SUSCEPTIBILITY OF THREADFIN SHAD TO IMPINGEMENT[1]

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ABSTRACT

Threadfin shad impingement at 13 Tennessee Valley Authority electric generating plants from August 1974 through July 1975 was analyzed to assess mortality resulting from low water temperature. Concurrent laboratory experiments were conducted to evaluate the ability of cold-stressed threadfin shad to avoid impingement. Temperatures of 12°C stressed fish in the laboratory, while those below 8°C caused high impingement mortality. At 5 of 12 fossil-fuel plants, 90 percent or more of the annual threadfin impingement occurred when water temperatures were below 10°C. At four plants, impingement was not related to low temperatures. Impingement at the Browns Ferry Nuclear Plant generally coincided with low water temperatures, but individual impingement peaks were not consistently associated with cold shocks.

INTRODUCTION

The collection of fish on cooling water intake screens (impingement) at electric generating facilities is currently receiving attention throughout the country, owing primarily to licensing requirements for nuclear plants and enactment of the Federal Water Pollution Control Act, Section 316(b). In the southeast United States threadfin shad, *Dorosoma petenense* (Günther), comprise a large proportion of the fish which are impinged at inland generating facilities, occasionally accumulating in large enough numbers to cause physical damage to the intake screens.

Often the greatest threadfin shad impingement occurs during the colder winter and spring months. Threadfin shad are known to be sensitive to low water temperatures and are frequently observed in an apparent moribund condition throughout many reservoirs during this cold period. Laboratory studies have suggested that exposure of threadfin shad to temperatures below approximately 7-9°C causes high mortality, especially when associated with rapid decreases in temperatures (cold shocks) (Parsons and Kimsey 1954; Strawn 1965).

The Tennessee Valley Authority (TVA) has been conducting studies at its 12 fossil-fuel and one nuclear electric generating plants to assess the magnitude of fish impingement and its effect on the reservoir fish populations. Because of high impingement during the colder months of the year at several TVA power plants, it was hypothesized that much of the impingement represented a collection of threadfin shad that were dead or dying because of cold stress. To evaluate this hypothesis a cooperative study was undertaken between TVA and Oak Ridge National Laboratory in 1975. The purpose of this report is to present preliminary results of that study. Specific objectives are:

1. To describe the behavior and swimming ability of threadfin shad exposed to laboratory-induced cold temperatures.
2. To evaluate the susceptibility of cold-stressed threadfin shad to, and ability to recover from, impingement under experimental conditions.
3. To examine the quantitative seasonal aspects of threadfin shad impingement at each TVA electric generating station.
4. To assess the amount of impingement that may be attributed to cold stress.

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MATERIALS AND METHODS

Experimental Cold Stress and Impingement

Approximately 650 threadfin shad 9-14 cm in length were dip netted during the periods May 8-12 and June 2-6, 1975, from a tributary of the Clinch River in Roane County, Tennessee. Fish were transported with negligible mortality 12 km to the Oak Ridge National Laboratory, where they were held in circular 770-1 and 1700-1 fiberglass tanks for 4-8 days before testing. An inflow of 8 l/min circulated from the outer edge to the central stand pipe of each tank at a velocity of approximately 6 cm/sec. Shad were fed brine shrimp *(Artemia salina)* nauplii at 0900 hr. daily during acclimation and experimentation.

Since threadfin shad continuously circled the tanks against the flow, measurements of this cruising speed were made on groups being cold acclimated at 1° C per day or less. Time to complete one circle, circumference of that circle, and water velocity were recorded for 20 individual fish at each of 13 temperatures over a range of 5.5 to 25° C. Cruising speed was calculated for each fish by dividing the circumference by the travel time and adding water velocity; individual values were averaged for fish at each temperature.

Impingement testing was conducted in an indoor 30 cm-wide x 30 cm-deep x 6.5 m-long concrete flume. Water depth was 17 cm. A variable-speed pump of 2000 l/min capacity was capable of circulating water from 10 to 30 cm/sec through three 1 m-long sections, each enclosed by sections of 12 mm-mesh intake screens used at TVA power plants. A set of baffles below the inflow from the pump reduced turbulence. Water temperature was maintained ± 0.2° C by adjusting the temperature of the 8-20 l/min of water being added at the head of the flume. Excess water flowed over stop-logs at the tail of the flume. To decrease water temperatures below 8° C, two Blue M model PCC-2 portable cooling units were used to compensate for room and pump heating. A minimum temperature of 6.5° C could be maintained. Water velocities were set at 23 cm/sec with a Marsh-McBirney model 722 electromagnetic current meter. Velocities in each section ranged from a minimum of 19.5 cm/sec along the sidewalls to 24 cm/sec. Dissolved oxygen ranged from 92 to 95 percent saturation throughout the tests.

The effect of temperature on the ability of threadfin shad (mean fork length 11.8 cm, range 10.1-13.3 cm) to swim without impingement in a current similar to that found at the intake of TVA power plants was assessed. To simulate fluctuating winter temperatures, fish were exposed to a gradual temperature decrease of 1, 2, 3, or 4° C during the four hours preceding testing. Two series of impingement tests were conducted at temperatures ranging from 6.5 to 20° C. In Series A, each of 12 groups of 8 threadfin shad was exposed to a drop of 1, 2, or 4° C before testing at 20, 16, 12 or 8° C. A total of 200 threadfin shad were placed in a 1700-1 circular tank at 24° C. After four days, 15 fish were transferred to each of two 770-1 circular tanks. Temperature in one of these tanks was held at 4° C above the test temperature (e.g., 24° C before the initial test at 20° C). Temperature was lowered 1° C per day in the other until a temperature 2° C above the test temperature was reached (e.g., 22° C before the initial test). Temperature in the 1700-1 tank was decreased 1° C each day. After four days this group reached the test temperature.

At 0900 hr. on the day of testing, temperatures in the small tanks were dropped 4° C and 2° C over a 4-hour period, at which time eight fish were randomly removed from each tank and placed in separate sections of the flume. Eight fish were also removed from the 1700-1 tank and placed in the third flume section. Groups were randomly assigned to flume sections. Fish were held in the flume for one minute at a water velocity of 10 cm/sec, after which velocity was increased to 23 cm/sec for two hours. The number of fish impinged, or immobilized on the downstream screen, and the number of body contacts made with the downstream screen was recorded every five minutes. The position of fish in the flume was monitored and occasionally filmed with an 8-mm movie camera. After two hours, velocity was returned to zero. Fish were retained in each section for 17 hours at the test temperature (± 1° C) to assess latent mortality. Length and sex of all fish were then recorded. Fish remaining in each of the three circular tanks were periodically observed for mortality or signs of stress. Those in the two small tanks were removed 17 hours after conclusion of the flume test, and three new groups of fish were immediately introduced to repeat the procedure at a new (colder) test temperature.

Series B was conducted similarly at test temperatures of 18, 14, 12, 10, 8, and 6.5° C. The upstream section of the flume was not used; the two groups of fish in each trial were exposed to 1 or 3° C decreases during the four hours preceding testing in the same manner described above. In contrast to Series A in which impinged fish were not removed from screens, in Series B fish were transferred to a holding tank after 10 minutes of impingement to assess their survival.

Table 1. Physical characteristics, number of impingement samples and threadfin shad composition of impinged fish at TVA's fossil-fueled and nuclear power plants.

Plants[1]	*Number of screens*	*Maximum cooling water required (m^3/sec)*	*Average water velocity (cm/sec) in front of trashracks (range)*	*Number of 24-hr. impingement samples*	*Percent threadfin by number of all species impinged*
Tennessee River System					
John Sevier	8	28.6	13.8 (5.4-19.8)	44	24.1
Bull Run	3	25.1	34.4 (19.8-54.9)	44	87.2
Kingston	18	61.0	13.6 (3.0-27.4)	50	97.2
Watts Bar	6	17.7	Not available	42	58.7
Widows Creek:		68.9		48	87.0
Units 1-6	12		29.2 (8.5-47.2)		
Units 7-8	6		42.8 (25.2-67.7)		
Browns Ferry	18[2]	113.5	Not available	181	70.9
Colbert	12	54.6	21.3 (13.7-25.9)	51	83.9
Johnsonville	20	64.9	Not available	50	67.0
Cumberland River					
Gallatin	8	37.4	23.7 (19.8-27.4)	52	70.0
Cumberland	16	101.9	Not available	42	93.9
Green River					
Paradise	6	48.8	Not available	42	52.1
Ohio River					
Shawnee	20	67.9	Not available	38	30.9
Mississippi River					
Allen	9	21.7	8.2 (4.6-15.2)	52	10.5

[1] Fossil-Fuel except for Browns Ferry (nuclear).
[2] Only 12 screens of Units 1 and 2 in operation during the study period.

In separate experiments, the ability of threadfin shad to survive impingement for 0, 2, and 5 minutes at 10 and 20° C was briefly examined. At each of the two temperatures, 20 fish were placed in each of the three flume sections and held at 23 cm/sec until approximately 50 percent of each group was impinged. Fish were removed immediately after immobilization on the upper section screen, after two minutes on the middle section screen, and after five minutes on the lower section screen and held in tanks at the test temperature to assess mortality.

Impingement Monitoring at TVA Plants

At the 12 TVA fossil-fuel steam plants, all of which utilize vertical traveling screens, weekly fish impingement samples were collected from August 1974 through July 1975 (Table 1). At the beginning of the sample period all the vertical traveling screens in the intake pumping structure were rotated and washed clean, then stopped for 24 hours. All screens which had water passing through them during the sample period were then washed again, either individually or by unit. Impinged fish were collected in a catch basket installed in the screen wash sluice trench. All fish were separated by species into 25-mm total length increments and enumerated. Intake water temperatures were recorded during the sample periods at most plants.

Sampling at Browns Ferry Nuclear Plant differed somewhat from that at the fossil-fuel plants because of requirements established in the Environmental Technical Specifications for the plant. Thrice weekly 24-hour samples were collected from one screen designated the test screen. When this screen was not in operation, an alternate was used. Hourly surface river temperatures 2 km upstream of the Browns Ferry intake were compared with impingement counts.

RESULTS

Experimental Cold Stress

No mortality was observed above 12° C in test fish exposed to temperature drops of 1-4° C in four hours. Below 12° C, mortality rates increased with the magnitude of drop, but data were insufficient to make statistical comparisons. All moribund shad displayed a characteristic set of behavior patterns. In chronological order these were:

1. Movement to the surface of the water by an entire school. Dorsal fins of some fish broke the surface. (This pattern was displayed by most, but not all, groups of shad.)
2. Erratic, jerky swimming by a few fish. Group moved back to mid-depth in tank, schooling began to disintegrate.
3. Loss of equilibrium by individuals, with periods of inverted swimming.
4. Fish sank to bottom, or less frequently, floated to the surface remaining motionless except for occasional tail flickers and shallow opercular movement.
5. Death.

Cruising speed of threadfin shad varied directly with water temperature over the range studied (Figure 1) and can be characterised by the linear regression equation:

$$Y = 0.8597 X + 4.4463$$

where Y is cruising speed in cm/sec and X is temperature in degrees C; the correlation coefficient, r, is 0.968. No differences in cruising speed were noted among fish held in tanks of different sizes.

Experimental Impingement

Threadfin shad exhibited a series of relatively consistent behavior patterns in the test flume. All fish swam actively against currents of 10 and 23 cm/sec. At 23 cm/sec shad normally formed a school and explored boundaries of the test section for several minutes. During this period individuals occasionally brushed against the lower screen but quickly moved away. At warmer temperatures shad moved to the head of each section after the exploratory period and often attempted to continue upstream by pushing their heads into the openings of the upstream screen. Healthy fish remained upstream throughout the remainder of the two-hour test period, occasionally reexploring the downstream area and contacting the lower screen.

Fish not capable of swimming against the current displayed two patterns of behavior before they invariably became impinged. Some attempted to maintain position at the head or along the edge of the flume as long as possible, then drifted downstream sideways or headfirst. As they approached the lower screen they attempted to turn back into the current, and usually struck the posterior half of the body or the tail on the screen. Other individuals swam immediately in front of the screen for periods exceeding 10 minutes. They occasionally drifted back against the screen and pushed off from it with the caudal fin.

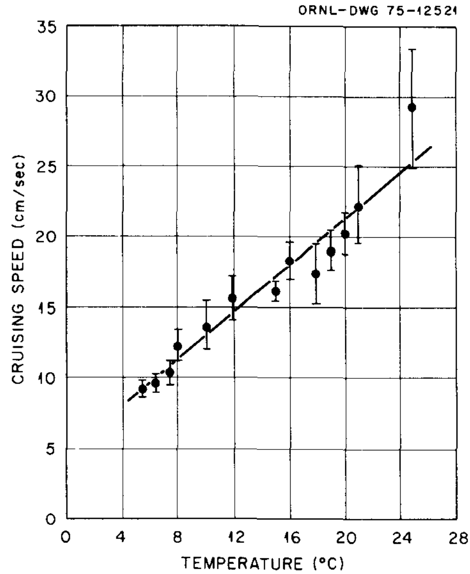

Figure 1. Effect of water temperature on cruising speed of 10-13 cm-long threadfin shad in circular 770 1 tanks. Mean values given as points, standard deviation as vertical bars.

Table 2. Impingement test results for 20 groups of 8 threadfin shad, 10-13 cm, tested for 2 hours at 23 cm/sec.

Test Series	*Test Temp., C*	*ΔT, C*	*Percent Impinged*	*Percent Mortality*[1]	*Average Screen Contacts Per Fish*[2]	*Length of Critical Period, min*[3]
A[4]	8	2	12	37	45.9	70
		4	12	100	123.7	95
	12	1	12	37	53.0	80
		4	12	37	55.2	70
	16	2	0	0	1.3	0
		4	12	25	39.0	85
	20	1	0	0	14.3	90
		2	0	12	26.1	95
B	6.5	1	75	88	109.6	60
		3	75	100	63.7	65
	8	1	12	25	2.9	10
		3	25	63	26.9	35
	10	1	25	37	23.5	30
		3	25	37	11.2	25
	12	1	12	37	19.1	60
		3	25	50	37.1	50
	14	1	0	12	20.8	30
		3	0	12	29.5	55
	18	1	0	25	20.4	95
		3	12	12	27.8	90

[1] At end of 17 hrs. after test.
[2] Calculated by dividing number of contacts per 5 min. period by number of fish present and summing results.
[3] Period during which contacts/fish/period ≥ 1.
[4] Data from upstream flume section not presented because of presence of high turbulence.

In the final stage preceding impingement many individuals struck and broke away from the screen 50 times or more before becoming immobile (Table 2). Threadfin shad that had remained on the screen for up to five minutes commonly broke away to swim briefly before becoming reimpinged.

Most impingement occurred during the first hour of the test. The duration of this critical period was defined as the time during which the calculated mean number of screen contacts per fish in a five minute period was ≥ 1. All but one of the 20 groups tested displayed such a critical period lasting 95 minutes or less (Table 2). After this time, remaining fish appeared to be swimming strongly and seldom contacted the downstream screen. Despite their healthy appearance, an average of 23 percent of the survivors of each two-hour test died within the following 17 hours. Several groups were held an additional 48 hours with no additional mortality.

Impingement increased at lower test temperatures (Figure 2). Some mortality (impingement and latent) occurred at the warmer test temperatures. Below 14° C mortality increased, reaching 100 percent for two groups tested at 8 and 6.5° C. Threadfin shad exposed to larger temperature drops showed poorer survival below 12° C, but more data are required to precisely define the effect of each of the rapid temperature decreases. Data from the upstream flume section have not been presented since high mortality occurred for all groups tested there and analysis of movie films of fish movement suggested the presence of increased turbulence.

No threadfin shad survived even brief impingement. All fish removed from screens after either a few seconds or after 2, 5, and 10 minutes of impingement were alive but died within 2-4 hours. No difference in survival of male and female shad was observed in impingement tests.

Impingement Monitoring at TVA Steam Plants

The relative composition by number of threadfin shad to all species impinged over the year averaged 72 percent for all plants and ranged from 10.5 percent (Allen) to 97.2 percent (Kingston, Table 1). Estimated total annual impingement of threadfin shad at TVA's plants ranged from approximately 13,000 to 4,990,000.

The number of threadfin shad impinged at TVA steam plants varied greatly among seasons (Table 3). Comparison of impingement during sample periods when minimum intake water temperatures were below 10° C (cold period) and above 10° C (warm period) showed that 90.5-99.9 percent of threadfin shad impingement occurred during the colder period at five plants (John Sevier, Kingston,

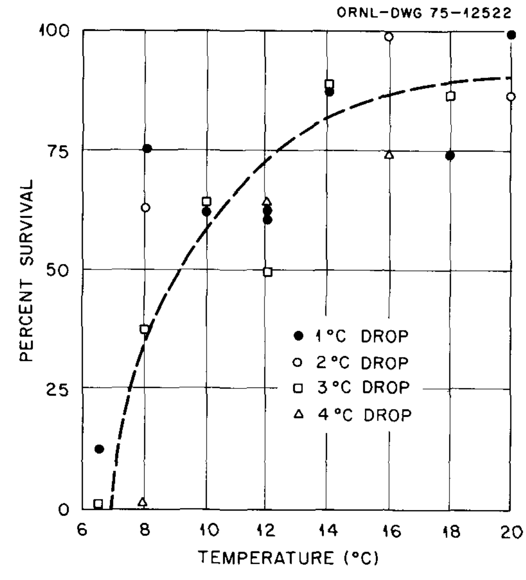

Figure 2. Effect of test temperature on threadfin shad survival 17 hrs. after swimming in water of 23 cm/sec velocity for 2 hrs. in a test flume. The 8 fish in each group subjected to temperature drops of 1-4° C before testing. Curve drawn by eye.

Table 3. Impingement of threadfin shad at TVA's Fossil-Fuel Steam Plants between August 1974—July 1975, given as percent by month.

Steam Plant	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Percent impinged at water temp.* <10 C[4]
Tennessee River													
John Sevier	0.0	0.0	0.0	0.0	3.3	0.04	81.4	15.2	0.1	0.0	0.0	0.0	99.9
Bull Run	0.3	2.2	5.2	52.5	8.0	12.8	4.8	6.5	2.2	2.1	1.6	1.8	50.0
Kingston	0.8	2.8	1.7	4.9	84.8	0.1	0.3	1.1	3.2	0.04	0.04	0.08	91.3
Watts Bar	1.1	7.9	0.2	0.8	4.2	6.1	27.9	21.2	16.2	11.3	0.8	2.2	48.9
Widows Creek	0.9	4.8	1.3	0.03	0.5	0.4	0.6	12.6	76.0	0.1	0.2	2.4	3.6
Colbert	5.4	1.4	0.1	0.1	2.0	1.2	13.6	20.2	53.1	0.0	0.1	2.8	—[3]
Johnsonville	1.3	0.3	0.3	0.4	22.3	32.0	24.9	15.5	2.6	0.01	0.0	0.4	96.5
Cumberland River													
Gallatin	4.5	61.4	10.8	10.4	6.8	0.8	3.1	1.4	0.6	0.2	0.02	0.01	12.8
Cumberland	31.8	42.1	14.5	7.6	0.6	1.6	1.7	—[2]	0.03	0.01	0.0	0.0	3.9
Green River													
Paradise	0.1	0.1	0.3	3.7	88.5	6.8	0.4	0.0	0.0	0.0	0.0	0.0	98.8
Ohio River													
Shawnee	—[1]	6.8	0.4	4.1	7.7	10.1	11.5	13.9	45.3	0.1	0.04	0.04	61.3
Mississippi River													
Allen	0.0	0.6	0.1	2.0	2.6	37.5	25.6	16.2	11.3	4.0	0.1	0.0	90.5

[1] Not sampled.
[2] Not in operation.
[3] Intake temperatures not available. 95.5% impinged between February 6 and April 17.
[4] Computed from average number impinged per 24-hour sample.

Table 4. Monthly impingement of threadfin shad at Browns Ferry Nuclear Plant between June 1974 and May 1975 and average daily maximum and minimum surface water temperatures in Wheeler Reservoir 2-km upstream of the intake channel.

	Jun.	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*
Mean number impinged per sample on test screen	102	706	1968	1545	328	824	413	1964	6618	6245	851	13
Range	5-1023	258-1569	147-8496	131-6683	108-620	92-3097	70-1714	202-6717	441-26,749	322-12,087	93-2018	2-47
Percent impinged on test screen	0.5	3.3	9.1	7.2	1.5	3.8	1.9	9.1	30.7	28.9	3.9	0.1
Mean of daily minimum temperatures (°C)	24.3	27.1	26.9	22.7	17.6	12.9	7.2	7.9	8.7	9.8	14.8	22.9
Mean of daily maximum temperatures (°C)	25.7	29.6	28.3	24.3	19.3	14.3	8.4	9.0	10.2	10.9	16.5	24.7

Table 5. Size distribution of threadfin shad impinged at Browns Ferry Nuclear Plant, June 1974—June 1975.

Total length (mm)	Percent in month												
	Jun.	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*
0- 25													
26- 50	96.0		0.3										11.0
51- 75	2.8	99.0	99.7	99.0	67.0	16.0	19.0	4.0	0.3				42.0
76-100	1.0	0.5		0.3	33.0	84.0	77.0	87.0	75.0	70.0	33.0	3.0	
101-125	0.1			0.5			3.0	8.0	23.0	28.0	62.0	39.0	11.5
126-150	0.1	0.5		0.3			0.8	0.5	1.5	1.5	4.0	45.0	24.0
151-175							0.3	0.3	0.3	0.3	0.8	13.0	11.0
176-200								0.3			0.3		0.5

Johnsonville, Paradise, and Allen, Table 3). At several of these plants most of the total impingement from all samples throughout the year occurred on one or a few sampling dates. At Kingston, 71.5 percent of all threadfin shad were impinged on December 11, 1974; at Paradise, 88.0 percent on December 21 and 27, 1974; at John Sevier, 71.6 percent on February 26, 1975.

At Bull Run, Watts Bar, and Shawnee Steam Plants approximately half of the impingement occurred during the cold period and about half either immediately preceded or followed it. Four plants (Widows Creek, Gallatin, Cumberland, Colbert) displayed high impingement (87.2-96.4 percent) during the warm period. Most threadfin shad were impinged at Widows Creek and Colbert just after the cold temperature period. Water temperature was not monitored at the Colbert plant, and the thermal regime near the plant was assumed to approximate that near the Browns Ferry plant located upstream. Cumberland and Gallatin steam plants showed highest impingement of threadfin shad during late summer and early fall when minimum intake temperatures exceeded 20° C.

Threadfin shad impingement at the Browns Ferry Nuclear Plant was also highly variable throughout the year. The average number impinged on the test screen per 24-hour sample ranged from one to three orders of magnitude within months (Table 4). Approximately 60 percent of the annual threadfin shad impingement occurred in February and March, during the end of the coldest period of the year. Between June and November, surface temperature (Table 4) remained well above 10° C, dropping to 10° C on November 29. During the subsequent 111-day period from November 30, 1974, to March 20, 1975, surface water temperature ranged from 5-10° C with occasional rises slightly above 10° C for short periods (Figure 3). Despite occasional periods of several days with water temperatures less than 8° C during December and January, impingement remained low (1.9 and 9.1 percent respectively of total annual numbers impinged). Several peaks during the highest impingement period (February 22 to mid-March) were immediately preceded by instances of cold shocks, while others were preceded by rising temperatures (Figure 4). After March 20, surface water temperature rapidly rose above 10° C while numbers of impinged fish sharply declined.

Threadfin shad less than 26mm total length were not impinged on the 10-mm mesh intake screens. At Browns Ferry Nuclear Plant, they first attained impingeable size in June at a total length between 26-50mm (Table 5). Few individuals greater than 125mm became impinged.

DISCUSSION

Laboratory studies indicated that water temperatures below approximately 12° C induced stress in adult threadfin shad, leading to increased impingement and mortality rates. The ability of threadfin shad to resist impingement in a test flume was severely impaired below 8° C. Further studies are needed to more clearly define the effects of rapid temperature decreases of various magnitudes.

It is clear that most unstressed adult threadfin shad are capable of swimming against the intake velocities encountered at most TVA power plants during warm periods of the year. At 22° C their cruising speed, as determined in the laboratory, approximates or exceeds the average intake velocities of five of eight TVA plants. The sustained swimming speed, or speed which they could maintain for several minutes, is expected to be twice the cruising speed at a given temperature (Bainbridge, 1958).

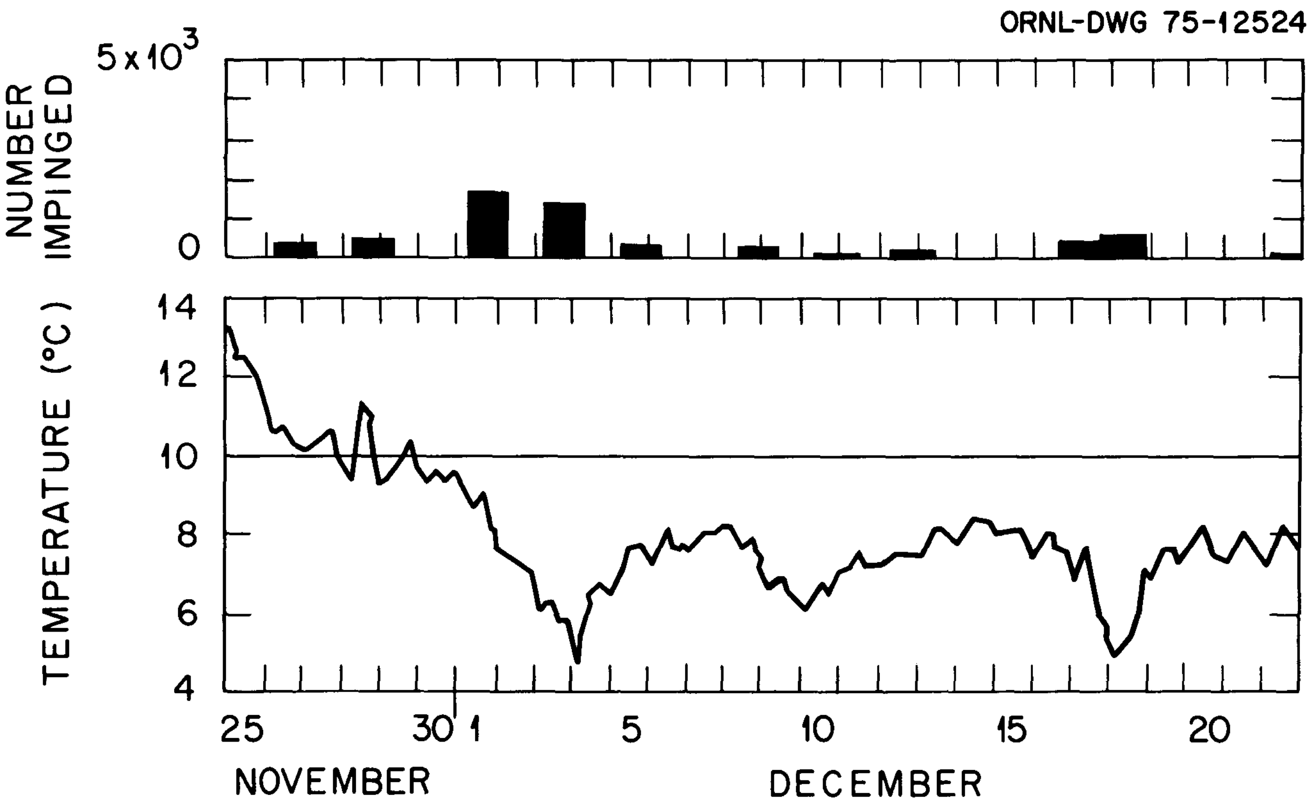

Figure 3. Numbers of threadfin shad impinged during 24-hr. sampling periods at Browns Ferry nuclear plant compared with surface water temperatures plotted at 6-hr. intervals during November-December 1974.

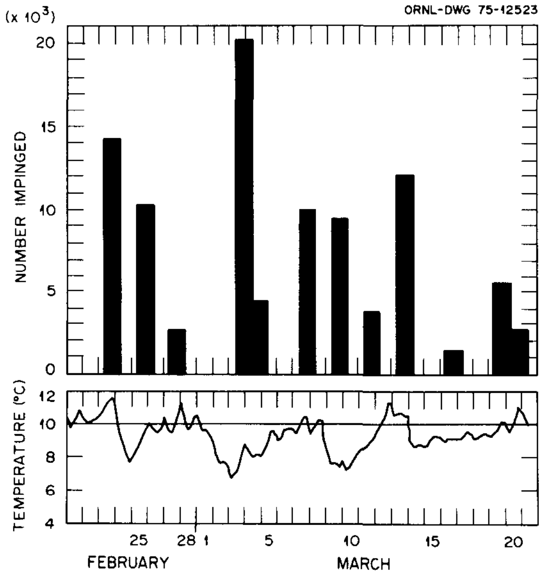

Figure 4. Numbers of threadfin shad impinged during 24-hr. sampling periods at Browns Ferry nuclear plant compared with surface water temperatures plotted at 6-hr. intervals during February-March 1975.

In the laboratory flume, unstressed shad explored the intake screen area and then attempted to swim upstream and leave the vicinity of the screen. This suggests that impingement of such fish may occur only if they are trapped by physical features of the intake structure or its associated environment (such as turbulence or turbidity) and cannot find a means of escape. In the laboratory, threadfin shad usually became impinged only after striking the screen repeatedly and becoming completely exhausted. In contrast to the ability of juveniles of some percichthyid and salmonid species to survive impingement for several minutes or more at velocities of 70 cm/sec or greater (Skinner, 1974; Bibko *et al.*, 1974), threadfin shad did not survive even momentary impingement.

Shad that were severely cold-stressed under laboratory conditions displayed a symptomatic, uncoordinated swimming behavior lasting several hours or more. This behavior closely paralleled that observed under natural conditions in reservoir populations of threadfin shad during the coldest period of the year. The extent of the population affected by cold shock as well as the mortality rate for the affected individuals is unknown and presumably varies considerably from reservoir to reservoir and year to year. Furthermore, it is not known to what extent cold-stressed fish would recover were they not pulled into the intake structure. Further laboratory and field study is needed to assess their ability to recover from varying degrees of cold stress.

Data collected at five TVA fossil-fuel plants indicated the existence of a strong relationship between threadfin shad rate of impingement and low ambient water temperature. These findings agree closely with those derived from studies at three Duke Power Company steam plants in North and South Carolina, in which greatest impingement of threadfin shad occurred during the colder winter period (T. J. Edwards, Duke Power Company, personal communication). Threadfin shad impingement at the remaining seven TVA fossil-fuel plants appeared to be only partially related, or completely unrelated, to low temperature.

The results of the more intensive sampling at the Browns Ferry Nuclear Plant, when combined with laboratory studies, suggest a hypothetical annual threadfin shad impingement cycle for that plant which is largely dependent on the size of the fish and the yearly temperature pattern.

During May, total impingement of threadfin shad consists of a few yearlings. In June, young-of-the-year threadfin, which previously had been susceptible to entrainment only, first attain impingeable size. For the next several months, impingement increases as this group becomes fully recruited into the impingeable population. Water temperature during this time is high, but due to their small size and/or behavior patterns, the young shad are incapable of avoiding impingement. Despite decreasing temperature in October and November, low impingement of threadfin shad may be attributed to their increasing size and swimming ability.

Although water temperatures in late November reach the levels which laboratory studies suggest stress threadfin shad, no elevation is noted in impingement. Similarly, water temperatures reach an annual minimum during December and January with little or no resultant increase in impingement. In February and March, temperatures increase only slightly above the cold December-January period, while numbers of impinged fish increase greatly and frequently include several mass mortalities throughout this period. The two-month lag between the onset of the cold period and the beginning of high impingement suggests that threadfin shad may tolerate prolonged exposure to sustained low temperature for several weeks, after which they become highly susceptible to low temperature and/or cold shock, or that the fish are able to seek out areas of warmer temperature.

During April and May, water temperatures increase rapidly accompanied by a sharp decline in impingement. Factors such as large size and improved condition of fish, warm water, spawning movements, and/or a reduced population due to spawning mortality (Berry, *et al.*, 1956) or over-winter mortality may contribute to the reduced impingement. In June this impingement cycle is renewed when young-of-the-year reach impingeable size.

Future studies will attempt to resolve the discrepancy found between laboratory and Browns Ferry field findings and may facilitate a more accurate predictability of sudden mass mortalities and resulting increased impingement of threadfin shad due to cold stress.

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