

**Survival of Larval Striped Bass Exposed to  
Fluid-Induced and Thermal Stresses  
in a Simulated Condenser Tube**

Charles C. Coutant    Robert J. Kedi

**MASTER**

Environmental Sciences Division Publication No. 637



**OAK RIDGE NATIONAL LABORATORY**  
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ORNL-TM-4695

Contract No. W-7405-eng-26

SURVIVAL OF LARVAL STRIPED BASS EXPOSED TO FLUID-INDUCED  
AND THERMAL STRESSES IN A SIMULATED CONDENSER TUBE

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JANUARY 1975

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Oak Ridge, Tennessee 37830  
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UNION CARBIDE CORPORATION  
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U.S. ATOMIC ENERGY COMMISSION

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## FOREWORD

This technical memorandum reports results of a series of experiments designed to assess the effects of mechanical stresses of power plant condenser tubes on survival of larval striped bass. The results are not definitive and the experimental design does not represent the entire sequence of mechanical, thermal and chemical stresses that larval fishes may experience during entrainment through a once-through, open circuit cooling system of a power plant. The objective was to isolate only those stresses which may occur in the condenser tubes. Stresses induced by pumps and other engineering features were left for subsequent analysis. While the survival levels indicated herein should not be used directly in predicting mortalities of entrained larvae at power plants, the data narrow the search for the loci of potential damage within the cooling system so that mitigating measures might be taken. Publication of this report prior to completion of more extensive entrainment simulation was influenced by the current high interest in larval striped bass by power plant regulatory agencies.

SURVIVAL OF LARVAL STRIPED BASS EXPOSED TO FLUID-INDUCED AND  
THERMAL STRESSES IN A SIMULATED CONDENSER TUBE

Charles C. Coutant  
Robert J. Kedl

ABSTRACT

Single passage of approximately 2 wk old larval striped bass, Morone saxatilis, through a laboratory mock-up of a power plant condenser tube (not including a pump) resulted in mortalities no greater than for controls, when only mechanical stresses were exerted. When temperature stress was added, mortalities were comparable to thermal bioassay results. The experiments were conducted using different combinations of turbulent shear, pressure change and temperature rise. The condenser tube is unlikely as the locus of mechanical damages to fish larvae seen at operating power plants. Further research with pumps is recommended.

Keywords: mechanical, thermal, striped bass, Morone saxatilis, condenser, mortality, survival.

INTRODUCTION

Entrainment of larval fishes through condenser cooling systems of steam electric generating stations is now recognized as an important source of potential environmental damage from electricity production (for example, see environmental impact statements prepared by the USAEC for nuclear power plants). This potential for damage requires (1) assessment of larval fish losses in planned generating stations (followed by evaluation of long-term effects of such losses) and (2) engineering

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modifications of the condenser cooling system (or its replacement by closed circuit cooling) to reduce levels of stress or mortality where these may be deemed excessive.

This study sought to determine levels of survival for larval striped bass which were exposed to but one segment of the condenser cooling system, namely the condenser tube itself. The senior author and a colleague (Goodyear and Coutant 1973) had hypothesized that mechanical damages to larval striped bass could be severe due to (1) stress of turbulence and shear forces exerted on the small larvae as they passed through the tube, and (2) a rapid sequence of pressurization and depressurization that larvae would experience from inlet to outlet of the tube.

Several studies have shown the existence of disruptive forces acting on suspended particles in fluid flow through tubes. A considerable body of empirical results and theoretical concepts has developed concerning these physical forces and the responses to them (see for example a review by Cox and Mason 1971 and Appendix A to this report). Studies have been made of the flow in tubes of macromolecules, of fiber suspensions in papermaking, of latex particles in emulsion paints, of reinforcing particles in polymer melts, of rock crystals in molten lava, and of red and white cells of blood.

In both laminar and turbulent flow any non-rigid particles are subject to deformation. Experiments by Rumscheidt and Mason (1961) have shown that in a local shear flow which is gradually increased, a drop of immiscible fluid deforms and breaks up. The deformation of a flexible fiber in shear flow has been studied by Forgacs and Mason (1959 a,b). Increasing the length of flexibility of a fiber caused a

progression of responses: 1) a springy behavior in which the fiber buckles under compression in the shear, 2) a snake-like behavior in which the fiber straightens itself periodically, 3) a permanent bending of the fiber into a helix, and 4) a complicated entanglement of the fiber.

Deformation studies of aquatic organisms have not been reported that compare with the detail of these fluid hydraulics investigations, with one exception. Morgan et al. (1973) have reported on preliminary experiments indicating that striped bass larvae could withstand shear of  $3.4 \text{ dynes/cm}^2$  for 1 min in a specialized apparatus with laminar flow. Eggs and larvae of fish would seem to closely approximate the sizes, shapes, and general composition of many non-living particles that have been studied. It seemed reasonable that the conceptual and mathematical framework exhibited in the engineering literature for describing fluid flow and particle deformation would also apply to passing fish eggs, fish larvae and other aquatic organisms through the cooling system of a power plant.

Turbulence and shear might also enhance damaging influences of pressure changes experienced as organisms enter the condenser tube under elevated pressure and leave under reduced pressure. Turbulence could theoretically enhance the formation of gas bubbles under supersaturated conditions, much as shaking releases bubbles in an opened bottle of carbonated beverage. The damaging effects of gas bubbles in fish tissues are well known (U.S. Army Corps of Engineers 1972; Ebel 1969).

### Procedures

Fish larva were added to a recirculating water loop where they were pumped through a heat exchanger tube typical of a steam electric plant.

The fish, however, did not go through the pump itself, but only through the tube and a collecting device.

Figure 1 is a schematic drawing of the loop. It consists of a pump, flow rate control station, loop cooler, fish addition station, 40 ft of heat exchanger tubing, and fish recovery station. All materials exposed to the water being pumped are stainless steel or glass, except for small amounts of plastic in gaskets, valve packing, and bellows. The plankton net in the recovery station is nylon fabric. The pump is a Westinghouse 150A canned rotor type from which lubricants cannot contaminate the water.

Operation is as follows: While the pump is on, and with the bypass valve open, the fish addition station (A) can be isolated and opened, and a sample of fish gently poured in. Then by opening the isolation valves and closing the bypass valve, the sample of fish is injected through the experimental tube (B). After passing through the main loop resistance (40 ft of 7/8 in. OD tubing), the fish are recovered with a plankton net (C) suspended in a 55 gal. drum. The fish are added to the loop downstream of the pump, are recovered upstream of the pump suction, and thus do not go through the pump itself. This was necessary because the pump is not typical of a power plant cooling water pump, and it would surely be lethal to fish larvae.

A brief survey at TVA steam power plants disclosed that most condenser tubes are 7/8 in. OD, and range in length from 30 ft to 60 ft, with most at the shorter end of the range. Thus, 40 ft of 7/8 in. tubing was installed in our loop as being typical. The same survey indicated that 7.0 ft/sec was typical for coolant water velocity in the tubes.

## NOTES:

1. ALL LOOP MATERIALS ARE EITHER GLASS OR STAINLESS STEEL. BELLOWS, GASKETS AND VALVE SEALS ARE PLASTIC.
2. PUMP IS WESTINGHOUSE 150 A CANNED MOTOR PUMP.
3. LOOP IS GENERALLY CONSTRUCTED FROM 2 in. GLASS AND STAINLESS STEEL PIPES, EXCEPT FOR TUBE WHICH IS AS SHOWN.

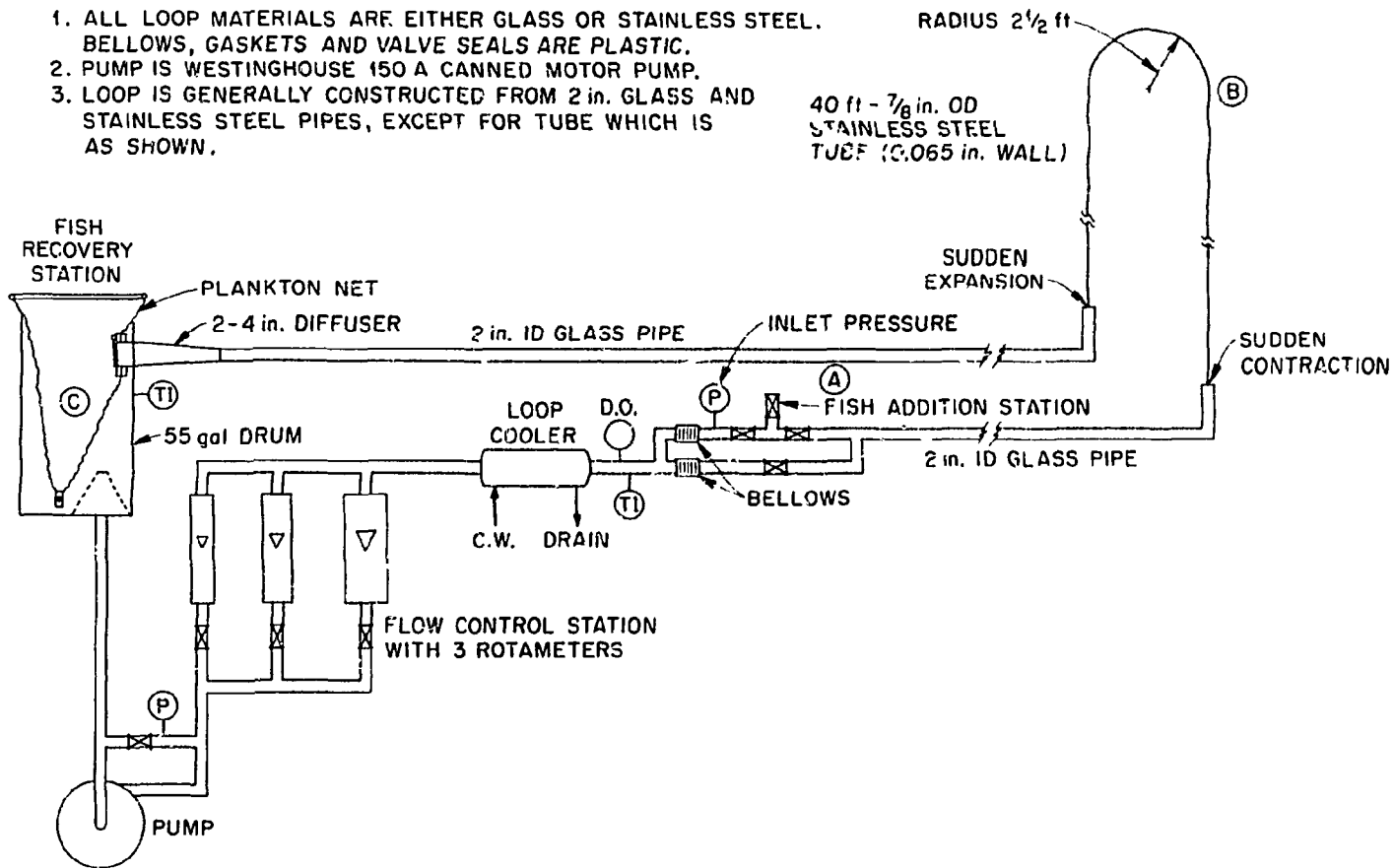


Fig. 1. Perspective diagram of the experimental loop, including fish addition station (A), experimental condenser tube (B) (40 ft, 7/8 in OD stainless steel with 0.065 in wall thickness and ID of 0.745 in), fish recovery station (consisting of a plankton net suspended in a 55-gal stainless steel barrel), pump, flow control devices, water jacket cooler and monitoring devices (hexagons) for temperature (T), pressure (P), dissolved oxygen (DO) and differential pressure ( $\Delta P$ ) between tube inlet and the fish recovery barrel. Inlet and outlet pipes for the condenser tube are at equal elevation.

Our loop has water velocity capability up to 19.0 ft/sec. The heat exchanger tube is U-shaped and mounted vertically. The vertical orientation gives a vacuum of about 1/2 atm near the top at low water velocities. The existence of vacuum is typical in the condensers at some power plants. The feed and discharge lines to the heat exchanger tube are 2-in. ID glass pipe. Thus the tube inlet and outlet configurations have a sudden contraction and sudden expansion respectively (velocity in tube = 7.2 x velocity in glass pipe), and simulate the power plant condenser headers.

In our experiments, the lowest velocity at which the fish are sent through the tube is 7.0 ft/sec and the highest velocity is 19.0 ft/sec. Figure 2 shows pressure distribution through the tube as a function of distance for both velocities. At 7.0 ft/sec a vacuum of about 1/2 atm is developed at the top of the tube, while at 19.0 ft/sec essentially no vacuum is developed. At 19.0 ft/sec the fish are subjected to a positive pressure of about 30 psig at the fish addition station. The turbulent energy dissipation rates for the two flows were calculated to be 0.00132 and 0.0217 cal/sec-gm, respectively (Appendix A).

The loop also has the capability of thermally shocking the organisms under study. This capability is obtained by operating the loop at the desired temperature above the fish acclimation temperature. Sudden temperature elevation at time of addition of fish to the loop is presumed to be equivalent to rapid warming during the several seconds of travel through the condenser tube of a power plant, although this similarity has not been tested. Temperature control is accomplished by the loop cooler working against heat added to the system by the pump.

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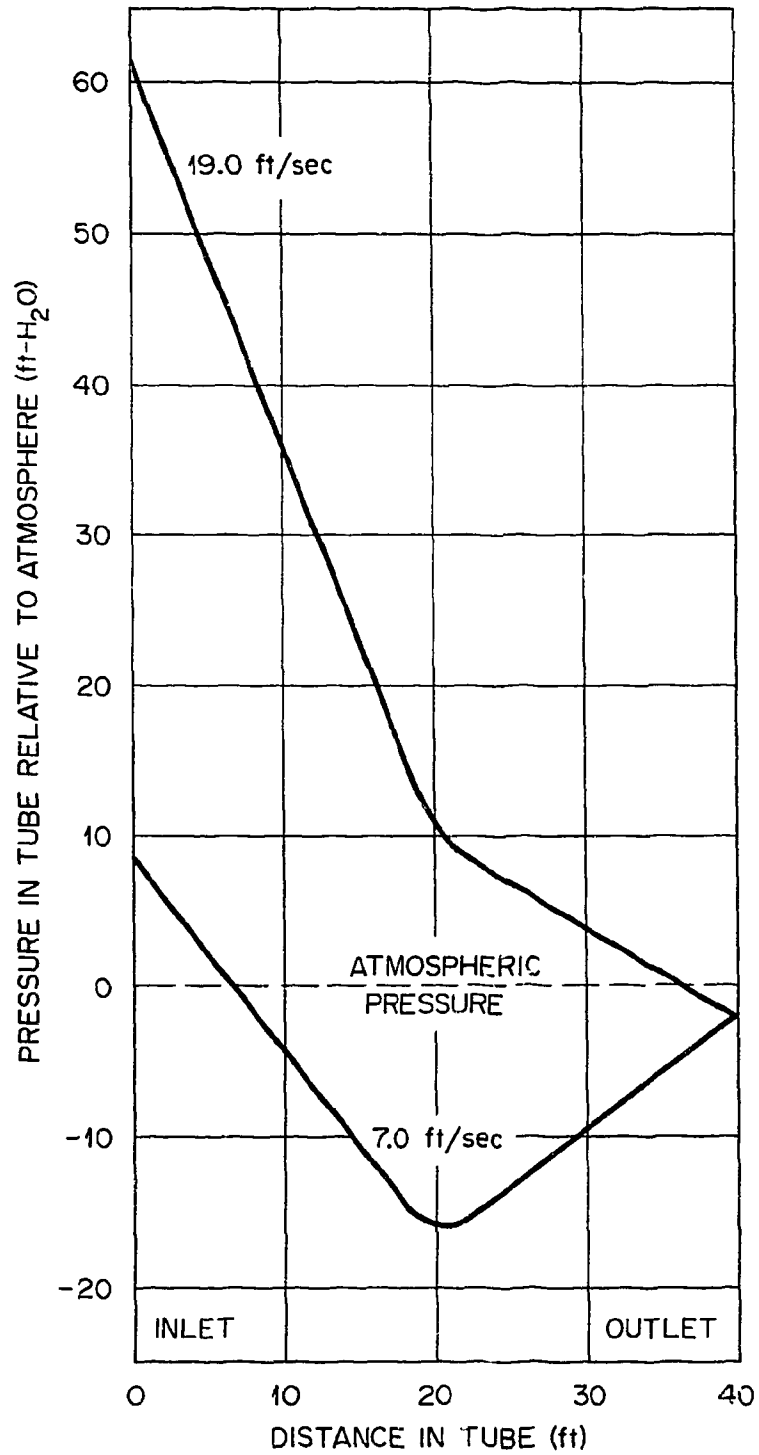


Fig. 2. Pressure distribution in the 7/8 in condenser tube at two flow velocities.

Precision was  $\pm 0.1^{\circ}\text{C}$  or better at high temperatures, but the loop cooler could not reduce the temperatures to the exact fish acclimation temperature.

The loop was filled with well water, and was aerated by bubbling air into the collection drum for 1 to 2 hr before the first run. Aeration continued each night when the loop was shut down. The dissolved oxygen content was always 95 to 100% of saturation.

Striped bass larvae were obtained from the Morristown Hatchery of the Tennessee Game and Fish Commission. The parent fish were of land-locked stock resident in Cherokee Lake, Tennessee, and were collected by electrofishing from below a small dam on the Holston River immediately upstream of the lake. We used two groups of larvae, one that hatched on April 23 and one that hatched on April 25, 1974. We experimented with them on May 6-9, so at that time they were about two weeks old, and were 4 to 6 mm in length. The fish were kept in 250 gal. fiberglass tanks in the Aquatic Ecology Laboratory and were delivered to the loop in another laboratory about 8 miles away on the day of their use. They were held at about  $21^{\circ}\text{C}$  ( $\pm 2^{\circ}\text{C}$ ). The temperature control system was not working properly, and the tank temperature varied somewhat with room temperature.

On May 5, one day prior to the runs through the experimental loop, thermal bioassays were conducted to determine the responses to thermal stresses alone. Groups of 20 larvae each were exposed to a series of timed exposures to 29, 31, and  $33^{\circ}\text{C}$ . Mortality was recorded at the end of the exposure, after 1 hr, and daily for a total of four days thereafter.

The experimental schedule called for runs with four different conditions in the experimental loop. These conditions along with the

stresses they induce are shown in Table 1. Fish were sent through the loop in batches of 50 or 100, depending on the number of fish that were available. The supply of fish was exhausted before the entire schedule could be completed.

Two kinds of controls were used for these experiments. The first (barrel controls) included handling stresses, principally during collection from the loop. For this, fish were added to the collecting barrel from a height of about 6 in., and were recovered with the plankton net. Usually a barrel control was taken after each run, with the loop at the same temperature as the run. A second kind of control (absolute control) was used in which the fish were simply transferred very gently from the transport bucket into a beaker of loop water. The only stresses to which these fish were subjected were those involved in living in a laboratory rather than their natural environment.

In all thermal shock experiments in the loop the length of the thermal exposure was controlled to 6 min. Time zero was taken when the fish was poured from a beaker into the (hotter) glass inlet station. At the end of 6 min the bucket at the bottom of the collection net was lowered into a beaker of water at ambient temperature. Barrel controls for the thermal stress runs were conducted similarly. Time zero was when the sample was poured into the (hotter) barrel, and after 6.0 min the sample was retrieved the same way.

The recovery for these experiments generally ranged from 90 to 95%. That is, for 100 fish put into the loop, 90-95 were recovered. Generally the others were stuck to the plankton net, or lost in the loop piping. The percentage mortality was computed on the basis of the number of fish

Table 1. Experimental design for striped bass experiments

Run Condition			Stress on Fish			
	Velocity in Heat Exchanger Tube (ft/sec)	Thermal Shock	Turbulence	Vacuum (atm)	Positive Pressure (psig)	Thermal Shock
I	7.0	Low (3-5°C)	Lower	~1/2	5	Low
II	19.0	Low	Higher	None	30	Low
III	7.0	High (10-12°C)	Lower	~1/2	5	High
IV	19.0	High	Higher	None	30	High

recovered and not the number added. All samples were observed in a room maintained at  $\sim 20^{\circ}\text{C}$  for four days after their run to determine latent mortalities.

## RESULTS

A general pattern of mortality of striped larvae held for several days after these experiments became apparent in the controls. There was a regular die-off in all controls, both absolute (in beakers only) and barrel, that amounted to 30 to 100% after four days (Figs. 3-11). This response necessitated that all mortality levels be viewed strictly in relationship to the control runs conducted on the test day.

### Fluid Stresses Alone

#### 7 Feet per Second

Three runs were made at 7 ft/sec over a two-day period, with a temperature change which was well within the tolerance range for larval striped bass (Table 2, Figs. 4, 5). Mortality of fish in the first two runs immediately after passage through the loop was low (0 and 5%) and comparable to those of two barrel controls (0 and 8%) (Fig. 4). Mortalities increased progressively for both test and barrel control groups throughout the four-day holding period (Figs. 4, 5). There was no apparent difference in death rates between test and control fish, although the variation was great (circa 30% on the second through fourth days).

#### 18-19 Feet per Second

Four experimental runs were made at 18-19 ft/sec on three different days in which temperature change experienced by the fish was minimal (Table 2, Figs. 6-8). Mortalities for two of the runs were enumerated

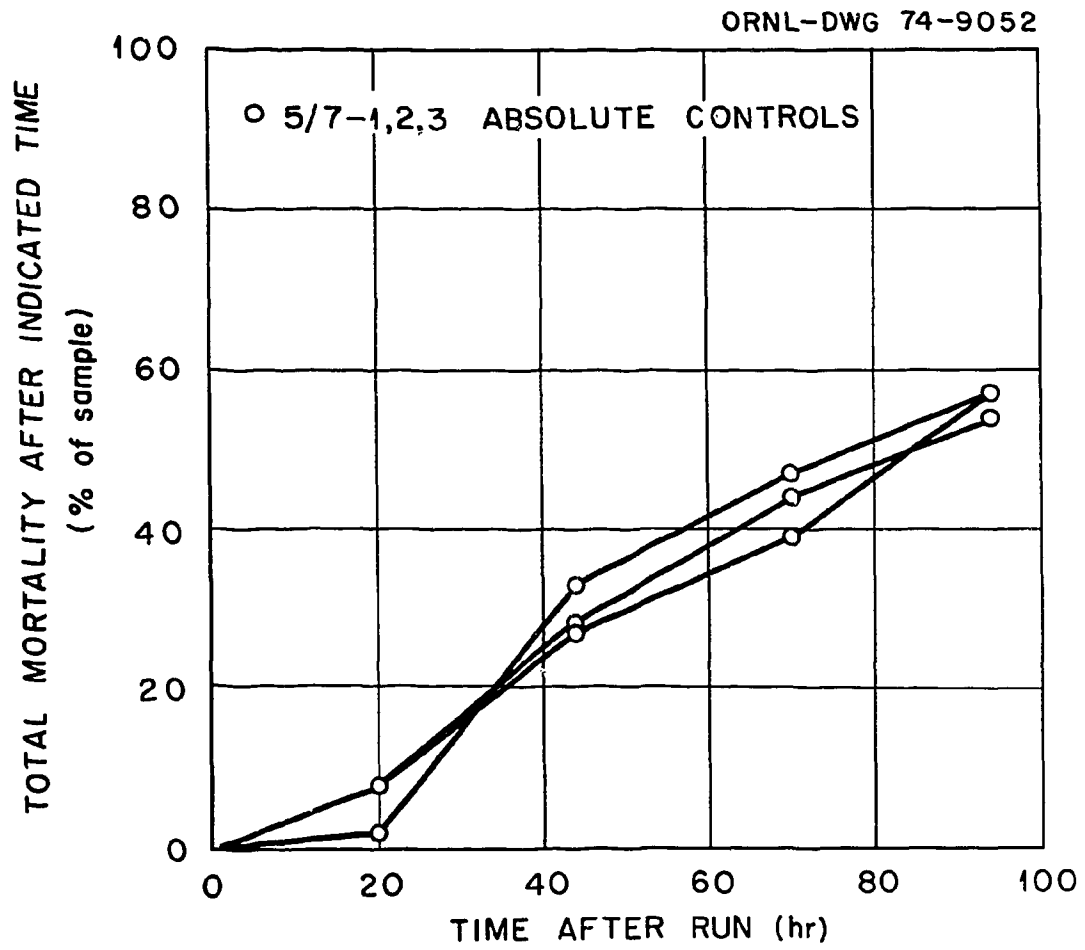


Fig. 3. Percentage mortality of striped bass larvae in absolute controls at various times after removal from stock tank.

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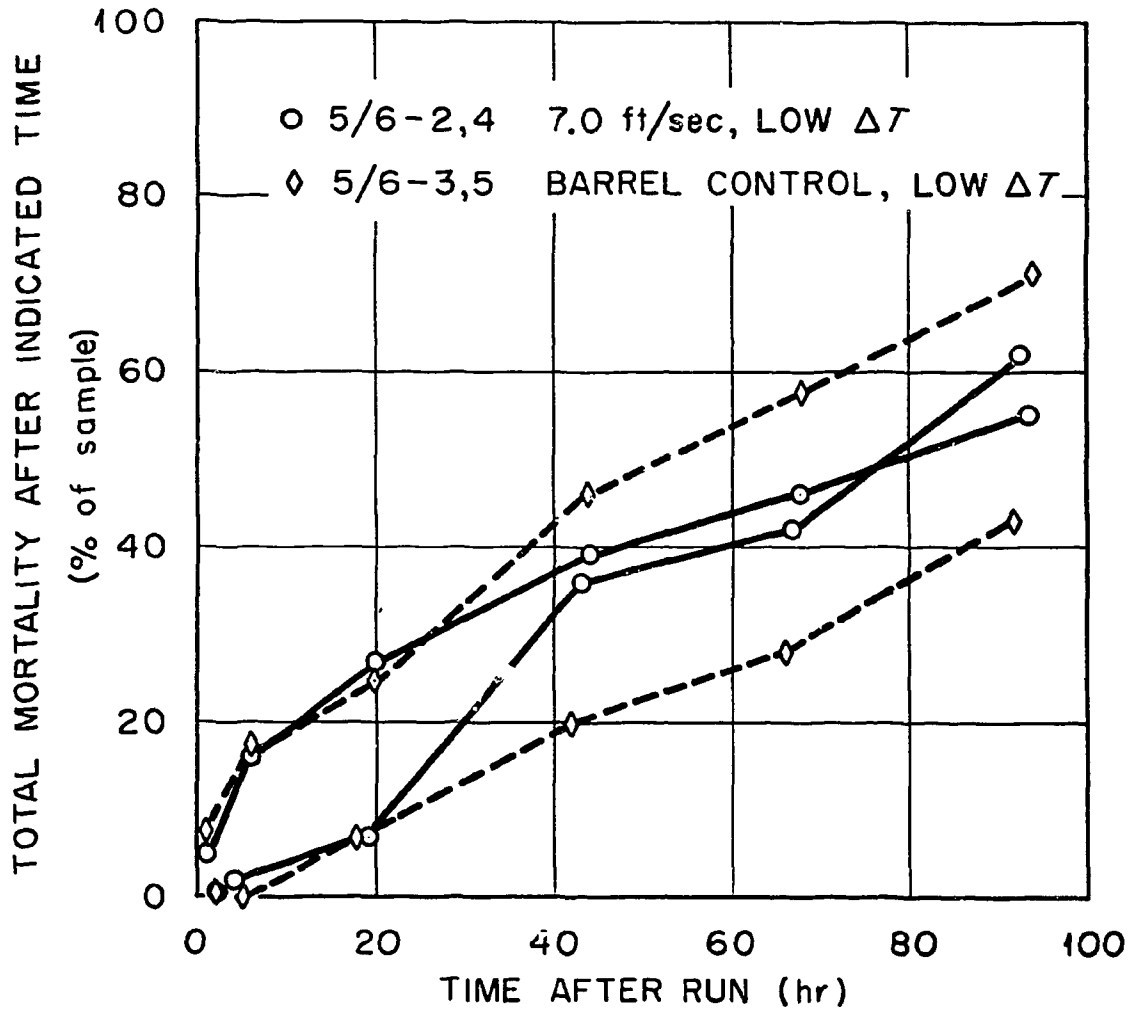


Fig. 4. Percentage larval mortality at various times after testing at 7 ft/sec and non-lethal temperature change, with barrel controls.

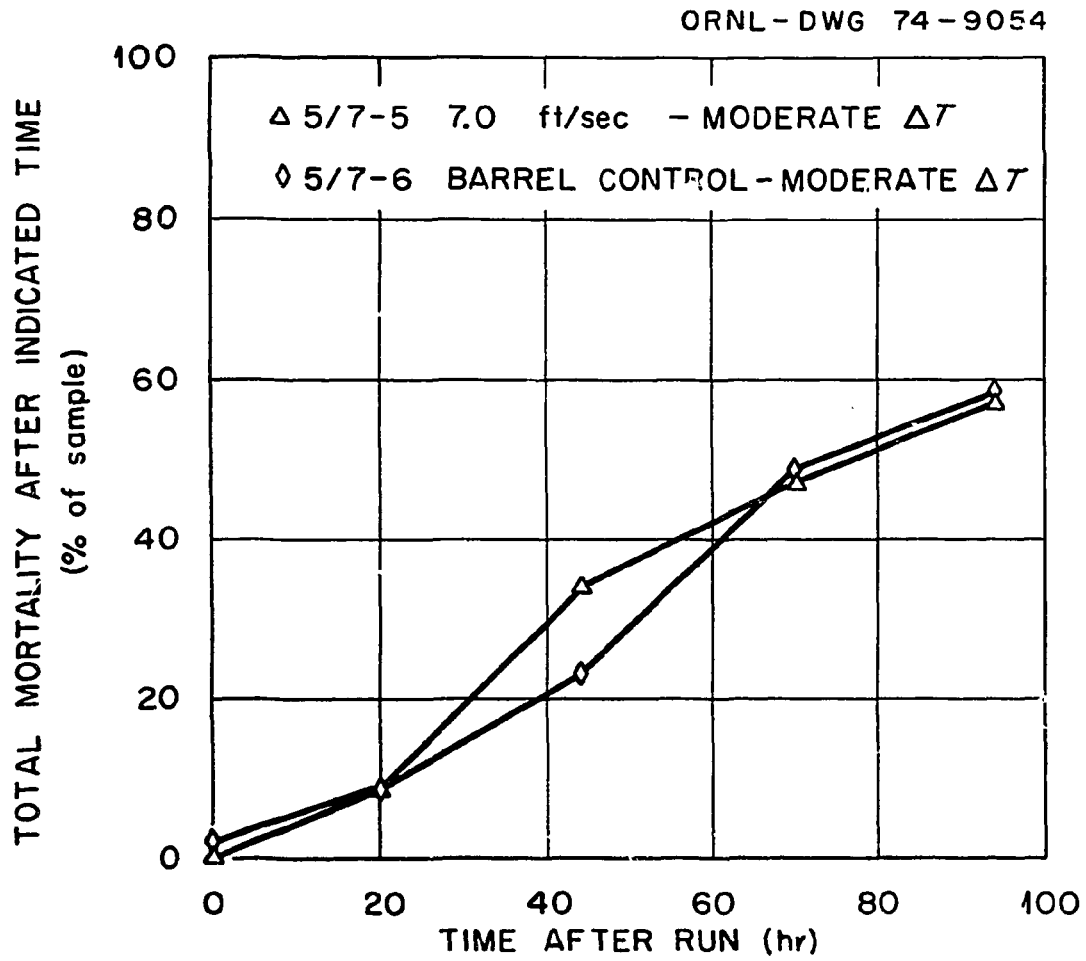


Fig. 5. Percentage larval mortality at various times after testing at 7 ft/sec and non-lethal temperature change, with barrel control.

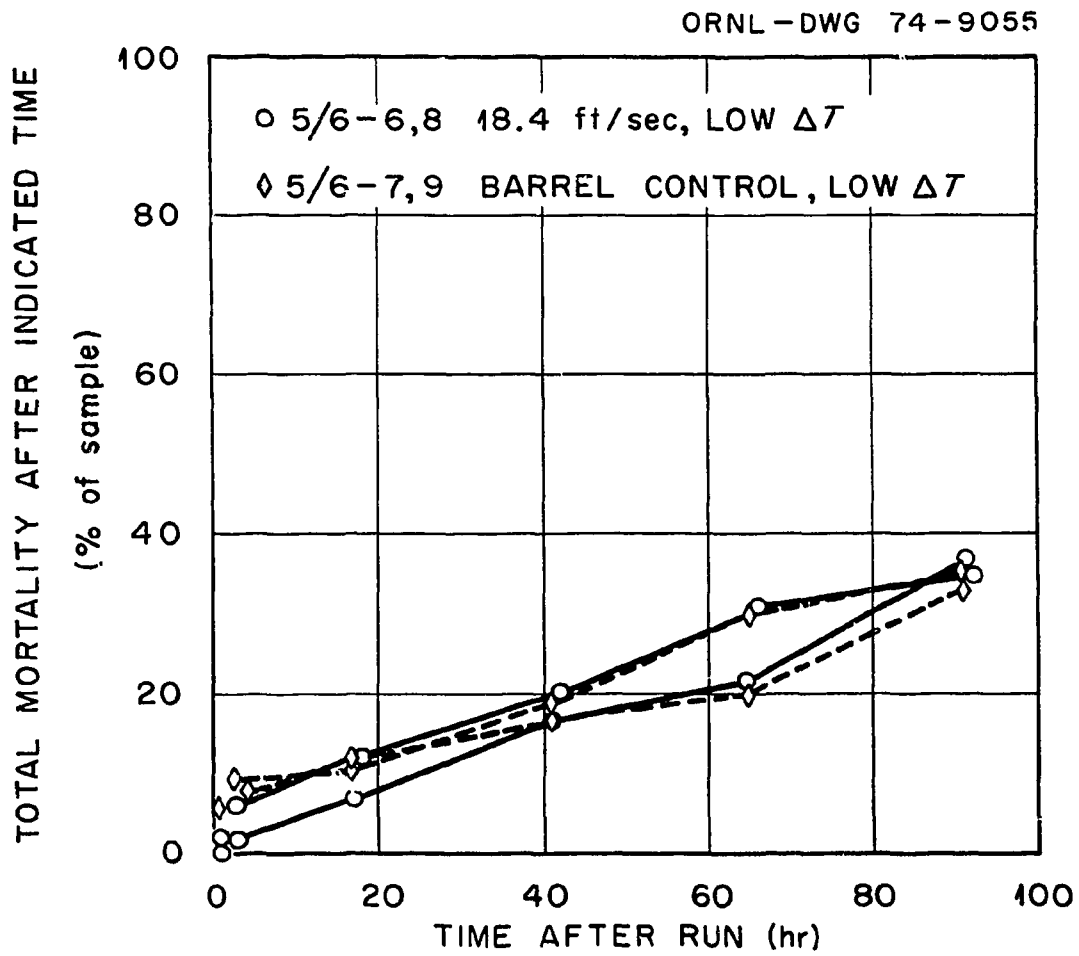


Fig. 6. Percentage larval mortality at various times after testing at 18.4 ft/sec and non-lethal temperature change, with barrel controls.

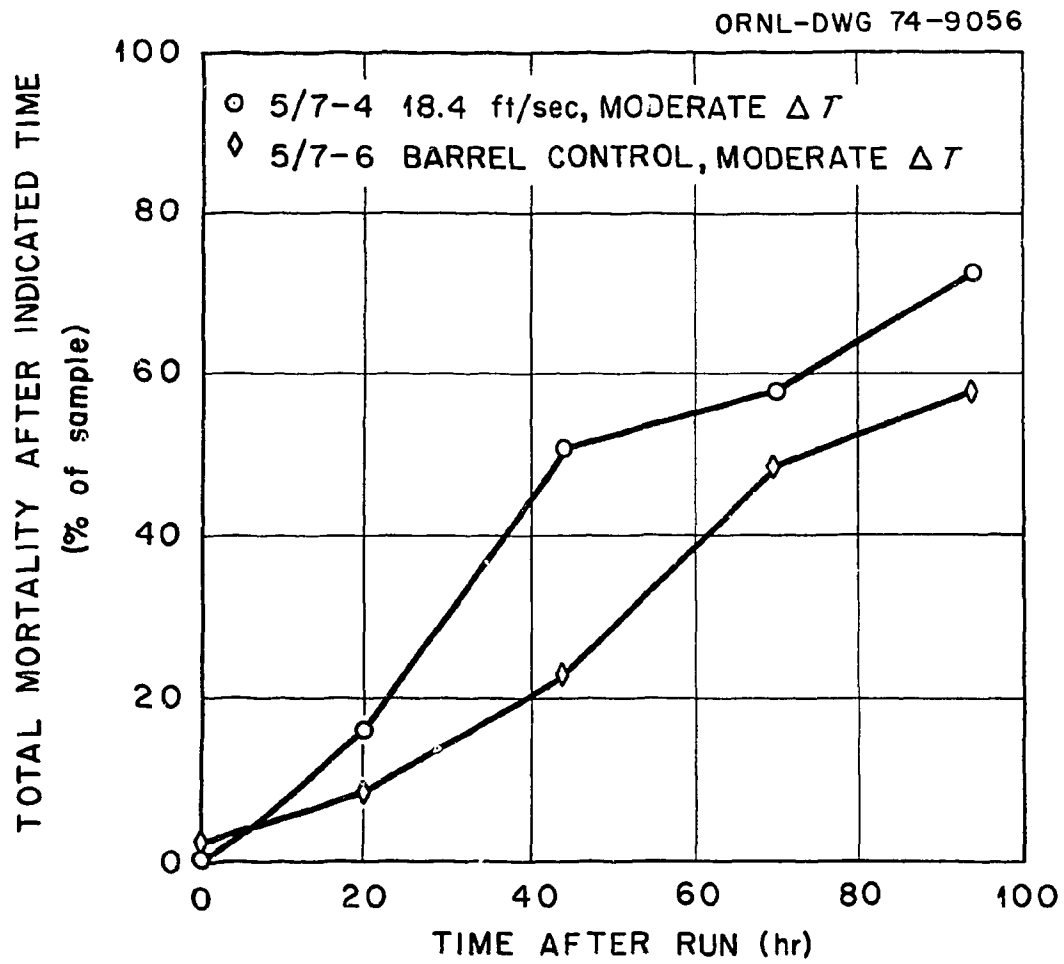


Fig. 7. Percentage larval mortality at various times after testing at 18.4 ft/sec and non-lethal temperature change, with barrel control.

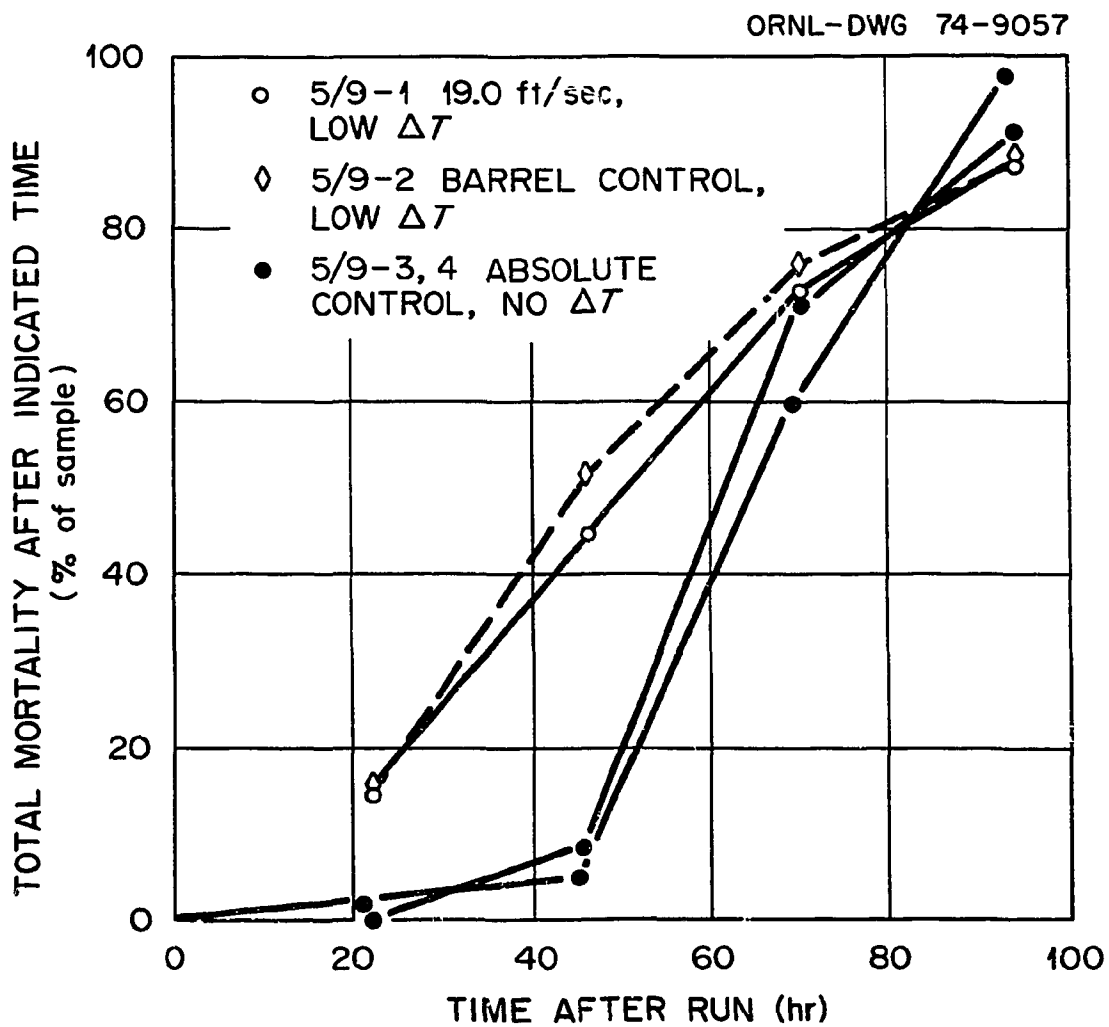


Fig. 8. Percentage larval mortality at various times after testing at 19.0 ft/sec and non-lethal temperature change, with barrel and absolute controls.

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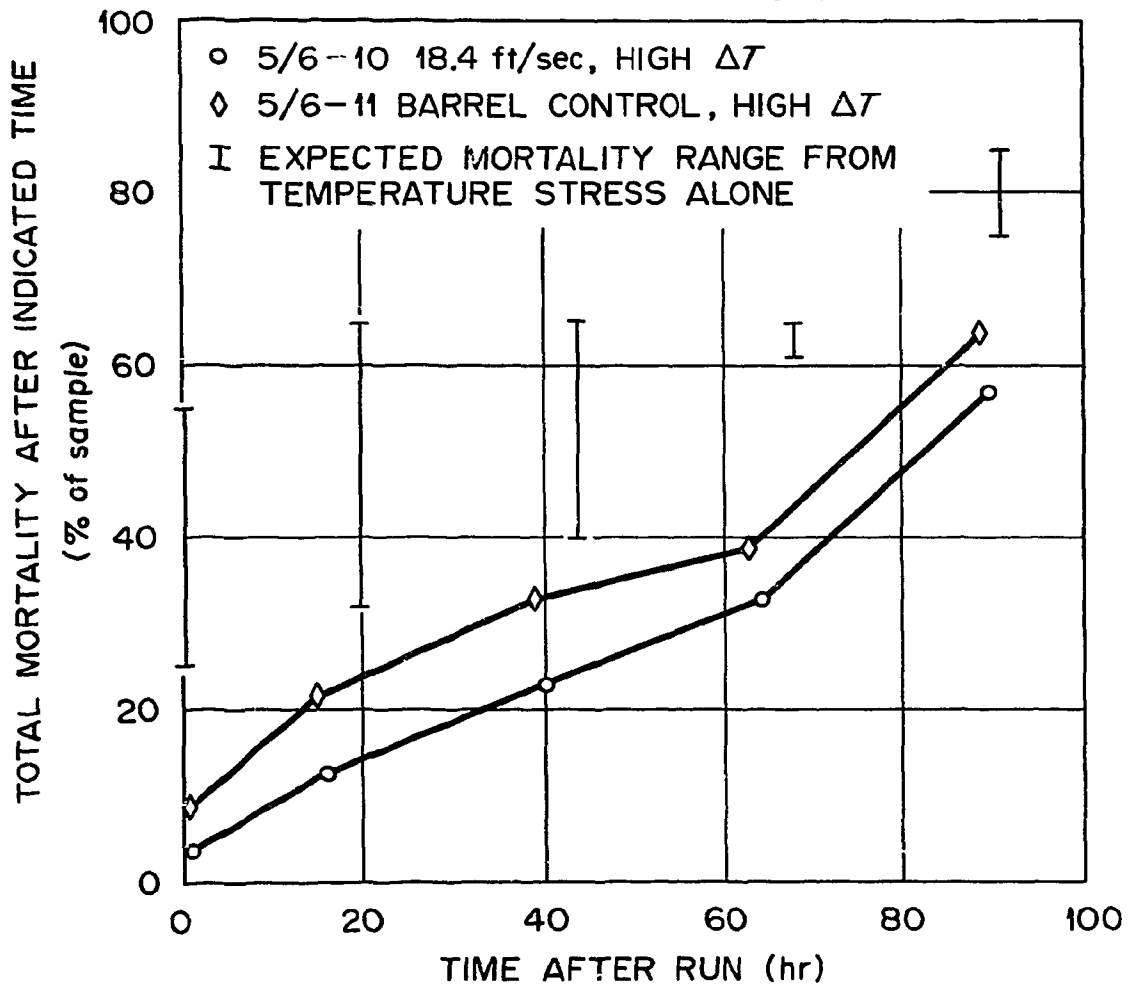


Fig. 9. Percentage larval mortality at various times after testing at 18.4 ft/sec and 31°C, with barrel control and expected mortality range (bars) from thermal exposure alone.

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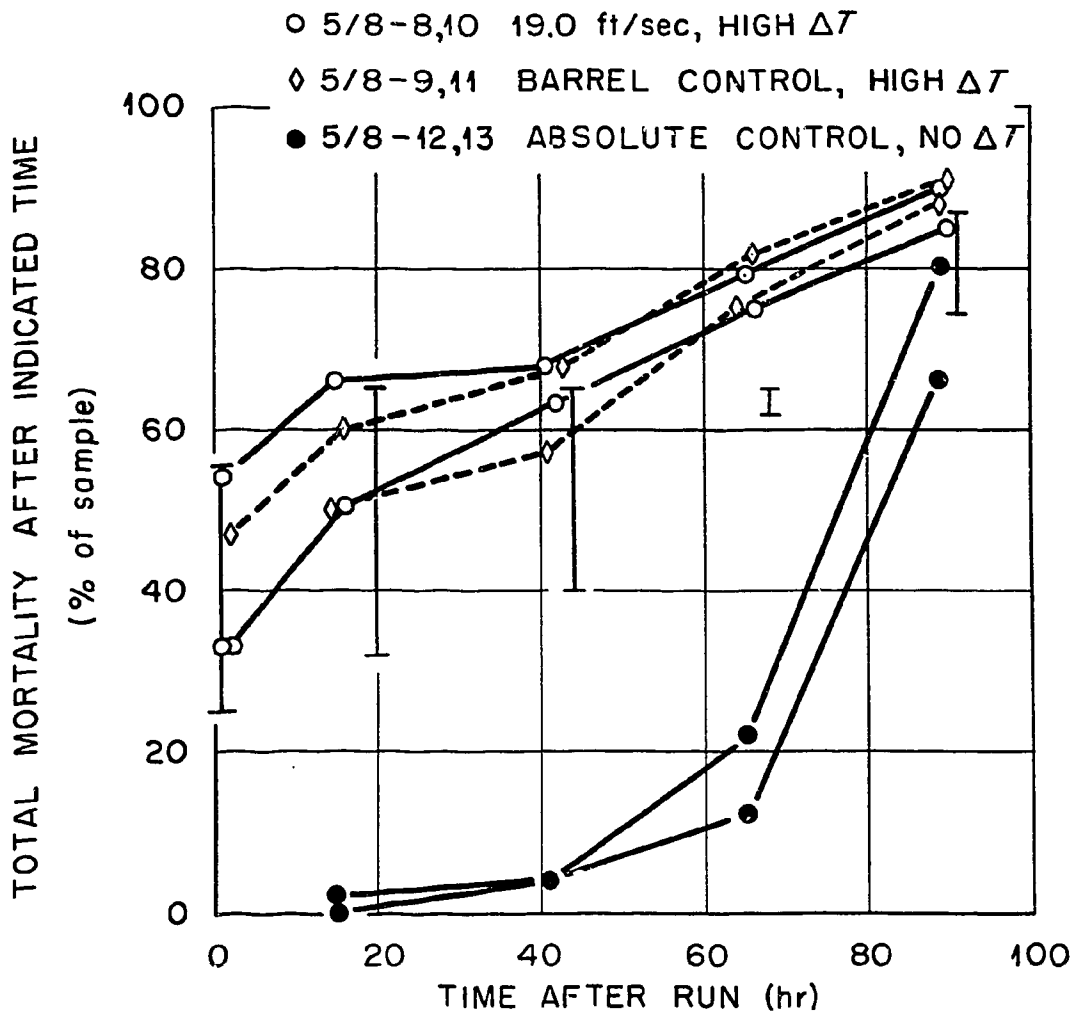


Fig. 10. Percentage larval mortality at various times after testing at 19.0 ft/sec and 31°C, with barrel and absolute controls, and the mortality range (bars) expected from thermal stress alone.

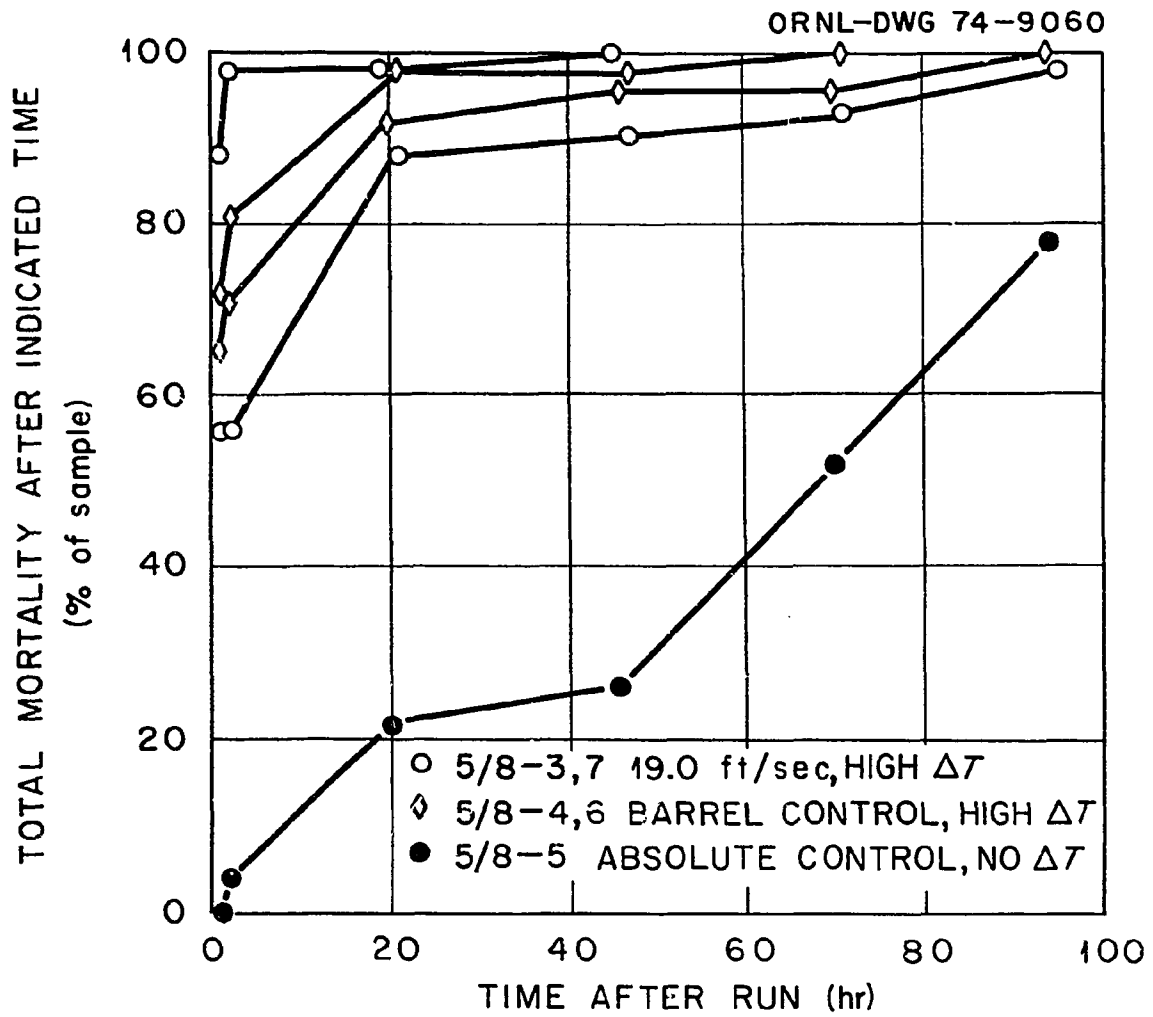


Fig. 11. Percentage larval mortality at various times after testing at 19.0 ft/sec and 32°C, with barrel and absolute controls.

Table 2. Summary of Runs with Striped Bass

Run No.	Tube Velocity (ft/sec)	Temperatures		Total Fish Recovered	Mortality (% dead fish after/hours)					
		Fish (°C)	Loop (°C)							
5/6-1	12.5	21*	25.5	38	0/2	8/8	18/22	37/46	74/70	82/96
5/6-2	I 7.0	21*	26	44	5/1	16/6	27/20	39/44	46/68	55/94
5/6-4	I 7.0	21*	24	45	0/1	2/4	7/19	36/43	42/67	62/93
5/6-3	BC	21*	24	48	8/1	17/6	25/20	46/44	58/68	71/94
5/6-5	BC	21*	24	46	0/1	0/4	7/18	20/42	28/66	43/92
5/6-6	II 18.4	21*	23	49	2/1	6/3	12/18	20/42	31/66	35/92
5/6-8	II 18.4	21*	23	46	0/1	2/3	7/17	17/41	22/65	37/91
5/6-7	BC	21*	23	48	6/1	8/3	12/17	17/41	21/65	33/91
5/6-9	BC	21*	23	47	6/1	9/3	11/17	19/41	30/65	36/91
5/6-10	IV 18.4	21*	31.0±0.1	90	4/1		13/16	23/40	33/64	57/90
5/6-11	BC	21*	31.0±0.1	92	9/1		22/15	33/39	39/63	64/89
5/7-1	AC			49			2/20	33/44	47/70	57/94
5/7-2	AC			49			8/20	27/44	39/70	57/94
5/7-3	AC			50			8/20	38/44	44/70	54/94
5/7-4	II 18.4	17*	25	45			16/20	51/44	58/70	73/94
5/7-5	I 7.0	17*	25	47			9/20	34/44	47/70	57/94
5/7-6	BC	17*	25	43			9/20	33/44	48/70	58/94

Table 2. (continued)

Run No.	Tube Velocity (ft/sec)	Temperatures		Total Fish Recovered	Mortality (% dead fish after/hours)						
		Fish	Loop								
5/8-1	IV	19.0	19*	33.0 $\pm$ 0.1	43	77/1	77/2	88/23	88/49	91/73	100/97
5/8-2		BC	19*	33.0 $\pm$ 0.1	47	68/1	72/2	94/22	96/48	96/72	96/96
5/8-3	IV	19.0	19*	31.9 $\pm$ 0.1	41	56/1	56/2	88/21	90/47	93/71	98/95
5/8-7	IV	19.0	19*	31.9 $\pm$ 0.1	42	88/1	98/2	98/19	100/45		
5/8-4		BC	19*	31.9 $\pm$ 0.1	47	72/1	81/2	98/21	98/47	100/71	
5/8-6		BC	19*	31.9 $\pm$ 0.1	78	65/1	71/2	92/20	96/46	96/70	100/94
5/8-5		AC			50	0/1	4/2	22/20	26/46	52/70	78/94
5/8-8	IV	19.0	20*	31.0 $\pm$ 0.1	88	33/1	33/2	50/16	63/42	75/66	85/90
5/8-10	IV	19.0	20*	31.0 $\pm$ 0.1	94	54/1		66/15	68/41	79/65	90/89
5/8-9		BC	20*	31.0 $\pm$ 0.1	91	44/1	47/2	60/16	68/42	82/66	91/90
5-8-11		BC	20*	31.0 $\pm$ 0.1	92	37/1		50/15	57/42	75/65	88/89
5/8-12		AC			98	0/1		2/15	4/41	22/65	80/89
5/8-13		AC			102	0/1		0/15	4/41	12/65	66/89
5/9-1	II	19.0	20	24	92			15/22	45/46	73/70	88/94
5/9-2		BC	20	24	84			15/22	52/46	76/70	88/94

Table 2. (continued)

Run No.	Tube Velocity (ft/sec)	Temperatures		Total Fish Recovered	Mortality (% dead fish after/hours)			
		Fish (°C)	Loop (°C)					
5/9-3	AC			47	0/22	9/46	72/70	91/94
5/9-4	AC			95	2/21	5/45	60/69	98/93

\*Approximate acclimation temperature -  $\pm 2^{\circ}\text{C}$ .

\*\*Refers to experimental design given in Table 1.

AC = Absolute control.

BC = Barrel control.

immediately and were low (0 and 2%) and were less than those for the barrel controls (6%) (Fig. 6). After about 3 hr, mortalities had risen to 2 and 6%, but were still less than the controls. Death rates for these fish closely approximated controls throughout the holding period. A third run, with a slightly higher  $\Delta T$ , showed higher mortality throughout the holding period than did its control and both test and control had higher mortalities than the first two runs (Fig. 7). The differences were less than the variation seen among other runs and controls, however. The fourth run at this flow rate resulted in closely matched mortalities for test and barrel control fish, although the absolute controls for this day showed an initial better survival (Fig. 8).

### Thermal and Fluid Stresses

#### Thermal Bioassay

Combined thermal and mechanical stress experiments were standardized to a 6-min thermal exposure time based on the results of thermal bioassays. Temperature assays conducted at 29, 31, and 33°C indicated that larval striped bass acclimated to about 22°C could tolerate about 1/2 hr exposure to 29°C (much longer than the 6-min exposure period in our experimental condenser tube or in most power plant cooling systems). Temperatures of 31 and 33°C, however, were lethal (50%) within 5-6 minutes (Table 3). As with control fish, thermally shocked survivors gradually experienced die-off under the conditions of holding. There was a large degree of variability in thermal resistance among the test fish. There was also some recovery of fish after the first (immediate) tally.

Table 3. Percent of larval striped bass found to be swimming after being exposed to three temperatures and examined periodically for 91 hr thereafter

Exposure Time (min)	Percent Swimming After Time (hr) <sup>1</sup>					
	Immediate	1	20	44	68	91
29.0°C						
5	95	95	65	55	40	35
10	60	85	70	55	45	35
13	85	85	70	75	65	65
15	75	80	90	65	45	40
20	45	45	35	30	20	20
27	95	100	95	85	50	45
31.0°C						
5	85	85	75	65	50	15
6	45	45	35	35	35	30
7.5	50	60	50	50	50	25
9	45	50	40	35	25	20
10	25	25	25	20	15	15
15	20	25	50	40	20	15
33.0°C						
2	80	95	80	75	75	75
4	5	90	55	50	50	45
5	0	50	50	20	15	5
6	0	25	35	25	20	15
6	0	15	30	30	20	20
8	0	10	40	30	20	20
10	0	35	25	15	5	5

<sup>1</sup>Initial No. = 20.

### 18-19 Feet per Second

Effects of combined thermal and fluid stresses were tested only at the higher flow rate (18-19 fps) which maximized turbulence and shear. Three temperatures were examined. Tests at 7 fps, which would have tested vacuum conditions, were not run due to insufficient fish.

#### Tests at 31°C

Conflicting results were obtained. Simultaneous mechanical and thermal stresses on one day (May 6) resulted in both test and barrel control fish having better survival than that which resulted from thermal stress alone (Fig. 9). Fish which traversed the loop survived better than did the barrel controls. On the other day (May 8), both barrel control and test fish died in a pattern that closely approximated thermal mortalities but slightly exceeded them during the later holding period (Fig. 10). In each case, the thermal mortalities alone are shown as ranges indicating the uncertainty of predicting survivorship for several days after a 6-min. thermal exposure.

#### Tests at 32°C

Two tests with barrel controls and an absolute control were conducted at 32°C (Fig. 11). Initial mortality after 6-min exposure was 56 to 88%, followed by rapid die-off. The test and barrel control groups responded similarly, but with considerable variability.

#### Tests at 33°C

One test and a barrel control were conducted at 33°C (Fig. 12). Both responded similarly, with high (68 and 77%) mortality initially which rose to nearly 100% by 24 hr.

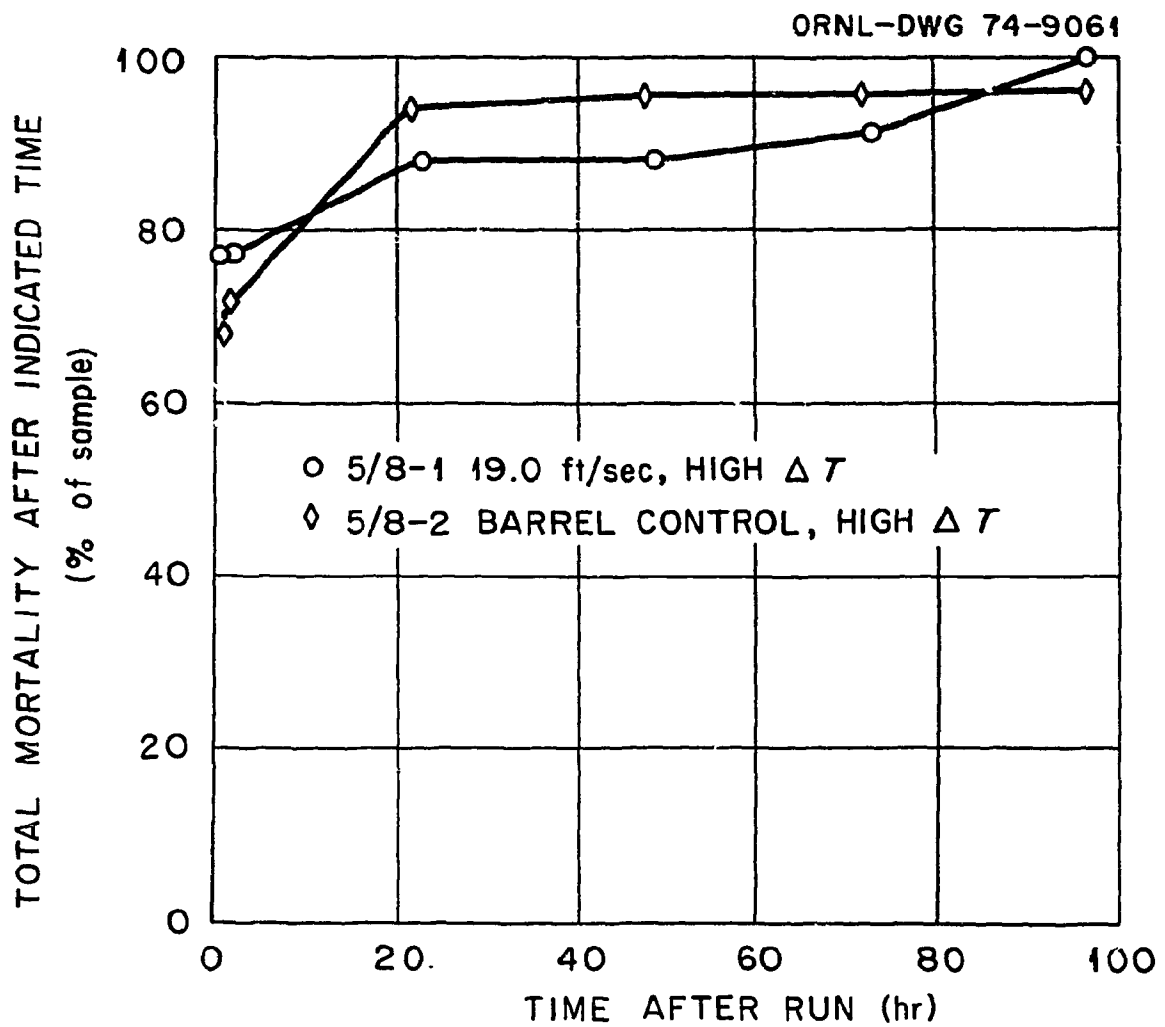


Fig. 12. Percentage larval mortality at various times after testing at 19.0 ft/sec and 33.0°C, with barrel control.

## DISCUSSION

Mechanical stresses in the experimental condenser tube and connecting piping appear to inflict minimal damage to larval striped bass. The low levels of mortality seen initially can probably be ascribed to handling effects since barrel controls also had some initial deaths. Our holding procedures (small beakers of well water with occasional feeding and water changes) were insufficient to ensure survival of even the absolute controls; yet controls and fish which traversed the loop experienced similar mortality rates. Minimal ( $\leq 15\%$ ) mortalities of older striped bass (yearlings, 2.1-8.3 cm) in condenser tubes had been shown by Kerr (1953), but we had anticipated greater mortalities of the seemingly more fragile larvae. The thermal bioassay results were similar to those seen by Kelley and Chadwick (1971). Our fluid flow analysis of the inside of the condenser tubing (Appendix A) cannot be directly compared with the recent report on tolerable shear levels for striped bass larvae by Morgan et al. (1973) because their experiments used idealized, laminar flow quite unlike the flow characteristics inside a condenser tube.

An unexpected result was the apparent enhanced survival of some bass larvae undergoing thermal exposure when they were simultaneously experiencing mechanical stresses. Fig. 9 would suggest that mortality was inversely related to the degree of mechanical stress (i.e., test fish < barrel control < thermal assay). Other runs with combined stresses indicated that thermal exposure was the predominant factor in mortality since test and control fish responded similarly. Variability throughout these experiments has been high, however, and the results shown in Fig. 9 may be circumstantial. They were not obtained in the tests two days later

(Figs. 10-12). Unsatisfactory temperature control of all fish during pre-experimental holding may have influenced thermal acclimation sufficiently to account for some anomalous results. Mixing cool water from the transfer beaker in the fish addition station may have slightly reduced exposure temperatures. Certainly these results were contrary to our anticipation of some positive synergistic effect, and thus they need to be explored further. The available supply of young striped bass precluded any additional experiments this year.

#### Relationship to Power Plant Entrainment

While these results suggest minimal mortalities, they should not be taken uncritically as indicative of overall effects of entrainment. Experiments reported here were designed to test one component of the cooling water system to which entrained organisms are exposed, namely, the condenser tube. Other components, principally the pump, which were not studied could also be the locus of mechanical damage. These should also be examined. The pump now appears to be the most logical site for damages that have been identified at operating power plants (e.g., Marcy 1971).

. Other factors may combine to make entrainment damages more severe than these experiments indicate. Tidal movements in an estuary may cause multiple exposures of larvae to condenser passage; we subjected larvae to only one pass. Presence of silt or other organisms in the water may also influence such factors as abrasion; our water supply was free of such material. Temperature increase through the condenser tube walls in an operating power plant may provide a different thermal exposure pattern to entrained larvae than did our experiments; our larvae

received an abrupt temperature rise as they entered the loop through the inlet valve.

Age of fish as a factor in mortality remains to be resolved. Our supply of striped-bass larvae was insufficient to allow testing of the large numbers required at more than one general age, about 2 weeks. Since experiments with inert fibers (Forgacs and Mason 1959a,b) showed increased deformation with increased length, older larvae may be more susceptible to damage than small larvae, even though yearlings (Kerr 1953) seem quite tolerant to mechanical damage (but were inclined to die of neurological shock). Younger larvae could also be more fragile.

#### CONCLUSIONS

Mechanical damage to larval striped bass approximately 2 wks old due to one passage through a typical power plant condenser tube (excluding passage through a pump) appears to be minimal (<5%). There does not appear to be a synergistic effect due to thermal and mechanical stresses acting simultaneously; there were indications that mechanical stress may have slightly enhanced thermal resistance, although this result needs further critical examination.

#### ACKNOWLEDGMENTS

We thank Mr. Robert Smith for technical assistance and Drs. W. Van Winkle and S. Christensen for review of the manuscript. Dr. G. P. Goodyear participated in initial trials of the apparatus with other fish species.

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## APPENDIX

Turbulence to which Larval Fish were Exposed

When water flows in a conduit, one of two basically different kinds of flow will exist, laminar flow or turbulent flow. At low velocities, laminar flow results. This flow is characterized by the individual streamlines running side by side in an orderly manner and without any irregular fluctuations. If the velocity is high, then we have turbulent flow. This flow is characterized by the individual streamlines fluctuating irregularly and becoming interwoven. A rather sharp line of demarkation exists between these two kinds of flow. The parameter that distinguishes between these flows is the Reynolds Number, defined as follows:

$$\text{Reynolds No.} = \frac{\rho d v}{\mu}$$

$\rho$  = fluid density

$d$  = diameter

$v$  = fluid velocity

$\mu$  = viscosity

In a pipe, if the Reynolds No. is less than 2100, then the flow is laminar; if the Reynolds No. is over 2100, then the flow is turbulent. In nature and in industry, turbulent flow is the common mode; as a matter of fact, laminar flow would be considered rather rare.

Turbulence, then, is the irregular and more or less random additional motions superimposed on a bit of fluid, that is flowing in a conduit at some average velocity. These bits of fluid moving at random are called eddies. Now, consider two eddies beside each other, but flowing in different directions relative to each other. A rather substantial shear field will

exist between them. If a larval fish happens to be located here, he will be exposed to viscous shear forces and possibly subjected to the reactions described in the body of this report. This is not the only force that the larval fish would be exposed to in a turbulent field. Consider a fish suspended in an eddy. If another eddy comes up from the side and hits him broadside, he would be buffeted by a so-called dynamic pressure force. Hinze<sup>1</sup> has shown that globules of non-rigid materials in a continuous turbulent field (e.g., oil droplets in water) are subjected to both forces, viscous shear and dynamic pressure.

Fluid turbulence is dissipative in nature, that is, the principal result of fluid turbulence is the dissipation of energy. A continuous supply of energy is necessary in order to maintain turbulence; without it, the turbulence would decay. One might expect that a quantity such as the energy dissipation rate per unit mass of fluid would be a first-order correlation function for relating larval fish mortalities to the level of turbulence. Indeed, this quantity is commonly used in correlating many closely related phenomena. For instance, Sevik and Park<sup>2</sup> have shown that the splitting of drops and bubbles in a turbulent fluid is related to the energy dissipation rate per unit mass. Thomas<sup>3</sup> has shown that flocs of particles are ruptured in a turbulent field and that the process is directly related to the energy dissipation rate per unit mass of fluid.

In our loop the principal resistance is 40 feet of 7/8 inch O.D. tubing. The pressure drop through this tube is the source of energy to generate turbulence. It can be shown that for a fluid flowing in a pipe, the energy dissipation rate per unit mass of fluid is represented by

$$\epsilon = \frac{v \Delta P}{\rho L}$$

where

$\epsilon$  = energy dissipation rate per unit mass

$v$  = fluid velocity

$\rho$  = fluid density

$\Delta P$  = pressure drop in tube

$L$  = length of tube.

Applying the above equation to pressure drop data from Fig. 2 of the main report, we can compute the parameters in the following table:

Velocity in Tube (ft/sec)	Overall Pressure Drop in 40 ft of 7/8 in. O.D. Tube (ft.)	Turbulent Energy Dissipation Rate per unit Mass of Fluid (cal/sec-gm)
7.0	10.6	0.00132
19.0	64.0	0.0217

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