Temperature Tolerance of Young-of-the-Year Cisco, *Coregonus artedii*[1]

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ABSTRACT

Young-of-the-year ciscoes (*Coregonus artedii*) acclimated to 2, 5, 10, 20, and 25 C and tested for tolerance to high and low temperatures provide the first detailed description of the thermal tolerance of coregonids in North America. The upper ultimate lethal temperature of the young ciscoes was 26 C (6 C higher than the maximum sustained temperature tolerated by adult ciscoes in nature) and the ultimate lower lethal temperature approached 0 C (near that commonly tolerated in nature by adult ciscoes).

The temperature of 26 C is slightly higher than the lowest ultimate upper lethal temperature recorded for North American freshwater fishes; however, published information on the depth distributions of fishes in the Great Lakes suggests that some of the other coregonids may be less tolerant of high temperatures than the cisco.

INTRODUCTION

The present paper is a contribution to a continuing study of the environmental requirements of the cisco, *Coregonus artedii*, an important food and forage fish in the Great Lakes area. Although considerable information is available on the biology of the cisco, no laboratory studies have been published on the temperature tolerance of the cisco or of any other North American coregonid.

MATERIALS AND METHODS

The fish used in the present study were hatched from eggs stripped from spawning adults captured in Pickerel Lake, Washtenaw County, Michigan, on December 1, 1967. The eggs were held in flowing water at 6 C until they hatched on February 19–23. The larvae were transferred to rearing troughs where the temperature was raised slowly until it reached 10 C early in March.

The larvae grew rapidly and reached the juvenile stage by the end of April. They were then divided into six groups and transferred to 130-liter fiber glass acclimation tanks at 10 C. One acclimation tank was held at 10 C; the temperatures in the other five tanks were increased or decreased at a rate of 1 C per day until the desired final acclimation temperature (2, 5, 15,[2] 20, or 25 C) was reached.

Although information on the rate of gain or loss of heat tolerance is lacking for coregonids, other Salmonidae have readily tolerated temperature changes of 1 C or more per day. To ensure that the ciscoes were fully acclimated, testing was delayed after attainment of final acclimation temperatures for an additional 3 weeks for the fish at 25 C, 2 weeks for those at 20 C, 4 weeks for the fish at 5 C, and 8 weeks for those at 2 C. The fish were held longer at 2 and 5 C because heat tolerance in most fishes is lost more slowly than it is gained (Brett, 1956). Although the fish in the 10 C acclimation tank experienced no temperature change after transfer from the rearing trough, they were held for 2 weeks before testing to allow for adjustment to the new environment.

A water flow of 1–2 liters per minute was maintained through each acclimation tank and temperature was controlled to ± 0.1 C after the final acclimation temperatures were reached. Photoperiod was controlled automatically and light intensity was adjusted manually with a rheostat. The light level was lowered shortly before the lights went off at 9 PM and was raised several minutes after the lights came on at 6 AM. Fish were

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[2] No data are given on the temperature tolerance of fish acclimated to 15 C because a disease killed nearly the entire group before they could be used in tests.

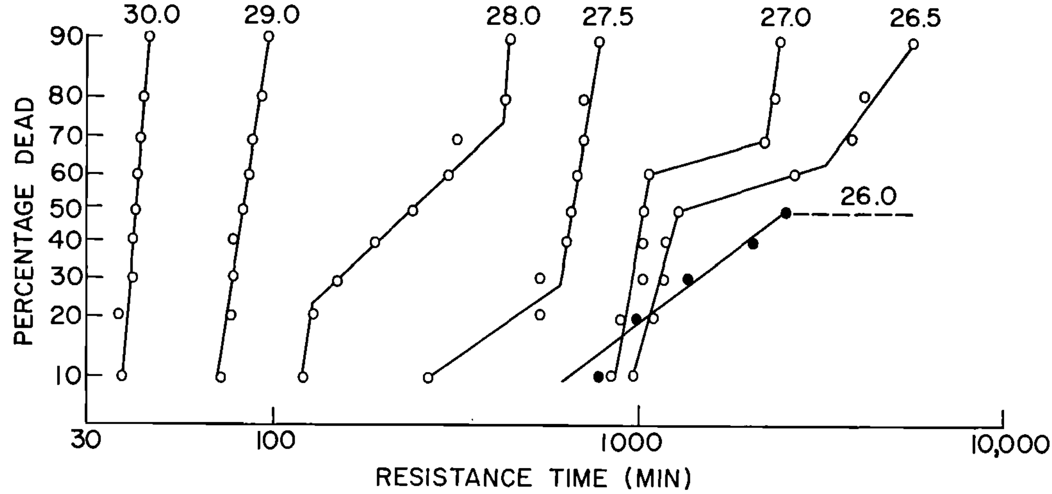

FIGURE 1.—Resistance times of young-of-the-year ciscoes acclimated to 25 C and exposed to various lethal temperatures from 26.0 to 30.0 C. At 26.0 C (data indicated by solid dots) only 50% of the test group died in 10,000 minutes.

shielded from direct light by translucent fiberglas covers on the tanks.

A chronic, low mortality accounted for 5.7% of the test population in the acclimation tanks during the study. Most of the fish that died were severely emaciated and did not feed. No emaciated fish were used in tests for lethal temperatures.

Tests to determine lethal temperature were conducted in rectangular 5-liter polyethylene baths. Temperature was controlled to ± 0.1 C and the water flow was maintained at about 0.1 liter per minute through each bath.

The procedure for testing the temperature tolerance of the ciscoes was essentially that used by Brett (1952) in his study of young Pacific salmon. Ciscoes that had been acclimated to one temperature were taken from their acclimation tank and distributed in groups of 10 among the experimental baths. Temperatures in the baths were higher or lower than that in the acclimation tank and were selected on the basis of preliminary testing to cover a range that would cause rapid, complete mortality in some groups and slow and possibly incomplete mortality in others; temperatures were tested at 0.5 or 1.0 C intervals within this range. Fish in baths were observed continually and records were kept of the resistance time (time to death) of each fish. Fish were considered dead at high temperatures when spontaneous activity ceased and the fish did not respond to strong mechanical stimulation with a glass rod; none of these fish recovered when returned to their acclimation temperature. At low temperatures fish approaching death lost equilibrium and entered a prolonged coma in which activity and response to mechanical stimulation ceased; these fish could often be revived by returning them to their previous acclimation temperature. A slight but permanent flaring of the opercula of commatose fish, however, marked the point at which fish could be pronounced dead.

Fish that died during the experiment and those that survived an exposure of 10,000 minutes (1 week) were removed from the experimental baths and measured (total length in millimeters). The 600 fish used in testing ranged from 38 to 61 mm long and averaged 48.0 mm (S.D., 4.12).

Water in the acclimation tanks was analyzed weekly for dissolved oxygen, pH, alkalinity, ammonia, nitrites, and nitrates. Heavy metals and total hardness were measured at the beginning and end of the study. Dissolved oxygen and pH were measured in the lethal-

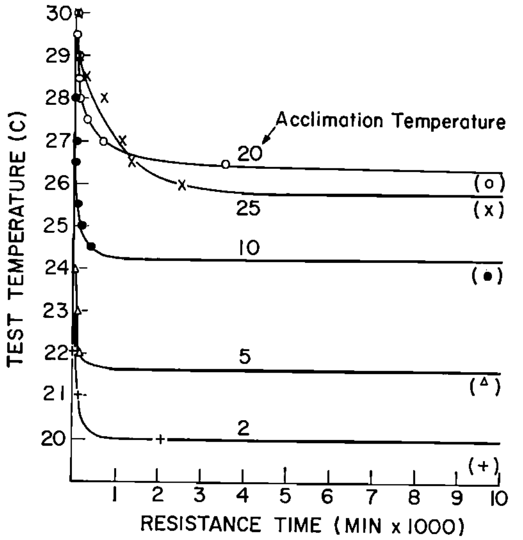

FIGURE 2.—Median resistance times of young-of-the-year ciscoes acclimated to various temperatures from 2 to 25 C. In parentheses, test groups that had less than 50% mortality; see text for explanation.

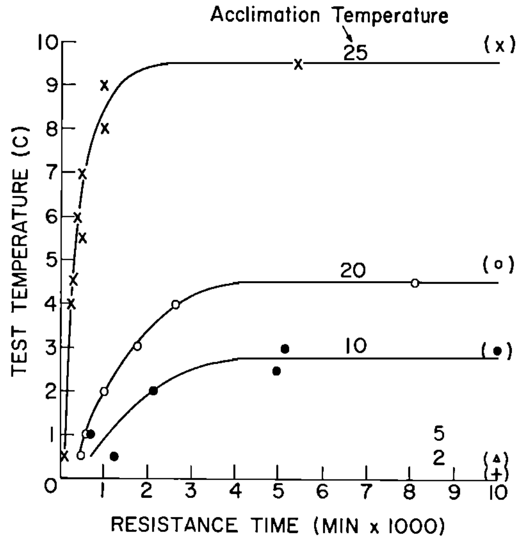

FIGURE 3.—Median resistance times of young-of-the-year ciscoes acclimated to various temperatures from 2 to 25 C. In parentheses, test groups that had less than 50% mortality; see text for explanation.

temperature baths at the beginning and end of each bioassay. Dissolved oxygen varied from 8.8 to 12.5 mg/l in the acclimation tanks and from 6.0 to 9.1 mg/l in the baths. Alkalinity in the water entering the acclimation tanks and baths was 212–242 mg/l, total hardness ($CaCO_3$) was 245–355 mg/l, and pH was 7.8–8.1. Heavy metals and metabolites did not reach concentrations normally considered to be deleterious to fish.

MORTALITY CURVES

The mortality data were analyzed by the method of Fry, Hart, and Walker (1946). Resistance times of individual fish in each test group were plotted on semilog-probability paper as accumulated percentage dead, and the median resistance time for the test group was then determined graphically. Examples of typical mortality curves for ciscoes are plotted in Figure 1.

Temperatures that were rapidly lethal for ciscoes produced simple mortality curves that were described by single straight lines, whereas test temperatures that were less rapidly lethal yielded more complex curves that were best described by a sequence of two or more straight lines (Figure 1). The mortality curves of Figure 1 are typical of those commonly reported for other fishes and invertebrates (see Tyler, 1966, for a review). The specific mechanisms for death in the various stanzas of mortality curves of fishes and invertebrates are almost unknown, but Bliss (1939) has attributed complex mortality curves similar to those in Figure 1 to the effects of multiple overlapping lethal factors.

LETHAL TEMPERATURES

The curves of Figures 2 and 3 show the relations among acclimation temperature, lethal temperature, and median resistance time; they are similar to those published for other fishes. Much of the curve for fish acclimated to 25 C fell below that for fish acclimated at 20 C (Figure 2), probably because 25 C was so close to the ultimate upper lethal temperature ("the temperature beyond which no increase in lethal temperature results from further increase in acclimation temperature"—Fry, Hart, and Walker, 1946) that these fish had partly exhausted their temperature resistance before they were placed in the experimental containers. Because it has been shown that the rate of dying in temperatures above the upper lethal temperature can be

TABLE 1.—*Effect of acclimation on upper and lower incipient lethal temperatures for the cisco,* Coregonus artedii

Lethal temperatures	Acclimation temperatures (C)				
	2	5	10	20	25
Upper	19.75	21.75	24.25	26.25	25.75
Lower	<0.3	<0.5	3.0	4.75	9.75

ascribed to the additive effect of previous thermal experience undergone at each temperature (Fry, Hart, and Walker, 1946), these data should provide a reliable estimate of the ultimate upper lethal temperature.

The "incipient" lethal temperature—the test temperature that kills exactly 50% of the test population during unlimited exposure (Fry, Hart, and Walker, 1946)—corresponds to the test temperatures at which the curves of Figures 2 and 3 level off and resistance times become unlimited. In the present study the incipient lethal temperature was defined as that temperature falling midway between the test temperature that killed 50% or more of a test group of 10 ciscoes in 10,000 minutes and a second test temperature that was 0.5 C closer to the acclimation temperature and killed less than 50% of a second test group of ciscoes in 10,000 minutes. For example, the incipient upper lethal temperature for fish acclimated at 10 C (Figure 2) was considered to be 24.25 C (Table 1), which is midway between 24.5 C (the lowest temperature at which 50% or more of a test group died) and 24.0 C (the temperature 0.5 C lower at which less than 50% of the test group died after 10,000 minutes of exposure).

The incipient upper lethal temperatures for ciscoes varied directly with the acclimation temperatures of 2, 5, and 10 C (Table 1, Figure 4); increasing 0.6 C for each 1.0 C elevation of acclimation temperature. According to the curve of Figure 4, increasing the acclimation temperature above 12.5 C yielded no further increase in heat tolerance and the ultimate upper lethal temperature is 26.0 C.

The ultimate upper lethal temperature for young-of-the-year ciscoes is similar to that reported by Brett (1952) for coho salmon, *Oncorhynchus kisutch* (25.0 C) and chinook salmon, *O. tshawytscha* (25.1 C), and by Fry, Hart, and Walker (1946) for brook trout, *Salvelinus fontinalis* (25.3 C), and is among

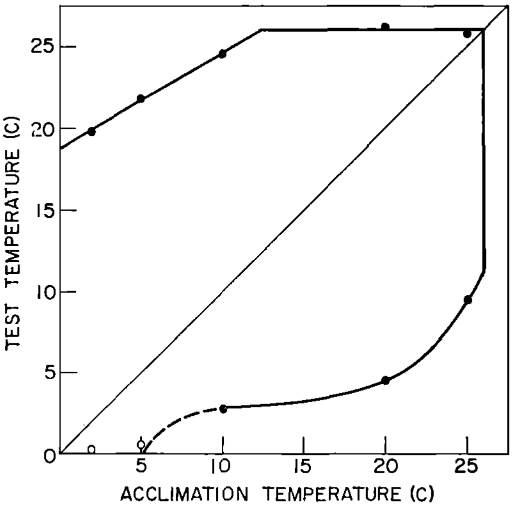

FIGURE 4.—Thermal tolerance of young-of-the-year ciscoes. Open circles indicate lowest temperature tested; see text for explanation.

the lowest recorded for North American fishes.

The effect of acclimation is much more complex for lower lethal temperature than for upper lethal temperature (Table 1, Figures 3 and 4). Ciscoes acclimated to 20 and 25 C had incipient lower lethal temperatures of 4.75 and 9.75 C, respectively, an average tolerance increase of 1.0 C for each 1.0 C decrease in acclimation temperature. Fish acclimated to 10 C had an incipient lower lethal temperature of 3.0 C and the average rate of gain in cold tolerance between 20 and 10 C was 0.2 C for each 1.0 C decrease in acclimation temperature. Difficulties in holding the test bath temperature constant (± 0.1 C) below 0.3 C prevented exact determination of the lower lethal temperature for ciscoes acclimated to 2 and 5 C. When these fish were exposed to temperatures of 0.3 and 0.5 C, respectively, less than 50% died in 10,000 minutes, suggesting that the ultimate lower lethal temperature for ciscoes acclimated to temperatures of 5 C and lower is nearly 0 C, as is common among fishes of the more northerly parts of North America (Brett, 1960).

EFFECTS OF AGE AND SIZE ON TEMPERATURE TOLERANCE

Our findings agree well with those of Fry (1937) and Kennedy (1941), who found that young coregonids in nature are more tolerant of high temperature than are adults. The maximum sustained temperature tolerated by adult ciscoes in nature appears to be about 20 C (Frey, 1955; Colby and Brooke, 1969), or 6 C lower than that for young-of-the-year fish in the present study. No information is available on the ultimate lower lethal temperature of young-of-the-year coregonids in nature, but our findings suggest that they can tolerate 0 C, which is the same temperature commonly tolerated by adult ciscoes (Frey, 1955).

The fish in our experiment were all of the same age, but the larger fish tended to survive longer at upper and lower lethal temperatures than did the smaller fish. In tests where mortality was less than 100%, a t-test comparing the mean length of the dead fish with that of the survivors indicated a highly significant difference ($P = 0.005$) at upper and lower lethal temperatures. In other tests where mortality was 100%, the regression of fish length on order of death (a measure of resistance time) also indicated that the larger fish tended to survive longer but the slope of the regression was significant ($P = 0.05$) only at lower lethal temperatures. The relation between fish length and order of death at upper and lower lethal temperatures, respectively, was $Y = 3.5693 + 0.0405\ X$ and $Y = -2.2739 + 0.1608\ X$, where Y = order of death from 1 through 10, X = fish length in millimeters, 3.5693 and –2.2739 are the Y-intercepts, and 0.0405 and 0.1608 are the slopes. Greater resistance of the larger members of an age group to lower, but not upper lethal temperatures, was also found by Brett (1952) for *Oncorhynchus*. A greater vitality of the larger, faster growing individuals of a population is to be expected, but no explanation can be given for the longer survival times of the larger fish at the lower, but not the upper lethal temperatures.

THERMAL TOLERANCE

Considerable information is available on the thermal tolerance[3] of fishes (see Brett, 1956, for a review); most is for eurythermal, warm-water species, but two detailed studies have been published for the Salmonidae. The young of Pacific salmon (*Oncorhynchus*) from fresh water have the lowest thermal tolerance (529–468 units) of the North American freshwater fishes studied (Brett, 1952). The thermal tolerance of the cisco (541 units, Figure 4) is slightly greater than the maximum reported for *Oncorhynchus* but is considerably lower than that for brook trout (625 units; Fry, Hart, and Walker, 1946), the only other salmonid for which a tolerance trapezium has been described. All available information on the thermal tolerance of the cisco and on the depth distributions of the cisco and other Great Lakes coregonids (Wells, 1968; Dryer, 1966; Smith, 1956) suggest that the temperature tolerances of some of these other coregonids are lower than that of the cisco and indeed may be the lowest for North American Salmonidae.

TEMPERATURE AND GEOGRAPHICAL DISTRIBUTION

Although little doubt exists that temperature is one of the most important factors limiting survival and geographical distribution of fishes (Brett, 1956), it has been difficult to demonstrate that thermal tolerance is actually restricting geographical distribution, because species in their native ranges are usually living well within the limits of the thermal tolerances (Brett, 1960). Frey (1955) and more recently Colby and Brooke (1969) have shown that the cisco, a cold stenotherm and glacial relict is clearly an exception, at the southernmost extension of its native range. Our study, supported by those of Fry (1937), Kennedy (1941), and Colby and Brooke (1969), confirms the finding of Frey (1955) that the southernmost extension of the range of the cisco is not limited by the ultimate upper lethal temperature of the young fish.

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[3] The thermal tolerance is the sum of the tolerance units enclosed within the trapezium formed by the upper and lower lethal temperatures (as in Figure 4); the unit of tolerance is equal to the area bounded by 1 C and expressed as degrees centigrade squared (Brett, 1956).

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