Arch. Hydrobiol.	99	4	529—536	Stuttgart, März 1984

The effects of rapid temperature decreases by five freshwater fish species

By Dan A. Cincotta, Jay R. Stauffer, Jr. and Charles H. Hocutt

With 1 table in the text

Abstract

Instantaneous cold shock experiments were conducted on five species of freshwater fish acclimated to two temperatures between 24 and 36 °C. The species, lethal temperature, and acclimation temperatures were: *Notemigonus crysoleucas*, 12 °C at both 30 and 25 °C; *Notropis analostanus*, 6 and 12 °C at 24 and 30 °C, respectively; *Rhinichthys atratulus*, 6 °C at both 24 and 28 °C; *Lepomis gibbosus*, 12 and 18 °C at 30 and 36 °C, respectively; and *Micropterus salmoides*, 12 °C at both 30 and 36 °C.

Introduction

The purpose of our study was to conduct acute cold shock tests on five freshwater fish species: golden shiner (*Notemigonus crysoleucas*), satinfin shiner (*Notropis analostanus*), blacknose dace (*Rhinichthys atratulus*) pumpkinseed (*Lepomis gibbosus*) and largemouth bass (*Micropterus salmoides*) at various acclimation temperatures. An test range of 24—36 °C was used to simulate the "worst case" condition of elevated temperatures in a heated, industrial discharge (Cincotta et al. 1982).

Literature pertaining to ichthyofaunal cold shock (Becker et al. 1977 a; Coutant 1972) is relatively uncommon when compared to upper tolerance and other temperature studies (Brown 1974; Hocutt et al. 1980; Richards et al. 1977). Cold shock causes fish mortality due to rapid decreases in water temperature under natural (Dahlberg & Smith 1970; Gunter 1941; Overstreet 1974) or artificial (Ash et al. 1974; Cairns 1972) conditions. Death probably ensues from a loss of nervous, circulatory respiratory, and/or osmoregulatory functions (Fisher 1958; Fry 1964).

Historically, lower incipent lethal temperatures were determined in thermal resistance experiments to complete species-specific temperature polygons (Brett 1944, 1952; Doudoroff 1942, 1945; Fry 1947; Fry et al. 1942, 1946; Hart 1947, 1952). Upper acclimation temperatures in these studies did not usually exceed 25 °C. Current research in cold shock effects on fish is to address impacts, prove compliance, or justify variance from federally-mandated environmental statutes (e. g., National Environmental Policy Act of 1969 and Section 316 a, Federal Water Pollution Control Act of 1972).

0003-9136/84/0099-0529 $ 2.00

A review of federal thermal legislation was presented by BRUNGS & JONES (1977). Recent acute cold shock investigations were conducted by BECKER et al. (1977 a), COUNTANT (1974 a), MELDRIM & GIFT (1971), and PETERSON & SHUTSKY (1976).

Material and methods

Instantaneous cold shock experiments were conducted at the Appalachian Environmental Laboratory (AEL), Frostburg, Maryland. Satinfin shiner (36.1—68.6 mm SL), blacknose dace (29.5—62.7 mm SL) and pumpkinseed sunfish (28.0—44.5 mm SL) were collected from the West Branch of Codorus Creek, York County, Pennsylvania. Specimens were captured by seine and transported to the laboratory in 94.6 liter (l) plastic barrels. Golden shiners (40.1—87.6 mm SL) and largemouth bass (27.9—66.0 mm SL) were purchased at a commercial fish hatchery in Pennsylvania and transported in styrafoam coolers (50 fish per container). Water temperatures in all containers were maintained at ambient ±2 °C. After a 24 h observation at AEL, fish that appeared diseased or ill were discarded.

Acclimation procedures were initiated by transfer of test specimens to a 37.8 liter or 75.7 liter aquarium located in a commercial walk-in refrigerator. Acclimation temperatures were controlled by Supreme aquarium heaters. Continuous water aeration and filtration were provided for all aquaria. Holding tanks were illuminated with Vitalites, and a Dayton timer maintained a photoperiod of 12 h L : 12 h D. An activated charcoal filter was used to remove impurities from the testing and holding water, which was obtained through the Frostburg water supply. Fish were fed daily, except on test days, to maintain stomach consistency.

Different acclimations were used for different species (Table 1), temperatures often approached or exceeded the ultimate upper incipient lethal temperature of the species. Fish were acclimated by raising or lowering water temperatures in holding tanks at a rate of 1 °C/day (FRY 1971). Adjustment ranges were small because test species were acquired near the intended acclimation level. Once the desired acclimation was reached, fish were held at that temperature ± 0.5 °C for a minimum of 20 days before testing.

Two groups of ten fish for each species and test condition were acclimated to the two highest acclimation temperatures. These individuals were then transferred to tanks which held water at the desired test temperature (Table 1). After each test all fish were discarded. Thus, naive fish were used for each experiment, including control tests. Observations were made every minute for the first 10 min, every 10th min for the first 100 min, every 100th min for the first 1,000 min, every 1,000th min for the for 10,000 min. The temperature at which 50 percent or greater mortality (LT_{50}) occurred during a 10,000 min (ca. 7 days) period was considered the cold shock temperature. Because of the "all or none" response, no attempt was made to interpolate LT_{50} from the data. An organism was declared "dead" when gill and muscular movement ceased, and proding with a glass rod produced no response.

Results and discussion

Results of the abrupt cold shock experiments are summarized in Table 1. The following species accounts for each species review the literature and note existing comparable data with regard to acclimation temperatures.

Table 1. Percent mortality at each acclimation temperature and exposure time period (1 = 10 min; 2 = 100; 3 = 1,000; 4 = 10,000). The asterisk (*) indicates the time and highest cold shock temperature where ≥ 50 percent mortality occurred in 10,000 min (LT_{50}).

Species	Acclimation temperature (°C)	Time period (Min)	Test shock temperatures (°C)							
			6	12	18	24	28	30	35	36
Cyprinidae										
Golden shiner	30	1	75	0	0	0	–	0[1]	–	–
		2	100	0	0	0	–	0	–	–
		3	100	0	0	0	–	0	–	–
		4	100	65*	10	0	–	0	–	–
	35	1	100	0	0	0	–	0	0[1]	–
		2	100	5	0	0	–	0	0	–
		3	100	75	15	0	–	0	5	–
		4	100	100*	30	0	–	0	25	–
Satinfin shiner	24	1	5	0	0	0[1]	–	–	–	–
		2	80	0	0	0	–	–	–	–
		3	95	0	0	0	–	–	–	–
		4	100*	0	0	0	–	–	–	–
	30	1	0	0	0	0	–	0[1]	–	–
		2	0	5	0	0	–	0	–	–
		3	100	20	0	0	–	0	–	–
		4	100	60*	0	0	–	0	–	–
Blacknose dace	24	1	0	0	0	0[1]	–	–	–	–
		2	0	0	0	0	–	–	–	–
		3	5	0	0	0	–	–	–	–
		4	90*	0	0	0	–	–	–	–
	28	1	30	0	0	0	0[1]	–	–	–
		2	35	0	0	0	0	–	–	–
		3	90	0	0	0	0	–	–	–
		4	100*	20	0	0	0	–	–	–
Centrarchidae										
Pumpkinseed	30	1	75	0	0	0	–	0[1]	–	–
		2	100	0	0	0	–	0	–	–
		3	100	10	0	0	–	0	–	–
		4	100	60*	0	0	–	0	–	–
	36	1	100	10	0	0	–	0	–	0[1]
		2	100	15	5	0	–	0	–	0
		3	100	100	40	0	–	0	–	0
		4	100	100	55*	0	–	0	–	0
Largemouth bass	30	1	90	0	0	0	–	0[1]	–	–
		2	100	0	0	0	–	0	–	–
		3	100	0	0	0	–	0	–	–
		4	100	90*	0	5	–	0	–	–
	36	1	100	0	0	0	–	0	–	0[1]
		2	100	100	0	0	–	0	–	0
		3	100	100	30	0	–	0	–	0
		4	100	100*	40	5	–	0	–	0

1 = control test

Golden shiner — Fish acclimated to 30 and 35 °C exhibited over 50 percent mortality when exposed to 12 °C. BRETT (1944) demonstrated a 3.4 °C lower incipient lethal temperature (i. e., LT_{50}) for the golden shiner acclimated to 21 °C. HART (1952) listed a lower incipient lethal temperature of 11.2 °C when this species was acclimated to 30.

Satinfin shiner — When acclimated to 24 and 30 °C, lethal cold shock temperatures were 6 and 12 °C, respectively. No other published instantaneous cold shock data are known for this species.

Blacknose dace — When acclimated to 24 and 28 °C, lethal cold shock temperatures for *R. atratulus* were 6 °C. HART (1947) indicated that this species had a lower incipient lethal temperatures of 2.2 and 5 °C, when acclimated to 20 and 25 °C, respectively.

Pumpkinseed — When acclimated to 30 and 36 °C, temperatures at which 50 percent or more mortality occurred in 10,000 min were 12 and 18 °C, respectively. BECKER et al. (1977 a) demonstrated an LT_{50} of 12.3 C when pumpkinseeds were acclimated to 30 °C. PETERSON & SHUTSKY (1976) indicated that specimens collected in 13—27 °C waters could withstand cold shock temperatures of 7—11 °C with no significant mortalities.

Largemouth bass — Specimens acclimated to 30 and 36 °C exhibited over 50 percent mortality when exposed to 12 °C. PETERSON & SHUTSKY (1976) concluded that largemouth bass could tolerate 8.5 and 8.0 °C abrupt temperature declines with no mortalities when acclimated to 24.5 and 27 °C, respectively. HART (1952) found only a 0.3 °C difference in lower lethal temperatures for northern and southern subspecies of *M. salmoides* (5.2 °C the for northern, 5.5 °C for the southern) when the fish were acclimated to 20 °C, but a 1.3 C difference (10.5 and 11.8 °C, respectively) when they were acclimated to 30 °C.

General discussion

Mortalities of ichthyofauna near thermal discharges have been a problem in recent decades (BECKER et al. 1977 b). Ambient discharge temperatures associated with cold winter temperatures in the receiving water body and abrupt potential for cold shock mortalities. Based on knowledge that fishes may not totally acclimate to the highest effluent temperature (KELSO 1976; NEILL & MAGNUSON 1974; SPIGARELLI 1975), occasional movements away from the elevated temperature area may play a role in preventing many kills. Abrupt effluent shutdowns can cause fish mortality.

Actual losses associated with thermal shutdowns are difficult to estimate. Estimate may be fairly accurate when species-specific data from the same geographic region are employed (BECKER et al. 1977 b). Cold shock mortality predictions, however, may be influenced by indirect factors such as susceptibility to impingement or entrainment (HOCUTT 1973), predation (COUTANT 1974 a), disease (DOUDOROFF 1942), asphixiation in bottom waters (PETROSKY & MAGNUSON 1973), and death via secondary shock from lower cold water layers (BECKER et al. 1977 a). COUTANT (1974 b, 1977) offered guidance in power plant siting, design, and operation that would minimize fish loss from cold shock. Furthermore, BECKER et al. (1977 b) discussed the problem of predicting the effects of cold shock and proposed a model to estimate temperature declines in thermal plumes originating from suddenly terminated off-shore discharges.

MATHUR et al. (1981) recently discussed statistical similarities relative to thermal behavior data for geographically separated populations of the same species of fish and among species within a family. Although no comparison has been demonstrated for species in regard to lethal tolerance levels, BRUNGS & JONES (1977) suggested such a correlation for cold shock events. They constructed a nomograph, summarizing data for 20 species of frehswater fish and suggested it could be used as a replacement for species-specific information covering all "warm water and cold water species." CINCOTTA et al. (1982) discussed the restricted merit of this approach in thermal impact evaluations, and indicated caution when such an application is used.

We did not attempt to isolate the "exact" lower incipient lethal temperatures in this study. As discussed by FRY (1947), this classical value (where 50% mortality is achieved) is ordinarily derived from time mortality curves or a dosage mortality methodology. Our data provide safe, economical, and expedient ecological winter evaluations for artificially heated waters (e.g., CINCOTTA et al. 1982; PETERSON & SCHUTSKY 1976). Recently, BECKER et al. (1977 a, b) indicated that, although mortality might be underestimated, gradual shock information or "Critical Thermal Minimum" data (see COWLES & BOGART 1944) could be utilized for realistic fish kill predictions. To offset underestimations, they suggested a "safety factor" be incorporated to provide a more accurate assessment. The abrupt cold shock tests we performed provide an overestimation of mortalities and, hence, have a margin of safety automatically incorporated into the experiment.

Acknowledgements

Special thanks are extended to Dr. ROBERT F. DENONCOURT (York College of Pennsylvania, York) for his advice and encouragement throughout this study. We are also grateful to the following biologists who aided the study during various aspects: ANNE G. CINCOTTA, DONAT G. DENONCOURT, KENNETH L. DULL, LENWOOD W. HALL, EDWARD L. MELISKY, and JOHN W. STAMBAUGH. This research was funded in part by P. H. Glatfelter Paper Company, Spring Grove, Pennsylvania.

Literature cited

Ash, G. R., Chyko, N. R. & Gallup, D. N. (1974): Fish kill due to "cold shock" in Lake Wabamum, Alberta. — J. Fish. Res. Bd. Can. **31:** 1822—1924.

Becker, C. D., Genoway, R. G. & Schneider, M. J. (1977 a): Comparative cold resistance of three Columbia River organisms. — Trans. Amer. Fish. Soc. **106:** 178—184.

Becker, C. D., Trent, D. S. & Schneider, M. J. (1977 b): Predicting the effects of cold shock: modelling the decline of a thermal plume. — Battelle, Pacific N. W. Lab. Rept. No. 2411, Richland, WA.: 1—25.

Brett, J. R. (1944): Some lethal temperature relations of Algonquin Park fishes. — Univ. Toronto Studies Biol. Ser., **52:** 1—49.

— (1952): Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. — J. Fish. Res. Bd. Can. **9:** 265—323.

Brown, H. W. (1974): A handbook of the effects of temperature on some North American fishes. — Amer. Elec. Power Surv. Corp., Canton, OH: 1—431.

Brungs, W. S. & Jones, B. R. (1977): Temperature criteria for freshwater fish: Protocol and procedures. — Environ. Res. Lab., Ecol. Res. Ser. EPA-600/3-77-061. Off. Res. Devel., U.S. Environ. Prot. Agency, Duluth, MN.

Cairns, J., Jr. (1972): Coping with heated waste discharges from steam electric power plants. — Bio. Sci. **22:** 411—420.

Cincotta, D. A., Stauffer, J. R., Jr. & Hocutt, C. H. (1982): Application of fish responses to temperature to assess the effects of a thermal discharge on biological integrity. — Wat. Res. Bull. **18:** 437—450.

Coutant, C. C. (1972): Time-temperature relationships for thermal resistances of aquatic organisms, principally fish. — Rep. ORNL-EIS-72-27. Oak Ridge National Lab., Oak Ridge, Tenn.

— (1974 a): Effects of cold shock on vulnerability of juvenile channel catfish *Ictalurus punctatus* and largemouth bass *Micropterus salmoides* to predation. — J. Fish. Res. Bd. Can. **31:** 351—354.

— (1974 b): Cold shock: tolerable temperature and guidance for power plants. — Trans. Amer. Nucl. Soc. **18:** 47—48.

— (1977): Cold shock to aquatic organisms: guidance for power plant siting, design, and operation. — Nuclear Safety **18:** 329—342.

Cowles, R. B. & Bogert, C. M. (1944): A preliminary study of the thermal requirements of desert reptiles. — Bull. Amer. Mus. Nat. Hist., **83:** 265—298.

Dahlberg, M. D. & Smith, F. G. (1970): Mortality of estuarine animals due to cold on the Georgia coast. — Ecol. **51:** 931—933.

Doudoroff, P. (1942): The resistance and acclimatization of marine fishes to temperature changes. I. Experiments with *Girella nigricans* (Ayres). — Biol. Bull. **83:** 194—206.

— (1945): The resistance and acclimatization of marine fishes to temperature changes. II. Experiments with *Fundulus* and *Atherinops*. — Biol. Bull. **88** (2): 194—206.

Fisher, K. C. (1958): An approach to the organ and cellular physiology of adaptation to temperature in fish and small mammals, pp. 3—49. — In: C. L. Prosser, ed.: Physiological adaptation. — Amer. Physiol. Soc., Washington, D.C.

Fry, F. E. J. (1947): Effects of the environment on animal activity. — Univ. Toronto Stud. Biol. Ser. 44, Publ. Ont. Lab. **68:** 1—91.

— (1964): Animals in aquatic environments: Fishes, pp. 1—63. — In: D. B. Dill, E. F. Adolph, & C. G. Wilber, eds.: Adaptation to the environment (Handbook of Physiology, Section 4). Amer. Physiol. Soc., Washington, D.C.

— (1971): The effects of environmental factors on the physiology of fish. pp. 1—87. — In: W. S. Hoar & D. J. Randall, eds.: Fish Physiology. — Academic Press, New York.

Fry, F. E. J., Brett, J. R. & Clawson, G. H. (1942): Lethal limits of temperature for young goldfish. — Rev. Can. Biol. **1:** 50—56.

Fry, F. E. J., Hart, J. S. & Walker, K. F. (1946): Lethal temperature relations for a sample of young speckled trout, *Salvelinus fontinalis.* — Univ. Toronto Stud., Biol. Ser. 54, Publ. Ontario Fish. Res. Lab. **66:** 9—35.

Gunter, G. (1941): Death of fishes due to cold on the Texas coast, Jan 1940. — Ecol. **22:** 203—208.

Hart, J. S. (1947): Lethal temperature relations of certain fish of the Toronto region. — Trans. Royal Soc. Can. Vol. **41,** Series 3 (Section 5): 57—71.

— (1952): Geographical variations of some physiological and morphological characteristics in certain freshwater fishes. — Univ. Toronto Stud. Biol. Series No. 60. Publ. Ontario Fish. Res. Lab. No. **72:** 1—79.

Hocutt, C. H. (1973): Swimming performance of three warmwater fishes exposed to a rapid temperature change. — Chesapeake Sci. **14:** 11—16.

Hocutt, C. H., Stauffer, J. R., Jr., Hall, L. W. Jr., Edinger, J. E. & Morgan II, R. P., eds. (1980): Powerplant: Effects on fish and shellfish behavior. — Academic Press, New York.

Kelso, J. R. M. (1976): Movement of yellow perch (*Perca flavescens*) and white sucker (*Catostomus commersoni*) in a nearshore Great Lakes habitat subjected to a thermal discharge. — J. Fish. Res. Bd. Can. **33:** 42—53.

Mathur, D., Schutsky, R. M., Purdy, E. J. Jr. & Silver, C. A. (1981): Similarities in acute temperature preferences of freshwater fishes. — Trans. Amer. Fish Soc. **110:** 1—13.

Meldrim, J. W. & Gift, J. J. (1971): Temperature preference, avoidance and shock experiments with estuarine fishes. — Ichthyological Assoc. Bull. **7:** 1—75.

Neill, W. H. & Magnuson, J. J. (1974): Distributional ecology and behavioral thermoregulation of fishes in relation to heated effluent from a power plant at Lake Monona, Wisconsin. — Trans. Amer. Fish. Soc. **103:** 663—710.

Overstreet, R. M. (1974): An estuarine low-temperature fish kill in Mississippi, with remarks on restricted necropsies. — Gulf Res. Rept. **4:** 328—350.

Peterson, S. E. & Schutsky, R. M. (1976): Temperature experiments with fishes, pp. 5—1 and 5—125. — In: T. W. Robbins & D. Mathur, eds.: Peach Bottom Atomic Power Station, Postoperational Report No. 5 on the Ecology of Conowingo Pond for the period of July 1975—December 1975. Ichthyological Assoc., Inc., Drumore, Pennsylvania: 1—501.

Petrosky, B. R. & Magnuson, J. J. (1973): Behavioral responses of northern pike, yellow perch and bluegill to oxygen concentrations under simulated winter kill conditions. — Copeia **1973:** 124—133.

Richards, F. P., Reynolds, W. W. & McCauley, R. W. (1977): Temperature preference studies in environmental impact assessments: An overview with procedural recommendations. — J. Fish. Res. Bd. Can. **34:** 728—761.

SPIGARELLI, S. A. (1975): Behavioral responses of Lake Michigan fishes to a nuclear power plant discharge, pp. 479—498. — In: Environmental effects of cooling systems at nuclear power stations. (AEA) Int. Atomic Energy Agency, Vienna.

Addresses of the authors:

DAN A. CINCOTTA, West Virginia Department of Natural Resources, Wildlife Resources Division, P. O. Box 67, Elkins, West Virginia 26241.

Dr. JAY R. STAUFFER, Jr. Appalachian Environmental Laboratory, University of Maryland, Center for Environmental and Estuarine Studies, Frostburg, Maryland 21532.

CHARLES H. HOCUTT, University of Maryland, Horn Point Environmental Laboratories, Center for Environmental and Estuarine Studies, Cambridge, Maryland 21613.