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Field and laboratory evaluations of the effects of "cold shock" on fish resident in and around a thermal discharge: an overview

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Abstract

In the 1970s, resource agencies suggested that thermal discharges could affect aquatic life including macrophytes, plankton, and fish. It was suspected that heat and cold shock would affect fish health and behavior, and that thermal plumes might affect migration. From 1978 to 1985, Rochester Gas & Electric Corporation (RG&E) conducted field and laboratory studies on fish to evaluate a power plant's rapid winter shutdown. Lake Ontario studies included observations of fish in the near-field plume during a shutdown, and resident fish were tagged and used to study immediate and acclimated cold shock. Over 500 fish representing 17 species, captured in and around a power station plume, were used in these cold-shock studies. Five coldwater species accounted for approximately 65% of the tested fish, although clupeids, and coolwater and warmwater fish were evaluated when captured. The internal temperature of many fish was recorded upon capture. Survival for the dominant species was ≃100%, although clupeid survival was ≤10% (n = 128). Tagged fish also provided long-term survival, migration, and plume-residence data. To confirm field data, laboratory cold-shock tests were conducted under controlled conditions using hatchery-reared juvenile rainbow trout. The results indicated, for example, that the lower lethal limit for rainbow trout was slightly below 1.0°C, corroborating field data for rainbow trout. These cold-shock studies suggest that previous generic guidelines, such as those provided by the United States Environmental Protection Agency (USEPA), are probably too conservative. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In the 1970s, state and federal agencies suggested that thermal discharges could affect aquatic life including macrophytes, zooplankton, phytoplankton, and fish residing in the receiving waters. General information on fish thermal tolerance (Brett, 1956) was available at the time, and later publications discussed ecological effects of thermal discharges (Langford, 1990).

It was suspected that thermal plumes could affect fish migration and/or the heated water would cause thermal shock. Most literature dealt with the heat-shock issue (Ash et al., 1974). However, it was suggested that fish in temperate lakes would acclimate to a discharge in winter and become dependent on the warm water to maintain their body temperature and then, if the power station shut down, the fish would experience thermal stress (i.e., cold shock) (Edsall and Yocum, 1972; Templeton et al., 1974; Reutter and Herdendorf, 1974; Coutant, 1977). Cold shock of fish resident in a relatively long discharge canal on a small lake in Alberta was evaluated (Ash et al., 1974) and provided insight on winter study conditions. However, literature specific to cold shock in a Great Lakes discharge plume was not available at the time the studies discussed in this paper were conducted.

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The potential for cold shock during a power station shutdown was generally addressed in the Federal Water Pollution Control Act (Clean Water Act) Amendments of 1972. Section 316(a) of the Act specifically addresses the issue of thermal discharge, although the section has not been promulgated. To comply with Clean Water Act mandates as administered by USEPA, New York State incorporated the wording of Section 316(a) into the state's equivalent to the National Pollution Discharge Elimination System (NPDES) permit process, i.e., the State Pollution Discharge Elimination System (SPDES). There were several utilities with power plants on the Great Lakes that required a SPDES permit, including RG&E plants.

Field data on plant shutdown and cold shock for Great Lakes fish were limited, partially because of the difficulty and dangers in conducting winter studies at this latitude. Freezing water temperatures, wave activity and ice posed a threat to the field scientist, as well as the boats and gear used to capture or observe fish. Study costs were high and were compounded by several factors, in addition to safety issues. A cold shock study in the field had to account for fish that might die in a plume and sink out of sight, making it difficult to track them (Brett, 1944), and to determine if mortalities occurred over the long term. As a result of these problems in the field, most cold shock assessments were based on theoretical analyses and laboratory findings (Spigarelli, 1975). The lack of in-situ data made it difficult to determine the accuracy of the theoretical estimates of cold shock. Agencies stocked several exotic salmonid species in the lake beginning in 1968 (Parsons, 1973; NYSDEC, 1999), and further complicated cold shock evaluations, as the relationship of these fish to a lake discharge plume was unknown. The permit process, and the lack of direct information for Lake Ontario, prompted RG&E to conduct in-situ investigations in winter. Field studies were designed to determine if fish were resident in the vicinity of a discharge plume and, if so, whether they were susceptible to cold shock. Laboratory studies also were conducted to compare with the field studies and relevant literature. This paper provides an overview of methods and results.

From 1978 to 1983, RG&E conducted a winter fisheries program at the Ginna Nuclear Power Station (GNPS) and the Russell (Fossil) Power Station. The primary study site was the GNPS located on Lake Ontario, approximately 32 km east of Rochester, NY. The station uses a once-through cooling system (~25 m^3/s; ~400,000 gpm), and heated water flows into a short discharge canal, which directs the heated water to the lake shore. The water depth at the mouth of the canal is typically 2.5 m, but varies with lake level. The depth increases towards the head of the canal. If fish in the lake are capable of swimming against the discharge current, they can move in and out of the canal at will. At the shoreline, the heated water layers on the surface of the lake and forms a thermal plume. It was speculated that in winter, when the plume cooled to 4°C, it would "dive" below the unheated lake water because of the density transition.

Prior to conducting the field cold shock studies reported herein, RG&E completed a pilot study at the GNPS to assess the potential for a cold shock event (RG&E, 1982). The field methods developed in the pilot study were used in the cold shock studies. The following overview of the cold shock studies concentrates primarily on field studies conducted from 1980 to 1983 at the GNPS site, and the 1984–1985 laboratory bioassays conducted in the RG&E environmental laboratory located in Rochester, NY, on the Genesee River.

2. Methods

Winter studies were conducted between late December and early April at the GNPS. Considerable effort was applied to monitor and capture the fish species residing in the discharge canal and in or near the thermal plume. As conditions permitted, several techniques were used to monitor (or capture) fish in the canal, lake and plume. The methods used included gill nets, underwater video cameras and lights, time-lapse VCRs, SCUBA diving, and electrofishing. When possible, fish captured by electrofishing were tagged. A schematic of the discharge canal and plume area, indicating relative locations of the sampling areas and gear types, is presented in Fig. 1. Although one of the primary objectives was to evaluate cold shock, fish used in the cold shock tests were, in some cases, also used in subsequent heat-shock tests. Information on heat shock is discussed only where it is directly associated with cold shock tests.

Electrofishing was the most versatile technique for winter studies and was used in three ways to monitor or capture fish. A fiberglass shocking boat, outfitted to fish in the rocky, near-shore areas of the lake or in the plume, was used when the water was clear of ice. During ice-in, the fiberglass boat was replaced with rubber rafts. The rafts were dragged across the ice to the plume area. The rafts were outfitted with holding tanks, generators, and electrofishing equipment. A land-based electrofishing system with modified electrodes and long handled nets provided the means to stun and retrieve fish in the canal from shore. Fish were landed on the narrow walkway between the GNPS screenhouse and discharge canal. Smith-Root Type VIa power supplies, set to provide pulsed-DC electric fields, were used

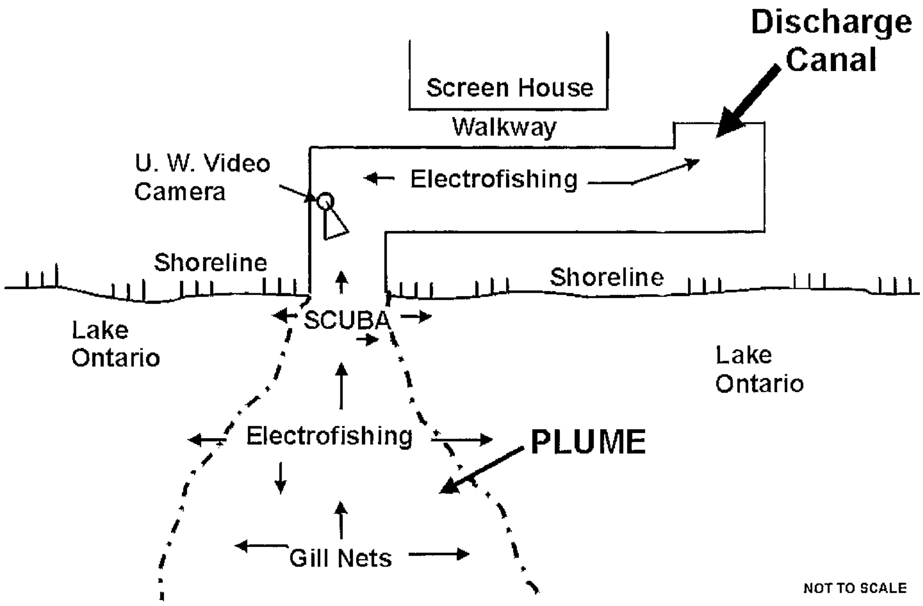

Fig. 1. Ginna discharge, canal, plume and relative sampling locations/types (top view).

on boats, rafts, and shore. The electric field generated in near-shore areas and the discharge canal was distributed from the surface to bottom as a result of electrode placement. The actual time a field was applied in the water (i.e. system activated time) was recorded.

Each fish captured by electrofishing was typically tagged using a numbered internal anchor tag. The tags were used to track individual fish during the studies. At the conclusion of a cold shock test, live fish were returned, complete with tags, to the discharge canal or lake (or the heated acclimation tank for a heat-shock test, prior to return to the canal). It was anticipated that long-term survival and migration information for these fish (or others tagged in the plume or canal and immediately released) could be obtained if recaptured during RG&E efforts or via angler return. The tags advertised a reward for anglers who returned the tag, along with information on when and where the fish was caught.

When a fish was captured by electrofishing, its internal temperature (anal) was typically measured with a digital thermometer (calibrated against a precision thermometer). Application of a tag or collection of internal temperature data was omitted if a fish were too small or it was presumed especially susceptible to handling stress [e.g., gizzard shad (*Dorosoma cepedianum*) typically were not tagged because of the stress].

Many resident or transient fish captured in or near the plume were used in Immediate Cold Shock or Acclimated Cold Shock (ICS or ACS) tests[1] to determine the potential effect of a rapid plant shutdown in winter. Most of these fish were obtained during canal electrofishing.

In an ICS test, when the lake was iced-in and rafts were used, captured fish were carted to shore and quickly trucked to the plant, or if conditions permitted use of the fiberglass boat, fish were passed to shore-personnel at the plant (ice permitting). The collection of internal temperatures or the tagging procedure at times were deferred until the fish could be attended to on shore if weather conditions were not suitable. All fish were placed into a 200-g holding tank and/or 500-g recovery tank, maintained with a flow of discharge water in the GNPS screenhouse. Fig. 2 provides a schematic of the tank configuration in the screenhouse. Fish caught from the walkway were passed through a window in the screenhouse and into either the 200 or 500-g tank. ICS fish were held in these tanks for a relatively short period (on the order of 1 h, typically < 24 h). The temperature of the canal water and holding/recovery tanks varied between 10 and 17°C as a function of plant operations and ambient lake temperature, but was typically between 11 and 15°C. The holding period allowed fish some recovery from electrofishing and other handling stress. After the holding period, the fish were dip-netted from the holding/acclimation tank(s) and transferred to one of three 100-g cold-shock tanks.

ACS test fish were handled similarly except they

[1] For the purposes of this paper, ICS tests are defined as those where captured fish were held in a recovery tank for short periods (typically < 24 h) prior to the fish placement in a cold-shock test tank. ACS tests are defined as those tests where captured fish were held in a warm water acclimation tank for many days (typically 14) prior to the fish placement into a cold-shock test tank.

were held in the 500-g recovery/acclimation tank for 7–14 days (typically 14 days) before transfer to one of the 100-g cold-shock tanks. The ICS and ACS fish were treated the same once they were in a cold shock tank.

An individual fish's behavior initially was tracked closely for several hours, then intermittently until the end of the test. A test typically lasted for ≥96 h. Dead fish were removed. At the conclusion of a test and before release, the length and weight of a fish were typically recorded, as well as qualitative information on fish condition [e.g., swimming normally (sn), sn with fungus, sn with contusions, scars, etc.]. Fish not swimming upright at the end of a test were considered dead. Loss of equilibrium when transferred into a cold-shock tank was noted, if observed.

Four insulated tanks were used to hold cold water, each fitted with a chiller. The water was circulated in a closed-loop system between tanks via submersible pumps and siphons. Only three of the tanks in the system (cold-shock tanks) held fish. The fourth was used to increase coldwater volume and maintain temperatures. Small volumes of water were added to the system, as necessary, to compensate for evaporative losses. The temperatures in these tanks were typically between 0.4 and 0.6°C, although temperatures became as low as 0.2°C. All tank temperatures routinely were monitored and logged, along with the condition of the fish. Fish were not fed while in the tanks.

Control tanks and fish were not used in the field studies for cost and logistic reasons. It was decided that any mortality would be attributed to thermal stress, although electrofishing or handling stress, acting alone or synergistically with cold shock, may have contributed to mortality.

The laboratory bioassay (cold shock study) was conducted in 1984–1985, and results were compared to the GNPS field data and the literature. Hatchery-reared fingerling rainbow trout (*Oncorhynchus mykiss*, formerly *Salmo gairdneri*) 70–150 mm in length were used. Laboratory tests were run under controlled conditions. These tests were designed to replicate experiments reported by Becker et al. (1977). Fish were acclimated to 10–15°C for a period of two to three weeks, and then immediately transferred to a test tank maintained at 0.5, 1.0, 2.0, or 3.0°C. Fish were held in the test tanks for 96–240 h and frequently observed for loss of equilibrium (LOE) and survival rate. In 1985, these experiments were repeated to focus on the lower thermal limit of rainbow trout acclimated to 15°C. In this study, they were immediately transferred into one of six coldwater tanks. Average temperatures (and ranges) in these tanks were 0.65 (0.33–0.90), 0.57 (0.55–0.59), 0.74 (0.69–0.79), 0.77 (0.75–0.80), 0.91 (0.88–0.98), and 0.97 (0.88–1.14)°C for the duration of the 10-day study period. The slight difference in temperatures between tanks allowed us to evaluate six different temperature conditions near or below the lower limit of 1.0°C, as determined in 1984. The data for both years have been combined in this paper.

3. Results and discussion

In the 1981–1983 field tests, 358 fish from 10 species were subjected to ICS tests and 180 fish from 13 species were subjected to ACS tests

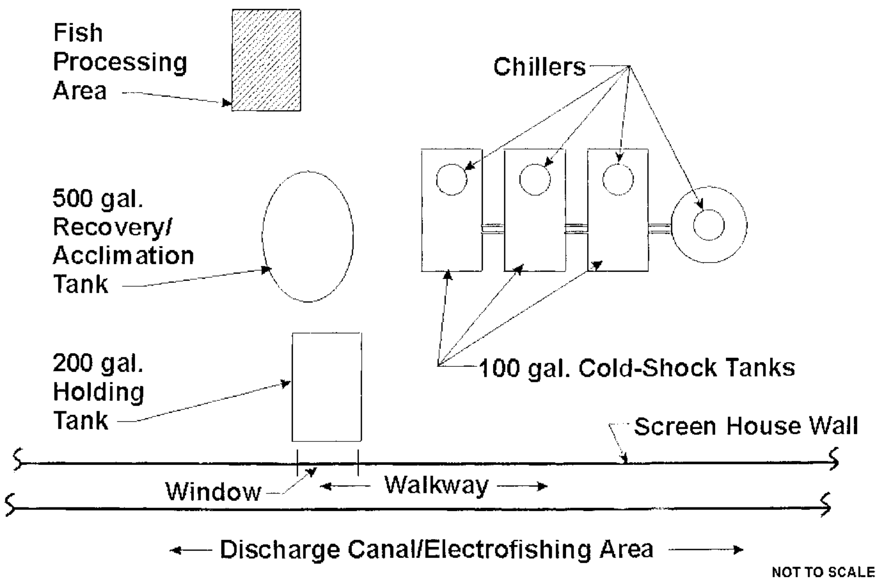

Fig. 2. Ginna screenhouse holding/acclimation and test tank configuration (top view).

(Table 1). Coldwater, coolwater, and warmwater species were included. Only four species were tested in sufficient numbers (minimum of 25 specimens) to warrant discussion in this overview: brown trout (*Salmo trutta*); rainbow trout (*Oncorhynchus mykiss*); walleye (*Stizostedion vitreum*); and gizzard shad, although other species were captured and tested. Because so few of the other species were caught and tested, the cold-shock data for these fish provide no definitive information. However, as it is difficult to capture fish in winter and these species are of interest to many scientists, the data are presented in Table 1.

Most fish captured were used in the ICS tests. In ICS or ACS studies, large salmonids were most commonly represented in electrofishing efforts and throughout most of the period of study. Other species were found relatively few times and in relatively low numbers, but were tested when captured. Gizzard shad were often not represented in the electrofishing catches, but when present, they were found typically in relatively high numbers. In ACS tests, there was some selection both for and against the use of a salmonid species in a test. For example, once sufficient test data were obtained for brown trout, they were often excluded from later tests when tank space was limited, even though they may have been the major fish in a catch. The capture data from other gear types suggested the electrofishing data closely reflected species diversity in the area.

Internal temperatures of fish when caught were typically near (±1.0°C) the temperature of the discharge waters, indicating that these fish were in warm water long enough for their body tissues to reach the discharge temperature.

While the strict criteria established for laboratory testing were not met in the field tests (e.g., no control, variability in test conditions), it is believed that the field data provided representation of the primary fish resident in the discharge canal and plume in winter. Also, the test conditions were typically more extreme (i.e., worst-case) than the fish might encounter at the power station (i.e., test temperatures were typically 0.4–0.6°C, whereas lake ambient temperatures were frequently > 1–2°C) (RG&E, 1982).

With the exception of gizzard shad, most fish at test end were classified as being in excellent condition (e.g., swimming normally) or good condition (e.g., swimming normally with fungus). Most of the surviving gizzard shad, along with a small percentage of fish of other species, were in poor condition upon release (e.g., swimming upright, but covered with fungus or contusions, etc.). Some of the tagged brown and rainbow trout released at the end of a cold-shock study were recaptured months later and/or miles away from the GNPS site, which indicated long-term survival of

Table 1
Summary of field ICS and ACS study results (1980–1983)

Test	Species	No. tested	Survival rate (%)	Average length (cm)
ICS	Brown trout	112	96	45.9
	Gizzard shad	117	10	40.3
	Rainbow trout	72	76	41.8
	Walleye	25	92	40.3
	Chinook salmon	16	38	48.8
	Coho salmon	5	80	42.5
	Lake trout	3	100	61.6
	White perch	3	67	29.0
	Smallmouth bass	3	67	35.2
	White bass	2	100	33.0
	Total	358		
ACS	Brown trout	85	99	42.9
	Rainbow trout	52	77	40.9
	Pumpkinseed	16	31	13.1
	Gizzard shad	11	0	25.9
	White perch	5	100	24.0
	Smallmouth bass	2	100	30.0
	Goldfish	2	100	24.1
	Yellow perch	2	100	17.2
	White Sucker	1	100	39.6
	Bluegill	1	100	15.2
	Brown bullhead	1	100	–
	White bass	1	100	33.2
	Rock bass	1	0	14.8
	Total	180		

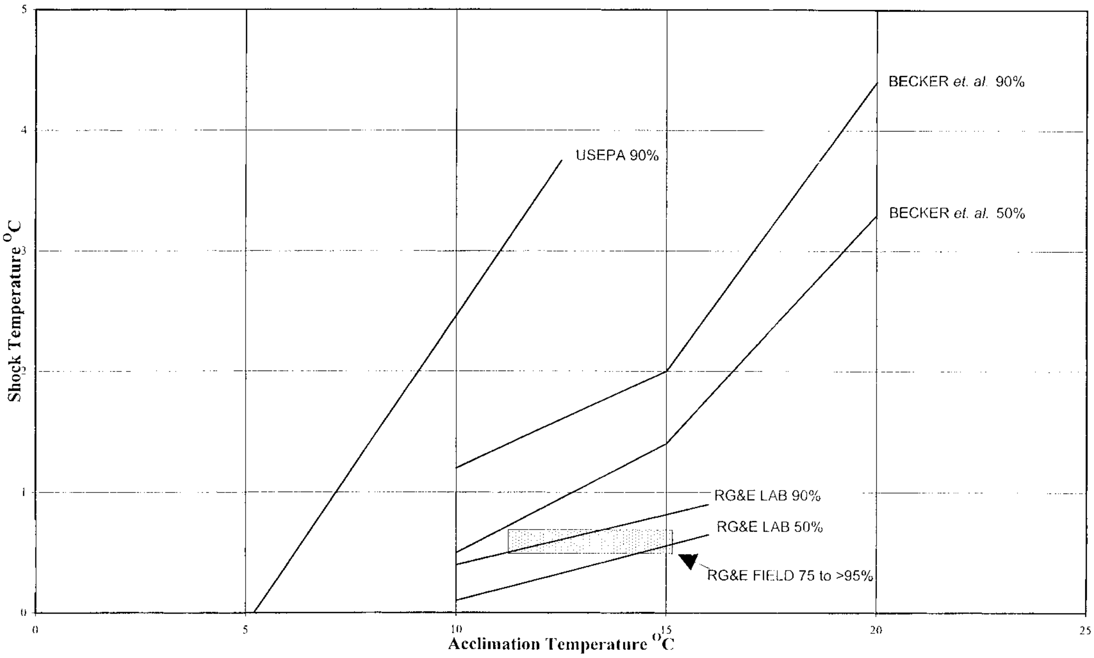

Fig. 3. Comparison of USEPA, Becker et al. and RG&E cold-shock survival curves.

these fish. Salmonid species generally showed little sign of loss of equilibrium and, if observed, they typically recovered quickly.

In laboratory tests of rainbow trout, survival was 100% for fish acclimated to 10°C and shocked at any of the test temperatures. In the 1984 experiments, the fish acclimated to 15°C showed a 40% survival rate when shocked at 0.5°C and a 100% survival rate when shocked at the next highest test temperature of 1.0°C. Thus, the lower lethal temperature[2] for fish acclimated to 15°C was between 0.5 and 1.0°C. In the 1985 experiments, which focused on determining the lower lethal temperature for rainbow trout acclimated to 15°C, survival rates ranged from 10 to 90% for the six temperature conditions tested. Furthermore, it generally was found that little mortality occurred during the first 48 h; most mortality occurred during the third to sixth day of a test, after which the rate was low for the remaining four days of testing. The only LOE was found in fish acclimated to 15°C and shocked at 1.0°C (50% LOE) and at 0.5°C (100% LOE). Fig. 3 includes mortality curves developed from the results of the 1984 and 1985 laboratory cold-shock studies.

4. RG&E results vs literature data

While the potential for cold shock has often been hypothesized, specific findings on studies relating to its occurrence are sparse. Two items directly applicable are the USEPA nomograph for cold-shock evaluation (USEPA, 1975) and a paper by Becker et al. (1977) referring specifically to rainbow trout. The USEPA material refers to salmonids in general and is based upon literature regarding temperature tolerances of various salmonid species, plus an added safety factor to ensure survival of most fish. The findings from these references are presented in Fig. 3.

Based on the USEPA data, salmonids at a discharge (or acclimation) temperature of 10°C could survive an immediate drop in temperature to 2.5°C at a rate of 90%. Based on Becker et al. (1977), rainbow trout acclimated to 10°C and shocked to 1.2°C would survive at a 90% rate. Similarly, Becker et al. indicate that this species, if acclimated at 15°C and cold shocked at 2.0°C, also would survive at the 90% rate.

In comparison, rainbow trout and brown trout, test data from the GNPS (confined in the rectangle in Fig. 3) indicated that 90% of brown trout acclimated at 11–15°C would survive at 0.4–0.6°C, nearly 2° colder than the USEPA guidelines. Under similar test conditions at GNPS, rainbow trout survived at a rate of 76%, whereas Becker et al.'s results (Fig. 3) indicated that < 50% would survive.

Clearly, these results show that the USEPA nomograph is too general and conservative for practical use in cold shock evaluations. Coutant (1977) states that the nomograph should be used when no species-

[2] Defined as the temperature at which 50% died during the ~96-h holding period.

specific data are available. The USEPA information is a general trend derived from a compilation of tests performed on various species of salmonids, to which a "safety factor" was added.

Furthermore, the ICS, ACS, and lab test results indicate that the results of Becker et al. (1977) also are very conservative. The difference seen between our tests results and those of Becker et al. cannot be explained so easily, since the same species were compared using similar test procedures. We can, however, discuss possible reasons for the differences.

Becker et al. used laboratory-hatched and raised juvenile fish. The fish we used in field studies were also hatchery fish, but the similarities end there. Our hatchery fish were stocked in Lake Ontario by agencies and most fish had grown to adult size in the lake before we captured and used them in our ICS or ACS studies at the GNPS. Thus life stage or size may account for different results, at least in field ICS and ACS tests. However, Fry et al. (1946) reported that thermal resistance was unrelated to fish size (at least for fish of the same year class), and juvenile fish were used by Becker et al. and our lab tests. Possibly the results were influenced by a difference in the genetic strain of the rainbow trout.

Our results showed similar survival rates between fish in field ICS tests and in ACS tests (i.e., rainbow trout: 77% survival in ACS vs 76% survival in ICS; brown trout: 99% survival in ACS vs 96% survival in ICS). If the ICS fish were not acclimated to the plume temperatures, it would be logical to expect that the survival rate of fish in field ICS tests would be higher than for the fish used in the Becker et al. (1977) tests or our field ACS tests, (i.e. the Becker et al. and our ACS fish were acclimated to the same temperature). However, the Becker et al. fish had a lower survival rate than our ICS fish (or ACS fish from our field or lab tests). Thus, acclimation period cannot account for the differences between our results and those of Becker et al. (1977).

The similarity in our field ACS and ICS survival rates suggests that fish captured in the plume at GNPS were already acclimated to the plume temperatures when captured. If the ICS fish were acclimated, the slight differences between our field ACS and ICS survival rates could have been due to tank recovery factors.

Continuing the comparison to Becker et al's results: it is probable the Becker fish and our field test fish had quite different life histories. For example, it is known that the source of many of the rainbow trout in Lake Ontario is the Caledonia, New York Fish Hatchery, where daily temperature fluctuations can be ~6°C (D. Longacre, Caledonia Fish Hatchery, pers. comm.). Younger fish or fish raised in a more stenothermal environment may be more susceptible to thermal stress. The ACS and ICS fish tested at the GNPS were hatchery stocked fish. After stocking these fish were also exposed to the extremes in natural temperature fluctuation in Lake Ontario as the fish grew, possibly cropping less tolerant fish from the population. The adult fish eventually captured in the plume area might then have had a physiological advantage.

The susceptibility of gizzard shad to cold shock has been reported previously and has been demonstrated again in the present study (Cox and Coutant, 1976; Balesic, 1977). More than 100 gizzard shad were tested in the ICS method, but only 10% survived the four-day test, while none of the 11 tested in the ACS method survived. Thus, the potential for gizzard shad to survive a cold shock experience during a winter shutdown would be slight, unless handling stress played a major part in the test mortality.

Based on data from Cox and Coutant (1977) and Balesic (1977), the lower lethal temperature for gizzard shad acclimated to 15°C appears to be slightly >5°C. Since the present study utilized gizzard shad acclimated to 11–15°C, and if we disregard handling stress, the lower lethal limit for these fish is probably somewhat below 5°C. LOE curves for gizzard shad developed by Cox and Coutant (1977) indicate that gizzard shad, acclimated to 15°C and shocked to 1°C, would lose equilibrium after ~2 min. In the present study, LOE data were recorded for nine fish. Gizzard shad obtained from water at 13.1–13.2°C and shocked in water at 0.4–0.6°C exhibited severe LOE in an average time of 5.7 min, somewhat longer than reported by Cox and Coutant. Overall, the fish in the present study were larger than those studied by Cox and Coutant, but no relationships were found in the our tests between fish size and time to LOE. Fry et al. (1946) also reported no relation between LOE and size. In summation, it can be stated that gizzard shad exposed to these cold shock conditions would show LOE in 2–5 min followed by death within four days.

Although only 25 walleyes were captured and used in the ICS studies, it is apparent that these resident fish were little affected by cold shock (survival rate of 92%). There was, however, little to compare our data to. The temperature requirements of walleye are not well established (Wrenn and Forsythe, 1978) and generally the literature discusses upper temperature limitations for the species. Relative to cold temperatures, Miller, (1967) and Hokanson, (1977) reported that walleye reproduction can be affected if winter temperatures do not fall below 10°C. Thus, if walleye remained in the plume for the winter it could be a problem. However, our data indicates few of these fish are found in the plume and then only for a short time.

5. Conclusions

Cold shock should have limited effect on brown trout, rainbow trout, and walleye at GNPS. However, the potential for gizzard shad to survive cold shock would be slight. Laboratory experiments showed that the lower thermal tolerance limit for juvenile rainbow trout acclimated to 15°C is ~1°C, and that <1°C, mortality is linear with decreasing temperature. Data from the field and laboratory for adult and juvenile rainbow trout were similar, and indicated that previous data, such as provided by the USEPA's nomograph, is probably too conservative for providing realistic mortality estimates for some species.

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