) Should not be raised above 34° C (93°F) at any place or at any time;

2) should not be raised above 23° C (73° F) at any place or at any time during the months of December through April; and

3) should not be raised in streams suitable for trout propagation.

McKee and Wolf (1963) in their discussion of temperature criteria for the propagation of fish and other aquatic and marine life refer only to the progress report of ORSANCO's Aquatic Life Advisory Committee (1956).

In 1967 the Aquatic Life Advisory Committee of ORSANCO evaluated and further modified their recommendations for temperature in the Ohio River watershed. At this time the committee expanded their recommendation of a 93° F (33.9° C) instantaneous temperature at any time or any place to include a daily mean of 90° F (32.2° C). This, we believe, was one of the first efforts to recognize the importance of both mean and maximum temperatures to describe temperature requirements of fishes. The 1967 recommedations also included:

1) Maximum temperature during December, January, and February should be 55° F (12.8° C);

2) during the transition months of March, April, October and November the temperature can be changed gradually by not more than 7° F (3.9° C);

3) to maintain trout habitats, stream temperatures should not exceed 55° F (12.8° C) during the months of October through May, or exceed 68° F (20.0° C) during the months of June through September; and

4) insofar as possible the temperature should not be raised in streams used for natural propagation of trout.

The National Technical Advisory Committee of the Federal Water Pollution Control Administration presented a report on water quality criteria in 1968 that was to become known as the "Green Book." This large committee included many of the members of ORSANCO's Aquatic Life Advisory Committee. The committee members recognized that aquatic organisms might be able to endure a high temperature for a few hours that could not be endured for a period of days. They also acknowledged that no single temperature requirement could be applied to the United States as a whole, or even to one state, and that the requirements must be closely related to each body of water and its fish populations. Other important conditions for temperature requirements were that (1) a seasonal cycle must be retained, (2) the changes in temperature must be gradual, and (3) the temperature reached must not be so high or so low as to damage or alter the composition of the desired population. These conditions led to an approach to criteria development different from earlier ones. A temperature increment based on the natural water temperature was believed to be more appropriate than an unvarying number. The use of an increment requires a knowledge of the natural temperature conditions of the water in question, and the size of the increment that can be tolerated by the desirable species.

The National Technical Advisory Committee (1968, p. 42) recommended:

> "To maintain a well-rounded population of warmwater fishes .... heat should not be added to a stream in excess of the amount that will raise the temperature of the water (at the expected minimum daily flow for that month) more than 5° F."

A casual reading of this requirement resulted in the unintended generalization that the acceptable temperature rise in warmwater fish streams was 5° F (2.8° C). This generalization was incorrect! Upon more careful reading the key word "amount" of heat and the key phrase "minimum daily flow for that month" clarify the erroneousness of the generalization. In fact, a 5° F (2.8° C) rise in temperature could only be acceptable under low flow conditions for a particular month and any increase in flow would result in a reduced increment of temperature rise since the amount of heat added could not be increased. For lakes and reservoirs the temperature rise limitation was 3° F (1.7° C) based "on the monthly average of the maximum daily temperature."

In trout and salmon waters the recommendations were that "inland trout streams, headwaters of salmon streams, trout and salmon lakes, and reservoirs containing salmonids should not be warmed," that "no heated effluents should be discharged in the vicinity of spawning areas," and that "in lakes and reservoirs, the temperature of the hypolimnion should not be raised more than 3° F (1.7° C)." For other locations the recommended incremental rise was 5° F (2.8° C) again based on the minimum expected flow for that month.

An important additional recommendation is summarized in the following table in which provisional maximum temperatures were recommended for various fish species and their associated biota (from FWPCA National Technical Advisory Committee, 1968).

PROVISIONAL MAXIMUM TEMPERATURES RECOMMENDED AS

COMPATIBLE WITH THE WELL-BEING OF VARIOUS SPECIES

OF FISH AND THEIR ASSOCIATED BIOTA

93 F:	Growth of catfish, gar, white or yellow bass, spotted bass, buffalo, carpsucker, threadfin shad, and gizzard shad.
90 F:	Growth of largemouth bass, drum, bluegill, and crappie.
84 F:	Growth of pike, perch, walleye, smallmouth bass, and sauger.
80 F:	Spawning and egg development of catfish, buffalo, threadfin shad, and gizzard shad.
75 F:	Spawning and egg development of largemouth bass, white, yellow, and spotted bass.
68 F:	Growth or migration routes of salmonids and for egg development of perch and smallmouth bass.
55 F:	Spawning and egg development of salmon and trout (other than lake trout).
48 F:	Spawning and egg development of lake trout, walleye, northern pike, sauger, and Atlantic salmon.

NOTE: Recommended temperatures for other species, not listed above, may be established if and when necessary information becomes available.

These recommendations represent one of the significant early efforts to base temperature criteria on the realistic approach of species and community requirements and take into account the significant biological factors of spawning, embryo development, growth, and survival.

The Federal Water Pollution Control Administration (1969a) recommended revisions in water quality criteria for aquatic life relative to the Main Stem of the Ohio River. These recommendations were presented to ORSANCO's Engineering Committee and were based on the temperature requirements of important Ohio River fishes including largemouth bass, smallmouth bass, white bass, sauger, channel catfish, emerald shiner, freshwater drum, golden redhorse, white sucker, and buffalo (species was not indicated). Temperature requirements for survival, activity, final preferred temperature, reproduction, and growth were considered. The recommended criteria were:

1. "The water temperatures shall not exceed 90° F (32.2° C) at any time or any place, and a maximum hourly average value of 86° F (30° C) shall not be exceeded."

2. "The temperature shall not exceed the temperature values expressed on the following table:"

AQUATIC LIFE TABLE[a]

	Daily mean (° F)	Hourly maximum (° F)
December-February	48	55
Early March	50	56
Late March	52	58
Early April	55	60
Late April	58	62
Early May	62	64
Late May	68	72
Early June	75	79
Late June	78	82
July-September	82	86
October	75	82
November	65	72

[a]From: Federal Water Pollution Control Administration (1969a).

The principal limiting fish species considered in developing these criteria was the sauger, the most temperature sensitive of the important Ohio River fishes. A second set of criteria (Federal Water Pollution Control Administration, 1969b) considered less temperature-sensitive species, and the criteria for mean temperatures were higher. The daily mean in July and September was 84° F (28.9° C). In addition, a third set of criteria was developed that was not designed to protect the smallmouth bass, emerald shiner, golden redhorse, or the white sucker. The July-to-September daily mean temperature criterion was 86° F (30° C).

The significance of the 1969 Ohio River criteria was that they were species dependent and that subsequently the criteria would probably be based upon a single species or a related group of species. Therefore, it is extremely important to select properly the species that are important otherwise the criteria will be unnecessarily restrictive. For example, if yellow perch is an extremely rare species in a water body and is the most temperature-sensitive species, it probably would be unreasonable to establish temperature criteria for this species as part of the regulatory mechanism.

In 1970 ORSANCO established new temperature standards that incorporated the recommendations for temperature criteria of the Federal Water Pollution Control Administration (1969a, 1969b) and the concept of limiting the amount of heat that would be added (National Technical Advisory Committee, 1968). The following is the complete text of that standard:

> " All cooling water from municipalities or political subdivisions, public or private institutions, or installations, or corporations discharged or permitted to flow into the Ohio River from the point of confluence of the Allegheny and Monongahela Rivers at Pittsburgh, Pennsylvania, designated as Ohio River mile point 0.0 to Cairo Point, Illinois, located at the confluence of the Ohio and Mississippi Rivers, and being 981.0 miles downstream from Pittsburgh, Pennsylvania, shall be so regulated or controlled as to provide for reduction of heat content to such degree that the aggregate heat-discharge rate from the municipality, subdivision, institution, installation or corporation, as calculated on the basis of discharge volume and temperature differential (temperature of discharge minus upstream river temperature) does not exceed the amount calculated by the following formula, provided, however, that in no case shall the aggregate heat-discharge rate be of such magnitude as will result in a calculated increase in river temperature of more than 5 degrees F:
>
> Allowable heat-discharge rate (Btu/sec) = 62.4 X river flow (CFS) X $(T_a - T_r)$ X 90%

Where:

T_a = Allowable maximum temperature (deg. F.) in the river as specified in the following table:

	T_a		T_a
January	50	July	89
February	50	August	89
March	60	September	87
April	70	October	78
May	80	November	70
June	87	December	57

T_r = River temperature (daily average in deg. F.) upstream from the discharge

River flow = measured flow but not less than critical flow values specified in the following table:

River reach		Critical flow in cfs[a]
From	To	
Pittsburgh, Penn. (mi. 0.0)	Willow Is. Dam (161.7)	6,500
Willow Is. Dam (161.7)	Gallipolis Dam (279.2)	7,400
Gallipolis Dam (279.2)	Meldahl Dam (436.2)	9,700
Meldahl Dam (436.2)	McAlpine Dam (605.8)	11,900
McAlpine Dam (605.8)	Uniontown Dam (846.0)	14,200
Uniontown Dam (846.0)	Smithland Dam (918.5)	19,500
Smithland Dam (918.5)	Cairo Point (981.0)	48,100

[a]Minimum daily flow once in ten years.

Although the numerical criteria for January through December are higher than those recommended by the Federal Water Pollution Control Administration, they are only used to calculate the amount of heat that can be added at the "minimum daily flow once in ten years." Additional flow would result in lower maxima since no additional heat could be added. There was also the increase of 5° F (2.8° C) limit that could be more stringent than the maximum temperature limit.

The next important step in the evolution of thought on temperature criteria was Water Quality Criteria 1972 (NAS/NAE, 1973), which is becoming known as the "Blue Book," because of its comparability to the Green Book (FWPCA National Technical Advisory Committee, 1968). The Blue Book is the report of the Committee on Water Quality Criteria of the National Academy of Sciences at the request of and funded by the U.S. Environmental Protection Agency (EPA). The heat and temperature section, with its recommendations and appendix data, was authored by Dr. Charles Coutant of the Oak Ridge National Laboratory. These materials are reproduced in full in Appendix A and Appendix B in this report. A discussion and description of the Blue Book temperature criteria will be found later in this report.

The Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) contain a section [304 (a) (1)] that requires that the administrator of the EPA "after consultation with appropriate Federal and State agencies and other interested persons, shall develop and publish, within one year after enactment of this title (and from time to time thereafter revise) criteria for water quality accurately reflecting the latest scientific knowledge (A) on the kind and extent of all identifiable effects on health and welfare including, but not limited to, plankton, fish, shellfish, wildlife, plant life, shorelines, beaches, esthetics, and recreation which may be expected from the presence of pollutants in any body of water, including ground water; (B) on the concentration and dispersal of pollutants or their byproducts, through biological, physical, and chemical processes; and (C) on the effects of pollutants on biological community diversity, productivity, and stability, including information on the factors affecting rates of eutrophication and rates of organic and inorganic sedimentation for varying types of receiving waters."

The U.S. Environmental Protection Agency (1976) has published Quality Criteria for Water as a response to the Section 304(a)(1) requirements of PL 92-500. That approach to the determination of temperature criteria for freshwater fish is essentially the same as the approach recommended in the Blue Book (NAS/NAE, 1973). The EPA criteria report on temperature included numerical criteria for freshwater fish species and a nomograph for winter temperature criteria. These detailed criteria were developed according to the protocol in the Blue Book, and the procedures used to develop those criteria will be discussed in detail in this report.

The Great Lakes Water Quality Agreement (1972) between the United States of America and Canada was signed in 1972 and contained a specific water quality objective for temperature. It states that "There should be no change that would adversely affect any local or general use of these waters." The

International Joint Commission was designated to assist in the implementation of this agreement and to give advice and recommendations to both countries on specific water quality objectives. The International Joint Commission committees assigned the responsibility of developing these objectives have recommended temperature objectives for the Great Lakes based on the "Blue Book" approach and are in the process of refining and completing those objectives for consideration by the commission before submission to the two countries for implementation.

SECTION 3

THE PROTOCOL FOR TEMPERATURE CRITERIA

This section is a synthesis of concepts and definitions from Fry et al. (1942, 1946), Brett (1952, 1956), and the NAS/NAE (1973).

The lethal threshold temperatures are those temperatures at which 50 percent of a sample of individuals would survive indefinitely after acclimation at some other temperature. The majority of the published literature (Appendix B) is calculated on the basis of 50 percent survival. These lethal thresholds are commonly referred to as incipient lethal temperatures. Since organisms can be lethally stressed by both rising and falling temperatures, there are upper incipient lethal temperatures and lower incipient lethal temperatures. These are determined by removing the organisms from a temperature to which they are acclimated and instantly placing them in a series of other temperatures that will typically result in a range in survival from 100 to 0 percent. Acclimation can require up to 4 weeks, depending upon the magnitude of the difference between the temperature when the fish were obtained and the desired acclimation temperature. In general, experiments to determine incipient lethal temperatures should extend until all the organisms in any test chamber are dead or sufficient time has elapsed for death to have occurred. The ultimate upper incipient lethal temperature is that beyond which no increase in lethal temperature is accomplished by further increase in acclimation temperature. For most freshwater fish species in temperate latitudes the lower incipient lethal temperatures will usually end at 0° C, being limited by the freezing point of water. However, for some important species, such as threadfish shad in freshwater and menhaden in seawater, the lower incipient lethal temperature is higher than 0° C.

As indicated earlier, the heat and temperature section of the Blue Book and its associated appendix data and references have been reproduced in this report as Appendix A and Appendix B. The following discussion will briefly summarize the various types of criteria and provide some additional insight into the development of numerical criteria. The Blue Book (Appendix A) also describes in detail the use of the criteria in relation to entrainment.

MAXIMUM WEEKLY AVERAGE TEMPERATURE

For practical reasons the maximum weekly average temperature (MWAT) is the mathematical mean of multiple, equally spaced, daily temperatures over a 7-day consecutive period.

For Growth

To maintain growth of aquatic organisms at rates necessary for sustaining actively growing and reproducing populations, the MWAT in the zone normally inhabited by the species at the season should not exceed the optimum temperature plus one-third of the range between the optimum temperature and the ultimate upper incipient lethal temperature of the species:

$$\text{MWAT for growth} = \text{optimum temperature} + \frac{\text{ultimate upper incipient lethal temperature} - \text{optimum temperature}}{3}$$

The optimum temperature is assumed to be the optimum for growth, but other physiological optima may be used in the absence of growth data. The MWAT need not apply to accepted mixing zones and must be applied with adequate understanding of the normal seasonal distribution of the important species.

For Reproduction

The MWAT for reproduction must consider several factors such as gonad growth and gamete maturation, potential blocking of spawning migrations, spawning itself, timing and synchrony with cyclic food sources, and normal patterns of gradual temperature changes throughout the year. The protection of reproductive activity must take into account months during which these processes normally occur in specific water bodies for which criteria are being developed.

For Winter Survival

The MWAT for fish survival during winter will apply in any area in which fish could congregate and would include areas such as unscreened discharge channels. This temperature limit should not exceed the acclimation, or plume, temperature (minus a 3.6° F (2.0° C) safety factor) that raises the lower lethal threshold temperature above the normal ambient water temperature for that season. This criterion will provide protection from fish kills caused by rapid changes in temperature due to plant shutdown or movement of fish from a heated plume to ambient temperature.

SHORT-TERM EXPOSURE TO EXTREME TEMPERATURE

It is well established that fish can withstand short exposure to temperatures higher than those acceptable for reproduction and growth without significiant adverse effects. These exposures should not be too lengthy or frequent or the species could be adversely affected. The length of time that 50 percent of a population will survive temperature above the incipient lethal temperature can be calculated from the following regression equation:

$$\log \text{time (min)} = a + b\ (\text{temperature in } ^\circ\text{C});$$

or

$$\text{temperature } (^\circ\text{C}) = (\log \text{time (min)} - a)/b.$$

The constants "a" and "b" are for intercept and slope and will be discussed later. Since this equation is based on 50 percent survival, a 3.6° F (2.0° C) reduction in the upper incipient lethal temperature will provide the safety factor to assure no deaths.

For those interested in more detail or the rationale for these general criteria, Appendices A and B should be read thoroughly. In addition, Appendix A contains a fine discussion of a procedure to evaluate the potential thermal impact of aquatic organisms entrained in cooling water or the discharge plume, or both.

SECTION 4

THE PROCEDURES FOR CALCULATING NUMERICAL TEMPERATURE CRITERIA FOR FRESHWATER FISH

MAXIMUM WEEKLY AVERAGE TEMPERATURE

The necessary minimum data for the determination of this criterion are the physiological optimum temperature and the ultimate upper incipient lethal temperature. The latter temperature represents the "breaking point" between the highest temperatures to which an animal can be acclimated and the lowest of the extreme upper temperatures that will kill the warm-acclimated organism. Physiological optima can be based on performance, metabolic rate, temperature preference, growth, natural distribution, or tolerance. However, the most sensitive function seems to be growth rate, which appears to be an integrator of all physiological responses of an organism. In the absence of data on optimum growth, the use of an optimum for a more specific function related to activity and metabolism may be more desirable than not developing any growth criterion at all.

The MWAT's for growth were calculated for fish species for which appropriate data were available (Table 1). These data were obtained from the fish temperature data in Appendix C. These data sheets contain the majority of thermal effects data for about 34 species of freshwater fish and the sources of the data. Some subjectivity is inevitable and necessary because of variability in published data resulting from differences in age, day length, feeding regime, or methodology. For example, the data sheet for channel catfish (Appendix C) includes four temperature ranges for optimum growth based on three published papers. It would be more appropriate to use data for growth of juveniles and adults rather than larvae. The middle of each range for juvenile channel catfish growth is 29° and 30° C. In this instance 29° C is judged the best estimate of the optimum. The highest incipient lethal temperature (that would approximate the <u>ultimate</u> incipient lethal temperature) appearing in Appendix C is 38° C. By using the previous formula for the MWAT for growth, we obtain

$$29^\circ\ C + \frac{(38-29^\circ\ C)}{3} = 32^\circ\ C.$$

The temperature criterion for the MWAT for growth of channel catfish would be 32° C (as appears in Table 1).

TABLE 1. TEMPERATURE CRITERIA FOR GROWTH AND SURVIVAL OF SHORT EXPOSURES (24 HR) OF JUVENILE AND ADULT FISH DURING THE SUMMER (° C (° F))

Species	Maximum weekly average temperature for growth[a]	Maximum temperature for survival of short exposure[b]
Alewife	--	--
Atlantic salmon	20 (68)	23 (73)
Bigmouth buffalo	--	--
Black crappie	27 (81)	--
Bluegill	32 (90)	35 (95)
Brook trout	19 (66)	24 (75)
Brown bullhead	--	--
Brown trout	17 (63)	24 (75)
Carp	--	--
Channel catfish	32 (90)	35 (95)
Coho salmon	18 (64)	24 (75)
Emerald shiner	30 (86)	--
Fathead minnow	--	--
Freshwater drum	--	--
Lake herring (cisco)	17 (63)[c]	25 (77)
Lake whitefish	--	--
Lake trout	--	--
Largemouth bass	32 (90)	34 (93)
Northern pike	28 (82)	30 (86)
Pumpkinseed	--	--
Rainbow smelt	--	--
Rainbow trout	19 (66)	24 (75)
Sauger	25 (77)	--
Smallmouth bass	29 (84)	--
Smallmouth buffalo	--	--
Sockeye salmon	18 (64)	22 (72)
Striped bass	--	--
Threadfin shad	--	--
Walleye	25 (77)	--
White bass	--	--
White crappie	28 (82)	--
White perch	--	--
White sucker	28 (82)[c]	--
Yellow perch	29 (84)	--

[a]Calculated according to equation:
maximum weekly average temperature for growth = optimum for growth + (1/3) (ultimate incipient lethal temperature - optimum for growth).

[b]Based on: temperature (° C) = (log time (min) - a)/b - 2° C, acclimation at the maximum weekly average temperature for summer growth, and data in Appendix B.

[c]*Based on data for larvae.*

SHORT-TERM MAXIMUM DURING GROWTH SEASON

In addition to the MWAT, maximum temperature for short exposure will protect against potential lethal effects. We have to assume that the incipient lethal temperature data reflecting 50 percent survival necessary for this calculation would be based on an acclimation temperature near the MWAT for growth. Therefore, using the data in Appendix B for the channel catfish, we find four possible data choices near the MWAT of 32° C (again it is preferable to use data on juveniles or adults):

Acclimation temperature (° C)	a	b
30	32.1736	-0.7811
34	26.4204	-0.6149
30	17.7125	-0.4058
35	28.3031	-0.6554

The formula for calculating the maximum for short exposure is:

$$\text{temperature } (°C) = (\log \text{time (min)} - a)/b$$

To solve the equation we must select a maximum time limitation on this maximum for short exposure. Since the MWAT is a weekly mean temperature an appropriate length of time for this limitation for short exposure would be 24 hr without risking violation of the MWAT.

Since the time is fixed at 24 hr (1,440 min), we need to solve for temperature by using, for example, the above acclimation temperature of 30° C for which a = 32.1736 and b = -0.7811.

$$\text{temperature } (°\ C) = \frac{\log 1{,}440 - a}{b}$$

$$\text{temperature } (°\ C) = \frac{3.1584 \ -32.1736}{-0.7811} = \frac{-29.0152}{-0.7811} = 37.146$$

Upon solving for each of the four data points we obtain 37.1°, 37.8°, 35.9°, and 38.4° C. The average would be 37.3° C, and after subtracting the 2° C safety factor to provide 100 percent survival, the short-term maximum for channel catfish would be 35° C as appears in Table 1.

MAXIMUM WEEKLY AVERAGE TEMPERATURE FOR SPAWNING

From the data sheets in Apendix C one would use either the optimum temperature for spawning or, if that is not available, the middle of the range of temperatures for spawning. Again, if we use the channel catfish as an example, the MWAT for spawning would be 27° C (Table 2). Since spawning may occur over a period of a few weeks or months in a particular water body and only a MWAT for optimum spawning is estimated, it would be logical to use that optimum for the median time of the spawning season. The MWAT for the next earlier month

TABLE 2. TEMPERATURE CRITERIA FOR SPAWNING AND EMBRYO SURVIVAL OF SHORT EXPOSURES DURING THE SPAWNING SEASON (° C (° F))

Species	Maximum weekly average temperature for spawning[a]	Maximum temperature for embryo survival[b]
Alewife	22 (72)	28 (82)[c]
Atlantic salmon	5 (41)	11 (52)
Bigmouth buffalo	17 (63)	27 (81)[c]
Black crappie	17 (63)	20 (68)[c]
Bluegill	25 (77)	34 (93)
Brook trout	9 (48)	13 (55)
Brown bullhead	24 (75)	27 (81)
Brown trout	8 (46)	15 (59)
Carp	21 (70)	33 (91)
Channel catfish	27 (81)	29 (84)[c]
Coho salmon	10 (50)	13 (55)[c]
Emerald shiner	24 (75)	28 (82)[c]
Fathead minnow	24 (75)	30 (86)
Freshwater drum	21 (70)	26 (79)
Lake herring (cisco)	3 (37)	8 (46)
Lake whitefish	5 (41)	10 (50)[c]
Lake trout	9 (48)	14 (57)
Largemouth bass	21 (70)	27 (81)[c]
Northern pike	11 (52)	19 (66)
Pumpkinseed	25 (77)	29 (84)[c]
Rainbow smelt	8 (46)	15 (59)
Rainbow trout	9 (48)	13 (55)
Sauger	12 (54)	18 (64)
Smallmouth bass	17 (63)	23 (73)[c]
Smallmouth buffalo	21 (70)	28 (82)[c]
Sockeye salmon	10 (50)	13 (55)
Striped bass	18 (64)	24 (75)
Threadfin shad	19 (66)	34 (93)
Walleye	8 (46)	17 (63)[c]
White bass	17 (63)	26 (79)
White crappie	18 (64)	23 (73)
White perch	15 (59)	20 (68)[c]
White sucker	10 (50)	20 (68)
Yellow perch	12 (54)	20 (68)

[a] The optimum or mean of the range of spawning temperatures reported for the species.

[b] The upper temperature for successful incubation and hatching reported for the species.

[c] Upper temperature for spawning.

could approximate the lower temperature of the range in spawning temperature, and the MWAT for the last month of a 3-month spawning season could approximate the upper temperature for the range. For example, if the channel catfish spawned from April to June the MWAT's for the 3 months would be approximately 21°, 27°, and 29° C. For fall spawning fish species the pattern or sequence of temperatures would be reversed because of naturally declining temperatures during their spawning season.

SHORT-TERM MAXIMUM DURING SPAWNING SEASON

If spawning season maxima could be determined in the same manner as those for the growing season, we would be using the time-temperature equation and the Appendix B data as before. However, growing season data are based usually on survival of juvenile and adult individuals. Egg-incubation temperature requirements are more restrictive (lower), and this biological process would not be protected by maxima based on data for juvenile and adult fish. Also, spawning itself could be prematurely stopped if those maxima were achieved. For most species the maximum spawning temperature approximates the maximum successful incubation temperature. Consequently, the short-term maximum temperature should preferably be based on maximum incubation temperature for successful embryo survival, but the maximum temperature for spawning is an acceptable alternative. In fact, the higher of the two is probably the preferred choice as variability in available data has shown discrepancies in this relationship for some species.

For the channel catfish (Appendix C) the maximum reported incubation temperature is 28° C, and the maximum reported spawning temperature is 29° C. Therefore, the best estimate of the short-term survival of embryos would be 29° C (Table 2).

MAXIMUM WEEKLY AVERAGE TEMPERATURE FOR WINTER

As discussed earlier the MWAT for winter is designed usually to prevent fish deaths in the event the water temperature drops rapidly to an ambient condition. Such a temperature drop could occur as the result of a power-plant shutdown or a movement of the fish itself. These MWAT's are meant to apply wherever fish can congregate, even if that is within the mixing zone.

Yellow perch require a long chill period during the winter for optimum egg maturation and spawning (Appendix A). However, protection of this species would be outside the mixing zone. In addition, the embryos of fall spawning fish such as trout, salmon, and other related species such as cisco require low incubation temperatures. For these species also the MWAT during winter would have to consider embryo survival, but again, this would be outside the mixing zone. The mixing zone, as used in this report, is that area adjacent to the discharge in which receiving system water quality standards do not apply; a thermal plume therefore is not a mixing zone.

With these exceptions in mind, it is unlikely that any signficant effects on fish populations would occur as long as death was prevented.

In many instances growth could be enhanced by controlled winter heat addition, but inadequate food may result in poor condition of the fish.

There are fewer data for lower incipient lethal temperatures than for the previously discussed upper incipient lethal temperatures. Appendix B contains lower incipient lethal temperature data for only about 20 freshwater fish species, less than half of which are listed in Tables 1 and 2. Consequently, the available data were combined to calculate a regression line (Figure 1) which gives a generalized MWAT for winter survival instead of the species specific approach used in the other types of criteria.

All the lower incipient lethal temperature data from Appendix C for freshwater fish species were used to calculate the regression line, which had a slope of 0.50 and a correlation coefficient of 0.75. This regression line was then displaced by approximately 2.5° C since it passed through the middle of the data and did not represent the more sensitive species. This new line on the edge of the data array was then displaced by a 2° C safety factor, the same factor discussed earlier, to account for the fact that the original data points were for 50 percent survival and the 2° C safety factor would result in 100 percent survival. These two adjustments in the original regression line therefore result in a line (Figure 1) that should insure no more than negligible mortality of any fish species. At lower acclimation temperatures the coldwater species were different from the warmwater species, and the resultant criterion takes this into account.

If fish can congregate in an area close to the discharge point, this criterion could be a limit on the degree rise permissible at a particular site. Obviously, if there is a screened discharge channel in which some cooling occurs, a higher initial discharge temperature could be permissible to fish.

An example of the use of this criterion (as plotted in the nomograph, Figure 1) would be a situation in which the ambient water temperature is 10° C, and the MWAT, where fish could congregate, is 25° C, a difference of 15° C. At a lower ambient temperature of about 2.5° C, the MWAT would be 10° C, a 7.5° C difference.

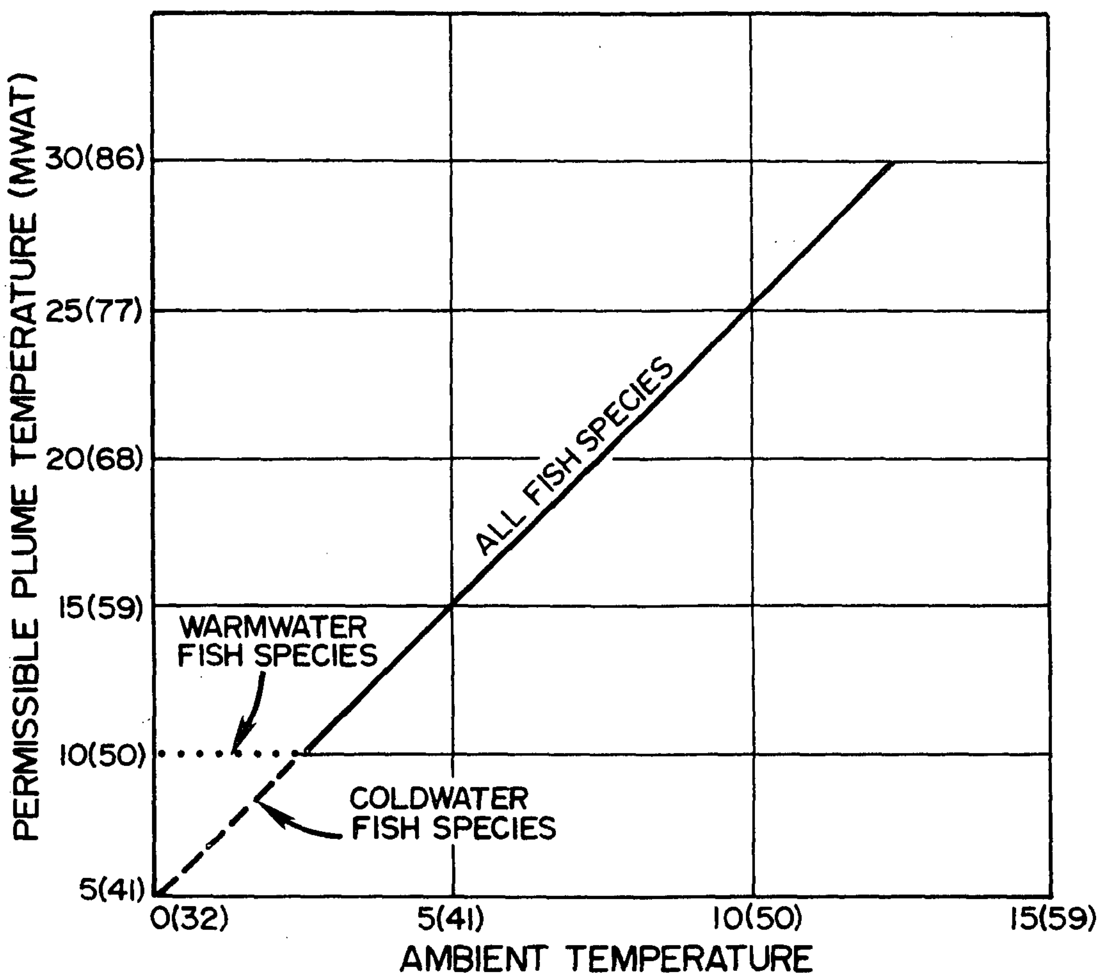

Figure 1. Nomograph to determine the maximum weekly average temperature of plumes for various ambient temperatures, °C (°F).

SECTION 5

EXAMPLES

Again, because precise thermal-effects data are not available for all species, we would like to emphasize the necessity for subjective decisions based on common-sense knowledge of existing aquatic systems. For some fish species for which few or only relatively poor data are available, subjectivity becomes important. If several qualified people were to calculate various temperature criteria for species for which several sets of high quality data were available, it is unlikely that they would be in agreement in all instances.

The following examples for warmwater and coldwater species are presented only as examples and are not at all intended to be water-body-specific recommendations. Local extenuating circumstances may warrant differences, or the basic conditions of the examples may be slightly unrealistic. More precise estimates of principal spawning and growth seasons should be available from the local state fish departments.

EXAMPLE 1

Tables 1 and 2, Figure 1, and Appendix C are the principal data sources for the criteria derived for this example. The following water-body-specific data are necessary and in this example are hypothetical:

1. Species to be protected by the criteria: channel catfish, largemout bass, bluegill, white crappie, freshwater drum, and bigmouth buffalo.

2. Local spawning seasons for these species: April to June for the white crappie and the bigmouth buffalo; other species, May to July.

3. Normal ambient winter temperature: 5° C in December and January; 10° C in November, February, and March.

4. The principal growing season for these fish species: July through September.

5. Any local extenuating circumstances should be incorporated into the criteria as appropriate. Some examples would be yellow perch gamete maturation in the winter, very temperature-sensitive endangered species, or important fish-food organisms that are very temperature sensitive. For the example we will have no extenuating circumstances.

In some instances the data will be insufficient to determine each necessary criterion for each species. Estimates must be made based on available species-specific data or by extrapolation from data for species with similar requirements for which adequate data are available. For instance, this example includes the bigmouth buffalo and freshwater drum for which no growth or short-term summer maxima are available (Table 1). One would of necessity have to estimate that the summer criteria would not be lower than that for the white crappie, which has a spawning requirement as low as the other two species.

The choice of important fish species is very critical. Since in this example the white crappie is as temperature sensitive as any of the species, the maximum weekly average temperature for summer growth is based on the white crappie. Consequently, this criterion would result in lower than optimal conditions for the channel catfish, bluegill, and largemouth bass. An alternate approach would be to develop criteria for the single most important species even if the most sensitive is not well protected. The choice is a socioeconomic one.

Before developing a set of criteria such as those in Table 3, the material material in Tables 1 and 2 should be studied for the species of concern. It is evident that the lowest optimum temperature for summer growth for the species for which data are available would be for the white crappie (28° C). However, there is no maximum for short exposure since the data are not available (Appendix C). For the species for which there are data, the lowest maximum for short exposure is for the largemouth bass (34° C). In this example we have all the necessary data for spawning and maximum for short exposure for embryo survival for all species of concern (Table 2).

During the winter, criteria may be necessary both for the mixing zone as well as for the receiving water. Receiving-water criteria would be necessary if an important fish species were known to have gamete-maturation requirements like the yellow perch, or embryo-incubation requirements like trout, salmon, cisco, etc. In this example there is no need for receiving-system water criteria.

At this point, we are ready to complete Table 3 for Example 1.

EXAMPLE 2 *

All of the general concerns and data sources presented throughout the discussion and derivation of Example 1 will apply here.

1. Species to be protected by the criteria: rainbow and brown trout and the coho salmon.

2. Local spawning seasons for these species: November through January for rainbow trout; and November through December for the brown trout and coho salmon.

3. Normal ambient winter temperature: 2° C in November through February; 5° C in October, March, and April.

TABLE 3. TEMPERATURE CRITERIA FOR EXAMPLE 1

Month	Maximum weekly average temperature, (° C (° F)) Receiving water	Heated plume	Decision basis
January	--[a]	15(59)	Figure 1
February	--[a]	25(77)	Figure 1
March	--[a]	25(77)	Figure 1
April	18(64)[b]	--	White crappie spawning
May	21(70)	--	Largemouth bass spawning
June	25(77)	--	Bluegill spawning and white crappie growth
July	28(82)	--	White crappie growth
August	28(82)	--	White crappie growth
September	28(82)	--	White crappie growth
October	21(70)	--	Normal gradual seasonal decline
November	--[a]	25(77)	Figure 1
December	--[a]	15(59)	Figure 1

Month	Short-term maximum	Decision basis
January	None needed	Control by MWAT in plume
February	None needed	Control by MWAT in plume
March	None needed	Control by MWAT in plume
April	26(79)	Largemouth bass[b] survival (estimated)
May	29(84)	Largemouth bass[b] survival (estimated)
June	34(93)	Largemouth bass[b] survival
July	34(93)	Largemouth bass[b] survival
August	34(93)	Largemouth bass[b] survival
September	34(93)	Largemouth bass[b] survival
October	29(84)	Largemouth bass[b] survival (estimated)
November	None needed	Control by MWAT in plume
December	None needed	Control by MWAT in plume

[a] If a species had required a winter chill period for gamete maturation or egg incubation, receiving-water criteria would also be required.

[b] No data available for the slightly more sensitive white crappie.

4. The principal growing season for these fish species: June through September.

5. Consider any local extenuating circumstances: There are none in this example.

At this point, we are ready to complete Table 4 for Example 2.

TABLE 4. TEMPERATURE CRITERIA FOR EXAMPLE 2

Month	Maximum weekly average temperature, (° C (° F)) Receiving water	Heated plume	Decision basis
January	9(48)	10(50)	Rainbow trout spawning and Figure 1
February	13(55)	10(50)	Normal gradual seasonal rise and Figure 1
March	13(55)	15(59)	Normal gradual seasonal rise and Figure 1
April	14(57)	15(59)	Normal gradual seasonal rise and Figure 1
May	16(61)	--	Normal gradual seasonal rise
June	17(63)	--	Brown trout growth
July	17(63)	--	Brown trout growth
August	17(63)	--	Brown trout growth
September	17(63)	--	Brown trout growth
October	12(54)	15(59)	Normal gradual seasonal decline
November	8(46)	10(50)	Brook trout spawning and Figure 1
December	8(46)	10(50)	Brown trout spawning and Figure 1

Month	Short-term maximum	Decision basis
January	13(55)	Embryo survival for rainbow trout and coho salmon
February	13(55)	Embryo survival for rainbow trout and coho salmon
March	13(55)	Embryo survival for rainbow trout and coho salmon
April	--	
May	--	
June	24(75)	Short-term maximum for survival of all species
July	24(75)	Short-term maximum for survival of all species
August	24(75)	Short-term maximum for survival of all species
September	24(75)	Short-term maximum for survival of all species
October	--	
November	13(55)	Embryo survival for rainbow trout and coho salmon
December	13(55)	Embryo survival for rainbow trout and coho salmon

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APPENDICES

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 acquatic 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 ecosystem 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

*From: National Academy of Sciences (1973). See pp. 151-171, 205-207.

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.

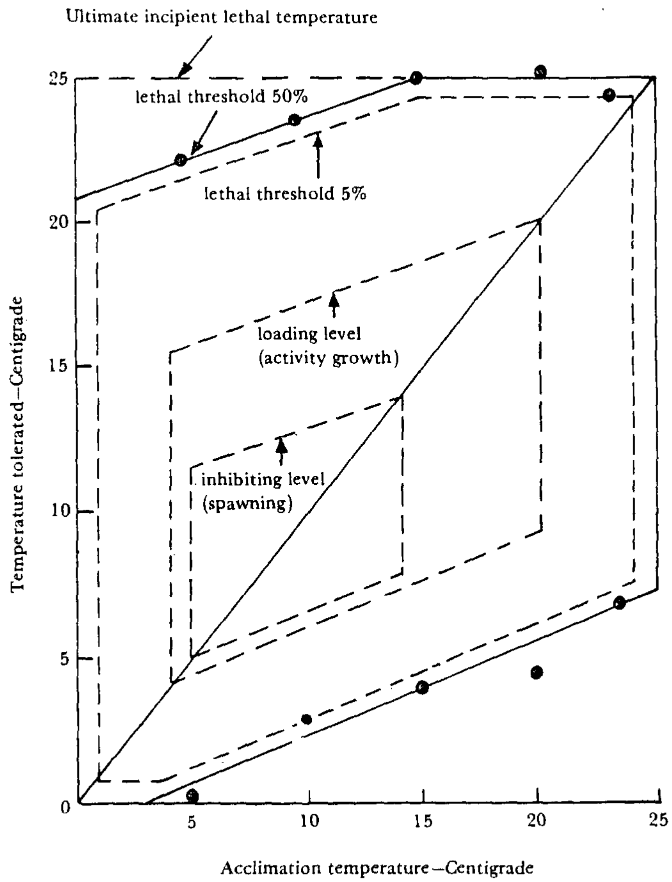
DEVELOPMENT OF CRITERIA

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

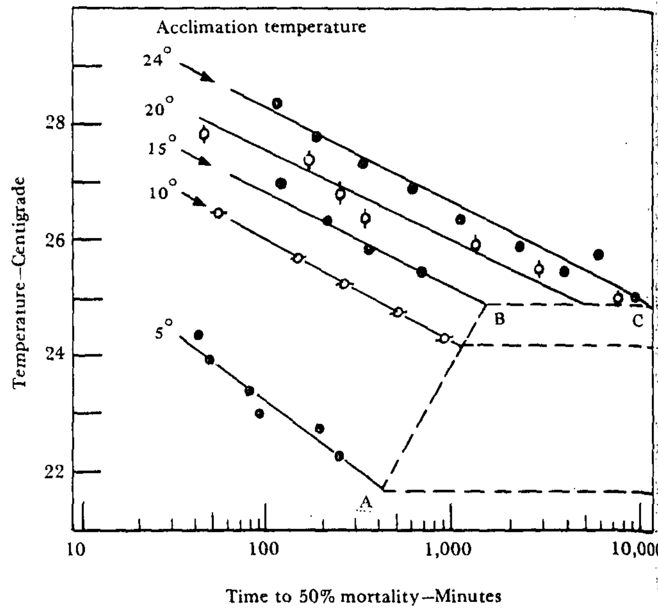
Some basic thermal responses of aquatic organisms will be referred to repeatedly and are defined and reviewed briefly here. Effects of heat on organisms and aquatic communities have been reviewed periodically (e.g., Bullock 1955,[259] Brett 1956;[253] Fry 1947,[276] 1964,[278] 1967;[279] Kinne 1970[296]). 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 "extreme." 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 to a few hours will not greatly affect the thermal tolerance limits, since acclimation to changing temperatures requires several days (Brett 1941).[251]



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.*



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.*

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]

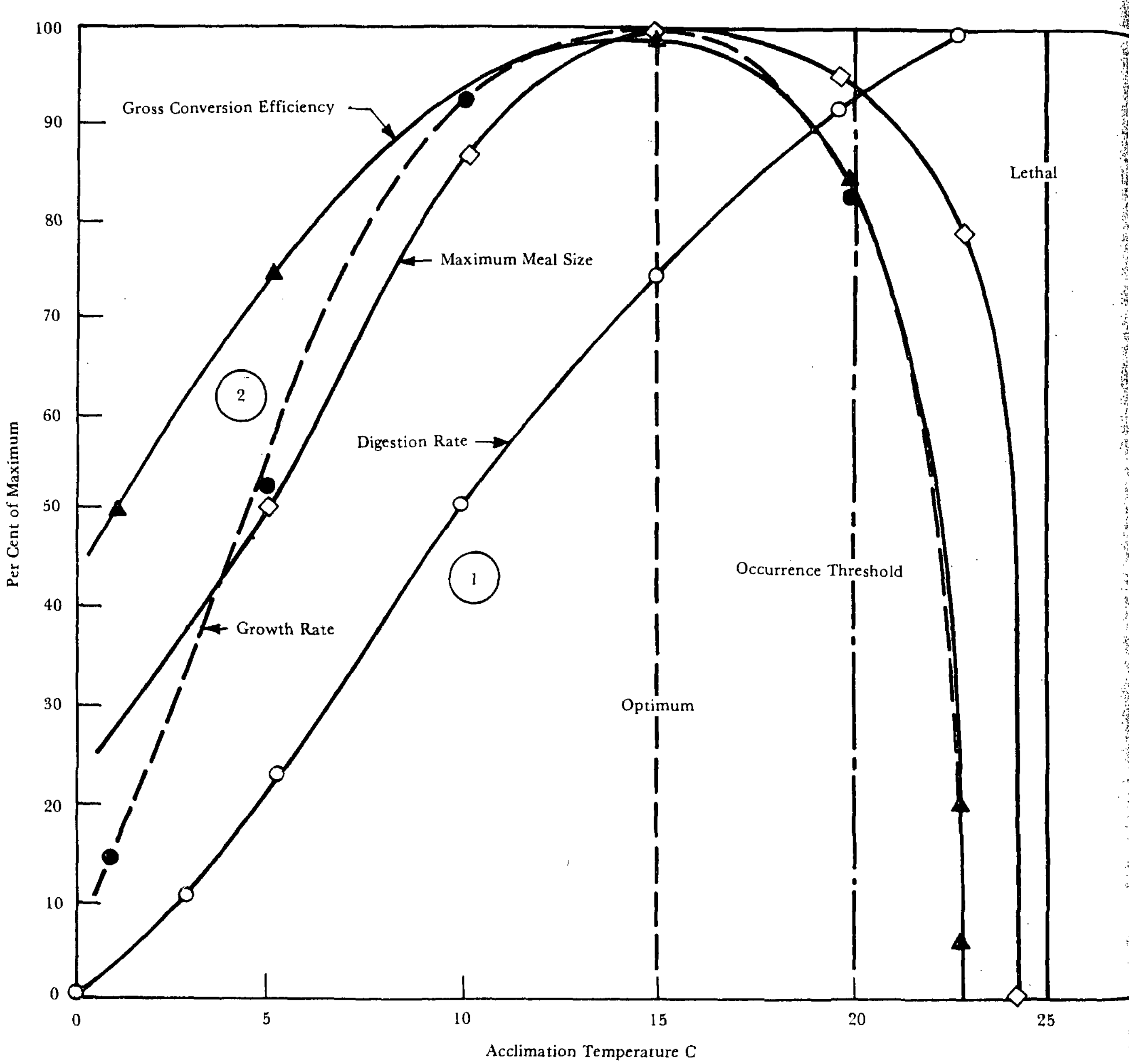
These observations suggest that an average of the optimum temperature and the temperature of zero net growth [(opt. temp. + z.n.g. temp)/2] would be a useful estimate of a limiting weekly mean temperature for resident organisms, providing the peak temperatures do not exceed values recommended for short-term 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	(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[320]	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

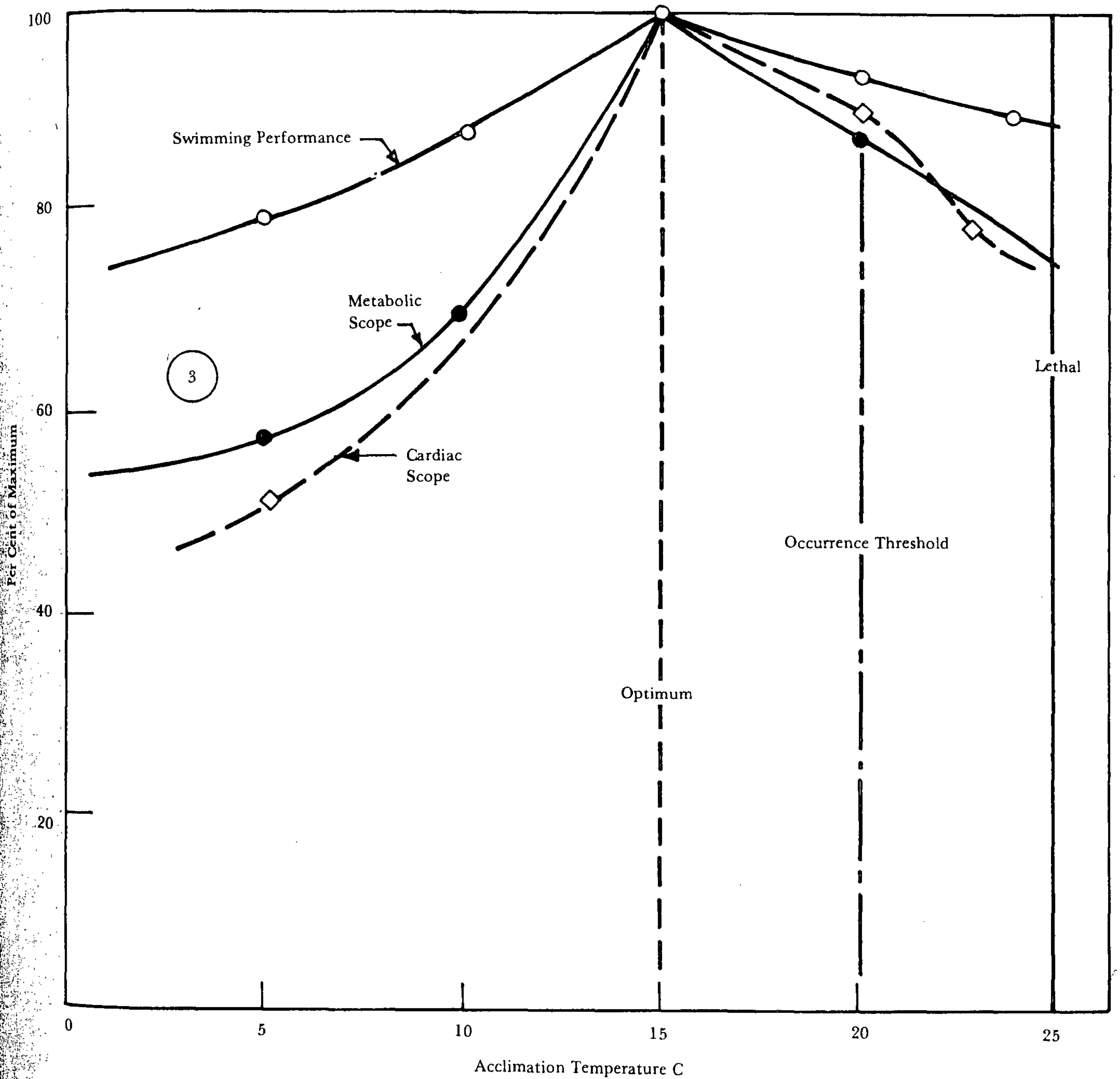
*National Water Quality Laboratory, Duluth, Minn., unpublished data.[328]



After Brett 1971[256]

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

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.

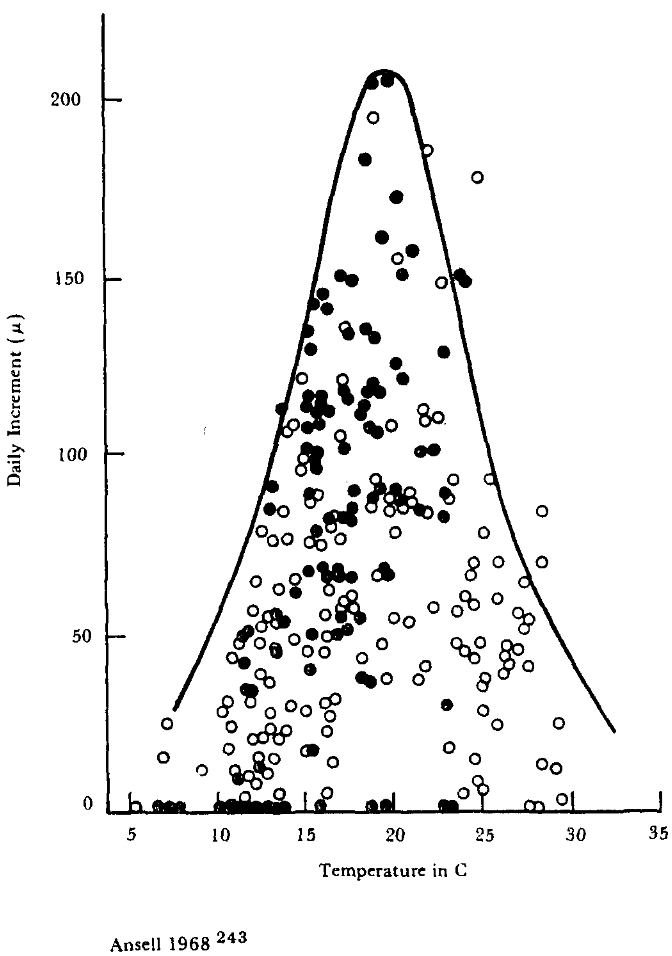


FIGURE III–4c*—M. mercenaria: *The general relationship between temperature and the rate of shell growth, based on field measurements of growth and temperature.

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

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. Nonmobile 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.

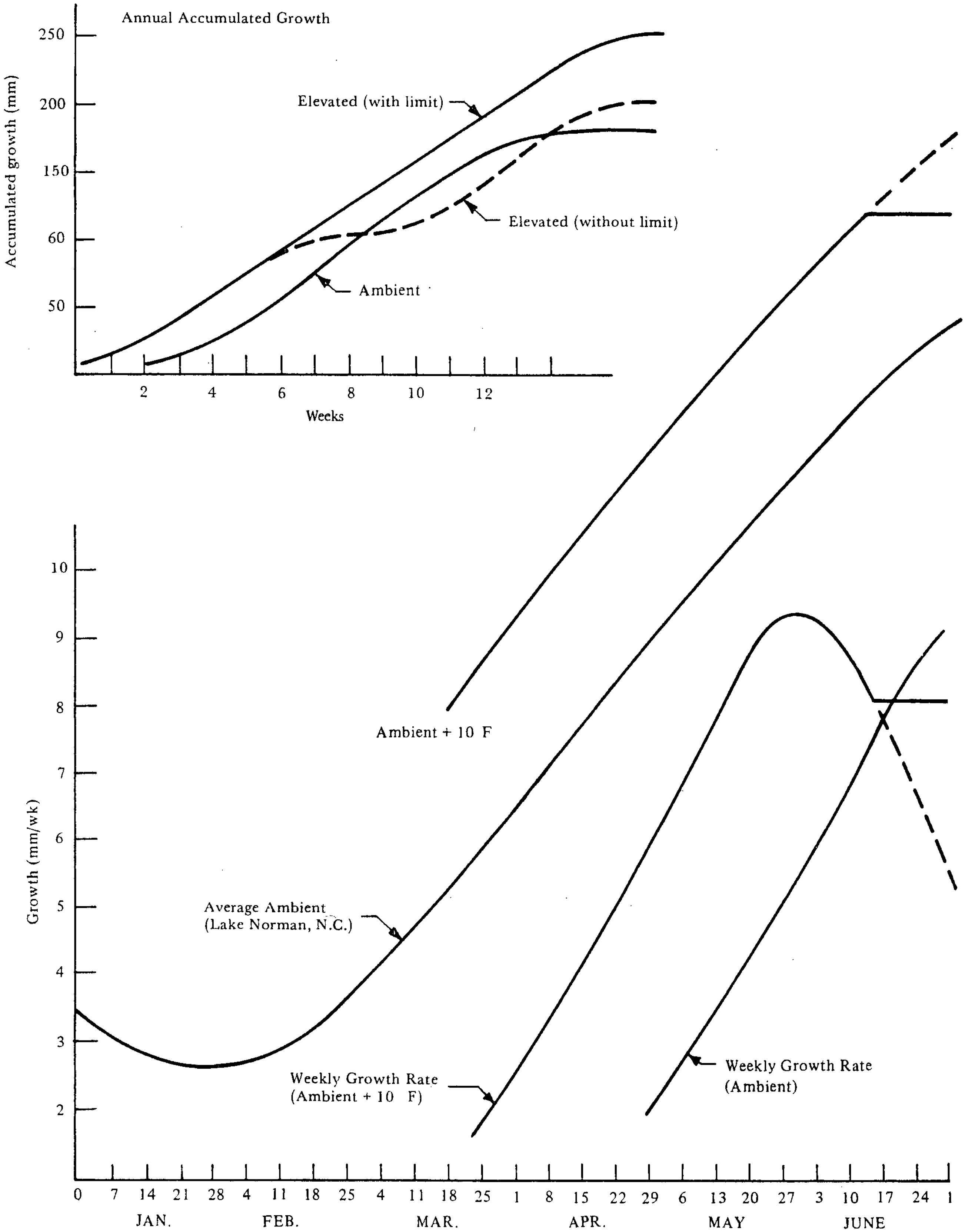

Annual Accumulated Growth
Accumulated growth (mm)
250
200
150
60
50
Elevated (with limit)
Elevated (without limit)
Ambient
2
4
6
8
10
12
Weeks
Growth (mm/wk)
10
9
8
7
6
5
4
3
2
Ambient + 10 F
Average Ambient
(Lake Norman, N.C.)
Weekly Growth Rate
(Ambient + 10 F)
Weekly Growth Rate
(Ambient)
0 7 14 21 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

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.

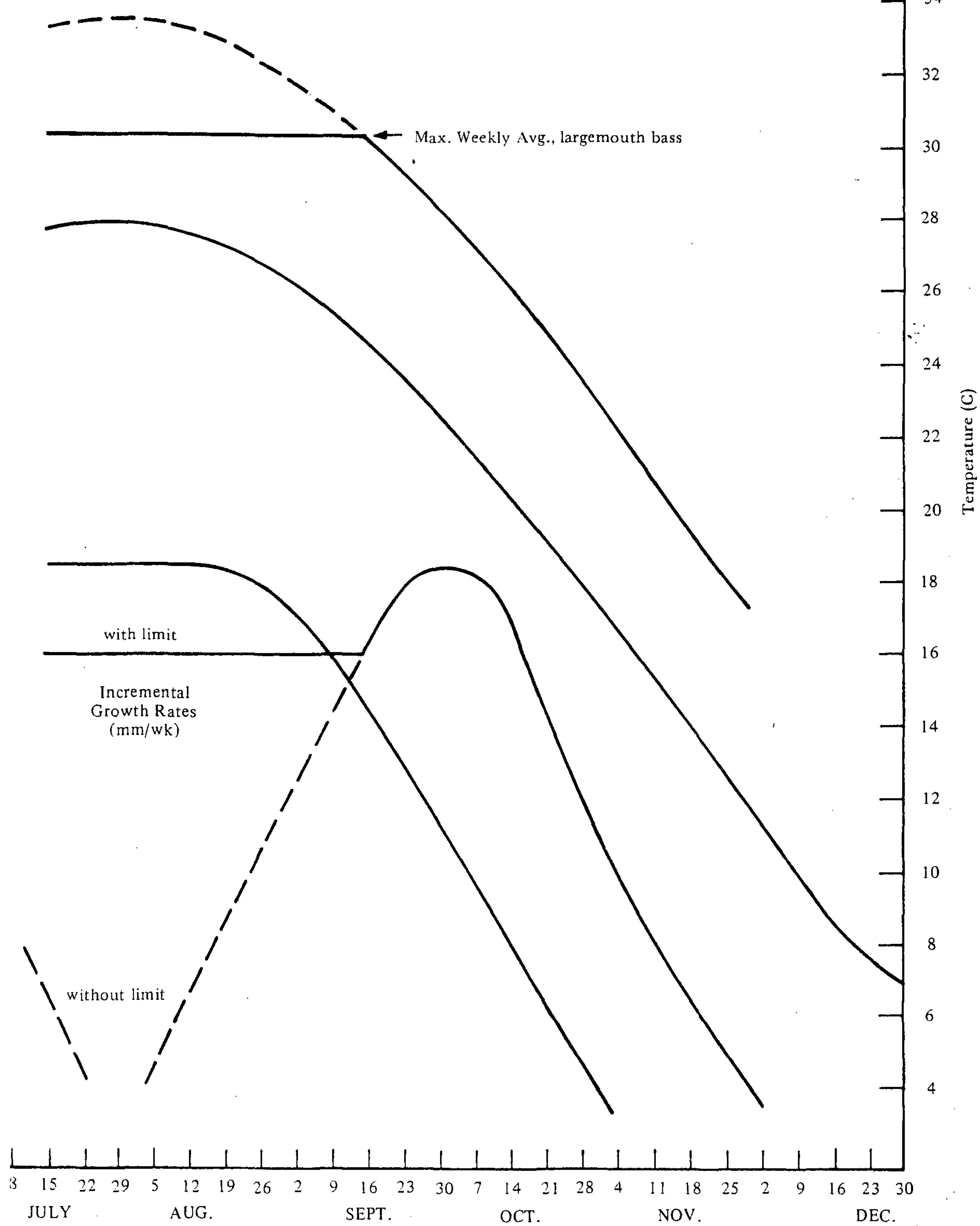


TABLE III-12—Summary of Some Upper Limiting Temperatures for Prolonged Exposures of Fishes Based on Optimum Temperatures and Ultimate Upper Incipient Lethal Temperatures (Equation 1).

Species	Optimum C	Optimum F	Function	Reference	Ultimate upper incipient lethal temperature C	Ultimate upper incipient lethal temperature F	Reference	Maximum weekly average temperature (Eq. 1) C	Maximum weekly average temperature (Eq. 1) 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[302]	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[257]	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 temperatures 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 discharge 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:

$$\log(\text{time}) = a + b\,(\text{temp.}) \qquad (\textit{Equation 2})$$

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 semi-logarithmic 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;[280] 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 simultaneous 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:

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

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:

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

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 recommendation 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 annuiaris	14.0–16.0	Submerged materials in shallows	...	Day	Bottom	1 (21.1–23.2)
Fathead minnow Pimephales promelas	14.4 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 Ictalurus punctatus	20.0 20.0 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 (25.0–28)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	1½–4 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;[276] 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:

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

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 (ft^3/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

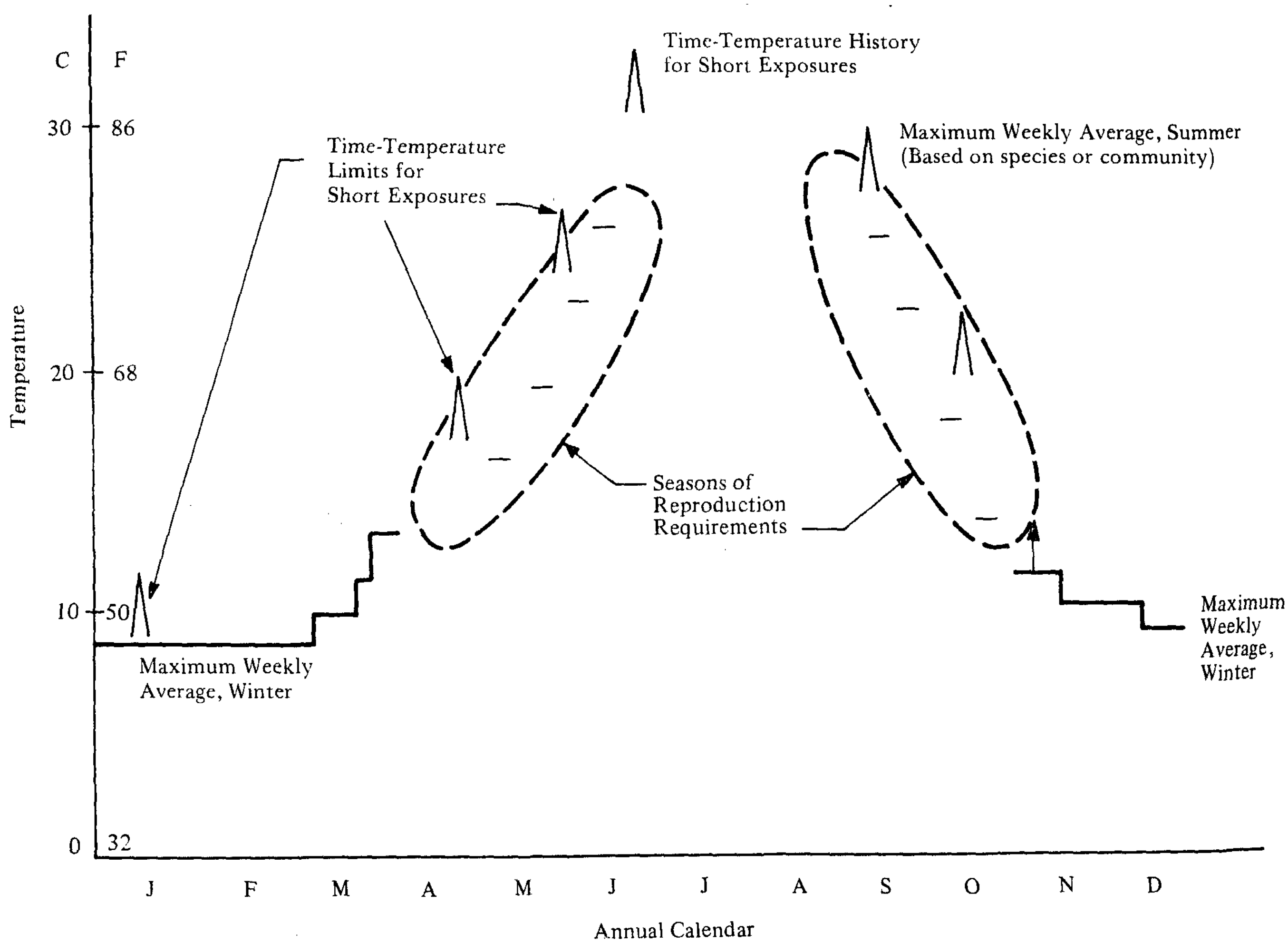


FIGURE III–6—Schematic Summary of Thermal Criteria

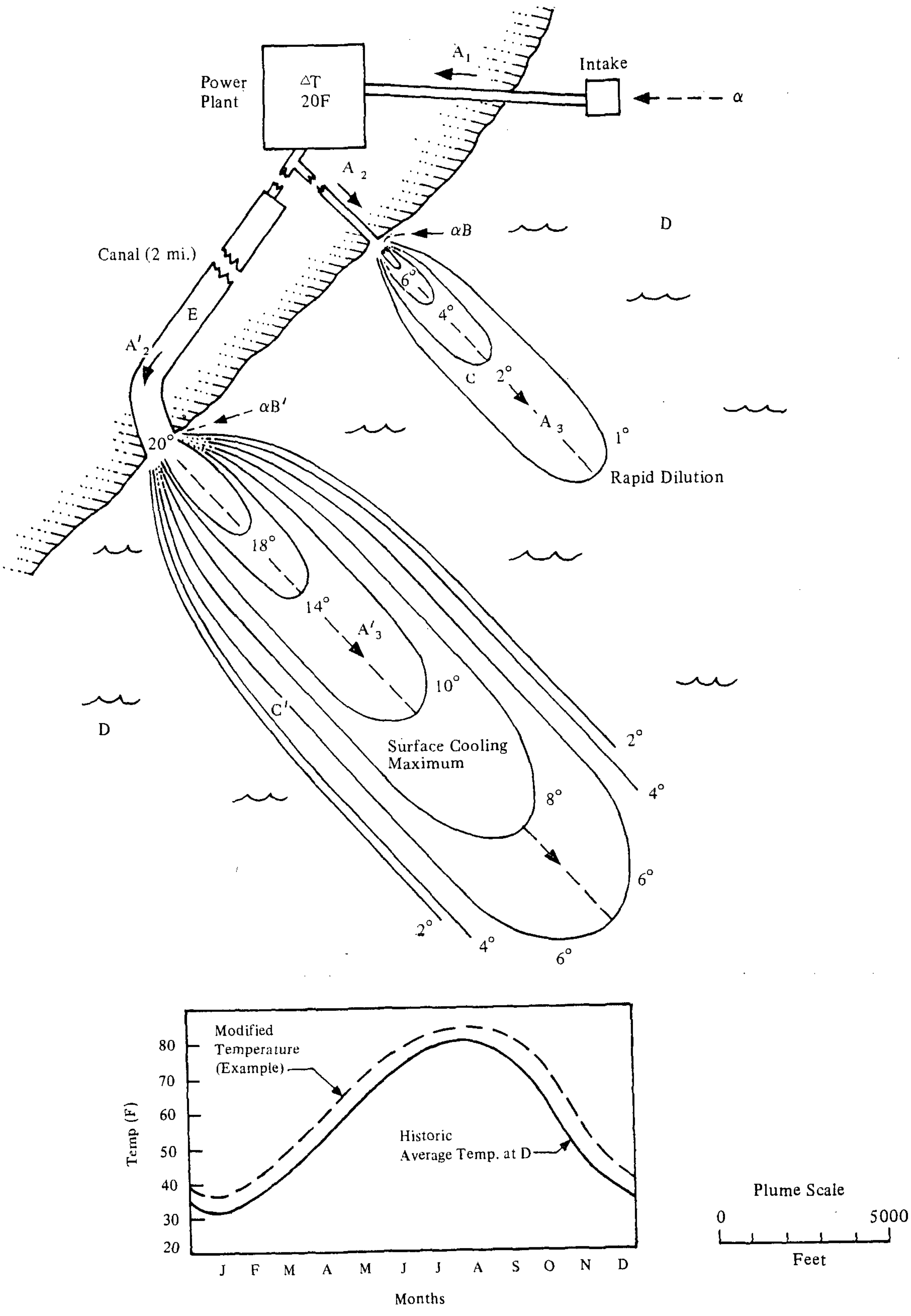


FIGURE III-7—Hypothetical Power Plant Site For Application of Water Temperature Criteria

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.

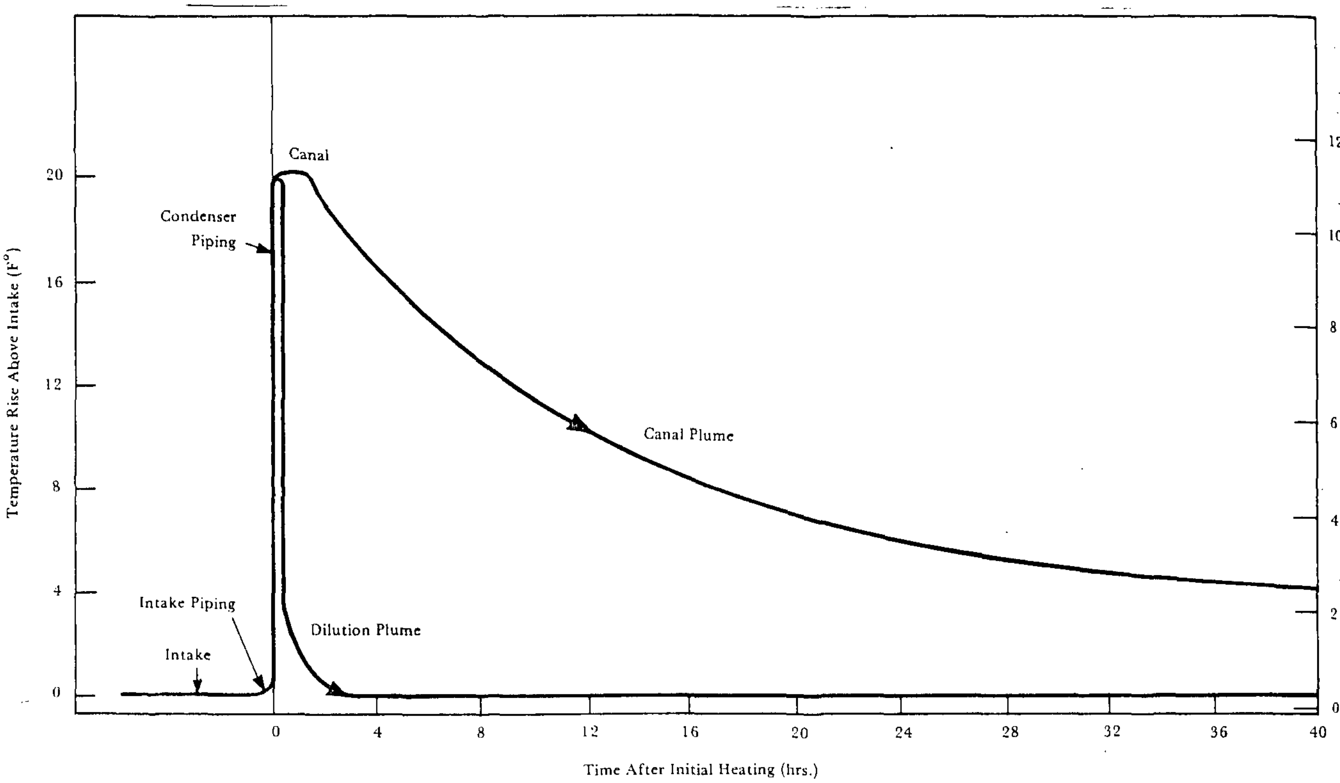
Detrimental effects of thermal exposures received during entrainment can be judged by using the following equation for short-term exposures to extreme temperatures:

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

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).

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

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 employing 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,

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

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:

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

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[281]). 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:

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

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 discharges 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.

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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 saxatilis (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 Killifish)	Adult	...	...	...	Jefferson Co., Texas	Strawn and Dunn (1967)[99]	Upper	35	(0 ‰)[e]	21.9337	−0.4866	6	−0.9930	43.0	40.5	...	...
								35	(5 ‰)[e]	27.7919	−0.6159	6	−0.9841	43.5	41.0	...	...
								35	(10 ‰)[e]	26.8121	−0.5899	6	−0.9829	43.5	41.0	...	...
								35	(20 ‰)[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 ‰)	57.9980	−0.1643	2	...	35.0	34.0	...	...
								27	(5 ‰)	85.1837	−2.3521	2	...	35.0	34.5	...	...
							Lower	16	(26–30 ‰)	...	...	...	...	7.0	3.0	...	6.5
								18	(10 ‰)	...	...	...	...	7.0	3.0	...	6.5
Brevoortia tyrannus (Atlantic menhaden)	Yearling	...	...	...	Beaufort, N.C.	Lewis and Hettler (1968)[92]	Upper	21	(5 ‰)	35.7158	−1.0468	3	−0.9174	34	33	...	...
								22–23	(4–6 ‰)	21.8083	−0.6342	10	−0.9216	35	31	...	32.5
Carassius 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 commersonni (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.

*From: National Academy of Sciences (1973). See pp. 410-419, 444-445, Appendix II-C.

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	lower	LD50
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	...
								5	4 wks	10.2799	−0.3645	3	−0.9264	24.0	20.0	...
								10	>2 wks	12.4993	−0.4098	6	−0.9734	28.0	24.0	...
								20	2 wks	17.2967	−0.5333	8	−0.9487	30.0	26.0	...
								25	3 wks	15.1204	−0.4493	7	−0.9764	30.0	25.5	...
							Lower	2	8 wks	...	...	...	...	1.5	0.3	...
								5	4 wks	...	...	...	...	1.0	0.5	...
								10	>2 wks	2.7355	0.3381	5	0.9021	3.0	0.5	...
								20	2 wks	2.5090	0.2685	6	0.9637	4.5	0.5	...
								25	3 wks	1.7154	0.1652	9	0.9175	9.5	0.5	...
Coregonus hoyi (bloater)	Juvenile (age 1)	60.0 mm 5.0. 5.8	...	*Mixed*	Lake Michigan at[f] Kenosha, Wisc.	*Edsall, Rottiers* & Brown, 1970[80]	*Upper*	5	11 da[g]	15.8243	−0.5831	5	−0.9095	26.0	22.0	...
								10	5 da	9.0700	−0.2896	6	−0.9516	30.0	23.0	...
								15	5 da	17.1908	−0.5707	4	−0.9960	28.0	24.5	...
								20	5 da	28.6392	−0.9458	4	−0.9692	29.0	25.5	...
								25	5 da	21.3511	−0.6594	5	−0.9958	30.0	26.5	...
Cyprinodon variegatus (sheepshead minnow)	Adult	...	...	...	Jefferson County, Texas	Strawn and Dunn (1967[99])	Upper	35	(0 ‰)	27.9021	−0.6217	6	−0.9783	43.0	40.5	
								35	(5 ‰)	35.3415	−0.7858	6	−0.9787	43.5	41.0	...
								35	(10 ‰)	30.0910	−0.6629	6	−0.9950	43.5	41.5	
								35	(20 ‰)	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)[88]	Upper	25	field & 3-4 da	47.1163	−1.3010	3	−0.9975	35.5	34.5	...
								30	"	38.0658	−0.9694	4	−0.9921	38.0	36.5	...
								35	"	31.5434	−0.7710	5	−9.9642	39.0	37.0	...
							Lower	25	...	...	...	...	...	...	...	...
								30	...	...	...	...	...	...	...	...
								35	...	...	...	...	...	...	...	...
Dorosoma cepedianum (gizzard *shad*)	Underyearling	...	...	...	Knoxville, Tenn.	Hart (1952)[88]	Upper	25	...	32.1348	−0.8698	2	...	35.5	35.0	...
								30	...	41.1030	−0.0547	4	−0.9991	38.0	36.5	...
								35	...	33.2846	−0.8176	6	−0.9896	39	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	−0.9990	34.5	32.5	...
								27.5	...	17.4439	−0.4490	5	−0.9985	35.0	33.0	...
								30.0	...	17.0961	−0.4319	5	−0.9971	35.5	33.5	...
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	...
								27.5	...	20.0817	−0.5283	5	−0.9911	35.0	33.0	...
								30.0	...	18.9506	−0.4851	5	−0.9972	35.5	33.5	...
Esox hybrid (*luciusx 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	...
								27.5	...	20.7834	−0.5460	5	−0.9995	35.0	33.0	...
								30.0	...	19.6126	−0.5032	5	−0.9951	35.5	33.5	...
Fundulus chrysotus (golden topminnow)	Adult	...	...	...	Jefferson County, Texas	Strawn & Dunn (1967)[99]	Upper	35	(0 ‰)—	23.7284	−0.5219	9	−0.9968	43.0	39.0	...
								35	(5 ‰)—	21.2575	−0.4601	7	−0.9969	43.5	40.0	...
								35	(20 ‰)—	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)[84]	Upper	15	(0 ‰)[i]	...	...	...	...	...	...	...
								15	(14 ‰)	...	...	...	...	...	...	...
								15	(32 ‰)	...	...	...	...	...	...	...
Fundulus grandis (gulf killifish)	Adult	...	...	...	Jefferson County, Texas	Strawn & Dunn (1967)[99]	Upper	35	(0 ‰)	22.9809	−0.5179	8	−0.9782	42.0	38.5	...
								35	(5 ‰)	27.6447	−0.6220	7	−0.9967	42.5	39.5	...
								35	(10 ‰)	24.9072	−0.5535	9	−0.9926	43.0	39.0	...
								35	(20 ‰)	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)[84]	Upper	15	(0 ‰)[j]	...	...	...	...	...	...	...
								15	(14 ‰)	...	...	...	...	...	...	...
								15	(32 ‰)	...	...	...	...	...	...	...

[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] 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 ‰ 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		log time=a+b (temp.)				Data limits (°C)		LD50	Lethal threshold[d] (°C)
								Temp[a]	Time	a	b	N[b]	r[c]	upper	lower		
Fundulus parvipinnis (California killifish) (tested in seawater except as noted)	Adult	6-7 cm	....	Mixed	Mission Bay, Calif. (seawater)	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	....	24.5437	−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 pulvereus (bayou killifish)	Adult	....	....	....	Jefferson County, Texas	Strawn and Dunn (1967)[99]	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 killifish)	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 (mosquitofish)	Adult	....	....	Mixed	Knoxville, Tenn.	Hart (1952)[58]	Upper	25	....	39.0004	−0.9771	2	... .	39	38	....	37.0
								30	....	30.1523	−0.7143	6	−0.9938	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)[88]	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 aculeatus (threespine stickleback)	Adult	37 mm ave.	0.50 g ave.	Mixed	Columbia River near Prescott, Oregon	Blahm and Parente (1970)[101] unpublished 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, California (33°N)	Doudoroff (1942)[78]	Upper	12	....	21.1277	−0.6339	6	−0.9338	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	0.9556	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) nebulosus (brown bullhead)	....	....	....	....	Florida to Ontario (4 locations) combined	Hart (1952)[88]	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	....	28.3281	−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 punctatus (channel catfish)	Juvenile (44–57 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).[83]

[e] 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)
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
								30	...	17.7125	−0.4058	4	−0.9934	40.0	37.5	...	37.0
								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
								20	...	39.4967	−1.1234	4	−0.9980	34.0	33.0	...	32.8
								25	...	46.2155	−1.2899	5	−0.9925	35.0	34.0	...	33.5
							Lower	15	...	...	...	...	...	...	...	...	0.0
								20	...	...	...	...	...	...	...	...	0.0
								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
								20	...	28.0663	−0.7826	6	−0.9978	34.5	32.5	...	32.0
								25	...	23.8733	−0.6320	10	−0.9750	36.0	33.0	...	33.0
								30	...	25.7732	−0.6581	5	−0.9965	38	34.5	...	33.8
							Lower	15	...	...	...	...	...	...	...	...	2.5
								20	...	...	...	...	...	...	...	...	5.0
								25	...	...	...	...	...	...	...	...	7.5
								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	...	...
								30	...	30.1609	−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	...	35.6
								30	...	20.5981	−0.4978	22	−0.9625	39.0	36.5	...	36.8
								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 ‰)[e]	20.7487	−0.4686	7	−0.9747	42.0	39.0	...	...
								35	(5 ‰)	23.5649	−0.5354	6	−0.9975	42.0	39.0	...	...
								35	(20 ‰)	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 ‰)[e]	21.2616	−0.4762	9	−0.9844	42.5	38.5	...	...
								35	(5 ‰)	24.3076	−0.5460	8	−0.9846	42.5	39.0	...	...
								35	(10 ‰)	24.3118	−0.5467	8	−0.9904	42.5	39.0	...	...
								35	(20 ‰)	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
								14	...	18.7499	−0.6001	6	−0.9616	27.0	23.0	...	25.0
								21	...	65.7350	−2.0387	6	−0.9626	32.0	28.0	...	30.4
								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
								14	...	−1.2884	2.5597	6	0.8594	5	1	...	2.0
								21	...	−1.4801	1.1484	6	0.9531	7	2	...	4.3
								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.[illegible]
								25	...	19.9918	−0.5123	8	−0.9972	36.5	33	...	33.[illegible]
								30	...	17.5645	−0.4200	8	−0.9920	38	34.5	...	33.7(d)
							Lower	20	...	...	...	...	...	...	...	...	5.2
								25	...	...	...	...	...	...	...	...	7.0
								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
								25	...	26.3169	−0.6846	3	−0.9973	36.5	35	...	34.5
								30	...	29.0213	−0.7150	4	−0.9959	38.5	37	...	36.4(d)
							Lower	20	...	...	...	...	...	...	...	...	5.5
								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
								35	...	23.9185	−0.5632	6	−0.9958	40	37.5	...	36.4(d)
Micropterus salmoides (largemouth bass)	...	...	...	...	Lake Mendota, Wisconsin	Hart (1952)[98]	Upper	22	...	34.3649	−0.9789	4	−0.9789	33.8	32.0	...	31.5
								30	...	35.2777	−0.9084	4	−0.9845	37.5	35.5	...	...
Mysis relicta (Opposum shrimp)	Adult	...	...	Mixed	Trout Lake, Cook County, Minnesota	Smith (1970)[98]	Upper	7.5C	>1 wk	6.1302	−0.1470	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

...cies	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[p] (°C)
...swat- ...s (opos- ...rimp)	Adult	>7 mm	...	Mixed	Sacramento-San Joaquin delta, California	Hair (1971)[86]	Upper	10.3[e]	...	...	...	...	...	...	...	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[f]
								21.7	...	...	...	...	...	...	...	77.0(48)	...
								22.0	...	...	...	...	...	...	...	77.5(48)	...
								22.4	...	...	...	...	...	...	...	76.0(48)	...
...nus ...ucas ...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
...theri- ...emerald	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	2	...	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
...rnutus ...n shiner)	Adult	...	...	...	Toronto, Ontario	Hart (1952)[88]	Upper	10	...	...	...	1	...	29.0	29.0	...	29.0
								15	...	45.4331	−1.3979	2	...	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)
...rnutus	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
...rnutus ...shiner)	Adult	...	...	...	Knoxville, Tenn.	Hart (1952)[88]	Upper	25	...	25.5152	−0.6794	6	−0.9938	35.5	33.0	...	33.0
								30	...	24.9660	−0.6297	10	−0.9978	38.0	34.5	...	33.5(u)
...hus ...a (pink	Juvenile fresh-water 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
...hus ...um	Juvenile fresh-water 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	...	...	...	...	...	...	...	...	...
								10	...	...	...	...	...	1	...	...	0.5
								15	...	...	...	...	...	5	...	...	4.7
								20	...	...	...	...	...	7	...	...	6.5
								23	...	...	...	...	...	8	...	...	7.3
...hus ...um	Juvenile	...	...	...	Big Creek Hatchery, Hoodsport, Wash.[h]	Blahm and Parente (1970)[101] unpublished data	Upper	9	10%[i]	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	−0.9995	29	17	...	23.6

...med in this table that the acclimation temperature reported is a true acclimation in the context of Brett

...of median resistance times used for calculating regression equation.
...ion coefficient (perfect fit of all data points to the regression line=1.0).
...ent ethal temperature of Fry, et al., (1946).[83]
...ratures 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.

[i] Mortality Value.

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	lower	LD50
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	....
								10	....	19.5721	−0.6820	4	−0.9847	26.0	24.5	....
								15	....	20.4066	−0.6858	6	−0.9681	27.0	24.5	....
								20	....	20.4022	−0.6713	4	−0.9985	27.5	25.5	....
								23	....	18.9736	−0.6013	5	−0.9956	27.5	25.0	....
							Lower	5	....	....	....	.....	....	....	.....	....
								10	....	....	....	.....	....	1	.....	....
								15	....	....	....	.....	....	3	.....	....
								20	....	....	....	.....	....	5	.....	....
								23	....	....	....	.....	....	7	1.0	....
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	....
									(50%)	18.4136	−0.6410	6	−0.9705	29	17.0	....
									(90%)	15.9026	−0.5423	4	−0.9730	29	17.0	....
								14[g]	(10%)	8.5307	−0.2969	10	−0.9063	29	14.0	....
									(50%)	8.5195	−0.2433	10	−0.8483	29	0.14	....
									(90%)	....	....	.....	....	....	.....	....
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	....
								10	....	14.7319	−0.4988	8	−0.9833	26.5	23.5	....
								15	....	15.8799	−0.5210	7	−0.9126	27.5	24.5	....
								20	....	19.3821	−0.6378	5	−0.9602	27.5	24.5	....
								23	....	20.0020	−0.6496	4	−0.9981	26.5	24.5	....
							Lower	5	....	....	....	.....	....	0	0	....
								10	....	....	....	.....	....	4	0	....
								15	....	....	....	.....	....	5	0	....
								20	....	....	....	.....	....	5	0	....
								23	....	....	....	.....	....	7	1.0	....
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	....
									50%	18.5833	−0.6437	6	−0.9750	29	17	....
									90%	20.6289	−0.7166	6	−0.9553	29	17	....
								20	10%	17.5227	−0.5861	6	−0.9739	29	21	....
									50%	16.7328	−0.5473	6	−0.9552	29	21	....
									90%	15.7823	−0.5061	6	−0.9539	29	21	....
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	....
									(90%)	9.0628	−0.2859	4	−0.9534	32	14	....
								12″	(10%)	13.2412	−0.4475	4	−0.9955	29	17	....
									(50%)	18.1322	−0.6178	4	−0.9598	29	17	....
									(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	....
									(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	....
									(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	....
								10	....	16.4595	−0.5575	5	−0.9996	26.5	24.5	....
								15	....	16.4454	−0.5364	4	−0.9906	27.0	25.5	....
								20	....	22.9065	−0.7611	7	−0.9850	27.5	25.0	....
								24	....	18.9940	−0.5992	9	−0.9923	27.5	25.0	....
							Lower	10	....	....	....	.....	....	1.0	0	....
								15	....	....	....	.....	....	3.0	0.5	....
								20	....	....	....	.....	....	5.0	0.5	....
								23	....	....	....	.....	....	8.0	1.0	....

[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] 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 (and may have included a few fish from other upstream sources). River water was supersaturated with 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.

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	lower	LD50	Lethal threshold[d] (°C)
...rhynchus ...wytscha (...nook ...on)	Juvenile	39–124 mm averages for various test groups	....	Mixed	Columbia River at Prescott, Oregon	Snyder & Blahm (1970)[106] 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%[f])	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%)	15.1563	−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
...rhynchus ...wytscha (...nook salmon ...ing run)	Juvenile	84 mm ave.	6.3g ave.	Mixed	Little White Salmon, River Hatchery, Cook, Washington	Blahm & McConnell (1970)[100] unpublished data	Upper	11	2–3-wks								
									10%[i]	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
...rhynchus ...wytscha (...nook 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	....	?
...rhynchus ...wytscha (...nook salmon ...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	−0.9240	29	17	....	24.5
							Upper	20	1C/day rise from 10C								
									10%	21.6756	−0.7438	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
...rhynchus ...wytscha (...nook ...)	"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
...flavescens (...ow 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	....	?
...flavescens (...ow 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	−0.8994	30.5	28.5	....	27.7
								25	....	21.2718	−0.5909	6	−0.9698	33.0	30.0	....	29.7
							Lower	25	....	......	....	.....	....	....	.....	....	3.7
... (sea ...y, land-...)	Prolarvae	....	....	....	Great Lakes	McCauley (1963)[94]	Upper	15 and 20[m]	....	17.5642	−0.4680	18	−0.9683	34	29	....	28.5

...assumed in this table that the acclimation temperature reported is a true acclimation in the context of Brett
...of median resistance times used for calculating regression equation.
...tion coefficient (perfect fit of all data points to the regression line=1.0).
...ent lethal temperature of Fry, et al., (1946).[83]
...tested shortly after capture by beach seine.
...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	log time=a+b (temp.) a	b	N[b]	r[c]	Data limits (°C) upper	Data limits (°C) lower	LD50	Lethal threshold[d] (°C)
Pimephales (Hyborhynchus) *notatus (bluntnose 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	....	28.0
								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 (fathead 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 ‰)[e]	27.4296	−0.6279	6	−0.9902	42.5	38.5	....	....
								35	(5 ‰)	25.6936	−0.5753	6	−0.9835	42.5	39.0	....	....
								35	(10 ‰)	28.8808	−0.6535	7	−0.9949	42.0	39.0	....	....
								35	(20 ‰)	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)	....
Pseudopleuronectes americanus (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 & Westman (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	0.2344	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 (blacknose dace)	Adult (?)	....	....	....	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 (Blacknose 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]		Raised in soft water									
							Upper	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).[83]

[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.[68]

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		
o gairdnerii (adromous) teelhead out)	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
o 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	....	....		....	....
mo 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	−0.9878	28.0	20.0	....	22.0
mo 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	−0.8689	26.0	22	....	23.3
								20	....	11.5471	−0.3406	3	−0.9143	26.0	22	....	23.5
mo 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	....	....		....	....
mo 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]	....	....		....	....
mo 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]	....	....		....	....
mo trutta (Brown trout)	Newly hatched fry	....	....	Mixed	Cullercoats, North Shields, England (hatchery)	Bishai (1960)[73]	Upper	8 (raised to test temp. over 6 hr period)		12.7756	−0.4010	6	−0.9747	28.0	20.0	....	22.0
mo trutta (Brown trout, sarun)	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
mo trutta (Brown trout, sarun)	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	....	....		....	....
mo trutta (Brown trout, sarun)	Smolts (2 yr.)	About 21 cm ave.	....	Mixed	River Axe, Devon, England	Alabaster (1967)[68]	Uppe	9.3 (field)		18.4667	−0.6667	2[g]	....	....		....	....
								10.9"		33.0000	−1.2500	2	....	....		....	....
velinus fontinalis (Brook trout)	Juvenile	....	....	....	Pleasant Mount Hatchery, Wayne Co., Penna. and Chatsworth Hatchery, Ontario[h]	McCauley (1958)[93]	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).[83]

[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.

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	lower	LD50	Lethal threshold (°C)
Salvelinus fontinalis (brook trout)	Yearling	....	X̄=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	....	24.0
								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	....	[illegible]
								20	....	19.4449	−0.6342	9	−0.9744	28.0	24.5	....	24.0–24.[illegible]
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 erythrophthalamus (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	−0.9844	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	....	[illegible]
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	....	11.3999	−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	....	[illegible]
								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	....	[illegible]
								26	....	14.0458	−0.2800	5	−0.2140	37.92	37.5	....	[illegible]
								28	....	41.1610	−0.9950	4	−0.3107	38.09	37.9	....	[illegible]
								29	....	94.8243	−2.4125	5	−0.7781	38.10	37.0	....	[illegible]
								30	....	41.3233	−1.0018	6	−0.9724	38.50	37.6	....	[illegible]
								32	....	34.0769	−0.8123	4	−0.9209	38.4	37.6	....	[illegible]
								34	....	123.1504	−3.1223	3	−0.9938	38.4	38.2	....	[illegible]
								36	....	68.6764	−1.7094	6	−0.8053	38.77	37.9	....	[illegible]
Tinca tinca (tench)	*Juvenile*	*4.6±0.4 cm*	....	*Mixed*	*England*	Alabaster & Downing[69] (1966)	*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).[71]

[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.[68]

APPENDIX II-C

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APPENDIX C (ALL DATA ARE IN ° C)

FISH TEMPERATURE DATA

Species: Alewife, *Alosa pseudoharengus*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	5		15		5
	10			20	5
	15			23	5
	20			23	5
		*ultimate incipient		32*	2
Lower					

II. Growth:

	larvae	juvenile	adult	
Optimum and [range]				

III. Reproduction:

	optimum	range	month(s)	
Migration	13*(3)	<10(1)-?		1,3
Spawning		16-28(1)	Apr-Aug(5)	1,5
Incubation and hatch	17	11-27		1

*peak run

IV. Preferred:

acclimation temperature	larvae	juvenile	adult	
24			23*	2
31			23*	2
18		20		4
21		22		4

*age unknown

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FISH TEMPERATURE DATA

Species: Atlantic salmon, *Salmo salar*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	5		22*		1
	6	22			1
	10		23*		1
	20		23*		1
	27.5		27.8**		8
Lower					

*30 days after hatch
**ultimate upper incipient temp.

II. Growth:

	larvae	juvenile	adult	reference
Optimum and [range]	10(9)	16-18(4)		4,9

III. Reproduction:

	optimum	range	month(s)	reference
Migration	adults 23 or less,	smolt 10 or less		3
Spawning	4-6(3)	2-10(11)	Oct-Dec(7)	3,7,11
Incubation and hatch		3(3)-11(12)		3,12

IV. Preferred:

acclimation temperature	larvae	juvenile	adult	reference
4	14			2
Summer		17(5)	14-16(6)	5,6
			14	10

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Atlantic salmon

References

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FISH TEMPERATURE DATA

Species: Bigmouth buffalo, *Ictiobus cyprinellus*

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	16-18(6)	14(1)-27(6)	Apr(4)-June(3)	1,3,4,6
Incubation and hatch		14(5)-17(2,5)		2,5

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	
				31-34*	7

*Ictiobus sp. field

[1] References on following page.

Bigmouth buffalo

References

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FISH TEMPERATURE DATA

Species: Black crappie, *Pomoxis nigromaculatus*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	29		33*		2
Lower					

*Ultimate incipient level

II. Growth:	larvae	juvenile	adult	reference
Optimum and		22-25		2
[range]		(11-30)*		2

*Limits of zero growth

III. Reproduction:	optimum	range	month(s)	reference
Migration				
Spawning		14(4)-20(3)	Mar(4)-July(3)	3,4
Incubation and hatch				

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference
	Summer	18-20(5)		24-34(1)	1,5
			27-29*		6

*50% catch/effort

[1] References on following page.

Black crappie

References

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FISH TEMPERATURE DATA

Species: Bluegill, *Lepomis macrochirus*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	15(2), 12(8)		27(8)	31(2)	2,8
	20			32	2
	25(2), 26(8)		36(8)	33(2)	2,8
	30		34		2
	33		37		8
Lower	15(2), 12(8)		3 (8)	3(2)	2,8
	20			5	2
	25(2), 26(8)		10(8)	7(2)	2,8
	30			11	2
	33		15		8

II. Growth:	larvae	juvenile	adult	
Optimum and		30(10)	24-27(3)	3,10
[range]		(22-34)(10)	[16(1)-30(4)]	1,4,10

III. Reproduction:	optimum	range	month(s)	
Migration				
Spawning	25(5)	19(5)-32(6)	Feb(6)-Aug(1)	1,5,6
Incubation and hatch	22-24	22-34		8

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	
	26 Aug(11)		32(9,11)		9,11
	8 Nov		18		11
	3 Feb		16		11
	26 June		31		11
	30 June		32		7

[1] References on following page.

Bluegill

References

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FISH TEMPERATURE DATA

Species: Brook trout, *Salvelinus fontinalis*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	3		23		3
	11		25		3
	12	20*, 25**			2
	15		25		3
	20		25		3
Lower	25		25		3

*Newly hatched
**Swimup

II. Growth:

	larvae	juvenile	adult	reference[1]
Optimum and	12-15(2)		16(1)	1,2
[range]	(7-18)(2)		(10-19)(1)	1,2

III. Reproduction:

	optimum	range	month(s)	reference[1]
Migration				
Spawning	<9(1)	4 (6)-12(1)	Sept-Dec	1,5,6
Incubation and hatch	6	?-13		1

IV. Preferred:

acclimation temperature	larvae	juvenile	adult	reference[1]
6		12		4
24		19		4

[1] References on following page.

Brook trout

References

1. Hokanson, K. E. F., J. H. McCormick, B. R. Jones, and J. H. Tucker. 1973. Thermal requirements for maturation, spawning and embryo survival of the brook trout, *Salvelinus fontinalis* (Mitchill). J. Fish. Res. Bd. Canada. 30(7):975-984.

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FISH TEMPERATURE DATA

Species: Brown bullhead, *Ictalurus nebulosus*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	30		35		5
Lower					

II. Growth:

	larvae	juvenile	adult	
Optimum and [range]				

III. Reproduction:

	optimum	range	month(s)	
Migration				
Spawning		21(4)-?	Mar-Sept(3)	3,4
Incubation and hatch		21(4)-27(3)		3,4

IV. Preferred:

acclimation temperature	larvae	juvenile	adult	
18 May(2)		21(2)	29-31*(1)	1,2
26 July		31		2
23 Sept		27		2
10 Mar		26		2

*final preferendum

[1] References on following page.

Brown bullhead

References

1. Crawshaw, L. I. 1975. Attainment of the final thermal preferendum in brown bullheads acclimated to different temperatures. Comp. Biochem. Physiol. 52:171-173.

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FISH TEMPERATURE DATA

Species: Brown trout, *Salmo trutta*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	20(2)	23(2)		26*(5)	2,5
	23			25**	4
	20			25**	4
	15			25**	4
	10			24**	4
	5			22**	4
Lower					

*approx. ultimate upper incipient lethal
**age unknown

II. Growth:	larvae	juvenile	adult	reference
Optimum and [range]		7-19*		4

*ages 0-IV

III. Reproduction:	optimum	range	month(s)	reference
Migration	6-7			1
Spawning	7-9(11)	1(7)-13(8)	Oct(9)-Jan(10)	7,8,9,10,11
Incubation and hatch	7-12(4)	5(4)-15(3)		3,4

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference
				12-18	6

[1] References on following page.

Brown trout

References

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2. Bishai, H. M. 1960. Upper lethal temperatures for larval salmonids. Jour. du Conseil. 25:129-133.

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FISH TEMPERATURE DATA

Species: Carp, *Cyprinus carpio*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	20		31-34*		3
	26		36*		3
	25-27		40-41		10
			*24 hr. TL_{50}		
Lower					

II. Growth:	larvae	juvenile	adult	reference
Optimum and [range]				
	(16-30)(9)			9

III. Reproduction:	optimum	range	month(s)	reference
Migration				
Spawning	19-23(2)	14(4)-26(2)	Mar-Aug(5)	2,4,5
Incubation and hatch	17-22(7)	?-33(1)		1,7
	Limit for 10 min. exposure of early embryo is 35°			1

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference
	25-35		31-32		6
	Summer			33-35	8
	10		17		6

[1] References on following page.

Carp

References

1. Frank, M. L. 1973. Relative sensitivity of different stages of carp to thermal shock. Thermal Ecology Symposium, May 3-5, 1973, Augusta, Georgia.

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FISH TEMPERATURE DATA

Species: Channel catfish, *Ictalurus punctatus*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	15		30*		2
	25(2) 26(1)		37(1) 34(2)*		1,2
	29	31			3
	30		37		1
	34		38		1
Lower			*88-122 grams		
	15			0	2
	20			3	2
	25			6	2

II. Growth:

	larvae	juvenile	adult	reference
Optimum and	29-30(3)	28-30(8)		3,8
[range]	(27-31)(3)	(26-34)(4)		3,4

III. Reproduction:

	optimum	range	month(s)	reference
Migration				
Spawning	27(5)	21-29(5)	Mar(10)-July(6)	5,6,10
Incubation and hatch		24-28(5)		5

IV. Preferred:

	acclimation temperature	larvae	juvenile	adult	reference
	Summer			30-32*	7
	2 Jan(11)		11(11)	32**(9)	9,11
	22		35		11
	29		35		11

*field
**14-hr. photoperiod

[1] References on following page.

Channel catfish

References

1. Allen, K. O., and K. Strawn. 1968. Heat tolerance of channel catfish, *Ictalurus punctuatus*. Proc. 21st Ann. Conf. S.E. Assoc. Game and Fish Comm., 1967, p. 399-411.

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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
Lower	5		0.2		1
	10		2		1
	15		3		1
	20		5		1
	23		6		1

*Accl. temp. unknown

II. Growth:

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

*unlimited food
**depending upon season

III. Reproduction:

	optimum	range	month(s)	reference
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	reference
Winter			13	4

[1] References on following page.

Coho salmon

References

1. Brett, J. R. 1952. Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. J. Fish. Res. Bd. Canada. 9:265-323.

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FISH TEMPERATURE DATA

Species: Emerald shiner, *Notropis atherinoides*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	5		23		1
	10		27		1
	15		29		1
	20		31		1
	25		31		1
Lower	15		2		1
	20		5		1

II. Growth:	larvae	juvenile	adult	reference[1]
Optimum and		29		2
[range]		(24-31)		2

III. Reproduction:	optimum	range	month(s)	reference[1]
Migration				
Spawning		20(3)-28(5)	May-Aug(1,4)	1,3,4,5
Incubation and hatch				

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference[1]
	Summer		25*		3

*unknown age

[1] References on following page.

Emerald shiner

References

1. Carlander, R. D. 1969. Handbook of Freshwater Fishery Biology, Vol. 1. Life History Data on Freshwater Fishes of the United States and Canada, Exclusive of the Perciformes. Iowa State Univ. Press, Ames, Iowa. 752 p.

2. McCormick, J. H., and C. F. Kleiner. 1976. Growth and survival of young-of-the-year emerald shiners (*Notropis atherinoides*) at different temperatures. J. Fish. Res. Bd. Canada. 33:839-842.

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FISH TEMPERATURE DATA

Species: Fathead minnow, *Pimephales promelas*

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

II. Growth:	larvae	juvenile	adult	reference[1]
Optimum and [range]			23.5-30	1

III. Reproduction:	optimum	range	month(s)	reference[1]
Migration				
Spawning	23.5(1)	18(2)-30(1)	May-Aug(2)	1,2
Incubation and hatch	23-28	23.5-30		1

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference[1]

[1] References on following page.

Fathead minnow

References

1. Brungs, W. A. 1971. Chronic effects of constant elevated temperature on the fahead minnow (*Pimephales promelas* Rafinesque). Trans. Am. Fish. Soc. 100:659-664.

2. Carlson, D. R. 1967. Fathead minnow, *Pimephales promelas* Rafinesque, in the Des Moines River, Boon County, Iowa, and the Skunk River Drainage, Hamilton and Story Counties, Iowa. Iowa State J. Science. 41:363-374.

FISH TEMPERATURE DATA

Species: Freshwater drum, *Aplodinotus grunniens*

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		18-24(4)	May(1)-Aug(3)	1,3,4
Incubation and hatch		22(2)-26(1)		1,2

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	
				29-31*	5
				*Field	

[1] References on following page.

Freshwater drum

References

1. Wrenn, B. B. 1969. Life history aspects of smallmouth buffalo and freshwater drum in Wheeler Reservoir, Alabama. Proc. 22nd Ann. Conf. S.E. Assoc. Game and Fish Comm., 1967. p. 479-495.

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FISH TEMPERATURE DATA

Species: Lake Herring (cisco), *Coregonus artedii*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	2(3), 3(2) 5(3), <10(5)	20(2)	20(3) 22(3)	20(4)* <24(5)	2,3,4 3,5
	>13		26		3
	20		26		3
	25		26		3
			*accl. temp. unknown		
Lower	2		0.3		3
	5		0.5		3
	10		3		3
	20		5		3
	25		10		3

II. Growth:

	larvae	juvenile	adult	reference
Optimum and	16			2
[range]	(13-18)			2

III. Reproduction:

	optimum	range	month(s)	reference
Migration	To spawning grounds at ≃ 5			7
Spawning	3(6,7)	1-5(8)	Nov-Dec(6)	6,7,8
Incubation and hatch	6(1)	2-8(1)	Nov(6)-May(8)	1,6,8

IV. Preferred:

acclimation temperature	larvae	juvenile	adult	reference
			13	6

[1] References on following page.

Lake herring (cisco)

References

1. Colby, P. J., and L. T. Brooke. 1970. Survival and development of the herring (*Coregonus artedii*) eggs at various incubation temperatures. In: Biology of Coregonids, C. C. Lindsay and C. S. Woods, ed. Univ. Manitoba, Winnipeg, Manitoba, Canada. pp. 417-428.

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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

[1] References on following page.

Lake trout

References

1. Edsall, T. A., and W. E. Berlin. 1973. In: Progress in Fishery Research 1973, Eschmeyer, P. H., and J. Kutkuhn, eds. U. S. Fish and Wildlife Service, Great Lakes Fishery Laboratory. Ann Arbor, Michigan.

2. Carlander, K. D. 1969. Handbook of Freshwater Fishery Biology, Vol. 1. Life History Data on Freshwater Fishes of the United States and Canada, Exclusive of the Perciformes. Iowa State Univ. Press, Ames, Iowa. 752 p.

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4. McCauley, R. W., and J. S. Tait. 1970. Preferred temperature of yearling lake trout, *Salvelinus namaycush*. J. Fish. Res. Bd. Canada. 27:1729-1733.

5. Ferguson, R. G. 1958. The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. J. Fish. Res. Bd. Canada. 15:607-624.

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)	
Migration				
Spawning		0.5-10	Sept-Dec	2
Incubation and hatch	3-8			1

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	
				13*	3

*2 year old

[1] References on following page.

Lake whitefish

References

1. Brooke, L. T. 1975. Effect of different constant incubation temperatures on egg survival and embryonic development in lake whitefish (*Coregonus clupeaformis*). Trans. Amer. Fish. Soc. 3:555-559.

2. Carlander, K. D. 1969. Handbook of Freshwater Fishery Biology, Vol. 1. Life History Data on Freshwater Fishes of the United States and Canada, Exclusive of the Perciformes. Iowa State Univ. Press, Ames, Iowa. 752 p.

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FISH TEMPERATURE DATA

Species: Largemouth bass, *Micropterus salmoides*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	20		33		1
	25		35		1
	30		36		1
Lower	20		5		1
	25		7		1
	30		12		1

II. Growth:	larvae	juvenile	adult	reference
Optimum and	27(2)	30(8)		2,8
[range]	(20-30)(2)	(23-31)(8)		2,8
		29(10)	22(11)	10,11

III. Reproduction:	optimum	range	month(s)	reference
Migration				
Spawning	21(4)	16-27(4)	Apr-June(3) Nov-May(4)	3,4
Incubation and hatch	20(5)	13(6)-26(9)		5,6,9

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference
			30-32*		7
			27-28**		7

*Lab., small
**Field, larger

[1] References on following page.

Largemouth bass

References

1. Hart, J. S. 1952. Geographic variations of some physiological and morphological characters in certain freshwater fish. Univ. Toronto, Toronto, Ontario. Biological Series No. 60.

2. Strawn, Kirk. 1961. Growth of largemouth bass fry at various temperatures Trans. Amer. Fish. Soc. 90:334-335.

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6. Kelley, J. W. 1968. Effects of incubation temperature on survival of largemouth bass eggs. Prog. Fish. Cult. 30:159-163.

7. Ferguson, R. G. 1958. The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. J. Fish. Res. Bd. Canada. 15:607-624.

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10. Johnson, M. G., and W. H. Charlton. 1960. Some effects of temperature on metabolism and activity of largemouth bass *Micropterus salmoides* Lacepede. Prog. Fish. Cult. 22:155-163.

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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
Lower					
	18	3*			2

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

*At hatch and free swimming

II. Growth:

	larvae	juvenile	adult	reference[1]
Optimum and [range]	21	26		2
	(18-26)			2

III. Reproduction:

	optimum	range	month(s)	reference[1]
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[1]
		24,26*		6

*Grass pickerel and musky, respectively

[1] References on following page.

Northern Pike

References

1. Scott, D. P. 1964. Thermal resistance of pike (*Esox lucius L.*), muskellunge (*E. masquinongy,* Mitchell), and their F_1 hybrid. J. Fish. Res. Bd. Canada. 21:1043-1049.

2. Hokanson, K. E. F., J. H. McCormick, and B. R. Jones. 1973. Temperature requirements for embryos and larvae of the northern pike, *Esox lucius* (Linnaeus). Trans. Amer. Fish. Soc. 102:89-100.

3. Fabricus, E., and K. J. Gustafson. 1958. Some new observations on the spawning behavior of the pike, *Esox lucius* L. Rep. Inst. Freshwater Res., Drottningholm, Sweden. 39:23-54.

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FISH TEMPERATURE DATA

Species: Pumpkinseed, *Lepomis gibbosus*

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

II. Growth:	larvae	juvenile	adult	
Optimum and			30	1
[range]			15-?	1

III. Reproduction:	optimum	range	month(s)	
Migration				
Spawning		20-29	May-Aug	3
Incubation and hatch				

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	
	19 May		21		2
	24 June		31		2
	26 Sept		33		2
	8 Nov		10		2

[1] References on following page.

Pumpkinseed

References

1. Pessah, E., and P. M. Powles. 1974. Effect of constant temperature on growth rates of pumpkinseed sunfish (*Lepomis gibbosus*). J. Fish. Res. Bd. Canada. 31:1678-1682.

2. Peterson, S. E., R. M. Schtusky, and S. E. Allison. 1974. Temperature preference, avoidance and shock experiments with freshwater fishes and crayfishes. Ichthyological Associates, Inc., Drumore, Pennsylvania. Bulletin 10.

3. Breder, C. M., Jr. 1936. The reproductive habits of the North American sunfishes (family centrarchidae). Zoologica. 21:1-48.

FISH TEMPERATURE DATA

Species: Rainbow smelt, *Osmerus mordax*

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	4-5			1
Spawning		0.6-15	April	2
Incubation and hatch		5-15		3

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	
				6-14	4

[1] References on following page.

References

1. McKenzie, R. A. 1964. Smelt life history and fishery in the Miramichi River, New Brunswick. J. Fish. Res. Bd. Canada, Ottawa, Ontario. Bull. 144. 77 p.

2. Hale, J. G. 1960. Some aspects of the life history of the smelt (*Osmerus mordax*) in Western Lake Superior. Minn. Fish & Game Invest. Fish Ser. 2:25-41.

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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)	6,7,10
Incubation and hatch	5-7(9)	5-13(4)	Feb-June(7)	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.

Rainbow trout

References

1. Alabaster, J. S., and R. L. Welcomme. 1962. Effect of concentration of dissolved oxygen on survival of trout and roach in lethal temperatures. Nature (London). 194(4823):107.

2. Coutant, C. C. 1970. Thermal resistance of adult coho (*Oncorhynchus kisutch*) and jack chinook (*O. tshawytscha*) salmon, and the adult steelhead trout (*Salmo gairdnerii*) from the Columbia River. Atomic Energy Commission, Battelle Northwest Laboratory, Richland, Washington, publication No. 1508, 24 p.

3. Ferguson, R. G. 1958. The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. J. Fish. Res. Bd. Canada. 15:607-624.

4. McAfee, W. R. 1966. Rainbow trout. In: Inland Fisheries Management, A. Calhoun, ed. Calif. Dept. Fish and Game. pp. 192-215.

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FISH TEMPERATURE DATA

Species: Sauger, *Stizostedion canadense*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	10		27		4
	12		27		4
	18		29		4
	22		30		4
	26		30		4
Lower					

II. Growth:	larvae	juvenile	adult	
Optimum and		22		4
[range]		(16-26)		4

III. Reproduction:	optimum	range	month(s)	
Migration				
Spawning	9-15(4)*	6(1)-15(4)	Apr(1)-June(3)	1,3,4
Incubation and hatch	12-15	9-18		4

*for fertilization

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	
				19*	2
				27-29	5

*field

[1] References on following page.

Sauger

References

1. Nelson, W. R. 1968. Reproduction and early life history of sauger, *Stizostedion canadense*, in Lewis and Clark Lake. Trans. Amer. Fish. Soc. 97:159-166.

2. Ferguson, R. G. 1958. The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. J. Fish. Res. Bd. Canada. 15:607-624.

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FISH TEMPERATURE DATA

Species: Smallmouth bass, *Micropterus dolomieui*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper		38*(8)	35(3)		8,3
		*acclimation not given			
Lower	15(3)	4(8)*	2(3)		3,8
	18		4		3
	22		7		3
	26		10		3
		*acclimation temperature not given			

II. Growth:	larvae	juvenile	adult	
Optimum and [range]	28-29(2)	26(3)		2,3

III. Reproduction:	optimum	range	month(s)	
Migration				
Spawning	17-18(5)	13-23(9)	May-June(7)	5,7,9
Incubation and hatch		13-22		10

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	
	Summer			21-27	6
	Winter			>8*(1)-28(4)	1,4
	18&30		23&31 resp.		11
			*juvenile and adult		

[1] References on following page.

Smallmouth bass

References

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FISH TEMPERATURE DATA

Species: Smallmouth buffalo, *Ictiobus bubalus*

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	17(1)-24(5)	14(1)-28(5)	Mar(3)-Sept(5)	1,3,5
Incubation and hatch		14(1)-21(2)		1,2

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	
				31-34*	4

*Ictiobus sp. field

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Smallmouth buffalo

References

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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	reference
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)	reference
Migration		7-16		4
Spawning		7-13	Fall	6
Incubation and hatch				

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference
	Summer		15		3

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Sockeye salmon

References

1. Brett, J. R. 1952. Temperature tolerance in young Pacific salmon, genus, *Oncorhynchus*. J. Fish. Res. Bd. Canada. 9:265-323.

2. Griffiths, J. S., and D. F. Alderdice. 1972. Effects of acclimation and acute temperature experience on the swimming speed of juvenile coho salmon. J. Fish. Res. Bd. Canada. 29:251-264.

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FISH TEMPERATURE DATA

Species: Striped bass, *Morone saxatilis*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	not given		35*	28**	2
Lower					

*Laboratory
**Field observation

II. Growth:

	larvae	juvenile	adult	
Optimum and [range]				

III. Reproduction:

	optimum	range	month(s)	
Migration		6-8		2
Spawning	16-19(2)	12-22(1)	Apr-June(1)	1,2
Incubation and hatch		16-24		1

IV. Preferred:

acclimation temperature		larvae	juvenile	adult	
5	Dec		12		3
14	Nov		22		3
21	Oct		26		3
28	July		28		3

[1] References on following page.

Striped bass

References

1. Shannon, E. H. 1970. Effect of temperature changes upon developing striped bass eggs and fry. Proc. 23rd Conf. S.E. Assoc. Game and Fish Comm., October 19-22, 1969. pp. 265-274.

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FISH TEMPERATURE DATA

Species: Threadfin shad, *Dorosoma petenense*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper					
Lower			9*		1

*lowest permitting some survival

II. Growth:	larvae	juvenile	adult	reference[1]
Optimum and [range]				

III. Reproduction:	optimum	range	month(s)	reference[1]
Migration				
Spawning		14(3)-23(4)	Apr-Aug(4)	3,4
Incubation and hatch		23(4)-34(5)		4,5

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference[1]
				>19	2

[1] References on following page.

Threadfin shad
References

1. Strawn, K. 1963. Resistance of threadfin shad to low temperatures, Proc. 17th Ann. Conf. S.E. Assoc. Game and Fish Comm., 1962. pp. 290-293.

2. Adair, W. D., and D. J. DeMont. 1970. Effects of thermal pollution upon Lake Norman fishes. N. Carolina Wildlife Res. Comm., Div. Inland Fisheries, Raleigh, North Carolina. Summary Report, Fed. Aid Fish Restoration Project F-19-2. 14 p.

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5. Hubbs, C., and C. Bryan. 1974. Maximum incubation temperature of the threadfin shad, *Dorosoma petenense*. Trans. Amer. Fish. Soc. 103:369-371.

FISH TEMPERATURE DATA

Species: Walleye, *Stizostedion vitreum*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	12		29		1
	16		31		1
	22		31		1
Lower	26		31		1

II. Growth:	larvae	juvenile	adult	reference
Optimum and		22(1)	20(6)	1,6
[range]		(16-28)		1

III. Reproduction:	optimum	range	month(s)	reference
Migration		3-7		4
Spawning	6-9(1)*	4(7)-17(5)	Apr-May(4)	1,5,7,4
Incubation and hatch	9-15			1

*for fertilization

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference
				23*	2
			22-25(1)	25(3)*	1,3

*field

[1] References on following page.

Walleye

References

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FISH TEMPERATURE DATA

Species: White bass, *Morone chrysops*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper					
Lower	17	14*			3

*% mortality not given

II. Growth:	larvae	juvenile	adult	reference[1]
Optimum and [range]		24-30		7

III. Reproduction:	optimum	range	month(s)	reference[1]
Migration				
Spawning		14-20 (north)	May-June (north)	4
		12-? (Tenn)	Mar-May (Tenn)	1
Incubation and hatch		16(2)-26(6)		2,6

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference[1]
	Summer			28-30*	5

*Field

[1] References on following page.

White bass

References

1. Webb, J. F., and D. D. Moss. 1967. Spawning behavior and age and growth of white bass in Center Hill reservoir, Tennessee. M.S. Thesis, Tenn. Tech. Univ.

2. Yellayi, R. R. 1972. Ecological life history and population dynamics of white bass, *Morone chrysops* (Rafinesque) in Beaver Reservoir. Part 2. A contribution to the dynamics of white bass, *Morone chrysops* (Rafinesque) population in Beaver Reservoir, Arkansas. Report to Arkansas Game and Fish Commission. Univ. of Arkansas., Fayetteville.

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FISH TEMPERATURE DATA

Species: White crappie, *Pomoxis annularis*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	29		33		4
Lower					

II. Growth:

	larvae	juvenile	adult	reference
Optimum and [range]		25		4

III. Reproduction:

	optimum	range	month(s)	reference
Migration				
Spawning	16-20(5)	14-23(5)	Mar-July(3)	3,5
Incubation and hatch	19	14-23		5
	Hatch in 24-27-1/2 hrs. at 21-23			2

IV. Preferred:

acclimation temperature	larvae	juvenile	adult	reference
27 July(6)		28(6)	28-29(1)	1,6
3 Jan		8		6
5 Mar		10		6
24 June		26		6

[1] References on following page.

White crappie

References

1. Gammon, J. R. 1973. The effect of thermal input on the populations of fish and macroinvertebrates in the Wabash River. Purdue Univ. Water Resources Research Center, Lafayette, Indiana. Tech. Rept. 32. 106 p.

2. Breder, C. M., and D. E. Rosen. 1966. Modes of Reproduction in Fishes. Nat. History Press, Garden City, New York. 941 p.

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4. Kleiner, C. F., and K. E. F. Hokanson. Effects of constant temperature on growth and mortality rates of juvenile white crappie, *Pomoxix annularis* Rafinesque. Unpublished data. U. S. Environmental Protection Agency, Duluth, Minnesota.

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6. Peterson, S. E., R. M. Schutsky, and S. E. Allison. 1974. Temperature preference, avoidance, and shock experiments with freshwater fishes and crayfishes. Ichthyological Associates, Inc., Drumore, Pennsylvania. Bulletin 10.

FISH TEMPERATURE DATA

Species: White perch, *Morone americana*

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		11(3)-20(1)	May-June(3)	1,3
Incubation and hatch				

IV. Preferred:

	acclimation temperature	larvae	juvenile	adult	
	6		10		2
	15		20		2
	20		25		2
	26-30		31-32		2

[1] References on following page.

White perch

References

1. Holsapple, J. G., and L. E. Foster. 1975. Reproduction of white perch in the lower Hudson River. New York Fish and Game J. 22:122-127.

2. Meldrim, J. W., J. J. Gift, and B. R. Petrosky. 1974. Supplementary data on temperature preference and avoidance responses and shock experiments with estuarine fishes and macroinvertebrates. Ichthyological Associates, Inc., Middletown, Delaware. 56 p. mimeo.

3. Sheri, A. N., and G. Power. 1968. Reproduction of white perch, *Roccus americana*, in the bay of Quinte, Lake Ontario. J. Fish. Res. Bd. Canada. 25:2225-2231.

FISH TEMPERATURE DATA

Species: White sucker, *Catostomus commersoni*

I. Lethal threshold:

	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	5		26(2)		2
	10	28(1)*	28(2)		1,2
	15	31(1)	29(2)		1,2
	20(2), 21(1)	30(1)	29(2)		1,2
	25		29		2
	25-26		31		3
Lower		*7-day TL50 for swimup			
	20		2-3		2
	21	6*			1
	25		6		1

*7-day TL50 for swimup

II. Growth:

	larvae	juvenile	adult	reference
Optimum and	27			1
[range]	(24-27)			1

III. Reproduction:

	optimum	range	month(s)	reference
Migration				
Spawning	∿10(5)	∿4-18(5,6)	Mar-June(2)	2,5,6
Incubation and hatch	15	9-20		1

IV. Preferred:

acclimation temperature	larvae	juvenile	adult	reference
			19-21	4

[1] References on following page.

White sucker

References

1. McCormick, J. H., B. R. Jones, and K. E. F. Hokanson. 1976. Temperature effects on embryo development, early growth, and survival of the white sucker, *Catostomus commersoni* (Lacepede). J. Fish. Res. Bd. Canada. In press.

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6. Raney, E. C. 1943. Unusual spawning habitat for the common white sucker *Catostomus c. commersonii*. Copeia. 4:256.

FISH TEMPERATURE DATA

Species: Yellow perch, *Perca flavescens*

I. Lethal threshold:	acclimation temperature	larvae	juvenile	adult	reference[1]
Upper	5			21	1
	10(1), 10(4)	10(4)*		25(1)	1,4
	15(1), 20(4)	19(4)*		28(1)	1,4
	25			32	10
		*swimup			
Lower	25		9		10

II. Growth:	larvae	juvenile	adult	reference
Optimum and		28		11
[range]		(26-30)(11)	[13(6)-20(7)]	6,7,11

III. Reproduction:	optimum	range	month(s)	reference
Migration				
Spawning	12(3)	2(5)-15(3)	Mar-June(3)	3,5
Incubation and hatch	10 up 1°/day to 20	7-20		4

IV. Preferred:	acclimation temperature	larvae	juvenile	adult	reference
	Winter			21(2)	2
	Summer		24		2
	24		20-23	18-20	9
	25		22		8
	7		19		8
	2		20		8

[1] References on following page.

Yellow perch

References

1. Hart, J. S. 1947. Lethal temperature relations of certain fish of the Toronto region. Trans. Roy. Soc. Can., Sec. 5. 41:57-71.

2. Ferguson, R. G. 1958. The preferred temperature of fish and their midsummer distribution in temperate lakes and streams. J. Fish. Res. Bd. Canada. 15:607-624.

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6. Coble, D. W. 1966. Dependence of total annual growth of yellow perch on temperature. J. Fish. Res. Bd. Canada. 23:15-20.

7. Weatherley, A. H. 1963. Thermal stress and interrenal tissue in the perch, *Perca fluviatilus* (Linnaeus). Proc. Zool. Soc., London. 141:527-555.

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10. Hart, J. S. 1952. Geographic variations of some physiological and morphological characters in certain freshwater fish. Univ. Toronto, Toronto, Ontario. Biology Series No. 60. 78 p.

11. McCormick, J. H. 1976. Temperature effects on growth of young yellow perch, *Perca flavescens* (Mitchell). U. S. Environmental Protection Agency, Duluth, Minnesota. Report EPA-600/3-76-057.

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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	Water Quality Criteria	06 S
Fresh Water Fishes	Water Quality Standards	06 F
Growth	Temperature Requirements	06 C
Reproduction (biology)	Thermal Pollution	
Mortality		
Water Pollution		

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