THERMAL DISCHARGE FROM A NUCLEAR POWER PLANT: PREDICTED EFFECTS ON LAKE ERIE FISH[1]

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ABSTRACT

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The Davis-Besse Nuclear Power Station, currently under construction on the south shore of Lake Erie near Locust Point, will use water from the lake for cooling purposes. Based on thermal specifications for this plant, we conducted laboratory experiments to try to predict the effects of thermal effluents on the Lake Erie fishery resource. Over 2000 fish representing 24 of the 47 local species were tested to determine their seasonal final temperature preferenda. All final preferenda were above lake temperature during fall, winter, and spring indicating attraction to thermal discharges during these seasons. Summer final preferenda were approximately equal to or slightly higher than lake temperature for all species tested indicating indifference or slight attraction to thermal plumes. Heat shock tests were conducted on 852 fish of 33 species and cold shock tests were conducted on 443 fish of 22 species. Heat and cold shock results indicated that the absolute temperature to which fish were subjected was more important than the size of the temperature change. Therefore, summer heat shocks and winter cold shocks caused the greatest stress. The species most likely to be harmed by thermal effluents were *Alosa pseudoharengus* (alewife), *Aplodinotus grunniens* (freshwater drum), *Dorosoma cepedianum* (gizzard shad), and *Morone chrysops* (white bass).

Thermal pollution has been a subject of great concern in recent years. Any increase in the temperature of an ecosystem may cause ecological changes, but these changes need not be disastrous. Reduction and regulation of the amount of heat added and the manner in which it enters any body of water can greatly reduce the potential ecological dangers. Some waters, depending on their flora, fauna, and physical characteristics, are capable of safely dissipating thermal discharges better than others.

The Davis-Besse Nuclear Power Station is being built 21 miles east of Toledo, Ohio on the south shore of Lake Erie near Locust Point. This plant, scheduled for completion in fall 1976, will utilize a closed condenser cooling water system to dissipate heat from the steam condenser to the atmosphere by means of a natural draft cooling tower. Water from Lake Erie will be used to replenish the supply and dilute the cooling tower blowdown water which, according to the USAEC 1973 Final Environmental Statement, will be returned to the lake at a maximum of 11.1°C (20°F) above ambient lake temperature. This effluent will be discharged from the lake bottom, through a high velocity nozzle, over a rockfill approximately 305 meters off shore. The area of the 0.56°C (1°F) isotherm of the thermal plume formed by this discharge will be less than 1.6 hectares and the area of the 1.67°C (3°F) isotherm will be approximately 0.3 hectares (U. S. Atomic Energy Commission, 1973).

Since June 1971, The Ohio State University has conducted experiments to determine the effects of thermal effluents on the Lake Erie fishery resource. Experiments during the first year were performed by Barans and Tubb (1973) on *Micropterus dolomieui* (smallmouth bass), *Morone chrysops* (white bass), *Notropis atherinoides* (emerald shiner), and *Perca flavescens* (yellow perch). We have attempted to determine the "seasonal" final temperature preferenda and predict the direct effects of sudden temperature

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changes on the remaining fish species of western Lake Erie. Fry (1947) first defined the final preferendum as that temperature range in which the fish will ultimately congregate in an infinite gradient.

METHODS AND MATERIALS

Apparatus—Tests to determine the seasonal final temperature preferenda were conducted within a horizontal wooden tank 8.7 m long, 79 cm wide, and 50 cm high (Barans and Tubb, 1973). A system of alternating transverse baffles each 56 cm long, formed a series of 28 virtually identical compartments. This arrangement did not greatly restrict the movements of the fish and, in effect, increased the length of the tank to 24 m. Filtered lake water was passed through tygon tubing at a rate of approximately 2*l*/min into the cold end of the gradient. The water was first routed through copper pipe in a cooling reservoir to lower the water temperature during the spring, summer, and fall. Examination of the water quality in the intake line and in the gradient indicated no significant increase in the level of copper in the water due to this cooling system. The water was then heated progressively higher in each of the 28 compartments as it flowed to a standpipe, 25 cm high, at the opposite end of the trough.

A Vycor 500 watt heater, ARC static switch relay, and corresponding Jumo thermoregulator maintained a relatively constant water temperature in the center of each compartment. By adjusting the thermoregulators a change of 0.5–1.5°C could be developed between compartments. Each season a different temperature range was established within the gradient from a low of several degree below ambient lake temperature (late spring, summer, and early fall) or slightly above ambient (winter), to a high of 15–28°C above ambient.

Aeration from three air stones in each compartment greatly reduced vertical temperature stratification and maintained dissolved oxygen near saturation levels in all compartments (Barans and Tubb, 1973). The water temperature at the center of alternate compartments was measured with probes from a YSI multi-channel telethermometer. by moving these probes temperatures could be obtained for every compartment. Sudden temperature change testing was done using two 190-liter aquaria equipped with a Jumo thermoregulator, ARC static switch relay, Vycor 500 watt heater, and 2 air stones.

Procedures—Lake Erie fish for these experiments were captured near F. T. Stone Laboratory on South Bass Island and at the northeast corner of North Bass Island with a fyke net, and south of Rattlesnake Island and at Locust Point by trawling (table 1). Fish for winter

TABLE 1

Species found in the Locust Point area 1963–1974.

Scientific Name	Common Name	Tests*
Amiidae		
Amia calva	bowfin	H
Atherinidae		
Labidesthes sicculus	brook silversides	
Catostomidae		
Carpiodes cyprinus	quillback carpsucker	P, H, C
Catostomus commersoni	common white sucker	P, H
Minytrema melanops	spotted sucker	H, C
Moxostoma erythrurum	golden redhorse	
Ictiobus cyprinellus	bigmouth buffalo fish	
Centrarchidae		
Ambloplites rupestris	northern rockbass	P, H, C
Lepomis cyanellus	green sunfish	
L. gibbosus	pumpkinseed sunfish	P, H, C
L. humilis	orangespotted sunfish	H
L. macrochirus	northern bluegill sunfish	P, H, C
L. microlophus	redear sunfish	H
Micropterus dolomieui	smallmouth bass	P, H, C
M. salmoides	largemouth bass	H, C
Pomoxis annularis	white crappie	P, H, C
P. nigromaculatus	black crappie	P, H, C
Clupeidae		
Alosa pseudoharengus	alewife	P, H
Dorosoma cepedianum	gizzard shad	P, H, C
Cyprinidae		
Carassius auratus	goldfish	P, H, C
C. auratus x *Cyprinus carpio*	carp x goldfish hybrid	H
Cyprinus carpio	carp	P, H, C
Hybopsis storeriana	silver chub	
Notropis atherinoides	emerald shiner	P, H, C

TABLE 1. *Continued.*

Scientific Name	Common Name	Tests*
Cyprinidae (continued)		
N. hudsonius	spottail shiner	P, H, C
N. spilopterus	spotfin shiner	
N. volucellus	northern mimic shiner	
Esocidae		
Esox lucius	northern pike	
Ictaluridae		
Ictalurus melas	black bullhead	
I. natalis	yellow bullhead	P, H
I. nebulosus	brown bullhead	P, H, C
I. punctatus	channel catfish	P, H, C
Noturus flavus	stonecat madtom	P, H
Lepisosteidae		
Lepisosteus osseus	longnose gar	P
Osmeridae		
Osmerus mordax	rainbow smelt	H
Percidae		
Perca flavescens	yellow perch	P, H, C
Percina caprodes	logperch darter	
Stizostedion v. vitreum	walleye	H
Percichthyidae		
Morone chrysops	white bass	P, H, C
Percopsidae		
Percopsis omiscomaycus	troutperch	H
Petromyzontidae		
Petromyzon marinus	sea lamprey	
Salmonidae		
Oncorhynchus kisutch	coho salmon	P
Sciaenidae		
Aplodinotus grunniens	freshwater drum	P, H, C
Other species common to western Lake Erie		
Ichthyomyzon unicuspis	silver lamprey	H, C
Notemigonus crysoleucas	golden shiner	P, H, C
Pimephales notatus	bluntnose minnow	H
Salmo gairdneri	steelhead trout	H, C

*P = Preference tests, H = Heat shock tests, C = Cold shock tests.

testing were collected in November and early December from the same sites and held in 420-liter holding tanks with a constant flow of untempered lake water until ready for use. During all other seasons fish were tested as soon as possible after capture. Fish were maintained and tested under normal seasonal photoperiods. Natural lighting from windows in the north and east walls was adequate for most observations.

Preferences—Twenty-four hours prior to testing, the test fish were placed in an acclimation tank half as long as the gradient tank, with the same system of baffles as the gradient tank, but with no heaters or thermoregulators. The water temperature in the acclimation tank was maintained as close to ambient lake temperature as possible (usually within 2°C). The fish were then transferred to the gradient compartment which had a temperature closest to ambient lake temperature (within 0.5°C).

Fish location and behavior were observed at 2-hr intervals during daylight hours. The number of fish in each compartment and the temperature of that compartment were recorded and averaged to give a mean temperature preference for each observation. Fish were left in the gradient until their mean temperature preference had remained constant for approximately 24 hours. This temperature was termed the seasonal final temperature preferendum (Reutter and Herdendorf, 1975a).

The number of fish per test varied from one for large *Micropterus dolomieui* (smallmouth bass) to 27 for *Notropis hudsonius* (spottail shiner). The duration of each test varied from 1–2 days in the summer and early spring to 3–4 days in winter. Barricades were necessary in late fall, winter, and early spring to keep fish from entering warm water too rapidly and being killed. The barricades were gradually moved into warmer water as the fish became acclimated to the new surroundings.

Sudden Temperature Change—To determine the effect of a heat shock (swimming into the plume) 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. It was deemed necessary to determine the Critical Thermal Maximum (CTM

—the temperature at which the fish loses locomotor control) of each species during each season. When the one hour observation period was completed, the temperature was gradually increased to the CTM of each fish. If the original shock temperature was above the CTM of the fish, as was often the case in summer, the fish was removed soon after it lost swimming ability. It was then returned to ambient temperature, and observed to test for survival. This was done to simulate a fish losing locomotor control in a heated plume and being forced to cooler water by a discharge current.

To determine the effect of a cold shock (a fish which resided in the plume swimming out of the plume), fish were maintained at a temperature 11.1°C above ambient in a 190-liter aquarium for at least 24 hours. They were then transferred to a 420-liter holding tank at ambient lake temperature and observed.

Ambient lake temperature, as recorded in the holding tanks, ranged from approximately 0.5°C to 25.6°C in 1973 and 0.5°C to 26.5°C in 1975.Results from tests starting at 5.5°C or lower were considered winter results, spring temperatures were 5.5°C to 20.0°C, summer temperatures were considered to be those of 20.0°C and above, and fall temperatures ranged from 20.0°C to 5.5°C.

RESULTS

Preferences. Data were obtained from over 2000 fish representing 24 of the 47 local species (table 2). The remaining 23 species were not tested due to difficulty in obtaining sufficient numbers of individuals. A complete listing of individual test results are detailed by Reutter and Herdendorf (1975b).

The final temperature preferenda of all fish tested were above lake temperature during fall, winter, and spring. Barricades were necessary during these seasons to keep fish from swimming into warm water too rapidly and being killed. All species tested would have exceeded their CTM, if barricades were not present. Summer preferenda were approximately equal to or slightly higher than lake temperature for all species tested except *Dorosoma cepedianum* (gizzard shad) and *Pomoxis annularis* (white crappie). However, the authors believe that further testing may reveal the summer temperature preferenda for these species were too low based on the higher preferenda of the other seasons (Reutter and Herdendorf, 1975a).

Sudden Temperature Change. Heat shock tests (simulating a fish swimming into the plume) were conducted on 852 fish of 33 species and one hybrid (*Cyprinus carpio*×*Carassius auratus*). The highest observed CTM indicated which heat shock temperatures were lethal (table 2). Data on individual tests and test specimens are available (Reutter and Herdendorf, 1975b).

The most delicate species tested and the most likely to be harmed by a sudden temperature increase were *Alosa pseudoharengus* (alewife) and *Dorosoma cepedianum* (gizzard shad). Gizzard shad, however, have been found to be present in very large numbers in thermal plumes from other power plants and appeared to go unharmed (Gammon, 1971). Both shad and alewife were very fragile, and could only be maintained in the holding tanks for short periods (usually 2–3 weeks maximum). Beyond this time the condition of the fish became questionable and shed doubt on the validity of the test results. *Aplodinotus grunniens* (freshwater drum or sheepshead) was also quite delicate and difficult to maintain and test. The other 30 species were tested and maintained easily. No fish died from a heat shock when the temperature was less than 27.6°C. This would correspond to an ambient lake temperature of 16.5°C or less, because the maximum plume temperature can be 11.1°C above ambient temperature.

The CTM of each species tested was well above the maximum plume temperature during late fall, winter, and early spring. The CTM of each species also increased as ambient lake temperature increased, but not as rapidly. The significance of this fact was not fully realized until the highest lake temperatures were reached in late spring, summer, and early fall. At these times (especially summer), the maximum plume temperature will be above or very close to the CTM of every species tested.

In our testing program, we found that 69 fish survived from a total of 75 (92%) that were returned to ambient lake temperature after undergoing heat shocks which exceeded their CTM. Data of this type are somewhat subjective for they are dependent upon the amount of time the fish is held in the warm water. In all cases, our exposure time was longer than that which would occur at the Davis-Besse Nuclear Power Station.

TABLE 2

Summary of laboratory test results.

Species	Final Temperature Preferenda °C*				Highest CTM °C	Ambient Temp.	Observation Season
	Winter	Spring	Summer	Fall			
Alosa pseudoharengus		21.3			30.2	18.2	Sp
Ambloplites rupestris	21.6	19.6	20.2	22.8	36.0	23.5	Su
Amia calva					37.0	23.8	Su
Aplodinotus grunniens (YOY)**			31.3				
A. grunniens			26.5	19.6	34.0	21.2	Su
Carassius auratus	24.2	25.3	27.0	24.0	>35.0	23.9	Su
Carpiodes cyprinus				22.1	37.2	23.3	Su
Catostomus commersoni				22.4	31.6	19.0	Sp
Cyprinus carpio		27.4	29.7		39.0	23.3	Su
C. carpio x *Carassius auratus*					>25.3	9.3	Fa
Dorosoma cepedianum			19.0	20.5	31.7	15.9	Fa
Ichthyomyzon unicuspis					31.6	4.5	Wi
Ictalurus natalis			28.3		36.4	22.2	Su
I. nebulosus	10.9	22.4	24.9	23.6	37.8	23.0	Su
I. punctatus			25.2	25.3	38.0	22.7	Su
Lepisosteus osseus (YOY)**			25.3				
L. osseus			33.1				
Lepomis gibbosus		23.8	27.7		37.5	23.1	Su
L. humilis					26.0	5.6	Sp
L. macrochirus	27.4				38.3	22.8	Su
L. microlophus					37.4	22.7	Su
Micropterus dolomieui				26.6	36.3	23.3	Su
M. dolomieui† (YOY)**	18	19–24	31	24–27			
M. dolomieui†	12–13	15–16	30	21–23			
M. salmoides					>12.0	0.7	Wi
Minytrema melanops					>31.0	20.0	Su
Morone chrysops			27.8		35.3	21.7	Su
M. chrysops† (YOY)**	10–13	16–18	31	28			
M. chrysops†	12–17	12–17	28–30	16–17			
Notemigonus crysoleucas	16.8	23.7	22.3	21.0	30.5	14.4	Sp
Notropis atherinoides	8.3				28.6	7.8	Sp
N. atherinoides† (YOY)**	10–12	13–15	22–23	13–14			
N. atherinoides†	5–6	16	22–24	15–17			
N. hudsonius	9.0	14.3			32.8	21.7	Su
Noturus flavus	5.5			25.1	29.0	1.6	Wi
Oncorhynchus kisutch		11.4					
Osmerus mordax					24.9	6.0	Sp
Perca flavescens	14.1		20.9	19.9	35.0	22.0	Su
P. flavescens† (YOY)**	10–13	18	25–27	28			
P. flavescens†	7–12	13–16	27	22–25			
Percopsis omiscomaycus					22.9	1.7	Wi
Pimephales notatus					27.8	6.0	Sp
Pomoxis annularis	19.8	18.3	19.4	10.4	>32.8	24.4	Su
P. nigromaculatus	20.7	21.0	21.7	24.6	34.9	23.8	Su
Salmo gairdneri					>17.5	6.3	Fa
Stizostedion v. vitreum					>34.4	23.3	Su

*The mean of results conducted in a horizontal thermal gradient by allowing the fish to select a stable temperature preferenda.

**YOY designates young-of-the-year; all other specimens were considered adults.

†Tests conducted by Barans and Tubb (1973); all other tests were done by the authors.

Cold Shock Tests. A total of 443 fish of 22 species were tested in cold shock. Stress was only evident in the test specimens during the winter when lake temperatures were the lowest. The greatest stress was shown when ambient lake temperature was 1.0°C or less. Above 3.0°C, stress was seldom evident in the test specimens. Of the species tested, *Dorosoma cepedianum* (gizzard shad) and *Morone chrysops* (white bass) were stressed the most while stress often was not evident in *Cyprinus carpio* (carp) and the ictalurids.

DISCUSSION

The results indicated that the temperatures in a thermal plume will attract all species tested during fall, winter, and spring. Attraction to thermal plumes would be the greatest in winter when the differences between the final preferenda and ambient lake temperature are greatest. Therefore, relatively large fish populations should be found in and around plumes during fall, winter, and spring when attraction is greatest. Although fish probably will be attracted to the hottest point in the plume, the velocity of the discharge under actual conditions undoubtedly will keep many from reaching this area.

All species tested to date would be repelled by the hottest water at the plume origin during the summer, but could be attracted to the plume periphery where temperatures approach ambient lake temperature. Summer attraction will not be as great as winter attraction, since the differences between the final preferenda and ambient lake temperature are smaller. It appears that species such as *Cyprinus carpio* (carp), *Morone chrysops* (white bass), and the various ictalurids will be the most common plume dwellers during the summer due to their high temperature preferences and relative abundance in the discharge area (Reutter and Herdendorf, 1974). In addition, Gammon (1971) found *Dorosoma cepedianum* (gizzard shad) to be common plume dwellers as long as the temperature was below 34°C. Although little preference data are available on gizzard shad due to difficulties in maintaining them in the laboratory, field evidence indicates that they could be common in the Davis-Besse thermal plume. Studies on the abundance of gizzard shad at Locust Point indicated greatest abundance in the plume during the fall (Reutter and Herdendorf, 1974).

Sudden temperature change tests demonstrated that the temperature extremes to which the fish were subjected were more important than the 11.1°C temperature change. The greatest potential for harm lies with a summer heat shock or a winter cold shock. The danger due to a summer heat shock should be minimal because final temperature preferenda results indicate that fish will avoid the hottest part of the plume. Thus, the only fish to encounter this area are those that will be drawn in or swim in from the shoreside of the discharge. Due to the discharge velocity of 200 cm/sec, fish which are drawn into the plume and lose swimming ability should be carried to safer waters where results indicate that approximately 92 percent would recover.

Cold shock hazards occur when fish acclimated to the warm water of a plume swim out of the plume into ambient temperature water or if the plant shuts down, thus eliminating the plume. If the temperature change is great enough or ambient lake temperature extremely low, the fish experience a loss of swimming ability and an inability to return to the plume. Agersborg (1930) observed this in Lake Decatur, Illinois with *Dorosoma cepedianum* (gizzard shad). Even if a fish survived the shock, the stress could be severe enough to make it more susceptible to secondary fungal infections (Horning and Pearson, 1973). It would be very hard to monitor these secondary affects since they are not immediately evident.

Cold shock hazards could be greatly reduced by maintaining a discharge velocity high enough to keep fish out of the hottest plume temperatures. Under adverse high lake level conditions, the Davis-Besse discharge structure could hydraulically handle a maximum flow of 190,000 l/min. It was designed with 2 slots 137 cm long which could each discharge 76,000 l/min at 200 cm/sec. Initially, one slot will be closed resulting in a velocity of 113 cm/sec at the average flow rate of 41,800 l/min for the first unit (Eugene C. Novak, Chief Mechanical Engineer, Toledo Edison Co., personal communication, January 1974). A velocity of 200 cm/sec would probably be sufficient to keep fish away, but due to their swimming ability a velocity of 113 cm/sec is questionable. If the velocity of 113 cm/sec is too low, the amount of dilution water could be increased thereby increasing the discharge velocity. It would be necessary to monitor this closely for the use of additional water would mean greater intake velocities and a greater possibility of entrainment. Also, due to the cold shock danger, plant shut-downs should be avoided in winter.

Fish can attain burst speeds of 10 body lengths (BL) per second and crusing speeds of 3–4 BL/sec. These burst speeds can be maintained for only a period of seconds, but cruising speeds can be maintained for up to several hours (Bainbridge, 1958, 1960; Blaxter, 1969). Assuming this, a fish must be at least 20 cm long to attain the maximum discharge velocity of 200 cm/sec and 50–67 cm long to maintain position in the hottest section of the plume for any length of time. Moreover, this swimming ability decreases rapidly when the temperature is extremely high or low (Fry and Hart, 1947). Therefore, from swimming speed data alone, it would appear that no larvae or young-of-the-year fish and few adults could maintain position in the hottest section of the plume long enough to become acclimated and susceptible to cold shock dangers. Undoubtedly, a small number of fish will locate in the warmer water by finding places where the current is reduced, i.e., behind rocks in the rip-rap apron which will extend out 61 m in front of the discharge. This is not expected to be a significant factor.

Our results are mainly from adult fish because our laboratory has the capability for testing adults. Our discussion focused only on the direct effects of the discharge of heated water on fish from the point of view of an autecologist. Indirect effects such as fungal infections, early spawning, lactic acid increase due to fatigue, etc., are difficult to predict and should be studied in a monitoring program. No attempt was made to evaluate dangers that may be associated with the intake crib, chlorination, or radiation.

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