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REPORT SUMMARY

This report presents the results of a literature review of upper lethal thermal limits for freshwater fishes that potentially occur in thermal discharges. The review focuses on the quality of the database that is available to derive thermal criteria and evaluates factors that affect endpoint estimates. The thermal database was evaluated for three thermal guilds of freshwater fish—coldwater species (primarily salmonids), coolwater species (esocids and some percids), and warmwater species. This report will be of value to electric power company environmental staff and government regulators.

Background

Several states have reviewed or are in the process of reviewing their thermal standards, and electric power companies and others with thermal discharges have recently been required to prepare revised Section 316(a) demonstrations in accordance with the terms of the Clean Water Act. Setting state, regional, or site-specific thermal standards is problematic because although well-established procedures are in place for deriving criteria for most water quality parameters, clear guidance has not been established for deriving temperature criteria. This literature review updates earlier compilations in response to this recent regulatory activity.

Objectives

- To critically review the scientific foundation of the thermal toxicity literature and to evaluate its applicability for establishing thermal standards
- To provide guidance and recommendations regarding how to evaluate and standardize thermal endpoint data to support derivation of technically sound thermal criteria

Approach

The selection of species and species groups was based on whether they were near the sensitive end of the thermal tolerance range for coldwater, coolwater, and warmwater guilds. The size of the geographic area occupied by species and the type of habitat in which species occur was considered so that preference was given to widely distributed species, rather than local species. Selection also favored species likely to be encountered near power plant sites as opposed to fishes restricted to small streams or springs. The report reviews upper temperature tolerances of fishes, in the laboratory, based on the Fry or incipient lethal temperature (ILT) method, as well as the critical thermal maximum (CTM) and chronic lethal maximum (CLM) methodologies.

Results

- Thermal toxicity data representing primarily Upper ILT (UILT) and CTM endpoints were reviewed for eleven salmonids, five coolwater species representing pikes and large percids, and twenty warmwater species including eight cyprinids, four catostomids, two ictalurids, three centrarchids, and three darter species.

- Coldwater species had the lowest upper endpoints, and salmonids had very similar endpoint estimates, usually around 25°C for UILTs and 29 to 30°C for CTMs. The endpoints for coolwater species overlapped rather broadly with those for warmwater species, indicating the coolwater guild is largely artificial and certainly not rigorously defined by temperature tolerance.
- Among warmwater species, all ictalurids, centrarchids, and most cyprinids and darters are fairly tolerant. Within the warmwater guild, some of the more thermally sensitive species include northern hog sucker, redhorse, and especially white sucker, which has a UILT of about 30°C.
- There are inherent differences in the endpoints estimated by the CTM and ILT methods (UILT values are usually about 5°C lower than CTM estimates for the same species) that make it important that endpoints be adjusted or standardized when used to develop thermal criteria to make the different estimates comparable.
- It was found that acclimation temperature greatly affects upper endpoint estimates, and for warmwater species these estimates can vary by 10°C or more depending on acclimation temperature; thus adjustments or standardization of data is necessary before they are used to develop temperature criteria.

Applications, Value, and Use

This report provides thermal toxicity endpoints for various fish species and discusses methods for development of those endpoints for fish species that commonly occur near freshwater power plants and are potentially exposed to thermal discharges. In addition to summarizing thermal endpoints from the literature, the applicability of available endpoints for use in developing thermal criteria by regulatory agencies is discussed. Suggestions regarding laboratory methods, acclimation temperatures, and sample size are made for determining whether existing endpoints should be used to develop thermal criteria. The report provides a focused review of available thermal tolerance data, their development, and their application to establishing thermal criteria. It is important to note that none of the laboratory methods accurately reproduces what happens in the field where fish are exposed to spatially and temporally varying thermal fields and have the ability to select specific locations. Frequently, fish are observed where laboratory experiments predict they cannot survive. Modern tagging and telemetry technologies allow design of field experiments where fish behavior in response to thermal plumes can be studied in real time. EPRI is currently planning to conduct such experiments to resolve discrepancies between laboratory experimental results and field observations.

Keywords

Fish
Clean Water Act Section 316(a)
Critical thermal maximum (CTM)
Incipient lethal temperature (ILT)
Thermal discharges
Thermal tolerance

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1
INTRODUCTION

Several states including Colorado, Illinois, Pennsylvania, and Wisconsin have either recently reviewed or are in the process of reviewing their thermal standards and the Ohio River Valley Sanitary Commission (ORSANCO) also recently completed a thermal review for the Ohio River. Similarly, utilities and others (e.g., the British Petroleum Refinery in Whiting, Indiana) have recently been required to prepare revised §316(a) demonstrations. Setting state, regional, or site-specific thermal standards is problematic because although well established procedures are in place for deriving criteria for most water quality parameters (US EPA 1985), clear guidance has not been established for deriving temperature criteria.

Although the manner in which thermal standards have or will be developed will differ among states and other regulatory agencies, the “raw material” for developing standards will be thermal endpoint data. Most of these will be acute endpoints calculated from either the traditional experimental procedure for deriving upper (and lower) incipient lethal values (Fry 1947, 1967) or the procedure for developing critical thermal maxima (Hutchinson 1961, Becker and Galloway 1979, and Paladino et al. 1980).

In contrast to other water quality parameters, most of which had criteria documents developed by US EPA in the 1980s and 1990s and whose databases underwent a quality review as part of the development process, no such data compilation or quality control review has been done for temperature. Thus, poor quality temperature data has found its way into the existing databases.

The objective of this review is to critically review the scientific foundation of the thermal toxicity literature and to evaluate its applicability for establishing thermal standards. Relatively little endpoint data were found for marine species so this review concentrated on freshwater species. Also, little data were available on invertebrates (e.g., crayfish, mussels, and aquatic insects), so the review concentrated on fish. To make the results broadly applicable and ecologically relevant, the original plan was to divide the freshwater dataset into three groups (coldwater, coolwater, and warmwater) based on each species’ thermal preference. It soon became clear, however, that the coolwater group is poorly defined and little variation occurs among endpoints for coldwater species, most of which are salmonids. Nonetheless, this review does include reviews for the three categories.

Using existing literature reviews and data compilations (Brown 1976, Brungs and Jones 1977, Talmage and Opresko 1981, Wismer and Christie 1987, Smale and Rabeni 1995, and Beitinger et al. 2000) as well as searches of the literature from 1995 through 2010, a group of 400 or so titles was considered. Based on each title and the species tested, this initial list was reduced to about 60 papers. Each of these papers was reviewed and appropriate information extracted. In some cases, the selected papers did not provide usable information.

It is important to understand that this document is not a review of the entire voluminous thermal literature database. Instead, a critical review of species or species groups at the sensitive end of the thermal tolerance spectrum was conducted and included species that were approximately in the most sensitive 10 percent for each of the three temperature categories. Emphasis at the sensitive end of the spectrum was selected because in most cases, water quality standards, including those for temperature, are based on protecting sensitive species. Thus, sensitive species are given extra weight. For example, US EPA's procedure for deriving water quality standards for most toxicants is based primarily on the four most sensitive species with the remaining species having little effect on the resultant standard (US EPA 1985). Some methodologies for deriving thermal standards only use the most thermally sensitive species (Yoder and Emery 2004, Yoder 2008). Given that criteria are usually based on thermally sensitive species, it was decided to concentrate on such species. As a result, we purposely did not review papers on thermally tolerant species such as common carp (*Cyprinus carpio*), bluegill (*Lepomis macrochirus*), largemouth bass (*Micropertus salmoides*), channel catfish (*Ictalurus punctatus*), and gizzard shad (*Dorosoma cepedianum*). The thermally sensitive species we considered are discussed in Section 3.

2

ISSUES AFFECTING THERMAL ENDPOINTS

Upon reviewing the literature, it became apparent that there were several issues that were important regardless of the species tested. These issues are particularly important for determination of short-term (acute) endpoints, but some are broadly applicable to all thermal endpoint determinations. These generic issues are discussed below.

2.1 Methods to Determine Acute Thermal Endpoints

Upper (and lower) temperature tolerances of fishes have been quantified in the laboratory via three different experimental approaches: the Fry or incipient lethal temperature (ILT) method, critical thermal maximum (CTM), and chronic lethal maximum (CLM) methodologies. Although these three laboratory approaches generate endpoints that are (1) quantitatively expressed as a temperature, (2) determined experimentally with random samples of fish acclimated to specific temperatures, and (3) involve both time and temperature as major test variables, they do not quantify the same response (Beitinger et al. 2000). Thus, endpoints can vary by as much as 5°C for the same species tested at the same acclimation temperature (Beitinger et al. 2000, Wagner et al. 2001). In the ILT method, a temperature lethal to 50 percent of a fish sample is determined by plunging groups of fish from a specific acclimation temperature into a series of constant test temperatures near the estimated upper (or lower) temperature limits of a species (Fry 1947). For this review, we deal exclusively with upper temperature maximums, which are referred to as the upper incipient lethal temperature (UILT). In this report, the term ILT refers to the test methodology and UILT is the upper (=U) endpoint estimate. In ILT tests, mortality is the endpoint and is recorded over time. An estimate of the temperature tolerated by 50 percent of a sample for various exposure time intervals, usually 4-7 days, is made from a regression of percentage mortality on test temperature. Although this method requires a considerable number of test organisms (typically at least 30-50), it was the method of choice through at least the 1960s.

The critical thermal methodology or maximum (CTM) has replaced the ILT as the method of choice since about 1990. This preference for CTM appears to have less to do with any scientific superiority associated with the CTM but more because fewer test organisms and less time are needed to conduct CTM tests. In fact, a CTM can be (and has been) generated from a single fish. In this methodology, individual fish are heated at a constant rate (0.3°C/min is a commonly recommended rate, Becker and Genoway 1979) until physical disorganization (e.g., loss of equilibrium or onset of muscle spasms) occurs. The value reported is usually the arithmetic mean of individual tests. Also, the CTM requires less investigator effort than the ILT method. Once the acclimation period is over, an ILT test typically takes several days because the resistance time (i.e., time to death) of each test fish needs to be measured whereas the CTM test takes only an hour or two, depending on the rate of heating. Kilgour and McCauley (1986) developed a formula that can be used to estimate CTM values from ILT values and vice versa.

To obtain an accurate estimate of the CTM, the rate of temperature change must be slow enough so that a fish's core temperature does not significantly lag behind water temperatures, and rapid enough so test fish do not have time to thermally re-acclimate during a trial. If the rate of temperature change is either too rapid or too slow, the measured CTM values will be biased towards higher temperatures. In practice, some acclimation is likely to occur during most CTM tests unless the heating rate is extremely rapid or the acclimation temperature is close to the upper lethal temperature.

Neither method is particularly representative of conditions that are likely to be encountered in the field. In the case of the ILT method, fish are plunged directly from their acclimation temperature into a series of constant test temperatures. The temperature differential (ΔT) associated with this might be as much as 20 to 25°C. Although a few power plant discharges can generate ΔTs of this order, it is difficult to imagine a fish swimming from ambient temperatures of say 10°C into a plume (perhaps to grab a prey item) with a centerline temperature of 30 or 35°C and remaining there for more than a few minutes. For the CTM method, test fish are heated at a constant rate. The rate most commonly used is 0.3°C/min (18°C /hr). Again, it is difficult to imagine a fish staying in an area for an hour during which the temperature increases by 18°C.

To address some of the issues associated with the ILT and CTM methods, a relatively new method has emerged, referred to as either the chronic lethal method (CLM) or the slow heating method. Note, however, that the traditional CTM method is sometimes also referred to as the slow heating method because the heating rate is slow relative to the ILT method. In the CLM, test fish are exposed to very slow increases (usually about 1°C/day) or decreases until mortality occurs. This slow rate of change allows organisms to acclimate to each succeeding higher or lower temperature. Thus, in theory, the endpoint should approximate the ultimate upper ILT (UUILT), which is the highest temperature an organism can withstand regardless of acclimation temperature. The rate of temperature change during the CLM method likely approximates changes that temperate fishes go through on a daily basis each season and therefore appears to provide more realistic estimates of upper (and lower) temperatures. The principal drawback of the CLM method is that, depending on acclimation temperature, each test might take up to three weeks to complete. Likely for this reason, it is the least frequently used method but it has been occasionally applied (Fields et al. 1987, Currie et al. 1998, and Reash et al. 2000).

Based on a review of several papers, Beitinger et al. (2000) concluded that for the same acclimation temperature, the ILT method yielded the lowest estimate for upper lethal temperatures, the CTM method yielded the highest estimates, and the CLM yielded intermediate endpoints.

With regard to criterion development, it is important to remember that the endpoint temperatures used in the derivation procedure will depend on what test method was used to derive the endpoint estimates. As discussed in Sections 4 and 5, normalization of endpoints derived by the different methods is important.

2.2 Acclimation Temperature

Aside from possibly the test methodology as discussed above, the most important factor affecting temperature tolerance is acclimation temperature (Beitinger et al. 2000). For those species tested over a wide range of acclimation temperatures, a 10°C or greater change in the upper lethal temperature has been observed for some species. If CTM temperatures are plotted against acclimation temperatures, the slope of that line represents the relationship between these two factors. This relationship is linear for most species (Bietinger et al. 2000). The slope represents how much the upper thermal maximum changes for each degree change in acclimation temperature. Bietinger et al. (2000) reported that the average slope for 20 species ranged from 0.27 to 0.50 with a mean of 0.41. In other words, the upper lethal limit changes by 4°C for each 10°C change in acclimation temperature. This means that regulatory limits developed from endpoints based on fish acclimated to temperatures well below their upper temperature limit, regardless of how that limit is measured, will be overly restrictive because the temperature tolerance of such fish will be underestimated. Also, in some cases, values reported as CTMs were not derived using standard CTM methodologies. For example, Reutter and Herdendorf (1975, 1976) reported CTMs for 33 species of freshwater fish. However, their test methodology consisted of taking fish collected at ambient temperatures, transferring them to a test tank maintained at 11°C above ambient to mimic the ΔT from the Davis-Besse Power Plant, keeping them at this temperature for one hour, then increasing that temperature to establish the CTM. Thus, the first portion of the test follows standard ILT protocols by taking fish from an acclimation temperature and plunging them into a water bath at a pre-established temperature. The second half of the test more or less followed standard CTM protocols except that heating was at a rate much slower than often recommended (Becker and Genoway 1979), thus allowing some acclimation during the test (Beitinger et al. 2000). Further complicating matters was that different rates of heating were used for practically every test (Reutter and Herdendorf 1975). Further discussion of the Reutter and Herdendorf (1975, 1976) results are provided in Section 3.3.7.

2.3 CTM Endpoints

In Section 2.1, it was noted that there are three methodologies to derive acute thermal endpoints, one of those methods being the CTM. The CTM has been defined as *"the arithmetic mean of the collective thermal points at which locomotory activity becomes disorganized and the animal loses its ability to escape from conditions that will promptly lead to its death when heated (or cooled) from, a previous acclimation temperature at a constant rate just fast enough to allow deep body temperature to follow environmental test temperatures without a significant time lag"* (Cox 1974). Note that exact criteria for identifying the point of locomotory disorganization are not specified. The most commonly used endpoint is loss of equilibrium; however, other endpoints are often used such as the onset of muscle spasms (Matthews and Maness 1979), flaring of the operculars (Middaugh et al. 1975), non-reaction to prodding with a glass rod (Heath et al. 1994), cessation of opercular movements (Bettoli et al. 1985), and even combinations of the above (Hassam and Spotila 1976).

Thus, the CTM value at a particular acclimation temperature for a particular species reported by one group of researchers might differ from that reported by a different group of researchers simply because they were using different CTM endpoints.

2.4 Minimum Number of Fish to be Tested

Because the ILT methodology is based on transferring fish from an acclimation temperature to a series of test temperatures and multiple organisms are needed to establish resistance times (i.e., time to death) at each test temperature, a moderate number of test animals is required. However, for the CTM method, an estimate of the endpoint is established for each organism tested. Thus, a

CTM can be established based on testing one organism. A review of two related studies indicates that endpoints based on only a few test organisms can be common. As part of an effort to assess possible thermal impacts from the David-Besse Power Plant, Reuter and Herdendorf (1975, 1976) calculated CTMs for 33 freshwater fishes. They conducted tests under various seasonal regimes and reported the highest CTM for each species (Reutter and Herdendorf 1976). Of the 33 species tested, 17 CTMs reported were based on testing a single fish, and most of the rest were based on testing two to three individuals per species. In Section 5, we provide guidance regarding the minimum number of fish that should be used to establish CTM endpoints.

3
RESULTS

Based on the literature review, a number of species or species groups in each of three categories of fishes (i.e., coldwater, coolwater, and warmwater) were established for detailed review. As discussed in Section 2, the main criterion for selecting species or species groups was whether they were near the sensitive end of the thermal tolerance range for each category. In deciding which species to review, we also considered the size of the geographic area occupied by species and the type of habitat in which it occurs. We gave preference to species that are reasonably well distributed (e.g., occupies most of the Atlantic drainages or occurs throughout the Southeast) as opposed to those that occupy small ranges (say small portions of one or two states). Preference was also given to species likely to be encountered near power plant sites (e.g., medium to large freshwater and tidal rivers, the Great Lakes) as opposed to fishes restricted to small streams or springs. Clearly, species with restricted ranges or life history characteristics that keep them away from power plant discharges may be important in developing thermal standards at the state or regional level. However, widely-distributed, large waterbody species would play similar roles but in more places. Based on these criteria, species and species groups were selected as discussed below.

3.1 Coldwater Species

Although a few other species or groups (e.g., burbot, some sculpins, and most coregonids) are typically considered to be coldwater species, this category is dominated both numerically and especially in terms of political importance by the various trout, char, and salmon species. Because of their considerable recreational and commercial importance, this group (which we will hereafter refer to as the salmonids) has been widely tested. Information concerning the acute thermal tolerance of 11 salmonids representing four genera (*Oncorhynchus, Salmo, Salvelinus,* and *Thymallus*) is provided in Table 1. Some of these species are widespread and many have high recreational and/or commercial value. Although more data are available than that presented in Table 1, most of the other endpoint estimates were based on lower acclimation temperatures or on salmonids with limited distributions (e.g., Apache trout, *Oncorhynchus apache*). Examination of endpoints for the selected salmonids reveals several things. First, UILT values are consistently 4-5°C lower than CTM values for the same species tested at similar acclimation temperatures. This is consistent with the discussion in Section 2 indicating that under similar test conditions UILT endpoint estimates are consistently several degrees below CTM values for the same species. The second fact is the remarkably similar UILT values across the salmonid species and genera and the equally similar CTM values among species and genera. For eight species representing three genera, UILT values ranged only from 23.5 to 25.1°C, a difference of only 1.6°C: UILT estimates for Chinook salmon (*O. tshawytscha*), coho salmon (*O. kisutch*), sockeye salmon (*O. nerka*), and grayling (*T. arcticus*) were virtually identical (25.0 to 25.1°C, Table 1). Similarly, with one exception, CTM estimates for eight species representing four genera ranged from 27.4 to 30.0°C, with most values being between 29 and 30°C. The only exception was Atlantic salmon *(Salmo salar)* whose single CTM value was 32.7°C (Table 1).

Table 1. Salmonid Acute Upper Lethal Endpoints Using Two Test Methodologies

Species	UILT* (Acclimation)	CTM* (Acclimation)	Reference
Rainbow trout	--	29.8 (20)	Currie et al. 1998
Rainbow trout		29.8 (20)	Currie et al. 2004
Rainbow trout		29.0-29.7 (14)	Rodnick et al. 2004
Rainbow trout		28.4-28.8 (15)	Galbreath et al. 2004
Rainbow trout		29.3 (20)	Lee and Rinne 1980
Chinook salmon	25.1 (24)	--	Brett 1952
Coho salmon	25.0 (23)	--	Brett 1952
Coho salmon	--	28.7-29.7 (15)	Becker and Genoway 1979
Coho salmon		29.1-29.2 (15-17)	Konecki et al. 1995
Sockeye salmon	25.0 (20)	--	Brett 1952
Chum salmon	23.8 (23)	--	Brett 1952
Brook trout	25.0	--	Fry et al. 1946
Brook trout	--	28.0-28.9 (15)	Galbreath et al. 2004
Brook trout		29.8 (20)	Lee and Rinne 1980
Brown trout	--	27.4-29.0 (depending on strain) (12)	Carline and Machung 2001
Brown trout		29.0-29.3 (15)	Galbreath et al. 2004
Brown trout		29.9 (20)	Lee and Rinne 1980
Atlantic salmon	--	32.7 (20)	Elliott and Elliot 1995 (as cited by Beitinger et al. [2000])
Cutthroat trout	23.5-24.3 (18)	29.4-30.0 (18)	Wagner et al. 2001
Cutthroat trout	24.2 (18)	--	Johnstone and Rahal 2003
Grayling	25.0 (20)	29.3 (20)	Lohr et al. 1996
Bull trout	23.5 (20)	28.9 (20)	Selong et al. 2001

*All values in °C.

Although the range covered by the estimates was small, it appears that bull trout (*Salvelinus confluentus*) is slightly more sensitive than its relatives, while Atlantic salmon is somewhat more thermally tolerant compared to other salmonids. The consistency of the salmonid endpoint estimates supports the hypothesis of Myrick and Cech (2000) that, except for a few species restricted to high altitude, all salmonids have similar thermal tolerances irrespective of origin. This interpretation of data was echoed by Beitinger et al. (2000) who stated that “based on this finding” (i.e., very similar CTM values), “the upper thermal tolerance in this group is phylogenetically conservative”. We reviewed all but three of the studies cited in Table 1 and determined that they were well conducted and included reasonable sample sizes. Thus, as a practical matter, assuming that the derivation process is appropriate and that protection of salmonids is appropriate (i.e., the waterbody in question is a coldwater stream and does in fact support salmonids), then similar criteria will likely result regardless of which salmonid(s) is(are) to be protected.

Although the coldwater focus in this review is on salmonids, it appears that other coldwater species have very similar endpoints. Edsall and Colby (1970, as cited in Brungs and Jones 1977) reported an ILT of 26°C for lake herring (*Coregonus artedi*) acclimated to 25°C, which is nearly identical to the endpoints for the trout and salmon that have been tested (Table 1). Tests on sculpins (*Cottus* spp.), another mostly coldwater group, but one not closely related to salmonids, yielded results very similar to those in Table 1. Otto and Rice (1977) reported that the CTM of slimy sculpin (*Cottus cognatus)* acclimated at 20°C was 29.4°C. They reported that ILT temperatures were 2.5 to 5.0°C lower than the CTMs at equivalent acclimation temperatures, again very similar to the differentials seen for salmonids (Table 1). Lastly, they calculated an ultimate upper ILT value of 26.5°C for slimy sculpin. Kowalski et al. (1978) reported a CTM of 30.9°C for mottled sculpin (*Cottus bairdii*) acclimated to 15°C. Thus, it appears that coldwater fishes have narrow endpoint ranges, with CTM values of about 29-30°C and ILT values of 24-25°C.

3.2 Coolwater Species

As mentioned in the preface of the proceedings of the “*Selected Coolwater Fishes of North America*” conference (Kendall 1978), *“[t]he term ‘coolwater fishes’ is not rigorously defined, but refers generally to those species which are distributed by temperature preference between the ‘coldwater’ salmonid communities to the north and the more diverse, often centrarchid-dominated ‘warmwater’ assemblages to the south.”* The species covered by that symposium were all members of the esocid (pike) and percid (perches) families. As was the case with the above-cited symposium, this thermal review concentrates on five coolwater species that have major recreational and commercial value: walleye (*Sander vitreus*), sauger (*S. canadensis*), yellow perch (*Perca flavescens*), northern pike (*Esox lucius*), and muskellunge (*E. masquinongy*). We are not aware of tests that have determined the upper thermal tolerance of the other two North American esocids, redfin pickerel (*E. americanus*) and chain pickerel (*E. niger*); however, given their geographic distributions (Page and Burr 2011), both are likely to be less thermally sensitive than either muskellunge or especially northern pike, both of which have more northerly distributions. Yellow perch, sauger, and walleye are all members of the family Percidae. Numerically, this family is overwhelmingly dominated by darters. Although there are nearly 200 species of darters (Page and Burr 2011), less than 10 of them have been tested to determine their thermal tolerance (Beitinger et al. 2000). Of those that have been tested, CTM values are comparable to or slightly higher than those of the larger percids. Thus, we included the darters in the warmwater group (see Section 3.3) rather than the coolwater group.

Northern Pike

Despite being a popular game fish throughout much of North America, little testing has been done to establish the thermal tolerance of northern pike. Hokanson et al. (1973) reported that, when acclimated to 17.7°C, the 7-day upper TL50 increased from 25.0 to 28.4°C from the time of hatch to the free swimming stage. They also reported that the optimum range for hatching ranged from 6.4 to 17.7°C and that hatching rates were poor at temperatures greater than 20°C. Cvancara (1975, 1977) tested juvenile northern pike collected from the Mississippi River. Upon capture, the young northern pike (average length = 116 mm) were placed in 60 liter aquaria with the initial temperature corresponding to the ambient temperature at which they were captured, 24 to 33°C. The temperature of the experimental tank was raised at a rate of 2 to 4°C per hour to the desired series of test temperatures. Mortality was then monitored for 48 hr and a 48 hr TL50 was calculated. There were 20 fish in each test and control group. Cvancara (1975) reported a TL50 of 30.8°C for juvenile northern pike. The test method of Cvancara yields values that would best be described as UILT values. Because no acclimation period was provided, stress may have affected the resultant TL50 estimates. For example, Cvancara (1975) reported TL50s of 28.5°C for both bluegill and gizzard shad, temperatures well below the tolerance values reported by others (Talmage and Opresko 1981, Beitinger et al 2000) suggesting that at least some of the TL50 results reported by Cvancara (1975) are low. Also, Cvancara (1975) reported that the northern pike tested were collected at ambient temperatures as high as 33°C indicating that they can tolerate this temperature for at least brief periods. Similarly, Scott (1964), as reported by Brown (1976), found that young northern pike acclimated to 30°C had an UILT of about 33°C. Horning (as cited in Hokanson et al. [1973]), found that he could not maintain adult northern pike in the laboratory for more than one month at 29°C. Thus, depending on investigator and life stage tested, the upper lethal of northern pike varies from about 29 to 33°C.

Muskellunge

Hassan and Spotila (1976) determined CTM values for muskellunge fry that had been reared at 14°C. During transportation to the test facility, water temperature dropped to 8°C. Fry were to be tested at 25°C and were brought up to this temperature at a rate of 2°C per hour. This fairly rapid increase would not allow fry to acclimate to 25°C. Periodically over the next 19 days, six fry were heated at the rate of 1°C/min, to determine their CTM. This fast heating rate likely overestimated the CTM. Depending on the day on which the fry were tested, CTM ranged from 33.2 to 36.1°C. Control mortality was a problem by Day 13 of the test so the CTM values from Days 13 to 19 (33.2 to 34.2°C) appear to be compromised by the condition of the fry. Hassan and Spotila (1976) stated that the lower CTMs on Days 9 through 19 were “probably due to the deteriorating condition of the fry.” The CTM was lower (34.8°C) on Day 1 than on Days 3 through 7, probably because the fry hadn’t fully acclimated to 25°C. Based on this study, a reasonable estimate of the CTM for muskellunge acclimated to 25°C would be 35 to 36°C, the values measured during Days 3 through 7.

Sauger

Smith and Koenst (1975) evaluated the effects of temperature on the hatchability of sauger eggs, growth of sauger fry, and survival of fry. They found that optimum fertilization temperatures were 9 to 15°C. Optimum temperature for the growth of fry was 22°C and the UILT for juvenile sauger acclimated to 26°C was 30.4°C, a value that is likely low (Hokanson and Koenst 1986).

During studies to determine the effect of monochloramine on various fishes, Seegert et al. (1979) were able to hold juvenile sauger (average length = 81 mm) at 30°C for at least two months indicating that the UUILT for this species is greater than 30°C.

Walleye

Walleye is one of the most popular gamefish in the United States and Canada and supports substantial commercial fisheries in Canada. Smith and Koenst (1975) determined effects of various temperatures on walleye eggs, fry, and juveniles. Major findings were:

- Independent of fertilization temperature, the greatest percentage hatch was at incubation temperatures of 9 to 15°C
- An incubation temperature of 21°C appears to be lethal to walleye eggs regardless of the temperature at which they were fertilized
- Walleye fry growth was higher at 25°C than at 16 or 21°C
- Optimum temperature for growth was 22°C
- Walleye fry grew at 28°C, but growth was minimal
- Sudden changes (ΔTs as high as 17°C) in temperatures had little effect on walleye fry
- The upper lethal temperature of walleye juveniles increased as the acclimation temperature increased
- The TL50 at the highest acclimation temperature (26°C) was 31.6°C

Hokanson and Koenst (1986) attempted to reconcile the upper lethal of 34°C reported for walleye from experimental stream channels (Wrenn and Forsythe 1978) with the lower upper lethal value (31.6°C) reported in a laboratory setting (Smith and Koenst 1975). Hokanson and Koenst (1986) used a slow heating method (0.5°C/day) and reported UUILT values for walleye of 33.0, 34.1, and 34.1°C at acclimation temperatures of 22, 26, and 28°C, respectively. The latter two values are 2.5°C higher than the upper lethal reported by Smith and Koenst (1975). Hokanson and Koenst (1986) concluded that slow heating at less than 1°C/day with little or no handling of test organisms yields the best estimate of the upper lethal limit of fishes, whereas the ILT and the CTM methods, which both involve transferring fish from acclimation tanks to test tanks, stress the fish and result in lower upper endpoint estimates. Based on this finding, one would conclude that estimates derived from both the CTM and ILT methods often underestimate the thermal tolerance of fishes. Hokanson and Koenst (1986) also reported that the growth optimum for juvenile walleye was 22 to 28°C. They further found that positive, though not optimal, growth occurred at 29.9°C and concluded that *"juvenile walleye are capable of growing at temperatures above 30°C under these experimental conditions."*

Peterson (1993) tested juvenile walleye from distinct populations in Iowa and Mississippi using the CTM methodology. Fish were acclimated to 23°C for 7.5 months, then individual fish were heated in 5 liter flasks at 1°C/min. Fifteen fish from each population were tested. Endpoints were loss of equilibrium (LOE) and onset of spasms (OS). For both endpoints, there was no significant difference between the two populations. Values for LOE were 34.8 to 35.0°C, whereas values for OS were about a degree higher (35.8 to 35.9°C).

Yellow Perch

Yellow perch is an important recreational and commercial species that has been tested regularly. Cherry et al. (1977) determined the upper lethal temperature of hatchery-purchased yellow perch. Following acclimation, groups of 10 fish each were tested at a series of test temperatures which were reached by raising the temperature from the acclimation temperature (either 21 or 24°C) to the test temperatures (24 to 27°C) at the rate of 1°C/day. They calculated a 7-day upper lethal temperature that was defined as “the highest temperature at which no mortality occurred during a 7-day period.” Based on this methodology, they reported a 7-day upper lethal of 26°C, well below that reported by others. In contrast to the low upper lethal temperature reported by Cherry et al. (1977), McCormick (1976) reported that the upper lethal temperature for young-of-year (YOY) yellow perch was between 32 and 34°C. These results were based on groups of 72 yellow perch exposed to a series of temperatures. They also reported that optimal growth occurred between 26 and 30°C. Fish exposed to 32°C also experienced good growth but 85 percent of the test fish developed curved spines. Also in contrast to Cherry et al. (1977), Brooks and Seegert (1977) were able to maintain YOY yellow perch at 30°C for more than a month during tests to determine the sensitivity of this species to residual chlorine.

Brett (1944) reported that the UILT of yellow perch was 30.9°C and Hart (1947) reported that the UILT for yellow perch acclimated to 25°C was 29.7°C and the CTM for similarly acclimated yellow perch was 33.4°C based on an increase rate of 1°C/hr (0.017°C/min) from the acclimation temperature.

Black (1953) reported that the 24-hr UILT for yellow perch was 29.2°C. However, this value is not suitable for criteria development for several reasons. First, the temperature of the water where the test fish were collected was 22 to 24°C. The fish were then transferred to a coldwater hatchery where they were maintained for 5-11 days at 11°C before testing. Thus, the tolerance of these yellow perch was likely representative of fish acclimated at 11°C, which was the hatchery temperature, rather than the 22-24°C temperature at the time of capture. Second, Black (1953) noted that some of the yellow perch died upon transfer to 11°C and those that survived “showed signs of deterioration (external sores, etc.) during captivity.” Thus, these fish were stressed. Third, they were stressed further by what Black (1952) describes as high free CO_2 concentration in the water supply. Fourth, the fish were not fed during the 5-11 day holding period likely causing further stress. Therefore, the UILT of 29.2°C reported by Black (1953) is not a valid estimate of the temperature tolerance of yellow perch.

Hart (1952) determined UILT values for several species including yellow perch. He reported that when acclimated to 25°C, yellow perch collected from Lake Erie during the summer had an UILT of 32.3°C, whereas those from the Toronto area had an UILT of 29.7°C when tested during the winter. He attributed this difference to seasonal differences in thermal tolerance. In nature, yellow perch would not experience 25°C during the winter, so the estimate of 32.3°C is the value that should be used for any assessment of the upper temperature tolerance of yellow perch.

3.3 Warmwater Species

The large majority of North America's freshwater fish fauna (~900 species; Page and Burr 2011) falls into the warmwater category. This includes members of the most speciose families: Centrarchidae (sunfishes), Cyprinidae (minnows), Catostomidae (suckers), Ictaluridae (catfishes), and to some extent, Percidae (perches). As described below, many members of these families have not been tested to determine their thermal tolerance. A summary of what is known about each of these families follows. We had earlier indicated that this review concentrated on thermally sensitive species. Because of the number of warmwater species, two additional factors were considered—distribution and waterbody type. Widespread species were given preference over species with local distributions and waterbody type was considered because most of the nation's power plants that use freshwater as a cooling water source are located on either large lakes/reservoirs or large rivers. Therefore, species found primarily in these habitats were given preference while those restricted to small streams, springs, or swamps were excluded.

3.3.1 Centrarchidae (Sunfishes)

Sunfishes include many widespread and recreationally popular species such as bluegill, redear sunfish *(Lepomis microlophus)*, crappie (*Promoxis* spp.), and the black basses (*Micropterus* spp.) that have been widely tested. For example, Beitinger et al. (2000) reported bluegill CTMs from five groups of researchers. Centrarchids are among the most thermally tolerant species. At acclimation temperatures of 20°C or greater, all *Lepomis* and *Micropterus* tested had CTMs greater than 35°C, many species had CTMs in the upper 30s, and two species had CTMs greater than 40°C. Although none of the centrarchids are particularly thermally sensitive, a few are somewhat sensitive or are thought to be sensitive.

Perhaps because its range extends into southern Canada, smallmouth bass *(Micropterus dolomieu)* is sometimes thought to be thermally sensitive; however, a review of the literature reveals this is not the case. Smale and Rabeni (1995) determined CTM values for 34 fish species from the Ozark region of Missouri. All fish were acclimated to 26°C. Twenty-two species were found to be more thermally sensitive than smallmouth bass. In fact, even largemouth bass, a species widely considered to be thermally tolerant, had a lower CTM value (36.3°C) than smallmouth bass (36.9°C). Wrenn (1980) held juvenile smallmouth bass in outdoor channels for nearly a year to monitor growth. During the summer, maximum temperatures in these channels were near or above 35°C for 70 days. He reported that no smallmouth bass died at these temperatures and that they grew at temperatures as high as 32°C. He concluded that *"the smallmouth bass is as tolerant of elevated temperature as the largemouth bass, even at the southern limits of the smallmouth bass' native range."* Similar endpoint values for smallmouth bass are cited in Brungs and Jones (1977), namely 38°C for larvae (Larimore and Duever 1968) and 35°C for juveniles (Horning and Pearson 1973). Cherry et al. (1977) reported that the 7-day UILT for smallmouth bass acclimated to 33°C was 35°C.

Similar to smallmouth bass, crappie (*Pomoxis* spp.) are thought to be among the most thermally sensitive centrarchids. Brungs and Jones (1977) cited an upper lethal value of 33°C for juvenile white crappie *(P. annularis)* acclimated to 29°C, a value that is based on unpublished data so details are not available to assess the validity of the cited value. Brungs and Jones (1977), citing the same authors, reported that the upper lethal (33°C) for juvenile black crappie *(P. nigromaculatus)* acclimated to 29°C was identical to the upper lethal for white crappie. Baker and Heidinger (1996) determined upper lethal temperature for three sizes of Age 0 for black crappies. UILT values for black crappies acclimated to 24°C ranged from 31.5°C for black crappie that averaged 75 mm in total length to 35.1°C for those averaging 46 mm in total length. Baker and Heidinger (1996) did not provide exact CTM estimates; however, based on the data they provided, CTMs were 38 to 39°C for the two smaller size groups at each acclimation temperature (24, 30, and 32°C). CTM values for the largest specimens (75 mm TL) ranged from about 35°C when acclimated to 24°C to 37 to 38°C for those acclimated to 30 and 32°C. The fact that black crappie could be acclimated to 32°C indicates that their long term tolerance is greater than 32°C. Based on the collective results, both crappie species appear to be slightly more sensitive to temperature compared to other centrarchids but only marginally so, and are less sensitive than many other warmwater species.

3.3.2 Cyprinidae (Minnows)

Cyprinidae is the most speciose family, both globally and in the United States. There are about 300 cyprinid species in North America, not including Mexico (Page and Burr 2011. Although the thermal tolerance of about 40 cyprinids has been measured, many are small stream species not likely to occur near power plants. Others like common carp and goldfish *(Carassius auratus),* are highly tolerant and therefore were not considered for this review. We identified five cyprinids (red shiner, *Cyprinella lutrensis;* plains minnow, *Hybognathus placitus;* Arkansas River shiner, *Notropis girardi;* fathead minnow, *Pimephales promelas:* and bullhead minnow, *P. vigilax)* that are found in large waterbodies that had CTM values of 38.6°C or greater (Beitinger et al. 2000). Smale and Rabeni (1995) calculated CTM values for 16 cyprinids acclimated to 26°C. Although the majority of these are small stream species, five species are known to occur in larger waterbodies and therefore could be exposed to power plant discharges. Sand shiner *(Notropis stramineus)*, fathead minnow, and golden shiner *(Notemigonus crysoleucas)* were eliminated from further review based on high CTMs. Two species—rosyface shiner *(Notropis rubellus)* and bluntnose minnow *(Pimphales notatus)*—tested by Smale and Rabeni (1995) were considered further, as was emerald shiner (*N. atherinoides*), a widely occurring large river and large lake form that is somewhat thermally sensitive.

Rosyface Shiner

The literature contains upper thermal endpoints for "rosyface shiner" from three localities; however, rosyface shiner *(Notropis rubellus)* was recently split into four species (Page and Burr 2011). Specimens from two of the three sites are still referable to as rosyface shiner; however, the specimens reported as rosyface shiner by Smale and Rabeni (1995) are now known as carmine shiner *(N. percobromus)*. Because rosyface and carmine shiners are morphologically indistinguishable and occupy similar habitats, we considered the thermal data from all three studies as being appropriate. Both rosyface and carmine shiner occur primarily in small to medium streams with fast current but also occur occasionally in rivers as large as the Ohio River.

During studies to establish the thermal tolerances and preferences of fishes near the Glen Lyn Power Plant on the New River, Virginia, rosyface shiner was tested by Cherry et al. (1977). They reported that the 7-day upper lethal for fish acclimated to 30°C was 33°C. They also reported that when acclimated to temperatures equal to or greater than 27°C, its preferred temperature was about 28°C. Kowalski et al. (1978) measured CTMs for several fishes in Erie County, New York including rosyface shiner. They reported a CTM of 31.8°C for rosyface shiners acclimated to 15°C. The lower endpoint value reported by Kowalski et al. (1978) compared to that reported by Cherry et al. (1977) might be due to differences in how the endpoint was measured and particularly the relatively low acclimation temperature (15°C) used by Kowalski et al. (1978). Smale and Rabeni (1995) reported a CTM of 35.3°C for rosyface (carmine) shiners acclimated to 26°C. This CTM was second lowest of the 34 species tested, and the lowest of the 16 cyprinids tested. Collectively, the data show that rosyface shiner is among the most thermally sensitive cyprinids, especially among those that occur at least occasionally on larger waterbodies.

Bluntnose Minnow

Bluntnose minnow occupies a wide range of habitats from fairly small streams to large rivers, as well as nearshore areas of lakes and reservoirs. Overall, it is generally considered to be a tolerant species (Ohio EPA 1987, Lyons 1992). However, it is considered by some to be somewhat thermally sensitive (Yoder and Rankin 2005, Yoder et al. 2006). Provided below are several estimates of the temperature tolerance of bluntnose minnow:

Acclimation Temp. (°C)	**Upper Lethal Temperature (°C)**		**Author(s)**
	CTM	**UILT**	
25	34.8	33.3	Hart 1947
25	-	34.0	Hart 1952
30	-	32.0	Cherry et al. 1977
15	31.9	-	Kowalski et al. 1978
26	36.6	-	Smale and Rabeni 1995
24	37.9	-	Mundahl 1990

These data show that UILT values for bluntnose minnow acclimated to 25 to 30°C ranged from 32 to 34°C and CTM values ranged from 35 to 38°C for fish acclimated to 24 to 30°C. The lower CTM of 31.9°C is attributable to fish acclimated to 15°C, and thus not representative of the summer tolerance of bluntnose minnow. Collectively, these data indicate that bluntnose minnow is thermally tolerant.

Emerald Shiner

In contrast to rosyface shiner which only occasionally occurs in large rivers, and bluntnose minnow, which occurs in a wide range of habitats, emerald shiner is a large-water fish. It is common in large lakes including the Great Lakes and it is one of the most abundant fishes in the large rivers in the nation’s midsection such as the Ohio, Mississippi, and Missouri Rivers. Hart (1947) reported an UILT value of 30.7°C for emerald shiner acclimated to 25°C and a CTM value of 34.3°C. Hart (1952) subsequently reported an identical UILT for emerald shiner collected from Lake Erie and again acclimated at 25°C. Brungs and Jones (1977) reported UILT values ranging from 23 to 31°C depending on acclimation temperature. They incorrectly attribute these data to Carlander (1969), who in turn ascribed the data to Hart (1947) and Strawn (1958) when in fact all the data came from Hart (1947). Thus, there are considerably less tolerance data for emerald shiner than Brungs and Jones (1977) indicate. In a paper that was not reviewed, Matthews and Maness (1979, as cited by Beitinger et al. 2000) reported a CTM of 37.6°C for emerald shiner acclimated to 25°C, a value about 3°C higher than the CTM reported by Hart (1947) for emerald shiner acclimated to the same temperature. The most detailed evaluation of the thermal tolerance of emerald shiner was conducted by McCormick and Kleiner (1976) who studied the effects of temperature on both survival and growth. They reported that growth occurred at temperatures as high as 32.8°C with growth at 31°C comparable to growth at temperatures of 24-30°C. Emerald shiner were initially acclimated at 20°C, and then the water was heated at a rate of 1°C/day. This would yield what was earlier described as a chronic lethal maximum (CLM). Almost no fish died until the temperature reached 34.9°C and at 36.7°C all fish were dead within a week. They reported an UUILT of 35.2°C and opined that the lower ILT of 30.7°C reported by Hart (1947) was a result of his lower acclimation temperature (25°C). Given the number of fish tested and the carefully controlled conditions during testing, we believe the UUILT of 35.2°C reported by McCormick and Kleiner (1976) most closely approximates the true upper lethal limit for emerald shiner.

3.3.3 Etheostomatini (Darters)

As discussed earlier, the large-bodied members of the perch family—walleye, sauger, and yellow perch—are important recreational and commercial species but the diversity within the family comes from the darters (tribe Etheostomatini) which includes nearly 200 species (Page and Burr 2011). As opposed to the larger members of the family, which are often considered coolwater species, most darters are warmwater species. Despite the number of darter species, thermal tolerance values have been established for less than 10 darter species. Furthermore, almost all *Etheostoma* darters and many *Percina* darters are restricted to small streams, not large rivers where power plants are located. Of the species tested, only four could reasonably be expected near power plants: greenside darter *(Etheostoma blennioides)*, rainbow darter (*E. caeruleum)*, Johnny darter *(E. nigrum)*, and logperch *(Percina caprodes)*. The three *Etheostoma* species occur primarily in medium size rivers like the Wabash River in Indiana or the Muskingum River in Ohio, whereas logperch occur in the largest rivers of the United States.

Rainbow Darter

Upper lethal data for rainbow darter are as follows:

Acclimation Temp. (°C)	CTM (°C)	Author
15	32.1	Kowalski et al. 1978
20	32.8-34.0 (depending on season)	Hlohowskyj and Wissing* 1985
26	35.6	Smale and Rabeni 1995

*as cited by Beitinger et al. 2000

Again, the effect of acclimation temperature is clear with the CTM estimate at an acclimation temperature of 26°C being 3.5°C higher than the CTM estimate of 32.1°C at an acclimation temperature of 15°C. If acclimated to 30°C, the CTM for rainbow darter would likely be 36 to 37°C.

Greenside Darter

When acclimated to 15°C, Kowalski et al. (1978) estimated a CTM of 32.2°C for greenside darter, which is nearly identical to the CTM of 32.1°C they estimated for rainbow darter.

Hlohowskyj and Wissing (1985, as cited by Beitinger et al. 2000) reported CTMs of 32.2 to 34.5°C for this species depending on season when it was acclimated to 20°C. These seasonal estimates are very similar to those estimated for rainbow darter. Collectively, these data suggest that these two darters have similar thermal tolerances.

Johnny Darter

CTMs for johnny darter are as follows:

Acclimation Temp (°C)	CTM (°C)	Authors
15	30.7-31.4 depending on season	Kowalski et al. 1978
15	30.5-30.9 depending on season	Ingersoll and Claussen* 1984
20	~33	Lydy and Wissing* 1988
20-30	34.0-37.4	Smith and Faush* 1997
26	36.4	Smale and Rabeni 1995

*paper not reviewed

The CTM estimates for johnny darter are consistent with those for the other two *Etheostoma* and again clearly show the effect of acclimation temperature.

Logperch

No studies were found that used standard testing protocols to establish upper lethal estimates for any *Percina*, which is the darter genus most common in large rivers. However, logperch data from Hubbs (1961) has been considered for thermal criteria development (Yoder and Rankin 2005, Yoder et al. 2006). Hubbs (1961) indicated that he collected his test specimens “within a 200-mile radius of Austin, Texas.” Due to taxonomic changes, the species he tested which was then called *Percina caprodes* would now be known either as Texas logperch *(Percina carbonaria)* or bigscale logperch *(P. macrolepida)*, not the much more widespread logperch *(P. caprodes)* that is common in many Midwestern rivers. Because the species tested is unknown, we will simply refer to it as logperch *(Percina* sp*)*. For several reasons, we do not believe data from the Hubbs (1961) study is suitable to establish upper endpoint values. First, this study was designed to assess the hatching success of eggs, not to derive CTM or UILT values. Second, as the authors acknowledged, temperature control during testing was poor. According to Hubbs, *“the equipment works best at near room temperature, 18-23°C and at the low range the variation might be ± 4°C. The data presented are, therefore, not as accurate as desired.”* This level of control might have been adequate for Hubb’s purposes but it is not adequate to derive accurate thermal endpoints. Third, survival of logperch eggs was much poorer than the other three darter species tested. As shown below, the other species exhibited an expected survival pattern (i.e., low survival at low temperatures, slowly increasing survival as temperatures increase, and then declining survival as temperatures increase further):

Temperature (°C)	Percent Survival of Larvae			
	Etheostoma lepidum	***E. spectabile***	***Percina sciera***	***P. "caprodes"***
10	0	17	-	-
12	49	4	0	0
14	42	26	0	2
16	31	30	4	1
18	42	44	0	0
20	68	57	0	0
22	79	77	6	5
24	61	65	11	5
25	43	55	23	31
26	36	6	14	1
27	12	80	29	0
28	0	0	0	0

For example, *E. lepidium* had zero survival at 10°C, moderate survival between 12 and 18°C, maximum survival at 22°C, then declining survival at higher temperatures. *E. spectabile* had a pattern similar to that for *E. lepidum* except it had two survival peaks, at 22°C and 27°C. Survival of *Percina sciera* larvae ranged from 11 to 29 percent at temperatures from 24 to 27°C. In contrast to the other species, *P. "caprodes"* had poor survival at all temperatures except 25°C. Yoder et al. 2006 interpreted Hubbs results to indicate that the upper lethal for logperch was 25°C. In contrast, we believe the poor temperature control acknowledged by Hubbs coupled with the poor survival of logperch larvae at all but one temperature indicate that data from this study should not be used to determine thermal endpoints. This interpretation is supported by the fact ambient temperatures in the Ohio River often exceed 25°C, yet the river supports large numbers of logperch. Similarly, large numbers of adult logperch were collected from the Wabash River in July 2011 at temperatures of 30-32°C (unpublished EA data).

3.3.4 Ictaluridae (Catfishes)

The large commercially and recreationally important catfish and bullhead species are all thermally tolerant (Beitinger et al. 2000) so there is no need to discuss them further. Little data are available regarding the thermal tolerance of madtoms; however, based on their distribution being centered in the southeast, one can infer that, as a group, madtoms are not thermally sensitive. We are aware of only two studies that attempted to measure the tolerance of madtoms. Smale and Rabeni (1995) reported that the CTM for slender madtom *(Noturus exilis)* acclimated to 26°C was 36.5°C. It ranked almost exactly in the middle of the 34 species they tested. Yoder et al. (2006) reported a CTM of 29°C for stonecat (*Noturus flavus*) based on data taken from Reutter and Herdendorf (1975, 1976). Yoder et al. (2006) indicated incorrectly that this CTM is based on fish acclimated to 16°C. Actually, these stonecat were collected during the winter when the ambient temperature was 1.6°C not 16°C and they were immediately transferred to 12.8°C water, after which the CTM test immediately began. Thus, this CTM was for cold-acclimated fish and is certainly not appropriate for developing upper lethal tolerance values. Also, only two stonecat were tested; one had a CTM of 29°C and the other had a CTM of 26°C. For these reasons and others discussed in Section 3.3.7, the stonecat CTM of 29°C should not be used to develop summertime thermal criteria.

3.3.5 Catostomidae (Suckers)

The sucker family has two groups; the *Ictiobinae* (carpsuckers and buffalos), which are thermally tolerant and need no further discussion, and the more speciose *Catostominae* (sometimes referred to as the “round-bodied” suckers) that has several species or groups that are considered by some to be among the most thermally sensitive warmwater fishes. Species or groups that are considered to be somewhat thermally sensitive are spotted sucker (*Minytrema melanops*), white sucker (*Catostomus commersonii*), northern hog sucker (*Hypentelium nigricans*), and redhorse (*Moxostoma* spp.). Each is discussed below.

Spotted Sucker

Although spotted sucker has only been tested once (Reutter and Herdendorf 1975), it is a potentially important endpoint. It was included in a previous EPRI compilation of thermal data (Talmage and Opresko 1981) and the same thermal endpoint was proposed for use during standards development for the Ohio River (Yoder et al. 2006) and in Illinois (Yoder and Rankin 2005). The endpoint of greater than 31°C for spotted sucker listed by Reutter and Herdendorf (1975, 1976) has been referred to as a CTM by both Talmage and Opresko (1981) and Yoder and Rankin (2004, 2005). However, it is not a CTM. Reutter and Herdendorf (1975) tested only one spotted sucker that was collected on 2 July 1974 at an ambient temperature of 20.0°C, which was then subjected to a ΔT of 11.1°C. According to the remarks in Table 4 of their paper, Reutter and Herdendorf noted that this specimen was “normal” after the one-hour post-shock observation. For reasons that were not explained, these authors did not raise the temperature above 31.1°C and reported the CTM in Reutter and Herdendorf (1976) as greater than 31°C. The value of 31°C for spotted sucker should not be used for criterion development because it is not a CTM and only one fish was tested.

White Sucker

As shown below, white sucker has been tested by several investigations and appears to be one of the more thermally sensitive warmwater species.

Acclimation Temperature (°C)	Upper Endpoint (°C)		Author(s)
	CTM	UILT	
20		29.3	Hart 1947
25		29.3	Hart 1947
25-26		31.3	Brett 1944*
16	30-33		Seegert 1973
26	34.9		Smale and Rabeni 1995
15-21		30-32	McCormick et al. 1977

*paper not reviewed

Using standard ILT methods, Hart (1947) and Brett (1944) estimated the UILT for white sucker as 29.3°C and 31.3°C, respectively. McCormick et al (1977) reported that one to seven day UILT values ranged from 30 to 32°C for white sucker larvae acclimated to either 15 or 21°C. The lower CTM (30-33°C) reported by Seegert (1973) relative to the value reported by Smale and Rabeni (1995) is likely due to the lower acclimation temperature used by Seegert. Also, Seegert was monitoring the fish he was testing electronically so his endpoint detection was likely more sensitive than the visual methods that are typically used. Smale and Rabeni (1995) found that white sucker was the most thermally sensitive of the 34 warmwater species they tested. They did not test any other suckers, but did test 16 cyprinid, 6 sunfish, 4 darter, 3 catfish, and 3 topminnow species, plus brook silverside. Thus, we conclude that white sucker is indeed one of the most thermally sensitive warmwater species. This conclusion is supported by observations made by Seegert et al. (1979) who found that they could not hold small (5 to 9 g) white suckers for several weeks at a constant temperature of 30°C without significant mortality but were able to do so at 27°C.

Northern Hog Sucker

Only two studies have assessed the thermal tolerance of northern hog sucker *(Hypentilium nigricans)*. Kowalski et al. (1978) found that it had the lowest CTM (30.8°C) among 10 species acclimated to 15°C. The relatively low acclimation temperature used by Kowalski et al. (1978) suggests that the upper thermal tolerance of summer-acclimated northern hog suckers would be considerably higher than the CTM value they reported for fish acclimated to 15°C. This suggestion is supported by results from Cherry et al. (1977) who determined that the 7-day UILT was 33°C for northern hog suckers acclimated to 30°C, suggesting that the CTM for summer-acclimated northern hog suckers would be in the mid-30s.

Moxostoma (Redhorse)

The thermal tolerance of redhorse has long been an issue on Midwestern rivers. Unfortunately, little quantitative data are available to either support or refute the purported thermal sensitivity of this group. Neither the review by Talmage and Opresko (1981) nor the review that was conducted about 20 years later by Beitinger et al. (2000) listed any redhorse studies. However, two studies are now available that are relevant to this issue. In response to questions from Ohio EPA regarding to the thermal tolerance of golden redhorse *(Moxostoma erythrum)* and shorthead redhorse *(M. macrolepiditum)*.[1] American Electric Power sponsored studies to determine the upper thermal tolerance of these two species. Small to medium size (153 to 350 mm TL) specimens were field-collected and tested at the Conesville Power Plant. Tests were conducted to derive both UUILT and CTM values (Reash et al. 2000). UUILT values were based on the "slow-heating" method recommended by Hokanson and Koenst (1986). Reash et al. (2000) reported that the UUILT for shorthead redhorse was 33.3°C and the CTM for this species was 35.1°C for fish acclimated to 21°C. These authors reported a similar CTM of 35.4°C for shorthead redhorse acclimated to 20°C. Walsh et al. (1998) determined CTM values of 34.9 and 37.2°C for juvenile robust redhorse *(M. robustum)* acclimated to 20 and 30°C, respectively. Thus, CTMs of the three *Moxostoma* that have been tested range from 35 to 37°C. This range encompasses about three quarters of the range of CTM temperatures reported by Smale and Rabeni (1995) for 34 warmwater species suggesting that, on average, the thermal tolerance of

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[1] This species has now become *M. breviceps*

redhorse is similar to many other warmwater species. The endpoints for redhorse are roughly comparable to those of northern hog sucker and above those reported for white sucker.

Collectively, the thermal literature indicates that the thermal tolerance of catostomids tested to date can be characterized as follows—Ictiobinae is more tolerant than redhorse, the tolerance of redhorse is about equal to that of northern hog sucker, and northern hog sucker and redhorse are more tolerant than white sucker.

3.3.6 Other Species

Cook et al. (2006) reported the following UILT values for Age 0 striped bass (*Morone saxatilis*):

Acclimation Temperature (°C)	UILT (°C)
5	24.4
10	27.2
15	29.7
20	31.1
26	31.8
30	33.9

The strong direct relationship between acclimation temperature and UILT values is obvious in these data. At these acclimation temperatures, CTM values ranged from 27 to 38°C, about 4°C higher than the corresponding UILT values (Cook et al. 2006). At acclimation temperatures of 16 and 23°C, smaller striped bass (fork length = 22 cm) were slightly more tolerant than larger bass (fork length = 34 cm). The thermal tolerance of large striped bass (≥100 cm) is unknown.

Unionidae (Unionid mussels)

Recently, considerable attention has been focused on mussels because of declines among many mussel species (Williams et al. 1993). Dimock and Wright (1993) (as cited in Pandolfo et al. [2010]) reported a 96-h TL50 of 31.5°C for one week old juvenile *Utterbackia imbecellis* and 33°C for week old *Pygandon cataracta*. Recently, Pandolfo et al. (2010) determined TL50 values (the temperature that caused mortality in 50 percent of the test organisms) for glochida and juveniles of eight species of freshwater mussels. They reported that at acclimation temperatures of 22 and 27°C, TL50 values varied widely ranging from 21.4 to 42.7°C. It is not clear how one obtains TL50 values below the “acclimation” temperature. The authors acknowledged that the acclimation period *“might have been too short to establish a true acclimation.”* They reported that acclimation temperatures did not affect TL50 values, which is counter to what has been well established for fish. Also, they exposed the same eight species that had been “acclimated” to 17°C to test temperatures as high as 32°C but could not calculate TL50 values for any of the eight species *“because of a lack of sufficient mortalities.”* It is difficult to understand how temperature as high as 32°C would fail to elicit significant mortality to any of these species when they were acclimated to 17°C while tests on these species acclimated to temperatures of 22 and 27°C resulted in TL50 values below 32°C in eight of the 29 tests they conducted. No consistent pattern was established regarding the relative sensitivity of glochida and juveniles. In 10 of 13 cases where both juveniles and glochida were tested, juveniles were found to be more thermally resistant, but the reverse was true in three cases. When acclimated to 22°C, *Ligumia recta* glochida were more thermally resistant than *L. recta* juveniles, whereas the reverse was true when this species was acclimated to 27°C; again an unexpected result. Also, from an assessment point of view, it is important to note that glochida are present outside of their fish host only for a brief period. During the rest of their life, mussels are on the bottom and thus typically not exposed to the highest temperatures near power plants because of stratification of most thermal plumes. Clearly, more data on the thermal tolerance of mussels would be useful to clarify the rather confusing results presented by Pandolfo et al. (2010).

3.3.7 Review of Studies by Reutter and Herdendorff

These studies were reviewed because several lower than expected CTM values were reported and these low values have been cited in recent thermal criteria development papers (Yoder and Rankin 2005, Yoder et al. 2006). In the mid-70s, Reutter and Herdendorff (1975, 1976) conducted studies to assess possible impacts from the Davis-Besse Nuclear Plant, which was then under construction on the south shore of Lake Erie. They conducted tests to determine upper lethal temperatures, preference temperatures, and temperatures at which cold shock occurred. Of most relevance for this review are their studies to estimate the upper temperature tolerance of various Lake Erie fishes. Reutter and Herdendorff tested 33 fish species to determine their upper temperature tolerance. All fish tested were captured by trawl or fyke net from Lake Erie near the test facility. According to Reutter and Herdendorff (1976) *"fish were tested as soon as possible after capture."* Thus, no acclimation period was provided and the specimens may have been stressed by their recent capture. Upon capture, *"fish were transferred from ambient lake temperature to a 190-liter aquarium, which was maintained 11.1°C above ambient and observed for one hour."* The 11.1°C differential represents the maximum ΔT predicted for the Davis-Besse Plant. Thus, their method is similar to the ILT method because fish were plunged from ambient conditions to a much higher temperature. If the fish survived that initial 11.1°C ΔT, they were then heated at a constant rate as is done following the CTM method. Thus, the Reutter and Herdendorff method is a hybrid of the ILT and CTM methods. Further complicating interpretation of results is that the rate of temperature increases during the CTM portion of the testing was not constant. For all species, the rate of increase was quite slow, typically 0.03 to 0.08°C/min but the heating rate varied for each species and often from one test to the next, even for the same species. Sometimes the difference in the rate of increase was substantial. For example, the rate of increase used during the yellow perch tests ranged from 0.002°C/min to 0.165°C/min.

Also, a number of the values reported as CTMs were not CTMs because fish went into distress soon after they were transferred to the test tank or before the one-hour observation period was over. For example, Reutter and Herdendorff (1976) reported a CTM of 32.8°C for spottail shiner (*Notropis hudsonius*); however, this value was based on two fish collected at an ambient temperature of 21.7°C and placed in the test tank at 32.8°C. According to the notes in Reutter and Herdendorff (1975), one fish was removed after 20 minutes and the other at 55 minutes.

The biggest problem with this work was that they reported only the highest CTM, which was often based on extremely small sample sizes. Based on the raw data in Reutter and Herdendorff (1975), CTM values were almost always derived from tests using three or fewer fish and in six of the 33 cases, CTM was based on testing two fish and in over half the cases (18), the value reported was based on testing a single fish.

For reasons listed below, we do not believe the values reported by Reutter and Herdendorff (1976) are suitable for temperature criteria development:

- No acclimation period was provided;

- Test methodology did not follow standard test protocols;
- Rate of heating during CTM testing was variable both within and among species;
- Some of the endpoints were not CTM endpoints;
- Only the highest CTM was reported; and
- Sample size was consistently less than five fish and often as few as one or two fish

Data from the Reutter and Herdendorff papers have been proposed for use in developing thermal criteria. ORSANCO considered a short term standard for the Ohio River that was based on the spotted sucker CTM reported by Reutter and Herdendorff (1976) and one of the options presented to Illinois EPA for thermal standards on the Chicago Area Waterway System (Yoder and Rankin 2005) is based on Reutter and Herdendorff's CTM for stonecat. These data are not appropriate for these purposes based on our review the thermal literature.

4
DISCUSSION

One of the objectives of this study was to review the quality of the thermal data used to make decisions regarding thermal criteria. In particular, we evaluated the quality of the data collected on thermally sensitive species because those data typically drive criteria. Overall, we found few problems with the data. The main exception was a paper by Reutter and Herdendorf (1975) that involved a combination type exposure period, used variable heating rates for the CTM portion of their tests, provided no acclimation for field-collected fish, and often tested only one or two individuals per species (see Section 3.3.7 for further details).

A CTM value is calculated for individual fish so a final CTM estimate can literally be based on a single fish or a low number (e.g. 2 to 5) of individuals. Because of this, more information is needed to confirm CTM estimates for some species. We believe that estimates based on only one or two specimens are not valid. There were also a few cases where fish were likely not acclimated to the temperature described as the acclimation temperature; however, there were relatively few of these cases and the degree to which they affected the endpoint estimates is unknown.

4.1 Observations Regarding Each of the Species Groups

4.1.1 Coldwater Species

Fry (1947, 1967) and Brett (1944, 1952), the pioneers in the field of thermal biology, began studying the thermal tolerance and response of salmonids over 60 years ago. Since that time, many other researchers have followed up, either collecting additional data on the salmonid species studied by Fry and Brett or studying new species (Section 3.1). Thus, the thermal tolerance of most salmonids is well established. Furthermore, it appears that most salmonids have very similar upper thermal endpoints; about 25°C when measured using the ILT methodology and 29-30°C using the CTM methodology (Table 1). Bull trout appear to be the most sensitive of the salmonids with endpoint estimates about 1°C lower than most other species (Selong et al. 2001).

All the coldwater studies reviewed were well conducted so that thermal criteria to protect salmonids can be based on a wealth of data. Because this group includes both spring and fall spawning species, as well as some species whose eggs remain in the spawning redds over the winter, temperatures in seasons other than the summer are likely to be important for this group. Thus, facilities on waterbodies where protection of salmonids is appropriate may be as or more thermally limited in the spring, winter, or fall than in the summer.

4.1.2 Coolwater Species

We noted in Section 3.2 that the term coolwater species has not been rigorously defined but often has been used for the commercially and recreationally important members of the esocid and percid families, namely northern pike, muskellunge, walleye, sauger, and yellow perch. Recently, Lyons et al. (2009) attempted to define and characterize coolwater streams and their fish assemblages in Michigan and Wisconsin. They defined coolwater streams as ones having summer water temperatures suitable for both coldwater and warmwater species and used the observed distributions of 99 fish species to identify thermal boundaries for coolwater streams. Coolwater streams had June-through-August mean water temperatures of 17.0-20.5°C, July mean temperatures of 17.5-21.0°C, and maximum daily mean temperatures of 20.7-24.6°C. They identified two subclasses of coolwater streams: "cold transition" (having July mean water temperatures of 17.5-19.5°C) and "warm transition" (having July mean temperatures of 19.5-21.0°C). They found that fish assemblages in coolwater streams were variable and lacked diagnostic species but were generally intermediate in species richness and overlapped in composition with coldwater and warmwater streams. Based on upper lethal values in the literature, they initially classified northern pike, walleye, and yellow perch as "transitional" species meaning they fit neither their definitions of warmwater nor coldwater species. Because their data set was restricted to wadeable sites, they were not able to collect enough data to confirm their initial classifications of walleye, sauger, or muskellunge. However, based on field data, both northern pike and yellow perch were both reclassified as warmwater species.

Based on our review of multiple papers, but especially those of Wrenn and Forsyth (1978), Hokanson and Koenst (1986), and Peterson (1993), we recommend that walleye and sauger be considered warmwater species. Too few data are available to assign muskellunge to a thermal tolerance guild with any confidence.

Thus, of the five species often assigned to the coolwater guild, four show greater affinities to the warmwater guild and too few data are available to assign muskellunge to any thermal guild. In any case, there is little support for placing the larger percids and esocids in an artificially constructed group (i.e., coolwater species)

4.1.3 Warmwater Species

Our classification of smallmouth bass as a warmwater species is supported by Lyons et al. (2009) who classified it as such based on both laboratory and field data. Furthermore, they reported that it was more strongly associated with warmwater than its cousin, largemouth bass.

In Section 3.3, we concluded that the purported thermal sensitivity of stonecat is an artifact caused by a low number of test organisms (two) and even more so by the test being conducted on specimens collected when the ambient temperature was 1.6°C. The results from Lyons et al. (2009) clearly show that stonecat is not thermally sensitive. They not only classified it as a warmwater species but reported that the only species more strongly associated with high July water temperatures than stonecat was common carp.

As indicated in Section 3.3, most of the laboratory data show that bluntnose minnow and emerald shiner are not thermally sensitive despite fairly high rankings in terms of sensitivity by some authors (Yoder and Rankin 2005, Yoder et al. 2006). Lyons did not collect emerald shiner from enough locations to be able to either support or refute their assignment of this species to the warmwater guild based on laboratory data; however, bluntnose minnow was one of their most frequently collected species and field data strongly supported placing it in the warmwater guild.

We previously noted that of the cyprinids known to at least occasionally inhabit large streams, rosyface shiner was among the more thermally sensitive species. Based on field data, Lyon et al. (2009) assigned it to their warmwater guild. A reasonable interpretation of both the laboratory and field results is that rosyface shiner is relatively thermally sensitive compared to other cyprinids that occur in large waterbodies but that it is not particularly sensitive in an absolute sense.

Based on laboratory data, Lyons et al. (2009) initially classified nine of 10 darter species as warmwater species, with the tenth being a transitional species. They obtained sufficient field data to evaluate three of the darters considered in this review. They classified both rainbow darter and johnny darter as warmwater transition species. Logperch could not be assigned to any thermal guild. All three of these darter species showed fairly high associations with high July mean temperatures.

Lyons et al. (2009) collected field data on three of the sucker species discussed in Section 3.3, white sucker, northern hog sucker, and shorthead redhorse. In fact, white sucker was the most frequently encountered species during their study, occurring at 275 of 371 study locations. Lyons et al. (2009) classified white sucker as warmwater transition and placed the other two species in the warmwater guild. Consistent with this placement, white sucker was less associated with high average July stream temperatures than either shorthead redhorse or northern hog sucker. This is consistent with the laboratory data presented in Section 3.3 and supports our conclusion that at least among the widely occurring sucker species, white sucker is the most thermally sensitive.

The mussel paper reviewed in Section 3.3 indicated considerable variability in the thermal endpoints not only among species but also for individual species. One would not expect this much intraspecific variation suggesting that it may have been an artifact of the testing protocol. This excessive variability also indicates that further testing is needed of this important freshwater group. Except for a brief period, mussels are exclusively benthic. Thus they are not exposed to the highest discharge temperatures because most thermal plumes will be at or near the surface during the critical summertime period. By the time the plume becomes fully mixed, temperatures would typically be much reduced.

4.2 Factors to be Considered During Development of Thermal Criteria

4.2.1 Acclimation Temperature

Upper lethal estimates will increase with acclimation temperature until the UUILT is reached. The magnitude of the changes in endpoint estimates can be dramatic (Table 2). In each of these cases, the studies were done by the same group of researchers, so it is reasonable to assume that the differences in endpoints are the result of acclimation temperature. For the four warmwater species, CTM values varied by 7.5 to 11.8°C, depending on acclimation temperature and, except for channel catfish, the CTM changed by 10°C or more. The change in endpoint estimates, though still significant, appears to be less for coldwater species. The difference for slimy sculpin was 6.7°C, 3°C for sockeye salmon, and only 1.7°C for rainbow trout, *Oncorhynchus mykiss* (Table 2). Beitinger and Bennett (2000) also found that a salmonid (brook trout *[Salvelinus fontinalis]*) was the least affected by acclimation temperatures among the 21 species they considered. Thus, it is clear that testing warmwater species acclimated to temperatures below their expected UUILT, will yield erroneously low estimates of the true thermal tolerance of such species and the greater the difference between the acclimation temperature and each species' UUILT, the greater the underestimate. Underestimation also occurs for coldwater species but the magnitude will be less than for warmwater species. Beitinger and Bennett (2000) reported that acclimation doubles the size of a species' temperature polygon. They also established quantitative relationships between acclimation temperatures and temperature tolerance estimates that could be used by those developing thermal standards to adjust endpoint estimates derived at low acclimation temperatures.

Table 2.
Effect of acclimation temperature on CTM estimates

Species	Acclimation Temperature (°C)	CTM (°C)	Author(s)
Bluegill	16	31.5	Murphy et al. (1976)
	24	37.5	
	32	41.4	
Largemouth bass	8	29.2	Fields et al. (1987)
	16	33.6	
	24	36.5	
	32	40.9	
Fathead minnow	5	28.6	Richards and Beitinger (1995)
	12	30.7	
	22	36.4	
	32	40.4	
Channel catfish	12	34.5	Cheetham et al. (1976)
	16	34.2	
	20	35.5	
	24	37.5	
	28	39.2	
	32	41.0	
Slimy sculpin	5	22.7	Otto and O'Hara Rice (1977
	10	24.8	
	15	26.3	
	20	29.4	
Rainbow trout	10	28.1	Currie et al. (1998)
	15	29.1	
	20	29.8	
Sockeye salmon	5	22*	Brett (1952)
	10	23*	
	15	24*	
	20	25*	

*UILT values.

4.2.2 Methods to Estimate the Thermal Endpoint

As discussed in Section 2.1, the two principal methods for estimating thermal tolerance (ILT and CTM) yield different endpoint estimates. The difference in these endpoints is not trivial. For salmonids, it appears to be about 5°C on average (Table 1 and Section 3.1). Differences for warmwater species seem to be similar, on average, but are more variable (Section 3.3). Kilgour and McCauley (1986) indicate the difference is typically 2-6°C.

Historically, most endpoints were determined by the ILT method, which has largely been replaced by the CTM method because the latter method is quicker and requires fewer test fish. As a result, any database that has endpoints for multiple species is likely to contain endpoints generated by both methods. Even for the same species, there often are estimates derived from both methods (and sometimes variants of each). In this case, one could either chose one type of estimate over the other or adjust them in some way. Regardless of how the data are to be used for subsequent criteria development, these disparate estimates should be standardized, either all converted to CTMs or all to UILT estimates. Kilgour et al. (1985) and Kilgour and McCauley (1986) discuss the quantitative relationships between the methods. Although the method of standardization is subject to debate it seems that almost any attempt at standardization is preferable because ignoring the inherent differences is almost certain to lead to erroneous criteria.

4.2.3 Other Factors

The two factors just discussed are by far the most important in selecting and standardizing data to be used as part of criteria development. However, there are other factors that should also be taken into account

Condition of the Test Fish

Anything that reduces fish health likely lowers their thermal tolerance. Factors that could reduce the fitness of the fish include poor water quality (e.g. high ammonia levels), disease, overcrowding, and inadequate nutrition. Diligent researchers would not knowingly test fish whose health was comprised but many of these factors are difficult to detect unless their influence is severe. Given that it is effectively impossible to make fish too fit, any resultant bias would be unidirectional, i.e., the result would always be lower, not higher, endpoint estimates.

Season

Although the endpoints for some species have been shown to vary seasonally when acclimated to the same temperature, the magnitude of the effect usually appears to be small (~1°C) (Kowalski et al. 1978, Ingersoll and Clausen 1984, Hlohowskyj and Wissing 1985) but can be as high as 2.6°C (Hart 1952) so this does not appear to be a major concern.

Size or Life Stage

In general, juveniles are more thermally tolerant than adults of the same species but the difference again appears to be small (about 1-2°C, Baker and Heidinger 1996). Rodnick et al. (2004) found no difference in CTM values between small (40 to 140 g) and large (400 to 1400 g) redband (rainbow) trout. However, few species have been tested to determine size/tolerance relationships and few of these involve adults of large species (e.g., salmon, most catostomids, and *Micropterus*).

CTM Endpoints

In Section 2.3, we noted that multiple indicators have been used to determine CTM endpoints. The most common indicators are loss of equilibrium and onset of muscle spasms, but other indicators have been used. Again, the difference in endpoint values that are due to the indicator used appears to be on the order of about a degree (Peterson 1993).

Rate of Heating During CTM Tests

Although Becker and Genoway (1979) attempted to standardize the rate of heating to 0.3°C/min, the actual rate continues to vary widely due both to investigator preference and the heating capacity of the available equipment. Rates that are too slow allow some acclimation to occur during testing and rates that are too fast result in overestimating the CTM.

Sample Size

A CTM value can and has been reported on a single fish (Reutter and Herdendorf 1975) and small numbers (<5) of fish are tested rather frequently. Such small sample sizes increase the chance of erroneous endpoints being reported.

4.3 Areas for Future Research

In freshwater, some of the more speciose families are under-represented in terms of endpoint estimates. This is particularly true for cyprinids, including many large river forms that are common near many power plants. Redhorse are also underrepresented especially considering that they can dominate the biomass in medium size rivers. Lastly, the *Percina* darters, several of which are important in large rivers, are essentially untested. In contrast, salmonids and centrarchids are well studied.

Although it is well known that fish avoid high temperatures, little is known about where they go when avoiding high temperatures. At riverine plants, do they move upstream, downstream, into tributaries, or seek out mainstream thermal refugia? And once they leave the discharge, do they return as soon as temperatures moderate or tend to remain in the areas to which they have been displaced? Do all or most species have an equal ability to avoid lethal conditions? How would or how could avoidance be incorporated into thermal criteria, and even if it could, should avoidance be incorporated into such criteria. Lastly, how can avoidance be assessed/quantified? Would it be based on the size of the area from which some or all species are excluded or the period of time that avoidance occurs. Perhaps because of questions such as these, regulators have been reluctant to consider avoidance, except as a negative impact.

Related to the question of avoidance is how stratification affects the distribution of fish and whether cooler, near-bottom areas should be accepted as thermal refugia. At most power plants, summer will be the most critical period in terms of being able to maintain thermal compliance. During the summer and most of the rest of the year for that matter, the thermal plume will be buoyant and not attached to the bottom until it cools considerably or becomes completely mixed with the receiving water. In theory, there should be a considerable area under the plume in which fish and other aquatic life can prosper (assuming dissolved oxygen levels below the plume are acceptable). Similarly, movement past the plant should be possible by fish going under the plume. More information is needed to establish how fish react to and interact with thermal plumes. This seems a particularly relevant question in lakes, estuaries, and oceans where due to wind and currents, the position of the plume can change greatly over a short period of time.

5

GUIDANCE AND RECOMMENDATIONS

This section provides guidance regarding how to evaluate and standardize endpoint data to ensure that thermal criteria are derived appropriately. This guidance is consistent with recommendations by others designed to ensure that datasets undergo quality control checks before they are used to derive criteria or enforceable standards. For example, EPA's document for deriving numerical water quality criteria contains guidance for accepting or rejecting data and also indicates that "questionable data… should not be used" (EPA 1985). This same document recommends standard exposure periods for acute tests (e.g., 96 hrs for fish). The first cycle of water quality criteria reports produced by EPA after publication of their 1985 guidance document, resulted in databases being revised, sometimes significantly, to be consistent with the guidance. For example, the comprehensive chlorine review document (Mattice 1981) excluded roughly 80 percent of the papers originally utilized to develop chlorine criteria. Colorado developed screening procedures to ensure that only quality and standardized data would be used to derive thermal criteria they were developing (Todd et al. 2008). Thus, it is appropriate that guidelines be established for thermal data that may be used to develop temperature standards.

5.1 Acclimation Temperature

As noted in Section 2.2, acute maximum endpoints vary directly with acclimation temperature. Therefore, criteria should be developed using endpoint data that were derived from tests conducted at seasonal norms or preferably somewhat warmer. In many cases, summer will be the season when compliance with temperature standards will be most difficult. Therefore, summer acclimation temperatures are suggested below:

Thermal Tolerance Group	Suggested Acclimation Temperature (°C)
Coldwater	20
Coolwater	25-30
Warmwater	≥30

In each case, the suggested acclimation temperatures are about 5°C lower than the approximate midpoint for thermal tolerances of species making up these three groups. Upper lethal endpoints being considered for use in criterion development that were calculated using acclimation temperatures below these ranges should either be adjusted upward or removed from consideration if they cannot be adjusted. Ideally, any adjustments would be based on the slope of species-specific curves. These curves would show how much upper lethal temperatures change for each degree change in acclimation temperature. If the available data are inadequate to develop a species-specific curve, an adjustment could be made using the slope for other species of the appropriate family or by applying the mean slope of 0.41 (i.e., the endpoint changes 0.41°C for each degree that the acclimation temperature increases) calculated by Beitinger et al.

(2000). If no adjustment is made, the endpoint derived will underestimate the true short-term upper lethal for that species by several degrees. It could also be argued that an adjustment should be made even when acclimation temperatures are within the recommended acclimation ranges because, by definition, the upper lethal temperature will continue to increase as acclimation temperature increases until the UUILT is reached. Although true, the relationship between acclimation and lethal temperatures is not linear as the UUILT is approached (Fry 1947, 1967, Beitinger et al. 2000). Because any adjustment would likely be small for testing done within the recommended acclimation range, no adjustment may be necessary so long as acclimation temperatures are within or above the ranges listed above.

5.2 Test Method

As discussed in Section 2.2, acute upper lethal endpoint estimates for a given species depend on the methodology used to derive endpoints. Endpoints based on the CTM method tend to be 3-5°C higher than those based on the ILT method assuming acclimation temperatures are similar. Endpoints based on the "slow heating method" (usually about 1°C/day) are typically intermediate between the other two methods. Given the difference that 3 to 5°C can make in terms of compliance, standardization of endpoint estimates is appropriate. Based on thermal tolerance studies conducted over the past 10-20 years, it is clear that the CTM methodology has become the method of choice. It is equally clear that the CTM and ILT methods do not yield equivalent endpoint estimates. Given that the preponderance of acute estimates are now derived from CTM tests, the preferred approach would be to adjust ILT-based estimates into CTM estimates using methods described by Kilgour et al. (1985) and Kilgour and McCauley (1986). This approach would result in fewer values being adjusted, than the reverse (i.e., adjusting CTM values to their UILT equivalent). Given that databases for some species may be dominated by CTM values, another alternative would be to use only CTM estimates. Although the number of endpoints likely would be reduced for some species, few species would be eliminated. At a minimum, when compiling the database it should be acknowledged that test method does affect endpoint estimation and if no adjustment is made to the dataset, explain why adjustments were not made. Lastly, the adjustment process should be uniformly applied to all the species being considered for the database.

When Colorado was developing new thermal standards, they determined that standardization of acute thermal endpoints was necessary and that the UUILT was the most conservative endpoint and thus appropriate for their purposes. If UUILT values were not available for a particular species, they used UILT data generated at acclimation temperatures representative of "summertime conditions" in Colorado streams (Todd et al. 2008). When neither a UUILT nor an appropriate UILT was available for a species, the CTM estimate minus a conversion factor was used to approximate the UILT. Thus, Colorado converted all data to a common endpoint as we suggest, except they converted CTMs to UILTs, which is the reverse of what is suggested above. The direction one converts is largely a matter of personal preference and how the data will be used. The important point is to normalize or standardize the endpoints.

5.3 Minimum Number of Fish to be Tested

As discussed in Section 2.1, a CTM value can be generated with a single fish; however, test results based on a small number of test organisms should be rejected. We recognize that in some cases, it may be difficult to obtain an adequate number of test animals. In such cases, the data may be useful to establish the thermal sensitivity of such species relative to that established for other species in the study. Nonetheless, data on small sample sizes are not appropriate for characterizing the thermal sensitivity of a species. We recommend that CTM values based on tests with less than six fish not be used for criteria development. Ideally six or more fish would be tested and tests would be run on more than one "batch" of fish because there likely will be differences in thermal sensitivity due to a fish's overall condition, as well as its size, spawning condition, and recent exposure to stressors including disease pathogens. If the fish tested were all purchased or collected at the same time and place, variance in the endpoint estimate likely would be minimized. Conversely, because a single batch shares a common history, the natural variation in the factors just mentioned will not be captured (i.e., the batch will not be representative), so the fewer fish and batches tested, the less likely that the full range of thermal sensitivity will be captured.

5.4 Other Considerations

5.4.1 Reconciling Multiple Endpoint Estimates for the Same Species

For some of the more commonly tested species there may be multiple upper acute estimates. In similar situations for other parameters, EPA (1985) recommends using the geometric mean of the estimates to derive the Species Mean Acute Value. This approach is reasonable where estimates for one species can differ by an order or more of magnitude. However, for temperature, most estimates will be within 5°C of one another so an arithmetic mean should suffice. It could also be argued that the highest reported value should be used because numerous factors (e.g., handling or confinement stress and disease) can result in endpoint values being erroneously low, whereas there are no factors that can inflate the true endpoint for a species. Therefore, the highest value is the one that does the best job of reducing or eliminating these factors.

5.4.2 Life Stage

For small species (e.g., minnows and darters) either adults or juveniles are tested. But for species reaching moderate to large sizes as adults, tests are usually done on juveniles or YOY. This is simply a matter of convenience because testing larger fish requires larger test tanks and better temperature control systems. Although data are scant, it is believed that YOY and juveniles are more temperature tolerant than adults of the same species. Based on the fact that few species have been tested across a variety of life stages, we do not recommend making adjustments to the database based on the life stage tested, however, this recommendation could change as more data become available.

5.4.3 Derivation Methodology

Probably because of regional differences, EPA has not established national temperature standards like those set forth in their criteria documents for metals, ammonia, and many other water quality parameters. Thus, there is not an established method for deriving temperature criteria. It is beyond the scope of this report to discuss all the pros and cons of the different methods that have been used either at the state (Todd et al. 2008, Wenholz 2004) or regional level (Yoder et al. 2006). However, methods like those developed to establish thermal standards for Colorado and Wisconsin that use data from a cross-section of studies will be less affected by incorrect or aberrant data than methods like those proposed for the Ohio River (Yoder and

Emery 2004, Yoder et al. 2006) or the Chicago Area Waterway System (Yoder and Rankin 2005) that use the most thermally sensitive species to establish criteria. Note also that any database with a few data points is likely to lead to erroneous conclusions.

6

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