Temperature Shock Studies on White Perch and Striped Bass

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TEMPERATURE SHOCK STUDIES ON WHITE PERCH AND STRIPED BASS

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Temperature Shock Studies

A series of temperature shock studies were conducted with white perch, Morone americana and striped bass, Roccus saxatilis. In these studies four individuals of a species were transferred from their ambient acclimation temperature to 10 F degrees and 15 F degrees above acclimation and observed for 15 minutes. After the 15 minutes exposure, they were transferred back to the original acclimation temperature and observed for 15 minutes. Observations were recorded with reference to both fish mortality and behavior. In recording fish behavior, both opercular rates in movements per minute and any unusual stress were noted.

Initially both +10 F degree and +15 F degree studies were conducted for a given acclimation temperature. In later studies, if no mortalities or acute stress were noted in the +15 F degree experiment, the +10 F degree study was not run.

All studies were conducted in a 10-gallon porous plexiglas box placed in a Forma-Temp Circulating Water Bath. Temperature fluctuations during tests were less than $\pm$ 1 F degree.

The results of temperature shock studies with white perch are presented in Table 1. Table 2 includes the results of shock studies with striped bass.

Preliminary findings indicate that during the late summer months both white perch and striped bass can survive 15 minute exposures to +15 F degrees above ambient and return to ambient temperature if the ambient water is 80 F degrees or less. With summer ambient water temperatures of 85 F degrees or

higher fish mortality might be expected if these fishes are exposed for 15 minutes to temperatures 15 F degrees above ambient. In early autumn, however, sudden increases of 15 F degrees were found to result in mortalities of striped bass acclimated to 66°F. The innate factor noted in the discussion of the white perch temperature avoidance may again be involved, but the extent of its influence is difficult to assess at this time. Field temperatures began to drop rapidly in the latter half of October. It is possible, then, that the striped bass tested on 20 October were in fact acclimated to a temperature above 59°F (even though held at the temperature of capture, 59°F). Consequently, a 15 F degree increase at 59°F may not have been equivalent to a 15 F degree increase at 66°F. This is currently under study.

Table 1. -- Temperature Shock Treatment with White Perch, Morone americana.

Species: Morone americana Size: 61, 78, 68, 71 TL mm.
Date: 13 August 1970
Acclimation: 82°F for 24 hours
Dissolved oxygen approx. saturated; pH = 7.4; salinity = 4.0 °/oo

Direct transfer: acclimation - 10°F+

82°F → 92°F

Mortality To = 15:00

initial	5 min.	10 min.	15 min.	
4 live	4	4	4	All live

92°F → 82°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 82°F → 92°F

initial: 160/min. - opercular rate - no other aberant behavior
5 min.: 141/min. - opercular rate - no other aberant behavior
10 min.: 135/min. - opercular rate - no apparent stress
15 min.: 117/min. - opercular rate - no apparent stress

Transferred to 82°F

initial: 140/min. - opercular rate - no other apparent stress
5 min.: 100/min. - opercular rate - no other apparent stress
10 min.: 98/min. - opercular rate - no other apparent stress
15 min.: 90/min. - opercular rate - no other apparent stress

Table 1. -- (continued).

Species: Morone americana Size: 58, 73, 81, 58 TL mm.
Date: 13 August 1970
Acclimation: 82°F for 24 hours
Dissolved oxygen approx. saturated; pH = 7.4; salinity = 4.0 °/oo

Direct transfer: acclimation - 15°F+

82°F → 97°F

Mortality To = 16:30

initial	5 min.	10 min.	15 min.	
4 live	4	4	4	All live

97°F → 82°F

initial	5 min.	10 min.	15 min.	
	4	4	4	All live

Behavior 82°F → 97°F

initial: 141/min. - opercular rate - no apparent stress
5 min.: 124/min. - opercular rate - searching behavior (increased activity for duration of test)
10 min.: 120/min. - opercular rate - searching behavior (increased activity for duration of test)
15 min.: 105/min. - opercular rate - searching behavior (increased activity for duration of test)

Transferred back to 82°F

initial: 118/min. - opercular rate - no apparent stress
5 min.: 104/min. - opercular rate - normal activity level
10 min.: 114/min. - opercular rate - normal activity level
15 min.: 110/min. - opercular rate - normal activity level

Table 1.-- (continued).

Species: Morone americana Size: 87, 81, 80, 90, TL mm.
Date: 13 August 1970
Acclimation: 87°F for 24 hours
Dissolved oxygen approx. saturated; pH 7.4; salinity 4.0 °/oo

Direct transfer: acclimation - 10°F+

87°F → 97°F

Mortality To = 17:10

initial	5 min.	10 min.	15 min.	
4 live	4	4	4	All live

97°F → 87°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 87°F → 97°F

initial: 152/min. - opercular rate - no apparent stress
5 min.: 128/min. - opercular rate - some increase in activity
10 min.: 109/min. - opercular rate - some increase in activity
15 min.: 100/min. - opercular rate - activity level returning to normal

97°F → 87°F

initial: 128/min. - opercular rate - normal activity level
5 min.: 102/min. - opercular rate - normal activity level
10 min.: 94/min. - opercular rate - normal activity level
15 min.: 98/min. - opercular rate - normal activity level

Table 1. -- (continued).

Species: Morone americana Size: 74, 72, 74, 72 TL mm.
Date: 13 August 1970
Acclimation: 87°F for 24 hours
Dissolved oxygen approx. saturated; pH = 7.4; salinity 4.0 °/oo

Direct transfer: acclimation - 15°F+

87°F → 102°F

Mortality To = 17:45

initial	5 min.	10 min.	15 min.
4 live	3 live, 1 dead	1 live, 3 dead	4 dead

102°F → 87°F

initial	5 min.	10 min.	15 min.
	-	-	-

Behavior 87°F → 102°F

initial: irregular opercular - 1 belly up, great stress
5 min.: movement - acute shock - 1 dead, rest acute
10 min.: 3 dead, 1 losing equilibrium
15 min.: 4 dead, experiment terminated

no transfer back to 87°F due to death in 102°F

Table 1. -- (continued).

Species: Morone americana Size: 82, 70, 74, 81 TL mm.
Date: 8 September 1970
Acclimation: 77°F for 96 hours
Dissolved oxygen approx. saturated; pH = 7.4; salinity = 4.0 °/oo

+15 F° study 77°F → 92°F To = 15:50

Mortality 77°F → 92°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

92°F → 77°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 77°F → 92°F

initial: 134/min. - opercular rate - some increased activity
5 min.: 122/min. - opercular rate - no apparent stress
10 min.: 124/min. - opercular rate - normal behavior
15 min.: 126/min. - opercular rate - search behavior

92°F → 77°F

initial: 112/min. - opercular rate - normal behavior
5 min.: 116/min. - opercular rate - normal behavior
10 min.: 118/min. - opercular rate - normal behavior
15 min.: 116/min. - opercular rate - normal behavior

Table 1. -- (continued).

Species: Morone americana Size: 96, 84, 88, 78, TL mm.
Date: 28 September 1970
Acclimation: 76°F for 96 hours
Dissolved oxygen approx. saturated; pH = 7.4; salinity = 4.0 °/oo

+15 F° study 76°F → 91°F To = 15:00

Mortality 76°F → 91°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

91°F - 76°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 76°F → 91°F

initial: 132/min. - opercular rate - increased activity
5 min.: 126/min. - opercular rate - searching, no apparent stress
10 min.: 118/min. - opercular rate - no apparent stress, 1 searching
15 min.: 116/min. - opercular rate - behavior returning to normal

91°F → 76°F

initial: 122/min. - opercular rate - normal activity level
5 min.: 108/min. - opercular rate - normal activity level
10 min.: 90/min. - opercular rate - normal activity level
15 min.: 84/min. - opercular rate - normal activity level

Table 1. -- (continued).

Species: Morone americana Size: 82, 98, 84, 94 TL mm.
Date: 1 October 1970
Acclimation: 68°F for 72 hours
Dissolved oxygen approximately saturated; pH = 7.4, salinity = 4.0 °/oo

+15°F study 68°F → 83°F

Mortality

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

83°F → 68°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 68°F → 83°F

initial: 102/min. opercular rate - normal activity
5 min.: 96/min. opercular rate - normal activity
10 min.: 98/min. opercular rate - some increased activity
15 min.: 104/min. opercular rate - some searching

83°F → 68°F

initial: 102/min. opercular rate - normal activity
5 min.: 100/min. opercular rate - normal activity
10 min.: 92/min. opercular rate - normal activity
15 min.: 88/min. opercular rate - normal activity

Table 2. -- Temperature Shock Treatment with Striped Bass, Roccus saxatilis.

Species: Roccus saxatilis Size: 77, 76, 78, 72, TL mm.
Date: 3 September 1970
Acclimation: 79°F for 96 hours
Dissolved oxygen approximately saturated; pH = 7.4; salinity = 8.0 °/oo

+10 F° study 79°F → 89°F To = 11:30

Mortality 79°F → 89°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

89°F → 79°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 79°F → 89°F

initial: 121/min. - opercular rate - normal behavior
5 min.: 110/min. - opercular rate - normal behavior
10 min.: 108/min. - opercular rate - normal behavior
15 min.: 102/min. - opercular rate - normal behavior

89°F → 79°F

initial: 138/min. - opercular rate - normal behavior
5 min.: 104/min. - opercular rate - normal behavior
10 min.: 100/min. - opercular rate - normal behavior
15 min.: 98/min. - opercular rate - normal behavior

Table 2. -- (continued).

Species: Roccus saxatilis
Date: 25 September 1970
Acclimation: 79°F for 48 hours
Dissolved oxygen approx. saturated; pH = 7.5; salinity = 4.0 °/oo

+15°F study 79°F → 94°F

Mortality

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

94°F → 79°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 79°F → 94°F

initial: 154/min. - opercular rate - high activity level
5 min.: 140/min. - opercular rate - high activity level
10 min.: 134/min. - opercular rate - high activity level
15 min.: 130/min. - opercular rate - high activity level

94°F → 79°F

initial: 134/min. - opercular rate - reduced activity
5 min.: 128/min. - opercular rate - activity returning to normal
10 min.: 122/min. - opercular rate - activity returning to normal
15 min.: 118/min. - opercular rate - activity normal

Table 2. -- (continued).

Species: Roccus saxatilis Size: 88, 89, 99, 83, TL mm.
Date: 1 October 1970
Acclimation: 68°F for 48 hours
Dissolved oxygen approx. saturated; pH - 7.4; salinity = 4.0 °/oo

+15°F study 68°F → 83°F

Mortality

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

83°F → 68°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 68°F → 83°F

initial: 118/min. - opercular rate - increased activity
5 min.: 118/min. - opercular rate - some searching
10 min.: 108/min. - opercular rate - normal activity
15 min.: 102/min. - opercular rate - normal activity

83°F → 68°F

initial: 110/min. - opercular rate - normal activity
5 min.: 106/min. - opercular rate - normal activity
10 min.: 100/min. - opercular rate - normal activity
15 min.: 94/min. - opercular rate - normal activity

Table 2. -- (continued).

Species: Roccus saxatilis Size: 137, 135, 130, 145 TL mm.
Date: 16 October 1970
Acclimation: 66°F for 72 hours
Dissolved oxygen saturated; pH = 7.4; salinity = 4.0 °/oo

+10°F study To = 12:35

Mortality 66°F → 76°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

76°F → 66°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 66°F → 76°F

initial: 116/min. - opercular rate - searching behavior
5 min.: 110/min. - opercular rate - high activity level
10 min.: 106/min. - opercular rate - high activity level, no acute stress
15 min.: 102/min. - opercular rate - high activity level, 1 losing equilibrium

76°F → 66°F

initial: 104/min. - opercular rate - high activity level, 1 with equilibrium loss
5 min.: 106/min. - opercular rate - high activity level, all okay
10 min.: 102/min. - opercular rate - returning to normal activity
15 min.: 96/min. - opercular rate - normal behavior

Table 2. -- (continued).

Species: Roccus saxatilis Size: 168, 133, 113, 114 TL mm.
Date: 16 October 1970
Acclimation: 66°F for 72 hours
Dissolved oxygen saturated; pH = 7.4; salinity = 4.0 °/oo

+15°F study To = 11:15

Mortality 66°F → 81°F

initial	5 min.	10 min.	15 min.
4	3	1	1

81°F → 66°F

initial	5 min.	10 min.	15 min.
1	1	1	1

Behavior 66°F → 81°F

initial: 115/min. - opercular rate - rapid searching pattern
5 min.: 106/min. - opercular rate - 1 dead, 2 acute thermal shock
10 min.: irregular - opercular rate - 3 dead, last in acute shock
15 min.: irregular - opercular rate - 1 still in shock, transferred

81°F → 66°F

initial: 112/min. - opercular rate - high activity, recovery from shock
5 min.: 106/min. - opercular rate - return to normal activity
10 min.: 100/min. - opercular rate - normal activity
15 min.: 98/min. - opercular rate - normal activity

Table 2. -- (continued).

Species: Roccus saxatilis Size: 135, 115, 127, 132 TL mm.
Date: 16 October 1970
Acclimation: 66°F for 72 hours
Dissolved oxygen saturated; pH = 7.4; salinity 4.0 °/oo

+15°F study To = 11:45

Mortality 66°F → 81°F

initial	5 min.	10 min.	15 min.
4	3	3	3

81°F → 66°F

initial	5 min.	10 min.	15 min.
3	3	3	3

Behavior 66°F → 81°F

initial: 120/min. - opercular rate - high activity level
5 min.: irregular - opercular rate - 3 acute shock
10 min.: irregular - opercular rate - 3 acute shock with loss of equilibrium
15 min.: irregular - opercular rate - 3 with complete loss of equilibrium

81°F → 66°F

initial: irregular - opercular rate - 1 regained equilibrium, 2 still upside down.
5 min.: 96/min. - opercular rate - 2 okay, one still upside down
10 min.: 98/min. - opercular rate - 2 okay, one still upside down
15 min.: 94/min. - opercular rate - 2 okay, *one still upside down

* one with equilibrium loss at end of study died 1 hour later.

Table 2. -- (continued).

Species: Roccus saxatilis Size: 120, 133, 87, 114 TL mm.
Date: 20 October 1970
Acclimation: 59°F for 20 hours
Dissolved oxygen saturated; pH = 7.3; salinity = 4.0 °/oo

+15 F° study To = 9:30

Mortality 59°F → 74°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

74°F → 59°F

initial	5 min.	10 min.	15 min.	
4	4	4	4	All live

Behavior 59°F → 74°F

initial: 120/min. - opercular rate - some searching behavior
5 min.: 112/min. - opercular rate - high activity level
10 min.: 106/min. - opercular rate - activity returning to normal
15 min.: 102/min. - opercular rate - normal behavior

74°F → 59°F

initial: 118/min. - opercular rate - high activity level
5 min.: 96/min. - opercular rate - normal behavior
10 min.: 98/min. - opercular rate - normal behavior
15 min.: 94/min. - opercular rate - normal behavior

An Experimental Study of Temperature Preference and Avoidance of the White Perch

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AN EXPERIMENTAL STUDY OF TEMPERATURE PREFERENCE AND AVOIDANCE OF THE WHITE PERCH

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Introduction

In conjunction with an ecological study of the Delaware River estuary, experimental studies on the temperature preferences and avoidances of the fishes of the estuary have been conducted since July 1969. The white perch, Morone americana, unlike many of the other species under study, has been found to be present in the estuary all year long. The objectives of the present study was to determine the temperature preferences and avoidances of the white perch under varying conditions of light level and salinity throughout the year. Due to laboratory space limitations, the study has been performed on specimens less than 150 mm. total length.

General Materials and Methods

All white perch used in the study were taken from the Delaware River drainage by seine. They were transported to and held in the laboratory holding facilities 18-24 hours prior to testing. These facilities consisted of three 32-gallon plastic garbage pails immersed in a water bath. Each pail was aerated and contained water of 4 ppt., 6 ppt., and 9 ppt. salinity respectively. (On several occasions water of 1 ppt. was also used.) The water bath was maintained at the field collection temperature.

Light levels were maintained for the appropriate photoperiod at 40 foot-candles at the surface of the water using Duro Test "Vita-Lite" flourescent bulbs (which have a spectral energy distribution comparable to natural daylight). The fish were not fed either prior to or during testing. As a general procedure, all tests were conducted in the afternoon (thus allowing for any activity effects due to circadian rhythms).

Water used in all tests was taken from Appoquinimink Creek (a tributary of the Delaware) at high tide to approximate the quality of the Delaware at high tide. Due to its great turbidity, it was allowed to "settle" prior to use. Nearly saturated levels of dissolved oxygen and pH of 7.0-8.0 were maintained throughout testing.

Temperature Preference Studies

Each species of fish has an optimum temperature which is unique to that species (although many species may have a similar preferred temperature). Behavioral responses to long term temperature changes are primarily made with respect to (and are best understood in terms of) the species' optimum temperature.

Although innately independent of acclimation temperature, the temperature preference exhibited is initially dependent upon acclimation temperature and changes accordingly with the annual temperature cycle (Sullivan and Fisher, 1953). In order to understand these long-term patterns (as well as the short-term avoidance) it is necessary to determine the optimum temperature for the species under study.

The apparatus used for the preference study is illustrated in Figure 1. It consisted of a trough 13-feet in length, 6-inches wide, and 1-foot deep, having a 24-gauge (Type 304) stainless steel bottom in the center 12-feet. Water was introduced at one end of the trough from a temperature controlled circulating bath. As the water flowed down the trough it was heated by three banks of infra-red bulbs beneath the stainless steel bottom to form a stationary horizontal thermal gradient. Each bank consisted of four 250-watt bulbs connected to a dimmer switch and a temperature regulator. (Thus, the intensity of each bank could be varied as well as the length of time the bank was on). Upon reaching the other end of the trough, the water was returned to the circulating bath. The trough was partially enclosed by polyethylene sheeting for light control. Lighting was provided by three "Vita-Lites" which extended the length of the trough.

Initially the trough was filled to a depth of two inches with water of the acclimation temperature. Fish were then placed in the trough without the gradient having been established. (This provided a control for position effects.) Observations were made via overhead mirrors every five minutes for a 45-minute period. Upon completion of this control the fish were removed and a thermal gradient extending approximately 10 C degrees above and below the acclimation temperature was established in the trough. The fish were then re-introduced at the place in the trough having their acclimation temperature. Observations were again made at 5 minute intervals.

The temperature at the position of each fish was then recorded using one of 23 thermistors (placed at 6-inch intervals along the trough) which were connected to a temperature readout. The test was concluded when the same temperature was selected continuously for 20 minutes.

Temperature Avoidance Studies

The avoidance design found to be successful with white perch is a modification of the design employed first by Shelford and Allee (1913) and then by J. R. Jones (1952), B. F. Jones, et. al. (1956), Whitmore, et. al. (1960), Hill (1968), Sprague (1964, 1968), and Sprague, et. al. (1965). In this design (illustrated in Figure 2), temperature controlled circulating baths served as storage reservoirs. Water from the respective bath flowed (via gravity-flow) into each end of the sub-troughs and drained from their centers, where it was recirculated to the temperature baths. Dye tests showed a sharp boundary at the center drain. The apparatus was thus effectively divided into quadrants.

Equal numbers of fish were placed into each quadrant. Two of the quadrants (on opposite ends of the respective sub-troughs) contained water of the acclimation temperature ("T"), while the remaining two contained water of increased (or decreased) temperature ("T+"). After a five minute orientation period, the amount of time spent by each fish in each quadrant was measured for a period of ten minutes (which constituted a trial). The number of occurrences of fish in each quadrant was then multiplied by the amount of time they spent in the respective quadrants to give a frequency

distribution for each quadrant. A t-test was then performed to determine if a significant difference (P.05) (and thus avoidance) existed between the distributions.

If no significant difference existed, the respective temperatures were then increased in a step-gradient fashion by increasing "T" and "T+" 3 to 5 F degrees beyond their former points.

Because an avoidance response to "T+" could result from the action of factors other than temperature, those most probable (such as oxygen and pH) were monitored at the input and outflow of each sub-trou throughout a test to determine its validity.

Oxygen was monitored in per cent saturation (since the ppm. value is temperature dependent) using temperature compensated YSI oxygen analyzer probes. pH was monitored using an Orion multi-chemical pH meter. The thermal conditions were monitored by a Leeds and Northrup 24 channel temperature recorder (connected to thermocouples at 6-inch intervals along each sub-trough). Because the trough was enclosed (for light level regulation as well as to permit movement around the trough area), observation was made via closed-circuit television. Each test was recorded on video-tape and re-analyzed using the temperature recorder output.

Results and Discussion

Temperature Preference

All tests (both preference and avoidance) were run in settled Delaware River water with a pH between 7.5 and 7.8 and at near saturated oxygen levels (6.0-12.0 ppm.). Temperature preference results of the

white perch are presented in Table 1. All studies were conducted with juvenile fish between 38 and 144 mm total length.

No definitive effects of levels of salinity have yet been found on the thermal preferences of this species. The preferred temperatures usually were equal to or higher than the ambient, acclimation temperatures. Maximum preferred temperatures recorded were 90°F for perch acclimated to 75°F in mid-July and 88°F for perch acclimated to 86°F in mid-August. Minimum preferred temperatures found to date were 45°F for perch acclimated to 46°F in November and 45°F for fish acclimated to 43°F in March.

A phenomenon designated as low thermal responsiveness was observed during periods with low ambient temperatures (less than 60°F) as well as in September with ambient temperature of 77°F. Juvenile white perch in these studies would rapidly move into the warmest areas of the thermal gradient and show acute stress. Some individuals died in the warmer areas, others recovered if they were able to swim back into cooler sections of the tank. Other studies at this laboratory indicate that low thermal responsiveness is a size dependent phenomenon. Larger individuals of a species will actively avoid lethal water temperatures in selecting a preferred temperature in a steep thermal gradient. However, small individuals do not show as great a degree of thermal responsiveness. Consequently juveniles may move into waters with temperatures capable of producing stress. Juvenile perch which successfully avoided lethal conditions ultimately selected a preferred temperature. A preferred temperature was selected after one or two hours in the majority of these studies.

Temperature Avoidance

The results of temperature avoidance studies on juvenile white perch are presented in Table 2. These studies, conducted throughout the spring and summer under different levels of salinity and at two light levels, demonstrated no consistent relationship between light level or salinity and upper ultimate avoidance temperature.

There is a direct relationship between ambient acclimation temperature and the upper ultimate avoidance temperature. As ambient temperatures increased from low levels in late winter to maximum temperatures during the summer, upper avoidance temperatures increased. Maximum upper ultimate avoidance temperatures determined were 94°F for perch acclimated to 75°F in mid-July and 95°F for perch acclimated to 77°F in early August.

In a study conducted in late August, young perch acclimated to 79°F avoided 92°F water. It might be expected that perch acclimated to 79°F would have a higher upper avoidance temperature than fish acclimated to 75 or 77°F. However, the upper ultimate avoidance temperature of a fish appears to be regulated by two factors. Perhaps the most obvious is the fish's past thermal history, recorded as the ambient acclimation temperature in the present study. A second factor is undoubtedly genetic. Evidence in this study as well as that of Sullivan and Fisher (1953) suggests the presence of an innate rhythm which acts independently of acclimati temperature. This rhythm appears to operate with respect to the time of ar a species will be exposed to maximum and minimum water temperatures. or white perch it appears that late July and early August represent the maximum

period. Maximum upper avoidance temperatures occur in mid-summer and begin to drop in late August even though ambient temperatures are still high.

Avoidance reactions to lower temperatures were tested on two occasions. On 4 June, white perch acclimated to 68°F avoided 65°F water and on 13 July, perch acclimated to 77°F avoided 71°F water. White perch actively avoided water temperature a few degrees lower than their acclimation temperatures. This would be expected since acclimation to temperatures less than ambient have been shown to require much more time than acclimation to temperature increases (Brett, 1956).

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Table 1. -- Summary of test data of temperature preference of the white perch.

Date	No. of Fish Per Test	Size Range TL. in mm.	Light Level (ft.-candles)	Salinity (ppt.)	Acclimation Temperature (°F)	Preferred Temperature (°F)	Low Thermal Responsiveness shown*
24 November 1969	7	62-105	40	6	46	45	yes
24 February 1970	5	72-97	40	4	43	46	yes
19 March 1970	5	87-144	40	4	43	45	yes
10 April 1970	5	71-90	40	9	48	54	yes
28 April 1970	6	50-100**	40	4	59	68	yes
30 April 1970	5	50-100**	40	6	59	68	no
6 May 1970	4	50-100**	40	6	59	68	no
7 May 1970	6	50-100**	4	6	59	69	yes
21 May 1970	4	50-100**	40	4	60	70	no
5 June 1970	4	50-100**	40	4	68	82	no
25 June 1970	3	49-110	40	4	68	71	no
9 July 1970	2	38-40	40	1	75	82	no
16 July 1970	5	65-74	40	1	75	90	no
7 August 1970	3	74-81	40	4	64-82 (variable)	75	no
14 August 1970	3	75-83	40	4	86	88	no
10 September 1970	5	68-77	40	4	77	77	yes

* Thermal stress shown when fish moved into temperatures (usually) 15 C degrees above acclimation temperature. This sometimes resulted in mortality.

** Size ranged between 50 and 100 mm., exact measurements unknown.

24 September 1970	4	80-87	40	4	77	77	yes
2 October 1970	3	108-127	40	4	70	82	no
6 October 1970	3	81-92	40	4	68	77	yes

Table 2. -- Summary of temperature avoidance studies with white perch.

Date	Trial No.	No. of Specimens	Size Range (TL. in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
25 February 1970	1	4	72-97	4.0	20	43	39	43	no
	2	4	72-97	4.0	20		41	49	no
	3	4	72-97	4.0	20		47	54	yes - P.01
26 February 1970	1	4	72-97	4.0	2		39	42	no
	2	4	72-97	4.0	2		41	49	no
	3	4	72-97	4.0	2		46	52	yes - P.05
18 March 1970	1	4	87-144	4.0	20	43	47	52	no
	1R	4	87-144	4.0	20		47	52	no
	2	4	87-144	4.0	20		49	54	yes - P.05
	2R	4	87-144	4.0	20		49	54	yes - P.05
	3	4	87-144	4.0	2		51	56	yes - P.10
	3R	4	87-144	4.0	2		51	56	no
19 March 1970	1	4	87-144	4.0	20	43	45	50	yes - P.10
	2	4	87-144	4.0	20		44	48	yes - P.05
	3	4	87-144	4.0	2		45	49	no
	4	4	87-144	4.0	2		47	49	yes - P.01
15 May 1970	1	4	82-102	4.0	20	64	60	68	yes - P.05
	2	4	82-102	4.0	20		62	68	no
	3	4	82-102	4.0	20		68	73	yes - P.20
	4	4	82-102	4.0	20		72	78	yes - P.01

Table 2. -- (continued).

Date	Trial No.	No. of Specimens	Size Range (TL. in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
26 May 1970	1	4	87-125	4.0	2	64	60	66	no
	2	4	87-125	4.0	2		66	72	yes - P.01
	3	4	87-125	4.0	2		71	78	yes - P.01
	4	4	87-125	4.0	2		70	76	yes - P.05
3 June 1970	1	4	95-103	6.0	20	68	68	75	no
	2	4	95-103	6.0	20		72	78	no - T+ preferred
	3	4	95-103	6.0	20		76	82	no - T+ preferred
	4	4	95-103	6.0	20		80	85	yes - P.05
4 June 1970	1	4	95-103	4.0	20	68	68	65	yes - P.001
26 June 1970	1	4	44-49	4	20	72	72	76	n.s.
	2	4	44-49	4	20		76	81	T+ - preferred
	3	4	44-49	4	20		79	84	T+ - preferred
	4	4	44-49	4	20		82	86.5	n.s.
	5	4	44-49	4	20		83	89	yes - P.001
13 July 1970	1	4	42-60	1	20	77	77	71	yes - P.001
	1R	4	42-60	1	20	77	77	71	yes - P.05
	2	4	42-60	1	20		74	69	yes - P.05
	2R	4	42-60	1	20		74	69	yes - P.01

Table 2. -- (continued).

Date	Trial No.	No. of Specimens	Size Range (TL. in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
14 July 1970	1	4	62-70	1	20	75	75	80	T+ - preferred
	1R	2	70-70	1	20		75	80	n.s.
	2	4	62-70	1	20		77	83	T+ - preferred
	2R	2	70-70	1	20		77	83	n.s.
	3	4	62-70	1	20		81	87	T+ - preferred
	3R	2	70-70	1	20		81	87	n.s.
	4	4	62-70	1	20		86	91	T+ - preferred
	4R	2	70-70	1	20		86	91	n.s.
	5	4	62-70	1	20		89	94	yes - P.001
	5R	2	70-70	1	20		89	94	yes - but could not be analyzed
31 July 1970	1	4	55-67	1	2	77	76	82	n.s.
	2	4	55-67	1	2		77	85	T+ - preferred
	3	4	55-67	1	2		80	87	T+ - preferred
	4	4	55-67	1	2		83	90	n.s.
	5	4	55-67	1	2		86	91	yes P.05
5 August 1970	1	4	67-78	4	20	77	77	83	T+ - preferred
	2	4	67-78	4	20		79	85	T+ - preferred
	3	4	67-78	4	20		83	88	n.s.
	4	4	67-78	4	20		85	91	n.s.
	5	4	67-78	4	20		86	92	T+ - preferred
	6	4	67-78	4	20		86	93	T+ - preferred
	7	4	67-78	4	20		90	95	yes P.001

Table 2. -- (continued).

Date	Trial No.	No. of Specimens	Size Range (TL. in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
11 August 1970	1	4	81-85	4	2	77	76	82	T+ - preferred
	2	4	81-85	2	2		80	85	T+ - preferred
	3	4	81-85	4	2		83	87	T+ - preferred
	4	4	81-85	4	2		85	90	T+ - preferred
	5	4	81-85	4	2		86	92	T+ - preferred
	6	4	81-85	4	2		89	94	n.s.
	7	4	81-85	4	2		91	95	yes P.001
27 August 1970	1	4	63-80	4	20	79	79	85	T+ - preferred
	1R	4	63-80	4	20		79	85	n.s.
	2	4	63-80	4	20		83	88	T+ - preferred
	2R	4	63-80	4	20		83	88	T+ - preferred
	3	4	63-80	4	20		86	92	yes P.10
	3R	4	63-80	4	20		86	92	yes P.001

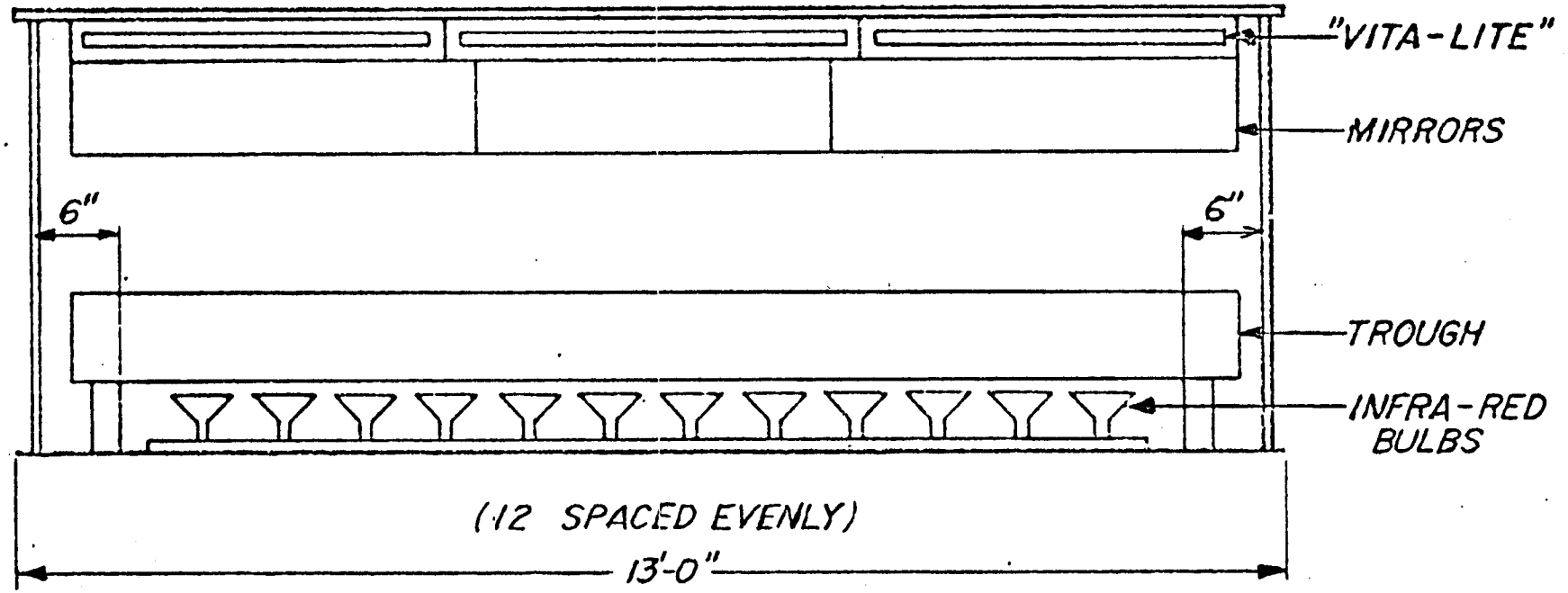

Figure 1. Temperature Preference Apparatus.

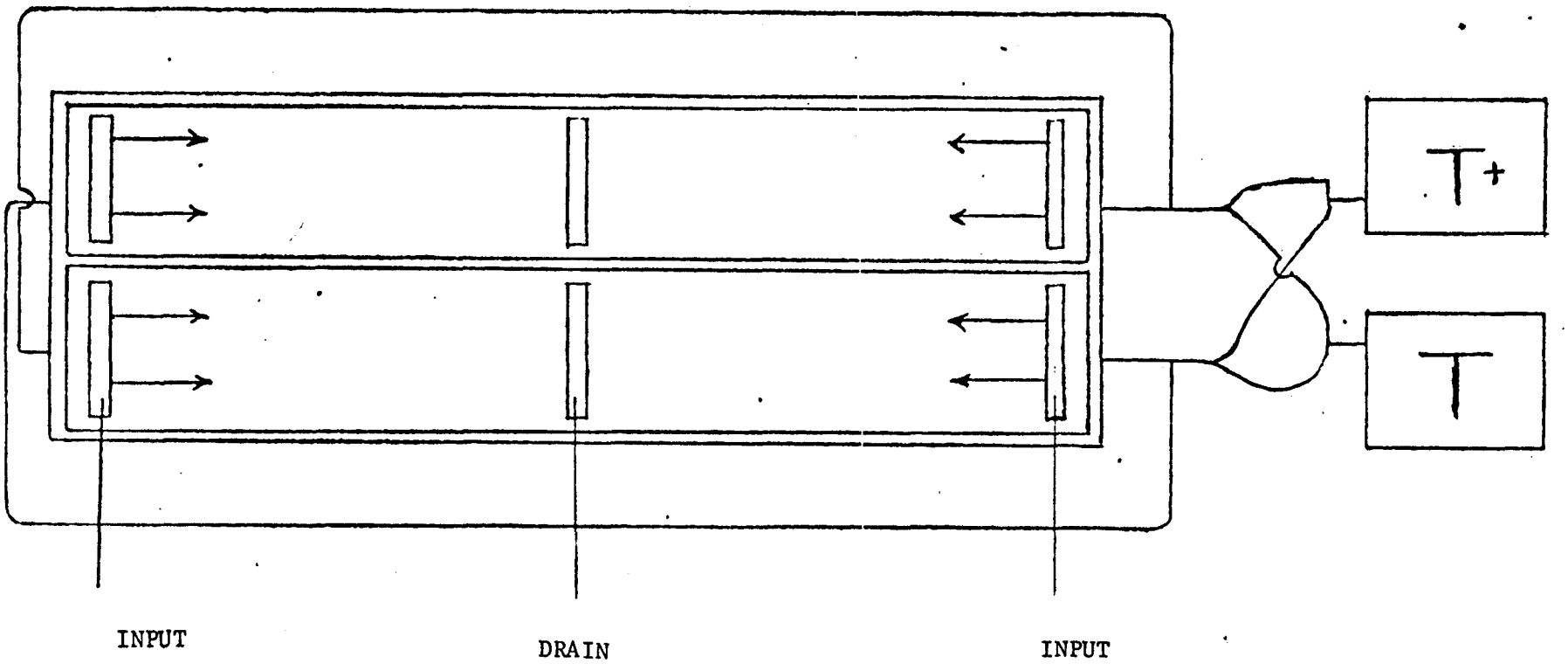

Figure 2. Diagram of the Modified Shelford-Allee Avoidance Design.

A Supplementary Report on An Experimental Study of Temperature Preference and Avoidance of the White Perch

By John W. Meldrim and James J. Gift

For

Consolidated Edison Company of New York, Inc.

No. 0-26156

To be Presented to

The Advisory Board on 2 December 1970

New York, New York

Ichthyological Associates

Edward C. Raney, Director, 301 Forest Drive,

Ithaca, New York 14850

24 November 1970

Introduction

The materials and methods used in obtaining the following data are described in the previous report of 29 October 1970.

Results and Discussion

As in the previous report, the results of temperature preferences of the white perch are given in Table 1, while the results of the temperature avoidance studies are presented in Table 2.

Temperature preference studies presented in Table 1 continue to demonstrate a direct relationship between ambient acclimation temperature and preferred temperature. As ambient temperatures drop during the fall, white perch generally select lower preferred temperatures.

The phenomenon of low thermal responsiveness was again observed in the 20 November study. This experiment was conducted using 5 white perch (sizes: 68, 69, 76, 92, 102 mm.). The 3 smaller individuals moved into warmer areas of the thermal gradient and failed to avoid lethal conditions, while the two larger individuals successfully avoided lethal conditions and ultimately selected a preferred temperature of 68°F. This size dependent phenomenon is under study in continuing experiments.

Temperature avoidance studies presented in Table 2 also demonstrate a direct relationship between ambient acclimation temperature and upper avoidance temperatures. During the summer period, white perch acclimated to 75 - 79°F water avoided 91 - 95°F temperatures, while during the fall perch acclimated to 52 - 61°F avoided 75 - 85°F temperatures.

No consistent relationship between light levels or salinities and upper avoidance temperatures have been observed to date.

Table 1. -- Summary of test data of temperature preference of the white perch (continued).

Date	No. of Fish Per Test	Size Range TL. in mm.	Light Level (ft. candles)	Salinity (ppt)	Acclimation Temp. (°F)	Preferred Temp. (°F)	Low Thermal Responsiveness Shown*
4 November 1970	4	98-110	40	4.5	57	67	No
20 November 1970	5	63-102	40	1.0	52	68	Yes

* Thermal stress shown when fish moved into temperatures (usually) 15 C degrees above acclimation. This sometimes resulted in mortality.

Table 2. -- Summary of temperature avoidance studies with white perch (continued). R designates replicates and n.s. designates nonsignificant response.

Date	Trial No.	No. of Specimens	Size Range (TL in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
21 October 1970	1	4	96-134	7.0	20	65	66	70	yes - P.001
	2	4	96-134	7.0	20		70	74	yes
27 October 1970	1	4	93-119	7.0	20	61	62	69	T+ preferred - P.001
	1R	4	93-119	7.0	20		62	69	T+ preferred - P.001
	2	4	93-119	7.0	20		66	74	n.s.
	2R	4	93-119	7.0	20		66	74	n.s.
	3	4	93-119	7.0	20		72	78	n.s.
	3R	4	93-119	7.0	20		72	78	n.s.
	4	4	93-119	7.0	20		77	83	yes - P.001
	4R	4	93-119	7.0	20		77	83	yes - P.001
28 October 1970	1	4	91-117	7.0	2	61	61	69	n.s.
	1R	4	91-117	7.0	2		61	69	n.s.
	2	4	91-117	7.0	2		66	75	n.s.
	2R	4	91-117	7.0	2		66	75	n.s.
	3	4	91-117	7.0	2		72	79	n.s.
	3R	4	91-117	7.0	2		72	79	n.s.
	4	4	91-117	7.0	2		75	82	yes - P.01
	4R	4	91-117	7.0	2		75	82	yes - P.01

Table 2. -- (continued).

Date	Trial No.	No. of Specimens	Size Range (TL in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
29 October 1970	1	4	94-118	4.5	2	61	60	67	n.s.
	1R	4	94-118	4.5	2		60	67	T+ preferred - P.01
	2	4	94-118	4.5	2		65	74	n.s.
	2R	4	94-118	4.5	2		65	74	n.s.
	3	4	94-118	4.5	2		72	78	n.s.
	3R	4	94-118	4.5	2		72	78	n.s.
	4	4	94-118	4.5	2		76	83	n.s.
	4R	4	94-118	4.5	2		76	83	n.s.
	5	4	94-118	4.5	2		79	85	n.s.
	5R	4	94-118	4.5	2		79	85	n.s.
	6	4	94-118	4.5	2		80	87	yes - P.001
	6R	4	94-118	4.5	2		80	87	n.s.
	7	4	94-118	4.5	2		85	90	yes - P.001
	7R	4	94-118	4.5	2		85	90	yes - P.001
30 October 1970	1	4	85-103	4.5	20	61	60	68	T+ preferred - P.05
	1R	4	85-103	4.5	20		60	68	n.s.
	2	4	85-103	4.5	20		70	76	yes P.1
	2R	4	85-103	4.5	20		70	76	yes P.05
	3	4	85-103	4.5	20		74	81	yes P.1
	3R	4	85-103	4.5	20		74	81	yes P.05
	4	4	85-103	4.5	20		78	85	yes P.01
	4R	4	85-103	4.5	20		78	85	yes P.001

Table 2. -- (continued).

Date	Trial No.	No. of Specimens	Size Range (TL in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
4 November 1970	1	4	72-95	4.5	20	58	58	65	T+ preferred - P.01
	1R	4	72-95	4.5	20		58	65	T+ preferred - P.01
	2	4	72-95	4.5	20		64	71	yes P.05
	2R	4	72-95	4.5	20		64	71	T+ preferred n.s.
	3	4	72-95	4.5	20		69	76	yes P.001
	3R	4	72-95	4.5	20		69	76	n.s.
	4	4	72-95	4.5	20		72	80	yes P.001
	4R	4	72-95	4.5	20		72	80	yes P.05
	5	4	72-95	4.5	20		75	83	yes P.001
	5R	4	72-95	4.5	20		75	83	yes P.001
11 November 1970	1	4	72-103	1.0	2.0	57	58	65	T+ preferred - P.01
	1R	4	72-103	1.0	2.0		58	65	T+ preferred - P.05
	2	4	72-103	1.0	2.0		65	73	yes - P.05
	2R	4	72-103	1.0	2.0		65	73	yes - P.05
	3	4	72-103	1.0	2.0		71	76	yes - P.01
	3R	4	72-103	1.0	2.0		71	76	yes - P.001
	4	4	72-103	1.0	2.0		75	80	yes - P.001
	4R	4	72-103	1.0	2.0		75	80	yes - P.01
	5	4	72-103	1.0	2.0		77	83	yes - P.001
	5R	4	72-103	1.0	2.0		77	83	yes - P.001

Table 2. -- (continued).

Date	Trial No.	No. of Specimens	Size Range (TL in mm.)	Salinity (ppt)	Light (ft. candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
17 November 1970	1	4	63-93	1.0	2	52	53	58	n.s.
	1R	4	63-93	1.0	2		53	58	n.s.
	2	4	63-93	1.0	2		58	64	n.s.
	2R	4	63-93	1.0	2		58	64	n.s.
	3	4	63-93	1.0	2		63	69	T+ preferred P.01
	3R	4	63-93	1.0	2		63	69	T+ preferred P.001
	4	4	63-93	1.0	2		70	76	T+ preferred P.001
	4R	4	63-93	1.0	2		70	76	n.s.
	5	4	63-93	1.0	2		75	81	yes - P.01
	5R	4	63-93	1.0	2		75	81	yes - P.001
19 November 1970	1	4	66-93	1.0	20	52	52	59	n.s.
	1R	4	66-93	1.0	2-		52	59	n.s.
	2	4	66-93	1.0	20		57	65	n.s.
	2R	4	66-93	1.0	20		57	65	n.s.
	3	4	66-93	1.0	20		65	71	T+ preferred P.001
	3R	4	66-93	1.0	20		65	71	n.s.
	4	4	66-93	1.0	20		71	77	n.s
	4R	4	66-93	1.0	20		71	77	n.s.
	5	4	66-93	1.0	20		75	81	yes - P.001
	5R	4	66-93	1.0	20		75	81	yes - P.001

SWIMMING SPEED OF THE WHITE PERCH, *MORONE AMERICANA*, STRIPED BASS, *MORONE SAXATILIS*, AND OTHER ESTUARINE FISHES

By Thomas R. Tatham

For
Consolidated Edison Company of New York, Inc.
No. 0-26156

Final Report on Summer Studies Using the MacLeod Apparatus

To be Presented at
Advisory Board Meeting on 7 January 1971
New York, New York

ICHTHYOLOGICAL ASSOCIATES
Edward C. Raney, Director, 301 Forest Drive,
Ithaca, New York 14850

5 December 1970

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INTRODUCTION

The purpose of this study was to determine the maximum swimming speed at various temperatures and to observe the behavior of white perch and striped bass. Fishes were taken from the Delaware River from early June through late August 1970. Most fish tested were young (young-of-the-year).

ACKNOWLEDGMENTS

Personnel of Ichthyological Associates who helped in collecting specimens or who contributed suggestions are William H. Bason, James J. Gift, Harold A. Hagerty, Michael T. Masnik, John W. Meldrim, C. Geoffrey Perry, Tim L. Preddice, Craig A. Shirey, Victor J. Schuler, Barry A. Smith, David L. Thomas, F. Thomas Unruh, Johnson C. S. Wang, and Harold B. Watts. Mrs. Kay Kapp typed the manuscript. Herbert W. Haight, Cornell University, constructed the modified MacLeod apparatus used in the study; funds were made available in 1967 by Philadelphia Electric Company. Substantial support in the field and laboratory was furnished through Public Service Electric and Gas Company at Ichthyological Associates Laboratories near Odessa, Delaware.

LITERATURE REVIEW

Among the most common types of experimental gear used in estimating the swimming speed of fishes were a rotating annular chamber (Fry and Hart, 1948; Gibson and Fry, 1954; Bainbridge, 1958; Brett et al., 1958; Boyar, 1961), a linear trough or glass tube (Kerr, 1953; Katz et al., 1959; Groves, 1960; Davis et al., 1963; Hocutt, 1970) and an open, oval trough (MacLeod, 1967; King, 1969; Kotkas, 1969). The linear trough and glass tube include screens which restrict fishes to a limited part of the apparatus. The oval trough and annular chamber allow fishes unimpeded movement in the apparatus. The use of an electrified screen may serve as a complicating factor (Davis et al., 1963). Swimming speed has also been measured by echo patterns (Sano, 1968), an underwater television camera (Brown, 1960), natural observations (Wales, 1950), cine photography (Bainbridge, 1958; Nashimoto, 1969), rod and reel studies (Walters and Fierstein, 1964), and use of magnets (DeGroot, 1967).

Different experimental methods measure different types of swimming speed. MacLeod (1967) defined maximum swimming speed as that at which fish swim for a three minute period in a current slightly greater than their swimming ability. Boyar (1961) stated that maximum swimming speed is equivalent to the water velocity beyond which no individual can maintain its position for more than 30 seconds. Fry and Hart (1948) define cruising speed as the "speed at which the fish could swim steadily for some considerable period of time." Brett et al. (1958) used final swimming speed, which he they defined as "the water velocity at which an individual fish apparently had been forced permanently against the screen." In testing larval walleye and yellow perch, Houde (1969) used sustained swimming speed, defined as the current velocity that 50% of the larvae could maintain for one hour. Rosenthal (1968) determined swimming speed of larval Atlantic herring from "the straight line distance between start and end points of a single swimming phase." Bainbridge (1958) measured burst speed using the formula $V = 1/4\ L\ (3f-4)$ where V=speed in cm/sec., L=body length in cm and f=frequency of tail beats/sec.

Fry (1947) noted two important principles in regard to activity. First, "since activity of the animal as a whole is the result of integrated metabolism,... the metabolism from which the activity results is not the total metabolism of the organism... but the difference between total metabolism and the metabolism required for the organism's integration." This difference he terms the scope of activity. The second principle regarding animal activity is "that previous experience of the organism in relation to the factor of the environment under consideration must always be taken into account."

Fishes, as aquatic heterotherms, have their body temperature determined by the environmental temperature. They cannot survice for an indefinite time beyond certain upper and lower incipient lethal temperatures (Fry, 1947). The upper incipient lethal temperature can be raised by acclimation to higher temperatures and the lower incipient lethal temperature can be lowered by acclimation to lower temperatures (Doudoroff, 1942; Fry et al., 1942; Brett, 194, 1952). The ultimate incipient lethal temperature is reached when the acclimation temperature equals the lethal temperature. The area bounded by the ultimate upper and lower incipient lethal temperatures is termed the biokinetic range (Fry, 1947) and organisms, with proper acclimation, are tolerant of all temperatures in this range. Beyond this range, organisms display thermal

resistance the duration of which depends on the "effective time" it takes to bring about the lethal factor. According to thermal history, organisms display temperature preferenda at which individuals tend to congregate if presented a range of temperatures. The "final preferendum" is "that temperature around which all individuals will ultimately congregate regardless of their thermal experience before being placed in the gradient."

Fry (In: Brown, 1957) recognizes three levels of oxygen consumption: (1) standard rate, an approximation of minimal metabolism, (2) routine rate, the metabolic rate when all activity is spontaneous, and (3) active rate, the metabolic rate at maximum activity. With increasing temperature, the standard rate rises until it reaches the upper incipient lethal temperature. The active rate either increases over the entire biokinetic range, increases to a point before declining in the upper part of the range, or increases to a point before leveling off in the upper part of the range (Fry: In: Brown, 1957). Where the active rate increases over the entire range (in the brown bullhead), the scope of activity also increases over the biokinetic range. Where the active rate declines or levels off in the upper part of the range (in lake trout and goldfish respectively), the scope of activity declines near the upper incipient lethal temperature. Over increasing temperatures, the reduction of oxygen concentration causes the active rate to decrease although the shape of the curve is unaffected. This decrease in active rate is reflected in a reduced scope of activity and reduced swimming speed (Ferguson: In: Fry, 1957).

"Respiratory dependence," the reduction of oxygen consumption at lower levels of ambient oxygen concentration, has been shown for the standard rate of brook trout, goldfish, and carp (Beamish, 1964a) and the active rate of many fishes (Graham, 1949; Gibson and Fry, 1954; Katz et al., 1959; Basu, 1959; Davis et al., 1963; Kutty, 1968; Dahlberg et al., 1968). Acclimation to lower concentrations are reported to lower the incipient lethal limit of oxygen (Shepard, 1955). However, Kutty (1968) found that low oxygen concentration acclimation, produced no significant difference in the "respiratory dependence" of swimming goldfish. No carbon dioxide concentration affected the standard rate of carp or brook trout at various oxygen concentrations (Beamish, 1964b).

However, the active rate of several freshwater fishes declined logarithmically as carbon dioxide concentration increased (Basu, 1959). With overnight acclimation to high carbon dioxide concentrations, the swimming speed of largemouth bass was unaffected by increased concentrations of carbon dioxide while the swimming speed of coho salmon decreased significantly (Dahlberg et al., 1968).

It is generally held that acclimation to higher temperature proceeds at a faster rate than acclimation to lower temperature (Doudoroff, 1942; Fry et al., 1942; Brett, 1944, 1946, 1956). Peterson and Anderson (1969) reported no difference in time required for acclimation of Atlantic salmon to higher and lower temperatures. Fry et al. (1942) reported that the upper incipient lethal temperature of goldfish increased linearly at 1.8 F for a 5.4 F increase in acclimation temperature while the lower incipient lethal temperature decreased 3.6 F for a 5.4 F decrease in acclimation temperature. Brett (1946) found the "temperature coefficient, Q_{10}, for the velocity constant in acclimation rate averaged 3, indicating a process (metabolic) which increased rapidly with increase in temperature." Although the gain of heat tolerance is a rapid process, it is lost slowly on cooling (Loeb and Wasteneys, 1912; Doudoroff, 1942; Brett, 1956) while the gain of low temperature tolerance is lost at the same rate it is acquired (Doudoroff, 1942; Brett, 1956). Varying acclimation times were used by different investigators. Hocutt (1970) acclimated channel catfish, largemouth bass and spotfin shiner for 14-20 hours; Kotkas (1970) acclimated striped bass and white perch for 16-26 hours, and Moss and Scott (1961) acclimated centrarchids and ictalurids 24 hours prior to testing. King (1969) used acclimation times of 42-48 hours for channel catfish. Doudoroff (1942) found that the opaleye required three days of acclimation at higher temperatures. Davis et al.(1963) acclimated Pacific salmonids three to five days; Brett (1952) used a one week acclimation period for Pacific salmonids; and Groves (1960) used a one week acclimation period for sockeye salmon. Dahlberg et al. (1968) acclimated largemouth bass and coho salmon for 18 days and Basu (1959) acclimated fishes for a month. Brett (1956) reported that a 24 hour acclimation period is sufficient for temperatures above 68 F.

Bardach and Bjorkland (1957), working with several species of North American freshwater fishes, demonstrated the ability of fish to discriminate temperature changes on the order of 0.09 F. Nerve endings in the skin and the spinal nerves serve as the thermoreceptors (Dijkgraaf: In: Bardach and Bjorkland, 1957). Fry and Hart (1948) were the first to report an increase in swimming speed with an increase in temperature. As temperature increased, the swimming speed of goldfish increased, to a point, and then declined in the upper part of the biokinetic range. The temperature of the maximum swimming speed corresponded to the preferendum. Sockeye and coho salmon demonstrated a similar increased cruising speed followed by a decline in the upper biokinetic range (Brett et al., 1958) as did largemouth bass, channel catfish, and spotfin shiner (Hocutt, 1970). The temperature of the maximum cruising speed of lake trout (Gibson and Fry, 1954) and the maximum swimming speed of brook trout (Graham, 1949) corresponded to the greatest potential scope of activity. Fry (In: Brown, 1957) showed that the square root of the scope of activity is linearly related to the cruising speed. Blaxter and Dickson (1959) reported that the swimming speed of several fishes was unaffected over a temperature range of 40-65 F.

Euryhaline fish, which are defined by Gunter (1956) as those "which will withstand or tolerate gross salinity changes", were of major interest in this study. Black (In:Brown, 1957) noted that transfer of euryhaline fish to higher salinities often resulted in temporary weight (water)loss and increased salt concentration of the blood. The necessary physiological adaptations to higher salinity were accomplished in 48 hours. Transfer of euryhaline fish to a more dilute medium resulted in weight gain and salt loss. The kidneys (Black: In: Brown, 1957) and the gills (Black: In: Brown, 1957; Motais et al., 1969) mediate adjustments to salinity change. When fishes are transferred to higher salinity, the kidneys reduce urine production; transfers to lower salinity result in increased urine production. Motias et al. (1969) reported that "diffusional and osmotic water flow in teleosts probably occur solely across the gills." Copeland (1950) found chloride cells in the gills of the mummichog which were responsible for the excretion and absorption of chloride in salt and fresh water respectively. These cells adapted to freshwater in four hours

and to sea water in seven to nine hours. The ability of euryhaline fish to survive direct transfer from fresh to sea water has been demonstrated for the cichlid, Mossambica tilapia (Ramamurthi, 1965) and for the striped bass (Tagatz, 1961). Swimming speed and metabolic studies have employed acclimation regimes of one part per thousand (ppt) per day followed by two weeks at the final salinity (Farmer and Beamish, 1969) and one week from freshwater to sea water (Groves, 1961). Seasonally increasing salinity tolerance and preference have been found in Atlantic salmon (Privol'nev, 1967) and have been shown as a possible orientation gradient for the migration of young Pacific salmon to the sea (MacInerney, 1964).

Bullivant (1961) reported that juvenile quinnat salmon tested in 50% sea water and freshwater showed no significant difference in oxygen consumption and Gordon et al. (1956) found the oxygen consumption in the mudskipper was unaffected by salinity. Farmer and Beamish (1969), however, demonstrated that both standard and active oxygen consumption of the euryhaline Tilapia nilotica varied with salinity. When the concentration of the blood equalled the concentration of the medium, the isosmotic point, the two rates of oxygen consumption were lowest; they increased, in either direction, beyond the isosmotic point. The oxygen requirement for swimming is salinity independent although the percentage of total oxygen consumption required for osmoregulation increased beyond the isosmotic point, thereby reducing the scope of activity. Rao (1968) found similar relations for oxygen consumption and salinity in rainbow trout. Hickman (1959) reported that at high salinities, a large percentage of the total energy went into osmoregulation. Working with orange chromid cichlids, Parvatheswararao (1965) showed that small fish exhibited their greatest oxygen consumption at high temperature and low salinity while larger fish displayed their highest oxygen consumption at high temperature and high salinity.

Both photoperiod and light level are important factors in rheotaxis and swimming performance. Northcote (1958) reported that juvenile rainbow trout subjected to a long photoperiod (16 hours light vs. 8 hours dark) exhibited weak rheotaxis and swam downstream while fish kept at a short photoperiod (8 hours light vs. 16 hours dark) demonstrated strong rheotaxis and swam upstream. This behavior was more pronounced at lower temperature (50 F) than at higher

temperature (68 F). Ferguson (1958) reported that preferred temperature tests for several salmonids required subdued lighting while yellow perch could be tested in full daylight. Keenleyside and Hoar (1954) found that visual stimuli were the most important factor in eliciting strong rheotaxis. In using an underwater television camera to monitor the swimming speed of caged Atlantic herring, Brown (1960) found that switching off the light for short intervals caused the fish to disorient and fall back in the cage. When the light was turned on, they regained their visual cues and swam well. MacLeod (1967) and King (1969) reported the use of a dark, covered area of the test chamber as a visual cue.

Size is an important factor in this study. In terms of absolute values (ft/sec), swimming speed increases as the size of the fish increases (Gray, 1957; Brett et al., 1958; Blaxter and Dickson, 1959; Katz et al., 1959; Boyar, 1961; Rosenthal, 1968) but in relative terms (body length/sec), smaller fish show a higher swimming speed (Blaxter and Dickson, 1959; Brett, 1965). Size alters the biokinetic range or the effective time outside this range. Hart (1952), Bailey (1955) and Brawn (1960) reported that certain young fish showed higher heat tolerances than adults although Hart (1952) also reported that immature bluegill sunfish die more readily than adults at higher temperatures.

METHODS AND MATERIALS

Fishes were tested in an apparatus modified from that used by MacLeod (1967). It consisted of a stationary, oval testing chamber which rested on two iron bars in the bottom of a rectangular galvanized tub. The test chamber was 5 1/2 inches (14 cm) deep x 3 5/8 inches (9.3 cm) wide, had a circumference of 6.6 feet (198 cm) measured midway between the inner and outer wall, and held five gallons of water (See Figure 1). Currents were generated in the test chamber by two paddlewheels connected to a Zero-Max Variable Speed power block number EL CCW 10-400 GA by a non-slip drive belt. The test chamber was painted with a white, latex-base paint while the galvanized tub was painted with Wetherill Yarnell Latex Flat Wall Finish. A one foot portion of the test chamber was painted black and covered to provide an area where fish could group and orient. The apparatus was set up in a garage at the Coléman Laboratory of Ichthyological Associates for ten weeks and was moved to a mobile research trailer during the final two weeks of the study.

Current speeds in the test chamber were measured by timing, with a stopwatch, a sponge ball of neutral density as it traveled around the test chamber (Fry and Hart, 1948). The ball was timed for three circuits of the test chamber and the average time was used to determine the current speed. As there were eddies and differential currents in the test chamber, this method may provide a better estimate of current than a stationary current meter.

Water used for holding and testing purposes was taken from Appoquinimink Creek, just off the Ichthyological Associates' dock and was transported in five gallon containers. Salinities ranged from two ppt in early June to six ppt in late August. Salinity was determined with an American Optical salinity refractometer.

Holding facilities consisted of two ten gallon plastic garbage pails in a 75 gallon fiberglass tank which served as a temperature bath. As all acclimation temperatures were equal to or above ambient air temperature, the only concern was in heating the water bath. Temperatures in the bath were maintained initially by three 75 watt aquarium heaters and later by a 500 watt immersion heater with thermoregulator. Temperature fluctuations were $\pm$ 3.6 F with the aquarium heaters and $\pm$ 1 F with the immersion heater and thermoregulator. A Little Giant submersible pump (Model 1, Cat. No. 501 003) was used to keep the temperature bath circulating. A Silent Giant aquarium pump supplied air through aquarium tubing and carborundum air stones. Water used in the holding pails was changed every two days and the pails were rinsed at this time.

The water in the test chamber was maintained at a constant temperature by use of the galvanized tub as a temperature bath. The temperature bath was heated and circulated as were the holding facilities. Water in the test chamber was changed after every ten tests.

Fishes were collected from the Delaware River at Augustine Beach, Sam Green's Beach, Peach House Ditch, and Woodland Beach. Collections from Appoquinimink Creek were made at Fenimore's Landing and the spillway and spillpool below Noxontown Pond. Specimens were also collected from the Bohemia River, the north bank just east of Maryland Route 213, the Chesapeake and Delaware Canal, the south bank 400-500 yards east of U.S. Route 13 bridge at St. Georges, and the cove on the north shore of the Chesapeake and Delaware Canal 200 yards west of the Penn Central railroad bridge. Seine collections with a 10'x4', 1/4" nylon

seine, a 25'x4', 1/8" mesh nylon beach seine and a 20'x4', 1/4" mesh nylon bag seine provided specimens with the least damage. Fish were trucked to the lab in five gallon styrofoam coolers which were aerated by a battery powered air pump. Handling of fish in the lab was done with fine mesh aquarium nets.

All specimens were held under a natural photoperiod. For eight to ten hours a day, the holding pails were also illuminated by a 100 watt incandescent bulb (in the garage lab) or two fluorescent bulbs (in the trailer lab). Light levels were measured with a Weston Foot Candle Meter (Model 614).

A Grey-Lab timer was used to time orientation and test periods. All temperatures were taken with a hand held mercury thermometer, calibrated at 32 F. Temperature fluctuations in the holding pails were monitored with Taylor Maximum-Minimum thermometers. Oxygen concentration in the test chamber was measured with a Yellow Springs Instrument oxygen meter. A 6"x2", 1/4" mesh plastic screen was placed in the test chamber to prevent the fish from passively drifting during the orientation period.

EXPERIMENTAL PROCEDURE

White perch, striped bass and tidewater silverside were acclimated overnight (20-28 hours) while rough silverside, bluefish and bay anchovy proved difficult to hold overnight and were tested at ambient river temperature upon return from the field (1-5 hours after collection). Fish held overnight were put in the holding pails upon return from the field, or if the pails still contained fish, they were kept in the styrofoam coolers, aerated by a Silent Giant aquarium pump, until the pails were available. The maximum time spent in the coolers was seven hours and time spent in the coolers was not counted as acclimation time.

If the temperature difference between the coolers and the holding pails was 2 F or less, the fish were transferred to the holding pails. If the temperature difference was greater than 2 F, the fish were held in the coolers until the temperature difference decreased to 2 F or less. Subsequent heating of the pails to the acclimation temperature proceeded at a maximum rate of 2 F every ten minutes.

In the garage, the light level over the MacLeod apparatus was 18 ft/candles, measured on an overcast day. In the research trailer, the light level over the apparatus was 44 ft/candles and over the holding pails was 22 ft/candles.

At the beginning of a test three fish were netted from the holding pails and transferred to the test chamber. Temperature differences between the holding pails and the test chamber never exceeded 2 F. The variation in size range per group of test fish averaged 3.8 mm (standard deviation = 2.3) with the maximum difference being 15 mm. After transfer, fish were given approximately two minutes to explore the test chamber; invariably they schooled in the dark area. A five minute orientation period followed during which the fish were subjected to an orientation current of 0.2 - 0.5 ft/sec (3.7 - 9.2 m/min), depending on the size of the fish. During this orientation period, the plastic screen was placed a distance of 8-10 inches (20.3 - 25.4 cm) behind the dark area to prevent the fish from drifting with the current. After the orientation period, the current was gradually increased to a point where the fish could no longer maintain their position under the cover. While the current was increased, the plastic screen remained in the test chamber because fish would often drift out of the dark area. Upon nearing or touching the screen, the fish would regain and maintain their position under cover. The current was held to be in excess of the maximum swimming speed when they could no longer maintain their position under the cover. The screen was then removed and a three minute test period begun. During the test period, the number of times a fish passed a fixed reference point was counted (laps lost). Following the test period and with the fish still in the test chamber, the sponge ball was introduced and the current determined. The fork length was measured and, up to 5 August 1970, all specimens were preserved in 10% formalin. After that date, all fish were bioassayed by Dr. John W. Meldrim.

The maximum swimming speed was determined by the formulae of MacLeod (1967):

$$S/Max = \frac{M - L}{M} \times V$$

$$M = \frac{N \times T \times V}{C}$$

S/Max = maximum swimming speed (ft/sec)

L = laps lost

V = current velocity (ft/sec)

N = number of fish per group

T = time of test period (seconds)

C = circumference of test chamber (feet

A sample calculation is given for a group of three fish which lost 20 laps during a three minute test period at a current of one ft/sec.

$$M = \frac{3 \times 180 \times 1}{6.6} = 81.8 \qquad S/Max = \frac{81.8 - 20}{81.8} \times 1 = 0.75 \text{ ft/sec}$$

Oxygen levels during the tests were at air saturation as determined by random checks with the oxygen meter. There was no difference in oxygen levels before and immediately after a test. Between tests, over a period of ten to fifteen minutes, the water in the test chamber was aerated with a Silent Giant aquarium pump.

All white perch, striped bass and bluefish tested were young. All rough silverside, tidewater silverside and bay anchovy were yearlings.

RESULTS

Linear regressions are reported for maximum swimming speed (S/Max) versus fork length wherever these regressions are significant at the 95% level. When only a few tests were conducted over a limited size range, the mean S/Max, mean fork length and standard error (S.E.) (Simpson et al., 1960: 166) were calculated. The t test on slope was from Simpson et al. (1960). The formulae used to calculate the t test on intercepts (King, 1969) and the F test in the analysis of covariance are given in Table 13. All tables and figures giving S/Max, correlation coefficients, regression equations, sample variances of estimates and confidence intervals on slopes express these values in ft/sec and m/min although all future discussion will refer to swimming speed in ft/sec. Calculations were done on a Monroe calculator.

Three tests of the rough silverside (mean fork length 91 mm) gave an S/Max of 0.7 ft/sec (S.E. = 0.06) at 76 $\pm$ 2 F and 2 ppt salinity (Table 1). It was tested at the ambient water temperature at the time of collection and immediately upon return from the field. It was delicate to handle, showed fair rheotaxis, but exhibited little swimming effort. For this species, test groups consisted

of two specimens. Test groups for all other species consisted of three individuals.

Four tests of the tidewater silverside (mean fork length 62 mm) gave an S/Max of 1.7 ft/sec (S.E. = 0.13) at 73 $\pm$ 2 F and 1 ppt salinity (Table 2). It was held overnight and proved to be a strong swimmer with good rheotaxis. It was able to maintain position or gain against a current of 1.8 ft/sec, the highest velocity practical for this apparatus.

Six tests of the bluefish (mean fork length 53 mm) gave an S/Max of 0.7 ft/sec (S.E. = 0.06) at 70 $\pm$ 2 F and 3 ppt salinity (Table 3). It was tested immediately at ambient temperature and proved to be a good swimmer with good rheotaxis.

Four tests of the bay anchovy (mean fork length 62 mm) gave an S/Max of 0.5 ft/sec (S.E. = 0.07) at 73 $\pm$ 2 F and 8 ppt salinity (Table 4). Despite immediate testing at the ambient collection temperature, it swam poorly with little rheotaxis.

During the early part of the summer, sufficient striped bass were available to test at 75 F (Table 5 and Figure 2) and 80 $\pm$ 2 F (Table 6 and Figure 3) and 3 $\pm$ 1 ppt salinity, with overnight acclimation. Striped bass proved to be vigorous swimmers with good rheotaxis. It performed well in currents well in excess of its maximum swimming speed and was unaffected by local current variations. Linear regression equations, correlation coefficients (r), sample variances for the estimates and confidence intervals for slopes are summarized in Table 7. A t test on the slopes proved to be nonsignificant at the 95% level ($t = 0.507$, $df = 34$) and the t test on the intercepts proved nonsignificant at the 95% level ($t = 0.607$, $df = 36$). The data for the two temperatures were combined to give a pooled estimate of regression over the temperature range. This pooled regression was $y = 0.185 + 0.0182x$ ($r = .83$) with the sample variance of the estimate and the confidence interval for slope given in Table 7.

The white perch was tested throughout the summer at 75 F (Table 8 and Figure 4), 80 F (Table 9 and Figure 5), 85 F (Table 10 and Figure 6), and 90 $\pm$ 2 F (Table 11 and Figure 7) and 4 $\pm$ 2 ppt salinity, with overnight acclimation. White perch swam well only at currents slightly above its maximum swimming speed. Its rheotaxis was highly variable and was greatly affected by test conditions. Unless the current was increased gradually, the

white perch displayed little rheotaxis during the test. Those with poor rheotaxis were readily affected by local current variations, particularly with increases due to the narrowing of the width of the test chamber. Individuals which showed little rheotaxis could be redirected into the current by momentarily placing the plastic screen in the test chamber. This redirection was often accomplished without the fish contacting the screen; its mere presence proved effective. Regression equations were significant at all four test temperatures and regression equations, correlation coefficients, the sample variances for estimates and the confidence intervals for slopes are summarized in Table 12.

Combining the white perch data over all temperatures was not justifiable since there was significant deviation from single regression ($F = 4.64$, $df = 6, 106$) at the 95% level. Combining the data over the three highest temperatures was justifiable since deviation from single regression was nonsignificant ($F = 1.89$, $df = 4, 94$) at the 95% level. The pooled regression equation was $y = 0.3153 + 0.0124x$ ($r = .70$) with the sample variance of the estimate and the confidence interval for the slope given in Table 12. Subsequent t tests between the pooled regression and the 75 F regression equation indicated the slopes were significantly different ($t = 3.23$, $df = 110$) at the 95% level as were the intercepts ($t = 2.36$, $df = 112$).

Comparison of the pooled regression of white perch to the regression calculated from Table 4 of Kotkas (1970) for white perch tested at 80 ± 2 F in freshwater indicated no significant difference. A t test on slopes ($t = 0.352$, $df = 114$) and a t test on intercepts ($t = 1.06$, $df = 116$) both proved nonsignificant at the 95% level.

Comparison of the pooled regression for striped bass to the pooled regression for white perch indicated the two regressions differed significantly. A t test on slopes ($t = 2.31$, $df = 134$) and a t test on intercepts ($t = 1.67$, $df = 138$) both proved significant at the 95% level although the t test on intercepts was nonsignificant at the 90% level.

DISCUSSION

Care should be used in the interpretation of the maximum swimming speeds obtained in this study. The estimate obtained from the MacLeod apparatus rests on the assumption that fish swim against the current with maximum effort throughout the test period. Although MacLeod validated this assumption using the fathead minnow, this is not true for all fishes. Tidewater silverside and striped bass exhibited maximum swimming effort and excellent rheotaxis while rough silverside and bay anchovy displayed minimal swimming effort and little rheotaxis. The bluefish and white perch showed intermediate swimming behavior. In the case of rough silverside and bay anchovy, the poor performance was attributable to poor condition rather than an inherently poorer swimming ability. Performance differences should be considered when making interspecific comparisons although intraspecific comparisons may be made with greater confidence.

Salinity differences between collection site and the water used for acclimation never exceeded 6 ppt for white perch or 4 ppt for striped bass and tidewater silverside. Gunter (1956) reported all three species to be euryhaline and overnight acclimation is sufficient for the salinity acclimation of these three fishes. In the case of those tested without overnight acclimation, all tests were conducted at the salinity found at the collection site.

A significant, increasing linear regression between maximum swimming speed and fork length was found in all tests of striped bass and white perch (Figures 2-7). Unless there was an interaction between temperature and the rate of increase of swimming speed with length, this rate, represented by the slope of the regression line, should not differ significantly at various temperatures. This should be reflected by nonsignificant t tests on slopes. If higher temperatures increase swimming speed, the regression line for higher temperature should be raised above that for lower temperature. This elevation should result in a significantly higher intercept of the vertical axis by the higher temperature regression line, as shown by a t test on intercepts.

The nonsignificant t test on slopes and on intercepts of the regression lines of striped bass indicated that a single regression equation for the combined data provided as good a description of the data as either of the two regression equations. Kerr (1953) found that 80% of the 19-38 mm striped bass

tested at 72 F was still swimming in a current of one ft/sec after ten minutes. Under the same test conditions, 95% of the 25-76 mm striped bass tested was still swimming in a current of two ft/sec. He reported that all 127-177 mm fish tested were able to withstand a current of two ft/sec and that only one fish in this size range was impinged on the screen at 2.75 ft/sec. These values are consistently higher than swimming speeds reported herein. Investigating striped bass in the same modified MacLeod apparatus used in this study, Kotkas (1969) reported swimming speeds that tended to be higher than those found in this study although his estimates were based on larger specimens (60-100 mm). He also reported that fish held 48 hours showed significantly higher swimming speeds than those fish tested after 24 hours of acclimation. Davis et al. (1963) reported swimming speeds of Pacific salmon which differed from those reported by Brett et al. (1958); they attributed these variations to different apparatus and experimental procedures.

For white perch, an F test of data collected at the three highest test temperatures proved nonsignificant and these data can be pooled to calculate a single, common regression equation. The significant F test for the data collected at all four test temperatures suggests that the 75 F data may differ significantly from those collected at 80 F, 85 F, and 90 F. T tests on slopes and on intercepts of the pooled regression and the 75 F regression indicated significant differences at the 95% level. The 75 F regression line showed a greater rate of increase of swimming speed with length (0.03699 ft/sec/mm) than the pooled regression line (0.0155 ft/sec/mm). The lower intercept of the 75 F regression line may not with confidence be attributed to temperature effects since the differing slope contributes to the lower intercept. The size range for the pooled regression was 33-81 mm while the range for the 75 F regression was 32-44 mm. This discrepancy in specimen size as well as the limited number of tests at 75 F may contribute to the differences between the two regression equations.

In the three higher temperature tests for white perch, no conclusive effect of temperature on swimming speed was found. Although the 90 F regression line had the highest intercept, it was nonsignificantly different from the

intercepts of the 80 F and 85 F regression lines. Fry and Hart (1948) found that goldfish showed no increase in swimming speed over a 68-86 F range although below this range there was a steady increase in swimming speed and above this range, the swimming speed declined rapidly as the upper incipient lethal temperature was approached. Blaxter and Dickson (1959) also reported no relation between temperature and swimming speed over the temperature tested.

Comparison of the pooled white perch regression equation to the 80 F regression equation reported by Kotkas (1970) revealed no significant difference even though his data were collected from larger fish. He reported a significant increase in swimming speed of those held for two nights over fish tested after one night of acclimation. Groves (1960) reported a tendency for higher swimming speeds of sockeye salmon in salt water than in freshwater but no difference was found between the maximum swimming speed of white perch tested in freshwater (Kotkas, 1970) and those tested in the low salinity regimes of this study.

The t tests on the slopes and the intercepts of the pooled regression lines of striped bass and white perch were significant at the 95% level. The maximum swimming speed of striped bass showed a greater rate of increase with length (0.0189 ft/sec/mm) than white perch (0.0155 ft/sec/mm) and above 40 mm, striped bass had a greater maximum swimming speed than white perch. At 80 F, Kotkas found this rate of increase to be greater for white perch although his correlation coefficient for the striped bass regression equation was nonsignificant at the 95% level. He found that despite the greater rate of increase for white perch, striped bass had a greater maximum swimming speed over the size range tested (40-100 mm). Since there were differences in the swimming performance of these two species, these reported differences in maximum swimming speed may not represent a true difference in the swimming ability of these two species.

SUMMARY AND CONCLUSIONS

All fish tested were either acclimated overnight (20-28 hours) or tested one to five hours after collection. Acclimation was always to temperatures above the collection temperature and fishes were not acclimated to a salinity difference greater than 6 ppt. Following a two minute recovery period and a five minute orientation period, a group of two or three fish were tested for three minutes in the modified MacLeod apparatus.

Yearlings of the rough silverside and tidewater silverside, swam at 0.7 and 1.7 ft/sec respectively.

Young bluefish swam at 0.7 ft/sec.

Yearling bay anchovy swam at 0.5 ft/sec.

A significant linear regression was found between maximum swimming speed and fork length for all striped bass and white perch tested.

The maximum swimming speed of striped bass over the temperature range of 75-80 F, as described by a pooled regression equation, increased at 0.0189 ft/sec/mm.

The maximum swimming speed of white perch over the range of 80-90 F, as described by a pooled regression equation, increased at 0.0155 ft/sec/mm. This pooled regression equation differed significantly from the 75 F regression equation which increased at 0.03699 ft/sec/mm.

Striped bass showed a significantly greater increase in maximum swimming speed with length and consequently showed a higher maximum swimming speed than white perch.

The swimming speed of fishes tested in the MacLeod apparatus is best evaluated when their swimming performance is also considered.

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Table 1. -- The maximum swimming speed (S/Max) of the rough silverside tested at 76 ± 2 F and 2 ppt salinity with acclimation.[t]

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
8 June 70-1	93	93[tt]	15.6	0.8
8 June 70-2	94	88-100	10.7	0.6
8 June 70-3	85	83-86	11.9	0.7
Mean	91	--	12.7	0.7
SE	--	--	1.47	0.06

[t]Test group consisted of two fish. Test group for all other species consisted of three fish.

[tt]Expression of fork length as a single number indicates all fish of that group as having the same fork length.

Table 2. -- The maximum swimming speed (S/Max) of the tidewater silverside tested at 73 ± 2 F and 1 ppt salinity with overnight acclimation.

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
12 June 70-3	63	60-65	23.7	1.3
12 June 70-4	65	63-66	29.2	1.6
12 June 70-5	61	60-62	34.9	1.9
12 June 70-6	60	58-61	32.1	1.8
Mean	62	--	30.0	1.7
SE	--	--	2.39	0.13

Table 3. -- The maximum swimming speed (S/Mac) of the bluefish tested at 70 ± 2 F and 3 ppt salinity without acclimation.

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
15 June 70-1	51	48-52	13.8	0.8
15 June 70-3	50	49-51	10.5	0.6
15 June 70-4	65	64-67	17.0	0.9
17 June 70-1	53	51-55	11.7	0.6
17 June 70-2	61	60-61	17.1	0.9
17 June 70-3	50	48-51	10.9	0.6
Mean	53	--	13.5	0.7
SE	--	--	1.21	0.06

Table 4. -- The maximum swimming speed (S/Max) of the bay anchovy tested at 73 ± 1 F and 8 ppt salinity without acclimation.

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
29 June 70-1	61	60-62	5.6	0.3
29 June 70-2	67	66-68	7.7	0.4
29 June 70-3	61	55-70	10.2	0.6
29 June 70-4	60	57-61	12.0	0.7
29 June 70-5	59	59-60	8.8	0.5
Mean	62	--	8.9	0.5
SE	--	--	1.08	0.07

Table 5. -- The maximum swimming speed (S/Max) of the striped bass tested at 75 ± 2 F and 3 ± 1 ppt salinity with overnight acclimation.

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
23 June 70-3	39	39	12.5	0.7
23 June 70-4	33	32-33	15.9	0.9
25 June 70-1	39	37-41	15.1	0.8
25 June 70-2	32	31-34	16.5	0.9
25 June 70-3	33	32-34	14.0	0.8
26 June 70-3	35	34-35	14.1	0.8
27 June 70-1	31	30-33	11.5	0.6
27 June 70-2	38	36-39	16.8	0.9
7 July 70-2	39	38-40	12.6	0.7
23 June 70-2	44	43-45	15.8	0.9
26 June 70-1	48	45-50	19.3	1.1
26 June 70-2	46	44-46	20.3	1.1
26 June 70-4	44	43-44	16.8	0.9

ft/sec. $r = .65$ (S/Max vs. length), significant at 95% level. Regression equation: $y = 0.215 + 0.0166X$, sample variance of the estimate (s^2_{yx}) = 0.0135, confidence interval for slope = 0.0105.

m/min. $r = .64$ (S/Max vs. length), significant at 95% level. Regression equation: $y = 4.16 + 0.2941X$, $s^2_{yx} = 4.73$, confidence interval for slope = 0.1988.

Table 6. -- The maximum swimming speed (S/Max) of the striped bass tested at 80 ± 2 F and 3 ± 1 ppt salinity with overnight acclimation.

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
24 June 70-1	38	35-42	17.1	0.9
24 June 70-2	33	32-33	10.6	0.6
24 June 70-3	34	33-35	16.5	0.9
24 June 70-5	33	32-34	11.4	0.6
24 June 70-6	32	32-33	11.7	0.6
7 July 70-1	34	33-34	14.3	0.8
7 July 70-2	39	37-40	12.6	0.7
7 July 70-6	39	38-40	13.8	0.8
8 July 70-2	34	34-35	12.9	0.7
8 July 70-3	36	35-38	15.3	0.8
10 July 70-1	40	39-42	15.5	0.8
10 July 70-4	36	35-37	12.9	0.7
24 June 70-4	49	48-50	24.1	1.3
7 July 70-5	47	45-49	21.7	1.2
7 July 70-7	44	43-44	17.1	0.9
8 July 70-8	43	42-44	16.5	0.9
10 July 70-2	43	40-44	14.8	0.8
10 July 70-3	46	43-48	15.6	0.9
17 July 70-4	48	45-51	15.5	0.8
10 July 70-5	54	51-55	21.3	1.2
10 July 70-6	58	55-63	21.2	1.2
17 July 70-1	52	50-55	20.6	1.1
17 July 70-2	59	58-60	20.3	1.1
17 July 70-3	63	60-63	22.6	1.2
17 July 70-5	61	60-63	22.5	1.2

ft/sec. $r = .85$ (S/Max vs. length), significant at 95% level. Regression equation: $y = 0.063 + 0.0193X$, $s^2_{yx} = 0.0123$, confidence interval for slope = 0.0037.

m/min. $r = .85$ (S/Max vs. length), significant at 95% level. Regression equation: $y = 1.24 + 0.3538X$, $s^2_{yx} = 4.42$, confidence interval for slope = 0.0764.

Table 7. -- Summary of sample size (N), correlation coefficients (r), regression equations, sample variance of estimates (s^2_{yx}) and confidence intervals for slopes of striped bass tested at two temperatures and 3 ± ppt salinity.

Experimental Temperature (° F)	S/Max	N	r	Regression Equation	s^2_{yx}	Confidence interval for slope[tt]
75 ± 2	ft/sec	13	.65[t]	6 = 0.215 + 0.0166X	0.0135	0.0105
	m/min	13	.64[t]	y = 4.16 + 0.2941X	4.73	0.1988
80 ± 2	ft/sec	25	.85[t]	y = 0.063 + 0.0193X	0.0123	0.0037
	m/min	25	.85[t]	y = 1.24 + 0.3538X	4.42	0.0764
Pooled*	ft/sec	38	.83	y = 0.185 + 0.0182X	0.0113	9,9933
	m/min	38	.82	y = 3.41 + 0.3362X	4.38	0.0326

* Pooled estimate of all data at 75 and 80 ± 2 F.

[t] Significant at 95% level with N-2 degrees of freedom.

[tt] All values calculated to 95% level with N-2 degrees of freedom.

Table 8. -- The maximum swimming speed (S/Max) of the white perch tested at 75 ± 2 F and 4 ± 2 ppt salinity with overnight acclimation.

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
23 June 70-1	37	35-40	9.3	0.5
25 June 70-4	40	38-41	12.3	0.7
25 June 70-5	32	31-33	6.3	0.3
25 June 70-7	36	33-38	9.9	0.5
25 June 70-8	38	38-39	8.7	0.5
25 June 70-9	38	37-39	9.4	0.5
25 June 70-10	37	36-37	15.2	0.8
27 June 70-4	33	31-34	12.6	0.7
27 June 70-7	37	35-38	10.2	0.6
25 June 70-6	43	41-45	12.3	0.7
27 June 70-3	41	40-43	14.5	0.8
27 June 70-5	44	43-44	13.7	0.7
27 June 70-6	41	40-43	12.2	0.7
7 July 70-3	44	44-45	18.4	1.0

ft/sec. $r = .66$ (S/Max vs. length), significant at 95% level.
Regression equation: $y = -0.5499 + 0.0309X$, $s^2_{yx} = 0.0189$,
confidence interval for slope = 0.0181.

m/min. $r = .65$ (S/Max vs. length), significant at 95% level.
Regression equation: $y = -8.98 + 0.5376X$, $s^2_{yx} = 6.08$,
confidence interval for slope = 0.3247.

Table 9. -- The maximum swimming speed (S/Max) of the white perch tested at 80 ± 2 F and 4 ± 2 ppt salinity with overnight acclimation.

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
1 July 70-1	40	38-42	13.9	0.8
1 July 70-3	35	34-37	9.9	0.5
1 July 70-4	35	33-37	11.9	0.6
2 July 70-1	36	35-37	13.5	0.7
2 July 70-2	33	31-35	12.9	0.7
3 July 70-1	38	34-43	13.5	0.7
22 July 70-1	37	35-39	11.9	0.6
22 July 70-2	38	34-40	13.8	0.8
1 July 70-2	42	39-43	12.8	0.7
1 July 70-5	41	40-42	16.7	0.9
1 July 70-6	41	40-44	16.5	0.9
2 July 70-3	47	45-49	17.4	1.0
17 July 70-6	51	50-53	16.2	0.9
18 July 70-1	53	49-56	16.0	0.9
25 August 70-1	57	56-60	20.7	1.1
25 August 70-4	60	57-62	22.3	1.2
25 August 70-6	59	57-61	19.8	1.1
25 August 70-7	53	49-56	17.8	1.0
25 August 70-8	60	58-61	21.8	1.2
25 August 70-9	57	56-58	18.6	1.0
14 July 70-1	67	65-70	14.8	0.8
14 July 70-3	66	63-68	15.3	0.8
14 July 70-4	69	65-72	13.3	0.7
14 July 70-5	68	64-70	14.5	0.8
21 July 70-1	67	66-70	17.9	1.0
21 July 70-2	66	63-68	13.1	0.7
25 August 70-2	64	62-65	21.2	1.2
25 August 70-3	65	64-65	23.5	1.3
25 August 70-5	62	60-65	20.6	1.1
25 August 70-10	68	65-70	20.8	1.1

ft/sec r = .56 (S/Max vs. length), significant at 95% level. Regression equation: $y = 0.414 + 0.0092X$, $s^2_{yx} = 0.0436$, confidence interval for slope = 0.0166.

m/min r = .53 (S/Max vs. length), significant at 95% level. Regression equation: $y = 7.79 + 0.1646X$, $s^2_{yx} = 10.51$, confidence interval for slope = 0.2569.

Table 10. -- The maximum swimming speed (S/Max) of the white perch tested at 85 ± 2 F and 4 ± ppt salinity with overnight acclimation.

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
23 July 70-5	35	34-35	10.8	0.6
23 July 70-1	43	42-43	14.7	0.8
23 July 70-2	46	45-47	19.9	1.0
23 July 70-3	42	41-45	24.0	1.3
23 July 70-4	43	41-44	17.3	0.9
23 July 70-6	43	41-45	11.2	0.6
23 July 70-7	48	47-50	16.6	0.9
23 July 70-8	48	46-50	15.5	0.8
4 August 70-2	49	47-50	15.7	0.8
23 July 70-9	57	57	17.7	1.0
4 August 70-1	54	52-56	21.9	1.2
4 August 70-3	57	55-58	19.2	1.0
5 August 70-4	57	55-59	20.2	1.1
7 August 70-3	53	51-54	18.9	1.0
24 July 70-1	69	66-73	23.6	1.3
24 July 70-3	63	59-65	20.2	1.1
24 July 70-4	69	68-70	22.1	1.2
24 July 70-5	63	63-64	20.4	1.1
28 July 70-1	65	64-66	17.0	0.9
4 August 70-4	68	65-70	22.8	1.2
5 August 70-1	67	63-70	21.5	1.2
5 August 70-2	62	60-63	23.4	1.2
5 August 70-3	70	67-73	24.9	1.4
6 August 70-5	63	61.65	20.9	1.1
24 July 70-2	73	68-75	24.5	1.3
28 July 70-2	80	76-84	22.8	1.2
28 July 70-3	75	74-75	17.6	1.0
28 July 70-4	73	70-75	22.5	1.2
28 July 70-5	73	70-79	26.7	1.5
4 August 70-5	76	75-77	17.0	0.9
4 August 70-6	71	70-71	18.3	1.0
4 August 70-7	73	70-77	22.4	1.2
5 August 70-4	78	77-79	21.9	1.2
6 August 70-1	73	71-75	25.3	1.4
6 August 70-2	72	68-75	22.7	1.2
6 August 70-3	75	73-79	23.0	1.3
6 August 70-4	72	70-75	22.6	1.2
7 August 70-1	71	68-77	25.4	1.4
7 August 70-2	74	72-77	25.6	1.4
7 August 70-4	77	73-82	23.8	1.3

Table 10. -- (continued)

ft/sec. r = .66 (S/Max vs. length), significant at 95% level. Regression equation: $y = 0.408 + 0.0113X$, $s^2_{yx} = 0.0270$, confidence interval for slope = 0.0035.

m/min. r = .67 (S/Max vs. length), significant at 95% level. Regression equation: $y = 7.41 + 0.2088X$, $s^2_{yx} = 8.517$, confidence interval for slope = 0.0638.

Table 11. -- The maximum swimming speed (S/Max) of the white perch tested at 90 ± 2 F and 4 ± 2 ppt salinity with overnight acclimation.

Experiment Number	Mean Fork Length (mm)	Fork Length Range	S/Max m/min	S/Max ft/sec
31 July 70-1	40	39-40	12.8	0.7
31 July 70-2	48	46-52	18.1	1.0
31 July 70-3	45	42-46	14.9	0.8
31 July 70-4	44	44-45	15.1	0.8
31 July 70-5	48	47-50	16.5	0.9
31 July 70-8	50	49-51	16.1	0.9
18 August 70-6	46	40-50	19.7	1.0
31 July 70-6	53	50-54	17.8	1.0
31 July 70-7	54	54	17.8	1.0
31 July 70-9	52	51-53	16.3	0.9
14 August 70-7	56	55-58	21.3	1.1
18 August 70-2	52	51-54	23.7	1.3
18 August 70-3	52	50-53	20.7	1.1
18 August 70-4	58	57-61	23.5	1.3
18 August 70-5	52	50-53	22.8	1.2
18 August 70-7	56	54-57	24.2	1.3
18 August 70-8	59	59-60	24.4	1.3
30 July 70-1	66	63-70	19.0	1.0
11 August 70-3	64	61-67	19.7	1.1
14 August 70-1	62	61-65	15.8	0.9
14 August 70-4	67	65-69	22.4	1.2
14 August 70-8	68	65-70	23.8	1.3
18 August 70-1	62	60-63	21.8	1.2
18 August 70-9	62	61-64	18.2	1.0
11 August 70-1	77	75-80	25.0	1.4
11 August 70-4	76	72-80	22.2	1.2
14 August 70-2	77	73-80	22.9	1.3
14 August 70-3	75	74-77	22.4	1.2
14 August 70-6	79	77-80	21.1	1.2
11 August 70-1	81	77-85	25.0	1.4

ft/sec r = .67 (S/Max vs. length), significant at 95% level. Regression equation: $y = 0.485 + 0.0104X$, $s^2_{yx} = 0.0233$, confidence interval for slope = 0.0051.

m/min r = .64 (S/Max vs. length), significant at 95% level. Regression equation: $y = 8.81 + 0.1913X$, $s^2_{yx} = 7.23$, confidence interval for slope = 0.0734.

Table 12. -- Summary of sample size (N), correlation coefficients (r), regression equations, sample variance of estimates (s^2_{yx}) and confidence intervals for slopes of white perch tested at various temperatures and 4 ± 2 ppt salinity.

Experimental Temperature (°F)	S/Max	N	r	Regression Equation	s^2_{yx}	Confidence Interval for Slope[tt]
75 ± 2	ft/sec	14	.66[t]	y = -0.5499 + 0.0309X	0.0189	0.0181
	m/min	14	.65[t]	y = -8.98 + 0.5376X	6.08	0.3247
80 ± 2	ft/sec	30	.56[t]	y = 0.414 + 0.0092X	0.0436	0.0166
	m/min	30	.53[t]	y = 7.79 + 0.1646X	10.89	0.2569
85 ± 2	ft / sec	40	.66[t]	y = 0.408 + 0.0113X	0.0270	0.0035
	m/min	40	.67[t]	y = 7.41 + 0.2088X	8.52	0.0638
90 ± 2	ft/sec	30	.65[t]	y = 0.485 + 0.0104X	0.0233	0.0051
	m/min	30	.64[t]	y = 8.81 + 0.1913X	7.23	0.0734
Pooled*	ft/sec	100	.70[t]	y = 0.3153 + 0.0124X	0.0267	0.0021
	m/min	100	.70[t]	y = 5.77 + 0.2305X	7.76	0.0362

* Pooled estimate of all data at 80, 85 and 90 ± 2 F.

[t] Significantat 95% level with N-2 degrees of freedom.

[tt] All values calculated to 95% level with N-2 degrees of freedom.

Table 13. -- Statistical formulae used in t test on intercepts and in the analysis of covariance F test.

t test on intercepts*

$$T = \frac{\hat{\alpha}_1 - \hat{\alpha}_2}{\sqrt{\text{Var}\,\hat{\alpha}_1 + \text{Var}\,\hat{\alpha}_2}}$$

$$\text{Var}\,\hat{\alpha} = \frac{\hat{\sigma}^2 \Sigma X^2}{n \Sigma x^2}$$

$$\hat{\sigma}^2 = \frac{\Sigma y^2 - (\Sigma xy)^2/\Sigma x^2}{n-2}$$

Analysis of covariance F test*

$$F = \frac{\sum_i (n\hat{\alpha}_i \bar{Y}_{i.} + \hat{\beta}_i \sum_j X_{ij} Y_{ij}) - \frac{Y_{..}^2}{n} + \frac{\sum_{ij} x_{ij}^2 y_{ij}^2}{\sum_{ij} x_{ij}^2}}{2(t-1)} \div \frac{\sum_{ij} Y_{ij}^2 - \sum_i (n\hat{\alpha}_i \bar{Y}_{i.} + \beta_i \sum_j X_{ij} Y_{ij})}{\Sigma(n-2)}$$

*Lower case letters denote corrected sums of squares and cross products.

Table 14.-- A List of Common and Scientific Names of Fish Mentioned in This Study. (American species follow Bailey, et al., 1960)

Common Name	Scientific Name
Atlantic herring	Clupea harengus harengus Linnaeus
Bay anchovy	Anchoa mitchilli (Valenciennes)
Coho salmon	Oncorhynchus kisutch (Walbaum)
Sockeye salmon	Oncorhynchus nerka (Walbaum)
Chinook salmon	Oncorhynchus tshawytscha (Walbaum)
Rainbow trout	Salmo gairdneri Richardson
Atlantic salmon	Salmo salar Linnaeus
Brook trout	Salvelinus fontinalis (Mitchill)
Lake trout	Salvelinus namaycush (Walbaum)
Goldfish	Carassius auratus (Linnaeus)
Carp	Cyprinus carpio Linnaeus
Spotfin shiner	Notropis spilopterus (Cope)
Fathead minnow	Pimephales promelas Rafinesque
Channel catfish	Ictalurus punctatus (Rafinesque)
Brown bullhead	Ictalurus nebulosus (LeSueur)
Rough silverside	Membras martinica (Valenciennes)
Tidewater silverside	Menidia beryllina (Cope)
Mummichog	Fundulus heteroclitus (Linnaeus)
Bluegill sunfish	Lepomis macrochirus Rafinesque
Largemouth bass	Micropterus salmoides Lacépède
Walleye	Stizostedion vitreum vitreum (Mitchill)
Yellow perch	Perca flavescens (Mitchill)
Striped bass	Morone saxatilis (Linnaeus)
White perch	Morone americana (Gmelin)
Bluefish	Pomatomus saltatrix (Linnaeus)
Opaleye	Girella nigricans (Ayres)
Orange chromide	Entroplus maculatus (Bloch)*
Nile bolti	Tilapia nilotica**
African mouthbreeder	Tilapia mossambica***
Mudskipper	Periopthalmus sobrinus***

*From Axelrod et al., 1962. **From Blair et al., 1968. ***From Herald, 1961.

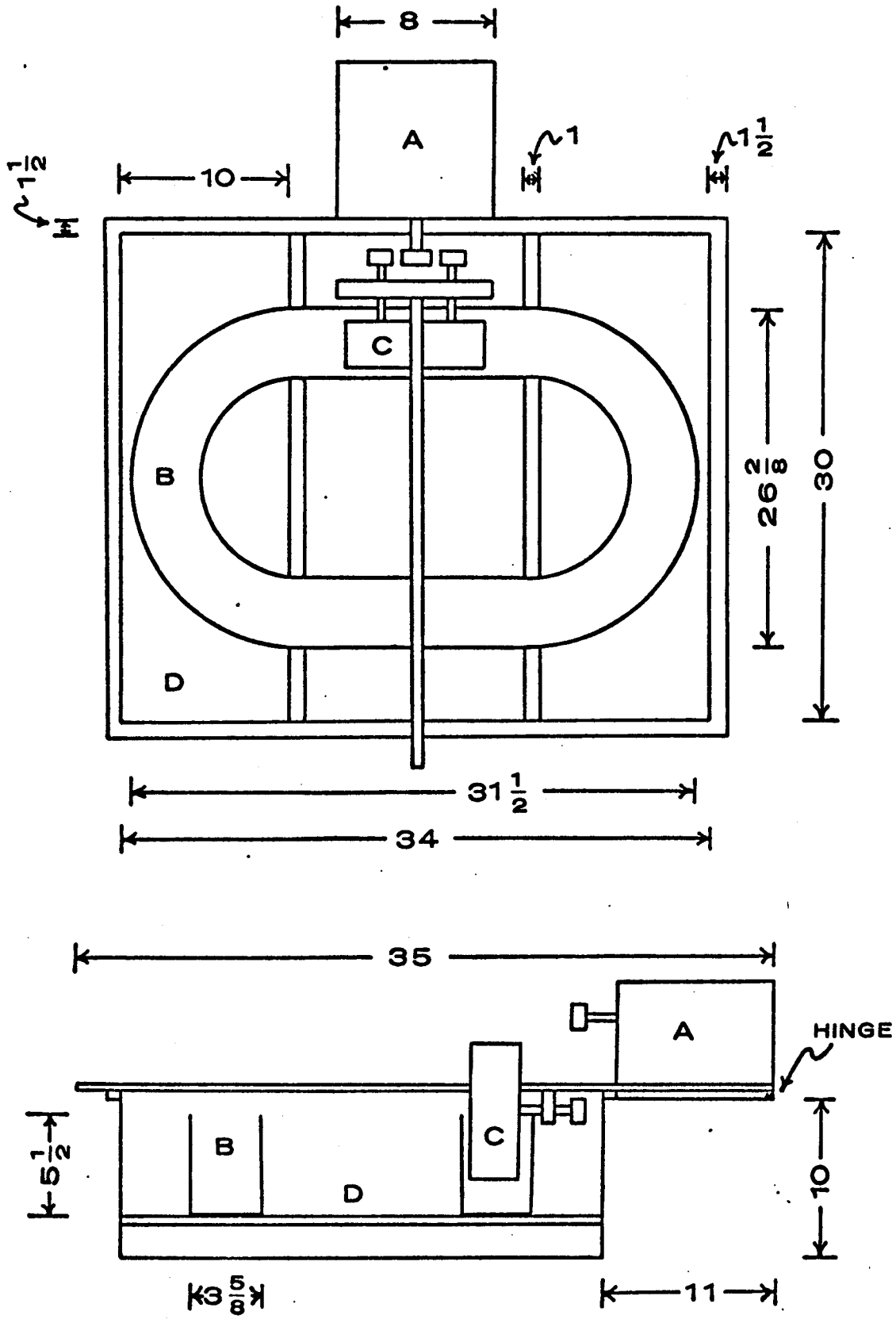

Figure 1. -- Schematic diagram of the modified MacLeod Apparatus. Scale: One inch equals approximately one foot. Dimensions are given in inches. A - Motor, B - Test Chamber, C - Paddle Wheels, D - Rectangular tub. (From King, 1969)

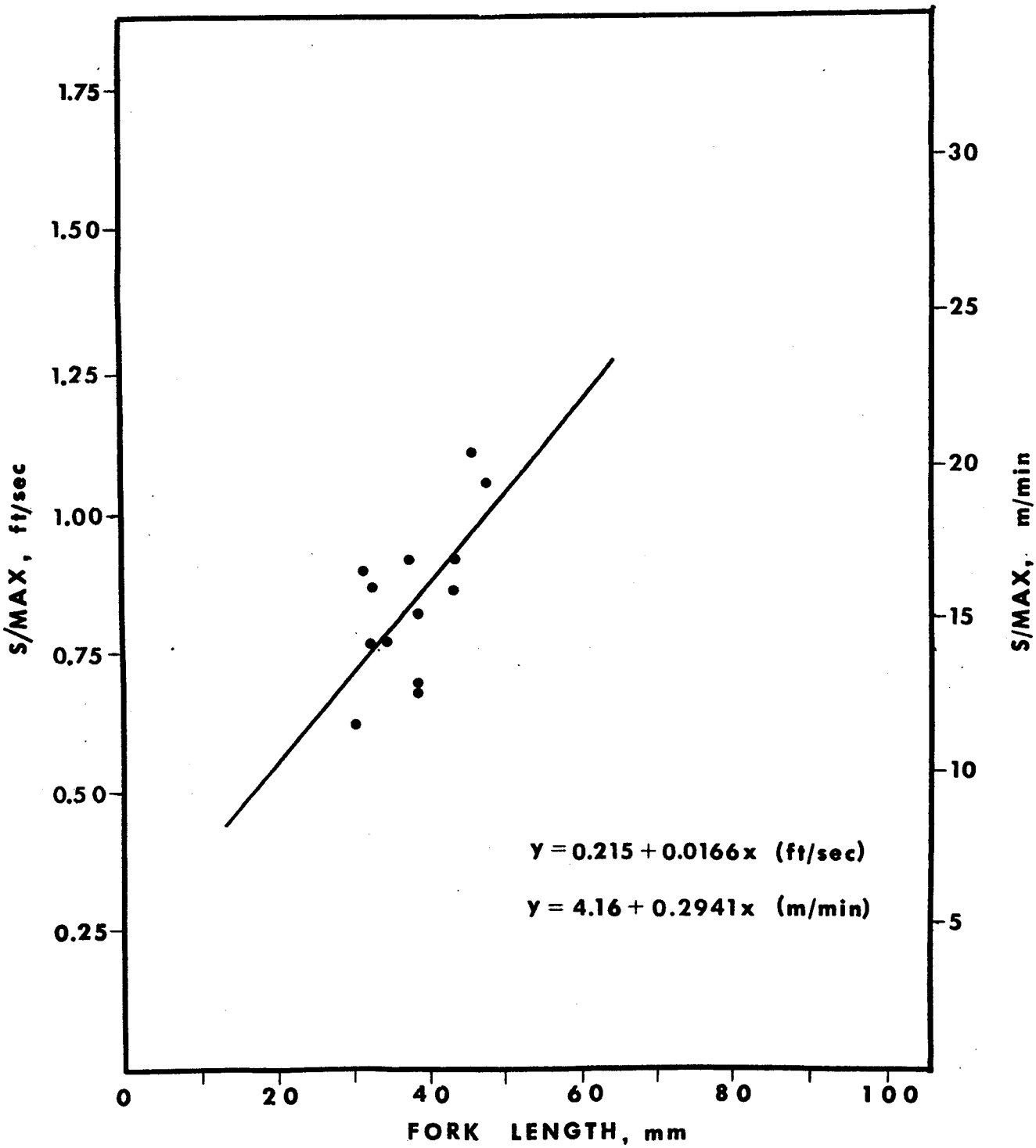

Figure 2. -- Maximum swimming speed (S/Max) vs. fork length of striped bass tested at 75 ± 2 F and 3 ± 1 ppt salinity.
r = .65, y = 0.215 + 0.0166X (ft/sec)
r = .64, y = 4.16 + 0.2941X (m/min)

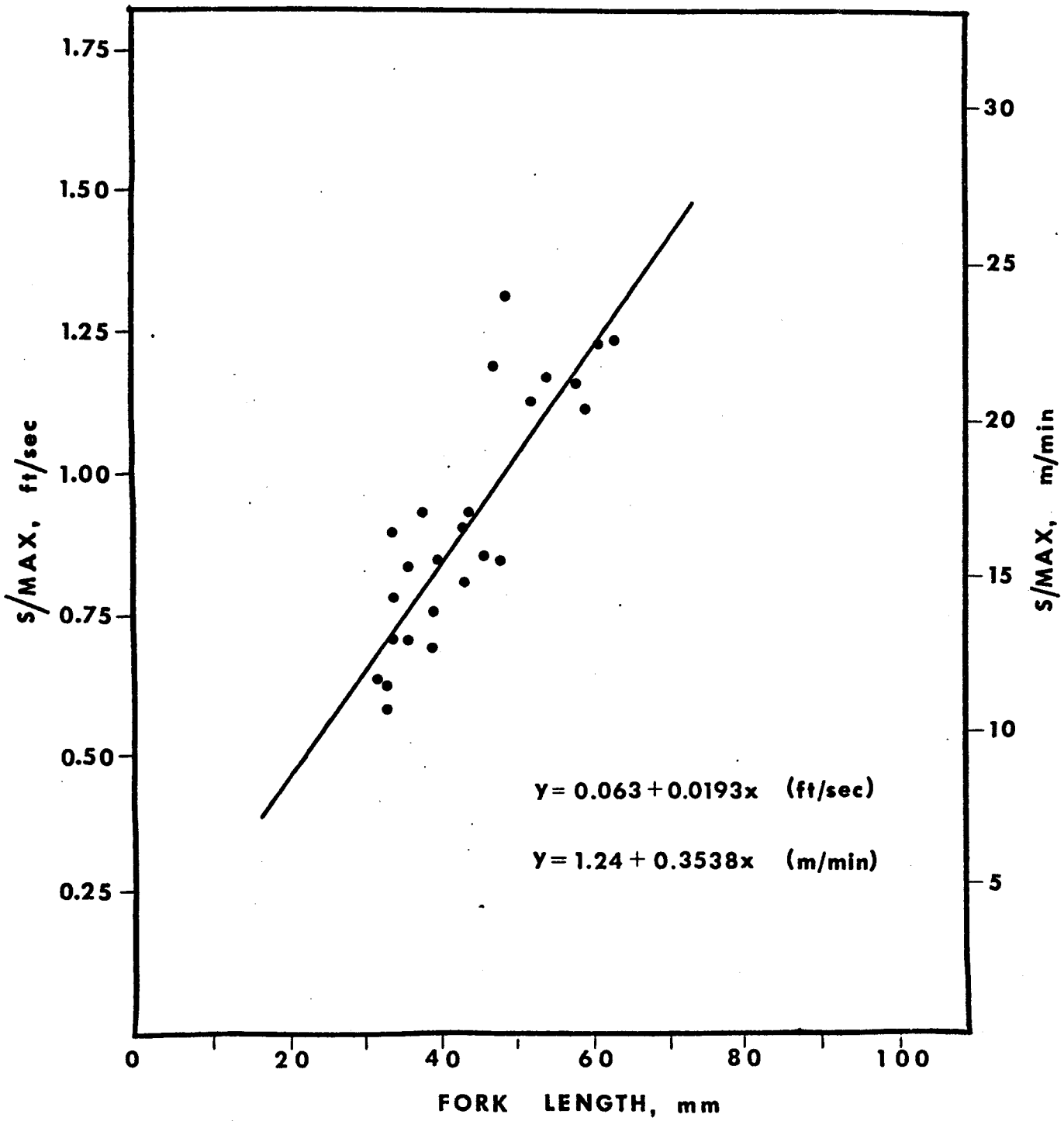

Figure 3. S/Max versus fork length of striped bass tested at 80 ± 2 F and 3 ± 1 ppt salinity.
r = .85, y = 0.063 + 0.0193X (ft/sec)
r = .85, y = 1.24 + 0.3538X (m/min)

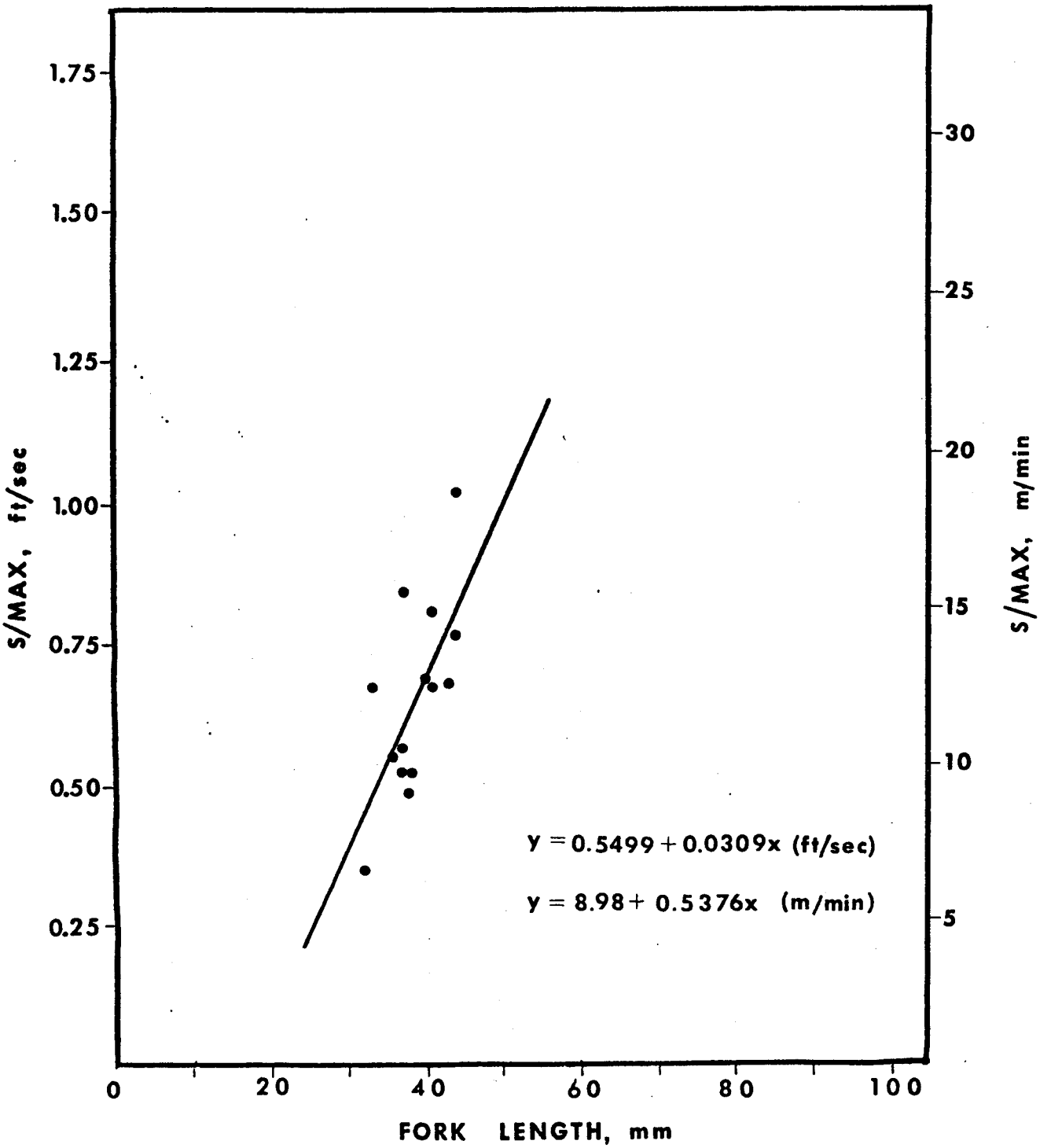

Figure 4. -- S/Max versus fork length of white perch tested at 75 ± 2 F and 4 ± 2 ppt salinity.
r = .66, y = 0.5499 + 0.0309X (ft/sec)
r = .65, y = 8.98 + 0.5376X (m/min)

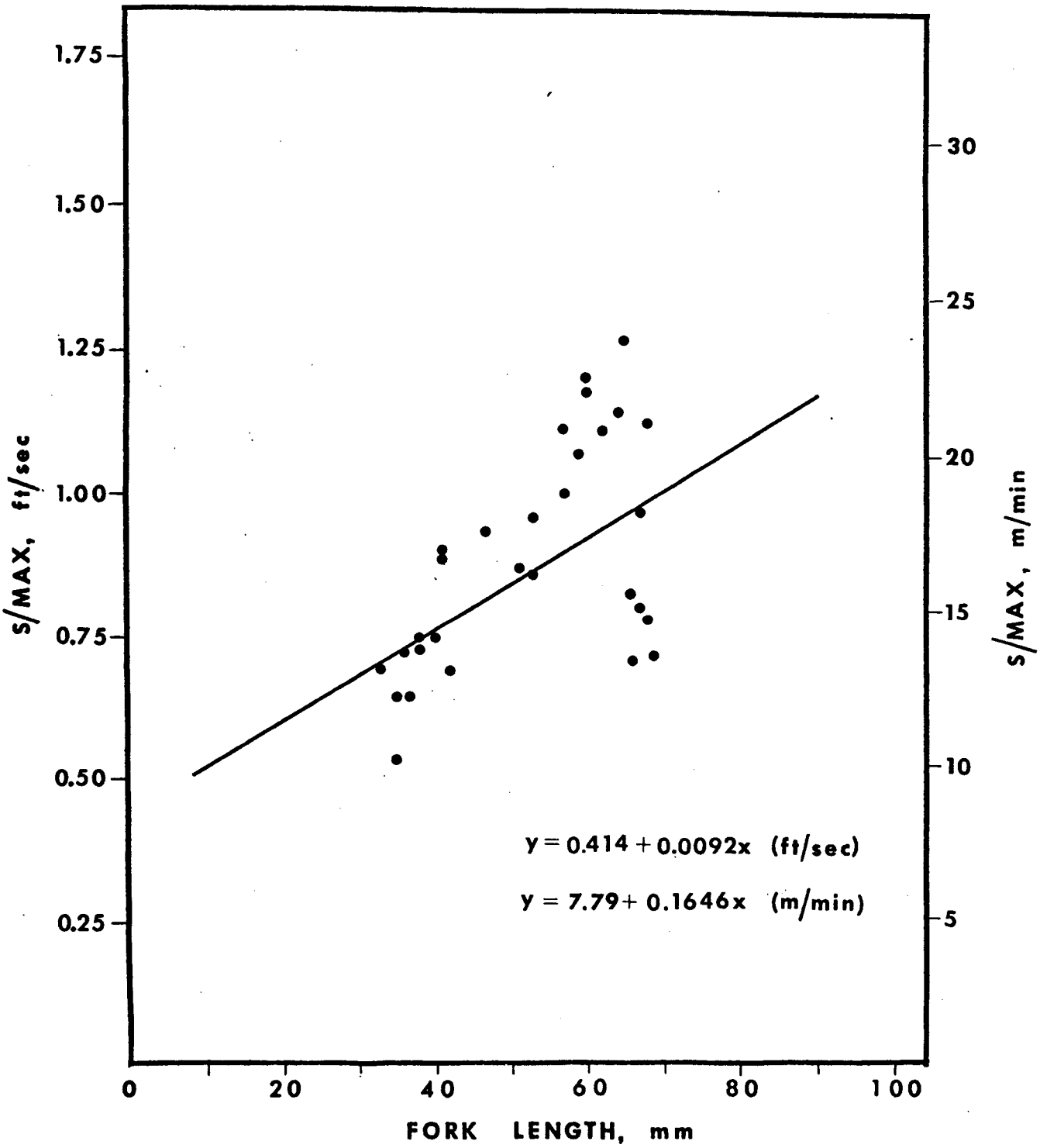

Figure 5. -- S/Max versus fork length of white perch tested at 80 ± 2 F and 4 ± 2 ppt salinity.
r = .56, y = 0.414 + 0.0092X (ft/sec)
r = .53, y = 7.79 + 0.1646 (m/min)

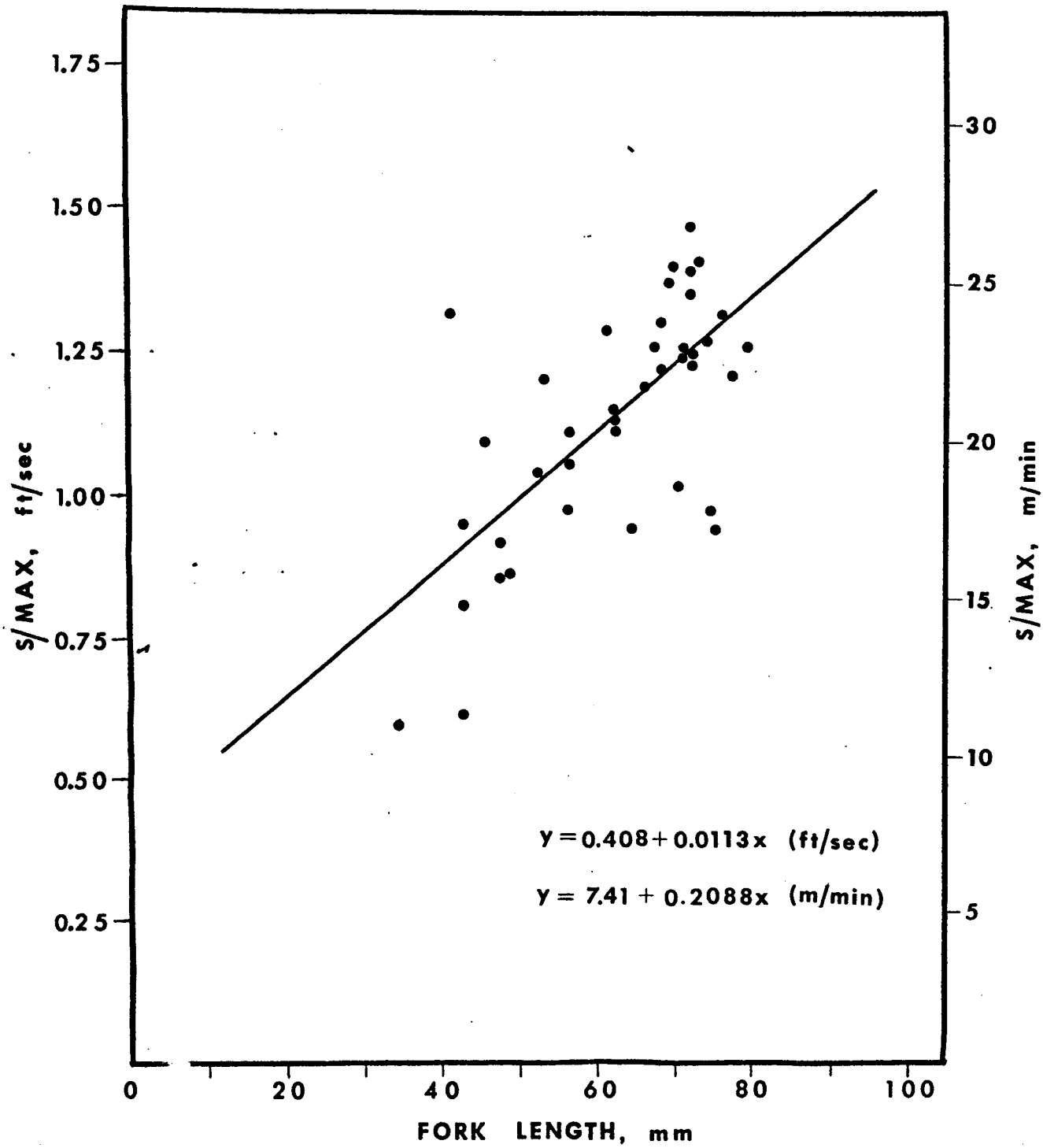

Figure 6. -- S/Max versus fork length of white perch tested at 85 ± 2 F and 4 ± 2 ppt salinity.
r = .66, y = 0.408 + 0.0113X (ft/sec)
r = .67, y = 7.41 + 0.2088X (m/min)

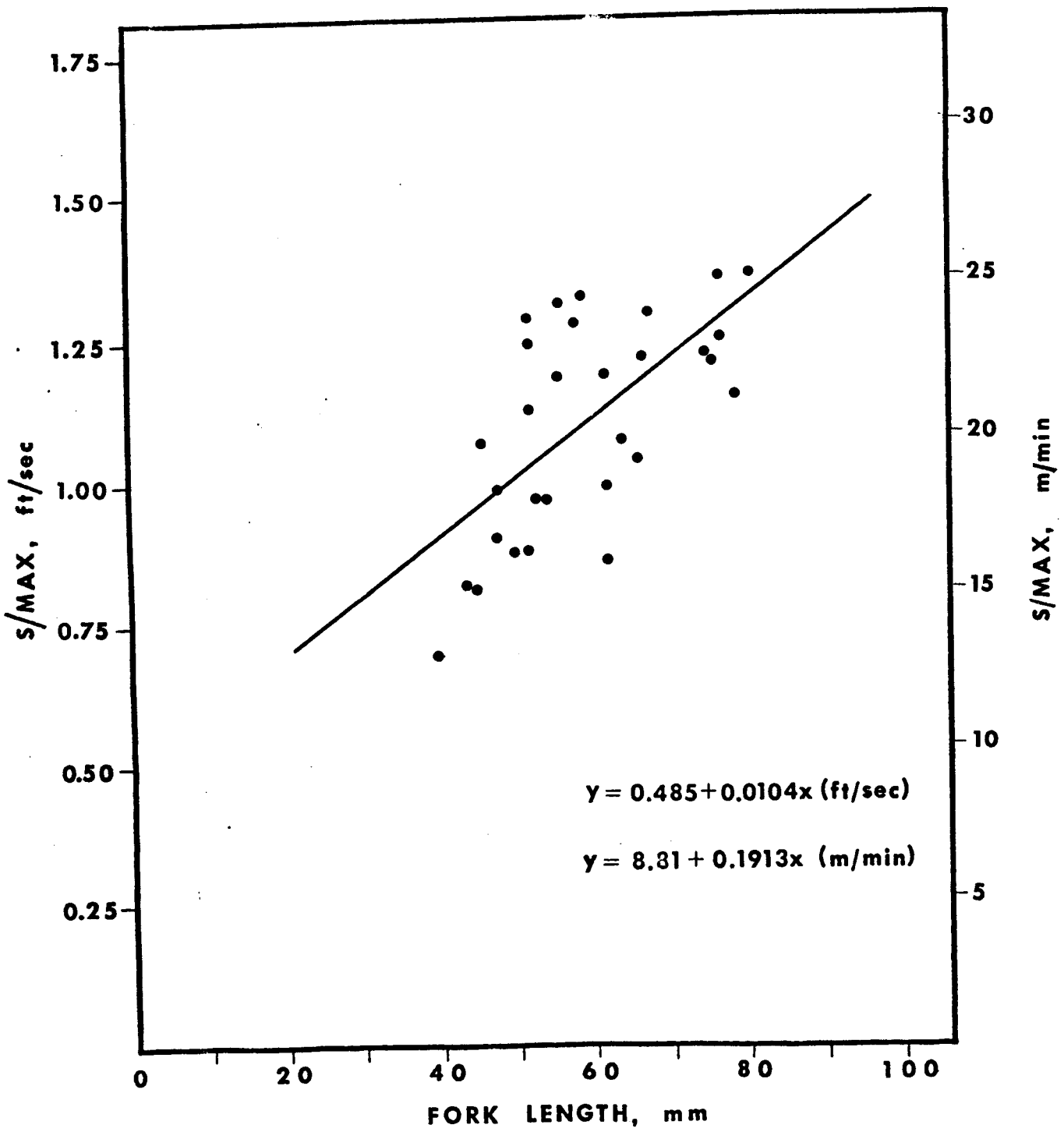

Figure 7. -- S/Max versus fork length of white perch tested at 90 ± 2 F and 4 ± 2 ppt salinity.
r = .67, y = 0.485 + 0.0104X (ft/sec)
r = .64, y = 8.81 + 0.1913X (m/min)

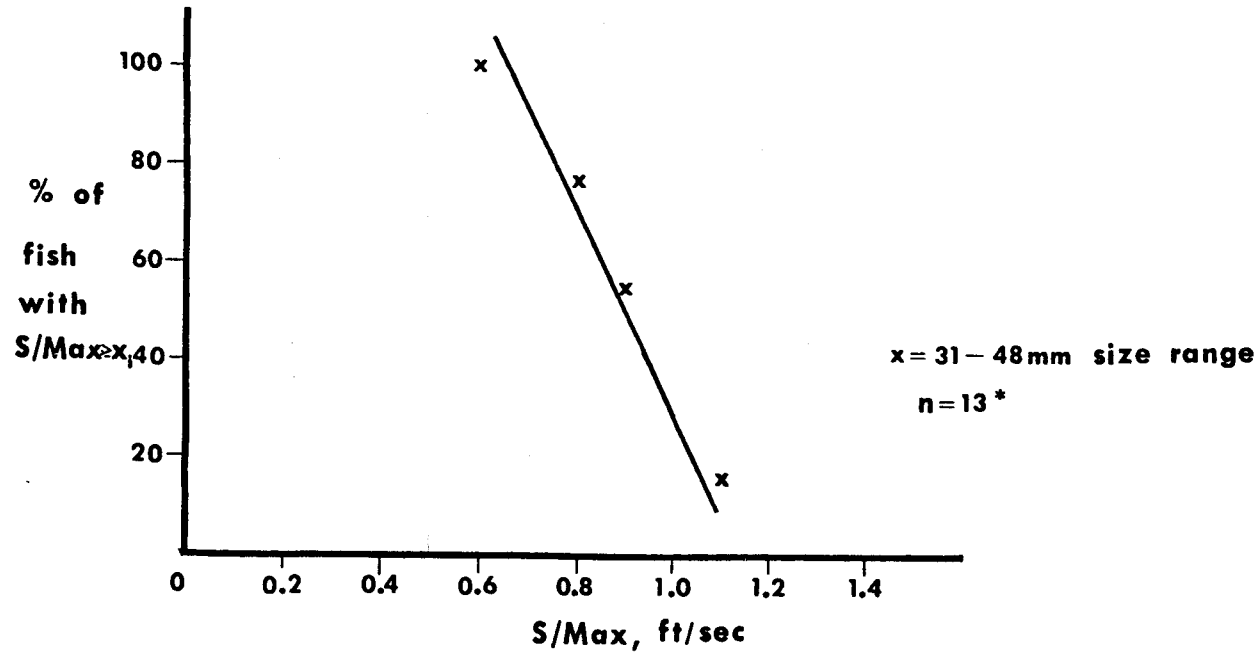

Figure 8. -- Plot of maximum swimming speed (S/Max) versus percentage of striped bass with S/Max $\geq$ x_i at 75 $\pm$ 2° F.and 3 $\pm$ 1 ppt salinity. Asterisk denotes number of groups tested. Three fish constituted a group.

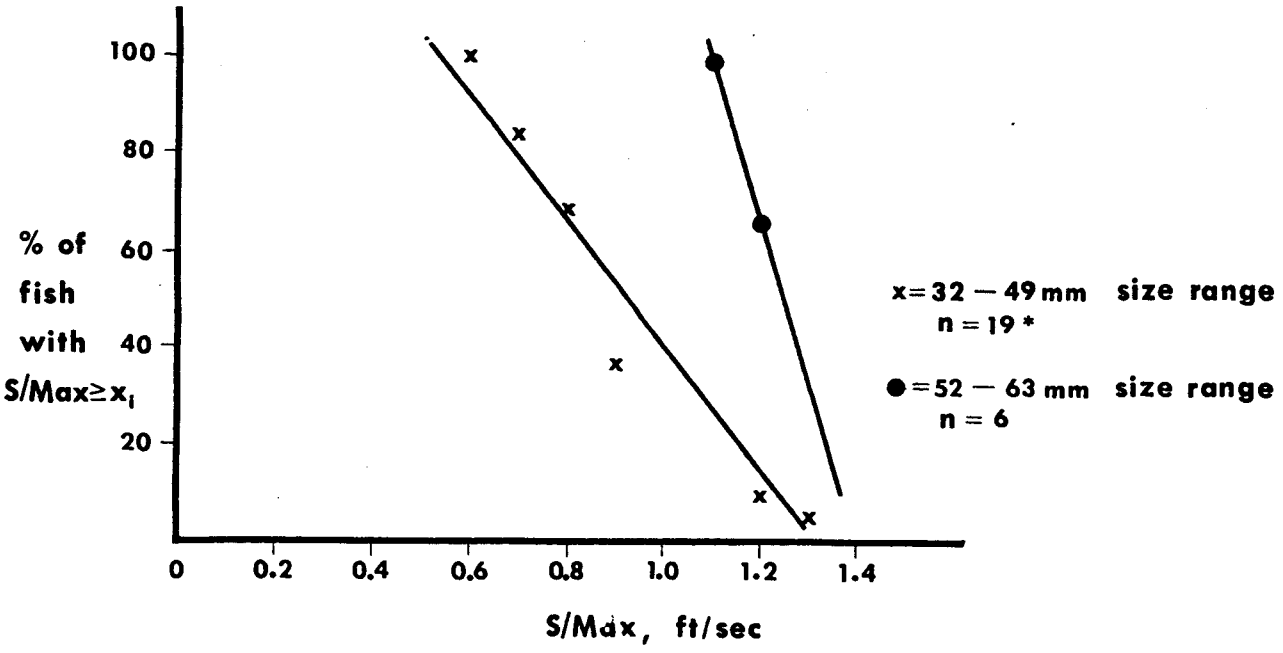

Figure 9. -- Plot of maximum swimming speed (S/Max) versus percentages of striped bass with S/Max $\geq$ x_i at 80 $\pm$ 2° F and 3 $\pm$ 1 ppt salinity. Asterisk denotes number of groups tested. Three fish constituted a group.

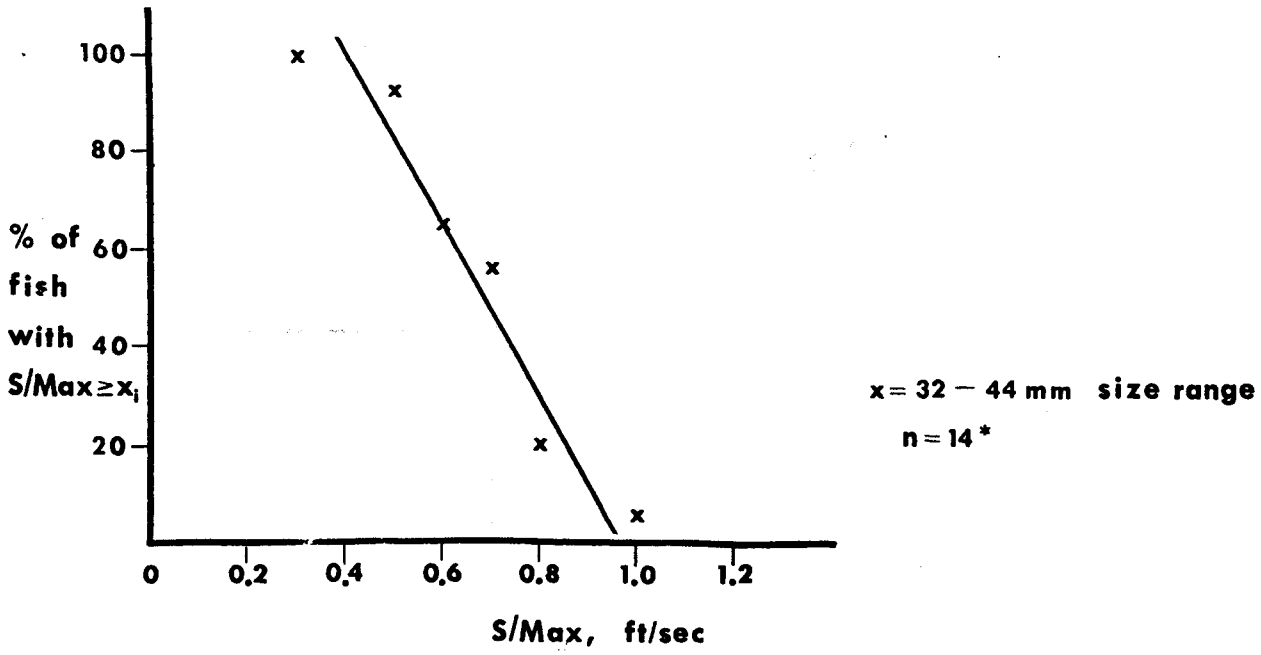

Figure 10.-- Plot of maximum swimming speed (S/Max) versus percentages of white perch with S/Max $\geq x_i$ at 75 ± 2° F and 4 ± 2 ppt salinity. Asterisk denotes number of groups tested. Three fish constituted a group.

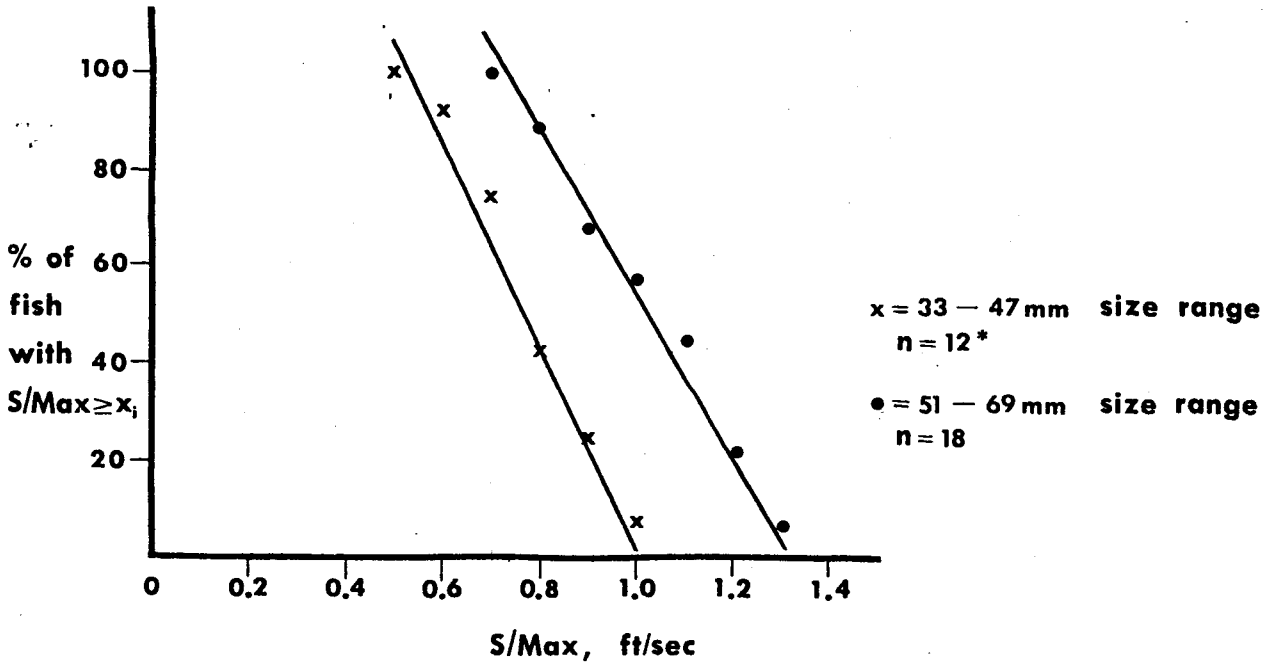

Figure 11.-- Plot of maximum swimming speed (S/Max) versus percentages of white perch with S/Max $\geq x_i$ at 80 ± 2° F and 4 ± 2 ppt salinity. Asterisk denotes number of groups tested. Three fish constituted a group.

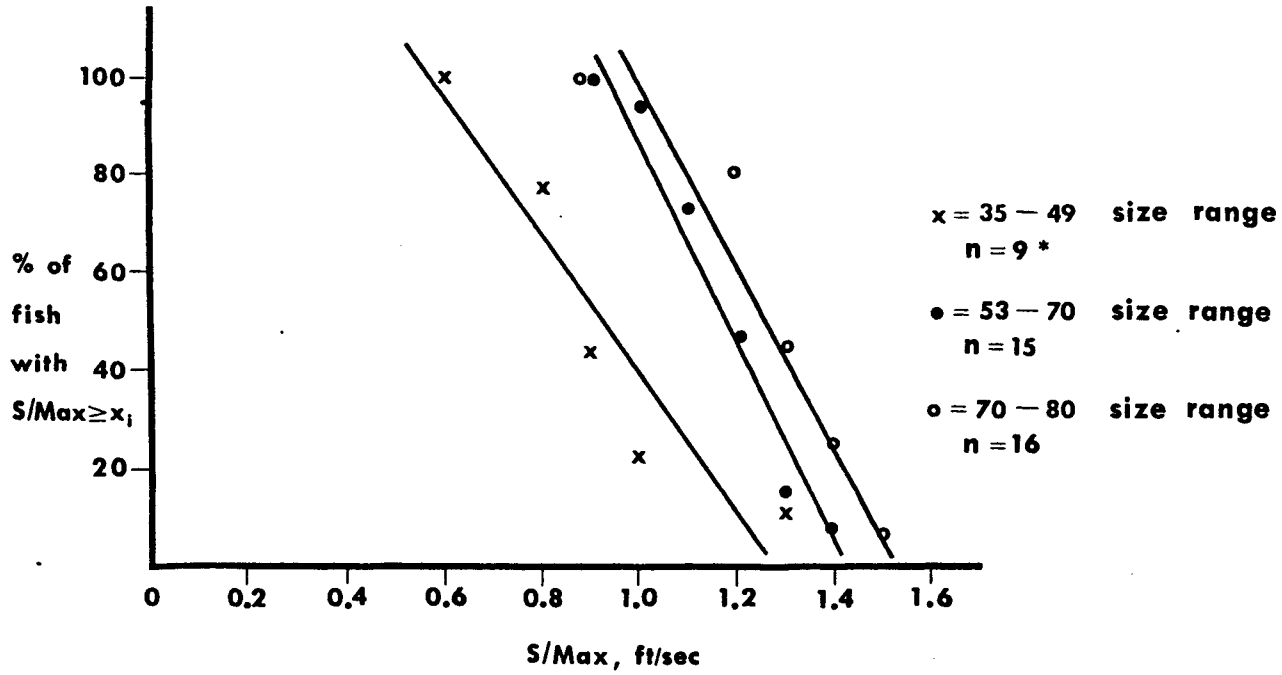

Figure 12.-- Plot of maximum swimming speed (S/Max) versus percentages of white perch with S/Max $\geq x_i$ at 85 ± 2° F and 4 ±2 ppt salinity. Asterisk denotes number of groups tested. Three fish constituted a group.

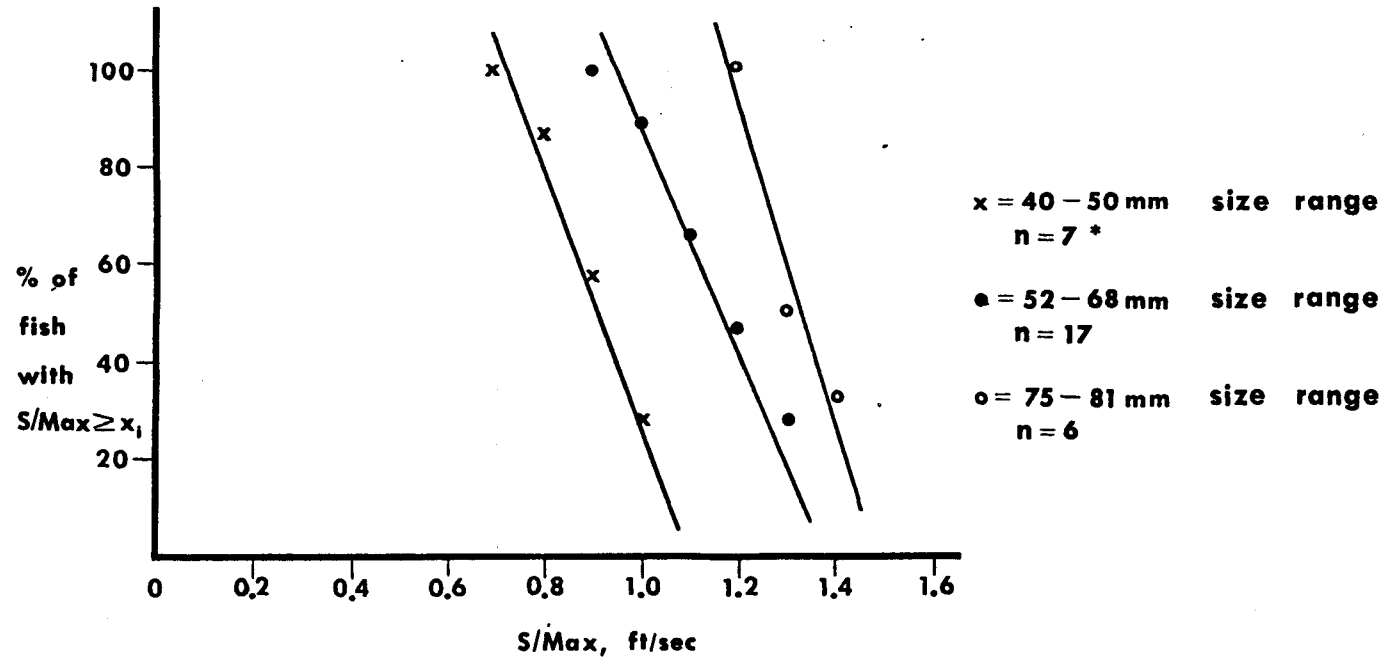

Figure 13.-- Plot of maximum swimming speed (S/Max) versus percentages of white perch with S/Max $\geq x_i$ at 90 ± 2° F and 4 ± 2 ppt salinity. Asterisk denotes number of groups tested. Three fish constituted a group.

Progress Reports of Temperature Preference and Avoidance, and of Swimming Speed of the White Perch and Other Fishes

John W. Meldrim, James J. Gift, Lawrence W. King and Thomas R. Tatham

PROGRESS REPORTS OF TEMPERATURE PREFERENCE AND AVOIDANCE, AND OF SWIMMING SPEED OF THE WHITE PERCH AND OTHER FISHES

BY

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2 October 1970

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Note: These studies are continuing at the Appoquinimink Creek, Delaware, laboratories of Ichthyological Associates.

An Experimental Study of Temperature Preference and Avoidance of the White Perch, Morone americana (Gmelin, 1788).

J. W. Meldrim
J. J. Gift
Ichthyological Associates
Middletown, Delaware

Introduction

In conjunction with an ecological study of the Delaware River estuary, experimental studies on the temperature preferences and avoidances of the fishes of the estuary have been conducted since July 1969. The white perch, Morone americana, unlike many of the other species under study, has been found to be present in the estuary all year long. The objectives of the present study was to determine the temperature preferences and avoidances of the white perch under varying conditions of light level and salinity throughout the year. Due to laboratory space limitations, the study has been performed on specimens less than 150 mm. total length.

General Materials and Methods

All white perch used in the study were taken from the Delaware River drainage by seine. They were transported to and held in the laboratory holding facilities 18-24 hours prior to testing. These facilities consisted of three 32-gallon plastic garbage pails immersed in a water bath. Each pail was aerated and contained water of 4 ppt., 6 ppt., and 9 ppt. salinity respectively. (On several occasions water of 1 ppt. was also used.) The water bath was maintained at the field collection temperature.

Light levels were maintained for the appropriate photoperiod at 40 foot-candles at the surface of the water using Duro Test "Vita-Lite" flourescent bulbs (which have a spectral energy distribution comparable to natural daylight). The fish were not fed either prior to or during testing. As a general procedure, all tests were conducted in the afternoon (thus allowing for any activity effects due to circadian rhythms).

Water used in all tests was taken from Appoquinimink Creek (a tributary of the Delaware) at high tide to approximate the quality of the Delaware at high tide. Due to its great turbidity, it was allowed to "settle" prior to use. Nearly saturated levels of dissolved oxygen and pH of 7.0-8.0 were maintained throughout testing.

Temperature Preference Studies

Each species of fish has an optimum temperature which is unique to that species (although many species may have a similar preferred temperature). Behavioral responses to long term temperature changes are primarily made with respect to (and are best understood in terms of) the species' optimum temperature.

Although innately independent of acclimation temperature, the temperature preference exhibited is initially dependent upon acclimation temperature and changes accordingly with the annual temperature cycle (Sullivan and Fisher, 1953). In order to understand these long-term patterns (as well as the short-term avoidance) it is necessary to determine the optimum temperature for the species under study.

The apparatus used for the preference study is illustrated in Figure 1. It consisted of a trough 13-feet in length, 6-inches wide, and 1-foot deep, having a 24-gauge (Type 304) stainless steel bottom in the center 12-feet. Water was introduced at one end of the trough from a temperature controlled circulating bath. As the water flowed down the trough it was heated by three banks of infra-red bulbs beneath the stainless steel bottom to form a stationary horizontal thermal gradient. Each bank consisted of four 250-watt bulbs connected to a dimmer switch and a temperature regulator. (Thus, the intensity of each bank could be varied as well as the length of time the bank was on). Upon reaching the other end of the trough, the water was returned to the circulating bath. The trough was partially enclosed by polyethylene sheeting for light control. Lighting was provided by three "Vita-Lites" which extended the length of the trough.

Initially the trough was filled to a depth of two inches with water of the acclimation temperature. Fish were then placed in the trough without the gradient having been established. (This provided a control for position effects.) Observations were made via overhead mirrors every five minutes for a 45-minute period. Upon completion of this control the fish were removed and a thermal gradient extending approximately 10 C degrees above and below the acclimation temperature was established in the trough. The fish were then re-introduced at the place in the trough having their acclimation temperature. Observations were again made at 5 minute intervals.

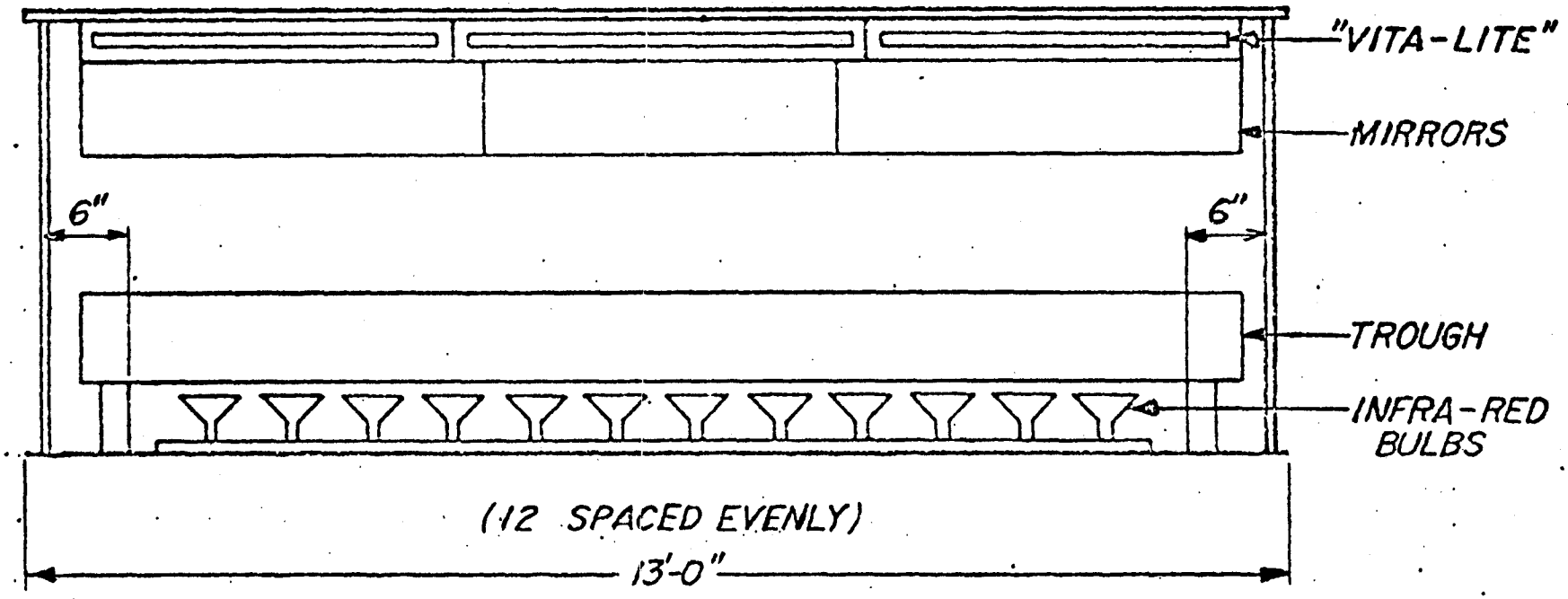

Figure 1. Temperature preference apparatus.

The temperature at the position of each fish was then recorded using one of 23 thermistors (placed at 6-inch intervals along the trough) which were connected to a temperature readout. The test was concluded when the same temperature was selected continuously for 20 minutes.

Temperature Avoidance Studies

The avoidance design found to be successful with white perch is a modification of the design employed first by Shelford and Allee (1913) and then by J. R. Jones (1952), B. F. Jones, et. al. (1956), Whitmore, et. al. (1960), Hill (1968), Sprague (1964, 1968), and Sprague, et. al. (1965). In this design (illustrated in Figure 2), temperature controlled circulating baths served as storage reservoirs. Water from the respective bath flowed (via gravity-flow) into each end of the sub-troughs and drained from their centers, where it was recirculated to the temperature baths. Dye tests showed a sharp boundary at the center drain. The apparatus was thus effectively divided into quadrants.

Equal numbers of fish were placed into each quadrant. Two of the quadrants (on opposite ends of the respective sub-troughs) contained water of the acclimation temperature ("T"), while the remaining two contained water of increased (or decreased) temperature ("T+"). After a five minute orientation period, the amount of time spent by each fish in each quadrant was measured for a period of ten minutes (which constituted a trial). The number of occurrences of fish in each quadrant was then multiplied by the amount of time they spent in the respective quadrants to give a frequency

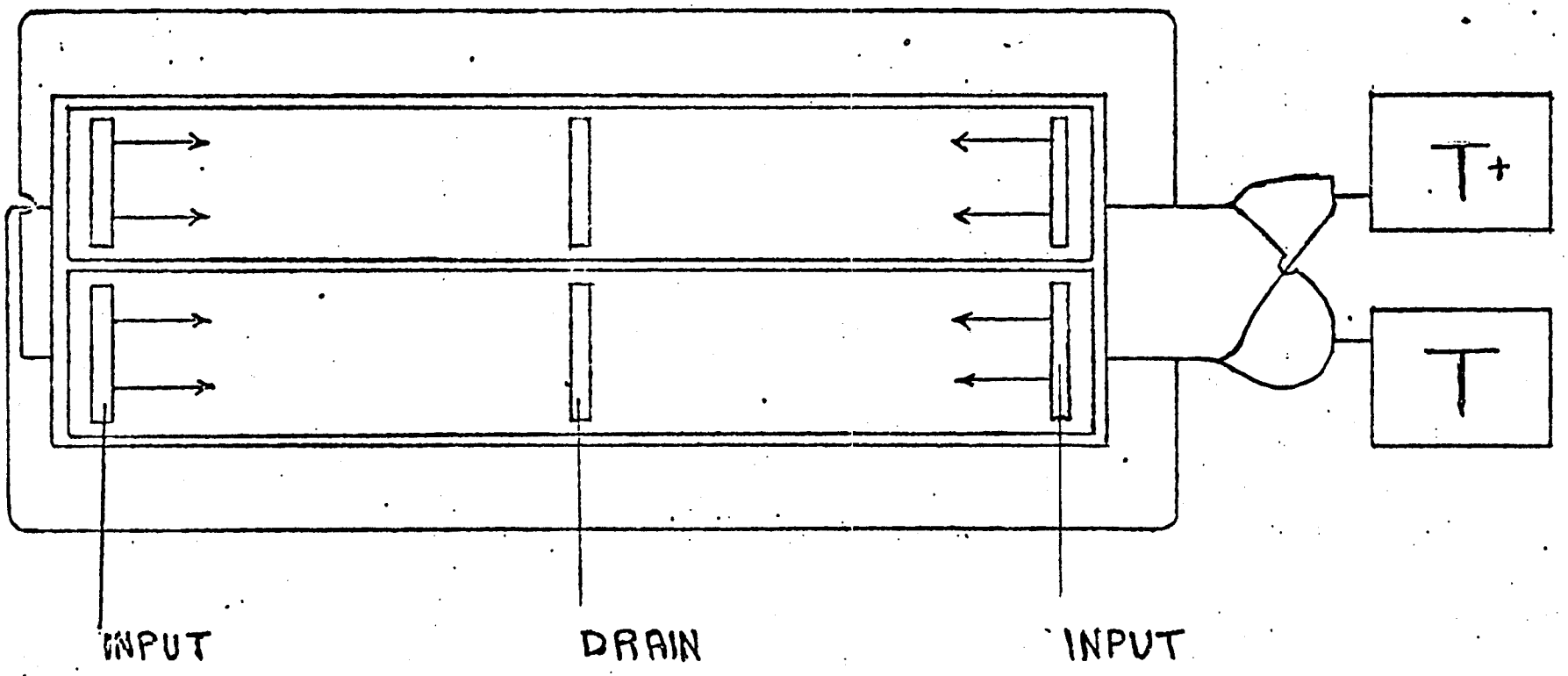

Figure 2. Diagram of the modified Shelford-Allee avoidance design.

distribution for each quadrant. A t-test was then performed to determine if a significant difference (P.05) (and thus avoidance) existed between the distributions.

If no significant difference existed, the respective temperatures were then increased in a step-gradient fashion by increasing "T" and "T+" 3 to 5 F degrees beyond their former points.

Because an avoidance response to "T+" could result from the action of factors other than temperature, those most probable (such as oxygen and pH) were monitored at the input and outflow of each sub-trough throughout a test to determine its validity.

Oxygen was monitored in per cent saturation (since the ppm. value is temperature dependent) using temperature compensated YSI oxygen analyzer probes. pH was monitored using an Orion multi-chemical pH meter. The thermal conditions were monitored by a Leeds and Northrup 24 channel temperature recorder (connected to thermocouples at 6-inch intervals along each sub-trough). Because the trough was enclosed (for light level regulation as well as to permit movement around the trough area), observation was made via closed-circuit television. Each test was recorded on video-tape and re-analyzed using the temperature recorder output.

Results and Discussion

Temperature Preference

All tests (both preference and avoidance) were run in settled Delaware River water with a pH between 7.5 and 7.8 and at near saturated oxygen levels (6.0-12.0 ppm.). Temperature preference results of the

white perch are presented in Table 1. All studies were conducted with juvenile fish between 38 and 144 mm total length.

No definitive effects of levels of salinity have yet been found on the thermal preferences of this species. The preferred temperatures usually were equal to or higher than the ambient, acclimation temperatures. Maximum preferred temperatures recorded were 90°F for perch acclimated to 75°F in mid-July and 88°F for perch acclimated to 86°F in mid-August. Minimum preferred temperatures found to date were 45°F for perch acclimated to 46°F in November and 45°F for fish acclimated to 43°F in March.

A phenomenon designated as low thermal responsiveness was observed during periods with low ambient temperatures (less than 60°F) as well as in September with ambient temperature of 77°F. Juvenile white perch in these studies would rapidly move into the warmest areas of the thermal gradient and show acute stress. Some individuals died in the warmer areas, others recovered if they were able to swim back into cooler sections of the tank. Other studies at this laboratory indicate that low thermal responsiveness is a size dependent phenomenon. Larger individuals of a species will actively avoid lethal water temperatures in selecting a preferred temperature in a steep thermal gradient. However, small individuals do not show as great a degree of thermal responsiveness. Consequently juveniles may move into waters with temperatures capable of producing stress. Juvenile perch which successfully avoided lethal conditions ultimately selected a preferred temperature. A preferred temperature was selected after one or two hours in the majority of these studies.

Table 1. -- Summary of test data of temperature preference of the white perch.

Date	No. of Fish Per Test	Size Range TL. in mm.	Light Level (ft.-candles)	Salinity (ppt.)	Acclimation Temperature (°F)	Preferred Temperature (°F)	Low Thermal Responsiveness shown*
24 November 1969	7	62-105	40	6	46	45	yes
24 February 1970	5	72-97	40	4	43	46	yes
19 March 1970	5	87-144	40	4	43	45	yes
10 April 1970	5	71-90	40	9	48	54	yes
28 April 1970	6	50-100**	40	4	59	68	yes
30 April 1970	5	50-100**	40	6	59	68	no
6 May 1970	4	50-100**	40	6	59	68	no
7 May 1970	6	50-100**	4	6	59	69	yes
21 May 1970	4	50-100**	40	4	60	70	no
5 June 1970	4	50-100**	40	4	68	82	no
25 June 1970	3	49-110	40	4	68	71	no
9 July 1970	2	38-40	40	1	75	82	no
16 July 1970	5	65-74	40	1	75	90	no
7 August 1970	3	74-81	40	4	64-82 (variable)	75	no
14 August 1970	3	75-83	40	4	86	88	no
10 September 1970	5	68-77	40	4	77	77	yes

* Thermal stress shown when fish moved into temperatures (usually) 15 C degrees above acclimation temperature. This sometimes resulted in mortality.

** Size ranged between 50 and 100 mm., exact measurements unknown.

Temperature Avoidance

The results of temperature avoidance studies on juvenile white perch are presented in Table 2. These studies, conducted throughout the spring and summer under different levels of salinity and at two light levels, demonstrated no consistent relationship between light level or salinity and upper ultimate avoidance temperature.

There is a direct relationship between ambient acclimation temperature and the upper ultimate avoidance temperature. As ambient temperatures increased from low levels in late winter to maximum temperatures during the summer, upper avoidance temperatures increased. Maximum upper ultimate avoidance temperatures determined were 94°F for perch acclimated to 75°F in mid-July and 95°F for perch acclimated to 77°F in early August.

In a study conducted in late August, young perch acclimated to 79°F avoided 92°F water. It might be expected that perch acclimated to 79°F would have a higher upper avoidance temperature than fish acclimated to 75 or 77°F. However, the upper ultimate avoidance temperature of a fish appears to be regulated by two factors. Perhaps the most obvious is the fish's past thermal history, recorded as the ambient acclimation temperature in the present study. A second factor is undoubtedly genetic. Evidence in this study as well as that of Sullivan and Fisher (1953) suggests the presence of an innate rhythm which acts independently of acclimation temperature. This rhythm appears to operate with respect to the time of year a species will be exposed to maximum and minimum water temperatures. For white perch it appears that late July and early August represent the maximum

Table 2. -- Summary of temperature avoidance studies with white perch.

Date	Trial No.	No. of Specimens	Size Range (TL. in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
25 February 1970	1	4	72-97	4.0	20	43	39	43	no
	2	4	72-97	4.0	20		41	49	no
	3	4	72-97	4.0	20		47	54	yes - P.01
26 February 1970	1	4	72-97	4.0	2		39	42	no
	2	4	72-97	4.0	2		41	49	no
	3	4	72-97	4.0	2		46	52	yes - P.05
18 March 1970	1	4	87-144	4.0	20	43	47	52	no
	1R	4	87-144	4.0	20		47	52	no
	2	4	87-144	4.0	20		49	54	yes - P.05
	2R	4	87-144	4.0	20		49	54	yes - P.05
	3	4	87-144	4.0	2		51	56	yes - P.10
	3R	4	87-144	4.0	2		51	56	no
19 March 1970	1	4	87-144	4.0	20	43	45	50	yes - P.10
	2	4	87-144	4.0	20		44	48	yes - P.05
	3	4	87-144	4.0	2		45	49	no
	4	4	87-144	4.0	2		47	49	yes - P.01
15 May 1970	1	4	82-102	4.0	20	64	60	68	yes - P.05
	2	4	82-102	4.0	20		62	68	no
	3	4	82-102	4.0	20		68	73	yes - P.20
	4	4	82-102	4.0	20		72	78	yes - P.01

Table 2. -- (continued).

Date	Trial No.	No. of Specimens	Size Range (TL. in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
26 May 1970	1	4	87-125	4.0	2	64	60	66	no
	2	4	87-125	4.0	2		66	72	yes - P.01
	3	4	87-125	4.0	2		71	78	yes - P.01
	4	4	87-125	4.0	2		70	76	yes - P.05
3 June 1970	1	4	95-103	6.0	20	68	68	75	no
	2	4	95-103	6.0	20		72	78	no - T+ preferred
	3	4	95-103	6.0	20		76	82	no - T+ preferred
	4	4	95-103	6.0	20		80	85	yes - P.05
4 June 1970	1	4	95-103	4.0	20	68	68	65	yes - P.001
26 June 1970	1	4	44-49	4	20	72	72	76	n.s.
	2	4	44-49	4	20		76	81	T+ - preferred
	3	4	44-49	4	20		79	84	T+ - preferred
	4	4	44-49	4	20		82	86.5	n.s.
	5	4	44-49	4	20		83	89	yes - P.001
13 July 1970	1	4	42-60	1	20	77	77	71	yes - P.001
	1R	4	42-60	1	20	77	77	71	yes - P.05
	2	4	42-60	1	20		74	69	yes - P.05
	2R	4	42-60	1	20		74	69	yes - P.01

Table 2. -- (continued).

Date	Trial No.	No. of Specimens	Size Range (TL. in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
14 July 1970	1	4	62-70	1	20	75	75	80	T+ - preferred
	1R	2	70-70	1	20		75	80	n.s.
	2	4	62-70	1	20		77	83	T+ - preferred
	2R	2	70-70	1	20		77	83	n.s.
	3	4	62-70	1	20		81	87	T+ - preferred
	3R	2	70-70	1	20		81	87	n.s.
	4	4	62-70	1	20		86	91	T+ - preferred
	4R	2	70-70	1	20		86	91	n.s.
	5	4	62-70	1	20		89	94	yes - P.001
	5R	2	70-70	1	20		89	94	yes - but could not be analyzed.
31 July 1970	1	4	55-67	1	2	77	76	82	n.s.
	2	4	55-67	1	2		77	85	T+ - preferred
	3	4	55-67	1	2		80	87	T+ - preferred
	4	4	55-67	1	2		83	90	n.s.
	5	4	55-67	1	2		86	91	yes P.05
5 August 1970	1	4	67-78	4	20	77	77	83	T+ - preferred
	2	4	67-78	4	20		79	85	T+ - preferred
	3	4	67-78	4	20		83	88	n.s.
	4	4	67-78	4	20		85	91	n.s.
	5	4	67-78	4	20		86	92	T+ - preferred
	6	4	67-78	4	20		86	93	T+ - preferred
	7	4	67-78	4	20		90	95	yes P.001

Table 2. -- (continued).

Date	Trial No.	No. of Specimens	Size Range (TL. in mm.)	Salinity (ppt.)	Light (ft.-candles)	Acclimation Temp. (°F)	T (°F)	T+ (°F)	Avoidance
11 August 1970	1	4	81-85	4	2	77	76	82	T+ - preferred
	2	4	81-85	2	2		80	85	T+ - preferred
	3	4	81-85	4	2		83	87	T+ - preferred
	4	4	81-85	4	2		85	90	T+ - preferred
	5	4	81-85	4	2		86	92	T+ - preferred
	6	4	81-85	4	2		89	94	n.s.
	7	4	81-85	4	2		91	95	yes P.001
27 August 1970	1	4	63-80	4	20	79	79	85	T+ - preferred
	1R	4	63-80	4	20		79	85	n.s.
	2	4	63-80	4	20		83	88	T+ - preferred
	2R	4	63-80	4	20		83	88	T+ - preferred
	3	4	63-80	4	20		86	92	yes P.10
	3R	4	63-80	4	20		86	92	yes P.001

period. Maximum upper avoidance temperatures occur in mid-summer and begin to drop in late August even though ambient temperatures are still high.

Avoidance reactions to lower temperatures were tested on two occasions. On 4 June, white perch acclimated to 68°F avoided 65°F water and on 13 July, perch acclimated to 77°F avoided 71°F water. White perch actively avoided water temperature a few degrees lower than their acclimation temperatures. This would be expected since acclimation to temperatures less than ambient have been shown to require much more time than acclimation to temperature increases (Brett, 1956).

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Life Stage Duration Studies on Hudson River Striped Bass, *Morone saxatilis* (Walbaum)

Final Report

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SUMMARY AND CONCLUSIONS

The effects of rearing temperature on the life stage durations of embryonic and larval striped bass, Morone saxatilis, were determined experimentally. Striped bass eggs, prolarvae, and postlarvae were maintained in the laboratory at five fixed temperatures of 12°, 15°, 18°, 21° and 24°C. The temperatures spanned the range encountered by these stages in their natural environment.

In all the stages studied, stage duration decreased with increasing temperature. The time from fertilization through hatching was related to temperature by:

$$\text{time to hatching (hours)} = 258.5e^{-0.0934\ (\text{Temp. }^\circ\text{C})}$$

The duration of developmental events prior to hatching was related to temperature in much the same way as was the time to hatching. The duration of the prolarval and postlarval stages decreased with increasing temperature. However, differences in the pattern of growth among the progeny of different matings resulted in marked variability in response among the stages examined. Under laboratory conditions, mortality at all stages increased with increasing temperature. There was heavy, largely unexplained mortality among the prolarvae in all lots.

It is concluded that while many factors affect larval survival and stage duration in nature and in the laboratory, the effect of temperature is important and should be taken into account in the preparation of life history models for the striped bass.

INTRODUCTION

This study was undertaken to provide experimental information on the effect of water temperature on the rate of growth and development of the early life stages of the striped bass, Morone saxatilis (Walbaum).

A number of simulation models have been devised for the Hudson River. In recent years these have achieved a high degree of reliability in describing the hydrodynamics of the lower Hudson and its estuary (Lawler et al., 1974). The value of hydrodynamic models in predicting the spatial and temporal distribution of the early life stages of fish can be improved by incorporating relevant specific biological information on the natural history, behavior, and developmental physiology of the species involved (Wallace, 1975).

Although growth is a continuous process from fertilization through adulthood, it is convenient to divide the early life history of fishes into a series of stages. These are based on the degree of structural development and the mode of larval nutrition (Hubbs, 1943).

Eggs, prolarvae or yolk-sac larvae, and the postlarvae can be identified in river ichthyoplankton samples. Because each of these stages defines a sequential part of the developing ability of the young fish to avoid entrainment, modellers have applied different avoidance factors to each stage. Within this context, stage duration defines the rate at which the young fish are growing toward a size at which they will ultimately be able to avoid entrainment. The duration of a life stage determines the length of time that these fish will be vulnerable to entrainment.

Knowledge of water movements, avoidance abilities of each stage, rates of egg production through the spawning season and some measure of the duration of each life stage permits development of life history models. These

may accurately predict the extent of losses attributable to power plant entrainment and to the complex of events that constitutes natural mortality.

To date estimates of life stage duration have been made empirically. That is, the time of appearance of various stages in plankton and beach seine collections following striped bass spawning has been observed. While this approach has provided good estimates of stage duration under natural conditions, experimental studies provide the best means of isolating the effect of a single given environmental factor from the many conditions that affect stage duration in the river. Although the study of larval fish biology is still in its infancy, it is clear that the pattern of growth seen in the increasing modal size of larvae is a result of the interaction of a variety of factors, including some not yet properly identified. Among factors that have been identified as affecting success and rate of embryonic and larval development are: temperature, salinity, dissolved oxygen, water-borne toxicants, food type, food abundance, density of individuals, and disease.

Although it is impossible to take all factors into account, some can be systematically varied and the results observed. This experimental approach permits the identification of particular factors, but introduces a measure of simplicity which does not exist in nature. This simplicity is due to elimination of the influence of other factors and factor interactions. The value of this approach is that it helps to identify which factors are important and which are not. In this study attention is limited to the role of temperature on the rate of development. From studies on other species there is every reason to expect that temperature plays a dominant role in determining the rate of development in striped bass eggs and prolarvae. It is also an important determinant of the rate of growth of feeding larvae and

juveniles. Yolk is the only source of nutrition for the developing egg and prolarva. Temperature affects the maintenance energy requirements of the embryo. Hence the efficiency of conversion of yolk to embryonic tissue is affected. After the change from endogenous to exogenous energy sources, the nature and abundance of food becomes the primary determinant of larval growth. The larva must receive sufficient food to meet its maintenance requirement. This includes the cost of searching and capturing prey as well as the energetic equivalent of whatever growth in biomass it is able to attain. The energetic costs of activity and maintenance are intimately related to temperature. Hence temperature determines the amount of energy available for growth. When the diet is more than adequate to meet the larva's nutritional requirements, maximum growth will occur at a temperature where appetite is high and maintenance requirements are relatively low.

There have been numerous studies of the effect of temperature on the rate of development and growth of larval fish, many of which have been reviewed by Blaxter (1969). The period between fertilization and hatching has received the most attention. This is also the case for striped bass (see Bayless, 1972). The time course of developmental events prior to hatching has been observed at one constant temperature by Bayless (1972) and at a slowly rising temperature by Mansueti (1958). While striped bass have been reared extensively over the past 10 years, there have been few detailed studies of the rate of growth of larvae as a function of temperature. Humphries and Cumming (1973) presented a composite growth curve for wild and hatchery reared striped bass grown under rising, but unspecified, temperature conditions. Rhodes and Merriner (1973) reported the growth of larvae and juveniles under intensive culture conditions and slowly rising temperature.

MATERIALS AND METHODS

Source of Study Material

The eggs and larvae used in these experiments were obtained from striped bass males and females collected on the spawning grounds in the Hudson River between Cornwall and Croton, New York. Samples of fertilized eggs were provided by Texas Instruments, which operates a striped bass hatchery at Verplank, New York. Ripe adults were captured using haul seine or gill nets. They were then taken to the hatchery where they were either allowed to progress toward ovulation naturally, or were induced to ovulate artificially using human chorionic gonadotropin hormone injections according to the methods of Bayless (1972). A total of nine lots of eggs were used, each derived from a separate mating. Vital statistics of the brood female and time and date of stocking of each lot are summarized in Table 1. Lots 1-7 were stocked as eggs. Lots 8-9 were obtained as newly hatched larvae after incubation in 20-21°C hatchery water.

Life Stage Definition

Three major developmental stages have been recognized within the period between fertilization and the attainment of essentially adult form. The egg or incubation stage begins with fertilization and ends at hatching when the embryo loses its protective chorion. The prolarval period or yolk sac stage extends from hatching until the young fish changes from an endogenous to an exogenous food source. The larval period begins when the prolarva has consumed all of its yolk and lasts until metamorphosis. At this time the fish has attained the full fin ray complement and characteristic silhouette of the adult fish.

TABLE 1

Summary of egg and larvae sources for life stage duration studies.

Lot #	Date Fertilized 1975	T.I. Hatchery Roe #	Female Weight (kg)	Female Length (cm)	Time of Fertilization	Time of Stocking	Water Source Water Hardening	Water Source Initial Culture
1	5/20	5	8.4	N.A.*	1115	1130 eggs	Quarry	Quarry
2	5/21	6	10.7	N.A.	0100	0115 eggs	Quarry	Quarry
3	5/21	7	10.4	N.A.	0845	0900 eggs	Quarry	Quarry
4	5/21	N.A.	7.7	N.A.	1345	1415 eggs	Quarry	Quarry
5	5/22	11	9.7	88.7	2015	2030 eggs	Quarry	Quarry, Hudson
6	5/22	12	12.0	93.2	2215	2230 eggs	Quarry	Quarry with antibiotic
7	5/25	14	7.3	54.6	0015	0030 eggs	Hudson	Quarry with antibiotic
8	5/27	15	7.0	54.6	N.A.	1300 larvae	Quarry	Quarry
9	5/31	16	N.A.	N.A.	N.A.	0930 larvae	Quarry	Quarry with antibiotic

*N.A. - data not available.

Life Stage:	Stage Demarcation Point:
	fertilization
egg	
	hatching
prolarva	
	yolk absorption
postlarva	
	metamorphosis

Growth in body weight is continuous throughout all these stages, and growth in body length is continuous from hatching. Concurrent with an increase in size and the passage through these growth phases is an increase in capacity for directed movement. This makes the distribution of the young fish less predictable on the basis of water transport alone.

Of the four major developmental landmarks, fertilization and hatching are fairly discrete. The exact time of yolk sac absorption and metamorphosis are more difficult to measure precisely.

Fertilization is assumed to have occurred at the time milt and eggs were mixed at the hatchery. Of all our developmental landmarks, the timing of fertilization can be determined with greatest precision. In practice, it is impossible to determine whether fertilization has occurred until the eggs are examined for cleavage several hours after spawning. Where large numbers of eggs are involved, the first sign of incomplete fertilization is the appearance of opaque, dead eggs 10 to 24 hours after spawning. The percentage of eggs that are fertilized varies between matings.

In following the time-course of developmental events between fertilization and hatching at different temperatures our observations of the developmental stage of eggs in our bi-hourly samples were compared to the photographs of a developmental series provided by Bayless (1972). Bayless' hour-

by-hour series permitted identification of these data in terms of equivalent hours of development at 19°C. In Figure 1 actual hours of development against equivalent hours of development at 19°C have been plotted at five temperatures. The time in hours after fertilization is accurate to a few minutes and was considered to qualify as an independent variable. Least-squares regression lines fitted to these observations at each temperature fitted the data well. They suggest not more than one 19°C-hour of development error in staging eggs at each temperature. Correlation coefficients on the regression of equivalent 19°C-hours of development on hours after fertilization ranged from $r = 0.987$ to $r = 0.997$. Within ten hours after fertilization equivalent stages were difficult to identify. The failure of regression lines for development at 12° and 15°C to extrapolate to zero hours of equivalent and observed development suggest that this approach is not applicable during the early hours after fertilization.

By connecting points representing the time of attainment of several easily identifiable developmental stages at each temperature (Figure 1), incubation temperature was related to the time since fertilization at which each stage was reached (Figure 4). Figure 4 was drawn by eye using data obtained from Figure 1.

Hatching occurs when the embryo emerges from its chorion. A group of eggs fertilized at the same time does not hatch at the same time. Hatching may last several hours. The estimated time of 50% hatch has been used as a measure of the end of the egg stage, because it was impossible to maintain an accurate cumulative count of emerging larvae within each culture container once hatching had begun.

Hatching is a relatively discrete event, but the assignment of a time of hatching is somewhat arbitrary. The end of the prolarval or yolk sac

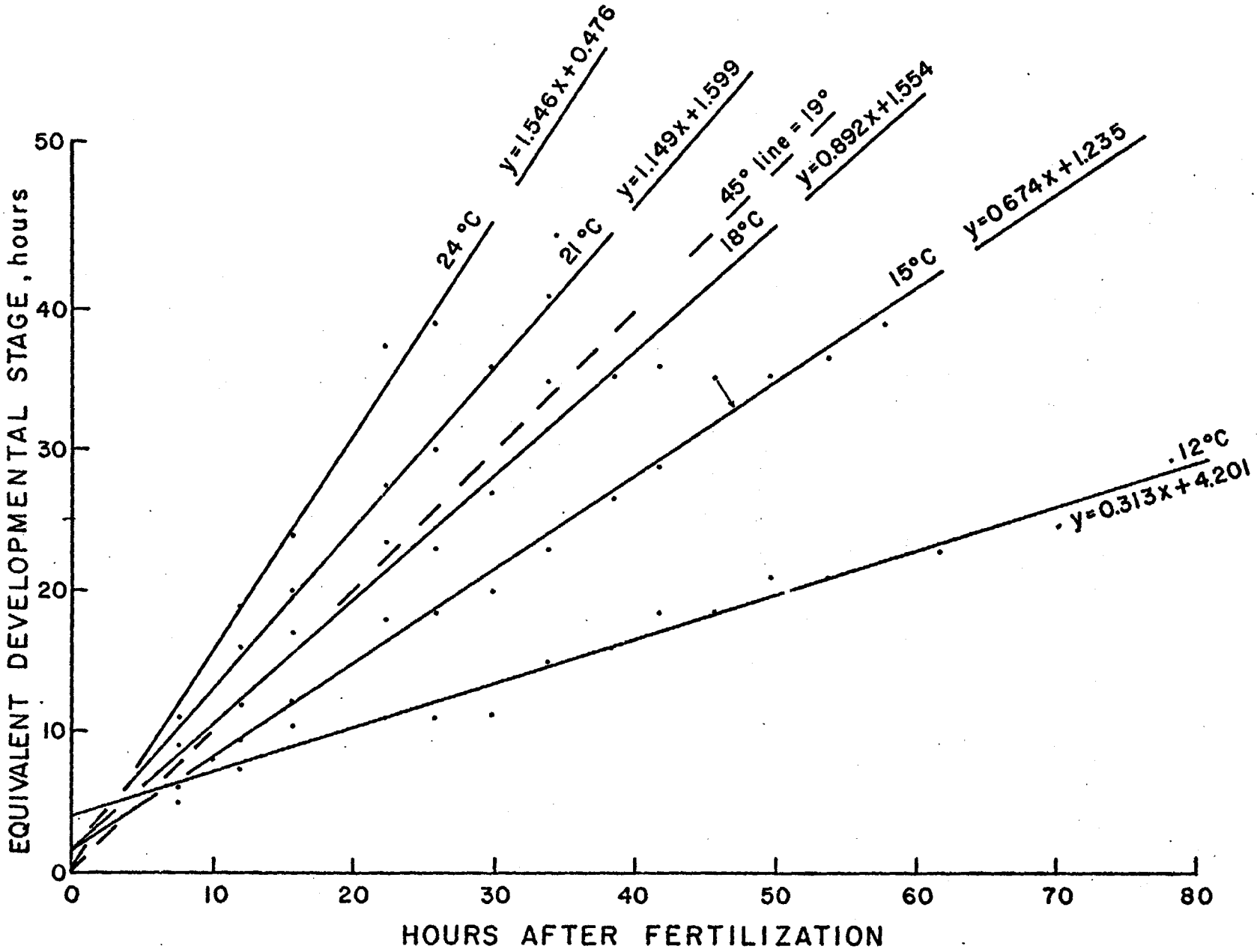


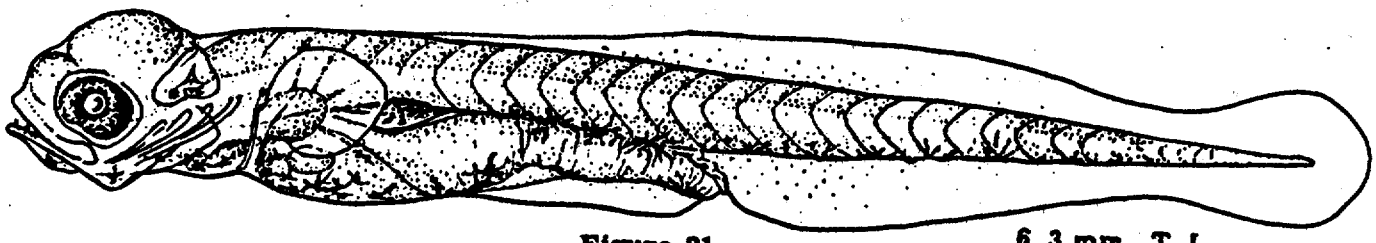
Figure 1

The regression of hours of embryonic development observed in this study at five experimental temperatures against those observed by Bayless (1972) at 19°C for the attainment of equivalent levels of structural development.

stage is less easily determined. The functional definition of the end of the yolk sac stage (i.e., the change to active feeding from passive yolk absorption) is difficult to determine from a specimen in hand. Feeding typically begins before all yolk has been absorbed and well before the oil globule disappears. For those reasons a structural definition of the end of the yolk sac stage was determined. A number of larvae which appeared to have consumed nearly all their yolk using Mansueti's (1958) figure #21 as a model (Figure 2) were examined. The mean total length of a sample of 32 fish judged to have just absorbed all their yolk was 5.84 mm. ± one standard deviation of 0.54 mm.

To help confirm the validity of this approach total lengths and yolk lengths of a series of prolarvae approaching yolk absorption were measured. Figure 3A shows plotted yolk length as percent of total length against total length. As complete absorption was approached the regression line approached 0% at a length of 6.2 mm. This was close to an estimate of 5.8 mm. based on direct examination. Based on these considerations a length range of from 5.30 mm. to 6.39 mm. (5.84 ± one standard deviation) was adopted as being typical of the size at which most of the larvae had absorbed all of their yolks and graduated from prolarval to postlarval status. In Figure 3B are plotted similar measurements from Mansueti (1958) for prolarvae of either Patuxent or Roanoke River stock. These appear to be somewhat larger at yolk absorption than the Hudson River fish used in this study.

Like yolk absorption, the point at which metamorphosis occurs is difficult to define. Fully metamorphosed striped bass resemble Mansueti's (1958) figure #27. The lateral silhouette is essentially that of the adult. The first dorsal is not fully developed and pigmented, but all bony meristic characteristics have attained their adult complement. While the fully



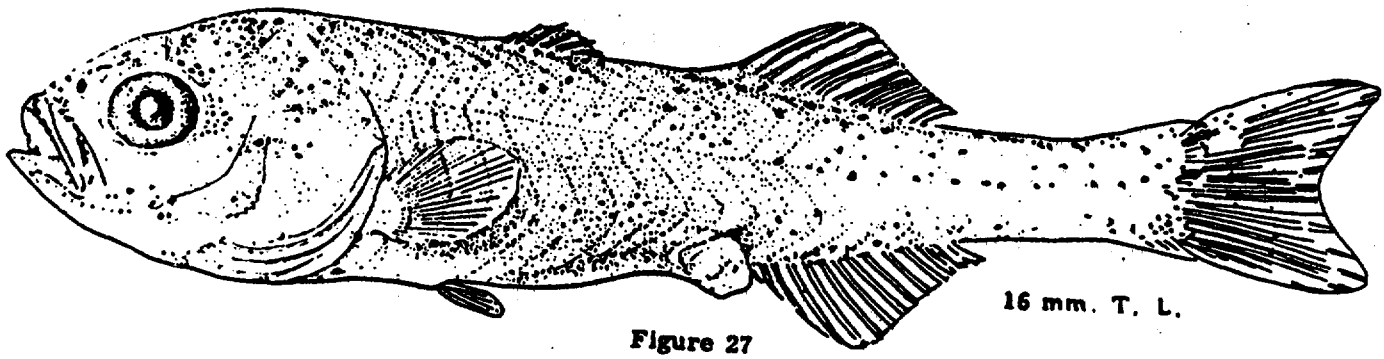


Figure 2. Drawings from Mansueti (1958) illustrating larva at yolk sac absorption (Fig. 21) and larva near metamorphosis (Fig. 27).

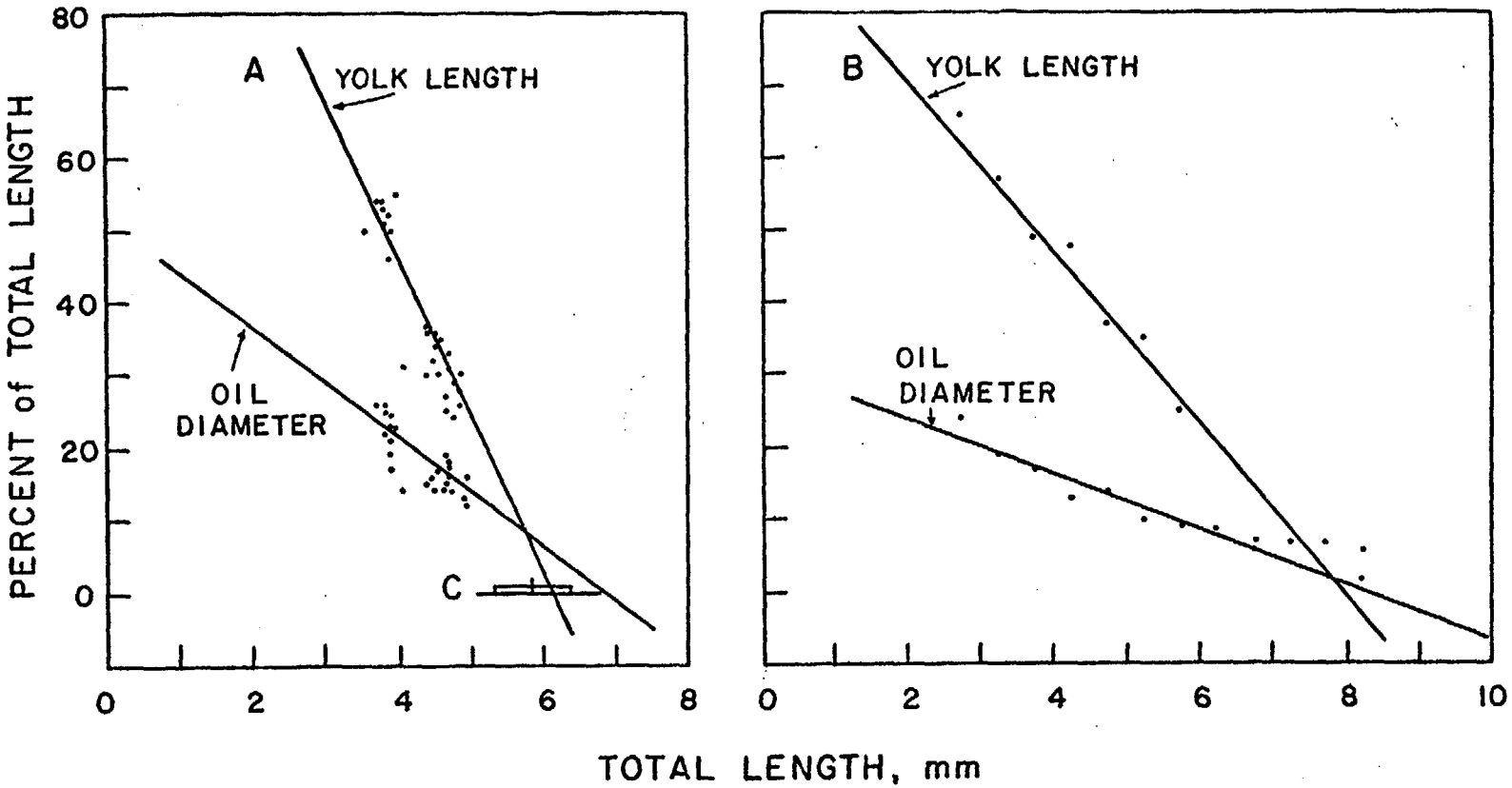


Figure 3. The determination of total length at yolk sac absorption from the regression of yolk length as a percent of total length (y) against total length (x). A. Observations on Hudson River prolarvae for which y = -21.885 x +133.759 (r = -0.900). B. Data from Mansueti (1958) for Chesapeake or Roanoke stocks for which y = -11.909 x +94.916 (r = -0.968). C. Range and mean ± one standard deviation of prolarvae measured at the point of complete yolk absorption.

metamorphosed fish is easy to recognize, the point of transition to this state is less distinct. As a working standard for a striped bass at metamorphosis a fish which resembled Mansueti's figure #27 (Figure 2) was chosen. While the juvenile in this drawing has not quite reached full metamorphosis, it is easy to recognize in the preserved state. In cleared and stained specimens the full adult number of fin rays is evident. The average total length of a sample of 35 figure #27 juveniles was 16.32 mm. ± one standard deviation of 1.33 mm. In this study the time to the attainment of a total length of from 14.90 mm. to 17.60 mm. (16.32 ± one standard deviation) from the time of yolk absorption was used as a measure of the duration of the larval stage.

The prolarval and larval stages were defined in terms of the range in lengths attained by individuals. At the beginning and end of each stage the duration of each stage was determined from empirical growth curves constructed for each treatment population. Because the length at the point of transition between stages was defined by a length interval rather than a fixed length, the duration of each life stage in each treatment population is expressed as a range in time units (Table 4, 7) corresponding to the shortest and longest expected duration for the stage in question.

Water Source, Water Quality, and Temperature Control

Water drawn from a flooded gypsum quarry owned by the Consolidated Edison Company of New York was used to supply the Texas Instruments hatchery. The majority of the eggs used in these investigations were water hardened and incubated in water from this source. Analyses of both quarry water and samples from the Hudson provided by Texas Instruments are presented in Table 2. Newly fertilized striped bass eggs water hardened to a slightly smaller

Table 2

Results of Water-Quality Analysis on Verplanck Quarry and Hudson River Water
(from: Texas Instruments, Inc., 1974. Table C-1, p. C-1.)

Parameter	Quarry	River
Alkalinity		
Methyl Orange (mg/ℓ-$CaCO_3$)	136.60	44.46
Phenophthalein (mg/ℓ-$CaCO_3$)	0.00	0.00
Aluminum (mg/ℓ)	0.081	0.232
Arsenic (mg/ℓ)	<0.001	0.002
Barium (mg/ℓ)	0.004	0.038
Beryllium (mg/ℓ)	<0.001	<0.001
BOD (mg/ℓ)	0.8	1.2
Boron (mg/ℓ)	0.007	0.026
Cadmium (mg/ℓ)	<0.001	0.001
Calcium (mg/ℓ)	76.80	20.65
COD (mg/ℓ)	17.8	14.2
Chlorides (mg/ℓ)	21.25	134.80
Chromium (hexavalent) (mg/ℓ)	<0.001	0.005
Chromium (total) (mg/ℓ)	0.001	0.005
Color (APHA units)	10	11
Conductivity (μmho/cm)	560	320
Copper (mg/ℓ)	0.002	0.006
Cyanides (mg/ℓ)	<0.001	<0.001
Fluorides (mg/ℓ)	0.0	0.2
Free CO_2 (mg/ℓ)	4.0	5.5
Total Hardness (mg/ℓ-$CaCO_3$)	338.40	67.20
Iron (mg/ℓ)	0.136	0.316
Lead (mg/ℓ)	0.001	0.003
Lithium (mg/ℓ)	0.0043	0.0068
Magnesium (mg/ℓ)	34.60	3.22
Manganese (mg/ℓ)	0.066	0.048
Mercury (mg/ℓ)	0.0005	0.0008
Molybdenum (mg/ℓ)	0.030	0.030

Parameter	Quarry	River
Nickel (mg/ℓ)	0.001	0.002
Nitrogen, ammonia (mg/ℓ-N)	0.019	0.094
Nitrogen, nitrate (mg/ℓ-N)	0.07	0.76
Nitrogen, nitrite (mg/ℓ-N)	0.002	0.008
Nitrogen, total Kjeldahl (mg/ℓ-N)	0.12	0.40
Oil and grease (mg/ℓ)	0.1	0.5
pH (units)	8.00	7.42
Phenols (mg/ℓ)	<0.001	0.004
Phosphorus, condensed phosphate (mg/ℓ-P)	0.000	0.002
Phosphorus, organic phosphate (mg/ℓ-P)	0.004	0.016
Phosphorus, osthophosphate (mg/ℓ-P)	0.050	0.031
Phosphorus, total phosphate (mg/ℓ-P)	0.054	0.048
Potassium (mg/ℓ)	5.00	2.256
Selenium (mg/ℓ)	<0.001	<0.001
Silica, suspended (mg/ℓ-SiO_2)	0.32	0.44
Silica, total (mg/ℓ-SiO_2)	2.66	5.88
Silver (mg/ℓ)	<0.001	<0.001
Sodium (mg/ℓ)	13.88	20.72
Solids, total dissolved (mg/ℓ)	332	302
Solids, total suspended (mg/ℓ)	2.4	22.0
Solids, volatile (mg/ℓ)	76.0	56.6
Sulfates (mg/ℓ-SO_4)	282	51
Sulfides (mg/ℓ-$S^=$)	0.01	0.04
Titanium (mg/ℓ)	<0.001	<0.001
Turbidity (FTU)	3	39
Vanadium (mg/ℓ)	<0.001	<0.001
Zinc (mg/ℓ)	0.010	0.022

chorion diameter in quarry water than in Hudson River water. In other respects this water supply appeared to be an adequate incubation medium.

In one experiment both quarry water and Hudson River water were used. In the same experiment sub-lots of eggs incubated in both Hudson River water and quarry water were treated with an antibiotic to retard bacterial growth. The antibiotic dosage used was 50,000 I.U./liter Penicillin G plus 50 mg./liter Streptomycin sulfate.

Most prolarval and larval rearing experiments were performed using filtered Narragansett, Rhode Island, tap water. This water was drawn from a well and contained no chlorine. As development progressed the salinity in the rearing containers was increased by the admixture of 10 micron filtered sea water. The salinity was maintained below 8 ‰, which is well within the range encountered by young bass on their estuarine nursery grounds. This salinity prolonged the life of Artemia nauplii between feedings and retarded the formation of filamentous aquatic fungi. These fungi have been observed to ensnarl and kill young larvae. The salinity occasionally exceeded 8 ‰ accidentally when too much brine was added while Artemia nauplii were being fed. There was no evidence that higher salinities adversely affected larval growth or survival.

Constant temperature treatments of 12°, 15°, 18°, 21°, and 24°C were maintained throughout all experiments. Temperatures were maintained by keeping all rearing containers immersed in a temperature controlled water bath. Haake (E-50) heater-thermoregulators operating against cooling coils were used to maintain the bath temperatures.

During egg incubation experiments temperatures were monitored every two hours. During larval rearing experiments rearing container temperatures were monitored at least three times daily. After June 6 a continuous record

of each bath temperature was maintained using a Y.S.I. recording thermometer. Although the mean daily temperature closely approximated the design temperature, short-term temperature excursions of up to several degrees occurred during the time rearing containers were being inspected or cleaned.

A record of water bath temperatures monitored for each design temperature throughout the study period is provided in Appendix A.

Dissolved oxygen, pH, ammonia, and salinity measurements were made regularly throughout these experiments. Dissolved oxygen was determined using a Y.S.I. D.O. probe, supplemented periodically with determinations using the azide-modification of the Winkler titration. The pH was measured using an Orion pH electrode. Ammonia was determined using a micro-modification of the indophenol technique of Solórzano (1969). Salinity measurements were made using an American Optical salinity refractometer. A record of water quality measurements is presented in Appendix A. With frequent water changes most of the water quality parameters changed insignificantly during the course of each experiment.

Experimental Procedures Using Eggs

Fertilized eggs were rinsed and stocked volumetrically into 4-liter glass beakers at a rate of 100 to 250 per liter. The beakers, which contained fresh quarry water, were stocked and placed in constant temperature water baths within 15 minutes after fertilization. Each beaker was agitated with a stream of compressed air. This was sufficient to maintain the eggs in suspension and to maintain a dissolved oxygen level near the air saturation level. The water in each beaker was changed at least once a day with fresh hatchery water of the same temperature. Dead eggs were removed and counted. A sample of 5 to 10 live eggs was taken every two hours during the incubation period from each temperature treatment. Sampled live eggs were

examined under the microscope and staged by visually comparing each with the photographs of a striped bass developmental series (Bayless, 1972) and with the staged drawings of Mansueti (1958). After examination live samples were preserved in Stockard's solution for subsequent examination. The cumulative time since fertilization was recorded for each lot at each sampling.

Experimental Procedures Using Larvae

Lots 6 and 7 were the only groups of eggs which yielded a sufficient number of larvae to merit continued rearing through the prolarval and larval stages. Lots 8 and 9 were not incubated under controlled temperature conditions, but were hatched in 20-21°C quarry water in the Texas Instruments hatchery. They were obtained 2-3 hours after hatching had begun. Larvae in these lots were gradually transferred to the test temperatures where they remained through the remainder of the experiments.

Larvae were stocked into 18 liter glass aquaria immersed in a temperature controlled water bath. A semi-static larval rearing system similar to that outlined by Houde (1973) was used in the experiments. Three-quarters of the volume of each rearing aquarium was exchanged each day. When the population in each container was reduced, water changes were made three times per week. Initial stocking densities ranged from 30 to 150 newly hatched larvae per liter. Dead larvae were removed and preserved as soon as they were observed. Uneaten food was removed daily with a pipette. Samples of live larvae were removed at regular intervals throughout the experiments. Both the frequency of sampling and the number of individuals in each sample were determined to a large extent by the number of larvae remaining in each temperature treatment population. In sampling each treatment an effort was made to bracket the size range present in each tank. Where the sample size was necessarily limited, attempts were made to sample the largest and

smallest fish in each treatment as well as several "average sized" individuals. In addition to providing a better representation of the size of individuals in each treatment population this procedure prevented extreme size disparities which, in our experience, generally resulted in a heavy incidence of cannibalism. If left unchecked, cannibalism can decimate a treatment population and shorten the observation period.

Our sampling strategy reflected a desire to provide an accurate indication of the size range of the animals in each treatment at a given time within practical limits described above. Samples were preserved in 10% buffered formalin and measured to the nearest 0.1 millimeter using either an ocular micrometer or dial indicating caliper.

Feeding was initiated in each population when an examination of the samples of larvae revealed peristalsis and the presence of functional mouth parts. Newly hatched Artemia nauplii were provided as the only food source in all treatments until near the termination of observations. In certain later treatments frozen adult Artemia were fed to the remaining post-metamorphosis juveniles. Artemia nauplii were fed twice daily. In most cases nauplii remained from the previous feeding. Food was available at all times, although the food density varied between feedings.

Larval size at hatching was determined by either measuring larvae as close to hatching as possible, or by back-calculating to the time of hatching from a series of measurements made every few hours up to forty hours after the time of 50% hatching. Growth in length during this period was essentially linear.

Larval dry weights were determined by drying to a constant weight in a vacuum desiccator at 80°C and weighing on a Cahn Gram electrobalance.

The efficiency of yolk utilization was estimated from the formula

$$\text{percent efficiency} = \frac{\text{Dry weight of larva at yolk absorption}}{\text{Average dry weight of unfertilized egg}} \times 100.$$

This ratio suggested by Blaxter and Hempel (1966) does not take into account chorion weight or the contribution of the oil remaining at the time all yolk is absorbed. This technique, while not a rigorous measure of the efficiency with which the embryo uses its stored nutrient reserves, is useful for between-treatment comparisons.

Statistical Procedures

All statistical analyses were performed according to procedures prescribed by Snedecor and Cochrane (1967). Linear regression analysis was performed on untransformed data using the method of least squares. Calculations were performed using a programmable Monroe 1860 statistical calculator. As part of the linear regression package, a correlation coefficient (r) was provided as a measure of the degree to which the data in question could be approximated by a straight line. An (r) value of 1.0 denotes perfect fit. Linear regression equations are presented in the form:

$$y = bx + a$$

where: y = dependent variable; most often stage duration, mortality or length in this study,

a = y intercept,

b = slope of regression line,

x = independent variable; most often time or temperature in this study.

Where growth is approximated using an exponential equation, length was first transformed to $\log_{10}$. The transformed variable was regressed against time using linear regression techniques yielding a regression equation of the form:

$$\text{Log}_{10} \text{ length} = bx + a.$$

Time to hatching as a function of temperature is expressed in the form:

$$T_h = ae^b,$$

where T_h = time to hatching in hours,
a = y-intercept of regression equation,
b = slope of regression equation,
e = base of natural logarithms.

In comparisons between means a Students-'t' statistic was calculated.

RESULTS

Developmental Events Prior to Hatching

Increased incubation temperature decreased the time between fertilization and the achievement of four developmental stages prior to hatching (Figure 4). From 15° through 24°C the decrease in development time to each stage was approximately linear with temperature. The attainment of stages early in development was accelerated by higher incubation temperatures to a greater degree than events closer to hatching. This is evident from the clearly steeper slope for the attainment of one-half yolk envelopment by blastoderm (Figure 4a) than for free tail bud stage (Figure 4d). The overall development time-temperature relationship for each stage was curvilinear with the greatest inflection between 12° and 15°C. Twelve degrees C. is a marginal temperature for incubation. Below 12°C incubation time appears to become infinite.

The Incubation Period (Fertilization to Hatching)

Eight observations were made on the effect of temperature on the time from fertilization to hatching. The data have been plotted with that of other workers in Figure 5. This information is presented in tabular form in Table 3. Observations made during the course of this study fit well with earlier published observations. The incubation period vs. temperature relationship is curvilinear and fitted by an exponential curve with the equation

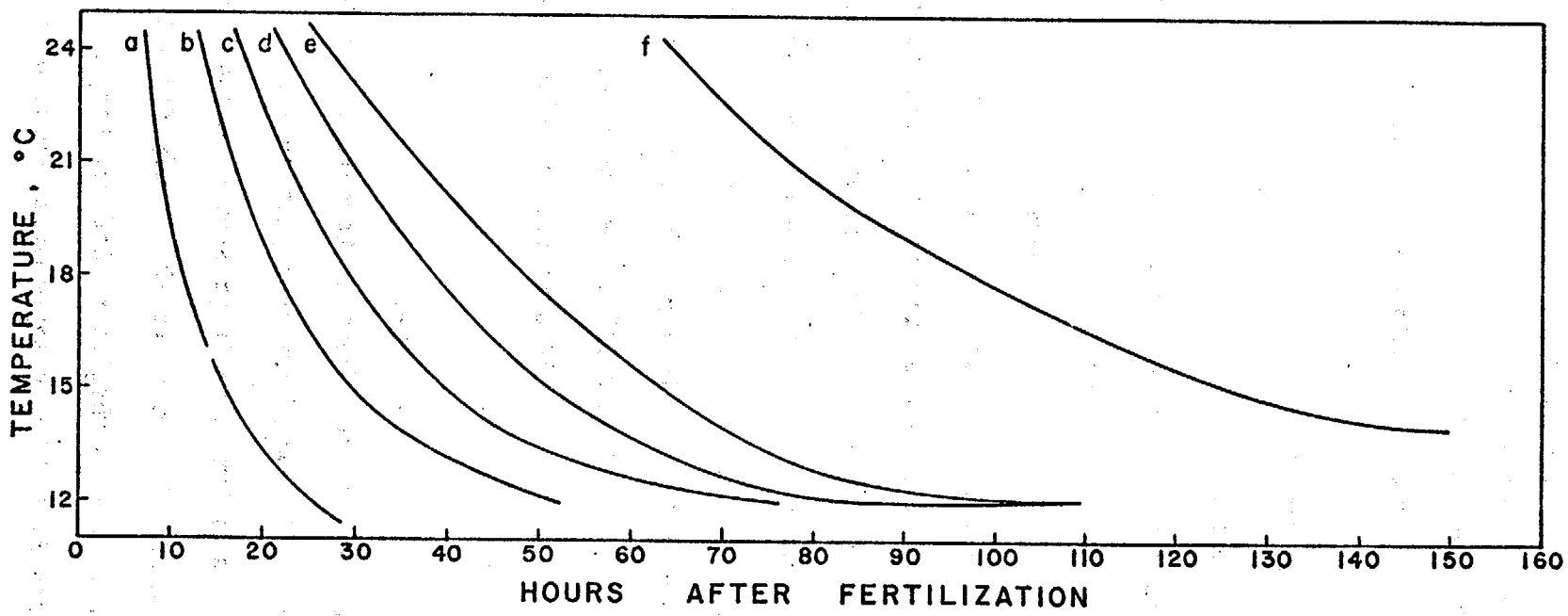
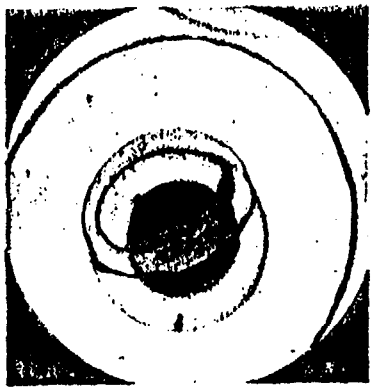


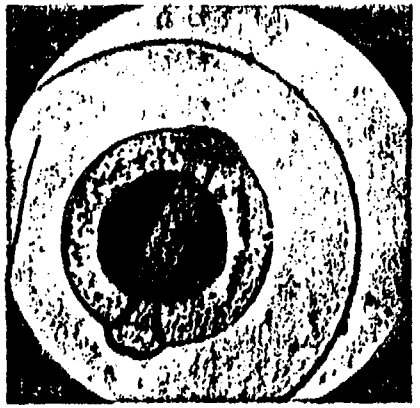
Figure 4A. The effect of incubation temperature on the time from fertilization to selected developmental stages before and after hatching.

a - half of yolk enveloped by blastoderm
b - embryo extending over half of yolk curvature
c - early tail development
d - free tail bud
e - hatching
f - development of eye pigmentation in prolarva

See figure 4B.



a



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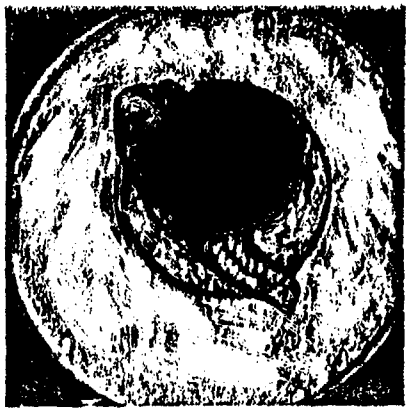

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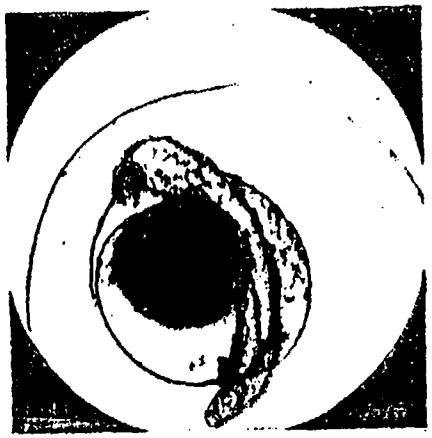

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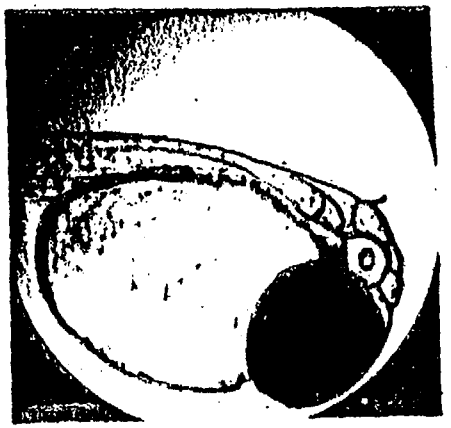

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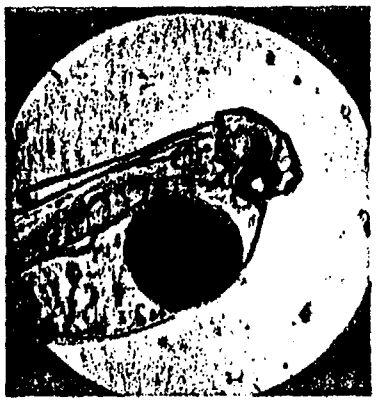

f

Figure 4B. Illustration of developmental stages described in Figure 4A. Original photographs from Bayless (1972).

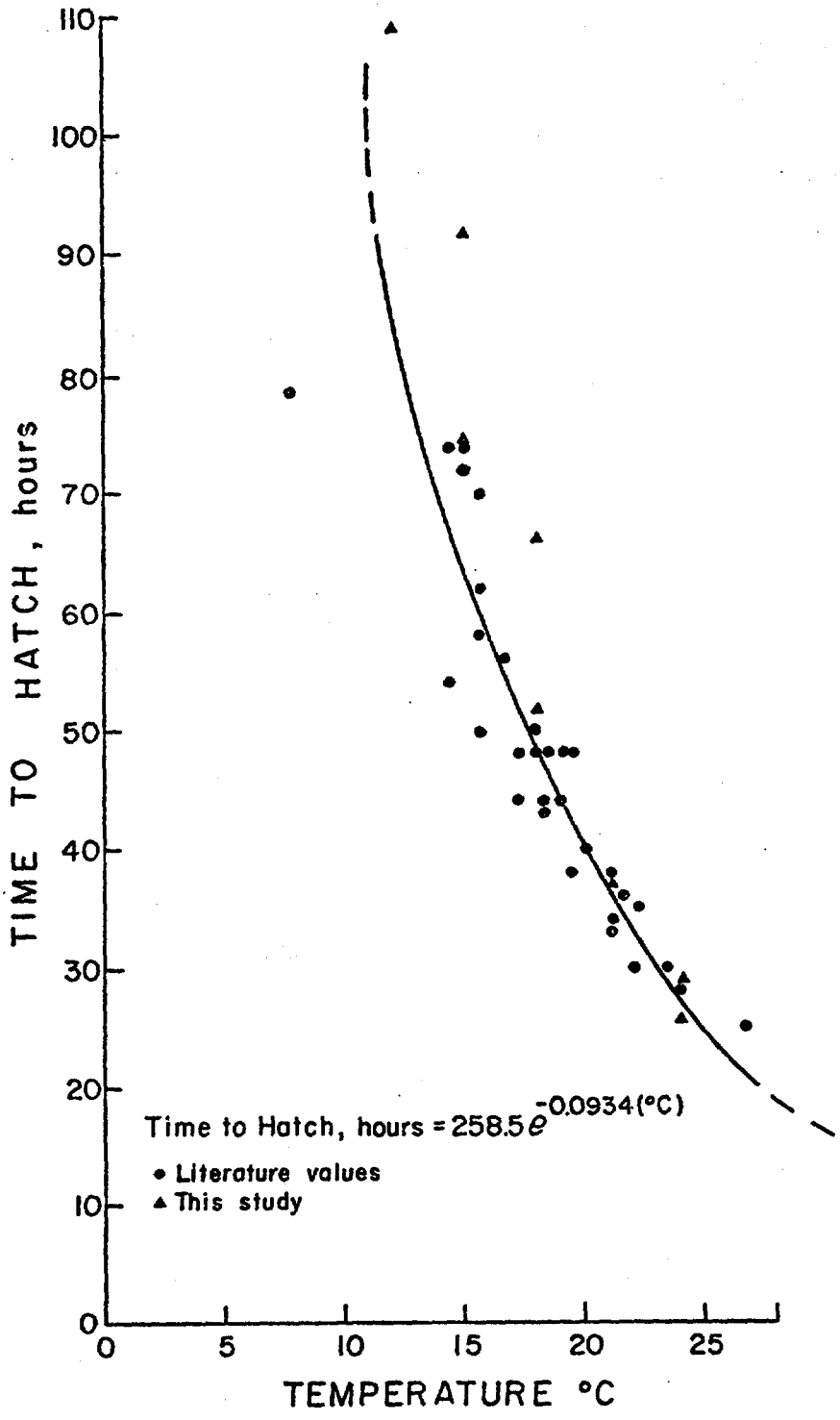

Figure 5. The effect of temperature on the incubation period of striped bass eggs based on observations listed in Table 3.

TABLE 3

Hatching time of striped bass eggs in relation to water temperatures.

Incubation Time (hours)	Water Temperature (°C)	Location	Author
25	26.67	N.C.	Shannon and Smith (1967)
25.8	24.00	N.Y.	Present study
28	23.89	N.C.	Shannon and Smith (1967)
28.5	24.00	N.Y.	Present study
30	23.33	N.C.	Shannon and Smith (1967)
30	23.33	S.C.	Bayless (1972)
30	21.7-22.2	N.C.	Bigelow and Schroeder (1953)
30	21.7-22.2	-	Merriman (1941)
33	21.11	S.C.	Stevens (1965)
33	21.1	N.C.	Regan et al. (1968)
34	21.11	N.C.	Shannon and Smith (1967)
35	22.22	S.C.	Bayless (1972)
36	21.67	N.C.	Worth (1884)
37	21.00	N.Y.	Present study
36-48	17.22	N.C.	Mansueti (1958)
38	19.4	N.C.	Regan et al. (1968)
38	21.11	S.C.	Bayless (1972)
40	20.00	S.C.	Bayless (1972)
43	18.3	N.C.	Regan et al. (1968)
44	18.33	S.C.	Stevens (1965)
44	18.89	S.C.	Bayless (1972)
48	19.4	N.C.	Bigelow and Schroeder (1953)
48	18.33	S.C.	Bayless (1972)
48	17.2	N.C.	Regan et al. (1968)
48	17.89	-	Pearson (1938)
48	18.89-19.44	N.C.	Worth (1882)
50	15.6	N.C.	Regan et al. (1968)
50	17.78	S.C.	Bayless (1972)
51.8	18.00	N.Y.	Present study
54	14.4	N.C.	Regan et al. (1968)

Table 3 (cont'd.)

Incubation Time (hours)	Water Temperature (°C)	Location	Author
56	16.67	S.C.	Bayless (1972)
58	15.56	N.C.	Shannon and Smith (1967)
62	15.00	N.Y.	Present study
62	15.56	S.C.	Bayless (1972)
66.3	18.00	N.Y.	Present study
70	15.56	S.C.	Stevens (1965)
70-74	14.4-15.6	N.C.	Bigelow and Schroeder (1953)
74.3	15.00	N.Y.	Present study
74	14.4-15.6	-	Merriman (1941)
74	14.44	Md.,Va.	Brice (1898)
91.8	15.00	N.Y.	Present study
109	12.00	N.Y.	Present study

$$\text{Time to hatching (hrs.)} = 258.5e^{-0.0934\ \text{temp.}(^\circ C)}$$

with correlation coefficient (r) = 0.93.

The degree of curvilinearity is determined predominantly by terminal observations. Between 15° and 24°C, the range over which incubation most often occurs, incubation time can be predicted as a linear function of temperature by the regression equation:

$$\text{Time to hatching (hrs.)} = -4.616\ \text{temp.}(^\circ C) + 134.310,$$

with correlation coefficient (r) = 0.878.

Incubation time is reduced approximately 4.62 hours for each increase of 1°C in incubation temperature between 15° and 24°C. The dotted portions of Figure 5 mark incipiently lethal temperatures and define the limits of utility of this relationship.

Mortality during the incubation period ranged from 30 to 100 percent in our experiments. Egg mortalities were high and appeared to vary in extent between lots. Highest survival occurred in 15°-18°C temperature treatments. Extremely low survival among lots 1-3 at all temperatures led to varying the water source and to antibiotic treatments in lot 5. The results of this experiment are presented below.

Percent Survival

	Hudson River Water		Quarry Water	
	with antibiotic	no antibiotic	with antibiotic	no antibiotic
15°C	70.6 n=930	2.1 n=529	0 n=563	0.6 n=508
18°C	62.5 n=1041	7.3 n=975	3.2 n=836	3.3 n=839

The use of Hudson River water in combination with antibiotic treatments clearly improved egg survival to hatching in this lot. The use of quarry water was continued in lots 6 and 7 but all experimental containers were

treated with antibiotics. Survival in these lots was improved, with 50% or higher survival at 15° and 18°C in both lots and 76% survival in lot 7 and 21°C. Eggs incubated at 12°C seldom survived to hatching. In all the lots used only four live larvae hatched at 12°C. Survival at 21°C and 24°C varied from lot to lot but was lower than at 15° and 18°C.

The Yolk Sac Stage

Growth during the yolk sac stage was divided into two phases. The first was characterized by a period of rapid essentially linear growth during the first two to three days after hatching. This period of rapid increase in length occurred among larvae reared at all temperatures.

The second growth phase was marked by a drastic decrease in growth rate. This growth plateau began three to four days after hatching at all temperatures and lasted from five days at 24°C to approximately fifteen days at 15°C. At 12°C total mortality occurred before the end of the growth plateau. In some lots growth in length stopped for a period of several days, while in others there was a scarcely discernable increase in length during the entire plateau period. In some lots there was a two to four day period of negative growth. This appeared progressively earlier at higher temperatures. At 24°C the negative growth period occurred five days after hatching. At 12°C negative growth began approximately twelve days after hatching and continued until all larvae had died. During the growth plateau the average larval length stayed below 6 mm. The occurrence of reduced growth during this period was clearly concurrent with the use of the last of larval yolk reserves. The end of the prolarval stage and the attainment of 5.84 mm. total length marked the end of the growth plateau. The length of the yolk sac period as a function of rearing temperature is presented in Table 4. The duration of the yolk sac stage as a whole was directly related

TABLE 4

The range in time (days) between hatching and yolk sac absorption based on mean total length at yolk sac absorption of 5.84 mm ± one standard deviation (SD) of 0.54 mm at four rearing temperatures.

Temperature	Lot	-1 SD (5.84-.54) 5.30 mm	Days to Mean Total Length at Yolk Sac Absorption 5.84 mm	+1 SD (5.84+.54) 6.39 mm
24°C	6	2.0	4.75	12.0
	8	4.0	7.25	11.0
	9	4.0	13.5	23.0
	Mean	3.3	8.5	15.3
21°C	7	3.0	9.75	19.0
	8	4.0	7.0	16.0
	9	5.0	12.5	18.0
	Mean	4.0	9.75	17.7
18°C	6	2.0	10.0	16.0
	7	4.0	13.5	27.0
	8	4.0	6.0	18.0
	9	4.0	17.5	23.0
	Mean	3.5	11.75	21.0
15°C	7	5.0	16.5	27.0
	8	5.0	24.0	34.0
	9	5.0	24.0	30.0
	Mean	5.0	21.5	30.3

to the duration of the period of reduced or suspended growth on the growth plateau.

Mortality During the Yolk Sac Stage

Mortality was higher in all lots during the yolk sac stage than at any other time after hatching. Mortality figures for each lot and temperature treatment are presented in Appendix B. The time-cumulative mortality relationship typically had the sigmoid shape characteristic of a dose-response curve. The maximum daily mortality occurred three to six days after hatching at 24° and 21°C, and eight to twenty days after hatching at 18°, 15°, and 12°C. The sigmoid portion of the time-mortality relationship typically lasted four to twelve days at 24°C, five to sixteen days at 12°C, sixteen to twenty-one days at 18°C, and twenty to forty days after hatching at 15°C. From 60 to 90% of each larval population died during this period. No clear relation between rearing temperature and the overall extent of losses was determined.

The sigmoid portion of the time-mortality curve coincided with the length of the yolk sac period as defined. The attainment of an average total length of 5.84 mm. was achieved slightly after half of the total cumulative losses during the period of sigmoid mortality had occurred. The period in days after hatching between the beginning of yolk sac absorption as defined by 5.84 mm. total length less one standard deviation (5.30 mm.) and the end of yolk sac absorption defined by a length of 5.84 mm. plus one standard deviation (6.39 mm.) encompassed slightly more than 100% of the period of sigmoid mortality at all temperatures. The percent of the original population at hatching which died each day during this stage appeared to be temperature related (Table 5). Daily percentage losses ranged from 4.0 to 20%, with the highest mean daily percentage mortality at the highest temperature.

TABLE 5

Larval mortality by developmental stage, expressed as the percentage of the number of larvae at the beginning of each stage which died each day during the course of that stage.

Temperature (°C)	Lot	Yolk Sac Stage (%)	Yolk Absorption to Metamorphosis (%)
24	6	20	4.3
	8	14	4.8
	9	8	10.0
	mean	14.0	6.37
21	7	10	4.5
	8	14	4.2
	9	8	5.6
	mean	10.67	4.7
18	7	7	3.8
	8	17	2.9
	9	6	4.3
	mean	10.0	3.7
15	7	6	1.8
	8	4	2.2
	9	4	1.6
	mean	4.67	1.7
12	8	6*	*reflects losses up to point of complete mortality
	9	4*	yolk sac stage not completed
	mean	5*	

For prolarvae at all temperatures for all lots:

$$\text{daily \% mortality} = 0.955\ (\text{temp.}^{\circ}\text{C}) - 8.800$$
$$r = 0.639$$

The Larval Stage (Yolk Sac Absorption Through Metamorphosis)

Growth rate increased during the larval stage from a low level at the end of the yolk sac stage growth plateau to a rate of increase in size which was strongly related to rearing temperatures. Growth during this stage can be approximated by an exponential model (Table 6). Although at 24°C there is considerable between-lot variability (see Table 6), the mean (between-lot) exponential growth equation slope at each temperature appears to increase at higher rearing temperatures (Figure 6B):

$$\text{slope } (\times 10^{3}) = 2.4\ (\text{temp.}^{\circ}\text{C}) - 27.966$$
$$r = 0.728$$

As a result, stage duration is a direct function of rearing temperature (Table 7). There were fewer differences between lots in the growth response within given temperature treatments during this stage than were observed during the yolk sac stage.

Mortality Between Yolk Sac Absorption and Metamorphosis

A period of significantly reduced mortality followed the sigmoid portion of the mortality curve which characterized the yolk sac stage. In treatment populations periodic sampling for growth measurements was the major source of mortality during the larval period. Each population had been reduced to 10 to 40% of the population originally present at hatching by the time this growth stage had begun. Mortality during the larval stage attributable to causes other than sampling ranged from 1.6 to 10% of the number alive at the beginning of the stage per day. The mortality rate again increased with increasing temperature. For postlarvae at all

TABLE 6

Total length versus days after hatching. Regression equations by life stage where:
y = total length (mm)
x = days after hatching
r = correlation coefficient.

Temperature and Lot	Hatching Through Yolk Sac Absorption	r=	Yolk Sac Absorption Through Metamorphosis	r=	Early Post-Metamorphosis	r=
24°C Lot 6	$\log_{10}y = 0.007x + 0.714$	0.581	$\log_{10}y = 0.017x + 0.662$	0.938	$\log_{10}y = 0.009x + 0.838$	0.985
8	$\log_{10}y = 0.008x + 0.682$	0.903	$\log_{10}y = 0.018x + 0.643$	0.971	$\log_{10}y = 0.008x + 0.915$	0.903
9	$\log_{10}y = 0.007x + 0.682$	0.919	$\log_{10}y = 0.048x + 0.089$	0.983	not available	—
21°C Lot 7	$\log_{10}y = 0.016x + 0.638$	0.922	$\log_{10}y = 0.024x + 0.491$	0.928	$\log_{10}y = 0.008x + 0.942$	0.981
8	$\log_{10}y = 0.010x + 0.691$	0.828	$\log_{10}y = 0.024x + 0.496$	0.960	$\log_{10}y = 0.009x + 0.922$	0.868
9	$\log_{10}y = 0.007x + 0.670$	0.898	$\log_{10}y = 0.028x + 0.352$	0.998	not available	—
18°C Lot 7	$\log_{10}y = 0.010x + 0.667$	0.915	$\log_{10}y = 0.017x + 0.504$	0.979	$\log_{10}y = 0.013x + 0.638$	0.942
8	$\log_{10}y = 0.013x + 0.679$	0.912	$\log_{10}y = 0.012x + 0.672$	0.961	$\log_{10}y = 0.005x + 1.002$	0.894
9	$\log_{10}y = 0.005x + 0.681$	0.891	$\log_{10}y = 0.017x + 0.472$	0.984	$\log_{10}y = 0.009x + 0.750$	0.897
15°C Lot 7	$\log_{10}y = 0.009x + 0.629$	0.824	$\log_{10}y = 0.007x + 0.679$	0.977	not available	—
8	$\log_{10}y = 0.005x + 0.684$	0.838	$\log_{10}y = 0.007x + 0.652$	0.989	not available	—
9	$\log_{10}y = 0.003x + 0.674$	0.850	$\log_{10}y = 0.007x + 0.565$	0.994	not available	—

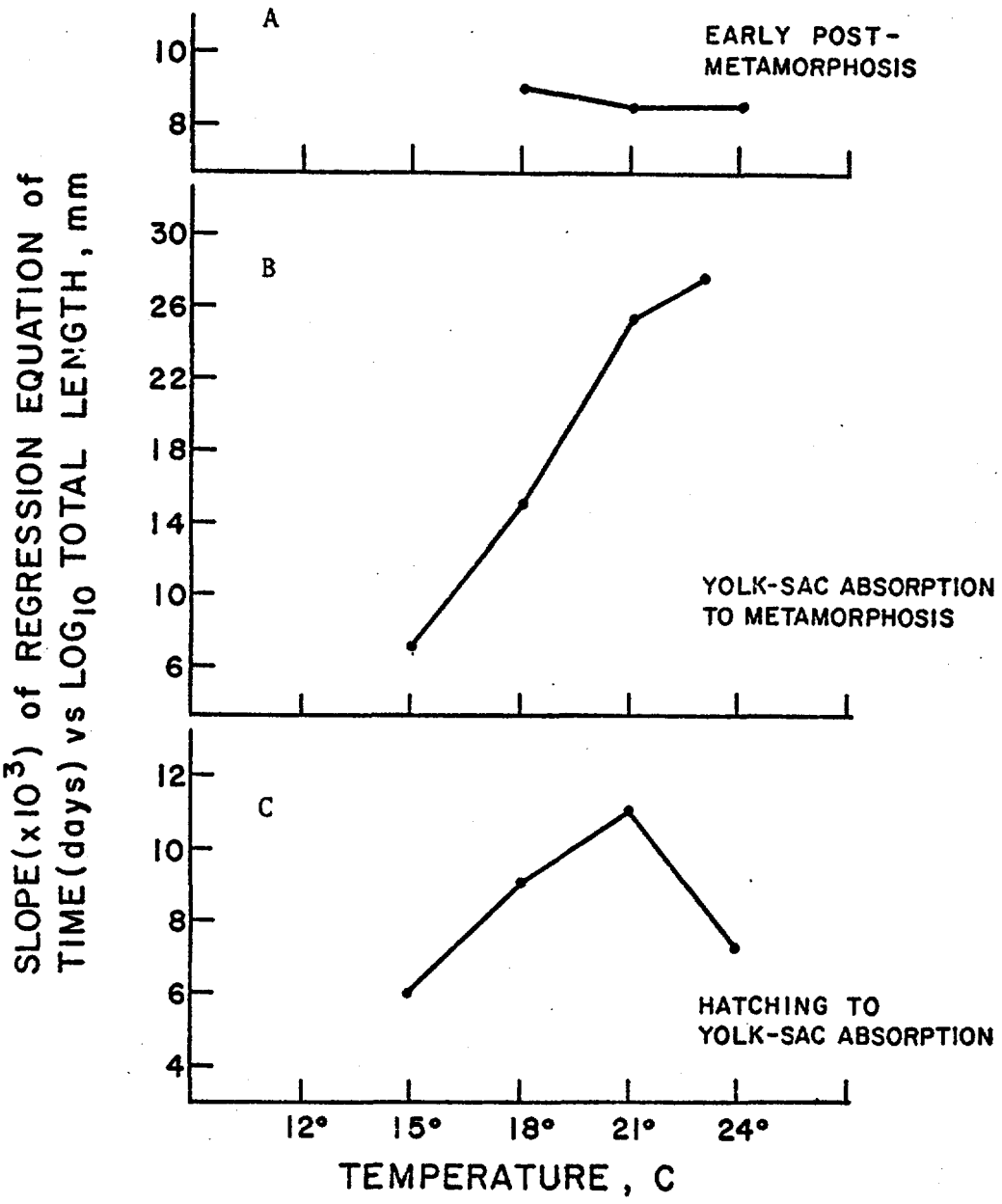

Figure 6. The effect of temperature on the mean slope, b ($x10^3$) of the regression equations of total length against days since hatching for each growth stage. The regression equations were in the form $\log_{10}$ length = b(days) + a.

TABLE 7

The range in time (days) from hatching to the attainment of adult fin-ray complement based on a mean total length of 16.32 mm at metamorphosis ± one standard deviation (SD) of 1.33 mm, at four rearing temperatures.

Temperature	Lot	-1 SD (16.32-1.33) 14.90 mm	Days to Mean Total Length at Metamorphosis 16.32 mm	+1 SD (16.32+1.33) 17.60 mm
24°C	6	26.0	28.0	29.0
	8	27.0	28.0	29.0
	9	23.0	23.5	24.0
	Mean	25.3	26.5	27.3
21°C	7	28.0	32.0	36.25
	8	28.25	31.0	33.75
	9	29.0	30.5	32.75
	Mean	28.4	31.2	34.3
18°C	7	38.25	40.0	44.0
	8	38.0	40.5	43.0
	9	39.0	41.0	45.0
	Mean	38.4	40.5	44.0
15°C	7	66.0	73.0*	82.0*
	8	66.0	70.0*	74.0*
	9	81.0	85.0*	90.0*
	Mean	71.0	76.0*	82.0*

*Estimated from fitted growth curve—no larvae attained this size.

temperatures and all lots:

$$\text{daily \% mortality} = 0.486\ (\text{temp.}^\circ\text{C}) - 5.323$$
$$r = 0.766$$

DISCUSSION

Development Through Hatching

The effect of temperature on the incubation time of striped bass eggs has been reported by a number of workers (see references in Table 3). In this study published observations have been supplemented, particularly at lower incubation temperatures. These data fall among points determined by other authors.

The exponential equation used to describe all of the available temperature-incubation time data for striped bass (Figure 5) is similar in form to the same relationship for other species (Blaxter, 1969; Lasker, 1964; Alderdice and Forrester, 1968). Most of the scatter of points around this regression line may be explained by the use of different hatching criteria by various authors. For example, the time of 50% hatching was used in this study while Bayless (1972) used the time of first observed hatching.

The time course of events prior to hatching is related to temperature in much the same way as is the length of the incubation period as a whole. Figure 4 is very similar to the same relationship for the garfish Belone (Fonds et al., 1974). Events early in embryonic development are typically less responsive to temperature than the later stages. A marked increase in the rate of development occurs between 12° and 15°C. Morgan and Rasin (1973) noted a similar rate increase between 13.5° and 16°C in striped bass eggs from upper Chesapeake Bay, but noted no significant effect of temperature on the developmental rate between 16° and 27°C. The results of our study indicate that the rate of development increases continuously with temperature

between 15° and 24°C at all stages. From Figures 4 and 5 it appears that below 12°C incubation time becomes infinite. Morgan and Rasin (1973) noted no successful hatching at 10.5° and 11°C. Eggs incubated at 12°C in our experiments experienced a steady mortality throughout the incubation period, which in most cases depleted the treatment population before hatching had occurred. Hatching at 12°C was complicated by the occurrence of premature chorion loss and the appearance of living but immobile and clearly moribund prolarvae at the time hatching would have been expected to occur. While striped bass eggs are taken in the Hudson when river temperatures are below 10°C (Carlson and McCann, 1969), it is doubtful that successful development occurs at temperatures of 12°C or less.

Hatching occurred successfully in our 24°C temperature treatment. Morgan and Rasin (1973) considered 23°C the upper end of the survival optimum for striped bass eggs in their study. They observed 100% mortality at 27°C. That 24°C is near the upper limit for successful development in striped bass is supported by the observations of Albrecht (1964) and Shannon (1970).

While these experiments permitted observation of the rate of development at all of the temperatures used, mortality from fertilization through hatching was generally high. Above 12°C no single lot gave a good survival series at all temperatures. Within each lot one or more temperature treatment experienced heavy egg mortalities which correlated in no reproducible way with the treatment temperature. Survival at 15° and 18°C was generally higher than at 12° or 24°C. Among treatments not affected by catastrophic losses survival ranged from 50 to 67%.

Mortality in these experiments can be attributed to several factors. Eggs were stocked into their rearing containers within 20 minutes following fertilization. Variable proportions of the mortality observed may have been

due to non-fertilization. Hence, these may have had no relation to the temperature treatment. The semi-static incubation methods used are vulnerable to chain-reaction deterioration in water quality. Heavy egg mortality early in an experiment can affect the quality of the incubation water to such an extent that the whole treatment population is affected before scheduled water changes can be made. Losses of this type are more likely at higher temperatures when bacterial proliferation is more rapid.

Survival in culture vessels was much improved by the use of a broad spectrum antibiotic mixture to reduce the microbial population. Similar success using this antibiotic on Maryland striped bass eggs held in river water was observed. Albrecht (1964) used the same antibiotic in his studies with striped bass eggs. Nash and Kuo (1975) suggest that much of the mortality observed among cultured fish eggs at temperatures between 18° and 25°C is not, in fact, a direct result of temperature per se, but instead a result of rapid bacterial growth that culture at this temperature permits. There is the possibility that what Nash and Kuo propose may be true in past work on striped bass, particularly where a natural water supply was used. Chemical or physical water sterilization methods are gaining wider acceptance in experimental studies using early life stages, e.g., Shelbourne (1964), Houde (1973), Nash and Kuo (1975).

A single experiment comparing quarry water and Hudson River water was run using eggs from lot 5. This experiment revealed that both antibiotic treated and untreated sub-lots reared in Hudson River water showed better survival through hatching than similarly treated lots in quarry water. We have no theories at present why survival in quarry water was reduced in this experiment. There is no evidence that incubation in quarry water in any way affected the rate of development observed in these studies.

Work on other species, and earlier studies on striped bass (Albrecht, 1964; Morgan and Rasin, 1973) defined a rather broad temperature range for maximum development rate and survival through hatching (16°-23°C). Bayless (1972) suggests that best survival through hatching occurs at 62°-65°F (16.7-18.3°C). Our limited mortality data suggest that best survival occurs at 15° and 18°C. Theoretically at an optimum temperature the conversion from yolk to embryonic tissue should be most efficient. Larval length at hatching should be a measure of the efficiency of yolk utilization through hatching (Alderdice and Forrester, 1968). The relationship between temperature and calculated length at hatching is presented in Figure 7C. Larval growth after hatching is very rapid at all temperatures. Hence, it is important to define the time at which measurements are taken. The method of back calculation used puts the time at which length at hatching is recorded on a common basis for all treatments. An optimum temperature for embryonic development through hatching of 18°C is suggested. However, these data are too limited to support any meaningful conclusions. Analyses of this sort may be confounded by differences in the amount of yolk originally present in the unfertilized egg (Blaxter and Hempel, 1963, 1966). Among striped bass the average dry weight of unfertilized eggs is a linear function of the weight of the female producing them (Rogers, unpublished data). In Figure 7C the amount of yolk originally present in eggs in lot 8 was greater than that in eggs from lot 7, based on dry weight measurements.

Development During the Yolk Sac Stage

Increase in larval length during the yolk sac stage generally took place in two phases: (1) a rapid increase in length for the first few days after hatching, the rate and duration of which appeared to be independent of temperature; and (2) a period of depressed growth, the duration of which was

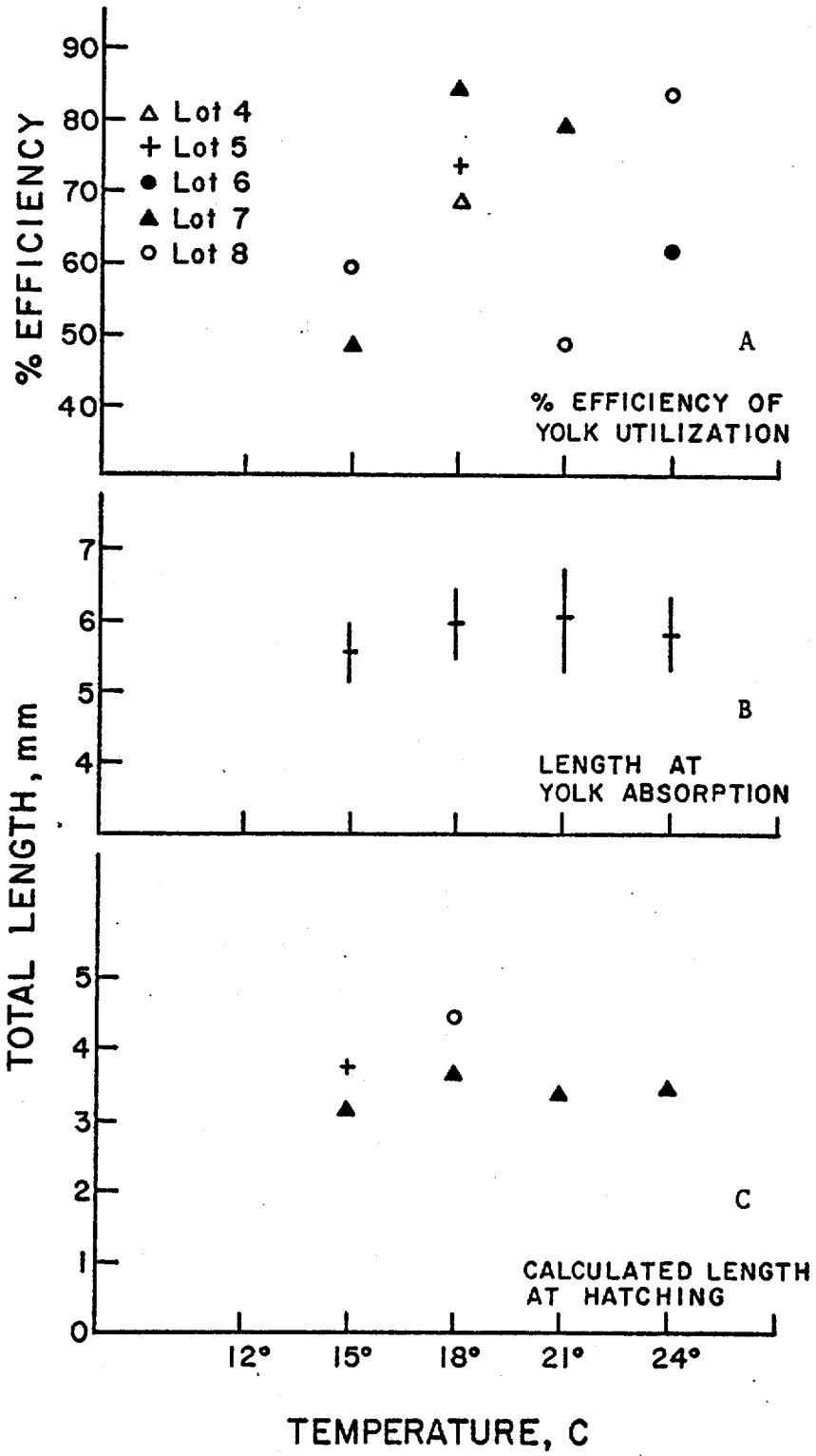

Figure 7. Estimates of the temperature optimum for growth through yolk absorption using three techniques.

directly related to rearing temperature. The pattern of growth observed in these studies is not unique to striped bass. The initial period of rapid growth following hatching is equivalent to section A of the growth curves of four species of marine fish described by Farris (1959). An initial period of rapid growth immediately following hatching was also described by Kuznetzov (1972) for a diverse group of fresh water species. As in other species, the period of essentially linear growth following hatching in striped bass ends well before full yolk absorption. The period between the end of linear growth and the disappearance of the yolk sac as a structure may last from 2 to 28 days depending on the temperature.

In other species the end of the period of linear growth following hatching is concurrent with the beginning of free swimming by the developing larva. Once free swimming has begun, growth in length and weight ceases and the use of remaining yolk is accelerated (Toetz, 1966; Laurence, 1969).

The onset of free swimming just followed mouth formation in these studies. Doroshev (1970) noted an increase in larval activity at about the same time as mouth formation in striped bass at two to five days after hatching at 17°-18°C. These observations correlate well with the timing at the beginning of the growth plateau in our experiments. Before free swimming all of the yolk energy available is used for maintenance and growth. After swimming is begun the remaining yolk energy is divided between maintenance and activity at the expense of growth in length or weight. Lasker and Theilacker (1962) showed that activity can increase the oxygen consumption, hence energetic demands of sardine larvae, up to 3.5 times that required by inactive larvae. It has been a common practice among striped bass culturists to provide heavy agitation in larval rearing containers. This turbulence probably induces larval activity sooner than it would normally occur. In later larval development it probably increases the level of forced activity.

The growth plateau we observed in most of our treatment populations coincides with Farris' section B (Farris, 1959) which was characterized by a period of reduced growth rate. Kuznetzov (1972) noted a similar marked reduction in larval growth before yolk absorption which he associated with the period of transition between an endogenous and exogenous food source.

Mortality curves for all of our experimental treatments are found in Appendix B. A common characteristic of nearly all treatments is a sigmoid pattern in the reduction in numbers. The majority of all mortalities that occurred during the whole experimental period took place before yolk sac absorption was complete. Mortality immediately following hatching was low, typically amounting to no more than five percent of the treatment population. A linear decline in numbers followed beginning three to four days after hatching at 24°C and progressively later at lower temperatures. The maximum mortality for one day followed a similar pattern, occurring at three to five days at 24°C, four to six days at 21°C, six to nine days at 18°C and nine to twenty-one days at 15°C. The period of heavy mortality ended when the treatment populations at 24°C had been reduced to an average of 16% of their original level, and when the treatment populations at 21°, 18° and 15°C had been reduced to an average of 24% of the number present at stocking.

The cause of this pattern of mortality is not clear. The sigmoid nature of the mortality curve suggests a dose-response curve. A number of factors which could have led to mortalities of this sort were investigated. None that might be active in as many different lots and temperature treatments as were observed in these experiments were found. Our experience confirms the observations of Otwell and Merriner (1975) and Davies (1973) that striped bass larvae are relatively hardy and can accommodate to a wide range in temperature and water quality conditions. Crowding was considered

a possible predisposing condition to mortality of this sort. There was a three-fold difference between treatments at all temperatures in the number of larvae per liter of culture water at the time mortality rate had stabilized. Some of the highest stocking densities persisted at 21° and 24°C. The effects of crowding and of epidemic disease remain as possible explanations for the mortalities observed. The pattern of mortality greatly resembles that observed by other workers among groups of larvae which were deprived of food or maintained on reduced rations (May, 1971; O'Connell and Raymond, 1970).

The larval populations were presented with Artemia nauplii two days after hatching at 24°C, three days after hatching at 21°C, and five to six days after hatching at 18° and 15°C. The time food was first presented was chosen on the basis of the apparent degree of structural development of larvae in samples from each population. Based on the average time to complete yolk absorption (Table 4) food became available after a small fraction of larvae had already absorbed all of their yolk. Feeding typically begins before all yolk is absorbed. Larvae which have exhausted their yolk reserves and have begun to resorb their body tissue lose their ability to capture and use food when it becomes available. This stage of irreversible starvation has been labeled the "point of no return" by Blaxter and Hempel (1963). The period of time between yolk absorption and irreversible starvation may be very short. Lasker et al. (1970), observed that for the northern anchovy irreversible starvation followed shortly by complete mortality occurred when food was withheld more than one day after yolk absorption. Bayless (1972) observed what appeared to be irreversible starvation in striped bass just under ten days after hatching at 18.9° to 20°C. In our experiments the mean time to yolk absorption occurred at 9.75 days at 21°C and 11.75 days

at 18°C. Among Bayless' fish which had undergone irreversible starvation, death followed four to five days after the ability to feed had been lost. If Bayless' observations and ours are combined, it appears that irreversible starvation occurs very near the time of complete yolk absorption in striped bass but that death from starvation takes considerably longer than among Lasker's anchovies.

It seems reasonable to expect that the time between hatching and yolk absorption, yolk absorption and the "point of no return" and between the "point of no return" and death would be compressed into a shorter time period among larvae reared at high temperatures. This is due to the effect of temperature on metabolic rate. The death of larvae which had not begun to feed is assured on or about the time of yolk absorption. If the time from hatching to yolk absorption for a given treatment population has a bell-shaped distribution the mortality pattern one would expect to observe would resemble a cumulative normal distribution or sigmoid. This is the shape approximated by most of the time-mortality curves generated in these experiments. While the progressive occurrence of irreversible starvation followed by death among larvae completing yolk absorption can explain the shape of the mortality curve, it does not explain the timing of heavy mortalities. At the mean time of yolk sac absorption, based on our criteria, the average size of the original treatment populations had already been reduced to 16%, 36%, 53% and 34% of its original complement at 24°, 21°, 18°, and 15°C, respectively.

A nutritional explanation of the pattern of mortality observed would entail the assumption that all larval populations received no food, or that the food presented was rejected or not in sufficient abundance to meet the demands of the entire population in each tank. Although we were unable to

monitor the size of the ration presented each tank, food was always available in varying amounts. At least 20% of the fish in most populations ultimately accepted and were able to grow on the food presented, suggesting that the diet was not entirely inadequate. The food concentration required for optimal growth and survival among striped bass larvae is unknown. Our approach in these experiments was to provide an excess ration at the time feeding began in the hope of encouraging a higher proportion of each population to start feeding. It may be that an intermediate food density may be required for best survival as was the case in the experiments of Saksena and Houde (1972) using Harengula.

These estimates of the mean time to yolk sac absorption are too long to satisfy the nutritional hypothesis. If this hypothesis were true and the distribution of lengths at yolk absorptions are as we have indicated, then at higher temperatures yolk is completely consumed among a portion of the population within a day of hatching. In this case provision of food at the second day after hatching at 24°C was clearly too late.

We assigned the time of mean yolk absorption in each lot by looking at the percentage of fish in a series of samples that had attained a total length of 5.84 mm. or greater. The time of attainment of the mean length at yolk absorption was determined by the appearance of larvae of greater than 5.84 mm. among 50% of the fish in each sample. This approach was applied consistently and was effective where there was a continuous increase in length over time. However, within the growth plateau at 24°, 21° or 18°C there appeared cases of negative growth or periods of decrease in length with increasing time. Lasker (1964) noted a similar shrinkage among unfed Pacific sardine larvae. This reduction in length occurs among larvae which are already undergoing tissue resorption, therefore are well past complete yolk

absorption. In treatments where negative growth appears, it usually does so just following the period of major mortality and just preceeding the period of rapid growth associated with the end of the yolk sac period.

That no period of significant mortality follows these periods of negative growth suggests that most of these larvae which had already absorbed all their yolk and some of their body tissues ultimately began to feed and grow rapidly. The time of yolk absorption by this group of larvae would have preceeded the period of negative growth and would have been missed by the interpolation method we used. If this were the case the actual time of yolk absorption for this segment of the population would be as follows, based on inspection of the growth curves in Appendix B.

Temperature (°C)	Lot #	Corrected Estimated Time to Mean Yolk Absorption (Days)	Previous Estimate (Table 4) (Days)	Difference (Days)
24	6	2.5	4.75	-2.25
	8	4.0	7.25	-3.25
21	8	5.5	7.0	-1.5
	7	8.0	9.75	-1.75
18	9	7.0	13.50	-6.50

Larvae reared at 12°C also underwent negative growth but never recovered. Although food was presented, there was no evidence that any larvae at this temperature ever fed.

Even if our estimates of the time of yolk absorption were excessive for treatment populations which underwent negative growth, larvae would have had to die immediately following yolk absorption to account for the timing of the observed mortalities. At least a portion of larvae in each population were capable of satisfactory recovery from tissue depletion. May (1971) noted a similar resistance to food deprivation in Leuresthes. In his experiments starved fish underwent arrested development and reduction in dry

weight during periods of starvation following yolk absorption of up to 16 days. The energy demands during this period were met at the expense of lipid reserves suggesting a similar function for the atypically large oil globule in striped bass.

The pattern of mortality in our experiments remains unsatisfactorily explained. Some factor other than starvation appears to have been responsible for the bulk of early mortalities. We have no explanation why larvae that ultimately survived showed symptoms of food deprivation when food was present in abundance.

The duration of the yolk sac period decreased with increasing temperature. The length of the yolk sac period as a function of temperature for different lots is presented in Figure 8, and summarized in Table 4. There are variations between lots. We have some evidence that the optimal temperature conditions for development occur between 18° and 21°C. In determining the average length of larvae at the point of yolk absorption we examined larvae reared at all temperatures and found that there was no statistically significant difference in length between temperatures. As a result we used the mean length at yolk absorption for larvae reared at all temperatures to define the mean cutoff point at 5.84 mm. Measurements of the efficiency of yolk utilization at different rearing temperatures yielded no meaningful trend (Figure 7A). The range in efficiencies observed fell within the range observed by Blaxter and Hempel (1966), as well as those reviewed by Blaxter (1969). Blaxter (1969) summarized some of the sources of error in efficiency calculations.

Exponential growth equations fitted to our growth data by life stage are presented in Table 6. The exponential approximation of the pattern of growth during the yolk sac stage was used on all lots and temperature treat-

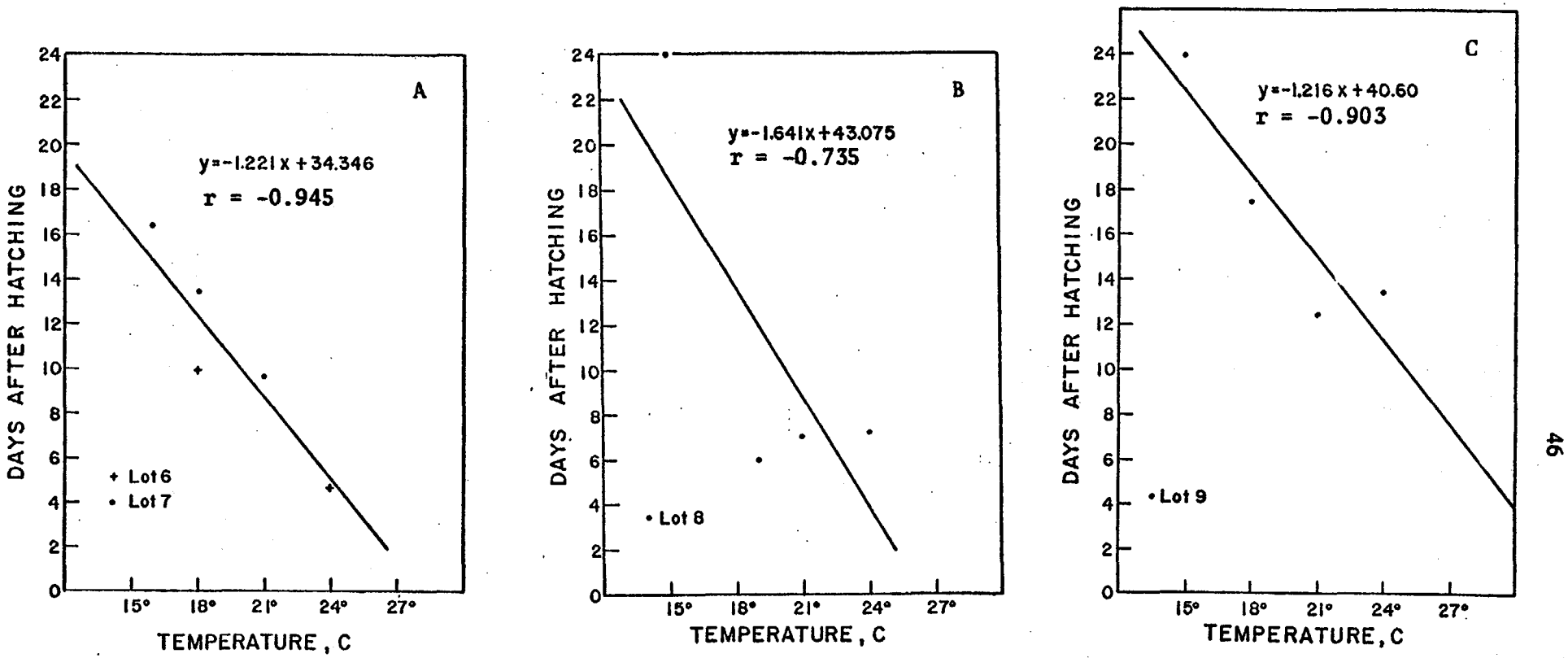

Figure 8. The effect of temperature on the duration of the yolk sac stage by lot.

ments for the sake of consistency. Growth measurements during the first three days after hatching were not used in calculating the growth equation for this stage. There was generally a lower correlation between time since hatching and larval length when prolarval growth was described using an exponential growth function, than was observed when the same function was applied to the growth of later stages (Table 6). This fact undoubtedly contributed to the considerable variability between lots in the slope of the exponential growth function at each temperature. The extent to which the exponential model fails to fit observed growth data is largely a function of the length of the growth plateau and the extent of negative growth in each treatment population. The mean (between-lot) slope for prolarval growth showed an apparent peak at 21°C (Figure 6C), indicating a shorter relative stage duration at this temperature. Empirical growth curves for lots at 21°C revealed no such peak in stage duration estimates (Table 4, Appendix B).

Development Between Yolk Sac Absorption and Metamorphosis

Growth during the larval stage was exponential with the slope of the growth equations increasing with the rearing temperature (Table 6, Figure 6B). Size-hierarchy effect (Blaxter, 1969; Brown, 1957) became a prominent feature of the distribution of larval lengths in all treatment populations. Size-hierarchies or ranges in length among larvae of the same age are a common phenomenon in captive fish populations. It is not known whether or not they occur to the same extent among natural populations as they do in the laboratory or hatchery. Our sampling procedure tended to reduce the size range in each population. We sampled the largest and smallest fish as well as what appeared to be average sized individuals. For the small samples we were forced to take in the later stages of each treatment the range was used

as a relatively efficient estimator of the standard deviation (Snedecor and Cochrane, 1967). In addition, we felt that removing the largest fish at each sampling prevented a high incidence of cannibalism. The size-hierarchies we observed occurred in spite of our sampling technique. The range in length within each sample appeared to increase in each treatment population as the time of metamorphosis was approached (see growth figures, Appendix B). The occurrence of size-hierarchies tends to reduce the predictive power of a growth curve in defining the time of metamorphosis. We based our estimates on the time of metamorphosis on our observations of the time in days after hatching it took the larvae in our experimental populations to reach a mean length of 16.32 mm. The range in lengths that occurred among individuals in the populations before this mean length was attained would determine the actual time course of the arrival of metamorphosis in the population as a whole. Our sampling procedure ideally amounted to periodic cropping of the population which had no size related bias. The extent of size-hierarchies is certainly a function of the size of the population. The treatment populations near the end of our experiments were quite small; as a result the range in sizes observed probably underestimates the range that would have occurred in a larger population.

The rate of mortality during the larval stage was less than half that observed up to yolk sac absorption (Table 5). The daily percentage mortality increased with temperature from a mean of 1.7% at 15°C to 6.37% per day at 24°C. Turner and Chadwick (1972) estimated a daily mortality rate for young bass ranging from 3.0 to 7% per day in the Sacramento-San Joaquin Estuary.

Development After Metamorphosis

Our temperature treatment populations were very much reduced by the time all the remaining individuals had attained metamorphosis. Conclusions

concerning growth of young bass after metamorphosis must be considered at best tentative. Growth curves in Appendix B suggest a reduction in the rate of growth after metamorphosis. Growth curves fitted to the last few samples in each treatment reflect this reduction (Table 6). For those temperatures for which growth observations are available there are indications that past metamorphosis the rate of increase in length is no longer so closely related to temperature as before metamorphosis (Figure 6A).

The rate of mortality after metamorphosis did not appear to change from that before metamorphosis.

Growth Curves

A mathematical function whose form matches the increase in some bodily dimension over time provides a convenient method for describing the growth process and may provide a basis for comparison of growth within the same species under different conditions. This is why we attempted to fit growth curves to our observed growth data. The data in the individual growth figures in Appendix B remain the best representation of the pattern of growth we observed in each treatment.

As is the case with growth functions which are used to describe the growth of adult fish, best fit can be expected when a particular function is applied to a well defined growth stanza, rather than to the entire growth process from metamorphosis to senility. The period of development spanned by our growth figures includes stages marked by different modes of larval nutrition. Hence, there is no reason to expect that a single simple function will adequately describe growth throughout the observation period. Early growth in most aquatic organisms is exponential (Royce, 1972). On this basis we are prejudiced toward the use of an exponential approximation. Kramer and Zweifel (1970) found that this simple relationship described the

growth of the northern anchovy quite well, but warned against the dangers of extrapolation, particularly at higher rearing temperatures.

In Table 8 we summarize the growth equations obtained using linear regression techniques on untransformed and $\log_{10}$ transformed sample means against days after hatching. The mean correlation coefficients (r) for the linear and exponential approximations in Table 8 did not differ significantly at the 0.05 level using a Students 't' test. Both approximations confirm the positive relation between rearing temperature and growth rate, with the slopes of each increasing with increasing temperature. The correlation between temperature and slope of the growth equations was $r = 0.908$ for its exponential and $r = 0.924$ for the linear equations. Although larval growth from hatching through metamorphosis appears exponential in form the exponential growth equation consistently fails to describe certain changes in growth rate that occur in experimentally defined growth curves. Figure 9 shows an example of the relationship between the exponential approximation and a curve fitted by eye to sample means. The exponential curve typically underestimates the size at metamorphosis, and the size during most of the yolk sac stage. The growth trajectory implied is misleading and the growth plateau during the yolk sac stage is inadequately represented. The sample data of Kramer and Zweifel (1970) has an early growth plateau like that observed in our experiments which neither the exponential nor the Gompertz model, nor the authors adequately describe.

Farris (1959), Kramer and Smith (1960) and Kuznetzov (1972), among others, have attempted to describe the growth of larval and early juvenile fish one growth stage at a time. We did this and Table 6 summarizes the exponential equations fitted to our growth observations by life stage. We used sample points near the transition between stages to calculate regression

TABLE 8

Total length versus days after hatching regression equations where:
y = total length (mm)
x = days since hatching
r = correlation coefficient.

Temperature	Size Range Total Length (mm)	Linear Growth Equation	r=	Exponential Growth Equation	r=
24°C Lot 6	4.79-26.20	$y = 0.357x + 3.570$	0.992	$\log_{10}y = 0.013x + 0.711$	0.974
8	4.86-29.55	$y = 0.403x + 2.781$	0.976	$\log_{10}y = 0.015x + 0.677$	0.978
9	4.86-21.50	$y = 0.427x + 2.335$	0.822	$\log_{10}y = 0.022x + 0.564$	0.896
21°C Lot 7	4.71-26.60	$y = 0.428x + 2.095$	0.973	$\log_{10}y = 0.016x + 0.645$	0.956
8	5.20-29.45	$y = 0.253x + 1.368$	0.544	$\log_{10}y = 0.016x + 0.644$	0.961
9	4.39-18.00	$y = 0.354x + 2.669$	0.906	$\log_{10}y = 0.018x + 0.595$	0.952
18°C Lot 7	5.04-26.50	$y = 0.313x + 2.491$	0.956	$\log_{10}y = 0.013x + 0.630$	0.973
8	5.36-26.15	$y = 0.301x + 3.489$	0.974	$\log_{10}y = 0.010x + 0.690$	0.973
9	5.04-23.85	$y = 0.290x + 2.662$	0.964	$\log_{10}y = 0.012x + 0.633$	0.972
15°C Lot 7	4.71-18.90	$y = 0.168x + 3.698$	0.989	$\log_{10}y = 0.008x + 0.673$	0.988
8	4.88-19.65	$y = 0.172x + 3.283$	0.964	$\log_{10}y = 0.007x + 0.657$	0.990
9	4.88-16.75	$y = 0.119x + 3.697$	0.947	$\log_{10}y = 0.006x + 0.647$	0.979
12°C Lot 8	4.88-5.69	$y = 0.015x + 5.244$	0.540	$\log_{10}y = 0.001x + 0.719$	0.540
9	4.71-5.36	$y = 0.011x + 5.085$	0.536	$\log_{10}y = 0.001x + 0.706$	0.538

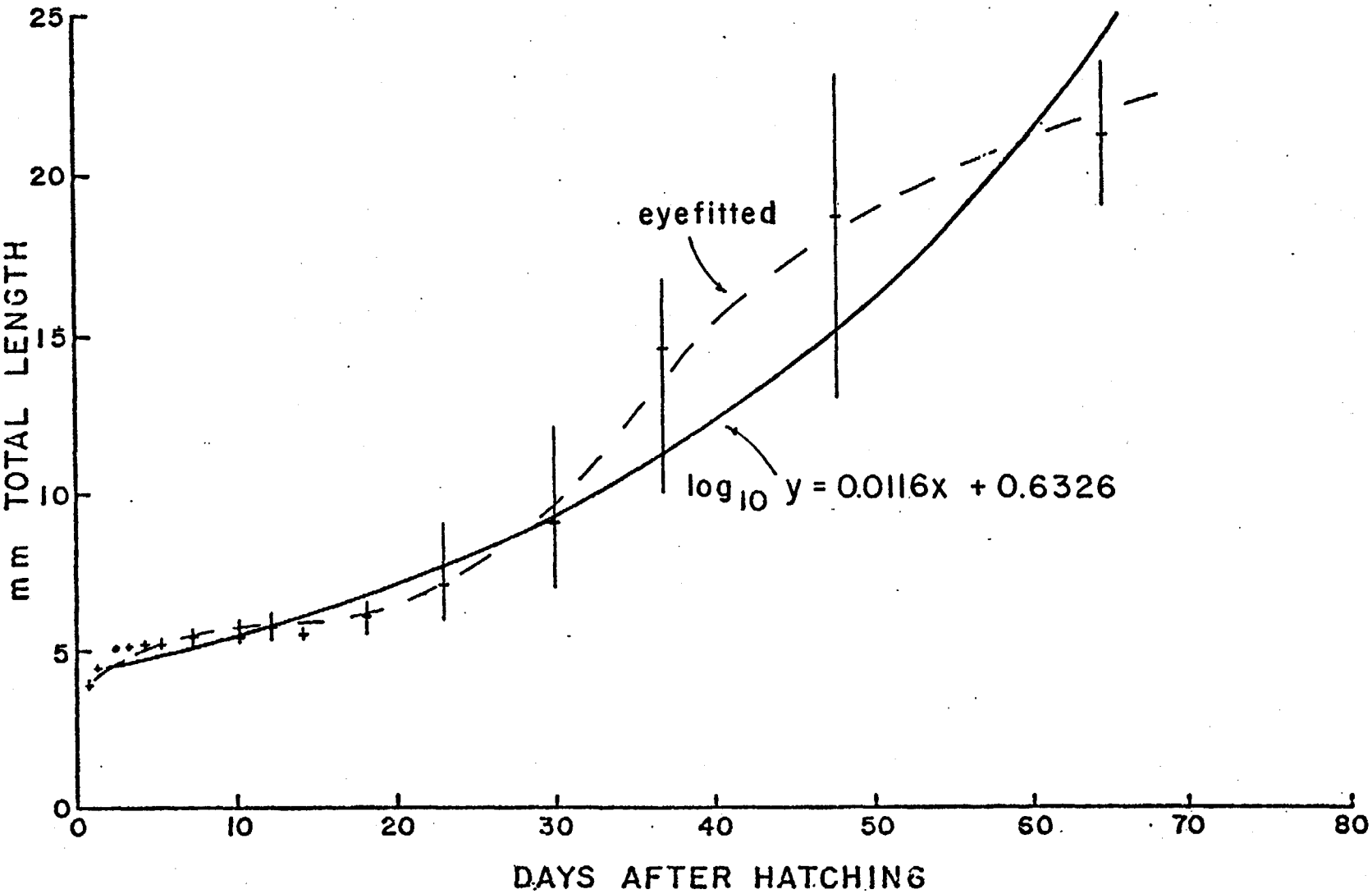

Figure 9. A sample comparison of a least squares exponential growth equation with an empirical growth curve fitted by eye to sample means.

equations for both stages where there was insufficient data. Based on the correlation coefficients the period between yolk absorption and metamorphosis is most adequately described by the exponential curve. The period from hatching to yolk absorption is more correctly logarithmic in nature. Few samples were available after metamorphosis. Describing this stage independently more accurately describes the change of slope that occurs at metamorphosis.

Applicability of Stage Duration Estimates

Life stage duration estimates used in life cycle simulation models are designed to bracket the range in stage duration that may be expected under natural conditions. In models of Lawler et al. (1974), and the United States Nuclear Regulatory Commission (U.S.N.R.C.) (1975) fixed stage lengths are proposed.

Life Stage:	Stage Duration	
	Lawler et al. (1974)	U.S.N.R.C. (1975)
egg	36-48 hrs.	48 hrs.
yolk sac larva	6-10 days	6 days
post-yolk sac larva	30 days	22 days
	Cumulative Days Since Hatching	
yolk sac larva	6-10	6
post-yolk sac larva	36-40	28

Our data indicate that the duration of life stages is strongly temperature dependent and probably affected by the nutritional state of the larvae as well. According to our results one would expect a yolk sac stage duration of six days at a fixed temperature of 21°-24°C. A ten day yolk sac stage would be expected to occur at a water temperature of between 18° and 21°C. On the basis of our results metamorphosis would be attained in twenty-eight days from hatching at a fixed water temperature of just under 24°C.

Metamorphosis would occur thirty-six to forty days after hatching at a fixed water temperature between 18° and 21°C. The validity of the stage duration estimates used on both models depends on which temperature more nearly approximates the temperature conditions which a striped bass egg or larva encounters during and after the spring spawning in the Hudson. Based on a ten year average (1959-1969) the temperature of the Hudson River at Indian Point rises at a rate of 1°C every five days between May 1 and July 1 (U.S.N.R.C., 1975). The interval between mid-May and mid-June (Rathjen and Miller, 1957) is the time in which spawning occurs in the Hudson. During this period the average water temperature at Indian Point rises from approximately 15° to 21°C. Our studies were carried out under fixed temperature regimes, hence can only approximate the timing of development over a period of rising temperatures. Our work does not reveal to what degree the thermal history of a larva might affect its later growth. Our experiments do indicate that the period between yolk absorption and metamorphosis is more responsive than earlier or later stages.

The pattern of growth defined in this study is compared with previous studies in Figure 10. In this figure growth at 15° and 24°C fixed temperatures bracket the growth observed by Mansueti (1958) and Rhodes and Merriner (1973). In Mansueti's experiments temperature was uncontrolled and ranged between 15° and 18°C. The temperature in Rhodes and Merriner's study rose irregularly from 17° to 27°C. The growth of fish in the latter study closely coincided with the growth of our fish at 18°C. Both Rhodes and Merriner and Mansueti state that their fish were "stunted" in comparison to wild populations. Compared to the growth rate attributed to "wild" striped bass (temperature unspecified) (Humphries and Cumming, 1973) both the present study and those of Mansueti and Rhodes and Merriner underestimate the growth rate of

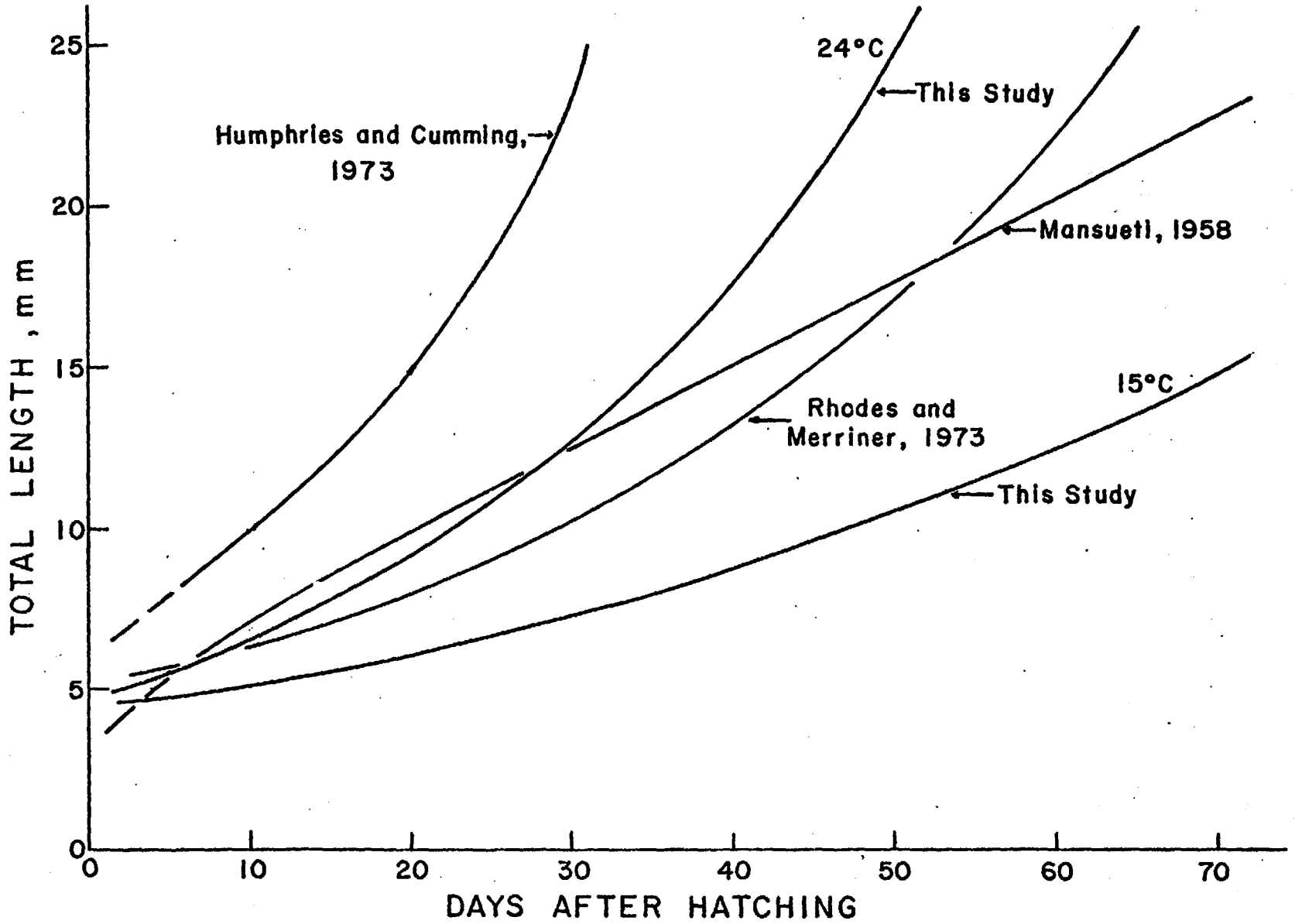

Figure 10. A comparison of growth rates observed under fixed temperature regimes with those obtained in earlier studies under conditions of increasing temperature.

fish in nature. All three were laboratory investigations. In the present study stage duration and growth were closely related. Our estimates of stage duration are too long to the extent that our observed growth rates underestimate those of wild fish. If our growth rates are conservative there would be a tendency for the duration of events later in development to be overestimated to a greater extent than events prior to or near hatching.

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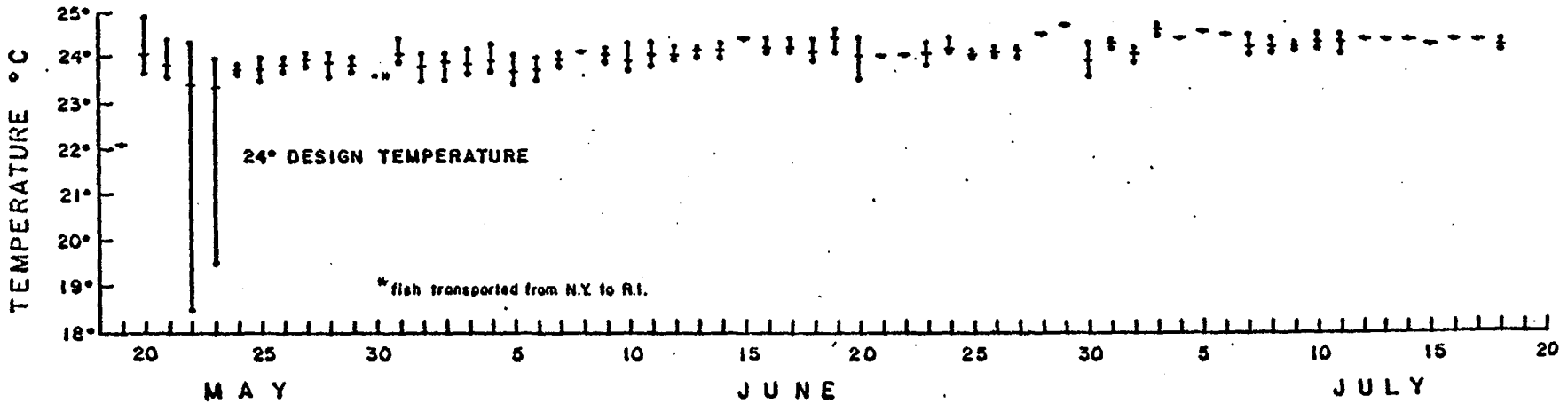
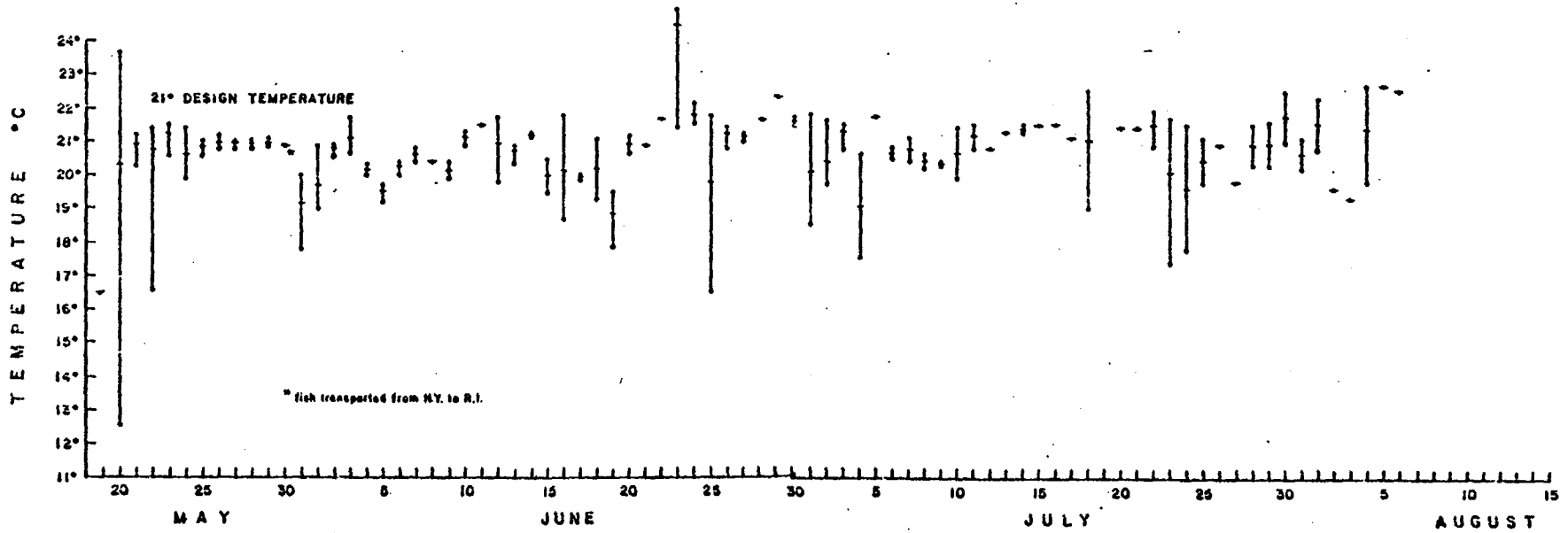
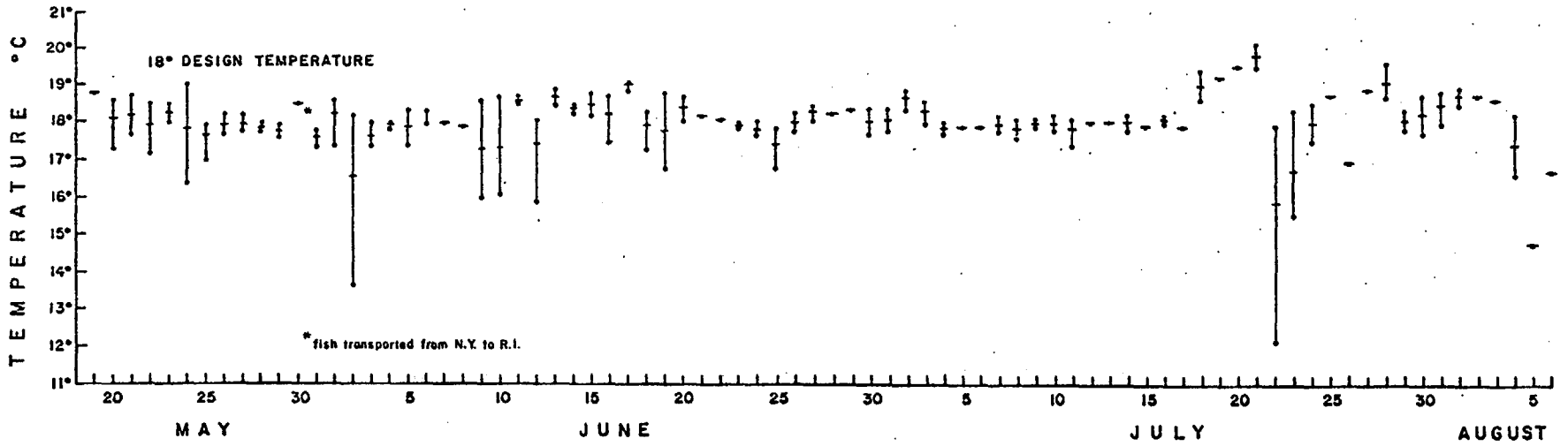
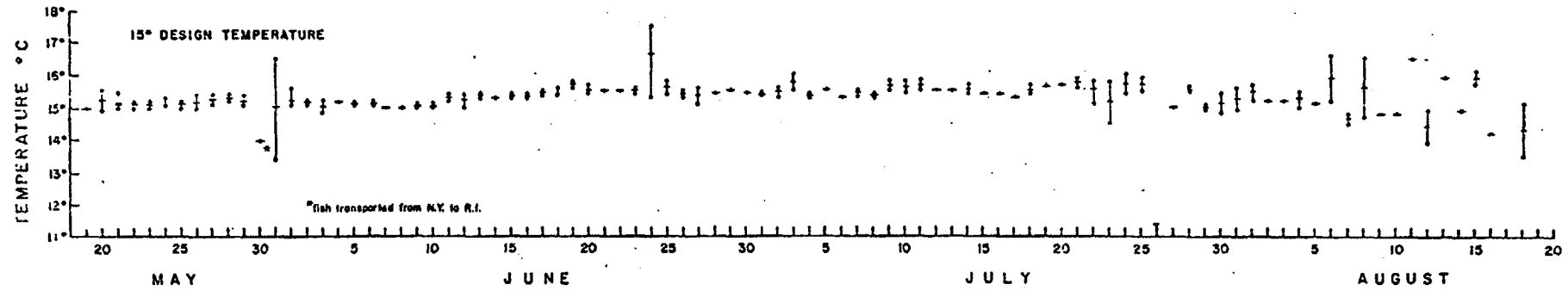
APPENDIX A



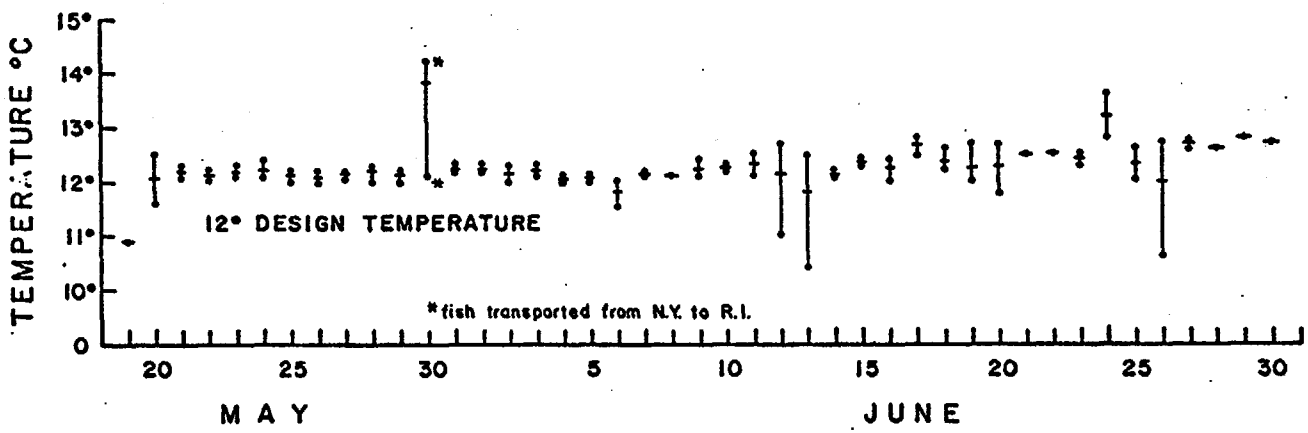


Record of observed temperatures in 24° and 21°C design temperature treatments.





Record of observed temperatures in 18° and 15°C design temperature treatments.



Record of observed temperatures in 12°C design temperature treatment.

AMMONIA CONCENTRATIONS (PPM) BEFORE WATER CHANGES

Date and Tank		12°	15°	18°	21°	24°C
20 May	#1	0.16	0.13	0.18	0.18	0.16
21 May	#1	0.33	0.23	0.33	0.69	--
	2	--	--	0.16	0.17	0.32
	3	--	--	--	--	0.14
23 May	#6	0.21	0.13	0.13	0.25	0.21
25 May	#7	0.13	0.17	0.13	0.19	0.63
28 May	#6	--	0.48	0.14	--	0.25
	7	0.13	0.21	0.35	0.30	0.28
	5	--	0.35	0.19	--	
5 June	#6	--	--	--	--	0.79
	7	--	0.30	--	1.56	--
	8	0.15	0.47	0.63	--	1.25
	9	--	--	0.18	0.43	0.31
16 June	#5	--	1.75	1.94	--	--
	6	--	--	--	--	2.31
	7	--	0.90	1.38	2.13	--
	8	0.80	1.11	1.16	1.44	>2.44
	9	0.56	0.89	0.89	1.56	2.13
17 June	#5	--	1.19	1.06	--	--
	6	--	--	--	--	1.25
	7	--	0.63	0.86	0.91	
	8	0.61	0.78	0.76	0.71	1.50
	9	0.63	0.61	0.60	0.94	1.25
19 June	#6	--	--	--	--	1.16
	7	--	0.90	1.16	0.83	--
	8	0.78	1.06	1.25	0.73	1.33
	9	0.88	0.75	1.11	0.99	1.25
26 June	#5	--	--	0.85	--	--
	6	--	--	--	--	1.28
	7	--	0.60	0.94	0.78	--
	8	0.74	0.73	0.75	0.81	0.68
	9	0.89	0.68	1.10	1.26	1.25

AMMONIA CONCENTRATIONS (PPM) BEFORE WATER CHANGES

Date and Tank		12°	15°	18°	21°	24°C
1 July	#5	--	--	1.12	--	--
	6	--	--	--	--	1.25
	7	--	0.71	0.86	0.66	--
	8	--	0.92	0.96	0.88	0.84
	9	--	0.96	1.70	1.10	1.08
17 July	(processing error)					
28 July	#5	--	--	1.10	--	--
	8	--	1.25	0.15	--	--
	9	--	0.89	0.30	--	--

DISSOLVED OXYGEN CONCENTRATIONS
(PERCENT SATURATION)

Date and Tank		12°	15°	18°	21°	24°C
22 May	#1	98	98	97	--	--
	2	100	99	97	91	--
	3	--	--	--	94	--
23 May	#4	--	95	92/95	--	96
	6	--	--	--	94	--
25 May	#6	--	98	99	--	--
	5	--	--	94/96* 80/81**	--	--
28 May	#5	--	98	98	--	--
	6	--	98	99	--	95
	7	87	98	99	91	96
	8	88	99	100	93	93
4 June	#7	--	98	95	98	--
	8	100	97	95	99	93
	9	96	96	96	--	95
23 June	#9	94	94	91	89	95

* Quarry/Hudson water with Penicillin (50 mg/l) and Streptomycin (50,000 I.U./l.)

** Quarry/Hudson water without Penicillin & Streptomycin

pH VALUES

Date and Tank		12°	15°	18°	21°	24°C
21 May	#1	8.2	8.1	7.8	7.85	--
	2				8.2	7.8
	3					8.15
23 May	#1			8.3		
	2			7.95		
	3			8.2		
	4			8.0/8.2		
25 May	#5*		7.9,-	8.0,7.8		
	**		7.8,7.6	7.7,7.5		
28 May	#6					8.2
	7		8.2	8.25	8.0	8.3
	5		7.8			
	4			8.1		
14 June	#8	8.15				
	9			8.0	8.0	8.0
	5		7.8			
16 June	All	8.0-8.3	8.1-8.2	8.0-8.4	8.3-8.4	8.1-8.2
24 June	#9	8.05	7.95	7.85	7.9	7.95
7 July	#8	--	8.0	7.95	7.9	8.0

* Quarry, Hudson water with Penicillin (50 mg/l) & Streptomycin (50,000 I.U./l.)

** Quarry, Hudson water without Penicillin & Streptomycin)

SALINITY (o/oo) RANGES BEFORE WATER CHANGES*

Date	12°	15°	18°	21°	24°C
3 June	0	2	2-3	2-3	0-3
6 June	0	2-4	3-5	3-5	4.5-5
10 June	0-1	2-4	3-4	3-4	4-6
16 June	2-4	4-7	5-8	6	6-8
20 June	5-8	6-9	7-10	9	10-12
23 June	3-5	6-8	5-9	8-10	12-13
24 June	4	5	7	6	8
25 June	5	5-6	6-9	7-8	8-10
26 June	3-4	4	4-6	4-6	4-6
27 June	2-3	3-4	4-5	4-6	4-6
30 June	--	4	4-7	4-5	5-6
1 July	--	4	4-6	4	4-6
2 July	--	5-6	6-8	6-7	6-8
3 July	--	5-6	6-9	5-6	8-10
7 July	--	5-6	6-8	6-7	8
8 July	--	4-5	4-6	5	7-9
9 July	--	6-7	6-9	6	8-10
10 July	--	4-5	4-6	4-5	5
11 July	--	7-8	6-8	8	10
14 July	--	6-8	6-8	7	12-14
15 July	--	5-6	5-7	4-5	7-9
17 July	--	4-6	4-6	4	7

SALINITY (o/oo) RANGES BEFORE WATER CHANGES*

Date	12°	15°	18°	21°	24°C
18 July	--	5-6	4-6	5-6	7
21 July	--	10-12	9-10	--	--
23 July	--	8-9	7-9	--	--
25 July	--	8-9	8-10	--	--
28 July	--	8-10	9-11	--	--
29 July	--	8-10	8-10	--	--
30 July	--	8-9	10	--	--
31 July	--	6-10	6-8	--	--
1 August	--	7-10	9-11	--	--
4 August	--	9-12	9-10	--	--
6 August	--	10-12	--	--	--
10 August	--	10	--	--	--
12 August	--	10	--	--	--
14 August	--	12	--	--	--

* Given as ranges for all tanks at each temperature.

APPENDIX B

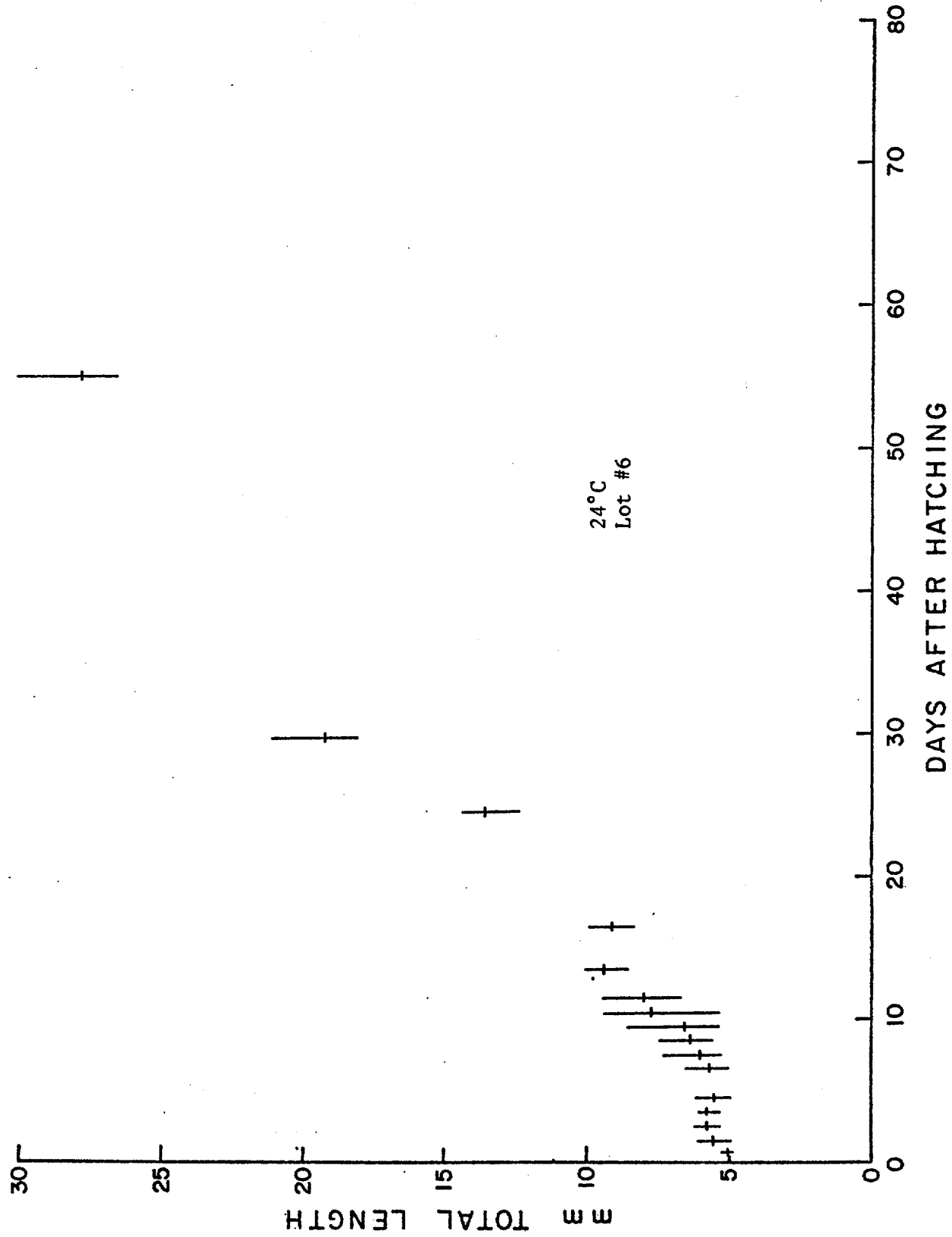
Appendix B

Larval Growth Figures

Legend

vertical bar represents range in length in each sample

cross bar is sample mean


24°C
Lot #6
DAYS AFTER HATCHING
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50
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70
80
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10
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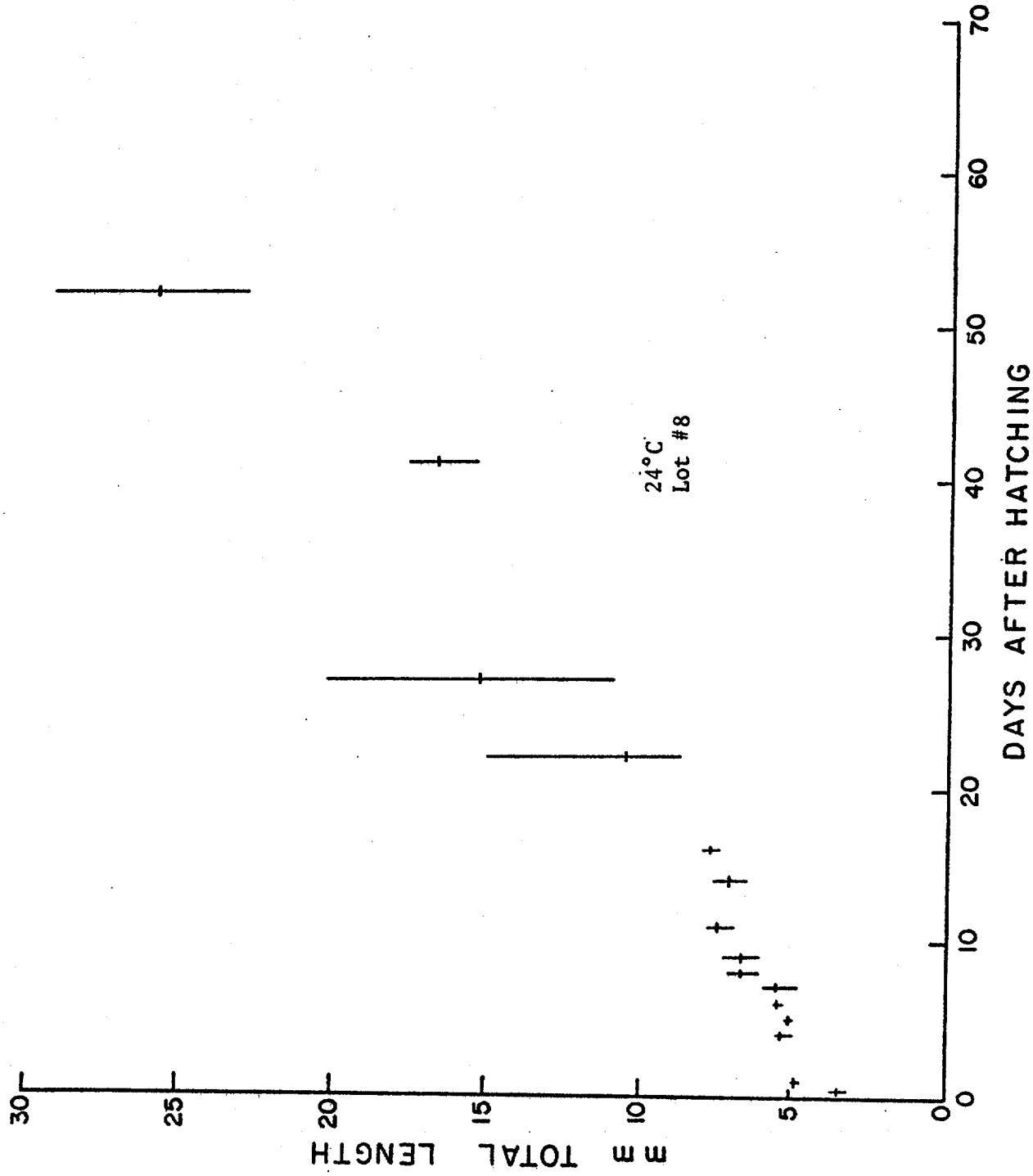
20
25
30


24°C
Lot #8
DAYS AFTER HATCHING
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30
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50
60
70
5
10
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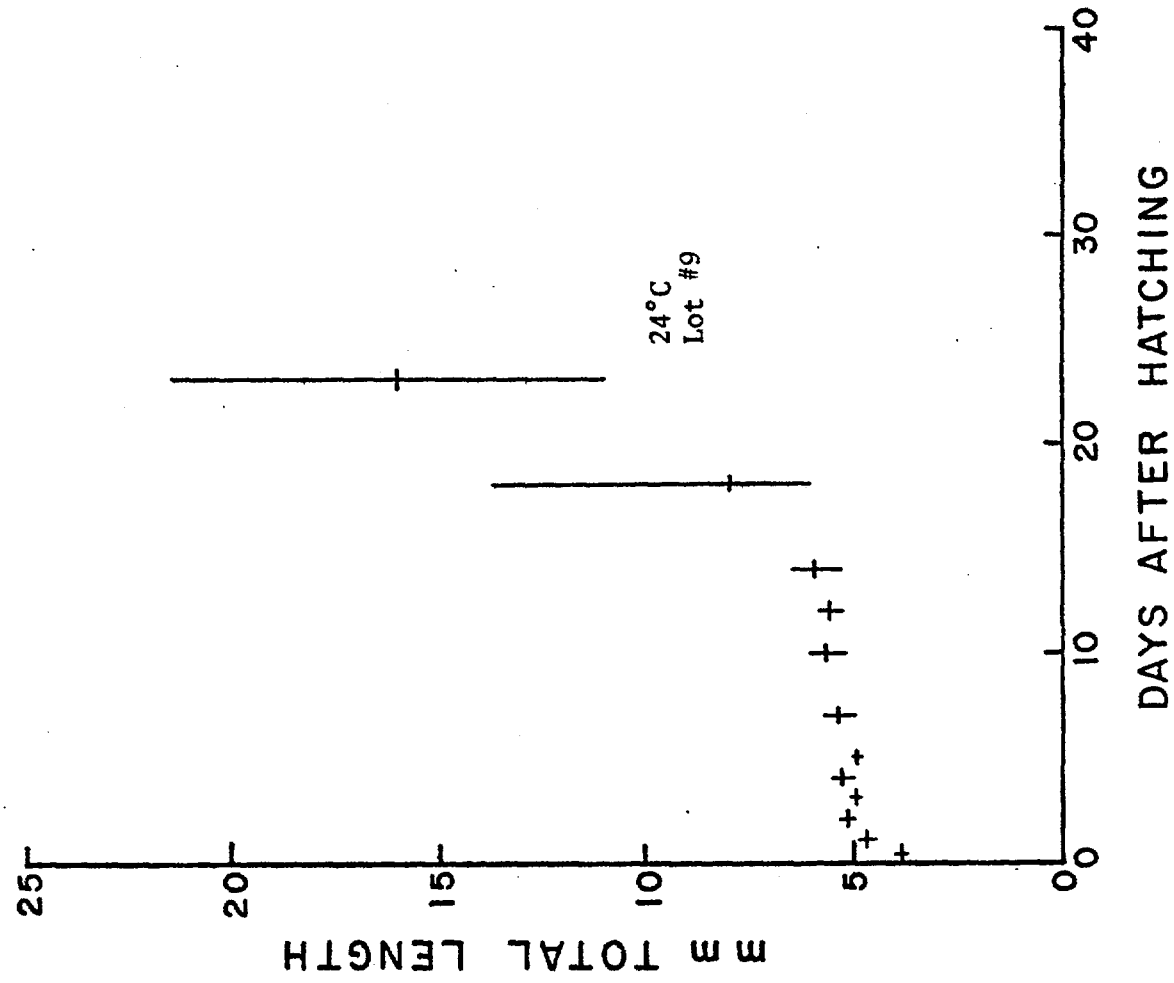
24°C
Lot #9
mm TOTAL LENGTH
DAYS AFTER HATCHING
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15
20
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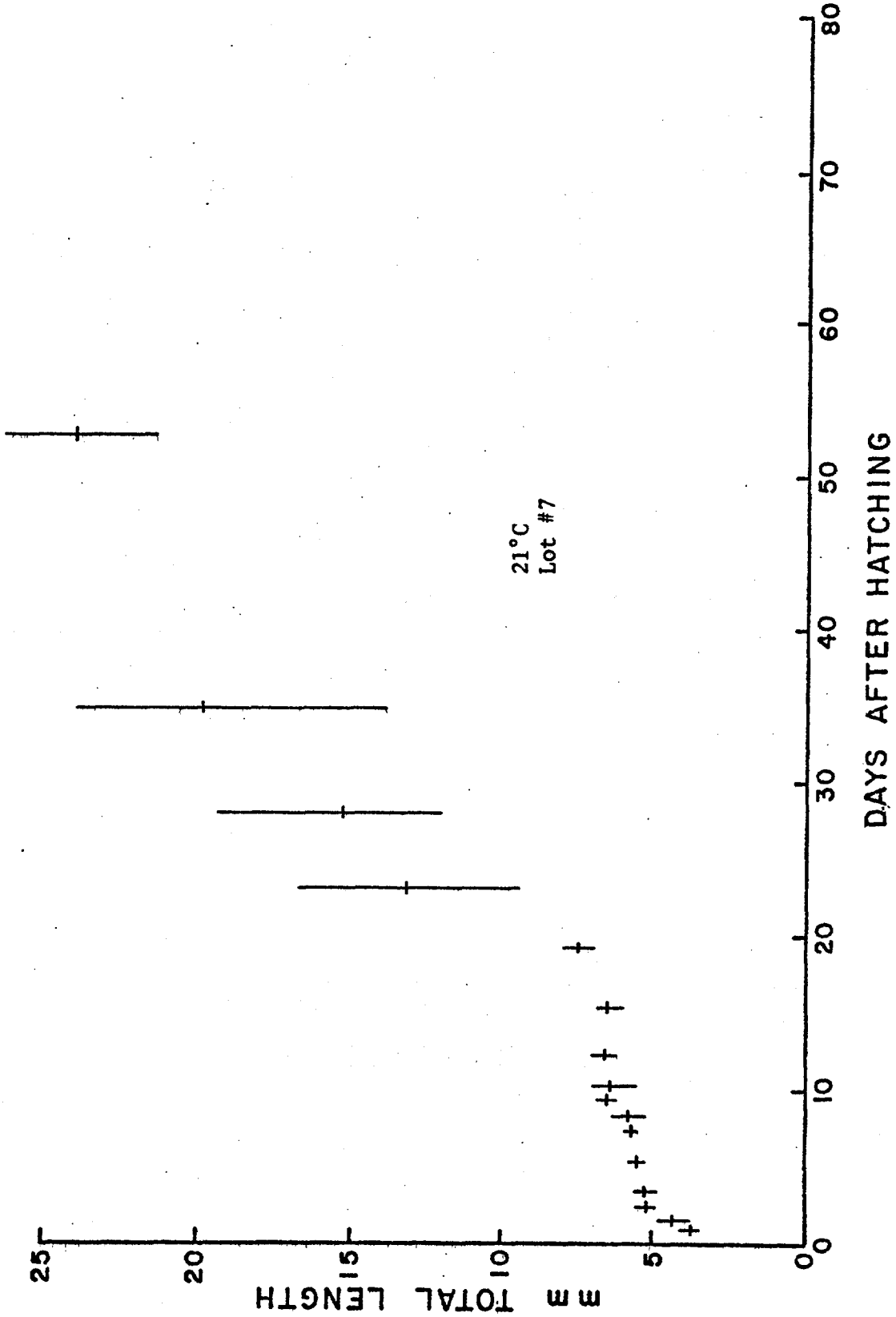
0
10
20
30
40


21°C
Lot #7
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DAYS AFTER HATCHING
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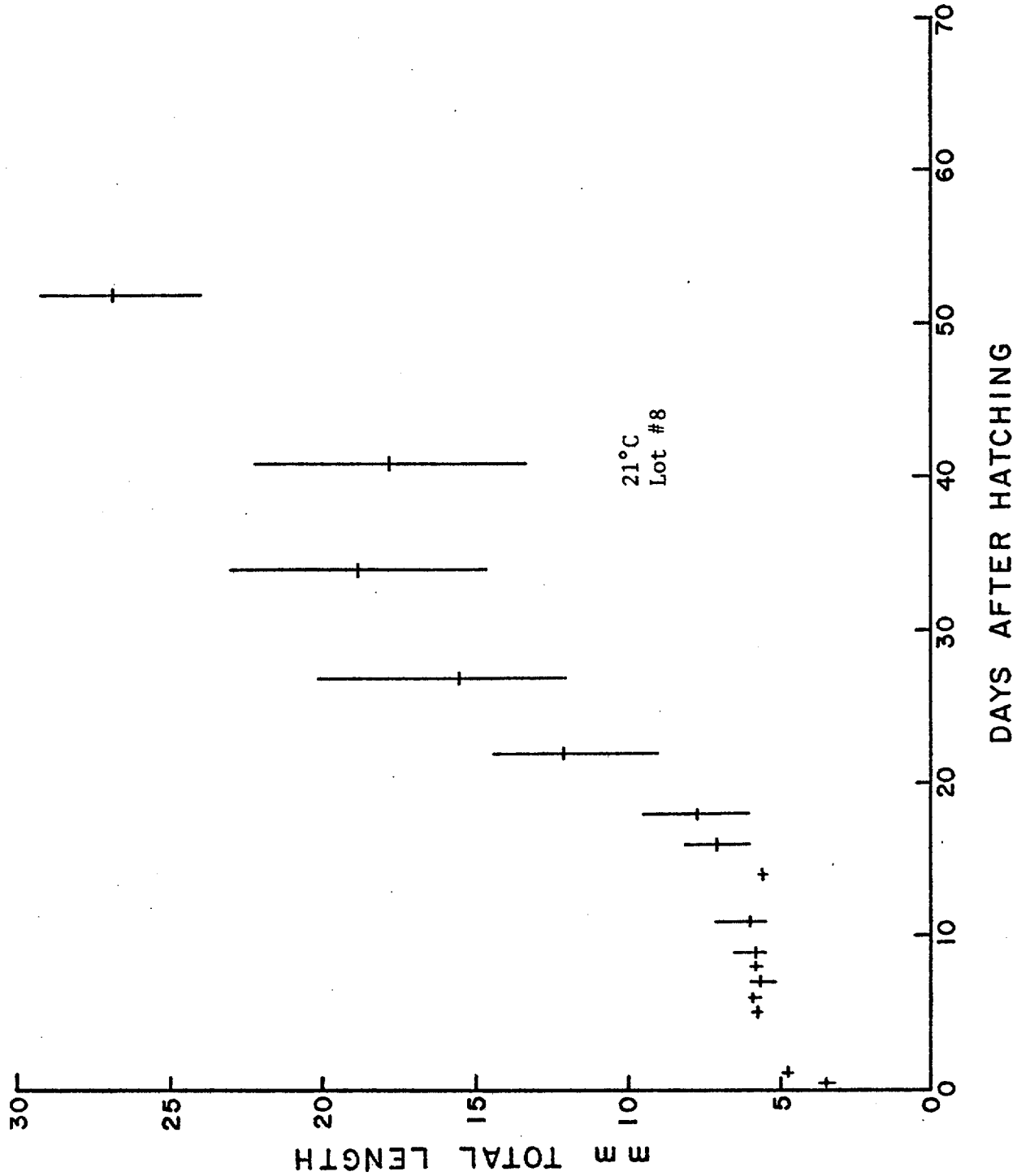
15
20
25
0
10
20
30
40
50
60
70
80


21°C
Lot #8
DAYS AFTER HATCHING
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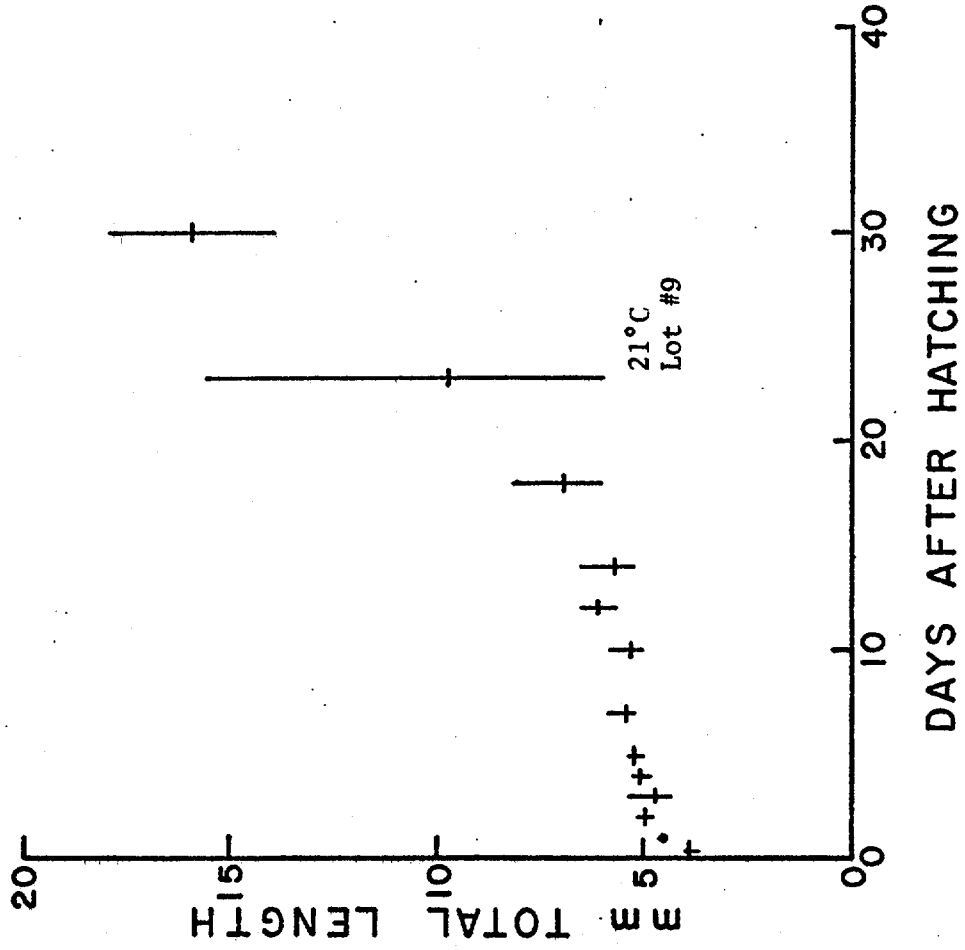
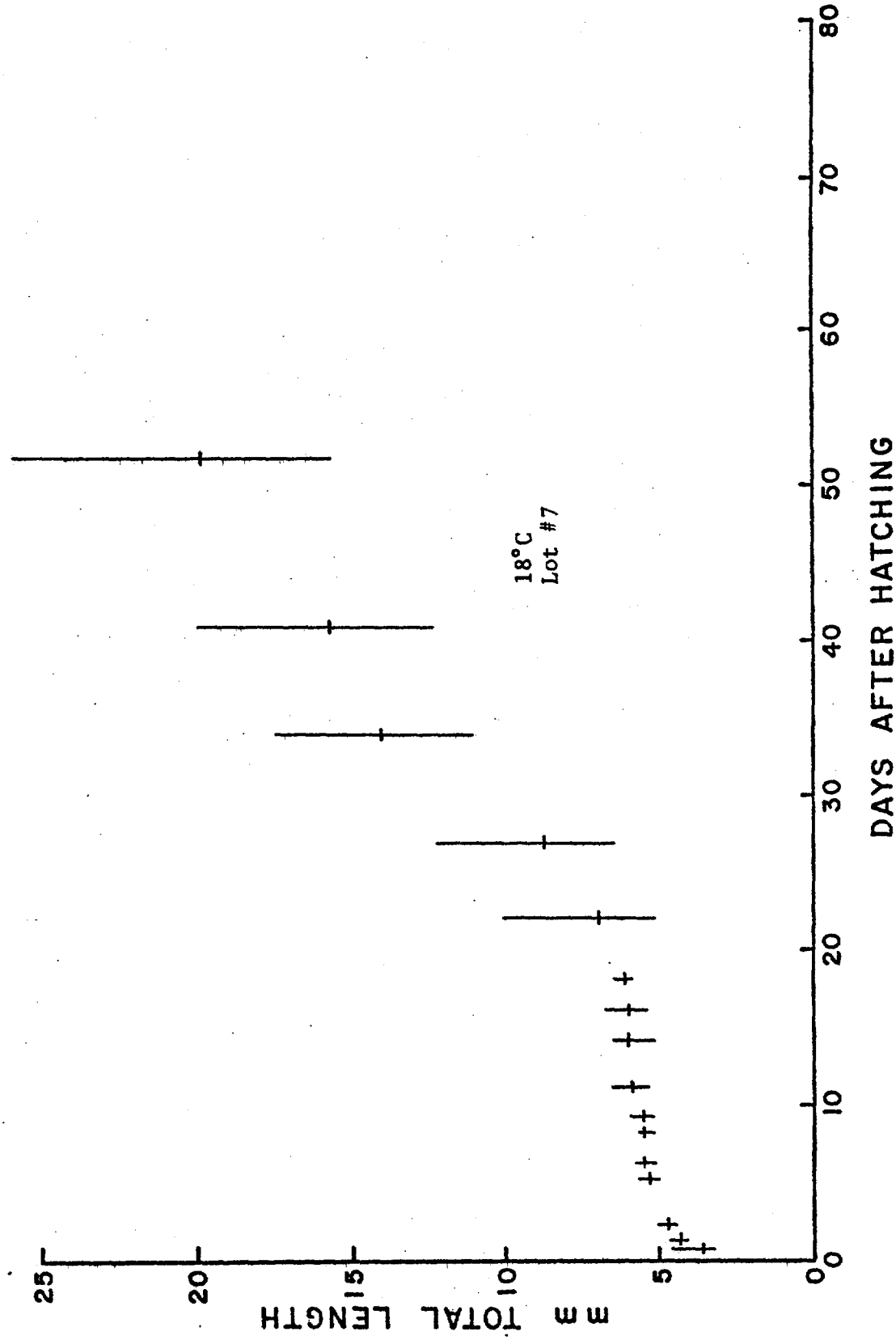
25
30


21°C
Lot #9
mm TOTAL LENGTH
DAYS AFTER HATCHING
0
5
10
15
20
0
10
20
30
40


18°C
Lot #7
mm TOTAL LENGTH
DAYS AFTER HATCHING
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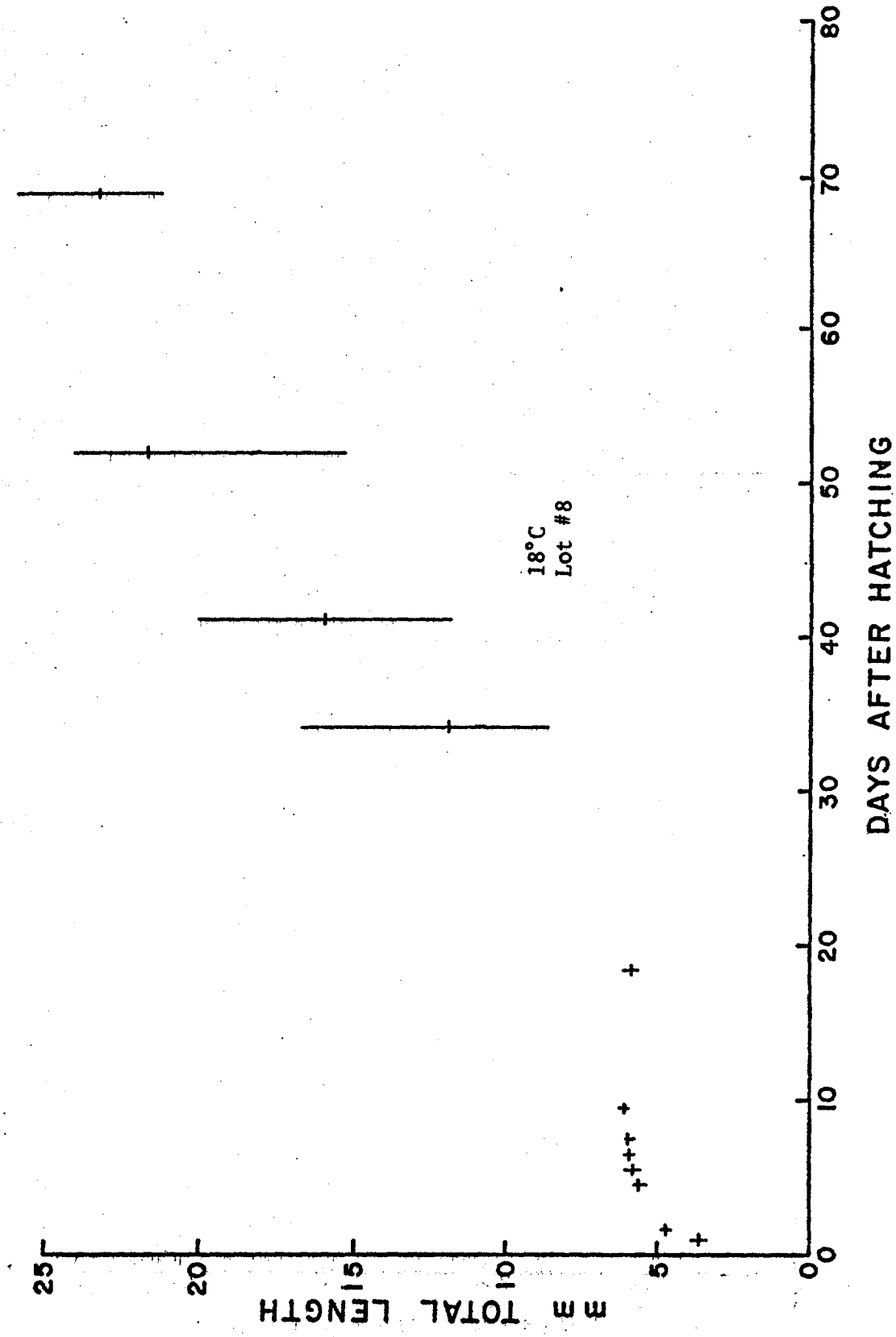
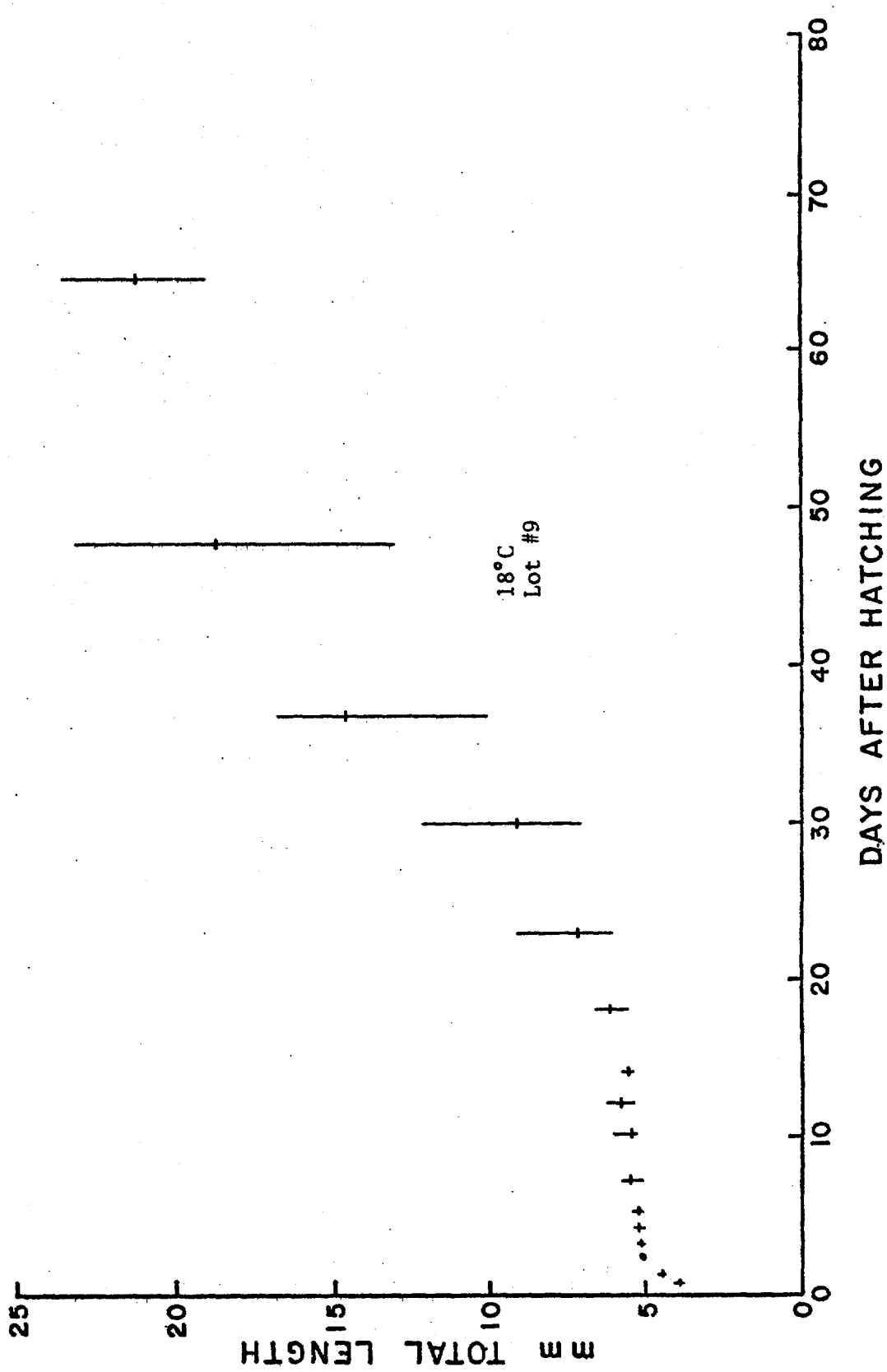
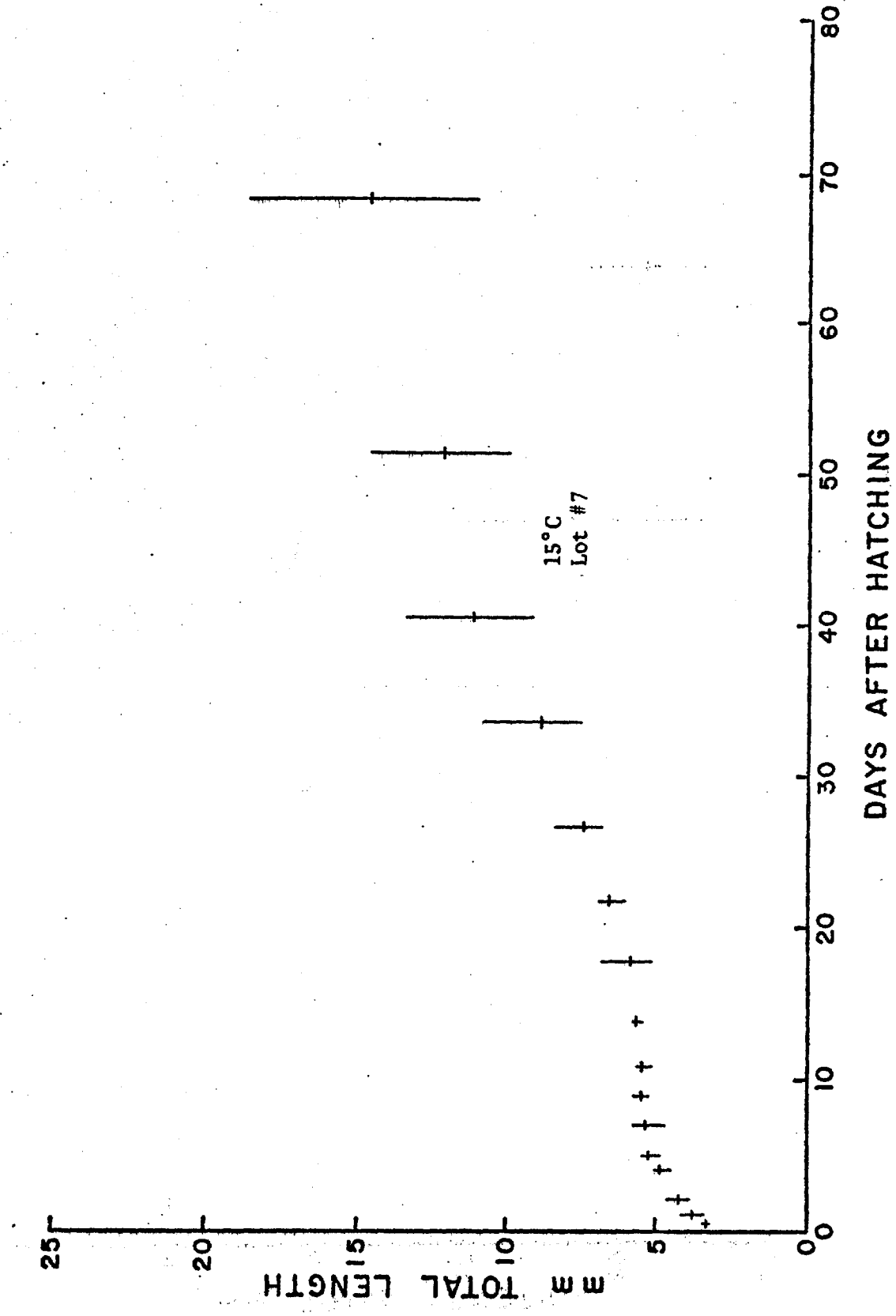
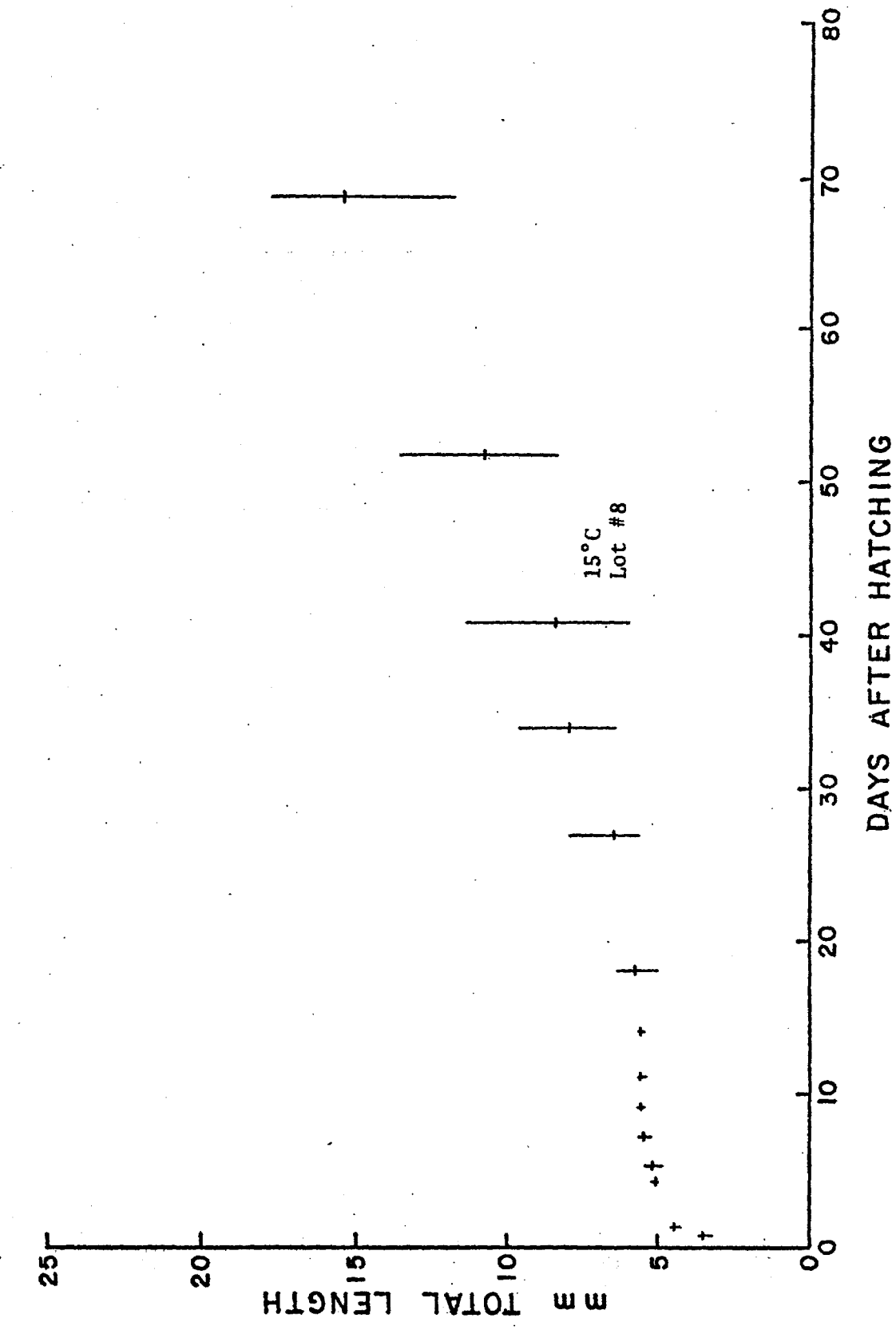
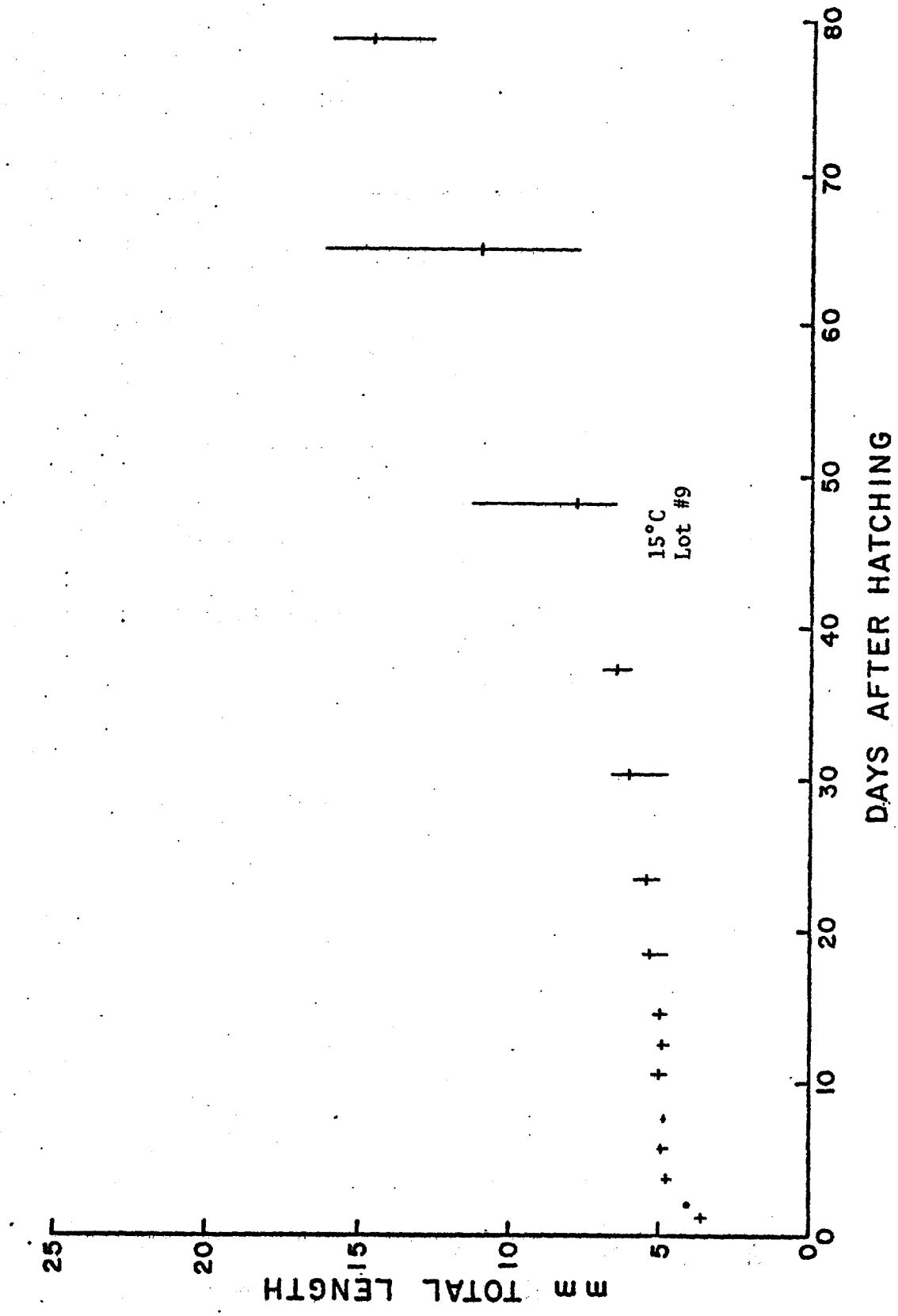
5
10
15
20
25
10
20
30
40
50
60
70
80

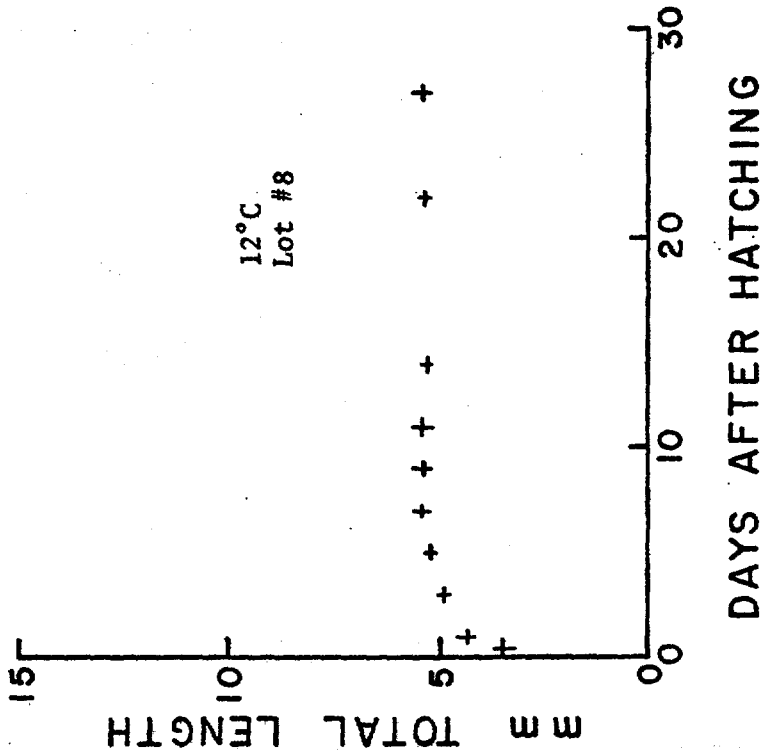

18°C
Lot #8
mm TOTAL LENGTH
DAYS AFTER HATCHING
0
5
10
15
20
25
0
10
20
30
40
50
60
70
80

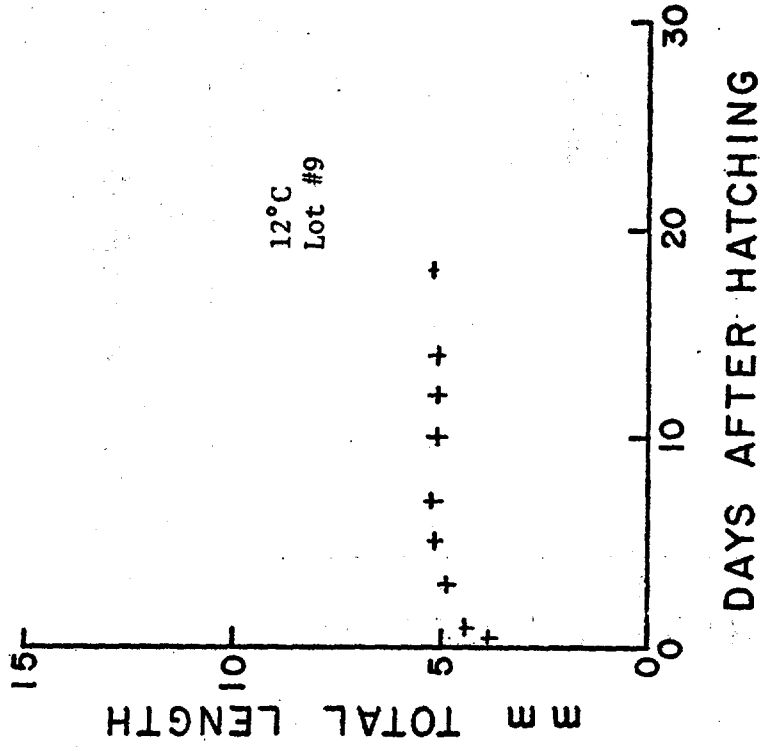

18°C
Lot #9
mm TOTAL LENGTH
DAYS AFTER HATCHING
0
5
10
15
20
25
10
20
30
40
50
60
70
80


15°C
Lot #7
DAYS AFTER HATCHING
mm TOTAL LENGTH
0
5
10
15
20
25
30
40
50
60
70
80


15°C
Lot #8
mm TOTAL LENGTH
DAYS AFTER HATCHING
0
5
10
15
20
25
0
10
20
30
40
50
60
70
80


mm TOTAL LENGTH
0
5
10
15
20
25
0
10
20
30
40
50
60
70
80
DAYS AFTER HATCHING
15°C
Lot #9


12°C
Lot #8
mm TOTAL LENGTH
0
5
10
15
0
10
20
30
DAYS AFTER HATCHING

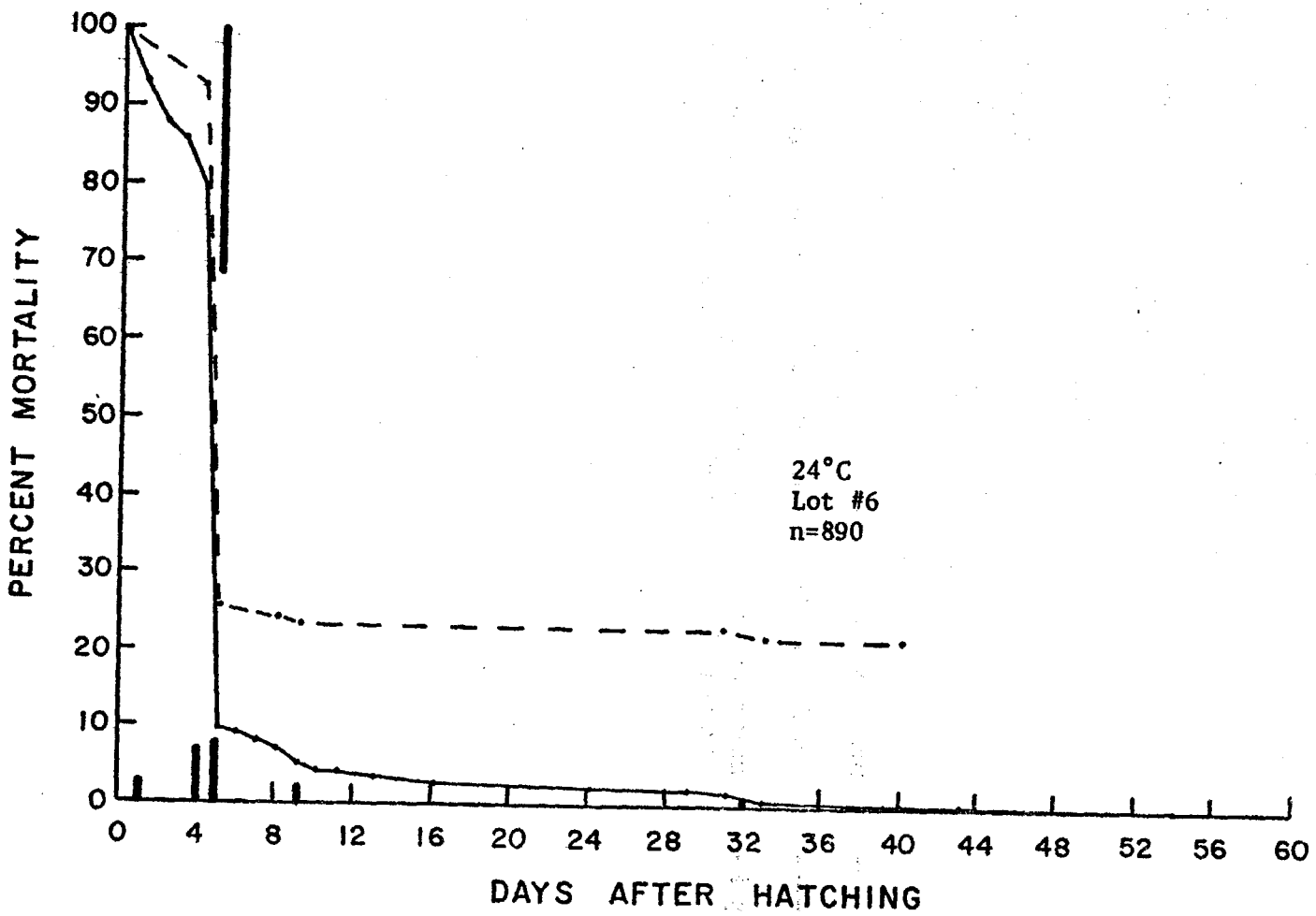

12°C
Lot #9
0
10
20
30
DAYS AFTER HATCHING
0
5
10
15
mm TOTAL LENGTH

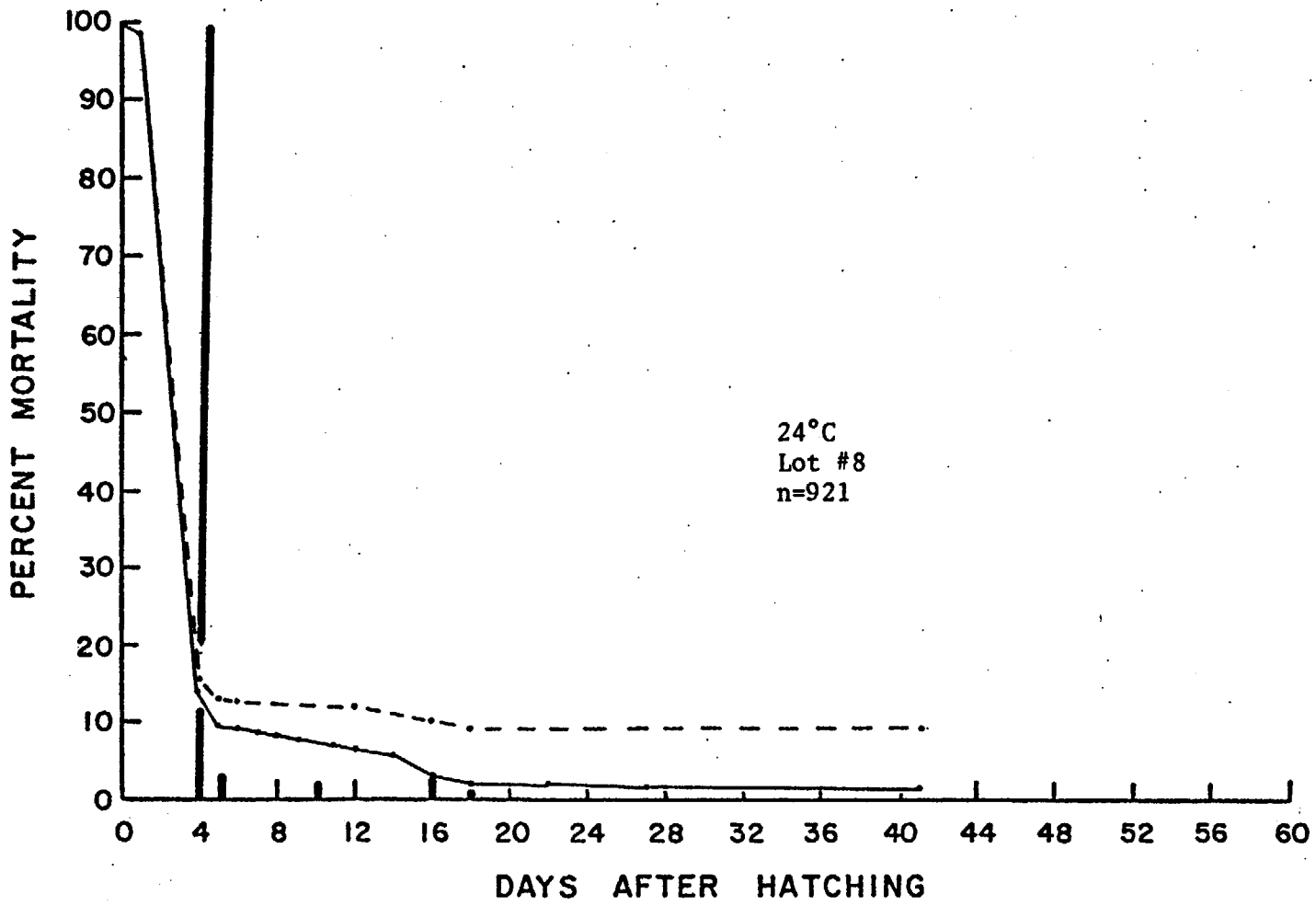
Appendix B

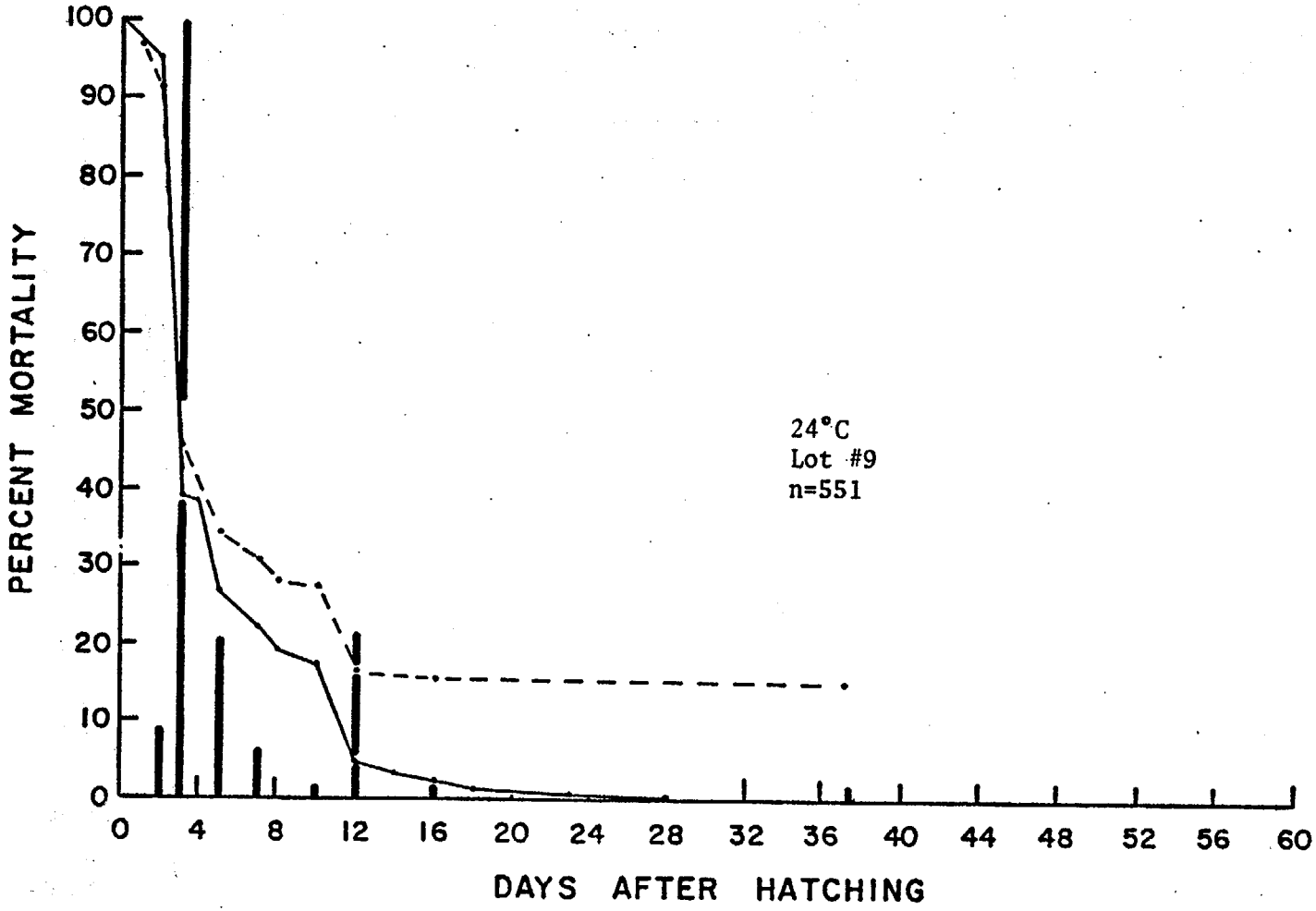
Larval Mortality Figures

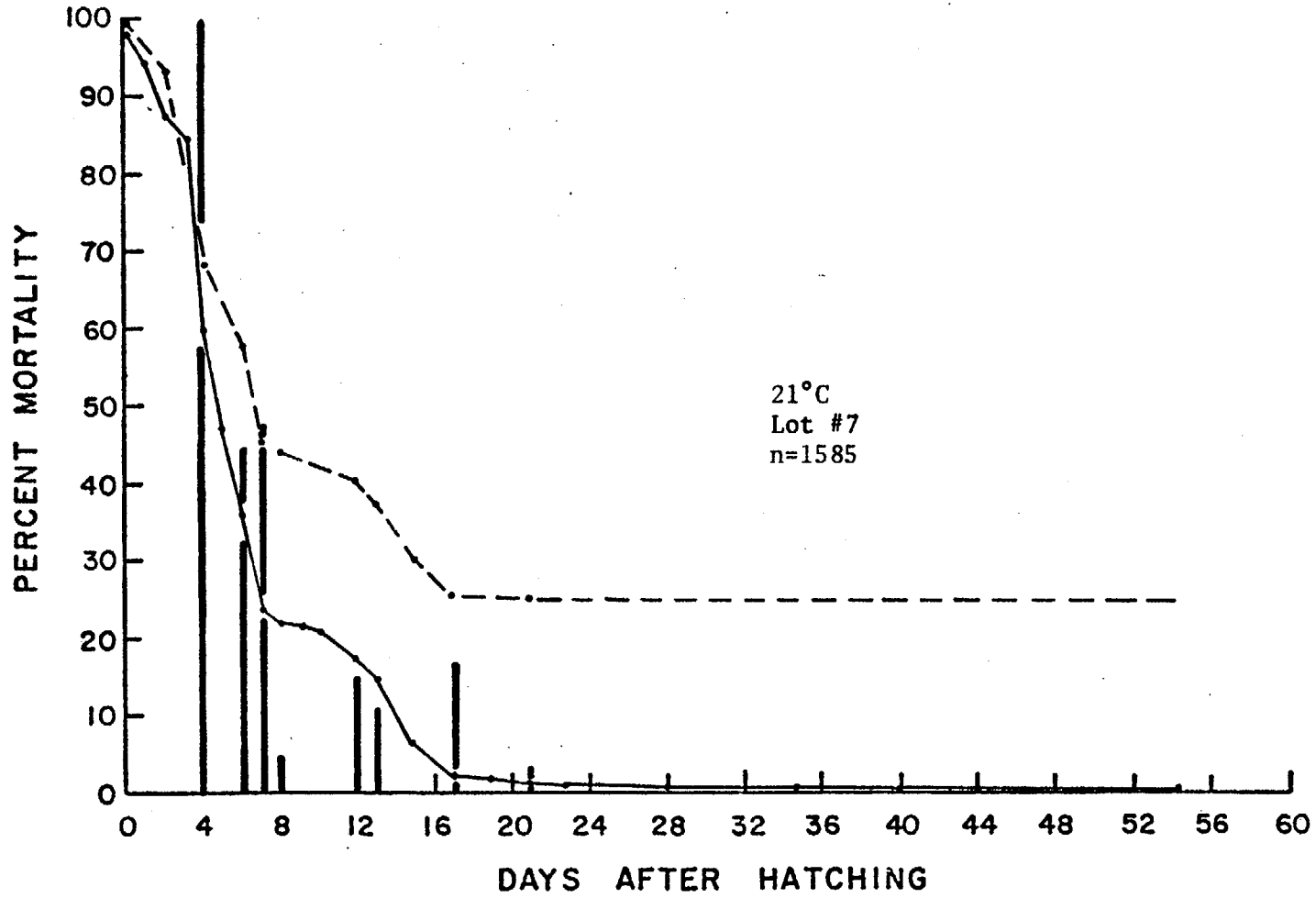
Legend

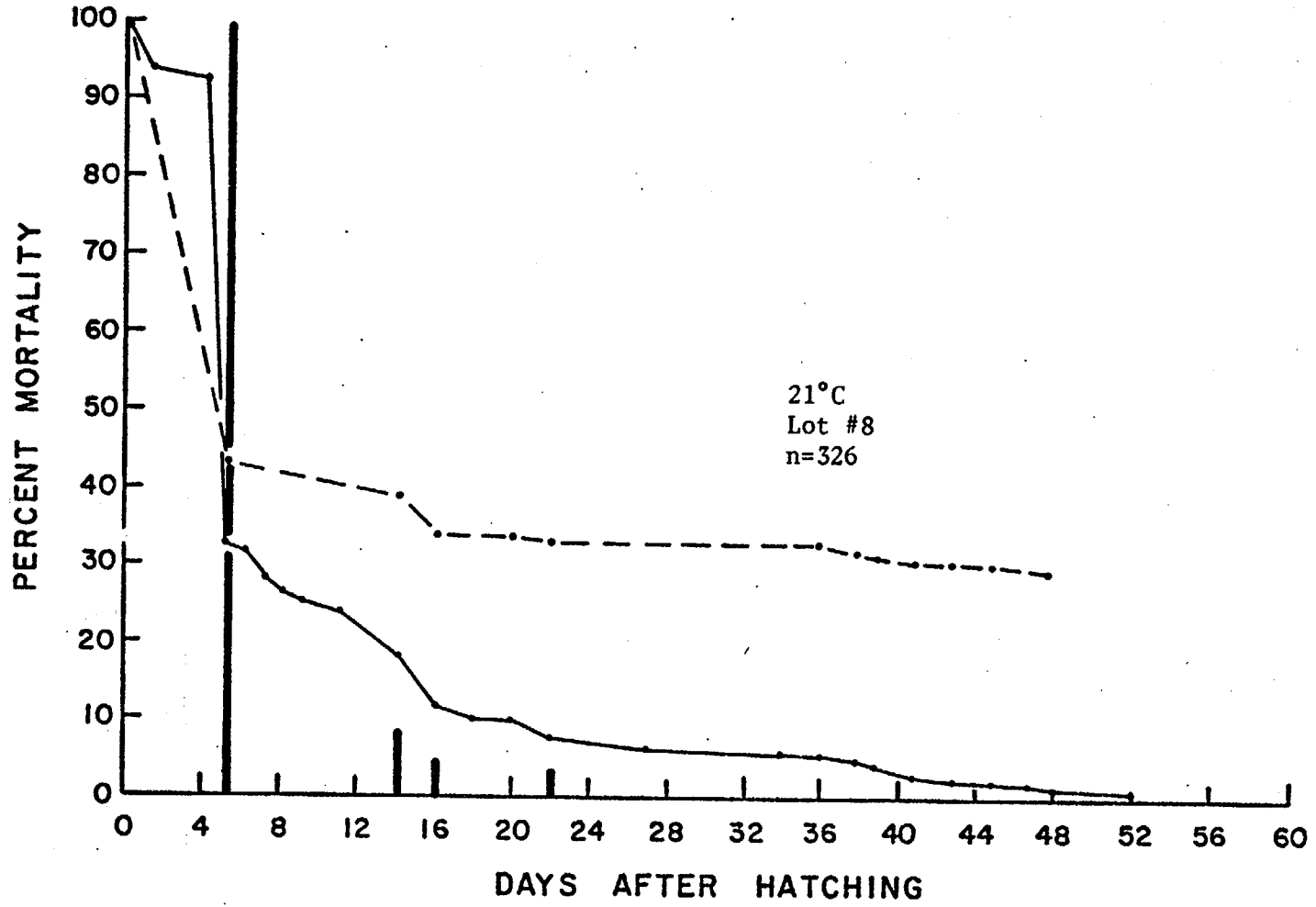
-----	non-sampling mortality
———	total mortality (sampling and non-sampling)
spike	mortality by day expressed as a percentage of the maximum observed mortality in one day

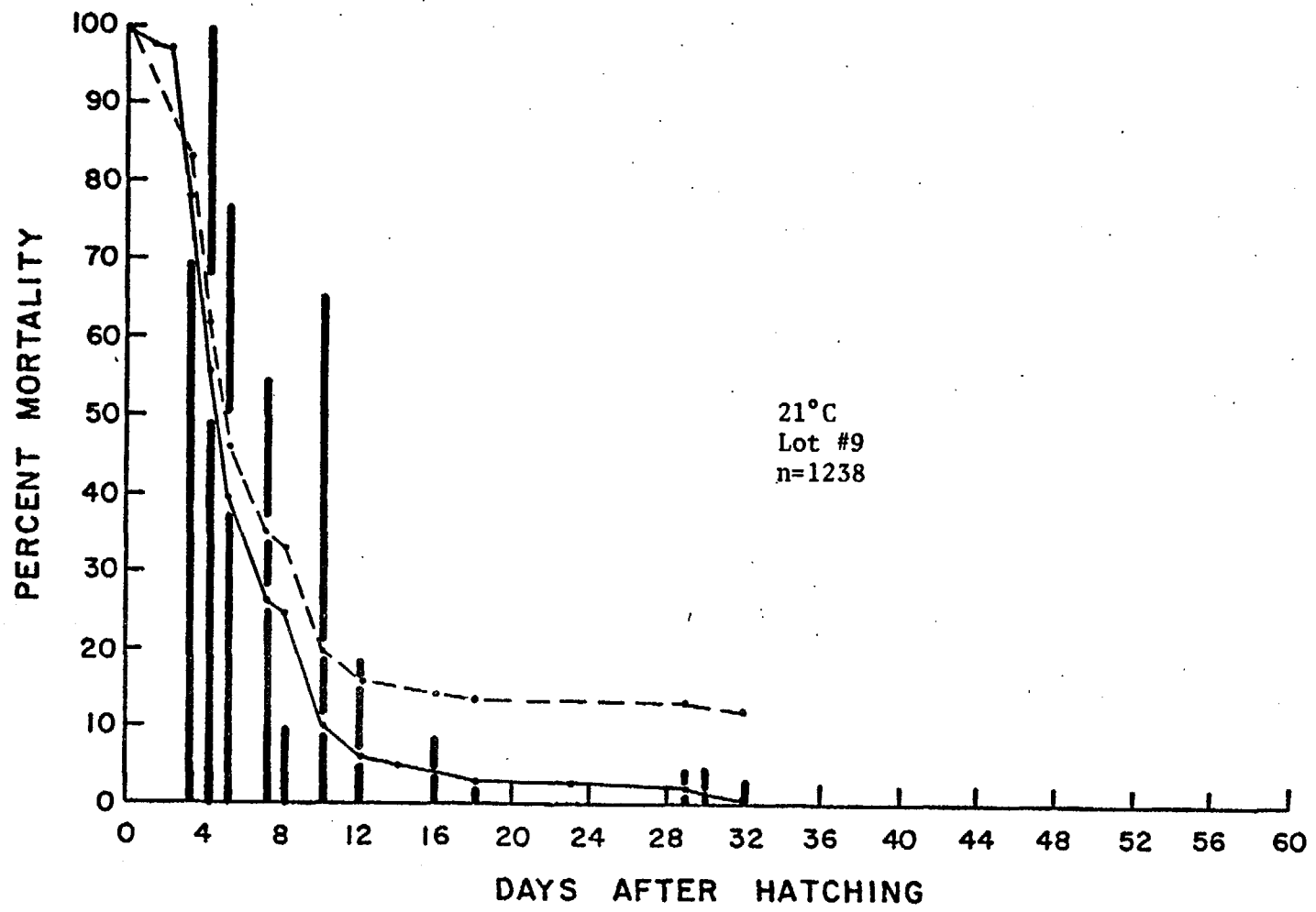

PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
DAYS AFTER HATCHING
24°C
Lot #6
n=890

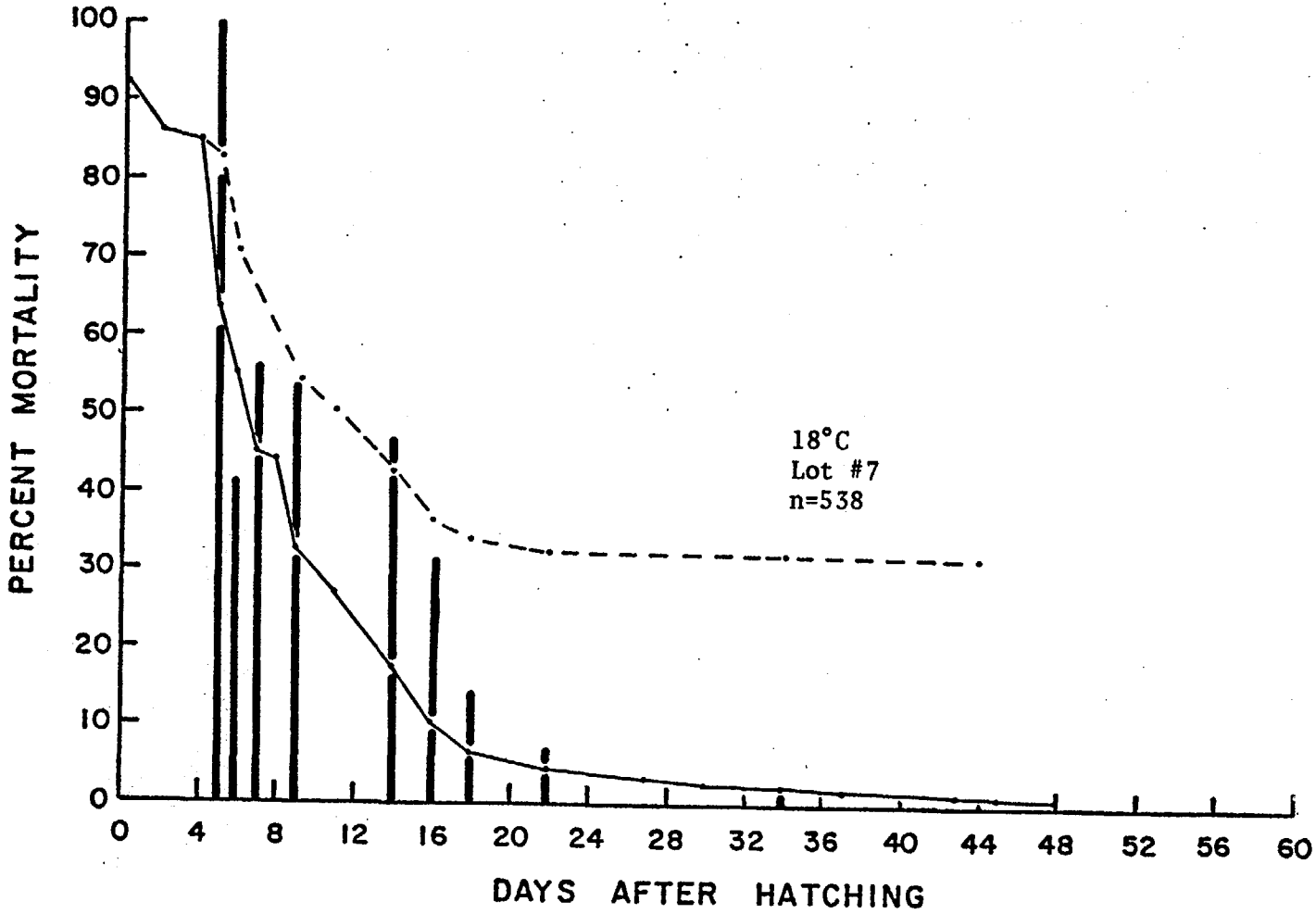

PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
DAYS AFTER HATCHING
24°C
Lot #8
n=921

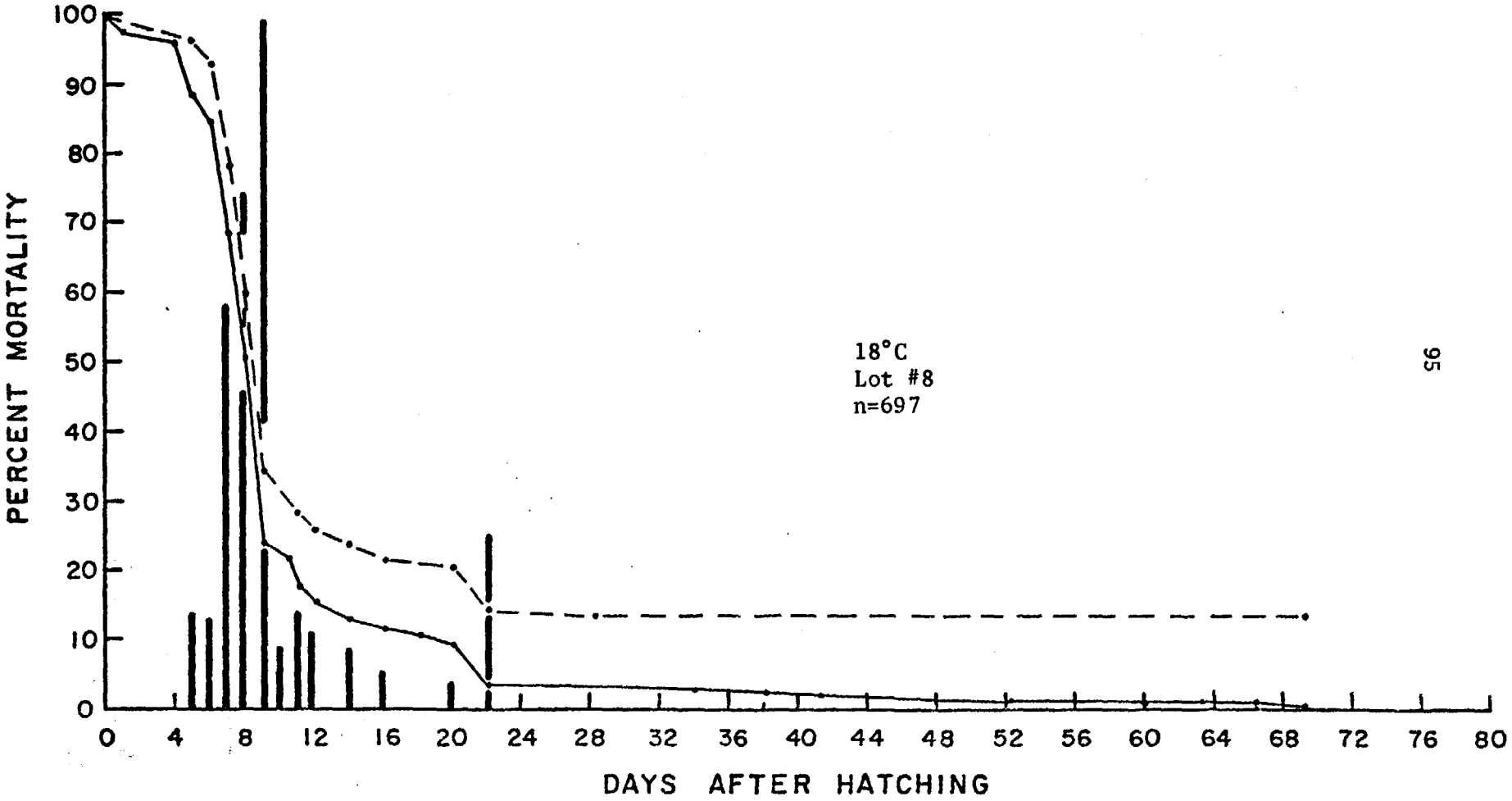

PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
DAYS AFTER HATCHING
24°C
Lot #9
n=551

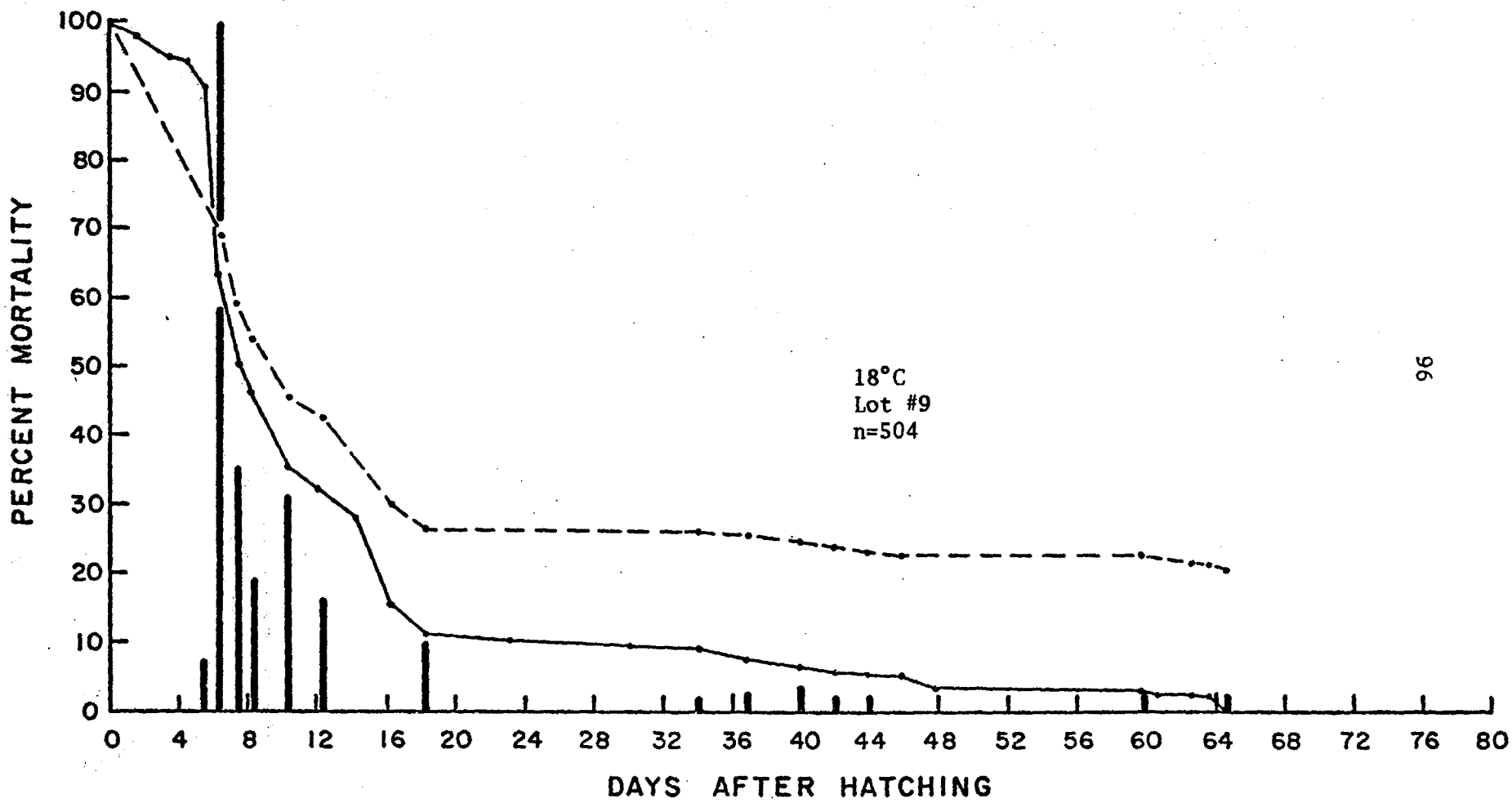

PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
DAYS AFTER HATCHING
21°C
Lot #7
n=1585

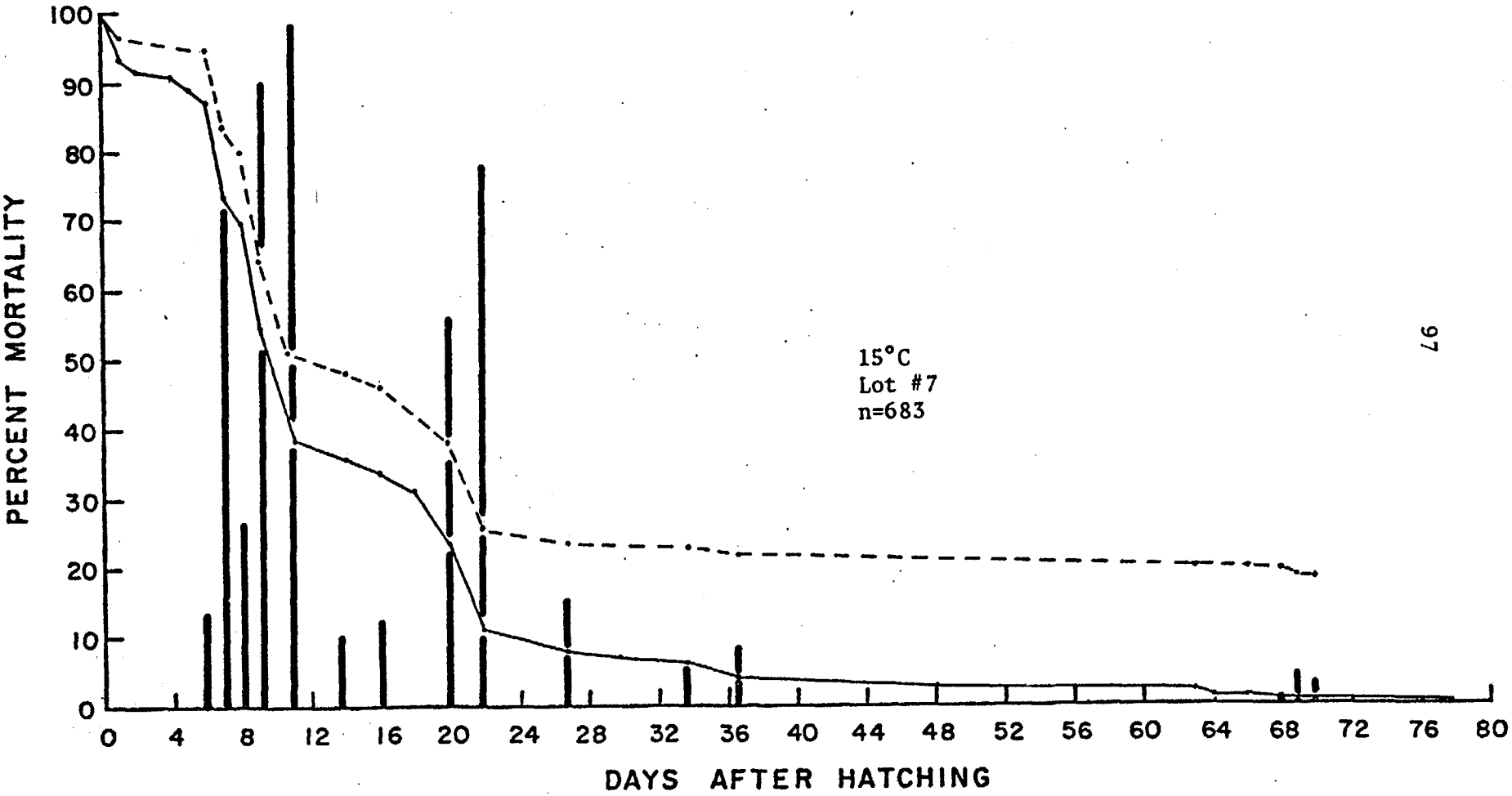

PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
DAYS AFTER HATCHING
21°C
Lot #8
n=326

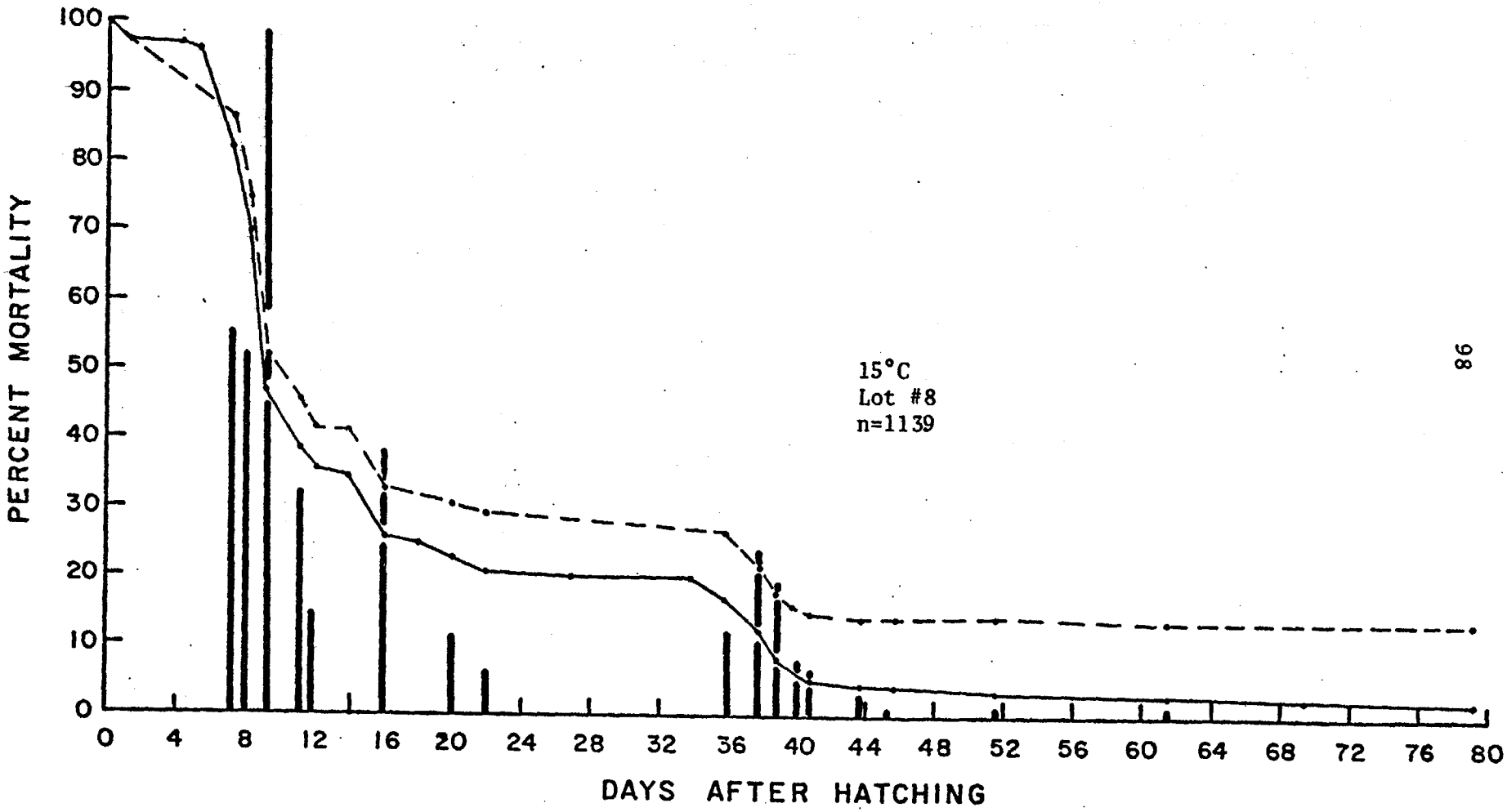

PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
DAYS AFTER HATCHING
21°C
Lot #9
n=1238

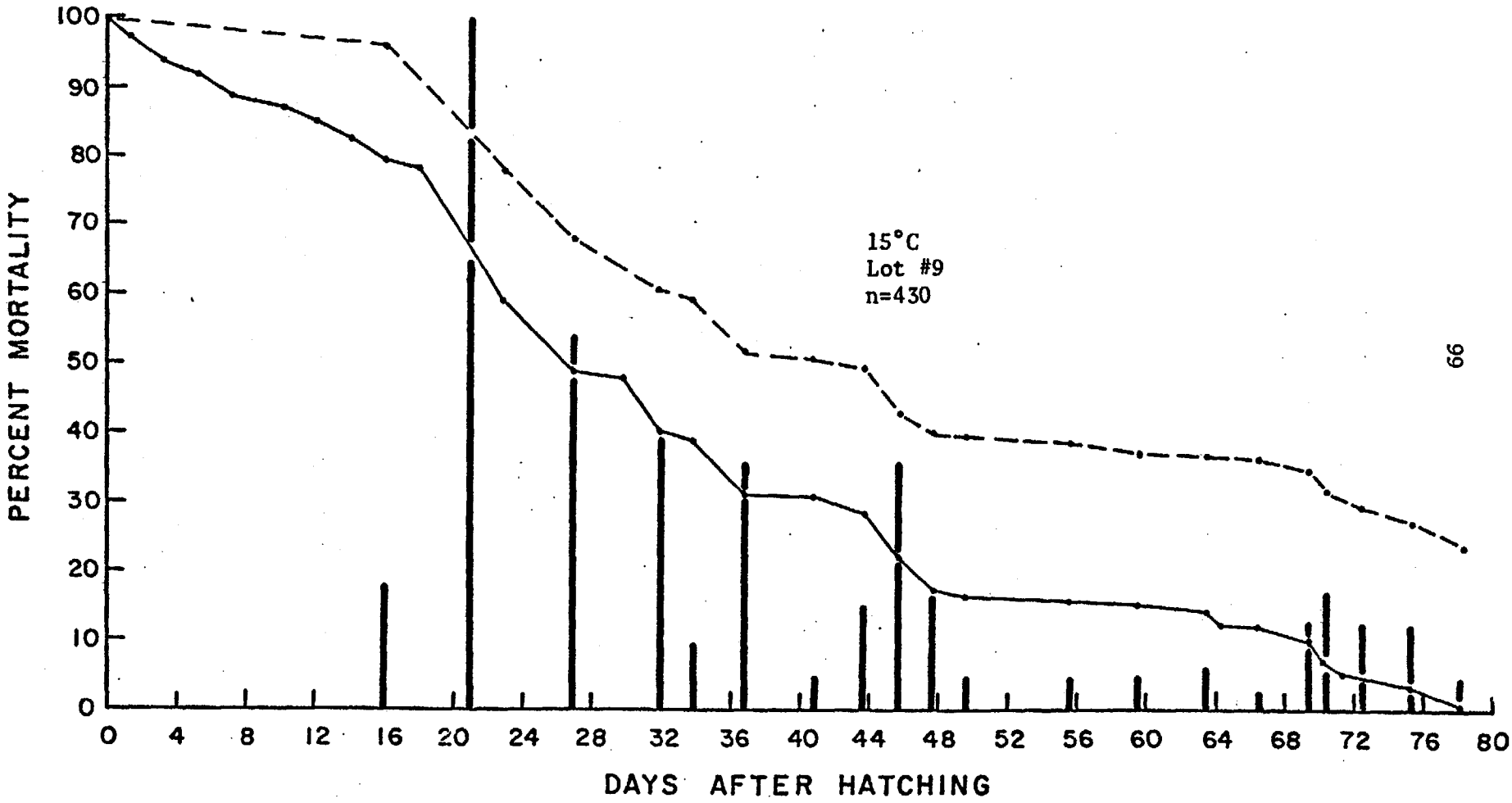

PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
DAYS AFTER HATCHING
18°C
Lot #7
n=538

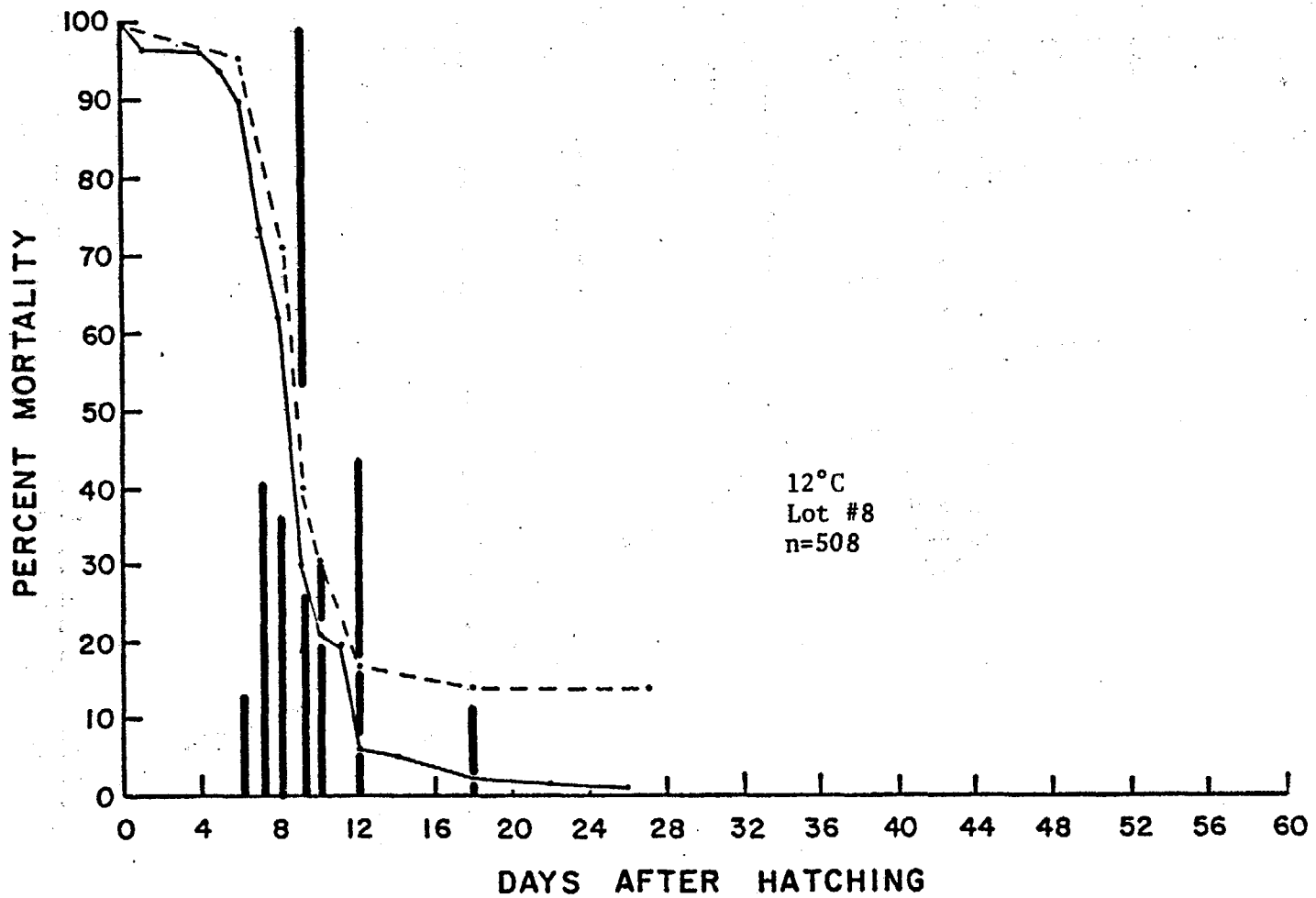

PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80
DAYS AFTER HATCHING
18°C
Lot #8
n=697

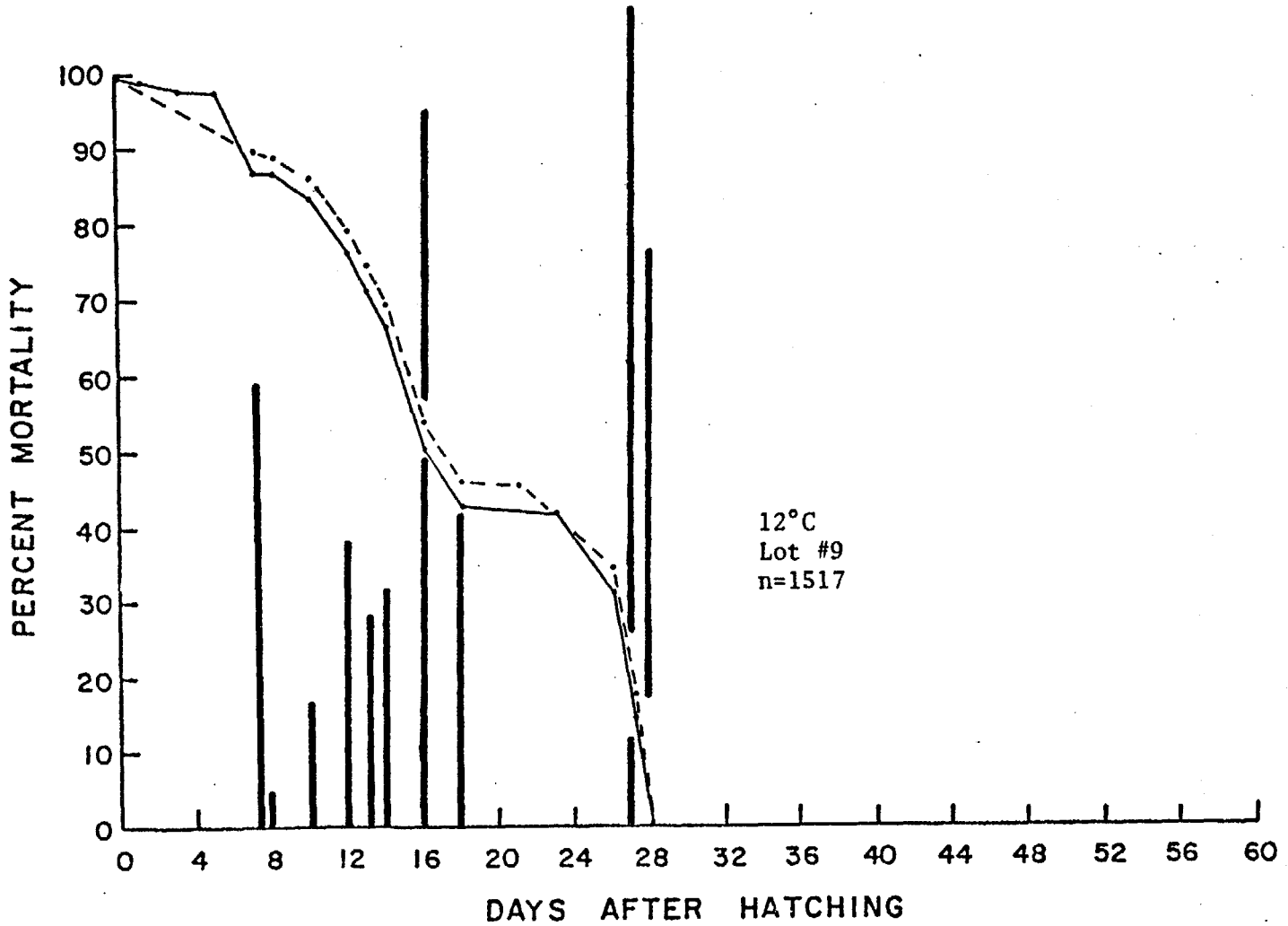

PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80
DAYS AFTER HATCHING
18°C
Lot #9
n=504


PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80
DAYS AFTER HATCHING
15°C
Lot #7
n=683


PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80
DAYS AFTER HATCHING
15°C
Lot #8
n=1139


PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72 76 80
DAYS AFTER HATCHING
15°C
Lot #9
n=430


PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
DAYS AFTER HATCHING
12°C
Lot #8
n=508


PERCENT MORTALITY
100
90
80
70
60
50
40
30
20
10
0
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
DAYS AFTER HATCHING
12°C
Lot #9
n=1517

Appendix C

APPENDIX C

TABULATED GROWTH DATA USED IN LIFE STAGE DURATION STUDIES

Lot #6 — Temperature 24°C

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
34	1	4.79 4.88 (5) 4.96 5.04 5.12	4.920	0.100
44	1	4.71 (2) 4.88 (2) 4.96 (2) 5.04 (3)	4.911	0.129
48	2	4.88 (2) 4.96 (2) 5.04 (2) 5.12	5.449	0.338
52	2	5.04 5.20 5.36 5.44 (3) 5.53	5.350	0.1715
56	2	5.53 5.44 5.69 (3) 5.85 (2)	5.675	0.152
60	2	5.36 5.44 5.53 (2) 5.61 5.69 (3) 5.77	5.587	0.133

*Number in parenthesis is the number that length in the sample.

Lot #6, Temp. 24°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
64	2	5.85 5.93 6.01	5.673	0.195
68	2	5.20 5.44 (2) 5.53 (2) 5.61 (2) 5.69 (4) 5.85 (2) 5.93 6.01	5.649	0.210
76	3	5.36 (2) 5.53 5.61 5.69 (2) 5.77 5.85	5.721	0.210
84	3	5.53 5.85 5.93 6.01 6.18	5.898	0.241
92	3	5.53 5.69 6.26	5.822	0.383
100	4	5.69 5.77 5.85 (2)	5.789	0.078
108	4	5.69 (2) 5.85	5.741	0.094
116	4	5.20 5.36 (2) 5.69 6.01 (2)	5.606	0.352
124	5	4.79 4.88 4.96 5.04 (2) 5.20 5.36 (2) 6.18 (3)	5.377	0.543

Lot #6, Temp. 24°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
132	5	4.88 5.20 5.53 5.85 6.01	5.492	0.465
	7	4.88 5.36 5.85 6.50	5.647	0.694
	8	5.20 (2) 5.36 5.69 5.85 (2) 6.01 6.99 7.15	5.922	0.713
	9	5.53 6.34 7.15	6.337	0.813
	10	5.36 5.53 (2) 5.85 6.50 8.45 8.61	6.546	1.406
	11	5.36 8.29 9.42	7.690	2.094
	12	6.66 7.15 8.61 9.42	7.961	1.278
	14	8.45 9.42 10.08 9.75 9.10	9.359	0.625
	17	9.10 9.59 9.91	9.035	0.741

Lot #6, Temp. 24°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	25	12.40 14.00 14.40	13.600	0.106
	30	21.20 18.20 18.40	19.267	1.677
	54	30.30 29.65 26.65 26.80 26.90	28.060	1.765

Lot #6		Temperature 18°C		
H†	0	4.39 (4) 4.46 (2) 4.55 (2) 4.63	4.468	0.091
4	1	4.23 4.39 4.55 (6)	4.489	0.121
8	1	4.39 4.47 (2) 4.55 (10) 4.63 (4) 4.71 (2)	4.567	0.079
12	1	4.39 4.55 4.71 4.79 (3) 4.88 (4) 4.96	4.771	0.167
16	1	4.79 4.88 (11) 4.96 (5) 5.04 (3)	4.915	0.067

†Sample near end of hatching time.

Lot #6, Temp. 18°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
20	1	4.88 5.20	4.915	
24	1	4.88 (2) 4.96 5.04 (4) 5.12 5.20 (3)	5.052	0.120
28	2	4.88 (2) 4.96 (2) 5.04 (2) 5.12 (2) 5.20	5.019	0.113
32	2	5.20 (2) 5.28 (3) 5.36 (2)	5.281	0.066
40	2	5.04 (2) 5.12 5.20 5.36	5.151	0.136
48	2	5.20 (2) 5.36 (2) 5.44	5.313	0.108
66	3	5.53 (3)		
74	3	5.20 5.77	5.482	
82	3	5.69		
90	4	5.36 5.53 5.69 (2)	5.565	0.156
98	4	5.53 5.69 5.85	5.687	0.163
	9	5.69 5.85 (2) 6.01	5.850	0.133
	10	5.53 5.69 5.85 (3) 6.01 (2)	5.827	0.174

Lot #6, Temp. 18°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	11	5.53 5.69 6.01 (2)	5.809	0.244
	16	6.01 (2) 6.18 (2) 7.31	6.337	0.551
	54	14.80 12.30 17.10	14.733	2.401
Lot #7		Temperature 21°C		
H†	0	3.25 3.33 (3) 3.41 (4)	3.361	0.060
4	0	3.49 3.58 (2)	3.547	0.048
8	0	3.41 3.58 (3) 3.66 (3) 3.82 3.74 (7)	3.672	0.103
12	1	3.58 3.66 3.74 (3) 3.82 (2) 3.90 (4) 4.06	3.930	0.179
16	1	3.98 4.06 (6) 4.23 (2)	4.089	0.082
24	1	4.06 4.41 4.23 4.38 (3)	4.310	0.139

†Sample near end of hatching time.

Lot #7, Temp. 21°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
32	1	4.55 (2) 4.63 (2) 4.59	4.590	0.040
40	2	4.88 (2) 4.96 5.04 (3)	4.969	0.080
48	2	4.88 (2)		
56	2	4.71 4.88 (2) 5.04 5.20 (3) 5.28	5.047	0.206
64	3	4.88 (4) 4.96 5.04 (3) 5.12 (2) 5.20 (3)	5.031	0.130
72	3	4.71 (3) 4.88 (7) 5.04 (8) 5.12 5.20 (3) 5.28 5.36 4.96 (3)	4.992	0.166
	5	5.04-5.53		
	7	5.36 5.53 (3) 5.69	5.525	0.115
	8	5.04 5.20 5.69 6.01 6.18	5.622	0.496
	9	6.01 6.18 6.34 6.66	6.297	0.277

Lot #7, Temp. 21°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	10	5.36 6.01 6.18 6.34 6.50 6.83	6.202	0.498
	12	6.01 (2) 6.34 (2) 6.50 6.66 6.83	6.384	0.307
	15	5.85 6.18 6.34 6.66 (2)	6.337	0.344
	19	6.83 7.31 7.80	7.312	0.488
	23	9.30 10.80 13.65 15.30 16.70	13.150	3.075
	28	11.90 19.40	15.237	
	35	13.80 24.00	18.900	
	53	26.60 25.55 24.25 22.45 21.65	24.100	2.068

Lot #7		Temperature 18°C		
H†	0	3.25 (2) 3.41 (8) 3.49 (2) 3.58 (3) 3.66	3.448	0.111

†Sample near end of hatching time.

Lot #7, Temp. 18°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
4	0	3.41 3.49 3.58 3.74	3.469	0.121
8	0	3.74 (3) 3.90 3.82 3.66 4.14 4.23 4.39	3.926	0.260
16	0	4.71		
24	1	4.23 (2) 4.31 4.39 (3)	4.319	0.080
32	1	4.39 4.55	4.467	
40	1	4.55 4.63 4.71	4.631	0.081
48	2	4.55 (2) 4.63 (2) 4.67 4.79 (2) 4.88 (2)	4.707	0.129
56	2	4.71 4.88 (3) 5.04 (4)	4.936	0.121
92	4	5.53 (6)		
128	5	5.04 5.36 (4) 5.53 (4) 5.69	5.427	0.175
152	6	5.20 5.36 5.53 5.85 (2)	5.557	0.291
	8	5.20 5.53 5.69 (3)	5.537	0.212

Lot #7, Temp. 18°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	9	5.36 (3) 5.53 5.69 5.85 6.01	5.594	0.263
	11	5.53 5.69 (2) 5.85 6.34 6.50	5.931	0.395
	14	5.36 6.01 6.34 (2) 6.66	6.142	0.493
	16	5.53 5.85 (2) 6.01 6.18 (3) 6.34 (2) 6.50 6.83	6.160	0.352
	18	6.01 (2) 6.18 6.34 6.50	6.207	0.212
	22	5.36 (2) 6.01 8.45 10.35	7.107	2.214
	27	6.66 7.64 7.80 9.70 12.45	8.850	2.294
	34	16.90 17.80 13.40 12.20 11.30	14.320	2.882
	41	12.60 15.00 20.40	16.000	3.995

Lot #7, Temp. 18°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	52	26.50 21.50 21.20 20.90 19.30 19.80 17.00 16.00	20.275	3.199

Lot #7		Temperature 15°C		
8	0	3.25 3.41	3.330	
16	0	3.41 3.49	3.450	
24	1	3.58 3.66 (2) 3.74 3.82	3.688	0.092
32	1	4.06 (4) 4.23	4.095	0.073
40	2	3.90 4.06 (4) 3.98 4.23 (2)	4.072	0.110
48	2	4.23 4.39 4.55 4.71	4.351	0.227
84	4	4.55 5.04 (2)	4.875	0.281
120	5	4.88 5.04 5.20 5.36 (4) 5.53 (3)	5.314	0.217

Lot #7, Temp. 15°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
169	7	4.71 5.04 5.20 5.36 5.26 5.69 (4) 5.85	5.443	0.361
	9	5.36 (2) 5.53 (2) 5.85 (2)	5.579	0.222
	11	5.20 (2) 5.69 (5)	5.548	0.238
	14	5.53 5.69 (3) 5.85	5.687	0.115
	18	5.20 5.36 5.53 5.69 (4) 5.85 (2) 6.83 6.99	5.850	0.558
	22	6.18 6.66 (2) 6.99	6.622	0.335
	27	6.99 7.15 7.48 (2) 8.61	7.540	0.636
	34	7.64 (2) 8.13 10.50 11.00	8.980	1.638
	41	9.60 9.30 12.00 13.60 11.80	11.260	1.797

Lot #7, Temp. 15°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	52	14.70 14.80 12.70 12.30 11.80 10.10 11.20 10.80	12.300	1.720
	69	18.90 16.30 15.30 11.20 12.20	14.780	3.124
	83	18.50		

Lot #8		Temperature 24°C		
	0	3.25 3.33 3.41 3.49 (8) 3.52 3.58 (25) 3.66 (6) 3.74	3.557	0.084
	1	4.71 4.79 (2) 4.71 4.88 (6) 4.96 5.04 (2)	4.868	0.102
	4	5.04 5.36 5.53	5.308	0.248
	5	5.04 (5) 5.20 (3)	5.098	0.084
	6	5.36 5.53 (2)	5.471	0.094

Lot #8, Temp. 24°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	7	4.88 (2)		
		5.36		
		5.53	5.502	0.491
		5.85		
		6.01 (2)		
	8	6.18		
		6.50	6.744	0.488
		7.15 (2)		
	9	6.18		
		6.50		
		7.15	6.784	0.537
		7.31		
	11	6.99		
		7.48	7.540	0.337
		7.64		
		7.80 (2)		
	14	6.50		
		6.99		
		7.15	7.150	0.445
		7.48		
		7.64		
	16	7.75		
		7.50		
		7.95	7.690	0.233
		7.40		
		7.85		
	22	8.75		
		9.70		
		9.50	10.540	2.525
		9.75		
		15.00		
	27	14.50		
		11.00	15.267	4.697
		20.30		
	41	15.50		
		17.75	16.625	1.591
	52	26.60		
		23.65		
		27.80		
		29.55		
		26.00	25.979	2.283
		25.25		
		23.00		

Lot #8		Temperature 21°C		
Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	0	3.25 3.33 3.41 3.49 (8) 3.52 3.58 (25) 3.66 (6) 3.74	3.557	0.084
	1	4.71 (7) 4.79 (2) 4.63 4.88 (7)	4.784	0.086
	4	5.53 (3)		
	5	5.53 5.69 (5) 6.01 (2)	5.748	0.172
	6	5.69 6.01 (2)	5.904	0.188
	7	5.20 (2) 5.69 (3) 5.85 (3) 6.01	5.669	0.287
	8	5.69 5.85 6.01 (2)	5.890	0.156
	9	5.53 5.69 (3) 6.50	5.817	0.388
	11	5.53 5.69 (2) 6.18 7.15	6.045	0.664
	14	5.53 (2) 5.69 (3)	5.622	0.089
	16	6.01 7.15 8.13	7.096	1.058

Lot #8, Temp. 21°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	18	6.01 6.66 6.99 9.50 9.25	7.682	1.587
	22	10.80 14.40 14.00 12.50 9.00	12.140	2.256
	27	20.10 17.50 12.30 12.00	15.475	3.985
	34	14.60 23.00	18.800	
	41	22.25 13.35	17.800	
	52	29.45 27.30 24.00	26.920	2.745

Lot #8		Temperature 18°C		
	0	3.25 3.33 3.41 3.49 (8) 3.52 3.58 (25) 3.66 (6) 3.74	3.557	0.084
	1	4.55 (2) 4.63 (2) 4.71 (6) 4.79 (3)	4.693	0.082
	4	5.36 5.53 (3) 4.69 (3)	5.571	0.123

Lot #8, Temp. 18°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	5	5.53 5.69 (6) 5.85 (5) 6.01	5.762	0.126
	6	5.69 5.85 (2) 6.01	5.850	0.133
	7	5.69 5.85 (2) 6.01 (2)	5.882	0.136
	9	5.85 (2) 6.01 (2) 6.18 (2)	6.012	0.145
	18	5.69 (2) 5.85 6.01	5.809	0.156
	34	11.40 10.00 14.00 10.30 16.80 8.65	11.858	3.013
	41	11.85 20.25	16.050	
	52	23.70 15.40 24.35 22.40 23.60	21.890	3.696
	69	26.15 24.60 21.45 22.10	23.575	2.189

Lot #8		Temperature 15°C		
Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	0	3.25 3.33 3.41 3.49 (8) 3.52 3.58 (25) 3.66 (6) 3.74	3.557	0.084
	1	4.39 (3) 4.47 (2) 4.55 (10) 4.63	4.510	0.073
	4	5.04 5.20 (3)	5.160	0.082
	5	4.88 5.04 5.20 (2) 5.36 5.53	5.120	0.230
	7	5.36 5.53 (3) 5.69	5.525	
	9	5.53 (3) 5.69	5.566	0.081
	11	5.53 (4) 5.69 (3)	5.594	0.087
	14	5.53 (2) 5.69 (2)	5.606	0.093
	18	5.04 5.53 (4) 5.69 5.85 6.18 (2) 6.50	5.752	0.428
	22	5.36 5.53 6.50 6.99	6.094	0.779

Lot #8, Temp. 15°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	27	5.85 5.69 6.34 6.50 6.66 8.00	6.506	0.823
	34	6.50 6.99 9.80 7.50 9.65	8.087	1.537
	41	6.34 6.01 8.60 8.70 9.35 9.40 11.50	8.557	1.890
	52	8.50 10.70 10.50 10.80 11.50 13.80	10.967	1.715
	69	18.00 14.10 12.05 15.70 18.10 16.10 16.00	15.736	2.131
	83	19.65		

Lot #8	Temperature 12°C		
	0	3.25 3.33 3.41 3.49 (8) 3.52 3.58 (25) 3.66 (6) 3.74	3.557	0.084

Lot #8, Temp. 12°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	1	4.23 (2) 4.31 4.39 (4) 4.47 (2) 4.55 (3)	4.407	0.116
	4	4.88 5.04 (2)	4.983	0.094
	5	5.20 (3) 5.36 (2)	5.265	0.089
	7	5.36 5.53 (2) 5.69	5.525	0.133
	9	5.36 5.53 (4) 5.69 (2)	5.548	0.112
	11	5.36 (2) 5.53 5.69 (3)	5.552	0.160
	14	5.20 5.53 (4)	5.460	0.145
	22	5.36 5.53 (4)	5.492	0.073
	67	5.36 5.69	5.525	0.230
Lot #9		Temperature 24°C		
	0	3.74 (3) 3.90 4.06	3.835	0.145
	1	4.55 (3) 4.71 (3) 4.88	4.666	0.123
	2	5.04 5.20 (4) 5.36	5.200	0.103

Lot #9, Temp. 24°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	3	4.88 (3) 5.04 (2)	4.940	0.089
	4	5.04 5.20 (2) 5.36 5.53 5.69	5.335	0.239
	5	4.88 5.04 (5)	5.010	0.066
	7	5.04 5.36 (2) 5.53 5.76	5.410	0.265
	10	5.20 5.69 5.85 6.01 (2)	5.752	0.337
	12	5.36 5.69 (3) 5.85	5.655	0.178
	14	5.36 5.85 6.01 6.18 6.34 6.50	6.039	0.404
	18	6.18 6.34 (2) 7.15 13.75	7.950	3.265
	23	11.00 15.50 21.50	16.000	5.268

Lot #9		Temperature 21°C		
	0	3.74 (3) 3.90 4.06	3.835	0.145

Lot #9, Temp. 21°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	1	4.55 (5)		
	2	4.88		
		5.04 (3)	4.997	0.081
	3	4.39 (3)		
		5.04	4.712	0.460
		5.36		
	4	4.88		
		5.04 (5)	5.010	0.066
	5	5.04 (2)		
		5.20 (2)	5.223	0.146
		5.36 (3)		
	7	5.20 (4)		
		5.36		
		5.53	5.480	0.253
		5.69 (4)		
		5.85		
	10	5.36		
		5.69	5.395	0.371
		5.85		
	12	5.69		
		6.01 (2)		
		6.34	6.142	0.371
		6.66		
	14	5.20		
		5.36 (2)		
		5.53	5.757	0.521
		6.01		
		6.34		
		6.50		
	18	6.01		
		6.34	6.987	1.028
		7.31		
		8.29		
	23	6.01		
		7.48		
		7.80	9.807	3.998
		12.00		
		15.75		
	30	14.00		
		18.00	16.000	

Lot #9		Temperature 18°C		
Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	0	3.74 (3) 3.90 4.06	3.835	0.145
	1	4.39 (2) 4.55 (3)	4.485	0.089
	2	5.04 (5)		
	3	5.04 (4) 5.20	5.070	0.073
	4	5.04 (2) 5.20 5.36	5.159	0.156
	5	5.04 (2) 5.20 (2) 5.36	5.167	0.136
	7	5.04 5.20 5.53 (2) 5.69	5.395	0.267
	10	5.20 (4) 6.01	5.362	0.363
	12	5.36 (2) 5.85 6.18	5.687	0.398
	14	5.36 (2) 5.53 (3)	5.460	0.089
	18	5.53 5.69 5.85 6.50 (2)	6.012	0.460
	23	6.18 6.01 6.83 7.48 9.25	7.147	1.310

Lot #9, Temp. 18°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	30	7.05 8.00 12.25 8.85 9.60	9.150	1.977
	37	16.90 15.75 16.65 14.00 10.10	14.680	2.801
	48	20.60 20.50 18.05 16.65 21.25 23.50 17.25 13.15	18.869	3.245
	65	23.85 20.55 19.70 19.30 20.10 23.60 21.99 22.65	21.468	1.790

Lot #9	Temperature 15°C		
	0	3.74 (3) 3.90 4.06	3.835	0.145
	1	4.39 (5)		
	3	5.04 (3) 4.88 5.20	5.037	0.115
	5	5.04 5.20 (5) 5.36	5.200	0.094

Lot #9, Temp. 15°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	7	5.04 (2) 5.20 (3)	5.135	0.089
	10	5.04 5.20 (3) 5.53	5.232	0.178
	12	5.04 (2) 5.20 5.36 (2)	5.200	0.163
	14	5.04 5.20 (3) 5.53	5.232	0.178
	18	5.04 5.53 5.85 (2)	5.566	0.384
	23	5.36 5.69 6.18	5.741	0.409
	30	5.04 6.66 6.50 (2) 6.99	6.337	0.754
	37	6.34 (2) 6.66 6.99 7.31	6.727	0.424
	48	6.83 7.31 (3) 7.96 8.13 11.75	8.085	1.675
	65	8.94 8.13 8.61 9.70 16.75 13.50 14.00	11.375	3.348

Lot #9, Temp. 15°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
	79	16.25 14.25 16.40 15.73 13.00	15.126	1.461
Lot #9		Temperature 12°C		
	0	3.74 (3) 3.90 4.06	3.835	0.145
	1	4.39 (2) 4.55 (3)	4.485	0.089
	3	4.71 5.04 (4)	4.972	0.145
	5	5.20 (4) 5.36	5.232	0.072
	7	5.20 (2) 5.28 5.36 (2)	5.281	0.081
	10	5.04 5.20 (2) 5.36	5.200	0.133
	12	5.04 (2) 5.36 (2)	5.200	0.188
	14	5.04 (2) 5.20 (2) 5.36	5.167	0.136
	18	5.20 (2) 5.36 (3)	5.297	0.089
Lot #5		Temperature 15°C		
1	0	3.58 (2) 3.66 (5) 3.74 (13) 3.82 (3) 3.90 (3)	3.737	0.086

Lot #5, Temp. 15°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
6	0	3.74 (2) 3.90 (5) 3.98 4.06 (2)	3.908	0.111
10	0	4.06 (5) 4.14 (2) 4.23 (6)	4.150	0.078
14	0	3.90 4.06 4.14 (2) 4.23 (7) 4.31 4.39	4.193	0.117
18	0	4.06 4.23 (4)	4.192	0.073
36	1	4.55 (2) 4.71 (3)	4.647	0.089
40	2	4.79 5.20 5.04	5.010	0.210
48	2	5.04 (3)		
64	3	5.36 (4) 5.53 (2)	5.281	0.237
100	5	5.36 (4) 5.53 (2) 5.69	5.455	0.128
108	6	5.53 (4) 5.69 5.61	5.565	0.068
Lot #7		Temperature 24°C		
4	0	3.58 (4) 3.66 (3) 3.74	3.625	0.060

Lot #7, Temp. 24°C, continued

Hours After Hatching	Days After Hatching	Total Length* (mm)	Mean Length	Standard Deviation
8	0	3.41 3.58 (5) 3.66 3.74	3.585	0.091
12	0	3.74 (2) 3.82 3.90 (2)	3.818	0.082
16	0	3.82 3.90 (2) 3.98 (2) 4.06 (7) 3.94	3.996	0.084
20	1	4.06 (4) 4.14 4.23 (5) 4.39	4.173	0.105
24	1	3.58 4.23 4.31 4.39 (7)	4.281	0.254
32	1	4.55 (3)		
40	1	4.71 (3)		
48	2	4.63 4.88	4.753	
56	2	4.71 4.88 5.04	4.875	0.163
64	2	4.79 5.53	5.159	0.518
72	3	4.88 4.96 5.04 (3) 5.12	5.010	0.084
80	3	4.88 5.04 (2) 5.36 5.53	5.167	0.267

TABULATED MORTALITY DATA USED IN

LIFE STAGE DURATION STUDIES

Lot #6, Temperature 24°C — Hatched 5/24/75, 890 Stocked

Days After Hatching	Number in Live Sample	Number of Dead Removed
1	39	17
2	51	
3	17	
4	14	43
5	21	600
6	4	
7	9	
8	3	8
9	8	10
10	3	
11	5	
13	5	
16	5	
24	3	
29	3	
31		3
32		10
33		2
40		1
43		1
54	5	

Lot #6, Temperature 18°C — Hatched 5/25/75, 1178 Stocked

0	26	173
1	75	
2	27	
3	9	183
4	8	476
9	5	80
10	8	74
11	4	
16	5	20
47		2
54	3	

Lot #7, Temperature 21°C — Hatched 5/26/75, 1585 Stocked

Days After Hatching	Number in Live Sample	Number of Dead Removed
0	40	
1	35	
2	17	88
3	47	
4		403
5	200	
6		178
7	5	192
8	11	20
9	4	
10	6	
12	7	59
13		44
15	7	123
17		67
19	3	
21		11
23	5	
28	5	
35	2	
40	1	
55	5	

Lot #7, Temperature 18°C — Hatched 5/27/75, 538 Stocked

0	43	
1	15	6
2	18	
4	6	
5	20	95
6	6	39
7		54
8	5	
9	7	54
11	6	25
14	5	44
16	11	30
18	5	14
22	5	6
27	5	
30	5	
34		1
37	3	

Lot #7, Temp. 18°C, continued

Days After Hatching	Number in Live Sample	Number of Dead Removed
43		1
44		1
45		1
48	8	

Lot #7, Temperature 15°C — Hatched 5/27/75, 683 Stocked

0	6	
1	14	20
2	13	
4	4	
5	15	
6		14
7	18	76
8		28
9	6	96
11	7	105
14	5	11
16		13
18	11	
20		60
22	5	83
27	5	16
30	5	
34		7
37	5	9
48	8	
63		1
64	5	
66		1
68		2
69		5
70		3
78	1	

Lot #8, Temperature 24°C — Hatched 5/27/75, 921 Stocked

0		
1	15	
4	3	778
5	11	29
6	3	
7	7	
8	4	

Lot #8, Temp. 24°C, continued

Days After Hatching	Number in Live Sample	Number of Dead Removed
9	4	
11	5	
12		10
14	5	
16	5	17
18		8
22	5	
27	3	
41	2	
52	7	

Lot #8, Temperature 21°C — Hatched 5/27/75, 326 Stocked

0		
1	18	
4	3	
5	14	185
6	4	
7	11	
8	4	
9	5	
11	5	
14	5	14
16	5	16
18	5	
20		1
22	5	2
27	4	
34	2	
36		1
38		3
39		2
41	2	2
43		1
45		1
47		1
48		1
52	3	

Lot #8, Temperature 18°C — Hatched 5/27/75, 697 Stocked

0		
1	17	
4	8	
5	30	25

Lot #8, Temp. 18°C, continued

Days After Hatching	Number in Live Sample	Number of Dead Removed
6	5	23
7	5	105
8		127
9	7	179
10		16
11		26
12		19
14		15
16		10
18	5	
20		8
22		46
34	6	
38		1
41	2	
52	5	
65		1
66		1
69	4	1

Lot #8, Temperature 15°C — Hatched 5/27/75, 1139 Stocked

0		
1	16	
4	4	
5	14	
7	20	144
8		138
9	7	261
11	8	84
12		36
14	5	5
16		98
18	16	
20		27
22	4	15
27	6	
34	5	
36		30
38		58
39		49
40		17
41	7	14
44		5
46		2
52	6	2

Lot #8, Temp. 15°C, continued

Days After Hatching	Number in Live Sample	Number of Dead Removed
62		2
69	7	
80		1
81		8
82		6
83	1	7

Lot #8, Temperature 12°C — Hatched 5/27/75, 508 Stocked

0		
1	12	
4	3	
5	13	
6		20
7	14	70
8		57
9	7	158
10		49
11	6	
12		70
14	5	
18		17
22	5	
27	2	

Lot #9, Temperature 24°C — Hatched 5/31/75, 551 Stocked

0		
1	15	
2	6	26
3	9	277
4	6	
5	6	59
7	8	17
8		17
10	5	3
12	10	60
14	10	
16		5
18	5	
23	3	
37		4

Lot #9, Temperature 21°C — Hatched 5/31/75, 1238 Stocked

Days After Hatching	Number in Live Sample	Number of Dead Removed
0		
1	16	
2	6	
3	54	205
4	6	260
5	7	200
7	20	142
8		24
10	5	170
12	11	47
14	7	
16		20
18	5	5
23	5	
29		8
30	2	8
32		5

Lot #9, Temperature 18°C — Hatched 5/31/75, 504 Stocked

0		
1	8	
2	5	
3	9	
4	4	
5	6	10
6		141
7	13	50
8		27
10	6	44
12	14	15
14	9	
16		64
18	5	17
23	5	
30	5	
34		2
37	5	3
40		5
41		1
42		3
44		3
46		1
48	8	

Lot #9, Temp. 18°C, continued

Days After Hatching	Number in Live Sample	Number of Dead Removed
60		2
61		2
63		1
64		1
65	8	3

Lot #9, Temperature 15°C — Hatched 5/31/75, 430 Stocked

0		
1	11	
3	14	
5	7	
7	15	
10	5	
12	10	
14	11	
16		14
18	5	
23	5	80
27		43
30	5	
32		32
34		7
37	5	28
41		3
44		11
46		28
48	7	13
50		3
56		3
60		3
64		4
65	7	
67		1
70		10
71		13
73		9
76		9
79	6	3

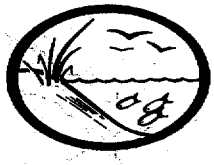
Lot #9, Temperature 12°C — Hatched 5/31/75, 1517 Stocked

Days After Hatching	Number in Live Sample	Number of Dead Removed
0		
1	10	
3	10	
5	7	
7	8	150
8		12
10	4	43
12	11	100
13		74
14		83
16		250
18	5	110
23		10
26		172
27		258
28		200

Effects of Heat Shock on Predation of Striped Bass Larvae by Yearling White Perch

Prepared for:

Central Hudson Gas & Electric Corporation
Consolidated Edison Company of New York, Inc.
Orange and Rockland Utilities, Inc.
Power Authority of the State of New York



ECOLOGICAL ANALYSTS, INC.

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EA Report CHG83B

EFFECTS OF HEAT SHOCK ON PREDATION OF STRIPED BASS LARVAE BY YEARLING WHITE PERCH

Prepared for:

Central Hudson Gas & Electric Corporation
Consolidated Edison Company of New York, Inc.
Orange and Rockland Utilities, Inc.
Power Authority of the State of New York

Prepared by:

Ecological Analysts, Inc.
Middletown, New York

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CHAPTER 1: INTRODUCTION

Power plants located on the Hudson River employ once-through cooling systems to dissipate waste heat. In the cooling sequence, river water is pumped through a condenser, where heat is transferred from the exhaust steam to the cooling water, and the warmed water is then returned to the river. Once-through cooling systems expose planktonic organisms, including fish larvae, to abrupt temperature increases during two events: (1) entrainment through the power plant with the cooling water (i.e., plant entrainment), and (2) entrainment with the dilution water into the thermal plume created by the cooling water discharge (i.e., plume entrainment).

The direct effects of plant and plume entrainment on striped bass larvae have been extensively studied and are summarized in 316(a) and 316(b) demonstrations and supporting documents for Hudson River power plants (CHG&E 1977, 1978; ORU 1977, 1978; Con Edison 1977, 1978; EA 1977, 1978a). The results of these studies have generally shown high levels of survival for plant entrained striped bass, and have indicated little or no plume entrainment mortality. However, controlled laboratory experiments conducted by Coutant (1973), Yocum and Edsall (1974), and Deacutis (1978) indicated that, in some tests, thermally stressed fish were more susceptible to predation than control fish, implying that indirect mortality may result from increased predation on young fish exposed to sublethal thermal stress during entrainment.

The purpose of this report is to examine the extent to which preferential predation may occur on striped bass larvae surviving entrainment at Hudson River power plants. To supplement the results of studies performed by Coutant (1973), Yocum and Edsall (1974), and Deacutis (1978), laboratory experiments were conducted on the effects of heat shock on predation of striped bass larvae. The objectives of these experiments were two-fold: (1) to determine if striped bass larvae are more susceptible to predation immediately following a heat shock than control larvae under experimental conditions partially simulating conditions in the natural environment (i.e., natural turbidity, large tank size, and availability of alternative food sources), and (2) to determine the length of time after a heat shock that striped bass remain more susceptible to capture than control larvae (i.e., recovery time). The methods and results of these experiments are presented in Chapters 3 and 4, respectively. The extent to which preferential predation of entrained striped bass larvae would be expected to occur at Hudson River power plants is discussed in Chapter 5. An abstract of the experimental results and highlights of the discussion are presented in the report summary (Chapter 2).

CHAPTER 2: SUMMARY AND CONCLUSIONS

To examine the extent to which preferential predation may occur on striped bass larvae surviving entrainment at Hudson River power plants, laboratory experiments were conducted on the effects of heat shock on predation of striped bass larvae by yearling white perch. Tests were conducted during the spring and summer of 1978 at Ecological Analysts' bioassay facility located at the Roseton Generating Station on the Hudson River. Two groups of experiments using different methodologies were conducted to detect and measure preferential predation.

The first group of experiments (preferential predation experiments) tested predation by white perch on thermally stressed and control striped bass larvae under conditions partially simulating conditions in the natural environment. Tests were conducted in large (1.9-m^3) circular experimental tanks supplied with unclarified Hudson River water. Gammarus were included with the larvae as alternative prey in some tests. Just prior to predation, stressed larvae were exposed to a 10 minute heat shock at approximately 32 C (7.0 to 10.1 C above ambient river temperatures). The results indicated that predation of stressed larvae in preference to control larvae was statistically significant for only 4 of the 14 tests (overall $\alpha = 0.05$) under these experimental conditions. The presence of Gammarus significantly ($P < 0.005$) decreased the overall predation of striped bass larvae but had no apparent effect on preferential predation of stressed larvae.

The second group of experiments (recovery time experiments) tested the predation efficiency of white perch on thermally stressed striped bass larvae after the larvae had been allowed to recover from a heat shock (10-minute exposure to 32 C) for 0, 30, 60, 120, 180, and 240 minutes. Results of these experiments indicated that thermally stressed larvae were significantly ($\alpha = 0.05$) more susceptible to capture for only 30 minutes after the heat shock. Consequently, any assessment of the extent to which preferential predation may actually occur as a result of power plant entrainment will likely overestimate mortality unless this recovery is taken into account.

The potential for preferential predation to occur with respect to thermal stresses other than the one tested was examined on the basis of the parallel relationship between the thermal tolerance response and the preferential predation response described by Coutant (1973). Based on this relationship, the difference between the exposure temperatures resulting in 50 percent mortality (TL50) and the approximate exposure temperature necessary to induce preferential predation was estimated to be 3.8 C for striped bass larvae. This application factor was combined with an empirical thermal tolerance prediction equation for striped bass larvae to predict minimum thermal stresses that would be sufficient to create a potential for preferential predation. A comparison between the time-temperature exposures that may be encountered by striped bass larvae entrained at Hudson River power plants and the estimated thermal stress required to induce selective predation indicates that most entrained striped bass are exposed to thermal stresses less than or only slightly greater than the minimum thermal stress resulting in increased vulnerability to predation. The limiting thermal stress used for this analysis (i.e., the minimum heat shock necessary to induce preferential predation) is based on the assumption that predation will occur within about 30 minutes

after return to the river (based on the results of the recovery time experiments), and thus, this assessment does not account for any decrease in the potential for preferential predation to occur as the amount of elapsed time between a heat shock and a predation event increases.

The results of these experiments, as well as other published studies on the effects of heat shock on predation of young fish (Coutant 1973, Yocum and Edsall 1974, Deacutis 1978), cannot be directly extrapolated to field situations without also considering the effects of important environmental factors that could substantially alter the potential for preferential predation to occur in and around cooling water discharges. The probable effects of some of these important natural variables are summarized below:

- Density of striped bass larvae - The larval densities tested in the preferential predation experiments were much higher than densities of striped bass larvae in the Hudson River (over 20 times higher than river densities during periods of peak occurrence). In the natural environment, the probability of a predator encountering an entrained striped bass larva prior to its recovery from the thermal stress is likely to be quite low.

- Density of alternative prey - The abundance of other food organisms far exceeds the abundance of striped bass larvae in the river. (For example, macrozooplankton densities typically exceed peak Morone spp. densities by over 10 times.) The extent to which the predation rate on larvae is reduced by the presence of other food organisms under natural conditions could substantially increase the probability that entrained larvae would avoid predation long enough to completely recover from the thermal stress.

- Density of predators - In the Hudson River, most fish predators likely to prey on larval fishes generally prefer bottom or shore-zone areas, and do not normally utilize offshore, surface waters characteristic of the thermal plumes from the Bowline Point, Roseton, and Indian Point power plants. Consequently, the probability that entrained striped bass larvae would encounter predators prior to recovery from the thermal stress would be expected to be quite low.

- Discharge velocities - The high discharge velocities and rapid dilution associated with the submerged, high-velocity diffusers at the Roseton, Bowline Point, and Indian Point plants would be expected to further reduce the potential for preferential predation to occur following an actual entrainment event by rapidly dispersing and mixing entrained larvae with other prey organisms in the river. In addition, the high discharge velocities actually exclude fish from inhabiting areas in the immediate vicinity of the discharge, where the highest plume temperatures occur, because the velocities in this area exceed the swimming speeds of most Hudson River fishes.

- Availability of cover - Another variable that may reduce the potential for preferential predation to occur in the natural environment is the availability of cover, such as vegetation, which may serve as a refuge for stressed larvae until they have recovered from the thermal shock.

In conclusion, increased predation on striped bass larvae entrained at Hudson River power plants is not expected to occur to any appreciable extent. The magnitude of the thermal exposure encountered by entrained larvae is usually insufficient to increase their susceptibility to capture. When time-temperature exposures are sufficient to increase susceptibility to predation, escape capabilities have been shown to quickly return to normal. Moreover, the probability that a predation event would occur on entrained striped bass larvae prior to recovery from the thermal stress at naturally occurring densities of striped bass larvae, alternative prey, and potential predators would be expected to be quite low in the natural environment in and around cooling water discharges at Hudson River power plants.

CHAPTER 3: MATERIALS AND METHODS

3.1 PREDATORS

White perch were seined from the Hudson River for use as predators in these experiments. Although white perch have not been shown to prey heavily on fish larvae (TI 1976), they are voracious predators and are abundant in the Hudson River throughout the striped bass larval season (May-July). Four groups of predators were used during experimentation:

Predator Group	Total Length (mm) Mean	Range	Experiments For Which Predator Group Was Used
1	85	76-98	Recovery time experiments
2	115	92-133	Preferential predation experiments (exploratory experiments only)
3	87	70-98	Recovery time and preferential predation experiments
4	87	71-100	Preferential predation experiments

White perch were acclimated to laboratory conditions in 600- and 1,000-liter holding tanks for 1-3 weeks prior to experimentation. During this time they were fed frozen brine shrimp each evening and treated 4-5 times per week with 2-3 ppt salt and 100 ppm Furacin (22 ppm active ingredient) for 1-4 hours to prevent disease.

Several tests were conducted with each predator group on consecutive days, using the same predators repeatedly. Predators were allowed to acclimate to the test tanks without feeding for 24 hours prior to each series of tests. The only food available to predators during each series of tests was the experimental prey. When testing was interrupted for more than 24 hours, the predators were removed from the experimental tanks to a large holding tank and fed frozen brine shrimp; prior to resuming experimentation, the predators were re-acclimated to the test tanks for 24 hours without feeding.

The normal feeding time for white perch has been reported to be from dusk to midnight, although significant daytime feeding has also been observed (Scott and Crossman 1973, p. 688). To increase the probability of obtaining a good feeding response by the predators, tests were conducted during the early evening hours prior to complete darkness (1700-2100 hours). Testing during complete darkness was avoided because of the need for some light, either artificial or natural, to conduct the tests.

3.2 PREY

Striped bass post-yolk-sac larvae were obtained from the Con Edison hatchery operated by Texas Instruments, Inc., at Verplanck, New York. All larvae were reared from eggs obtained from Hudson River striped bass. The larvae were held in the laboratory after transport to the bioassay facility for 3-4 days prior to testing to allow for handling mortality and recovery from stresses associated with transport. Larvae were held in continuous flow aquaria supplied with filtered Hudson River water and were fed live brine shrimp nauplii. Larvae used for testing ranged from 27 to 41 days old. Subsamples of 30-60

larvae were measured to the nearest millimeter on each day that tests were conducted; mean total lengths of larvae used in tests ranged from 12.1 to 26.0 mm. Gammarus were collected from the Hudson River on artificial substrates for use as alternative prey.

Prey were thermally stressed by exposure to an abrupt temperature increase from ambient river temperatures (22-25 C) to approximately 32 C for 10 minutes. Thermal shocks were accomplished by transferring larvae placed in cylindrical screen-bottomed containers (10 cm in diameter and 11 cm deep) to a water bath adjusted to the exposure temperature. The containers were transferred to the water bath in small bowls to prevent the fish from being exposed to the air. Temperature equilibration was typically achieved within 30 seconds after initiation of the thermal shock by flushing the container several times with heated water from the water bath; temperature fluctuations after equilibration were maintained within 0.1 C. Actual exposure temperatures ranged from 31.4 to 32.5 C, representing temperature increases above ambient river temperatures (delta-T) of 7.0-10.1 C. Few larvae died as a result of this exposure to these elevated temperatures, but larvae often exhibited signs of stress (i.e., erratic swimming and momentary loss of equilibrium). Larvae that died during the thermal exposure were not used for experimentation. Controls were handled in the same manner as experimental prey, but were not exposed to elevated temperatures.

3.3 PREFERENTIAL PREDATION EXPERIMENTS

Preferential predation experiments were conducted under conditions partially simulating the natural environment by using large experimental tanks (1.9 m^3) supplied with naturally turbid water. Other experimental procedures were similar to those reported by Coutant (1973). Stressed and control larvae were simultaneously introduced into tanks containing the predators, and the number of surviving stressed and control larvae were recorded at the end of the test (Figure 1). Stressed and control larvae were differentiated by dyeing one of the groups with neutral red prior to the test. All tests were conducted in replicate, using dyed control larvae for the first replicate and dyed stressed larvae for the second replicate. Paired replicates were conducted on consecutive days using the same predators, and the results of the two replicates were combined into a single test result in order to examine preferential predation resulting from thermal stress without adjusting for prey selection related to the dye. Gammarus were introduced into the tanks with the larvae for some tests to simulate the presence of other prey organisms in the natural environment.

Dyeing was accomplished by exposing larvae to a 2.5-3.0 ppm neutral red solution for 2.5-4 hours, depending on the size and number of larvae. The dyed larvae were then transferred to a holding container supplied with a continuous flow of river water for 4-6 hours prior to the test to allow the dye to fade to a light pink color.

Preferential predation experiments took place in six 1.9-m^3 (1,900-liter) circular polyethylene tanks (132 cm in diameter and 162 cm deep) with cone-shaped bottoms to permit complete drainage (Figure 2). The tanks were located outside (partially sheltered by translucent fiberglass roofing), and therefore subject to natural light conditions. A continuous flow of Hudson River water filtered through a 0.5-mm screen to remove macrozooplankton, fish larvae, and

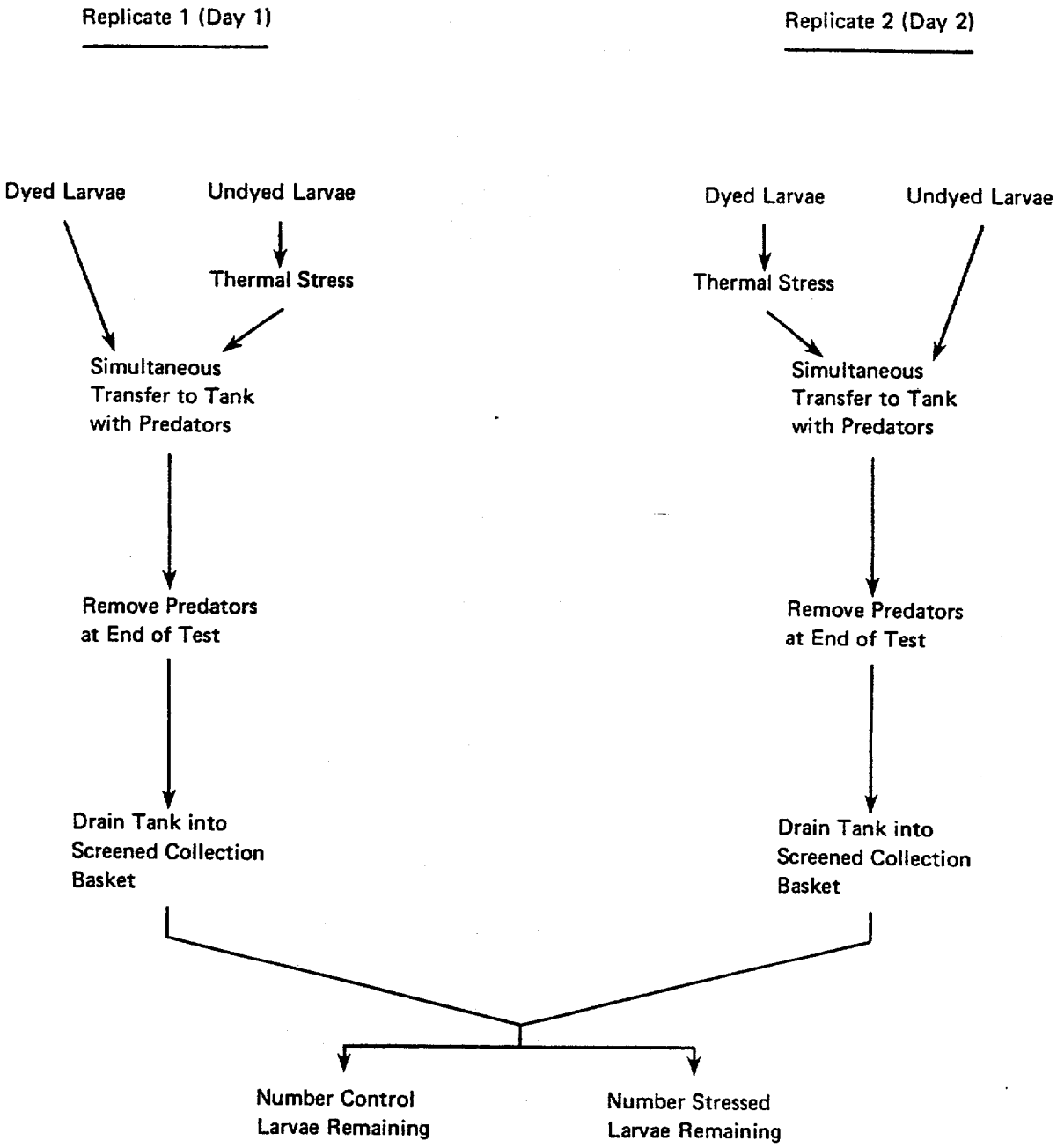

Figure 1. Flow diagram for conduct of each test to determine the relative vulnerability of thermally shocked and control larvae to predation.

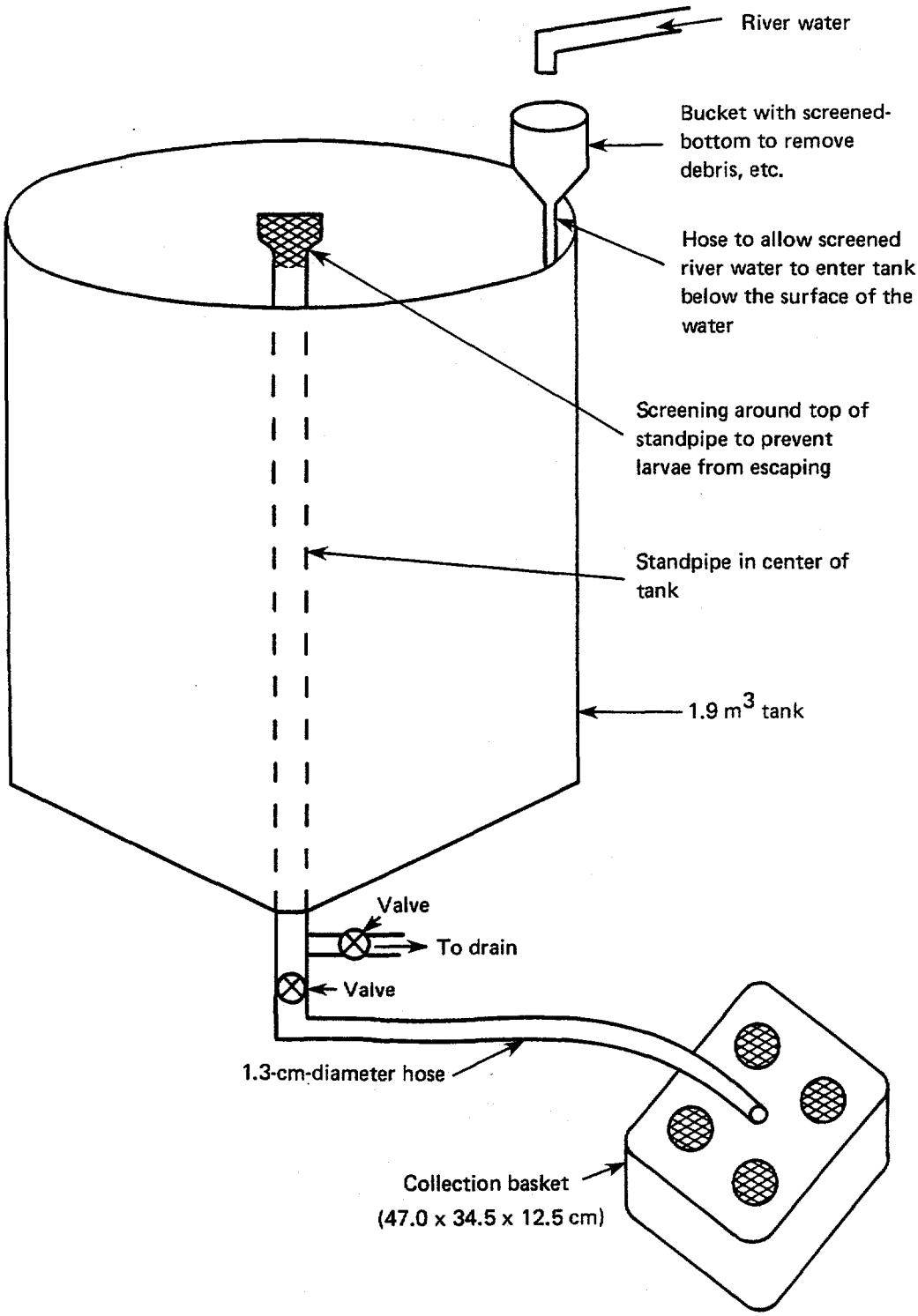

Figure 2. Illustration of apparatus used to conduct preferential predation experiments (not drawn to scale).

debris was maintained at approximately 4-6 liters/min, entering at the periphery of the tank below the surface of the water and leaving via a standpipe located in the center of the tank. The standpipe was provided with 0.5-mm-mesh screening to prevent the prey from escaping. There were no structures other than inlet hose, outflow standpipe, and tank walls to provide visual protection to the prey. Turbidity was measured prior to each test using a standard 20-cm-diameter Secchi disk. Secchi disk transparency within the test tanks ranged from 33 to 58 cm (13-23 in.) throughout the study. For perspective, New York University Medical Center (NYU 1978) reported Secchi disk transparencies ranging from 34 to 134 cm (13-53 in.) in the Hudson River during 1976.

Predators were removed at the end of the test using a 0.95-cm (3/8-in.) mesh drop net that was lowered into the tank along the sides, drawn across the bottom via draw strings, and then raised to the surface. Removal of the predators was usually accomplished within 5-10 minutes. It is unlikely that further predation occurred during this time, because of the disturbance created by the removal process. (Fish held in tanks supplied with clarified water were observed on many occasions to cease feeding when disturbed in this manner.) The drop net was rinsed thoroughly to remove any uneaten prey that may have adhered to the net. The predators were placed in 100-liter (30-gallon) pails containing water adjusted to 2-3 ppt salinity to reduce handling stress and 100 ppm Furacin as a precaution against disease. Predators remained in these holding vessels until the tanks were drained (approximately 5 hours) and were then returned to the same experimental tank from which they had been removed, in preparation for tests the following day.

After removal of the predators, the tanks were drained through a 1.3-cm diameter hose into a 47 x 34.5 x 12.5-cm collection basket. Four 11.5-cm diameter holes covered with 0.5-mm screening located in the lid of the collection basket retained the larvae as the tank drained. Nearly all larvae were recovered alive. The number of uneaten control and stressed larvae was recorded for each replicate. The number of uneaten supplemental prey (Gammarus) was also recorded for appropriate tests. Surviving prey were not used in subsequent tests.

The efficiency of retrieving prey from the tanks was determined by performing several tests without predators; recovery was determined to be 98.5 percent for striped bass larvae and 89.2 percent for Gammarus (Appendix B, Table B-1). In addition, two predator groups were sacrificed at the end of each series of tests and their stomach contents examined to determine the number of prey consumed; the average recovery of striped bass larvae from both stomachs and tanks was 96.4 percent (Table B-2).

The statistic chosen by Bams (1967) and Coutant (1973) and used in this study to express the difference in predation rates on the two groups of larvae is the ratio

$$d_p = \frac{i_1}{i_2},$$

where i_1 and i_2 are, respectively, the instantaneous mortality rates of the thermally stressed and control groups. The instantaneous mortality rate

when time is a unit interval is given by

$$i = -\log_e S,$$

where

$$S = \text{survival proportion, i.e., } \frac{\text{No. larvae at finish}}{\text{No. larvae at start}}.$$

Differential predation ratios (d_p) greater than 1 indicate that stressed larvae were consumed at a faster rate than control larvae, and d_p ratios less than 1 indicate that control larvae were consumed faster than stressed larvae. The magnitude of the d_p ratio provides a relative measurement of the difference between the rates of predation on the two groups of larvae.

To determine if the difference between the number of control and stressed larvae consumed was statistically significant, the chi-square test for independence (2 x 2 contingency table, Model II) was used (Sokal and Rohlf 1969, pp. 585-590).

$$\chi^2 = \frac{\left[\left(\begin{matrix}\text{No.}\\ \text{surviving}\\ \text{control}\end{matrix}\right)\left(\begin{matrix}\text{No.}\\ \text{consumed}\\ \text{stressed}\end{matrix}\right) - \left(\begin{matrix}\text{No.}\\ \text{consumed}\\ \text{control}\end{matrix}\right)\left(\begin{matrix}\text{No.}\\ \text{surviving}\\ \text{stressed}\end{matrix}\right)\right]^2 \left(\begin{matrix}\text{Total}\\ \text{no. of}\\ \text{larvae}\end{matrix}\right)}{\left(\begin{matrix}\text{No.}\\ \text{control}\\ \text{larvae}\end{matrix}\right)\left(\begin{matrix}\text{No.}\\ \text{stressed}\\ \text{larvae}\end{matrix}\right)\left(\begin{matrix}\text{No.}\\ \text{surviving}\\ \text{larvae}\end{matrix}\right)\left(\begin{matrix}\text{No.}\\ \text{consumed}\\ \text{larvae}\end{matrix}\right)}$$

Because this analysis was performed separately on the results of 14 experiments, the alpha level for each chi-square test was adjusted to yield an overall alpha level of 0.05, according to the following formula (Kendall and Stuart, 1976):

$$\alpha_o = 1 - (1 - \alpha_i)^m$$

where

m = number of comparisons (i.e., 14)
α_i = alpha level of individual chi-square test
α_o = overall alpha level ($\alpha = 0.05$).

After adjusting for multiple comparisons using the above formula, an individual test result was significant at an overall alpha of 0.05 when the probability of obtaining a larger chi-square was less than 0.005 (the resulting critical value of chi-square was 7.88).

The changing ratio of prey availability during a test can create a discrepancy between the measured rate of predation and the actual predation rate on each group (Bams 1967, p. 1142). Since the preferred group decreases in relative abundance as the test proceeds, the measured rate of predation on the preferred group is lower than the actual instantaneous rate for that group. The predation rate difference (d_p) is therefore biased to some degree, especially when the overall predation rate is high. For this reason, the results of tests in which 30 percent or less of the prey remained at the end of the test were not considered valid estimates of preferential predation. Similar

criteria were used by Coutant (1973) and Bams (1967) to keep the variation in availability ratios within limits.

Initial (exploratory) experiments were conducted with 5 predators ($2.6/m^3$) and 10 larvae ($5.3/m^3$) per tank to determine the length of time that tests should be conducted. These predator-prey densities were selected to approximate densities that might occur in the natural environment (see Discussion in Chapter 5). However, nearly complete predation occurred during these tests for test durations as short as 15 minutes. Other exploratory tests performed with 20 larvae per tank (10.5 larvae/m^3) and 3 predators per tank ($1.6/m^3$) also resulted in predation of more than 80 percent of the larvae within a 15-minute test period.

In order to measure a preferential predation response, it was necessary to test much higher prey concentrations than would normally be found in the natural environment. Subsequent tests were performed with three predators per tank ($1.6/m^3$) and 50 larvae per tank (25 stressed and 25 control, equivalent to $26.3/m^3$). Predation was allowed to continue for 15 minutes, after which the predators were removed. One hundred Gammarus (50 stressed and 50 control, equivalent to $52.6/m^3$) were included with the larvae in some tests to examine the effects of alternative prey on predation of striped bass larvae.

3.4 RECOVERY TIME EXPERIMENTS

The period of time following the thermal shock beyond which the potential for preferential predation no longer exists was determined for striped bass larvae by comparing the predation efficiency of yearling white perch on thermally stressed larvae with that for control larvae. Thermally stressed larvae were allowed to recover from the thermal shock for the following time intervals prior to testing: 0, 30, 60, 120, 180, and 240 minutes. The predation efficiency of the predators on larvae from each treatment group (recovery time) was measured by observing the number of attacks and captures during a 15-minute test period, according to procedures similar to those reported by Yocum and Edsall (1974).

Experiments were conducted in six 110-liter glass aquaria 73.5 cm long, 30.5 cm wide, and 43.5 cm deep, using clarified Hudson River water. Fluorescent lights were suspended above each tank to provide illumination, and the tanks were enclosed in a shrouded area of the laboratory to keep the observation area dark. The bottom and three sides of each aquarium were covered with black plastic to increase the visibility of the prey to the observer. The front of each tank was covered with a transparent plastic sheet that had been silvered on one side to allow the observer to view the fish without being seen.

Tests were conducted by releasing 23-30 larvae into a tank containing two predators and counting the number of attacks made on the larvae within 15 minutes. The larvae were released below the surface of the water by flushing them gently through a 2.5-cm-diameter tube inserted into the tank, or through a 2.5-cm-diameter tube permanently fixed to the front side of the tank. At the end of the tests, the predators were removed and the number of surviving prey was recorded. The predators were treated with a 2-ppm malachite green solution for 10 minutes to control ichthyophthiriasis (a condition observed among some fish) and then transferred to a common holding tank adjusted to

2-3 ppt salinity with 100 ppm (22 ppm active ingredient) Furacin to reduce handling stress and further reduce the potential for disease. The predators were held in this tank for 1-4 hours, and were then randomly redistributed among the six test aquaria in preparation for tests the following day. Randomizing the distribution of predators among the test tanks enabled statistical comparisons to be made between predation efficiencies observed among treatment groups without adjusting for differences in individual predator effectiveness. Surviving prey were not used in subsequent tests.

The predation efficiency of the predators was measured by the ratio of captures per attack. Two categories of predator behavior were classified as attacks: (1) actual strikes at prey, and (2) active pursuit of prey. The second behavioral category, active pursuit, was classified as an attack because evasive behavior by the prey often prevented an actual strike from occurring. Predators were also observed to slowly approach a prey, but not engage in active pursuit or strike at the prey. This lack of predatory response occasionally appeared to be the result of anticipatory evasive behavior by the prey, but was not included as an attack. Although most captures could be readily ascertained by visual observations, a more accurate measurement of captures was obtained by determining the difference between the number of larvae remaining in the tank at the end of the test and the initial number.

Low feeding responses by the predators occasionally resulted in erratic measurements of predator efficiencies. Therefore, a successful test was defined as one in which the predators made 15 or more attacks and captured more than 20 percent of the prey. Feeding responses not meeting this criterion were not included in the analysis of the results. (Yocum and Edsall [1974] also observed low feeding responses in some tests, and promulgated a similar criterion for successful tests.)

Analysis of variance was used to determine if recovery time was a significant variable among predation efficiencies (captures/attack) determined for each treatment group. The Student--Newman-Keuls multiple range test (for unequal sample sizes) was used to determine if differences between pairs of treatment means were significant (Steel and Torrie 1960, p. 114). Bartlett's test for homogeneity among treatment variances was performed prior to the analysis of variance to assure compliance with the assumption of homogeneity of variances (Sokal and Rohlf 1969, p. 370).

CHAPTER 4: RESULTS

4.1 PREFERENTIAL PREDATION

The results of predation experiments conducted in large (1.9-m^3) circular tanks supplied with naturally turbid Hudson River water were variable, but most tests resulted in higher numbers of stressed larvae consumed than control larvae (Table 1). The d_p ratios were greater than one for 10 of the 14 tests that resulted in acceptable levels of predation,* indicating that more stressed larvae were consumed than control larvae; however, statistical analysis of the data indicated that predation of stressed larvae was significantly greater than control larvae in only 4 of the 14 tests (overall $\alpha = 0.05$). The d_p ratios were less than one (indicating that more control larvae were consumed than stressed larvae) in 4 of the tests, although these differences were not statistically significant.

The presence or absence of Gammarus as an alternative prey had no discernable effect on the preferential predation observed on stressed larvae during these tests (Table 1). However, the overall level of predation on both control and stressed striped bass larvae was lower for tests in which Gammarus were present than for tests without Gammarus. The mean percentage consumption of larvae in the presence of Gammarus was 23.5, whereas the mean percentage consumption without Gammarus was 43.7. Chi-square analysis indicated that this difference was significant at $\alpha = 0.005$ ($\chi^2 = 64.174$, 1 d.f.).

There was some indication during the exploratory tests that predators might have been selecting dyed larvae in preference to undyed larvae. Dyeing procedures were subsequently refined to minimize the intensity of color at the time of the test such that it could still be accurately detected after the surviving larvae were retrieved from the tanks. For the 14 tests resulting in acceptable levels of predation, a two-way analysis of variance (Sokal and Rohlf 1969, p. 302) was conducted on the number of surviving larvae from each replicate to determine if any interaction between the condition of the larvae and the dye existed. As shown in Table 2, there was no significant difference in the number of surviving larvae due to the dye, or due to interaction

* Tests resulting in acceptable levels of predation (i.e., more than 30 percent of the larvae remained uneaten at the end of test) were conducted with three predators per tank (87 mm mean total length, predator groups 3 and 4) and 50 striped bass larvae per tank (25 stressed and 25 control). Exploratory experiments conducted with 3-5 white perch and 10-20 striped bass larvae per tank resulted in the consumption of more than 80 percent of the larvae, and tests performed with 50 larvae per tank and 3 of the larger predators (115 mm mean total length) resulted in nearly complete predation (see Table B-4). Although no preferential predation was observed on either stressed or control larvae among these exploratory tests, it is possible that the rate of predation on the preferred group may have been underestimated as a result of the high levels of predation (see previous discussion on changing ratios of prey availability during a test). Thus, the results of these exploratory tests were not considered valid for purposes of detecting and measuring preferential predation.

TABLE 1 NUMBER OF CONTROL AND STRESSED STRIPED BASS LARVAE (COMBINED FOR PAIRED REPLICATES) SURVIVING PREDATION BY YEARLING WHITE PERCH (87 mm MEAN TOTAL LENGTH), AND RATIOS OF INSTANTANEOUS PREDATION RATES (dp) [a] (FROM TABLE B-4)

Predator Group	Total Length of Larvae (mm) ($\bar{x}$ ± S.D.)	Presence (P) or[b] Absence (A) of Alternative Prey	Total No. Larvae at Start		Total No. Larvae Surviving		Total Larvae Surviving (%)	dp Ratio	Chi-Square (1 d.f.)
			Control	Stressed	Control	Stressed			
3	16.9 ± 1.03	A	50	50	20	24	44.0	0.801	0.649
		A	50	50	42	30	72.0	2.929	7.143
		P	50	50	37	27	64.0	2.046	4.340
		P	51	50	40	32	71.3	1.837	2.569
		P	50	50	33	36	69.0	0.791	0.421
		P	50	50	45	50	95.0	<1	5.263
3	19.3 ± 1.52	A	50	50	42	28	70.0	3.319	9.333*
		A	50	50	45	30	75.0	4.848	12.000*
		P	50	50	40	26	66.0	2.931	8.734*
		P	50	50	47	29	76.0	8.800	17.763*
		P	50	50	44	35	79.0	2.791	4.882
		P	50	50	47	45	92.0	1.703	0.543
4	17.4 ± 1.46	A	50	50	22	21	43.0	1.057	0.041
		A	50	50	16	18	37.0	0.897	0.178

(a) Tests were conducted at a larval density of 26.3/m^3 (½ stressed, ½ control) and a predator density of 1.6/m^3 (3 predators per tank). Thermally stressed larvae were exposed to elevated temperatures ranging from 32.0 to 32.5 C for 10 minutes, representing temperature increases above ambient river temperatures (delta-T) of 7.0-10.0 C.

(b) 100 Gammarus (50 stressed, 50 control) were included with the larvae in each replicate as alternative prey.

Note: Asterisk (*) denotes significance at an overall alpha level of 0.05; after adjusting for multiple comparisons, the critical value for each chi-square test (one degree of freedom) was 7.88 (i.e., $P \leq 0.005$).

TABLE 2 ANALYSIS OF VARIANCE[a] FOR DIFFERENCES IN PREDATION BETWEEN DYED AND UNDYED LARVAE (DATA FOR INDIVIDUAL REPLICATES ARE FROM TABLE B-4, PREDATOR GROUPS 3 AND 4, 50 LARVAE PER TANK)

	Number Larvae Surviving Predation for Each Replicate	
	Control Larvae	Stressed Larvae
Dyed larvae	10, 23, 20, 18, 13, 23, 18, 20, 19, 22, 20, 22, 6, 3.	13, 12, 11, 14, 18, 25, 17, 20, 13, 16, 17, 25, 13, 12.
Undyed larvae	10, 19, 17, 22, 20, 22, 24, 25, 21, 25, 24, 25, 16, 13.	11, 18, 16, 18, 18, 25, 11, 10, 13, 13, 18, 20, 8, 6.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Dye effects	1	11	11.000	0.3934
Thermal stress effects	1	141	141.000	5.0426*
Interaction	1	81	81.000	2.8968
Error	52	1,454	27.962	--
Total	55	1,687		

(a) Bartlett's test for homogeneity of variances resulted in a nonsignificant chi-square (3 df) of 2.85 ($0.50>P>0.25$)

Note: Asterisk (*) denotes significance at $\alpha = 0.05$.

between the condition of the larvae and the dye; significant differences did exist between the stressed and control groups, as previously indicated by the chi-square tests.

4.2 RECOVERY TIME

The predation efficiencies (captures per attack) of yearling white perch on striped bass larvae were determined for groups of thermally stressed larvae allowed 0, 30, 60, 120, 180, and 240 minutes recovery time prior to predation (treatment groups), and for larvae not subjected to a thermal stress (control group). These tests were conducted in small aquaria (110 liters) supplied with clarified Hudson River water and designed to allow direct observation of fish behavior. Because of occasional low feeding responses by predators, successful tests were defined as those in which the predators made 15 or more attacks and captured more than 20 percent of the prey (see Section 3.4). From 4 to 8 successful tests were completed with each treatment group, and 11 successful tests were completed with control larvae (Table 3).

After being released into the aquarium with the predators, the prey rapidly distributed themselves throughout the entire tank. The predators typically responded by immediately feeding on the larvae for the first 3-5 minutes of the test, after which the predators exhibited only occasional interest in the remaining prey. The prey responded to predation, in most cases, by segregating themselves in areas of the tank seldom frequented by the predators (i.e., along the bottom, sides, or in the corners). This predator avoidance behavior, as well as the partial satiation of the predators, probably contributed to the lower feeding response generally observed during the last 10 minutes of the test.

The average predation efficiency on treatment groups steadily decreased from 0.615 captures per attack for larvae allowed no recovery time to 0.326 captures per attack for larvae allowed 4 hours (240 minutes) recovery time (Table 3). The predation efficiency of predators on control larvae averaged 0.341 captures per attack. Analysis of variance (Table 4) indicated that the predation efficiency of predators varied significantly according to treatment groups. The Student--Newman-Keuls multiple range test indicated that the average predation efficiency for the control group was similar to predation efficiencies for all treatment groups except the 0- and 30-minute recovery time groups ($\alpha = 0.05$).

The initial behavior of larvae allowed 0- and 30-minute recovery times prior to predation was different from the behavior of larvae allowed longer recovery times. They often exhibited signs of disorientation early in the test, characterized by little swimming movement and an abnormal posture with the head pointed towards the surface and the tail angled downward. Larvae with longer recovery times usually exhibited a strong avoidance of predators almost immediately, whereas larvae with 0- and 30-minute recovery times often did not actively avoid predators until later in the test. These signs of stress were much less apparent for larvae allowed a 30-minute recovery time than for those allowed no recovery time.

TABLE 3 CAPTURES PER ATTACK BY WHITE PERCH YEARLINGS FED STRIPED BASS LARVAE THAT WERE ALLOWED TO RECOVER FROM A THERMAL SHOCK[a] FOR VARIOUS TIME PERIODS BEFORE TESTING. (FROM TABLES C-1 AND C-2).

Mean Total Length of Prey (mm)	Captures Per Attack — Recovery Time in Minutes						
	0	30	60	120	180	240	Control
Predator Group 1 (85 ± 7.0 mm total length)							
13.8	0.769	0.556	0.610	0.346	--	0.535	0.325
14.7	0.735	0.452	0.380	0.352	--	0.295	(b)
15.5	0.654	0.606	(b)	0.521	--	0.190	0.444
15.8	--	--	0.625	0.676	--	0.395	0.366
15.8	--	--	--	--	--	--	0.324
Predator Group 3 (87 ± 7.4 mm total length)							
15.4	--	(b)	--	0.192	0.281	0.180	(b)
15.9	0.412	(b)	0.429	--	0.263	0.362	0.288
16.3	0.599	(b)	0.397	0.476	0.248	--	0.541
17.8	(b)	0.641	0.281	0.382	0.599	--	(b)
18.9	--	(b)	0.291	--	--	--	(b)
16.6	0.541	0.472	(b)	0.324	--	--	0.424
18.2	0.592	0.395	--	--	--	--	0.200
18.2	--	--	--	--	--	--	0.346
18.2	--	--	--	--	--	--	0.189
18.2	--	--	--	--	--	--	0.303
Mean	0.615	0.520	0.430	0.409	0.348	0.326	0.341
Range bars spanning mean values not significantly different[c]							

(a) Thermally stressed larvae were exposed to elevated temperatures ranging from 31.4 to 32.4 C for 10 minutes, representing increases above ambient river temperatures (delta-T) of 7.9-10.1 C.
(b) Test results omitted from analysis because of low predator response.
(c) Results of Student-Newman-Keuls mutiple-range test at $\alpha = 0.05$.

Note: Dashes (--) indicate no data.

TABLE 4 ANALYSIS OF VARIANCE[a] AMONG PREDATION EFFICIENCIES (CAPTURES PER ATTACK) ON THERMALLY STRESSED AND CONTROL STRIPED BASS LARVAE ALLOWED VARIOUS RECOVERY TIMES (TREATMENT GROUPS)

Source	Degrees of Freedom	Sum of Squares	Mean Square	F
Treatment groups	6	0.4689	0.07815	4.8390*
Error	42	0.6783	0.01615	
Total	48	1.1472		

(a) The chi-square for Bartlett's homogeneity of variance test was 2.33 (6 df), which was not significant (P>0.50).

Note: Asterisk (*) denotes significance at $\alpha = 0.001$.

CHAPTER 5: DISCUSSION

5.1 DISCUSSION OF EXPERIMENTAL RESULTS

Two methodologies were used during this study to detect and measure the susceptibility of striped bass larvae to predation; the preferential predation experiments were patterned after methods used by Coutant (1973), whereas methodology used by Yocum and Edsall (1974) was used to conduct the recovery time experiments. The most important difference between the two methodologies is that stressed and control larve are presented to the predators simultaneously with the Coutant (1973) methodology, whereas stressed and control larvae are tested separately with the Yocum and Edsall (1974) methodology. The methodology used by Yocum and Edsall (1974) thus detects and measures the "susceptibility of prey to capture," and also permits behavioral observations. The methodology used by Coutant (1973) detects and measures actual "preferential" or "selective" predation because the predators are presented with a choice of stressed or control prey. The Coutant (1973) methodology does not require behavioral observations, and thus experimental conditions can be manipulated to some extent in order to simulate natural conditions, as was attempted in this study.

Although results of the two types of predation experiments are not directly comparable because of the differences in methodology, thermally stressed striped bass larvae tested under conditions partially simulating the natural environment did not appear to be "preferentially" or "selectively" preyed upon to as great an extent as expected solely on the basis of the predation efficiency tests. Predation efficiencies (captures per attack) determined in small (110-liter) aquaria supplied with clarified water indicated that striped bass larvae tested immediately after a heat shock were nearly twice as easy for yearling white perch to capture as control larvae. On the other hand, in preferential predation experiments where both stressed larvae (also tested immediately after a heat shock) and control larvae were simultaneously available to predators in large (1,900-liter) tanks supplied with turbid water, stressed larvae were significantly preyed upon in preference to control larvae in only 4 of the 14 tests (overall $\alpha = 0.05$). Thus, although thermally stressed striped bass larvae were shown to be more susceptible to capture than control larvae, yearling white perch predators were not always able to take advantage of this increased susceptibility in experiments designed to detect and measure preferential predation under less artificial conditions.

Another important finding of this study is that increased susceptibility of thermally stressed fish to predation is dependent on the amount of elapsed time between the heat shock and a predation event. The results of the recovery time experiments indicated that thermally stressed striped bass larvae were significantly more susceptible to capture ($\alpha = 0.05$) for only 30 minutes after the 10-minute heat shock. Similarly, Coutant (1973) found that 30- and 60-minute recovery times following heat shocks up to 9 minutes in duration resulted in a pronounced decrease in the magnitude of preferential predation observed on juvenile rainbow trout and chinook salmon. Thus, the components of performance affected by brief heat shocks appear to return to normal soon after the heat shock. Consequently, any assessment of the extent

to which preferential predation may actually occur as a result of power plant entrainment will likely overestimate mortality unless this recovery is taken into account.

A limitation inherent in both methodologies used during this study may lead to an overestimate of the potential for preferential predation to occur following an actual entrainment exposure. The time-temperature exposures used during this study actually consisted of two thermal shocks: the first was an abrupt rise in temperature at the time of transfer to the heated water, and the second was an abrupt decrease of similar amount upon return to ambient temperatures. The latter "cold shock" has been shown to create additional stress resulting in momentary loss of equilibrium in some fish exhibiting no signs of stress due to the initial "heat shock" (Coutant 1973; Hoss et al. 1974). Entrained organisms are seldom subjected to secondary cold shocks as severe as those employed during this study. For example, upon return to the river following entrainment at most Hudson River power plants, organisms are exposed to a fairly rapid decrease in temperature as the temperature cools to about 30-50 percent of the maximum discharge temperature, after which they are exposed to a gradual, fluctuating temperature decrease until ambient river temperatures are reached (Con Edison 1978; CHG&E 1978; ORU 1978). Although the effects of this secondary cold shock on the measurement of preferential predation could not be determined in these experiments, it is recognized that the unduly severe temperature decrease may have been an important factor contributing to the level of preferential predation observed during the study, since it occurred just prior to predation.

5.2 RELATIONSHIP BETWEEN THERMAL EXPOSURES ENCOUNTERED BY ORGANISMS DURING ENTRAINMENT THROUGH HUDSON RIVER POWER PLANTS AND THE POTENTIAL FOR PREFERENTIAL PREDATION OF ENTRAINED STRIPED BASS LARVAE

Because only a single time-temperature exposure was tested during this study, the direct application of these results to the assessment of additional entrainment mortality resulting from preferential predation is limited. However, Coutant (1973) studied the effects of various exposure times and shock temperatures on the increased vulnerability of small fish to predation by larger fish and found that a predictable relationship existed between the magnitude and duration of a heat shock and the magnitude of preferential predation. It is, therefore, possible to estimate the potential for preferential predation to occur with respect to plant-specific thermal stresses by applying this relationship to the results of the preferential predation experiments conducted during this study and time-temperature exposures encountered by organisms entrained through Hudson River power plants.

Coutant (1973) investigated the effects of various exposure times and shock temperatures on the vulnerability of juvenile salmon and trout to predation and found that, at a given exposure temperature, there was a minimum exposure duration necessary to induce increased predation on the shocked fish. Fish exposed to a given test temperature for shorter durations were less susceptible to predation than control fish. Beyond this minimum exposure time, the vulnerability of stressed fish relative to controls increased almost exponentially. Furthermore, the exposure time necessary to increase the susceptibility of thermally stressed fish to predation depended on the magnitude of the thermal shock. For example, Coutant reported that an exposure temperature of 26 C induced preferential predation of stressed juvenile trout acclimated to

15 C only after exposures exceeding 60 minutes, whereas preferential predation on stressed fish was observed after a 1-minute exposure to 30 C. Coutant concluded that the increased susceptibility of thermally stressed fish to predation immediately after the thermal shock followed the time-temperature response pattern similar to that exhibited by the death response (i.e., thermal tolerance). After plotting exposure temperature against the minimum exposure times necessary to induce selective predation, Coutant further observed that the response pattern for increased susceptibility to predation paralleled that for the median death response (TL50).

The parallel relationship determined by Coutant (1973) between the median death response and the time-temperature exposures necessary to induce selective predation can be used to approximate entrainment exposures other than the single time-temperature exposure used in this study that might result in an increased susceptibility of striped bass larvae to predation. For this purpose, the following prediction equation was derived empirically to estimate the median death response (TL50) of striped bass larvae on the basis of thermal tolerance tests conducted by Ecological Analysts, Inc. during 1976, 1977, and 1978 (see Appendix A for a description of the derivation of the thermal tolerance prediction equation):

$$TL50\ (C) = \frac{27.99 - 3.692(x_2x_4) + 47.92(x_3) + 0.8174(x_3x_4) - 0.2773(x_4)}{1.601(x_3)}$$

where

x_1 = exposure temperature (C)
x_2 = exposure duration ($\log_{10}$ minutes)
x_3 = acclimation temperature (C)
x_4 = total length (mm).

In order to equate the TL50 with the time-temperature exposure used during the preferential predation experiments, this equation was used to calculate TL50s for exposure durations ranging from 1 to 30 minutes after incorporating into the equation the acclimation temperature and length of larvae that best represented the acclimation temperatures and lengths of larvae tested in the preferential predation experiments (i.e., acclimation temperature = 24 C and mean total length = 18 mm). The median death response determined for these variables is shown in Figure 3.

Assuming that the parallel relationship observed by Coutant (1973) is also applicable for striped bass larvae, a parallel line intersecting the time-temperature exposure at which the preferential predation experiments were conducted (i.e., 10-minute exposure to 32 C), also shown in Figure 3, represents the estimated time-temperature exposure at which increased susceptibility of striped bass larvae to predation would be similar to that observed during the preferential predation experiments. Because significant preferential predation was detected in only 4 of the 14 tests conducted, the time-temperature exposure used during the preferential predation experiments is considered here to approximate the minimum thermal stress necessary to induce preferential predation. In spite of the 4 tests that resulted in statistically significant preferential predation of stressed larvae under these experimental conditions, this limiting time-temperature exposure may be underestimated, because of the unduly severe temperature decrease to which

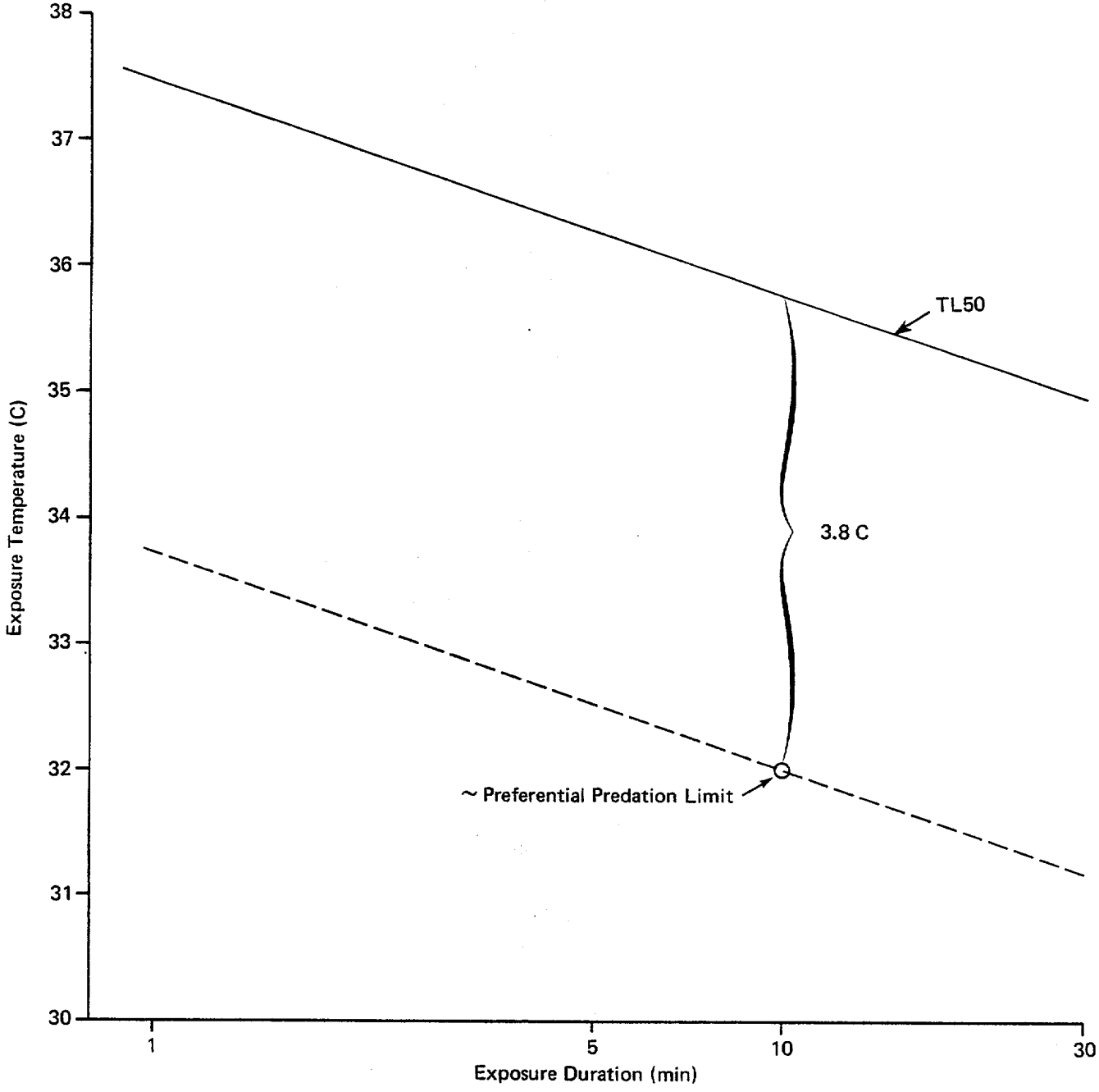

Figure 3. Estimated minimum time-temperature exposure necessary to induce selective predation on striped bass larvae, based on the relationship between the predation response and the median death response reported by Coutant (1973). The median death response shown was predicted based on an acclimation temperature of 24.0 C and a larval length of 18 mm.

heat-shocked larvae were exposed just prior to predation. In addition, this limiting thermal stress was based on the assumption that predation will occur within about 30 minutes after return to the river (based on results of the recovery time experiments), and thus does not account for any decrease in the potential for preferential predation to occur as the amount of elapsed time between a heat shock and a predation event increases (i.e., recovery time).

The difference between the exposure temperatures resulting in 50 percent mortality and the approximate exposure temperature necessary to induce preferential predation was 3.8 C. To approximate the magnitude and duration of thermal stress required to induce preferential predation for other acclimation temperatures and sizes of larvae, the thermal tolerance prediction equation was modified by subtracting 3.8 C from the predicted TL50. Using this modified equation, the time-temperature exposures that approximate the minimum thermal stress necessary to induce selective predation were calculated at three acclimation temperatures (spanning the range of acclimation temperatures that are found in the striped bass larval season) for both 10- and 20-mm larvae (Figure 4).

Discharge temperature and exposure duration, which determine, in part, the potential for increased susceptibility to predation of entrained fish larvae, vary among the Hudson River power plants and also depend upon operating conditions and ambient river temperatures. The transit times from the condenser inlet to the discharge of the cooling water as it passes through power plants located on the Hudson River, together with maximum delta-Ts (temperature elevations above ambient river temperatures) that would be generated by the power plants at 100 percent operating capacity, are presented in Table 5. Transit times for plant-entrained organisms are between 3 and 10 minutes, and maximum delta-Ts generally range from 8 to 11 C under normal operating conditions during the striped bass larval season (May-July). Upon return to the river, organisms are exposed to rapidly decreasing temperatures as the cooling water is diluted by ambient river water; transit times from the discharge port to a point within the thermal plume where the temperature has been reduced to less than half of the maximum discharge temperature are a few seconds (5-10) at the Roseton and Bowline Point plants (ORU 1978; CHG&E 1978) and varies from 1 to 3 minutes (depending on tidal conditions) at the Indian Point plant (Con Edison 1978).

Thus, the 10-minute exposure duration used in the preferential predation experiments approximates the maximum length of time that striped bass larvae would be subjected to elevated temperatures during plant entrainment, and far exceeds exposures to high temperatures during plume entrainment. Furthermore, the 32 C shock temperature used is generally applicable only for fish entrained when ambient temperatures are about 22 to 25 C, which usually occur near the end of the season for striped bass larval occurrence in the Hudson River (late June and July).

A comparison between the time-temperature exposures that may be encountered by striped bass larvae entrained at Hudson River power plants (Table 5) and the estimated thermal stress required to induce selective predation (Figure 4) indicates that most entrained striped bass are exposed to thermal stresses less than or only slightly greater than the minimum thermal stress resulting in increased vulnerability to predation. Discharge temperatures less than about 30.0 C would not be expected to induce any preferential predation on

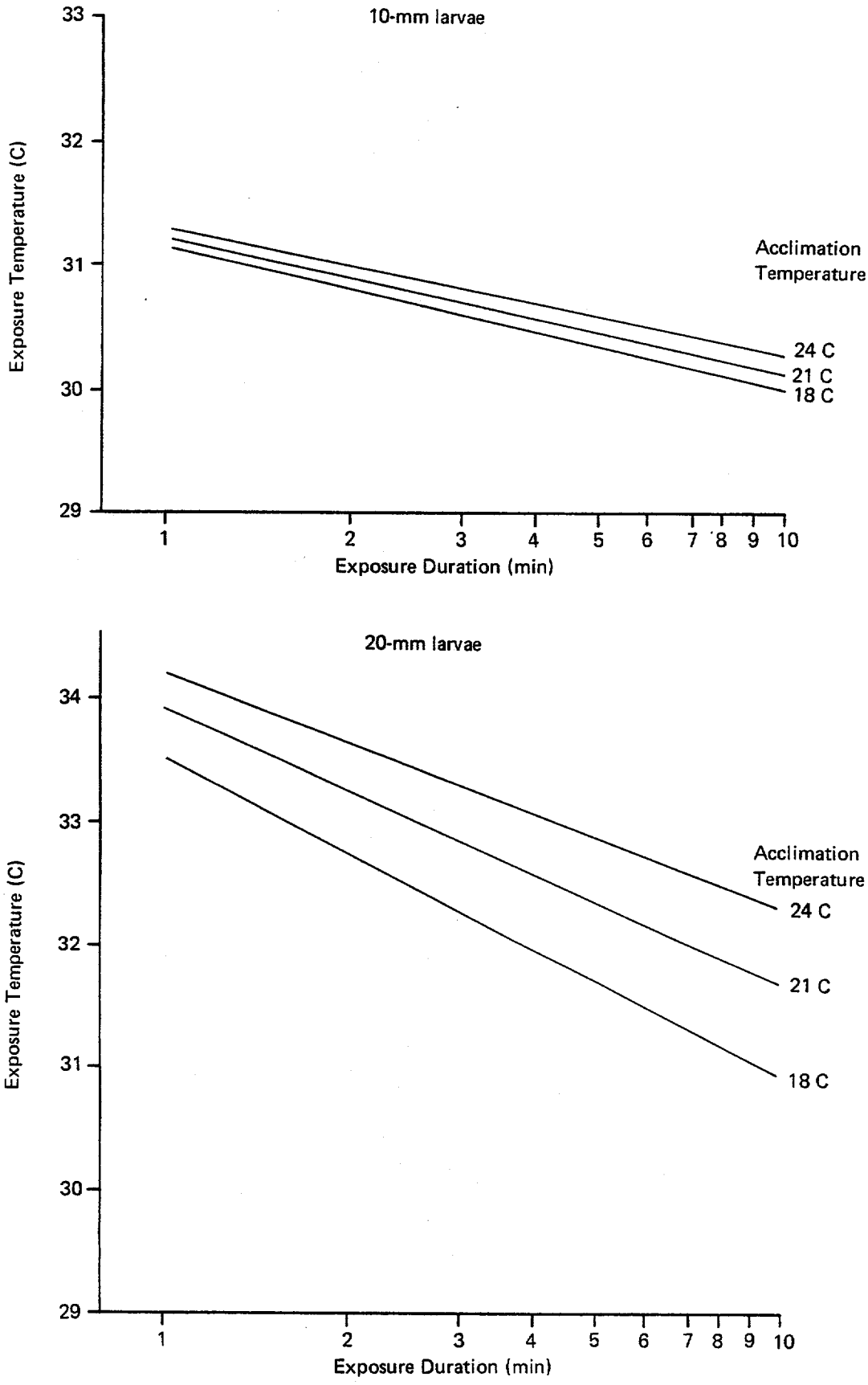

Figure 4. Estimated time-temperature exposures necessary to induce selective predation on entrained striped bass larvae.

TABLE 5 DURATION OF EXPOSURE TO HEATED WATER IN THE CIRCULATING WATER SYSTEMS AND RISE IN COOLING WATER TEMPERATURES (DELTA-T) AT HUDSON RIVER POWER PLANTS

Plant	No. of Pumps[a]	Exposure Time (min)	Delta-T[b] (C)
Roseton[c]	2	5.3	15.3
	3*	4.1	11.4
	4*	3.5	10.0
Bowline Point[d]	2 throttled	7.4	11.9
	2*	6.4	10.1
	3*	5.3	8.5
Indian Point Unit 2	4	13.1[e]	13.2[g]
	5*	10.1[e]	10.6[g]
	6*	8.2[e]	8.9[g]
Indian Point Unit 3	4	7.0[f]	14.5[g]
	5*	5.2[f]	11.6[g]
	6*	4.1[f]	9.6[g]

(a) Full mode operation, unless otherwise noted.
(b) Maximum delta-T at 100 percent capacity.
(c) Units 1 and 2 operating.
(d) Applies to either unit.
(e) Unit 2 with Unit 3 operating at an identical flow (Unit 1 not operating).
(f) Unit 3 with Unit 2 operating at an identical flow (Unit 1 not operating).
(g) Condenser temperature rise with river ambient temperature at 21.1 C.

Note: Asterisks indicate normal operation during striped bass larval season.

Source: EA (1977, Tables 3.2-1 and 3.2-2), Con Edison (1977, Tables 1-3, 1-6, 1-13 and 1-14), and NYU (1978, Table 1-1).

entrained striped bass larvae early in the season (river temperature = 18 C). As the season progresses, increasing ambient river temperatures and greater larval size results in progressively greater time-temperature exposures necessary to induce selective predation.

Thus, time-temperature exposures encountered by striped bass larvae during entrainment at Hudson River power plants would not be sufficient to increase their susceptibility to capture under most conditions. During the summer months, when the potential for preferential predation is probably greatest because of higher ambient river temperatures and, consequently, higher discharge temperatures, few striped bass larvae are entrained. Furthermore, the limiting thermal stress used in this evaluation does not account for the amount of elapsed time between a heat shock and a predation event (i.e., recovery time), and thus can lead to an overestimate of the potential for preferential predation to occur for predation events occurring beyond about 30 minutes after return to the river.

5.3 ASSESSMENT OF THE POTENTIAL FOR PREFERENTIAL PREDATION OF ENTRAINED STRIPED BASS LARVAE UNDER NATURAL CONDITIONS

An important aspect of the preferential predation experiments was the measurement of preferential predation under experimental conditions partially simulating conditions in the natural environment. Materials and methods designed to approximate natural conditions during these tests were the following:

1. Large experimental tanks were used to reduce possible effects of spatial constraints on the normal evasive behavior of larval prey.

2. Experimental tanks were supplied with naturally turbid water from the Hudson River.

3. Alternative prey (Gammarus) were included in some tests.

4. Tests were conducted in the presence of natural lighting and at dusk, an important feeding time for many fish predators (including white perch).

However, a number of important factors were not adequately simulated during these tests, such as naturally occurring densities of prey and possibly predators, the velocity and turbulence in and around the discharges of power plants, and the availability of cover. Thus, the results of the preferential predation experiments cannot be directly extrapolated to field situations without also considering these and possibly other important variables that could substantially alter the potential for preferential predation to occur.

One of the most important variables not adequately simulated during the preferential predation tests was prey density. The density of striped bass larvae tested during the preferential predation experiments was much greater than densities that would normally be present in the Hudson River.*

* The original objectives of this study included testing for preferential predation using lower prey densities; however, nearly complete predation of both stressed and control larvae was observed during these tests, precluding the detection or measurement of selective predation.

Preferential predation experiments were conducted at a larval density of 26.3/m^3. In contrast, river concentrations of Morone spp. larvae (striped bass and white perch combined) seldom exceed 1/m^3 (TI 1977, pp. B7-B34). The actual probability of a predator encountering an entrained striped bass larva prior to its recovery from the thermal stress is likely to be quite low in the natural environment. Under these conditions, appreciable preferential predation of entrained striped bass larvae might not occur, regardless of the extent to which larval performance was impaired by sublethal entrainment stresses.

Moreover, the abundance of other food organisms far exceeds the abundance of Morone spp. larvae in the river. In the vicinity of Indian Point, for example, river concentrations of macrozooplankton (predominately Gammarus, Neomysis, and Monoculodes) during June and July often exceed 10/m^3 (Con Edison 1977, Figures 8-5 and 8-6)--over 10 times the concentrations of Morone spp. larvae during periods of peak abundance. Although the presence of alternative prey did not appear to influence the degree of preferential predation observed during this study, the presence of alternative prey did result in a significant ($P < 0.005$) decrease in the overall predation rate on striped bass larvae. The extent to which the predation rate on larvae is reduced by the presence of other food organisms under natural conditions could substantially increase the probability that entrained larvae would avoid predation long enough to completely recover from the thermal stress.

The abundance of predators in the vicinity of a cooling water discharge would also have a pronounced impact on the extent to which indirect mortality would result from thermal stress encountered by larvae during entrainment. In the Hudson River, most fish predators capable of preying on larval fishes generally prefer bottom or shore-zone areas, and do not normally utilize offshore, surface waters characteristic of the thermal plumes from most Hudson River power plants. For example, available data on the Roseton plant plume indicated that few fish likely to prey upon striped bass larvae were present in the thermal plume area (EA 1978b); only six juvenile striped bass and no white perch were collected during 9 sampling efforts totaling 135 minutes of electrofishing during the spring and summer months (May-August). Consequently, the probability that entrained striped bass larvae would encounter predators prior to recovery from the thermal stress would be expected to be quite low.

In addition, the high discharge velocities associated with the submerged, high velocity diffusers at the Roseton, Bowline Point, and Indian Point plants exceed the swimming speeds of many Hudson River fishes in the immediate vicinity of the discharge (Con Edison 1978; ORU 1978; CHG&E 1978), preventing predators from inhabiting these areas, and perhaps even impeding their predation efficiencies in surrounding waters where discharge velocities are not excessive. Critical swim speed data indicate that velocities greater than 4 fps are unlikely to be negotiated continuously by most Hudson River fishes (see ORU 1978, Table 3.4-1). At the Roseton and Bowline Point plants, initial discharge velocities are 12.6 and 15.0 fps, respectively, and are reduced to less than 4 fps within about 9-15 meters from the diffuser ports (plume temperatures at this point are reduced to less than 30 percent of the maximum discharge temperature). At the Indian Point plant, initial velocities of 10 fps reduce to less than 4 fps within about 12 meters of the discharge ports (where plume temperatures are approximately 80 percent of the maximum

discharge temperature). The rapid dispersion and mixing of entrained larvae with other prey organisms in the river at these power plants would be expected to further reduce the potential for preferential predation to occur following an actual entrainment event.

Another variable that may reduce the potential for preferential predation to occur in the natural environment is the availability of cover, such as vegetation, which may serve as a refuge for stressed larvae until they have recovered from the thermal shock.

Thus, the results of this study, together with an assessment of some important natural variables not adequately simulated during the study, indicate that increased predation on striped bass larvae entrained at Hudson River power plants is not expected to occur to any appreciable extent. The magnitude of the thermal exposure encountered by entrained larvae is usually insufficient to increase their susceptibility to capture. When time-temperature exposures are sufficient to increase susceptibility to predation, escape capabilities have been shown to quickly return to normal. Moreover, the probability that a predation event would occur on entrained striped bass larvae prior to recovery from the thermal stress at naturally occurring densities of striped bass larvae, alternative prey, and potential predators would be expected to be quite low in the environment in and around cooling water discharges at Hudson River power plants.

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APPENDIX A: THERMAL TOLERANCE DATA FOR YOUNG STRIPED BASS AND DEVELOPMENT OF AN EMPIRICAL PREDICTION EQUATION

APPENDIX A: THERMAL TOLERANCE DATA FOR YOUNG STRIPED BASS AND DEVELOPMENT OF AN EMPIRICAL PREDICTION EQUATION

A.1 INTRODUCTION

Thermal tolerance experiments were conducted on early juvenile striped bass during July 1978 to supplement thermal tolerance data collected on post-yolk-sac larvae during 1976 and 1977. These data were combined to generate a prediction equation describing thermal mortality with respect to exposure temperature, exposure duration, acclimation temperature, and length. Methods and results for experiments conducted in 1978 are presented in this Appendix, along with a description of the thermal mortality prediction model. Experiments conducted in 1976 and 1977 were performed according to procedures similar to those used in 1978; the results of the 1976 and 1977 tests were reported in "Hudson River Thermal Effects Studies for Representative Species - Final Report" (EA 1978a).

A.2 METHODS AND MATERIALS

Experiments were conducted at Ecological Analysts' bioassay laboratory located on the Hudson River (River Mile 67). Young striped bass were obtained from a Con Edison hatchery operated by Texas Instruments, Inc., at Verplanck, New York. All striped bass used for testing were reared from eggs artificially spawned from adult striped bass collected from the Hudson River. After transport from the hatchery to the laboratory, fish were held for a minimum of 2-3 days prior to testing to allow for recovery from stresses associated with transport and handling. Holding tanks were supplied with a constant flow of clarified Hudson River water.

There were 24 series of tests conducted on striped bass ranging from 43 to 59 days old. The mean total length of fish for each series of tests was determined by measuring a subsample of 30 fish from each group tested; mean total lengths ranged from 20.0 to 26.1 mm. Striped bass were exposed to thermal shocks for 0.17 (10 seconds), 1, 5, 10, 30, and 60 minutes. One group of juveniles was held at ambient river temperatures (24.0-25.5 C), while the remaining fish were reacclimated to 18.0-18.5 C from an ambient temperature of 22.5 C at a rate of 1 C per day, and held at 18.0-18.5 C for 4-8 days prior to testing.

Each series of tests consisted of 4-6 test temperatures and a control. Tests were conducted by transferring approximately 20 fish placed in screen-bottomed containers 10 cm in diameter and 11 cm deep to aquaria adjusted to a series of test temperatures with submersible heaters. All 10-second and 1-minute tests were conducted by completely removing the larvae from the water for 1-2 seconds during transfer. Fish tested for longer exposure durations were transferred to the heated water without exposing them to the air, and containers were flushed several times with heated water from the test aquaria immediately after transfer to achieve rapid temperature equilibration; temperature equilibration was typically achieved within 60 seconds after initiation of these tests. Test temperatures were recorded with a calibrated mercury thermometer placed directly in the test container after equilibration. Temperature fluctuations during the test were maintained within 0.1-0.3 C, depending on the length of the exposure.

At the end of the exposure, fish were returned to flow-through water baths adjusted to the acclimation temperature and held without feeding for 24 hours prior to the mortality assessment to account for latent mortality that may have resulted from the thermal shock. Juveniles were transferred to small plastic buckets 20 cm in diameter and 15 cm deep which were immersed in the water bath. Each bucket was provided with light aeration and had perforations in the sides to allow exchange of water between the water bath and the bucket.

Controls were performed with each series of test temperatures. Control fish were treated in the same manner as experimental fish, except that the test aquaria contained water adjusted to the acclimation temperature rather than a higher test temperature. Control mortality averaged 10 percent and ranged from 0 to 35 percent for specific series of tests.

The percent mortality at each test temperature was determined from the original sample size and the number of live fish at the end of the 24-hour holding period, and corrected for control mortality using the following equation:

$$\text{Corrected Mortality (\%)} = \left[1 - \frac{\text{proportion surviving test temperature}}{\text{proportion surviving control}}\right] \times 100$$

Fish that were alive but exhibited loss of equilibrium were excluded from the live count. The correction for control mortality occasionally produced negative mortality values for tests where the control mortality exceeded the mortality observed for thermally shocked fish. These negative values were retained, rather than adjusting them to 0 percent mortality, to avoid biasing the data toward higher mortality values than were actually observed at those test temperatures.

Results of these tests were combined according to similar exposure durations, acclimation temperatures, and size of larvae tested. The temperature resulting in 50 percent survival (TL50) was interpolated from a linear regression of percentage mortality versus temperature for each group of similar tests. Responses at test temperatures markedly above or below the general range of test temperatures resulting in fractional mortality were excluded from the regression analysis. In addition, questionable responses resulting in large negative values after calculating the correction for control mortality were excluded.

A.3 RESULTS

The percentage mortality at each test temperature (after correcting for control mortality) was plotted for results that were combined according to similar exposure durations and acclimation temperatures, as shown in Figure A-1.

TL50s for striped bass juveniles ranged from 32.1-34.9 C for 60-minute exposures to 41.1-42.7 C for 10-second exposures, representing temperature increases above acclimation temperatures (delta-Ts) of 10.4-24.7 C (Table A-1). With the exception of the 10-second exposures, TL50s for fish acclimated to 24.0-25.5 C were higher than TL50s for fish acclimated to 18.0-18.5 C. The difference between TL50s at each exposure duration generally became more pronounced as exposure duration increased; TL50s for fish acclimated to the two temperature groups differed by 2.8 C for 60-minute exposures, but differed by only 0.7 C for 1-minute exposures (Table A-1).

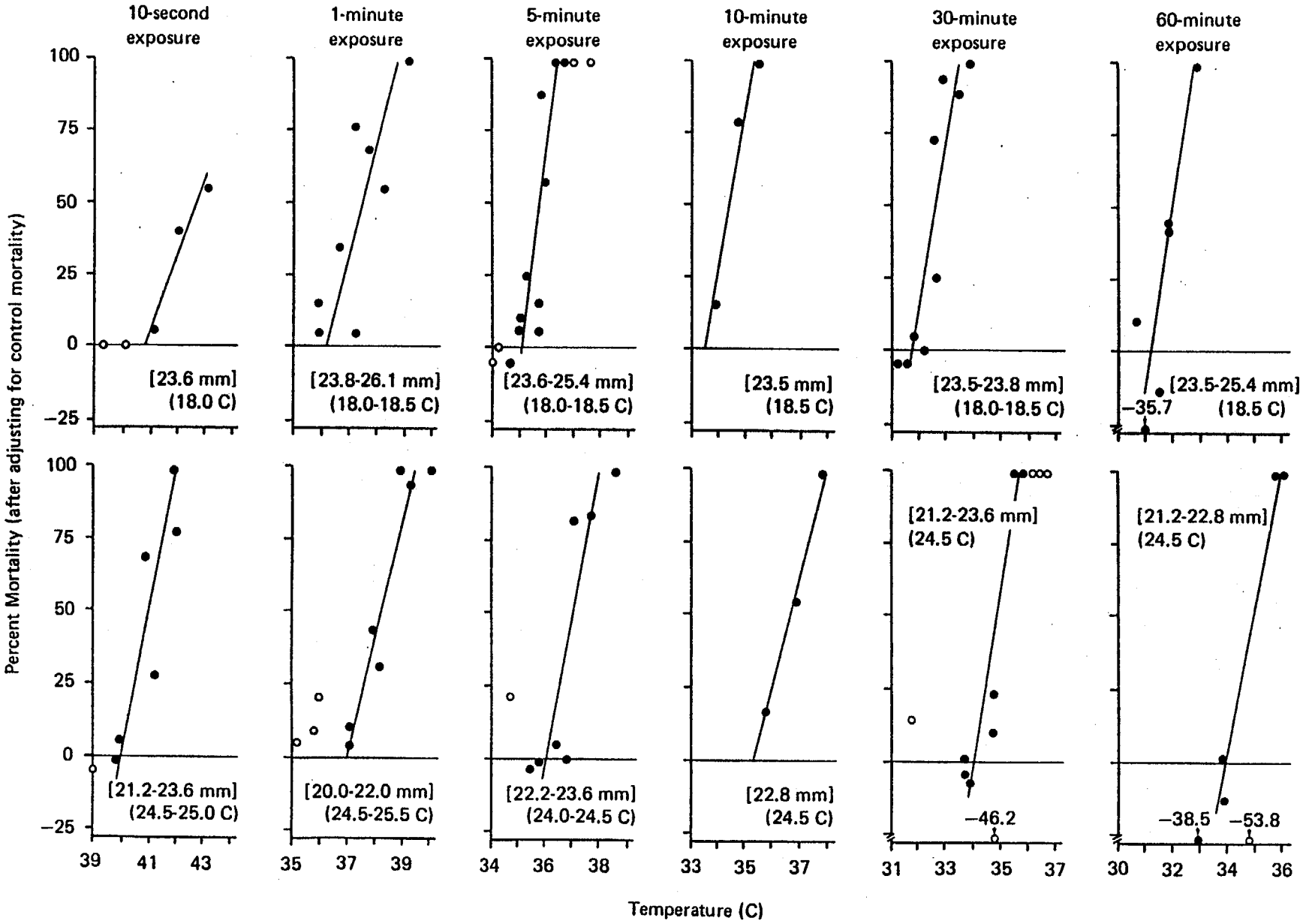

Figure A-1. Percent mortality versus test temperature for striped bass juveniles thermally shocked for 10-second, 1-, 5-, 10-, 30-, and 60-minute exposure durations. The mean total lengths of larvae tested and the acclimation temperatures are enclosed in brackets and parentheses, respectively. The linear regression line used to calculate the TL50s is also shown. Closed symbols denote test results included in the linear regression analysis; open symbols denote additional data points that were excluded from the linear regression analyses.

TABLE A-1 TL50s FOR YOUNG STRIPED BASS EXPOSED TO SHORT-TERM THERMAL SHOCKS, BASED ON MORTALITY OBSERVATIONS MADE 24 HOURS AFTER THE THERMAL EXPOSURE

	Length (mm)	Acclimation Temperature (C)	TL50 (C) Exposure Duration (min) 0.17	1	5	10	30	60
Juveniles[a]	23.5-26.1	18.0-18.5	42.7	37.5	35.8	34.5	32.8	32.1
	20.0-23.6	24.0-25.5	41.1	38.2	37.0	36.6	34.9	34.9
Post-yolk-sac larvae[b]	8.7-9.2	20.0-22.0	--	--	33.8	33.2	33.1	--
	11.4	23.5	--	--	34.8	34.4	33.7	--
	14.4	23.0	--	--	--	36.5	35.0	34.0

(a) 1978 tests.
(b) 1976 and 1977 tests.

Note: Dashes (--) indicate no data.

In contrast to results of tests performed at longer exposure durations, the 10-second TL50 for fish acclimated to 18.0 C was actually higher than the TL50 for fish acclimated to 24.5-25.0 C. This inverse relationship between acclimation temperature and thermal tolerance was probably observed because the interval temperature of a fish acclimated to 18.0 C may not have increased as high as the internal temperature of a fish acclimated to 24.5-25.0 C during the brief exposure duration, and therefore was not exposed to the same maximum temperature.

A.4 DEVELOPMENT OF PREDICTION MODEL

Thermal tolerance data on striped bass post-yolk-sac larvae obtained in 1976 and 1977 were combined with the 1978 results for multiple linear regression analysis and development of a prediction model. In 1976 and 1977, 17 series of tests with exposure durations ranging from 5 to 60 minutes were completed on post-yolk-sac larvae ranging from 18 to 35 days old (EA 1978a, Tables B-123 through B-149). The majority of tests were conducted on larvae 8.7-9.2 mm mean total length (18-30 days old) and acclimated to 20-22 C. Three series of 5-minute exposures and four series of both 10- and 30-minute exposures were conducted on larvae averaging 11.4 mm (30 days old) and acclimated to 23.5 C, and one series each of 10-, 30- and 60-minute exposures were conducted on larvae averaging 14.4 mm (35 days old) and acclimated to 23.0 C. These data were re-analyzed according to slightly different analytical procedures than described in Ecological Analysts (1978a); negative values resulting from control mortality corrections were retained and results were combined according to similar exposure durations, acclimation temperatures, and size of larvae tested, as shown in Figure A-2 (the 60-minute exposure results are not shown). TL50s were calculated according to procedures described for 1978 tests. The revised TL50s for post-yolk-sac larvae are presented in Table A-1.

An empirical predictive equation was constructed with multiple linear regression analysis (Draper and Smith 1966, Chapter 7) using the data points selected for calculation of the TL50s (i.e., responses at test temperatures markedly above or below the general range of test temperatures resulting in fractional mortality were omitted from the regression analysis, as shown in Figures A-1 and A-2). Ten-second data were not included in the regression analysis. The independent variables were exposure temperature, exposure duration, acclimation temperature, and length; the dependent variable was percentage mortality. Exposure duration was transformed to a logarithm because of a pronounced curvilinear relationship between exposure duration and mortality. Additionally, the cross-products and squares of the four independent variables were included in the initial model to account for possible variation resulting from interaction between the variables or possible curvilinear responses. Thus, the following model with 14 variables was considered for development of an empirical predictive equation:

$$y = b_o + b_1(X_1) + b_2(X_1)^2 + b_3(X_1X_2) + b_4(X_1X_3) + b_5(X_1X_4) + b_6(X_2) + b_7(X_2)^2 + b_8(X_2X_3) + b_9(X_2X_4) + b_{10}(X_3) + b_{11}(X_3)^2 + b_{12}(X_3X_4) + b_{13}(X_4) + b_{14}(X_4)^2$$

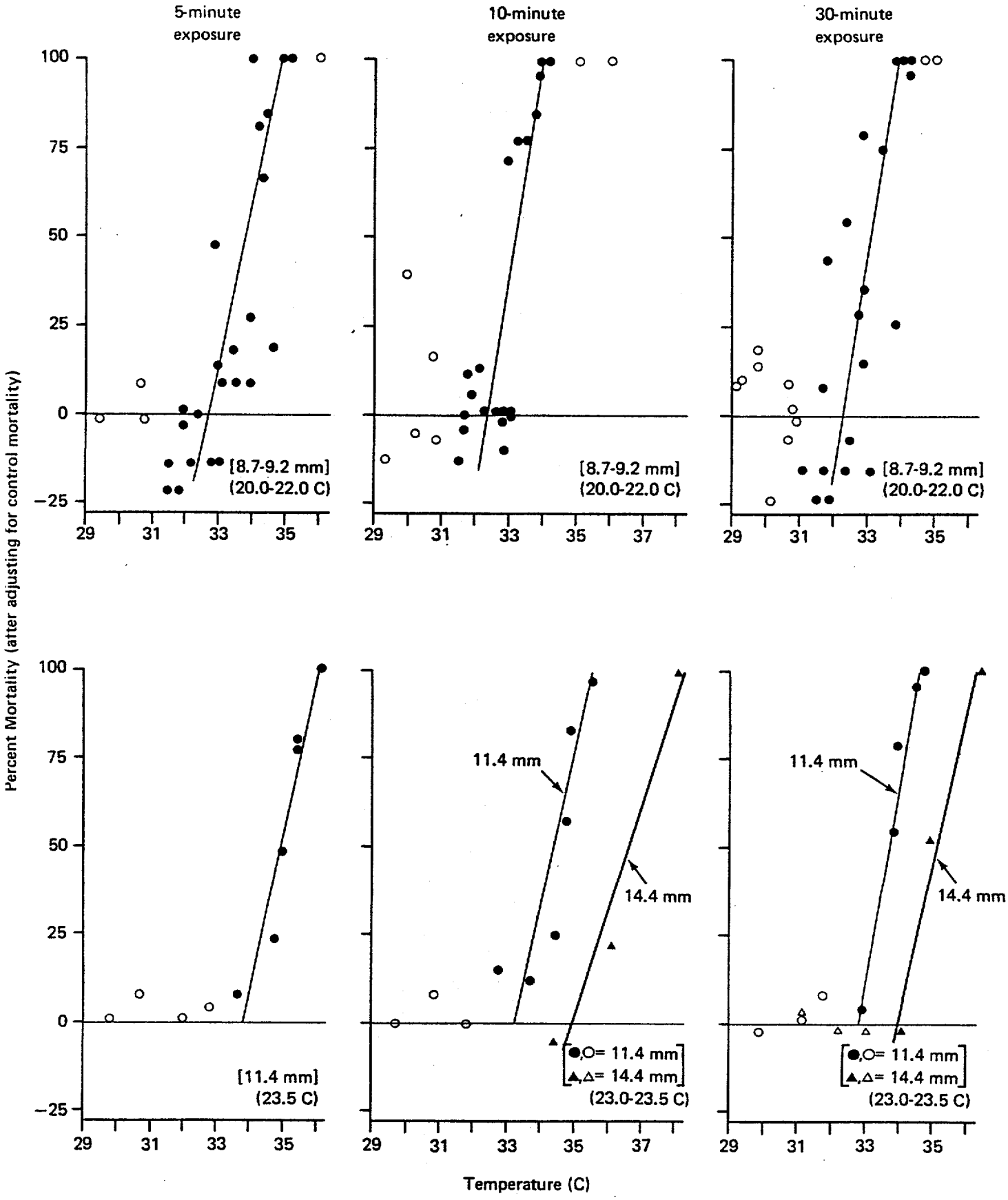

Figure A-2. Percent mortality versus test temperature for striped bass post-yolk-sac larvae thermally shocked for 5-, 10-, and 30-minute exposure durations. The mean total lengths of larvae tested and the acclimation temperatures are enclosed in brackets and parentheses, respectively, in the lower right-hand corner of each plot. The linear regression line used to calculate the TL50s is also shown. Closed symbols denote test results included in the linear regression analysis; open symbols denote additional data points that were excluded from the linear regression analyses.

where

y = percentage mortality
X_1 = exposure temperature (C)
X_2 = exposure duration ($\log_{10}$ minutes)
X_3 = acclimation temperature (C)
X_4 = total length (mm)

The variable selection procedure was based on backward elimination (Draper and Smith 1966, pp. 167-169) and Mallow's Cp statistic (Mosteller and Tukey 1977, pp. 385-387). The backward elimination procedure begins with the full model and eliminates unimportant variables in order from the least important to the most important. The "best" model is derived when no further variables can be eliminated from the model without significantly decreasing the regression sum of squares. Of the 14 variables considered here, the important variables chosen by backward elimination were acclimation temperature (X_3), length squared (X_4^2), and the cross-products of exposure temperature and acclimation temperature (X_1X_3), log exposure duration and length (X_2X_4), and acclimation temperature and length (X_3X_4). To determine if any of the variables rejected during the backward elimination procedure were important in terms of reducing bias, each was added to the 5-variable model, one at a time, and the Cp statistic was examined. The Cp statistic--a measure of total squared error--represents an alternative criterion to the backward selection procedure for identifying important variables. The last variable rejected by the backward elimination procedure--length (X_4)--resulted in a slightly lower Cp statistic than the 5-variable model. However, the 5-variable model was retained as the best predictive equation because the difference between Cp values for the two models was negligible. The resulting predictive equation for striped bass thermal tolerance was:

$$\text{Percent Mortality} = 22.01 + 1.601(X_1X_3) + 3.692(X_2X_4) - 47.92(X_3)$$
$$-0.8174(X_3X_4) + 0.2773(X_4)^2.$$

The statistics associated with this model are presented in Table A-2. Over the range of variables used to derive the regression equation (see Table A-1), the 95 percent confidence limits for the predicted values (percent mortality) ranged from ±6.1 to ±16.9.

To predict TL50s, a constant of 50 percent was substituted for percentage mortality (y) and the equation was rearranged to solve for temperature (X_1), as shown below:

$$TL50(C) = \frac{27.99 - 3.69^2(X_2X_4) + 47.92(X_3) + 0.8174(X_3X_4) - 0.2773(X_4)^2}{1.601(X_3)}$$

TABLE A-2 ANALYSIS OF VARIANCE TABLE AND TESTS OF SIGNIFICANCE OF THE REGRESSION COEFFICIENTS FOR THE STRIPED BASS THERMAL TOLERANCE PREDICTION EQUATION[a]

Variable	Regression Coefficient	Standard Deviation	t-statistic	Probability of a Greater t
Test Temperature x Acclimation Temperature	1.601	0.0983	16.28	P<<0.001
Log_{10} Exposure Duration x Length	3.692	0.3242	11.39	P<<0.001
Acclimation Temperature	-47.92	5.609	-8.543	P<0.001
Acclimation Temperature x Length	-0.8174	0.2003	-4.080	P<0.001
Length Squared	0.2773	0.1247	2.223	0.05>P>0.02

Source	Sum of Squares	Degrees of Freedom	Mean Square	F	Probability of a Greater F
Regression	192,100	5	38,420	54.57	P<<0.001
Error	105,600	150	704.1		

(a) Multiple correlation coefficient (r) = 0.8033; standard error of regression = 26.53; y-intercept = 22.01.

APPENDIX B: DATA TABLES FOR PREFERENTIAL PREDATION EXPERIMENTS

TABLE B-1 NUMBERS OF PREY RETRIEVED FROM EXPERIMENTAL TANKS WITHOUT PREDATORS

Date	Recovery of Larvae					Recovery of Gammarus		
	Tank	Mean Total Length (mm)	No. Larvae Per Tank	No. Larvae Recovered	Percent Recovery	No. Gammarus Per Tank	No. Gammarus Recovered	Percent Recovery
16 JUN 1978	A	12.1	10	10	100.0	0	NA	NA
23 JUN 1978	A	15.8	10	9	90.0	0	NA	NA
	B	15.8	10	10	100.0	0	NA	NA
	C	15.8	10	10	100.0	0	NA	NA
	D	15.8	10	9	90.0	0	NA	NA
	E	15.8	10	10	100.0	0	NA	NA
	F	15.8	10	10	100.0	0	NA	NA
30 JUN 1978	C	14.2	50	48	96.0	0	NA	NA
	F	14.2	50	50	100.0	0	NA	NA
11-14 JUL 1978	A	22.0	50	50	100.0	100	96	96.0
	B	22.0	50	50	100.0	100	76	76.0
	C	22.0	50	48	96.0	100	81	81.0
	D	22.0	50	53	106.0(a)	100	94	94.0
	E	22.0	50	50	100.0	100	92	92.0
	F	22.0	50	49	98.0	100	96	96.0
Total			470	463	98.5	600	535	89.2

(a) Percent recovery greater than 100 due to enumeration errors at start of test. The three "extra" larvae were not included in the calculation of the total percent recovery.

Note: NA indicates not applicable.

TABLE B-2 NUMBERS OF PREY RETRIEVED FROM THE EXPERIMENTAL TANKS AND THE STOMACHS OF THE PREDATORS USED IN EACH TANK

Tank	No. Larvae Per Tank	No. Gammarus Per Tank	Total Length of Predator (mm)	Recovery from Stomachs: No. Stressed Larvae	No. Control Larvae	No. of Gammarus	Percentage of Available Larvae	Percentage of Available Gammarus	Recovery from Tank: No. Stressed Larvae	No. Control Larvae	No. Gammarus	Total Percent Recovery: Larvae	Gammarus
						Predator Group 3							
A	50	0	88	5	10	NA	30	NA					
			83	1	3	NA	8	NA					
			82	6	2	NA	16	NA					
			Total	12	15		54		13	8	NA	96.0	NA
F	50	0	83	4	4	NA	16	NA					
			87	5	1	NA	12	NA					
			99	4	1	NA	10	NA					
			Total	13	6		38		11	19	NA	98.0	NA
B	50	100	95	3	2	8	10	8					
			92	6	4	1	20	1					
			76	5	2	12	14	12					
			Total	14	8	21	44	21	11	16	59	98.0	80.0
C	50	100	82	2	1	13	6	13					
			87	2	1	18	6	18					
			89	7	2	27	18	27					
			Total	11	4	58	30	58	14	22	27	102.0[a]	85.0
D	50	100	70	2	1	6	6	6					
			90	3	3	16	12	16					
			95	2	1	10	6	10					
			Total	7	5	32	24	32	17	20	62	98.0	94.0
E	50	100	86	0	3	13	6	13					
			98	0	0	21	0	21					
			90	0	0	30	0	30					
			Total	0	3	64	6	64	24	20	25	94.0	89.0

TABLE B-2 (CONT.)

Tank	No. Larvae Per Tank	No. Gammarus Per Tank	Total Length of Predator (mm)	Recovery from Stomachs: No. Stressed Larvae	No. Control Larvae	No. of Gammarus	Percentage of Available Larvae	Percentage of Available Gammarus	Recovery from Tank: No. Stressed Larvae	No. Control Larvae	No. Gammarus	Total Percent Recovery: Larvae	Gammarus
						Predator Group 4							
A	50	0	86	3	3	NA	12	NA					
			85	4	0	NA	8	NA					
			85	5	6	NA	22	NA					
			Total	12	9		42		13	10	NA	88.0	NA
D	50	0	90	3	2	NA	10	NA					
			90	5	6	NA	22	NA					
			88	5	4	NA	18	NA					
			Total	13	12		50		12	10	NA	94.0	NA
						Predator Group 4							
B	20	0	71	1	4	NA	25	NA					
			77	3	4	NA	35	NA					
			85	2	3	NA	25	NA					
			Total	6	11		85		3	0	NA	100.0	NA
E	20	0	88	4	2	NA	30	NA					
			94	4	4	NA	40	NA					
			92	2	3	NA	25	NA					
			Total	10	9		95		0	1	NA	100.0	NA
C	20	100	90	5	2	11	35	11					
			100	0	3	18	15	18					
			87	5	1	6	30	6					
			Total	10	6	35	80	35	1	4	74	105.0(a)	109.0(a)
F	20	100	89	2	3	11	25	11					
			77	1	2	9	15	9					
			86	6	5	0	55	0					
			Total	9	10	20	95	20	1	0	95	100.0	115.0(a)
			Grand Total	117	98	230	44.8	38.3	120	130	342	96.4(a)	91.3(a)

(a) Percent recovery greater than 100 due to enumeration errors at start of test. These "extra" prey were not included in the calculation of percent recovery for the grand totals.

Note: NA indicates not applicable.

TABLE B-3 RESULTS OF PREFERENTIAL PREDATION EXPERIMENTS

Date	Total Length of Larvae (mm) Mean	S.D.	Predator Group	No. Predators Per Tank	Tank	Length of Test (min)	Secchi Disk (cm)	Tank Temp. (C)	Thermal Stress Ambient Temp. (C)	Thermal Stress Shock Temp. (C)	No. Stressed Larvae At Start	No. Stressed Larvae At End	No. Control Larvae At Start	No. Control Larvae At End	Total No. Larvae At End	No. Gammarus At Start	No. Gammarus At End
15 JUN 1978	12.1	1.06	2	5	B	720	--	21.0	21.0	30.9	5	1	5	0*	1	0	0
					C	480	--	21.2	21.2	31.0	5	1	5	0*	1	0	0
					D	360	--	21.8	21.2	31.0	5	0	5	0*	0	0	0
					E	240	--	21.0	21.5	31.0	5	1	5	0*	1	0	0
					F	120	--	20.2	22.5	31.0	5	0	5	0*	0	0	0
16 JUN 1978	12.1	1.06	2	5	B	720	--	22.0	21.4	30.8	5	0*	5	0	0	0	0
					C	480	--	22.0	22.0	31.0	5	0*	5	3	3	0	0
					D	360	--	21.8	22.5	30.8	5	0*	5	3	3	0	0
					E	240	--	21.5	22.5	31.0	5	0*	5	3	3	0	0
					F	120	--	21.2	22.5	31.0	5	0*	5	0	0	0	0
20 JUN 1978	13.8	0.88	2	5	A	70	33	24.0	23.0	31.8	5	0	5	0*	0	0	0
					B	87	37	24.0	23.0	31.8	5	0	5	0*	0	0	0
					C	109	35	23.5	23.0	31.9	5	0	5	0*	0	0	0
					D	95	37	23.8	23.0	31.8	5	0	5	0*	0	0	0
					E	107	35	23.5	23.0	32.0	5	1	5	1*	2	0	0
					F	122	35	24.0	23.0	31.9	5	0	5	0*	0	0	0
21 JUN 1978	14.7	0.99	2	5	A	33	41	23.0	23.0	31.8	5	0	5	0*	0	0	0
					B	35	39	23.0	23.0	31.5	5	0	5	0*	0	0	0
					C	45	40	23.0	23.0	31.8	5	3	5	0*	3	0	0
					D	42	40	22.8	23.0	32.0	5	0	5	0*	0	0	0
					E	47	41	22.8	23.0	32.0	5	0	5	0*	0	0	0
					F	54	41	23.0	23.0	32.0	5	0	5	0*	0	0	0
22 JUN 1978	15.5	1.25	2	5	A	17	33	23.2	23.2	31.8	5	0	5	0*	0	0	0
					B	15	34	23.2	23.2	31.9	5	0	5	1*	1	0	0
					C	15	35	23.0	23.2	31.5	4	0	5	0*	0	0	0
					D	19	36	23.2	23.2	31.8	5	1	5	0*	1	0	0
					E	15	36	23.2	23.2	31.8	5	0	5	0*	0	0	0
					F	15	39	23.5	23.2	31.9	5	0	5	0*	0	0	0
26 JUN 1978	15.6	1.31	2	3	A	23	40	23.0	23.0	31.5	10	5	10	0*	5	0	0
					B	15	40	23.0	23.0	31.5	9	1	10	0*	1	0	0
					C	15	36	23.0	23.0	31.5	10	3	10	0*	3	0	0
	24.1	1.85	2	3	D	18	40	23.0	22.8	31.5	10	0	10	0*	0	0	0
					E	15	41	23.0	22.8	31.5	10	0	10	1*	1	0	0
					F	15	44	22.8	22.8	31.5	10	1	10	1*	2	0	0
27 JUN 1978	15.6	1.31	2	3	A	18	40	24.2	23.8	31.5	10	0*	10	0	0	0	0
					B	15	42	24.0	23.8	31.8	10	1*	10	1	2	0	0
					C	15	38	24.0	23.8	31.8	10	1*	10	0	1	0	0
	24.1	1.85	2	3	D	15	45	24.0	23.8	31.5	10	0*	10	0	0	0	0
					E	15	45	24.2	23.8	31.8	10	0*	10	3	3	0	0
					F	15	50	25.0	23.8	31.8	10	0*	10	2	2	0	0

TABLE B-3 (CONT.)

Date	Total Length of Larvae (mm) Mean	S.D.	Predator Group	No. Predators Per Tank	Tank	Length of Test (min)	Secchi Disk (cm)	Tank Temp. (C)	Thermal Stress Ambient Temp. (C)	Thermal Stress Shock Temp. (C)	No. Stressed Larvae At Start	No. Stressed Larvae At End	No. Control Larvae At Start	No. Control Larvae At End	Total No. Larvae At End	No. Gammarus At Start	No. Gammarus At End
29 JUN 1978	14.2	0.91	2	3	B	15	41	24.0	23.8	31.8	25	0	25	1*	1	0	0
					E	15	42	24.0	23.8	32.0	25	4	25	0*	4	0	0
					C	17	40	24.0	23.8	32.0	24	0	25	1*	1	0	0
					F	15	41	24.5	23.8	32.0	25	0	25	0*	0	0	0
	26.0	0.94	2	3	A	25	37	24.0	23.8	32.0	8	0	10	0*	0	100	52
					D	15	41	24.0	23.8	31.8	10	0	10	0*	0	100	63
30 JUN 1978	14.2	0.91	2	3	B	15	42	24.2	23.5	31.8	25	0*	25	3	3	0	0
					E	15	45	24.2	23.5	31.8	25	0*	25	1	1	0	0
					C	16	41	24.2	23.5	32.0	25	0*	25	1	1	0	0
	26.0	0.94	2	3	A	15	42	24.0	23.5	31.8	9	0*	10	1	1	100	22
5 JUL 1978	19.3	1.52	3	3	A	15	47	23.2	24.1	32.2	25	11	25	18*	29	0	0
					F	15	50	24.0	24.1	32.0	25	10	25	20*	30	0	0
					B	15	50	23.2	24.1	32.0	25	13	25	19*	32	100	72
					C	15	47	23.2	24.1	32.0	25	13	25	22*	35	100	75
					D	15	52	23.8	24.1	32.0	25	18	25	20*	38	100	61
					E	15	48	23.5	24.1	32.0	25	20	25	22*	42	100	64
6 JUL 1978	19.3	1.52	3	3	A	15	50	23.9	24.1	32.2	25	17*	25	24	41	0	0
					F	15	54	24.9	24.1	32.5	25	20*	25	25	45	0	0
					B	15	51	24.1	24.1	32.0	25	13*	25	21	34	100	77
					C	15	50	24.1	24.1	32.0	25	16*	25	25	41	100	84
					D	15	52	24.5	24.1	32.0	25	17*	25	24	41	100	81
					E	15	58	24.3	24.1	32.0	25	25*	25	25	50	100	90
7 JUL 1978	16.9	1.03	3	3	A	15	48	24.8	24.8	32.3	25	11	25	10*	21	0	0
					F	15	50	25.2	24.8	32.5	25	18	25	23*	41	0	0
					B	15	45	24.8	24.8	32.3	25	16	25	20*	36	100	73
					C	15	45	24.8	24.8	32.4	25	18	25	18*	36	100	59
					D	15	46	24.8	24.8	32.4	25	18	25	13*	31	100	82
					E	15	45	24.6	24.8	32.4	25	25	25	23*	48	100	40
8 JUL 1978	16.9	1.03	3	3	A	15	51	25.6	25.2	32.4	25	13*(a)	25	10(a)	23(a)	0	0
					F	15	50	26.0	25.2	32.4	25	12*(a)	25	19(a)	31(a)	0	0
					B	15	51	25.7	25.2	32.4	25	11*(a)	25	17(a)	28(a)	100	79(a)
					C	15	52	25.7	25.2	32.2	25	14*(a)	26	22(a)	36(a)	100	42(a)
					D	15	53	25.6	25.2	32.4	25	18*(a)	25	20(a)	38(a)	100	68(a)
					E	15	53	25.6	25.2	32.4	25	25*(a)	25	22(a)	47(a)	100	36(a)
3 JUL 1978	17.4	1.46	4	3	B	15	46	22.8	24.1	32.0	10	1	10	2*	3	0	0
					E	15	45	23.0	24.1	32.0	10	0	10	1*	1	0	0
					C	15	45	23.0	24.1	32.0	10	3	10	0*	3	100	63
					F	15	44	23.0	24.1	32.0	10	0	10	1*	1	100	51
					A	15	45	23.0	24.1	32.0	25	8	25	6*	14	0	0
					D	15	45	23.0	24.1	32.0	25	6	25	3*	9	0	0

TABLE B-3 (CONT.)

Date	Total Length of Larvae (mm) Mean	S.D.	Predator Group	No. Predators Per Tank	Tank	Length of Test (min)	Secchi Disk (cm)	Tank Temp. (C)	Thermal Stress Ambient Temp. (C)	Thermal Stress Shock Temp. (C)	No. Stressed Larvae At Start	No. Stressed Larvae At End	No. Control Larvae At Start	No. Control Larvae At End	Total No. Larvae At End	No. Gammarus At Start	No. Gammarus At End
4 JUL 1978	17.4	1.46	4	3	B	15	37	21.8	22.0	32.0	10	3*(a)	10	0(a)	3(a)	0	0
					E	15	40	21.8	22.0	32.0	10	0*(a)	10	1(a)	1(a)	0	0
					C	15	37	22.5	22.0	32.0	11	1*(a)	10	4(a)	5(a)	100	65(a)
					F	15	41	21.5	22.0	32.0	10	1*(a)	10	0(a)	1(a)	100	80(a)
					A	15	35	22.0	22.0	32.0	25	13*(a)	25	16(a)	29(a)	0	0
					D	15	40	21.5	22.0	32.0	25	12*(a)	25	13(a)	25(a)	0	0

(a) Recovery based on stomach contents. See Table B-2.

Note: Asterisk (*) denotes the dyed group of larvae; dashes (--) indicate no data.

TABLE B-4 PERCENTAGE OF LARVAE SURVIVING PREDATION FOR PAIRED REPLICATES (SUMMARY OF RESULTS FROM TABLE B-3; TEST DURATIONS WERE 15 MINUTES UNLESS NOTED OTHERWISE)

Predator Group	Mean Total Length of Predators (mm)	No. of Predators Per Tank	Mean Total Length of Larvae (mm)	Replicate 1[a]			Replicate 2[b]			Combined Replicates			Total Larvae Surviving (%)
				No. Larvae[c] Per Tank	No. Larvae Surviving		No. Larvae[c] Per Tank	No. Larvae Surviving		Total[c] No. Larvae	No. Larvae Surviving		
					Control	Stressed		Control	Stressed		Control	Stressed	
2[d]	115	5[e]	12.1	10	0	1	10	0	0	20	0	1	5.0*
				10	0	1	10	3	0	20	3	1	20.0*
				10	0	0	10	3	0	20	3	0	15.0*
				10	0	1	10	3	0	20	3	1	20.0*
				10	0	0	10	0	0	20	0	0	0.0*
2	115	3	15.6	20	0	5	20	0	0	40	0	5	12.5*[f]
				19[g]	0	1	20	1	1	39	1	2	7.7*
				20	0	3	20	0	1	40	0	4	10.0*
2	115	3	24.1	20	0	0	20	0	0	40	0	0	0.0*[f]
				20	1	0	20	3	0	40	4	0	10.0*
				20	1	1	20	2	0	40	3	1	10.0*
2	115	3	26.0	20	0	0	18[h]	1	0	38	1	0	2.7*[f,i]
				20	0	0	N.D.	N.D.	N.D.	20	0	0	0.0*[i]
2	115	3	14.2	50	1	0	50	3	0	100	4	0	4.0*
				50	0	4	50	1	0	100	1	4	5.0*
				49[j]	1	0	50	1	0	99	2	0	2.0*[f]
				50	0	0	N.D.	N.D.	N.D.	50	0	0	0.0*
3	87	3	16.9	50	10	11	50	10	13	100	20	24	44.0
				50	23	18	50	19	12	100	42	30	72.0
				50	20	16	50	17	11	100	37	27	64.0[i]
				50	18	18	51[k]	22	14	101	40	32	71.3[i]
				50	13	18	50	20	18	100	33	36	69.0[i]
				50	23	25	50	22	25	100	45	50	95.0[i]
3	87	3	19.3	50	18	11	50	24	17	100	42	28	70.0
				50	20	10	50	25	20	100	45	30	75.0
				50	19	13	50	21	13	100	40	26	66.0[i]
				50	22	13	50	25	16	100	47	29	76.0[i]
				50	20	18	50	24	17	100	44	35	79.0[i]
				50	22	20	50	25	25	100	47	45	92.0[i]

TABLE B-4 (CONT.)

Predator Group	Mean Total Length of Predators (mm)	No. of Predators Per Tank	Mean Total Length of Larvae (mm)	Replicate 1[a]			Replicate 2[b]			Combined Replicates			Total Larvae Surviving (%)
				No. Larvae[c] Per Tank	No. Larvae Surviving		No. Larvae[c] Per Tank	No. Larvae Surviving		Total[c] No. Larvae	No. Larvae Surviving		
					Control	Stressed		Control	Stressed		Control	Stressed	
4	87	3	17.4	20	2	1	20	0	3	40	2	4	15.0*
				20	1	0	20	1	0	40	2	0	5.0*
				20	0	3	21[l]	4	1	41	4	4	19.5*[i]
				20	1	0	20	0	1	40	1	1	5.0*[i]
				50	6	8	50	16	13	100	22	21	43.0
				50	3	6	50	13	12	100	16	18	37.0

(a) Control larvae dyed.
(b) Stressed larvae dyed.
(c) 50 percent of the larvae were stressed; 50 percent were control larvae (unless noted otherwise).
(d) Test durations for these tests ranged from 2-12 hours.
(e) Three additional replicates were performed with 5 predators and 10 larvae per tank, but since the control group was dyed in all three replicates, replicates could not be paired in this manner (see Table B-3). The total percent of larvae surviving these three replicates combined was 4 percent. Test durations ranged from 15 minutes to 2 hours.
(f) Actual test duration of one or both replicates deviated from 15 minutes by 1-10 minutes.
(g) Number of stressed larvae at start was 9.
(h) Number of stressed larvae at start was 8.
(i) 100 Gammarus (50 stressed, 50 unstressed) were included with the larvae for each replicate.
(j) Number of stressed larvae at start was 24.
(k) Number of control larvae at start was 26.
(l) Number of stressed larvae at start was 11.

Note: N.D. indicates no data.
Asterisk (*) indicates test results where the overall predation rate was too high for valid estimates of preferential predation (less than 30 percent survival).

APPENDIX C: DATA TABLES FOR RECOVERY TIME EXPERIMENTS

TABLE C-1 RESULTS OF RECOVERY TIME EXPERIMENTS CONDUCTED WITH PREDATOR GROUP 1[a]

Date	Total Length of Larvae (mm) Mean	S.D.	Range	Tank	Thermal Stress: Ambient Temp. (C)	Shock Temp. (C)	Delta-T (C)	Tank Temp. (C)	Recovery Time (min)	No. Larvae Per Tank	No. Attacks	No. Captures	Percent Capture	Captures Per Attack
20 JUN 1978	13.8	.877	12-16	1	22.0	NA	NA	27.0	Control	30	40	13	43.3	0.325
				2	22.0	32.0	10.0	27.3	0	30	39	30	100.0	0.769
				3	22.0	32.0	10.0	27.2	30	30	45	25	83.3	0.556
				4	22.0	32.0	10.0	27.3	60	30	46	28	93.3	0.610
				5	22.0	32.0	10.0	26.8	120	30	26	9	30.0	0.346
				6	22.0	32.0	10.0	27.1	240	30	43	23	76.7	0.535
21 JUN 1978	14.7	.985	13-17	1	21.9	NA	NA	24.6	Control	30	3	3	10.0	1.00[b]
				2	21.9	32.0	10.1	25.0	0	30	30	22	73.3	0.735
				3	21.9	32.0	10.1	24.1	30	30	31	14	46.7	0.452
				4	21.9	32.0	10.1	25.0	60	29	50	19	65.5	0.380
				5	21.9	32.0	10.1	24.8	120	30	54	19	63.3	0.352
				6	21.9	31.9	10.0	25.1	240	30	61	18	60.0	0.295
22 JUN 1978	15.5	1.253	13-19	1	23.3	NA	NA	24.7	Control	27	27	12	44.4	0.444
				2	23.3	32.1	8.8	24.9	0	30	46	30	100.0	0.654
				3	23.3	32.0	8.7	24.8	30	28	43	26	92.8	0.606
				4	23.3	31.9	8.6	25.1	60	30	14	10	33.3	0.714[b]
				5	23.3	31.9	8.6	24.5	120	29	52	27	93.1	0.521
				6	23.3	31.9	8.6	24.7	240	24	42	8	33.3	0.190
23 JUN 1978	15.8	.981	14-18	2	23.4	NA	NA	24.6	Control	24	41	15	62.5	0.366
				3	23.4	NA	NA	24.6	Control	23	68	22	95.6	0.324
				4	23.4	32.0	8.6	24.8	60	25	40	25	100.0	0.625
				5	23.4	31.9	8.5	24.2	120	23	34	23	100.0	0.676
				6	23.4	32.0	8.6	24.5	240	23	43	17	73.9	0.395

(a) Mean total length 85 mm; standard deviation 7.0 mm; range 76-98 mm.
(b) These data were not included in the analysis of results because of low predator response (i.e., less than 15 attacks or less than 21 percent capture).

Note: NA indicates not applicable.

TABLE C-2 RESULTS OF RECOVERY TIME EXPERIMENTS CONDUCTED WITH PREDATOR GROUP 3[a]

Date	Total Length of Larvae (mm) Mean	S.D.	Range	Tank	Thermal Stress Ambient Temp. (C)	Shock Temp. (C)	Delta-T (C)	Tank Temp. (C)	Recovery Time (min)	No. Larvae Per Tank	No. Attacks	No. Captures	Percent Capture	Captures Per Attack
26 JUN 1978	15.4	1.405	12-18	1	22.7	NA	NA	24.4	Control	30	12	4	13.3	0.333[b]
				2	22.9	31.8	8.9	24.7	30	30	13	4	13.3	0.308[b]
				3	23.0	31.8	8.8	24.6	120	30	52	10	33.3	0.192
				4	22.8	31.8	9.0	24.7	180	30	32	9	30.0	0.281
				6	22.7	31.7	9.0	24.3	180	30	12	4	13.3	0.333[b]
				5	22.9	31.8	8.9	24.5	240	30	39	7	23.3	0.180
27 JUN 1978	15.9	1.550	13-18	2	23.2	NA	NA	24.8	Control	30	104	30	100.0	0.288
				1	23.3	31.8	8.5	24.7	0	30	17	7	23.3	0.411
				3	23.2	31.4	8.2	24.8	30	30	11	3	10.0	0.272[b]
				4	23.2	31.6	8.4	24.9	60	30	21	7	30.0	0.429
				5	23.2	31.8	8.6	24.6	180	30	38	10	33.3	0.263
				6	23.2	31.8	8.6	24.7	240	30	58	21	70.0	0.362
28 JUN 1978	16.3	1.331	14-19	2	23.4	NA	NA	24.7	Control	29	24	13	44.8	0.541
				1	23.3	32.2	8.9	24.5	0	29	15	9	31.0	0.599
				3	23.5	32.0	8.5	24.6	30	29	1	0	0.0	0.000[b]
				4	23.5	32.0	8.5	24.8	60	29	63	25	86.2	0.397
				5	23.3	32.0	8.7	24.5	120	30	21	10	33.3	0.476
				6	23.3	32.2	8.9	24.6	180	30	93	23	76.7	0.248
29 JUN 1978	17.8	1.261	14-20	2	23.8	NA	NA	25.4	Control	30	16	5	16.7	0.312[b]
				1	23.8	32.0	8.2	25.3	0	25	14	10	40.0	0.714[b]
				3	23.9	32.0	8.1	25.4	30	29	36	23	79.3	0.641
				4	23.9	32.2	8.3	25.5	60	30	57	16	53.3	0.281
				5	23.8	32.1	8.3	24.9	120	26	42	16	61.5	0.381
				6	23.8	32.1	8.3	25.1	180	27	20	12	44.4	0.599
30 JUN 1978	18.9	1.303	15-21	1	24.1	NA	NA	24.3	Control	30	10	3	10.0	0.300[b]
				5	24.1	NA	NA	24.1	Control	30	15	6	20.0	0.400[b]
				4	24.1	32.1	8.0	24.0	30	29	16	4	13.8	0.188[b]
				2	24.1	32.0	7.9	24.4	60	29	31	9	31.0	0.291
3 JUL 1978	16.6	1.027	15-19	1	24.4	NA	NA	24.9	Control	30	38	6	20.0	0.158[b]
				6	24.4	NA	NA	25.0	Control	30	33	14	46.7	0.424
				4	24.2	32.3	8.1	25.1	0	30	37	20	66.7	0.541
				2	24.4	32.4	8.0	25.1	30	30	17	8	26.7	0.472
				3	24.4	32.3	7.9	25.1	60	28	38	4	14.3	0.105[b]
				5	24.4	32.4	8.0	24.8	120	28	34	11	39.3	0.324

TABLE C-2 (CONT.)

Date	Total Length of Larvae (mm) Mean	S.D.	Range	Tank	Thermal Stress Ambient Temp. (C)	Shock Temp. (C)	Delta-T (C)	Tank Temp. (C)	Recovery Time (min)	No. Larvae Per Tank	No. Attacks	No. Captures	Percent Capture	Captures Per Attack
4 JUL 1978	18.2	1.39	15-21	1	22.9	NA	NA	22.9	Control	30	35	7	23.3	0.200
				2	22.9	NA	NA	23.0	Control	30	26	9	30.0	0.346
				3	22.9	NA	NA	23.1	Control	30	37	7	23.3	0.189
				6	22.9	NA	NA	22.9	Control	29	33	10	34.5	0.303
				4	23.0	32.3	9.3	23.0	0	30	22	13	43.3	0.592
				5	23.0	32.3	9.3	22.8	30	30	43	17	56.7	0.395

(a) Mean total length 87.3 mm; standard deviation 7.4 mm; range 70-98 mm.
(b) These data were not included in the analysis of results because of low predator response (i.e., less than 15 attacks or less than 21 percent capture).

Note: NA indicates not applicable.

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FINAL REPORT

HUDSON RIVER FOUNDATION GRANT NO. 22/83C/49

Laboratory Verification of the Otolith Technique to Determine Age in Larval Striped Bass from the Hudson River Estuary

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Abstract

Effects of various feeding regimes on otolith increment deposition and the relationship between maximum otolith diameter and fish growth were investigated for known-age larval striped bass (Morone saxatilis) in the laboratory. Growth rates ranged from 0.07 mm/day for very low food levels to 0.50 mm/day for continuously fed larvae, and were comparable to field estimates from previous studies. Daily increments formed in all treatments regardless of body or otolith growth. Otolith size generally increased linearly with fish size. However, the relationship of maximum otolith diameter to larval total length reflected subtle differences between treatments. Results of this study support the use of the otolith increment technique to accurately age striped bass larvae under a wide range of feeding conditions. However, further investigation of the otolith to fish size relationship is necessary before growth can be back-calculated from increment widths.

Introduction

Panella (1971) first noted that the otoliths of some fishes grow by daily deposition of increments. This observation has been substantiated by several investigators for both freshwater and marine species (see the thorough review of Campana and Neilson, in press). Although otolith microstructure may provide greater accuracy in determining age and growth of fish, valid application of otolith techniques to analyze larval fish population dynamics requires knowledge of the effects of environmental variables on increment deposition. Photoperiod (Taubert & Coble, 1977; Tanaka et al., 1981; Radtke & Dean, 1982; Geffen, 1983; Campana, 1984), temperature (Taubert & Coble, 1977; Marshall & Parker, 1982; Geffen, 1983; Neilson & Geen, in press), and food (Methot & Kramer, 1979; Geffen, 1982; Neilson & Geen, 1982; Jones, 1984; and Neilson & Geen, in press) have all been shown to influence otolith microstructure. These variables also affect larval growth in general. In order to accurately age larval fish with this technique, one must show that the frequency of increment deposition is not simply a function of growth rate (as has been shown by Taubert & Coble, 1977; Barkman, 1978; Geffen, 1982; Radtke & Dean, 1982; and McGurk, 1984), but rather is a function only of larval age.

The objectives of this research were: (1) to examine the effects of various feeding regimes on increment formation in otoliths of known-age larval striped bass (Morone saxatilis), (2) to determine the age at which the initial increment is deposited, and (3) to quantify the relationship between otolith and body growth.

Methods

Newly hatched striped bass larvae were obtained from the Verplank Hatchery, Verplank, New York on June 4, 1984, and held for 5 days in 15 liter aerated tanks at 18°C, 14L:10D photoperiod, and 30 larvae/liter stocking density. During this period, salinity was gradually raised from 0 o/oo to 6 o/oo by mixing 30 o/oo seawater with 0 o/oo pond water (from Annaquatucket Pond, Rhode Island). At 3, 4, and 5 days after hatch (d.a.h.), 10 larvae were sampled for measurement of total length and dissection of sagittal otoliths. At 6 d.a.h., larvae were stocked at an initial density of 7 larvae/liter into 15 liter experimental tanks. Temperature and salinity were held constant at 18°C and 6 o/oo respectively, and photoperiod was 14L:10D. Twenty to twenty-five percent of the water volume was exchanged daily and dead larvae were counted and removed. Feeding treatments as described below were initiated at 7 d.a.h. Although small quantities of newly hatched Artemia had been offered to larvae at 5 d.a.h., no evidence of active feeding (as checked by water samples and gut observations) was noted until 7 d.a.h. This initiation of feeding agreed with findings in Rogers et al. (1980).

Experimental feeding levels were chosen to reflect zooplankton concentrations which larvae might encounter in the field. A review of literature on spawning areas of striped bass suggested that an average zooplankton concentration is 100/l, but sometimes exceeds this (Daniel, 1976; Setzler-Hamilton et al, 1981). Setzler-Hamilton et al. (1981) reported densities of preferred foods (such as cladocerans and late copepod stages) exceeding 1000/l. Therefore, 10, 100, and 1000 Artemia/l were chosen as low, average, and high food concentrations.

These food concentrations were administered once or twice a day, or were maintained (to more closely approximate field conditions) as described below.

The experimental design included seven treatments, each replicated twice (Table 1). In treatments 1-3, food level was kept "constant" at 10, 100, and 1000 Artemia/liter for six hours by supplying newly hatched Artemia at a constant rate from stock jars via a pump. Water volume was maintained in the experimental tanks by a constant-level siphon which allowed water to flow out while retaining food in the tanks. Food concentrations were monitored in these treatments five or six times during the six-hour period by taking 100 ml (Treatments 1 and 2) or 200 ml (Treatment 3) samples. Artemia supply rate was adjusted at the beginning of each day to account for changes in consumption with growth and with loss of larvae via sampling and mortality. Monitored Artemia densities varied slightly from the nominal concentrations during the six-hour period (Table 1). Artemia were always available to larvae in Treatment 1, whereas food was totally cropped by the following morning in Treatments 2 and 3.

In Treatments 4-6, food level was adjusted to 10, 100, or 1000 Artemia/liter twice daily. As with Treatment 1, food was always present in Treatment 4, whereas it was totally consumed prior to the second pulse in Treatments 5 and 6 and again prior to the next morning's pulse. In Treatment 7, food level was adjusted only once at the beginning of the day, but alternated between 10 and 100 Artemia/liter on a weekly basis. All tanks were aerated gently to insure mixing of Artemia throughout the water column.

Once a week, six larvae were removed from each tank. However, as mortality and sampling depleted the numbers of larvae, fewer fish were sampled near the end of the experiment in some treatments. Developmental characteristics were recorded and total length measured. As noted by Rogers and Westin (1981), neither standard nor total length is a consistently reliable measure of larval length for this species. Although standard length is easiest to measure for very young, transparent larvae, flexure of the notochord and increased pigmentation in older larvae results in difficulty in defining this measurement. Therefore, total length was used in this experiment. Sampled larvae were frozen on a labelled glass slide for later removal of otoliths.

Sagittal otoliths were removed with fine dissecting needles and the aid of a dissecting microscope equipped with a polarizing filter. Small otoliths were mounted in Euparol under a Coverslip with no further processing (after the procedure of Jones, 1984). Initially, larger otoliths were mounted with epoxy to a glass slide (Jones, 1984). However, epoxy tended to shatter the otolith while curing. Therefore, larger otoliths were mounted, sulcus side down, in "Crystalbond," a thermosetting plastic resin. These otoliths were then ground on a lapping wheel using 0.3 u alumina powder. Occasionally otoliths required grinding on both sides, in which case the otolith was removed from the Crystalbond with acetone, remounted with the sulcus side up, and reground. Some otoliths were acid-etched for periods of 60-90 seconds, which sometimes improved resolution. Prepared otoliths were examined at 400-1000X using a video system mounted to a light microscope. Maximum diameter (the greatest axis passing through the nucleus) was measured. All increment counts used for statistical

analyses represented the means of at least two independent counts. If counts differed by more than two for a given otolith, the mean was not included in the analysis.

A few otoliths were prepared for scanning electron microscopy to determine if this procedure provided greater resolution of increments which were difficult to distinguish with light microscopy. These otoliths were etched for 60-90 seconds with 1 percent HCl, remounted on a stub, and gold-plated prior to viewing at 500-1050X.

The frequency of ring deposition, the rate of body growth, and the relationship between maximum otolith diameter and larval total length were examined using least squares linear regression. Analysis of covariance was used to test for significant differences between regression slopes. A t-test was performed to determine whether the slope of the regression of increment count on age differed significantly from 1 increment/day. Confidence intervals were compared for slopes of regressions of larval total length on age and maximum otolith diameter on fish total length.

The frequency of ring deposition, the rate of body growth and the relationship between otolith diameter were examined using least squares linear regression.

Results

Growth in total length was adequately described by linear regressions for all treatments and was positive in all cases (Table 2). Analysis of covariance revealed a significant difference in larval size between treatments ($F = 1776.74$; d.f. = 6,476; $P < 0.0001$). Growth

rates ranged from 0.50 mm/day for Treatment 4 to 0.07 mm/day for Treatment 6. With the exception of Treatment 4, growth rates were generally greater for larvae in the "pumped tanks" (which received more food) than for those in Treatments 5-7. Although the feeding regimes differed for Treatments 1 and 4, for 3 and 5, and for 6 and 7, growth rates were similar, as shown by the 95 percent confidence intervals.

A total of 499 otoliths were processed for increment counts. Of these, 8.2 percent were cracked or damaged due to methodological problems and 18.4 percent were otherwise unreadable or presented problems in counting. The numbers and percentages of otoliths processed and excluded from analysis are shown in Table 3.

Several methodological problems were encountered. Small otoliths mounted with Euparol under coverslips were sometimes cracked or shattered. In addition, Euparol appeared to totally clear some rings with time. Similar problems were encountered by Struhsaker & Uchiyama (1976). As mentioned earlier, the use of epoxy as a mounting medium proved unsatisfactory, shattering the otoliths. As the sagitta grew, they generally became more elongate and curved, with the sulcus (proximal side) becoming convex and the distal surface, concave. Grinding of these otoliths sometimes revealed the nucleus without polishing the outer edges. Further grinding to clarify outer rings occasionally destroyed central rings. Subdaily rings were found not only in otoliths of larvae receiving two pulses of food a day, but also in those of fish from other treatments. Subdaily rings, however, were generally less distinct than daily rings. Accurate counting was more difficult in older larvae due to the greater frequency of checks and discontinuities. The greatest difficulty was encountered in reading

otoliths from larvae continuously exposed to food (Treatments 1 and 4). In these otoliths, often 8 or 9 clear central rings were followed by a wide band of very diffuse rings which were difficult to distinguish. Scanning electron microscopy (SEM) did not improve the resolution of otolith increments in these treatments. In fact, acid etching, a prerequisite to SEM, seemed to destroy rather than accentuate the difference between increments. Otoliths from older larvae of all treatments were generally more difficult to read due to the greater incidence of checks and discontinuities.

Scanning electron microscopy, although applied to very few otoliths in this study, did not improve the resolution of increments in otoliths of very rapidly growing larvae continuously exposed to food, as discussed above. However, it seemed to aid in distinguishing the more closely spaced increments in otoliths of larvae from treatments with lower food concentrations.

The frequency with which otolith increments were deposited was examined by analysis of covariance which indicated no difference in slopes of the regresions of increment count on age ($F = 1.01$; d.f. = 6, 342; $P < 0.42$). Therefore, data for all treatments were combined to give the single regression:

$$\text{Increment count} = -1.475 + 0.987\ (\text{Age post-hatch})$$

($n = 363$, $r = 0.99$, $P < 0.0001$). The rate of increment deposition, 0.987/day, was statistically different from 1/day ($t = -2.28$; d.f. = 361; $0.025 > P > 0.01$). However, given the length of the experiment and of the larval period of striped bass in general, the rate is considered to be daily for all practical purposes.

Initial ring deposition, as noted by examining otoliths of 3-5 day old larvae, occurred at 2-4 d.a.h., with a mean of 2.88 and a standard error of 0.17 d.a.h. (n = 17). This compares favorably with an age of 2.51 d.a.h. associated with the presence of 1 increment as obtained from the regression equation above.

Larvae exhibiting rapid growth had larger otoliths. The relationship between maximum otolith diameter and larval total length was linear for all treatments over the observation period. Analysis of covariance showed a significant difference between slopes of the regressions ($F = 5.08$; d.f. = 6, 367; $P < 0.0001$). The regression equations appear in Table 4 along with the 95 percent confidence limits. The slopes of Treatments 6 and 7 were not different from each other or from the other treatments, and the slopes of Treatments 1, 2, and 4 were significantly different from the slopes of Treatments 3 and 5.

Discussion

Striped bass larvae are unusual in their ability to withstand food deprivation in the laboratory for periods up to 31 days after fertilization and in their lack of a well-defined "point-of-no-return," i.e., a point of irreversible starvation, even when food is provided (Eldridge et al., 1981; Rogers & Westin, 1981). Striped bass larvae starved in the laboratory are externally indistinguishable from younger, feeding larvae and size is a poor indicator of age (Rogers & Westin, 1981). Estimates of growth based upon length-frequency analysis may therefore be suspect due to an inability to accurately represent age by

size. The otolith increment technique, if validated, could provide a more reliable means of examining growth and mortality of larvae of this species.

The degree to which striped bass larvae are exposed to conditions of starvation in the field is unknown. All previous laboratory studies of striped bass have consisted of either feeding the larvae to excess, starving them, or offering a single pulse of food at initial densities equated with field concentrations of zooplankton. Since food densities generally were not held constant in these experiments, laboratory rations may not be comparable to field rations. Eldridge et al. (1982) examined this possibility and found that daily food rations estimated from stomach content data of field-caught striped bass larvae greatly exceeded rations of larvae in their experiments.

The purpose of our study was to test the validity of daily increment formation in otoliths of striped bass larvae exposed to various feeding regimes. Food levels and the experimental design were chosen to provide zooplankton concentrations equivalent to those encountered by wild larvae, with the goal that experimental growth rates in this study might be comparable to field growth rates. Few estimates of growth of wild striped bass larvae are available, and, given the difficulties associated with the length-frequency analyses generally employed, they may not accurately represent true growth. However, these estimates are at present the only benchmarks available. Daniel (1976, citing unpublished data of Allen) gives 0.5 mm/day for growth of larval striped bass in the Sacramento-San Joaquin Estuary. Dey (1981) calculated growth rates for larvae and early juveniles from the Hudson River of 0.1-0.2 mm/day for spring (at temperatures of approximately

10-20°C) and 0.8-0.9 mm/day for summer (18-25°C). Growth rates for Treatments 1-5 in our experiment compare quite favorably with these estimates. Given the effects of temperature on growth obtained by Rogers & Westin (1981), it is possible that larvae would have consumed more and exhibited faster growth rates than we recorded, if they had been held at temperatures comparable to those reported by Dey (1981) for the summer months.

Results of our study show that increment deposition began at 2-4 d.a.h. (mean = 2.88 d.a.h.), prior to total yolk sac absorption and first feeding. This is earlier than the 4 d.a.h. reported by Jones (1984). This difference is unexplainable from the available data.

The frequency of increment deposition was not affected by feeding conditions or by growth rate, and it was constant and essentially daily (0.987 increments/day) for all treatments over the 50 day duration of the experiment. This was true even for larvae in Treatments 6-7 where calculated average food consumption was initially 1 Artemia/larva/day and increased to only 30-75 Artemia/larva/day at the close of the experiment. Although cannibalism was noted and supplemented the diet of some larvae in these treatments, growth was only slightly greater than that reported for starving larvae by Daniel (1976) and Jones (1984), and is definitely representative of very poor feeding conditons.

Jones (1984) found that striped bass larvae less than 68 days of age which were exposed to "excess" food, intermittent starvation (starved between 39-43, 51-55, and 62-66 d.a.h.), and a 15-day delay in initial feeding all deposited increments on a daily basis (1/day). Larvae starved for 30 days deposited 0.5 increments/day. For other species, Methot & Kramer (1979) found that starvation interrupted

increment deposition, although Marshall & Parker (1982), Campana (1983), Volk et al. (1984) and Neilson & Geen (in press) found no effect of total food deprivaton or very low rations. It may be that if sufficient energy reserves are available, the deposition of daily increments is unaffected.

Although Jones (1984) also reported that depositon was less than daily for larvae fed to excess for 97 d.a.h., and suggested that the same may be true for intermittently starved larvae, her results were based upon a limited sample size between 68-97 d.a.h. (3 larvae taken 97 d.a.h. for the fully fed treatment and 1 larva, 97 d.a.h., from the intermittently starved group). In addition, counting accuracy was reportedly poor, given the appearance between two and three months of peripheral centers of deposition. Such secondary centers were not a problem in our experiment which was of shorter duration, although indications of their appearance were seen in some otoliths from the last sampling period. It seems that the otolith increment technique is most accurately applied to larval striped bass and is of limited use for juveniles.

Providing two pulses of food daily did not alter the frequency of daily increment deposition. Taubert & Coble (1977) and Campana (1983) also obtained similar results, although Campana (1983) found an increse in the presence of subdaily rings with multiple meals. In our study, subdaily rings were no more prevalent in otoliths of larvae given two pulses of food a day than in those from other treatments. Neilson & Geen (1982; in press) found multiple feedings led to the production of more than 1 increment/day. Campana and Neilson (1985) suggest that

these results may be "more a matter of interpretation than of substance" since Neilson & Geen (1982; in press) did not differentiate between daily and subdaily increments.

Although otolith diameter generally increased linearly with an increase in larval total length, there were subtle differences between treatments. Jones (1984) found a linear relationship for larvae between 6.5 and 32.0 mm total length when data for all treatments were pooled, but presented no analysis of individual treatments. Marshall & Parker (1982) reported that the otolith diameter:body length relationship for sockeye salmon (Oncorhynchus nerka) varied between fed and starved larvae. McGurk (1984) found curvilinear relationships betwen fish length and otolith diameter for larval Pacific herring (Clupea harengus pallasi) which also varied between fed and starved groups. Although our results (Table 4) indicate a difference between fish fed at high (Treatments 1, 2, and 4) and intermediate (Treatments 3 and 5) levels, the interpretation is confounded by the greater variability associated with the data for the lowest food levels (Treatments 6 and 7). Larvae from these latter two treatments exhibited greater variability in growth. This variability seemed to be related to the early ability of some larvae to more successfully exploit the food source, which in this case included not only Artemia, but also other larvae.

Results of this study support the use of the otolith increment technique to accurately age striped bass larvae under a wide range of feeding conditions. Although Jones (1984) reported less than daily deposition for larvae starved for 30 days, we believe that prolonged starvation is probably a rare occurrence for these larvae in the field. Given the findings of Eldridge et al. (1982) concerning field rations,

along with the early development of strong swimming and food capturing abilities, and the broad diet reported by Meshaw (1969) at low zooplankton densities, it appears unlikely that striped bass larvae would often be exposed to absolute food deprivaton for extended periods of time.

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Table 1. Monitored *Artemia* concentratons for Treatments 1, 2, and 3. Values are the means ± 2 standard errors of the counts taken 5 or 6 times during the 6-hour daily sampling period for the entire experiment.

Treatment	Replicate	Nominal *Artemia* concentration (#/l)	Mean *Artemia* concentration (#/l)	n
1	1	1000	905 ± 28	(207)
1	2	1000	833 ± 37	(209)
2	1	100	68 ± 10	(224)
2	2	100	97 ± 11	(224)
3	1	10	10 ± 2	(215)
3	2	10	7 ± 2	(215)

Table 2. Linear regressions of larval total length (mm) on age (days after hatch), with 95 percent confidence intervals on the slope.

Treatment	n	intercept	slope	s.e. of slope	95% C.I. on slope	r
1	82	2.216	0.461	0.0091	0.443-0.479	0.98
2	77	2.940	0.373	0.0075	0.358-0.388	0.98
3	73	4.162	0.218	0.0107	0.197-0.239	0.93
4	73	1.773	0.496	0.0098	0.476-0.516	0.99
5	80	5.020	0.186	0.0061	0.174-0.198	0.96
6	53	5.291	0.068	0.0094	0.049-0.087	0.71
7	59	4.915	0.107	0.0107	0.086-0.128	0.80

Table 3. The number (and percentage) of larval striped bass processed for increment counts, including those discarded from analysis due to problems in processing (breakage or grinding errors) and in counting (disagreement between counts or inability to read).

TRT	total # processed	# discarded due to methodological problems	# discarded due to inability to read or discrepancies in counts
1	83	15 (18.1%)	36 (43.3%)
2	79	4 (5.1%)	9 (11.4%)
3	74	6 (8.1%)	2 (2.7%)
4	74	4 (5.4%)	26 (35.1%)
5	76	8 (10.5%)	3 (3.9%)
6	55	2 (3.6%)	5 (9.1%)
7	58	2 (3.4%)	11 (19.0%)
Total	499	41 (8.2%)	92 (18.4%)

Table 4. Linear regressions of maximum otolith diameter (um) on fish total length (mm) with 95 percent confidence intervals on to slope.

Treatment	n	intercept	slope	s.e. of slope	95% C.I. on slope	r
1	46	-247.0	41.2	0.88	39.43-42.97	.99
2	63	-202.6	39.2	0.51	38.18-40.22	.99
3	61	-225.8	44.8	0.91	42.98-46.62	.99
4	54	-229.9	40.2	0.74	38.71-41.18	.99
5	65	-231.0	45.0	1.15	42.70-47.30	.98
6	48	-187.4	41.9	2.65	36.60-47.19	.92
7	51	-188.1	40.6	1.60	37.39-43.81	.96

URI Grant #5-37254 -- Hudson River Foundation

ADVANCE & REIMBURSEMENT VOUCHER *

PERIOD COVERED BY THIS VOUCHER
From: 6 / 1 / 85 To: 6 / 30 / 8.

GRANT #: 22-83-C-49

TYPE OF PAYMENT (check one):
___ ADVANCE
XX REIMBURSEMENT
___ FINAL REIMBURSEMENT

PRINCIPAL INVESTIGATOR: Saul B. Saila

RECIPIENT ORGANIZATION: University of Rhode Island
Kingston RI 02881

SUBCONTRACTOR (if applicable):

EXPENDITURES OF: (check one)
___ GRANTEE
___ SUBCONTRACTOR

GRANTEE VOUCHER # 14

SUBCONTRACTOR VOUCHER #

DIRECT COSTS	Cost	Cost Sharing
Labor (list investigators by name, technical and support personnel by category)		
1- Mary Worobec	2,102	
2-		
3-		
4-		
5-		
6-		
7-		
A Total Labor Costs	2,102	
B Fringe Benefits		
Non-Expendable Equipment (list item and amount for each item exceeding $500)		
C Total Non-Expendable Equipment		
D Expendable Equipment		
E Equipment Rental		
F Boat Use		
G Computer Services	91	
H Consultant Services (other than subcontracts)		
I Travel		
J Publication Costs		
Office Support (only when directly relevant to performance of the proposed project)		
Materials and Supplies	241	
Telephone		
Postage	10	
Copying and Printing	2	
K Total Office Support	253	
L Miscellaneous (specify)		
M TOTAL DIRECT COSTS (A through L)	2,446	
N INDIRECT COSTS/OVERHEAD (specify) 10%	245	
O SUBCONTRACTS (attach separate budget(s))		
P TOTAL COSTS (M + N + O)	2,691	
Q RESIDUAL FUNDS (from previous support, being applied to proposed project)		
AMOUNT OF THIS REQUEST (P - Q)	2,691	

FORM G-2/84

*see instructions on reverse side

Angelo B. Mendillo, Chief Business Management Officer

URI Grant #5-37254 -- Hudson River Foundation

ADVANCE & REIMBURSEMENT VOUCHER *

PERIOD COVERED BY THIS VOUCHE
From: / / To: / /

HRF GRANT #: 22-83-C-49

TYPE OF PAYMENT (check one):
___ ADVANCE
___ REIMBURSEMENT
XX FINAL REIMBURSEMENT

PRINCIPAL INVESTIGATOR: Saul B. Saila

RECIPIENT ORGANIZATION: University of Rhode Island
Kingston RI 02881

SUBCONTRACTOR (if applicable):

EXPENDITURES OF: (check one)
___ GRANTEE
___ SUBCONTRACTOR

GRANTEE VOUCHER #
15
SUBCONTRACTOR VOUCHER

DIRECT COSTS

		Cost	Cost Sharing
	Labor (list investigators by name, technical and support personnel by category)		
	1-		
	2-		
	3-		
	4-		
	5-		
	6-		
	7-		
A	Total Labor Costs		
B	Fringe Benefits		
	Non-Expendable Equipment (list item and amount for each item exceeding $500)		
C	Total Non-Expendable Equipment		
D	Expendable Equipment		
E	Equipment Rental		
F	Boat Use		
G	Computer Services	300	
H	Consultant Services (other than subcontracts)		
I	Travel		
J	Publication Costs		
	Office Support (only when directly relevant to performance of the proposed project)		
	Materials and Supplies	24	
	Telephone	8	
	Postage		
	Copying and Printing	8	
K	Total Office Support	40	
L	Miscellaneous (specify)		
	academic computer -- no overhead charged	80	
M	TOTAL DIRECT COSTS (A through L)	420	
N	INDIRECT COSTS/OVERHEAD (specify) 10% (excluding line L)	34	
O	SUBCONTRACTS (attach separate budget(s))		
P	TOTAL COSTS (M + N + O)	454	
Q	RESIDUAL FUNDS (from previous support, being applied to proposed project)		
	AMOUNT OF THIS REQUEST (P - Q)	454	

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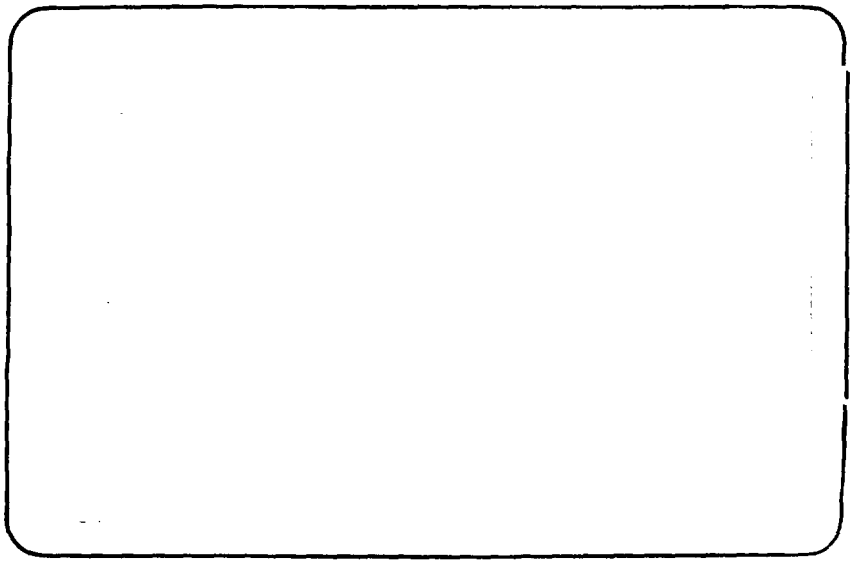

NORMANDEAU ASSOCIATES
ENVIRONMENTAL CONSULTANTS

RESPONSES OF YOUNG-OF-THE-YEAR WHITE PERCH AND STRIPED BASS, AND ADULT ATLANTIC TOMCOD IN AN ENCLOSURE TO UNDERWATER SOUNDS GENERATED BY AN ELECTRONIC FISH STARTLE SYSTEM

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RESPONSES OF YOUNG-OF-THE-YEAR WHITE PERCH AND STRIPED BASS, AND ADULT ATLANTIC TOMCOD IN AN ENCLOSURE TO UNDERWATER SOUNDS GENERATED BY AN ELECTRONIC FISH STARTLE SYSTEM

EXECUTIVE SUMMARY

The prototype Electronic Fish Startle System (EFSS) is an electronic device used to generate and monitor acoustic signals underwater. The EFSS elicited active avoidance responses in 142 out of 239 (62%) tests with young-of-the-year white perch and striped bass. Active avoidance responses were elicited in 5 out of 13 tests (38%) with adult Atlantic tomcod. Sounds produced by the EFSS in order of effectiveness were the recorded sound of a rock entering the water, FM log sweeps, single tones and broadband sound. The recorded rock sound elicited active avoidance responses in 93 out of 130 tests (72%) with white perch, 13 out of 19 tests (68%) with striped bass and both tests conducted with Atlantic tomcod. FM log sweeps elicited active avoidance responses in all 4 tests conducted with white perch. Striped bass and Atlantic tomcod were not exposed to FM log sweeps. Single tones elicited active avoidance responses in 23 out of 52 tests (44%) with white perch, and in none of the 11 and 4 tests conducted with striped bass and Atlantic tomcod, respectively. Broadband sound elicited active avoidance responses in 7 out of 17 tests (41%) with white perch, 2 out of 6 tests (33%) with striped bass and 1 out of 5 tests (20%) conducted with Atlantic tomcod. The strength of the active avoidance responses elicited by sounds produced by the EFSS ranged from weak to strong for white perch and striped bass. Only weak active avoidance responses were elicited in Atlantic tomcod. The sound produced by an actual rock being thrown in the water was a more effective deterrence than a recording of the same sound produced by the EFSS because the acoustic equipment used during this study was not capable of measuring, recording, and reproducing the real rock sounds over its full frequency spectrum, particularly at frequencies less than 100 Hz. White perch and striped bass appeared to acclimate to the recorded rock sound in approximately 30 minutes, although this acclimation may be an artifact of confining the fish in a

test cage because they were unable to escape from the ensonified area. White perch and striped bass were more active and exhibited more active avoidance responses to sounds produced by the EFSS during the day than at night. During the day, it was not possible to determine if light level affected the strength of active avoidance responses due to the acclimation response. During night testing the level of artificial light used for observation affected the strength of active avoidance responses. White perch and striped bass were more reactive at night when observed under constant low level light then when observed with brief flashes of light. It was not possible to determine if the active avoidance response was related to a specific frequency or range of frequencies due to uncontrolled variation in other variables such as light level, but sounds at frequencies less than 500 Hz were most effective. The active avoidance response appeared to be a positive function of sound amplitude, and the recorded rock sound at amplitudes greater than 138.8 dB//μPa/Hz at 1 m were most effective. An amplitude of 138.8 dB//μPa/Hz at 1 m in the quarry equates to a signal to noise ratio of 67 dB. Background levels of sound measured in the vicinity of Indian Point Nuclear Generating Station were higher than in the quarry, and amplitudes greater than 180 dB//μPa/Hz at 1 m are required to produce a similar signal to noise ratio. Future testing should focus on frequencies less than 500 Hz at amplitudes greater than 190 dB//μPa/Hz at 1 m. Testing conducted at night should use a method that does not increase light levels above ambient such as low light level cameras or hydroacoustics.

1.0 INTRODUCTION

Large numbers of fish are impinged annually at cooling water intakes and survival of these impinged fish is often low (Hanson *et al.* 1977). Yearly estimates of the number of fish impinged at Indian Point Generating Station Units 2 and 3 combined ranged as high as 3,121,797 fish/year during the period 1974 to present (TI 1982). Historically, white perch, Atlantic tomcod, and striped bass are among the most numerous fish impinged at Indian Point Units 2 and 3 and the period of peak impingement abundance occurs during the winter. A technology that could deter fish from entering the Indian Point cooling water intakes would reduce impingement and impingement mortality of these fish.

Underwater sound has been shown to elicit an avoidance response in fish (Schwarz and Greer 1984) and to effectively deter fish from entering water intake structures (Haymes and Patrick 1986; Ontario Hydro 1986; 1987). Sounds generated by fishing vessels and recorded sounds of less than 1000 Hz elicited an avoidance response in Pacific herring (*Clupea harengus pallasi*) (Schwarz and Greer 1984). Sound with a fundamental frequency of 50-60 Hz produced by underwater pneumatic air guns (poppers) effectively excluded adult alewife (*Alosa pseudoharengus*) from entering an experimental structure deployed in front of the intake of the Pickering Nuclear Generating Station on Lake Ontario (Haymes and Patrick 1986). However, the poppers were not found to be mechanically reliable and the sound produced by the poppers did not elicit an avoidance response in other species of fish such as coho salmon (*Oncorhynchus kisutch*) and white perch (*Morone americana*) (Ontario Hydro 1986). In addition, Con Edison of New York (1987) found that the pneumatic poppers had no significant influence on the numbers or species of fish impinged at or present near the Indian Point Unit 2 intake structure.

In an attempt to alleviate the problems of mechanical unreliability and selective response by fish to the poppers, Ontario Hydro developed a mechanical spring mass impact device (fishpulser) which produced a repetitive sharp sound of relatively high amplitude at frequencies less than 1000 Hz (Ontario Hydro 1986). When deployed at the Pickering Nuclear Generating Station, the fishpulsers were found to elicit an avoidance response in adult alewife at a distance of 5 to 10 m compared to 5 m for the poppers. This increase in effective range was attributed to the increased amplitude of the fishpulsers (Ontario Hydro 1986). However, the fishpulsers did not elicit an obvious avoidance response in yellow perch (*Perca flavescens*) and pumpkinseed (*Lepomis gibbosus*) when the devices were deployed at the Lennox Generating Station on Lake Ontario (Ontario Hydro 1986).

The majority of fishes that exhibited negative responses to sounds were Ostariophysian fishes such as the herring family. These fishes posses connections between the swimbladder and the inner ear that improve hearing ability (Alexander 1974). However at many facilities, particularly those on the Hudson River, the most numerous fish impinged at power plant are non-Ostariophysian fishes, e.g. white perch and striped bass (*Morone saxatilis*). To determine if the fishpulsers would elicit an avoidance response in white perch, several hundred young-of-the-year (YOY) white perch were introduced to a large indoor experimental enclosure at the Ontario Hydro research facility. A fishpulser was deployed at one end of the enclosure and, when it was activated, the white perch exhibited a strong avoidance response by moving to the other end of the enclosure or to locations where reflections of the sound apparently created quiet areas. Based on these results, a full scale field test of the fishpulsers was conducted during the winter of 1987-88 at the Indian Point Nuclear Generating Station Unit 3 located on the Hudson River. Preliminary results from this study indicated that fish abundance in the vicinity of Unit 3 intake structure decreased as much as 42% when the fishpulsers were activated (NYPA *et al.* in prep.).

However, the percent response by the fish community at Indian Point might be increased by using different frequencies and amplitudes than those produced by the fishpulsers. Frequency and amplitude can be varied more efficiently with an underwater electro-acoustic transmit system than with a mechanical fishpulser. A new end plate must be machined and the striker spring must be modified to vary frequency and amplitude with the fishpulser. The greater flexibility in sound production offered by an electro-acoustic transmit system and the unreliability experienced with the fishpulsers during the winter 1987-88 field tests encouraged development and testing of the prototype EFSS. The EFSS is a device consisting of various electronic components including a signal generator, power amplifier, and transducer that can generate acoustic signals underwater.

The objectives of this study were to:

1. determine if sound produced by the EFSS can elicit an avoidance response in YOY white perch and striped bass, and adult Atlantic tomcod,

2. characterize the effectiveness of each electronic sound that was tested, and

3. describe the acoustic properties of each electronic sound that was tested.

For those sounds which produced a response in the test fish, additional objectives were to:

4. determine if the fish acclimate to the sound,

5. determine if water temperature and light level are related to the response,

6. determine if the response is a linear function of sound amplitude, and

7. determine if the response is dependent on sound frequency.

2.0 MATERIALS AND METHODS

2.1 LOCATION

The study took place in a flooded rock quarry located along the east shore of the Hudson River at Verplanck, New York. The quarry has a surface area of approximately 14 hectares and a maximum depth of over 60 m. Water in the quarry was exceptionally clear and Secchi disk readings of greater than 12.2 m were common during the study. A heated shelter in a concrete building located in the quarry served as the base of operations for the studies (Figure 2-1). All electronic and video equipment were operated from the heated shelter in this quarry building.

2.2 COLLECTION AND ACCLIMATION OF FISHES

The fish used in this study were primarily YOY white perch, YOY striped bass and adult Atlantic tomcod. Lengths of white perch ranged from 50 to 100 mm total length (TL), striped bass lengths were between 50 and 150 mm TL and Atlantic tomcod lengths were between 225 and 275 mm TL. Most of the white perch and Atlantic tomcod were collected from a modified Ristroph traveling screen at the Indian Point Unit 2 power plant located on the Hudson River. Striped bass were primarily (90%) collected by trawling in the Hudson River in the vicinity of Manhattan Island, NY. Fish collected from the modified Ristroph screen were transported from Indian Point, a distance of 3.2 km, to the quarry in a 300-liter tank in the bed of a pickup truck. An artificial slime coat was mixed with the water in the transport tank to reduce stress resulting from abrasion during transport. At the quarry, the fish were gently transferred from the 300-liter tank to one of three circular hatchery tanks, each measuring 3.7 m in diameter, 0.6 m high, and filled with Hudson River water. Because quarry water had significantly lower conductivity and higher pH compared to Hudson River water, it was necessary to acclimate the fish to quarry water. The percentage of water from the Hudson River and the quarry in each circular tank was

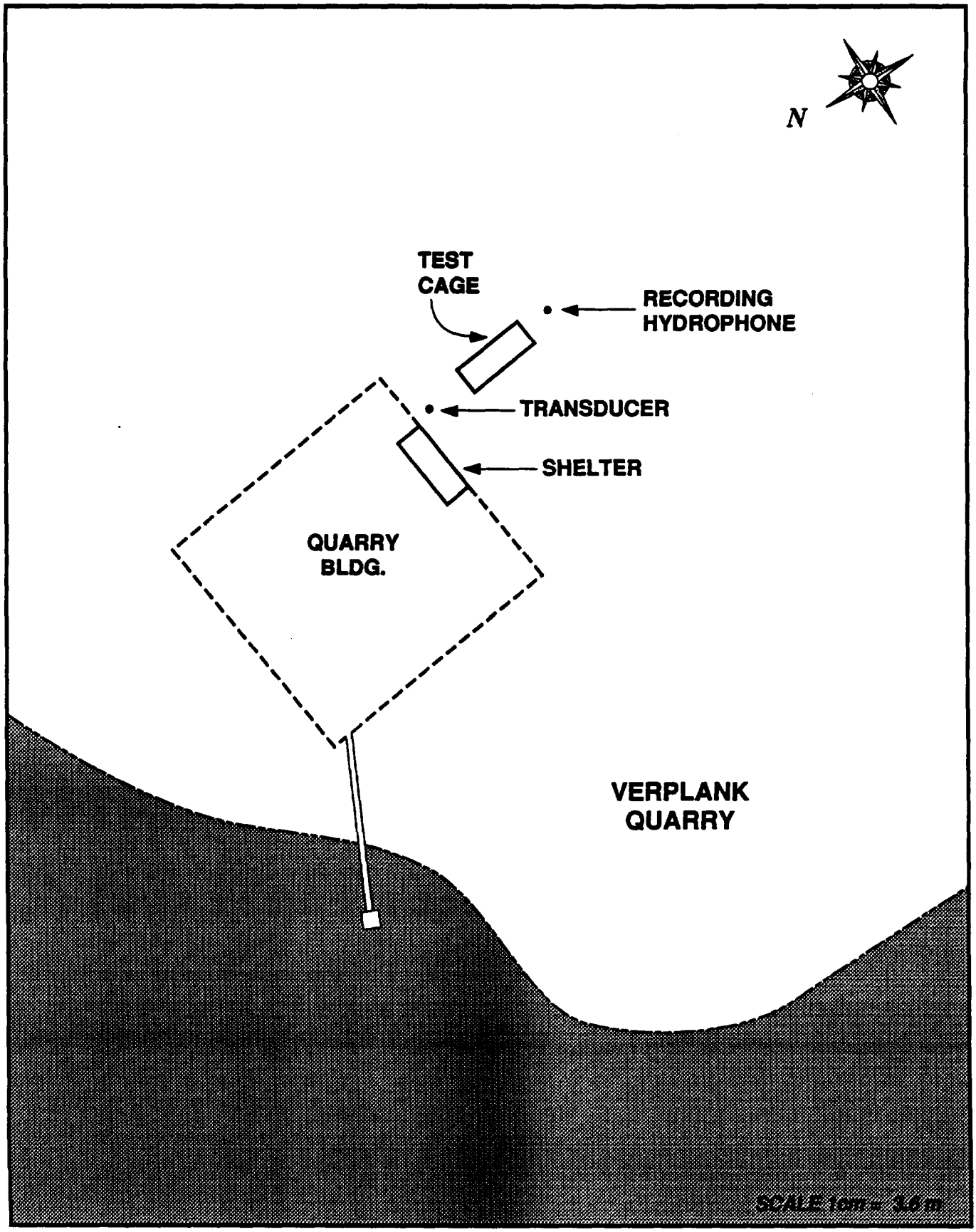


Figure 2-1. Site location for the 1988-1989 Fish Deterrence Studies.

controlled by valves which regulated the water flow from each source. Acclimation to quarry water from Hudson River water was accomplished by gradually increasing the percentage of quarry water over three days in a flow through system. Striped bass collected by trawling were transported to the hatchery site in an oxygenated 1140-liter tank and acclimated to quarry water using the same procedure as fish collected from the modified Ristroph screen.

After acclimation to quarry water, fish were transferred from the tanks and introduced to the test cage (Figure 2-1). Fish were removed from the circular tanks by draining water to a depth of 15 cm. Fish were then gently collected in nets or plastic scoops, placed in 19-liter containers, and then transported to the quarry. The fish in the 19-liter containers were quickly transported in a boat and introduced into the test cage through a closable opening in the top. The number of fish introduced to the experimental enclosure ranged from 75 to 300 per test. Fish were allowed to become accustomed to the test cage for 10-20 minutes before any experimentation began. Fish were held in the test cage and testing for their reactions to sounds took place for 1 to 14 days. Experimental sessions lasted from 4 to 10 hours during which one to several groups of fish would be tested. At least 12 hours elapsed each day between experimental sessions.

2.3 EXPERIMENTAL FISH ENCLOSURE AND UNDERWATER VIDEO SYSTEM

The experimental fish enclosure consisted of a 1.5 x 1.5 x 3.0 m PVC pipe structure floating approximately 0.3 m below the surface (Figure 2-2). The PVC piping was enclosed on all sides with 0.6 cm Internet plastic netting. This netting was thin enough so that it did not interfere with underwater photography. Holes were drilled in the PVC piping to permit flooding of the pipes to reduce acoustic reflections caused by air filled pipes. Two PhotoSea TV1000 underwater television cameras were mounted 2.1 m from the side of the experimental

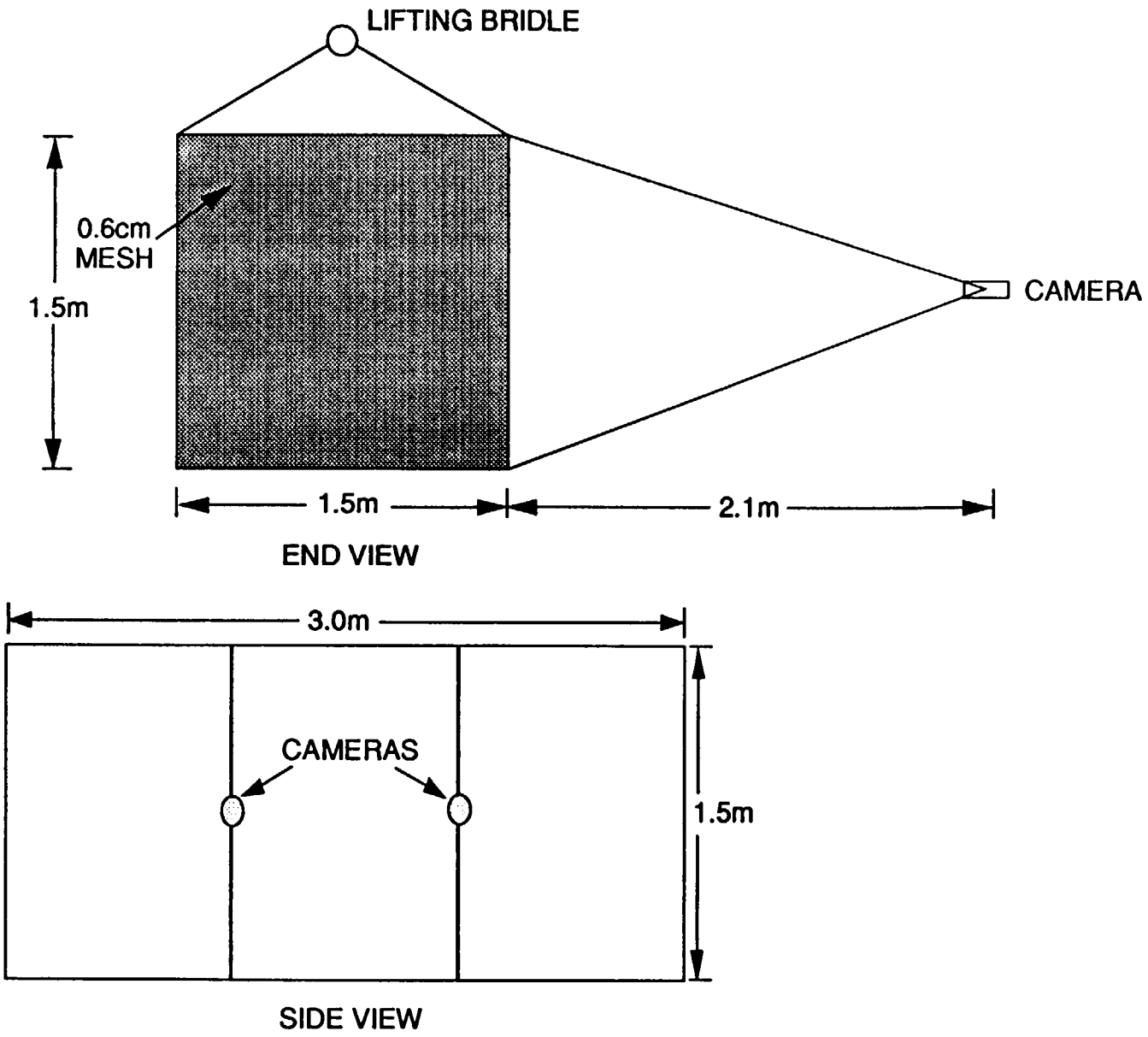


Figure 2-2. Test cage used for the 1988-89 Fish Deterrence Studies.

fish enclosure to record the movements of the fish. This arrangement of cameras provided 100% coverage of the test cage. The television cameras were connected to two Panasonic AG1950 video cassette recorders (VCRs) and television monitors. The VCRs were used to record all tests.

Water temperature and wave height were recorded for each test. During day testing, a relative scale of 1 to 5 was used to record light level with 5 being the brightest and 1 being the dimmest light. During night testing, the number and color of lights used were recorded along with the duration of illumination as a measure of light level. No effort was made to calibrate day and night light level observations.

2.4 THE PROTOTYPE ELECTRONIC FISH STARTLE SYSTEM

2.4.1 Functional Description

The prototype Electronic Fish Startle System (EFSS) is an electronic device used to generate and monitor acoustic signals underwater. Figure 2-3 illustrates the basic block diagram of the transmit subsystem. The EFSS as configured for the program produced low frequency (< 10,000 Hz) acoustic energy. The EFSS could be set to electronically generate an infinite variety of "sounds" that were transmitted at different source levels, pulse lengths, and repetition rates so that each parameter was infinitely variable. The types of sounds that could be produced by the EFSS include single frequency tones, dual tones, modulated tones, frequency modulated (FM) tones, band-limited noise, wideband noise, or recorded sounds via the tape recorder.

The transmitted signal parameters resided in software and could be changed by reprogramming the Erasable Pre-programmed Read Only Memories (EPROM). Four different pulse lengths and repetition rates were available from each EPROM, providing 16 different combinations of pulse length and repetition rate from each EPROM. Two EPROMs were used during the 1988-89 program. Table 2-1 depicts the pulse length and

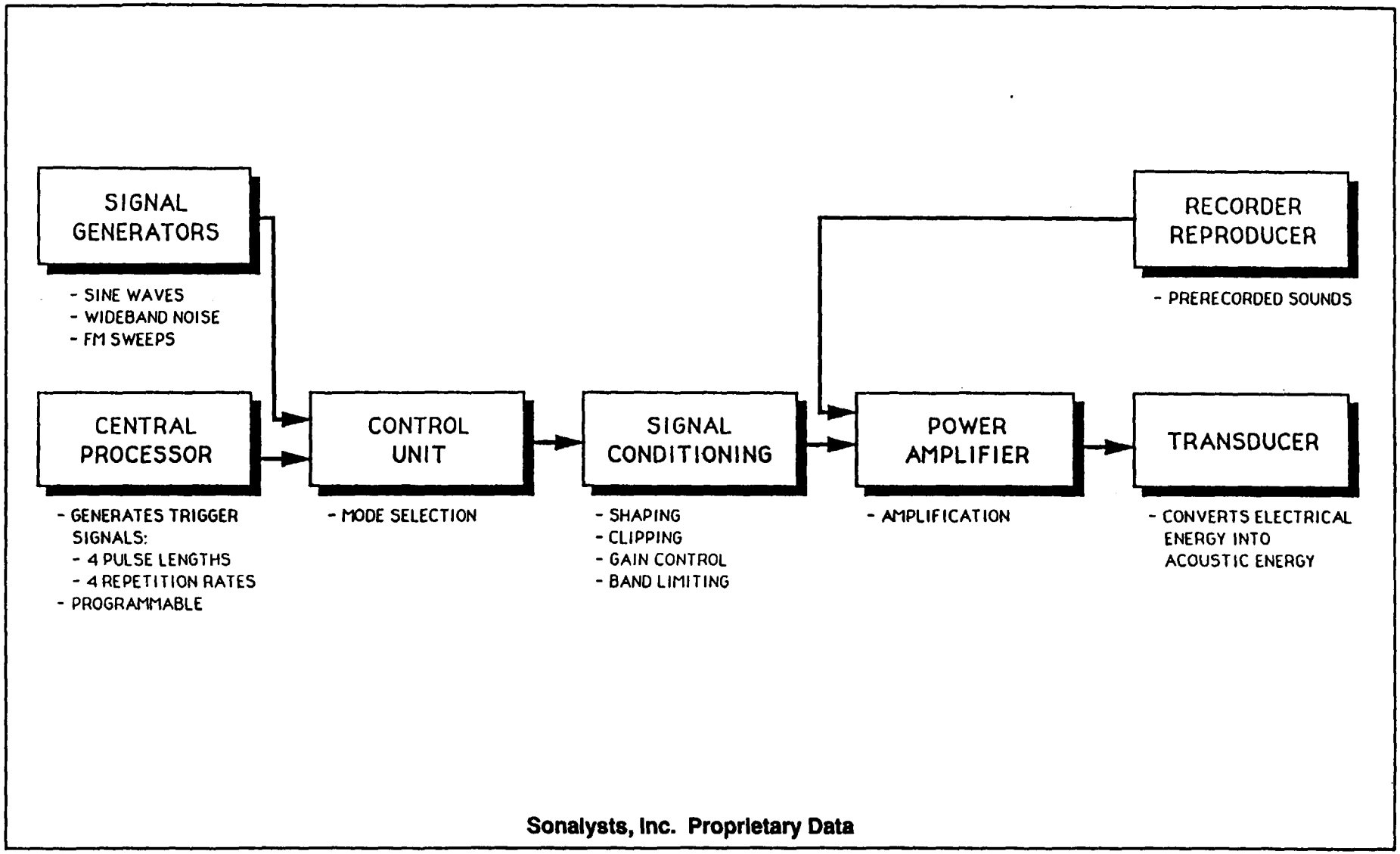


Figure 2-3. Prototype Electronic Fish Startle System Transmitter Basic Block Diagram.

TABLE 2-1. AVAILABLE PULSE LENGTHS AND REPETITION RATES FOR THE 1988-89 FISH DETERRENCE STUDIES.

EPROM	PULSE LENGTHS (ms)	TIME BETWEEN PULSES (ms)
#1	10, 20, 60, 100	1000, 3000, 5000, Random (1-7 seconds)
#2	20, 200, 500, 1000	20, 100, 1000, Random (20 ms-1 second)

repetition rate available during the testing. In addition, any of the signals could be transmitted continuously, and the desired acoustic information could be provided via a tape recorder.

The relative amplitude of a sound measured at a distance from the source is a function of the strength of the signal generated (sum of electronic gains and losses), distance from the source, and in the case of directional transducers, bearing of the test subject or recording hydrophone from the sound source; gains and losses of the measuring hydrophone; environmental conditions effecting sound propagation; frequency and bandwidth of the spectrum of interest; and the frequency and amplitude of background noise.

A decibel represents a unit of signal level or intensity relative to a chosen reference value. The intensity of the signal is usually referenced to a unit of pressure, measured at a given distance from the source. For acoustic pressure, 1 micronewton per square meter is the reference standard for decibel notation under the meter-kilogram-second system. This pressure unit is called the micropascal (μPa). The reference for range is one meter. Since we are typically measuring sound levels over a wide range of frequencies, the bandwidth must also be normalized; in this case to one hertz. Thus, the reference unit for amplitudes calculated for a majority of the measurements conducted in this study is:

> decibels referenced to one micropascal per hertz at a distance of one meter....

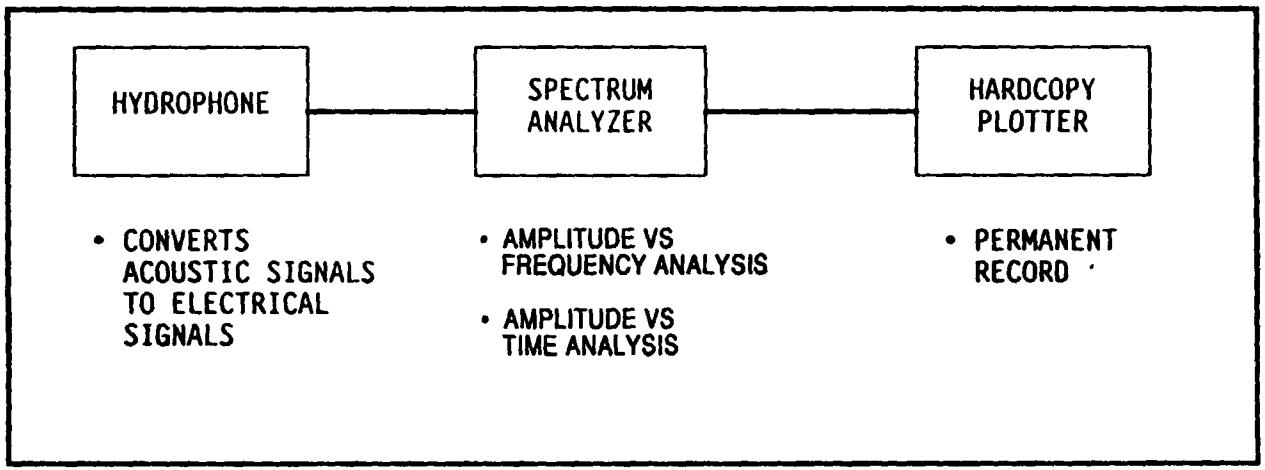
or

> dB//1μPa/Hz at 1 m.

For background noise the reference to 1 meter is dropped.

The EFSS System was capable of a maximum amplitude of 161 dB//1μPa/Hz at 1 m. The output was continuously variable up to the maximum. For programmable sounds, the control unit received trigger inputs from the central processor and acoustic signals from the signal generators. The control unit selected the type, duration, output level, and interval of the acoustic signal. The selected signal was sent to signal conditioning circuitry to compensate for the nonlinear output of the transducer. The signal was subsequently fed to a clipper to prevent exceeding maximum peak levels at the amplifier and transducer. The transducer was submerged in the water and converted the electrical signals into acoustic energy.

In addition to the transmitter section, the EFSS had a receive section to record and analyze the acoustic characteristics of the sound in the water. The receiver section provided verification of the transmitted frequency, spectral and sound shapes, pulse length, and repetition rate. In addition, the amplitude of the sound could be measured for quantitative analysis and correlation to the response of the species under test. Figure 2-4 depicts the receiver basic block diagram of the EFSS. The spectrum analyzer was a Hewlett Packard 3561A using a 400-point Fast Fourier Transform (FFT) process. Connected to the analyzer was an omnidirectional hydrophone immersed in the quarry water. The receiver hydrophone response was flat from 50 Hz to 40 kHz. The same hydrophone was immersed in the water at a known distance from the transducer. The hydrophone converted the underwater sound into electrical signals. The electrical signals were sampled by the spectrum analyzer, and a permanent copy was made of the spectrum analyzer display.



Sonalysts, Inc. Proprietary Data

Figure 2-4. Prototype Electronic Fish Startle System Receiver Basic Block Diagram.

2.4.2 Technical Description

The initial trigger signals for the EFSS were generated by software in a Z80 Central Processing Unit (CPU)(Figure 2-3). The EFSS System had pulse lengths of 10, 20, 60, and 100 milliseconds (ms) and repetition rates of 1, 3, 5, and random from 1 to 7 seconds programmed in the EPROM. To change the program, the EPROM was replaced by another one containing different parameters. The output was a trigger pulse compatible with the trigger input on the function and signal generators. The trigger signals from the Z80 CPU were coupled to the signal generators (Tektronix FG507 and both Wavetek 188's) via BNC-to-BNC connectors. Shielded cable was used to prevent unwanted signal components being introduced.

The Tektronix FG507 Function Generator was used only during FM log sweep operation. An FM log sweep is a sound that increases or decreases in frequency at a logarithmic rate at a constant amplitude between 2 frequency boundaries. The Function Generator generates waveform of increasing voltage (up-ramp) to sweep the Wavetek 188s in frequency. The up-ramp was input to the Voltage Controlled Generator (VCG) input of the Wavetek 188s. During all other types of transmission (e.g., single frequency, wideband noise) and Function Generator was not used.

The Function Generator produced four different waveforms (up-ramps) to satisfy the FM log sweep modes. A separate up-ramp was needed for each pulse length. The up-ramp started upon receipt of a trigger pulse from the CPU and reached the maximum level at the end of the pulse length to cause the Wavetek 188 to be at the maximum sweep frequency. The maximum up-ramp voltage was adjusted to sweep and signal generators in octave steps of 100 to 200 Hz, 200 to 400 Hz, and 400 to 800 Hz. The Wavetek 188 signal generators were used in all but the broadband sound mode.

During FM sweep mode, only Signal Generator A was used. The up-ramp from the Function Generator was input to the VCG input. The VCG input voltage was combined with the voltage level from the dial setting. The generator output frequency was proportional to the voltage input to the oscillator circuitry. At zero volts input at the VCG connection, the generator operated at the dial frequency. The signal generator output frequency increased proportionally as the VCG input increased from zero to the maximum value. Sine wave output was selected for initial tests; however, square wave and triangular waves were available.

In single frequency mode, one or both Wavetek 188s were used to generate one or two input frequencies. The VCG input was not used. One signal generator could be used to generate one frequency alone or both could be used to generate two different frequencies either sequentially, or amplitude modulated (AM) together.

Although the noise generator produced broadband sound (nominally) from 10 Hz to 20 kHz, its output was optionally fed to (or bypassed) the filter shaper circuit. The filter shaper circuit band-limited the noise spectra to 100 to 500 Hz and compensated for the non-linear response of the transducer. The compensation provided a flat spectrum of noise in the water over the 100 to 500 Hz band. Band-limiting reduces excessive power consumed by amplifying signals above and below the optimal response range of the transducer. With the filter bypassed, a wider frequency noise could be fed to the transducer at the expense of a slight reduction of source level in the water and the loss of flat frequency response. Manually selected electronic switching was used to switch between tone and noise operation.

The output of the shaper circuit was sent to the clipper, which limited peak current and voltage excursions from possibly damaging downstream hardware and reduced power requirements for the amplifier and transducer. A level control and output monitor were provided at the output of the clipper.

Signals from the clipper were routed to the burst gate, which performed two functions. One function was to stop signals from being transmitted until the proper level had been obtained with the burst gate disabled. The other function was to turn the wideband noise signals on and off as commanded by trigger input from the CPU. During tone operation, the burst gate was gated on continuously since the Wavetek 188's were turned on and off automatically by the CPU.

The power amplifier raised the output level to a maximum of 2000 volt amperes intermittent (1-second, 10% duty cycle) or 800 volt amperes continuous. This level was used to drive the transducer. The transducer converted electrical energy to acoustical energy.

2.5 CALCULATION OF BACKGROUND NOISE

The spectrum analyzer averaged the background noise 32 times to remove intermittent excursions in the noise field. Several measurements at different depths and different distances from the building were taken to ensure a uniform noise field. Background noise is an important parameter because it influences the perceived or relative strength of signals, or signal to noise ratio (SNR). During measurement of background noises, time data were also analyzed to ensure that no reflections from the quarry side walls caused "phantom" sources of sound that could confuse the fish.

The background noise level was measured in the region of interest, which is primarily in the range from 100 Hz to 500 Hz. For computations in this report, the noise level (-112.5 dBv) at 100 Hz was selected to represent the background noise level in the quarry. The voltage measurement from the analyzer at 100 Hz was combined with the receive hydrophone sensitivity to compute the acoustic level in the water. In addition, to allow direct comparisons, all data were corrected to a 1 Hz (spectrum) level.

2.6 EXPERIMENTAL DESIGN AND DATA ANALYSIS

This project was a pilot study that used empirical observations to determine if sound produced by the EFSS could elicit avoidance responses in fish. Therefore, the experimental approach in this study was to find sounds with fish deterrence potential and investigate these sounds further rather than fill all the cells in an experimental design matrix consisting of sound type, frequency, amplitude, and pulse length. The number of tests conducted with each species of fish was dependent on the availability of test subjects and the reactions of fish to the sounds produced by the EFSS. If a particular species exhibited an avoidance response to a sound, that response was further explored by varying experimental variables such as amplitude and frequency.

Fish were subjected to five types of underwater sound:

1. previously recorded sounds,
2. single tones,
3. band limited noise,
4. FM log sweeps, and
5. incidental sounds.

Previously recorded sounds, including a rock entering the water, were investigated for their fish deterrence potential. Single tones were sounds generated at one frequency between 50 and 10,000 Hz at one or more amplitudes, pulse lengths and repetition rates. Band limited noise consisted of Indian Point background noise and sound generated in frequency spectrums, generally 100 to 500 Hz and 1,330 to 3,000 Hz at a variety of amplitudes and durations. An FM log sweep is a sound that increases or decreases in frequency at a logarithmic rate at a constant amplitude between two frequency boundaries. In addition to sounds produced by the EFSS, a variety of incidental sounds were also examined for their fish deterrence potential. These included the sound of the

door of the equipment shelter opening and closing, movement of metal grating on the catwalk between the land and the quarry building, background sounds from Indian Point Station, and the sound of a rock being dropped in the water. The rock, door and background sounds from Indian Point Station were recorded and and played back through the EFSS, though not with the original frequency range due to equipment limitations. Individual sounds were characterized by their frequency, amplitude, and pulse length.

During the study it was observed that fish behavior in the absence of introduced sound differed under various light conditions. To explore the effect of light level on the reactions of fish to sound, testing was conducted during both the day and night. During the day, intensity of natural light during each test was ranked on a relative scale of 1-5 with 1 being the least light and 5 being the brightest light. To observe the fish at night, three 300 watt lights were mounted on the test cage, 1 m above the water surface. Two general methods were used to observe fish at night. In the first method, termed "constant low level light", the fish were observed under constant, low level, artificial light. Generally, the fish remained in darkness until actual testing began. At the start of testing the sound would be introduced and the lights turned on. Various combinations of red gels were used to reduce the intensity of the light. In the second method, termed "brief flashes", the lights were turned on for a duration of approximately one second prior to exposing fish to sound and the positions of the fish were observed and recorded. After exposure to sound, lights were turned back on and the position of the fish was observed again. This was not an optimum experimental design for investigating the nocturnal behavior of fish due to the potential influence of the lights being turned on and off. As a control, the effect of the lights alone in the absence of introduced sound on the behavior of fish was determined by exposing fish to the two methods of night observation and recording the results.

The responses of the fish were evaluated by direct observation and evaluation of underwater video recordings. The percentage of fish in the test cage that responded to sound was estimated to the nearest quartile. Fish were classified as exhibiting one of three behaviors when exposed to sound: no reaction, startle, or active avoidance.

- No reaction was defined as no observable movement in response to the sound.
- The startle reaction was defined as a movement that resulted in a decrease in the inter-fish distance or a momentary non-directed departure from normal movements.
- Active avoidance was defined as a movement away from the sound source.

The reaction of a test batch of fish was classified into one of these behaviors according to the response of the majority of fish in the test cage.

The active avoidance response was further characterized as a predominantly lateral, predominantly down (sounding), or a diagonal movement down and away from the sound source (diagonal). The relative strength of the active avoidance response was rated on a scale of 1 to 3. A rating of 1 indicated a movement of only 0.3 to 1.0 m within 10 seconds after application of the sound, and is referred to as a slight response. A rating of 2 indicated a movement of greater distance (1-2 m) within 10 seconds of the sound and is referred to as a moderate response. A rating of 3 indicated movement associated with the sound that was only limited by the boundaries of the test cage and is referred to as a strong response. Only one behavioral response and level of response was used to characterize the response of the test group of fish. We did not permit multiple classifications of behavioral responses within one test. For example, if 75% of the fish exhibited a diagonal response and 25% exhibited a startle reaction, the test was classified as exhibiting a diagonal response.

A computerized literature search of the BIOSIS and NTIS (National Technical Information Service) data bases was conducted to determine if literature exists pertaining to the behavior of white perch, striped bass and Atlantic tomcod. The BIOSIS data base contains 3.7 million citations and covers approximately 9,000 primary life science journals from 1969 to present. The NTIS data base contains 957,000 citations and covers research, development, and engineering analyses prepared by federal agencies and their contractors. Key words used in the literature search were "noise", "sound", "acoustic", and "behavior" in conjunction with "white perch", "striped bass", and "Atlantic tomcod".

3.0 RESULTS

This section discusses the responses of YOY white perch and striped bass and adult Atlantic tomcod to the recorded rock sound, single tones, broad band sound, FM log sweeps, and incidental sounds. The incidental sounds are discussed to the extent that they influenced the responses of fish to other sounds. Acclimation to sound is investigated along with the effect of light levels, sound frequency, sound amplitude, and water temperature on the reactions of the fishes. The control behavior of the test fish in absence of sound under day and night conditions is described along with the behavior of test fish at night in the presence of artificial illumination.

3.1 FISH BEHAVIOR

Significant differences between day and night behavior in the absence of introduced sound were observed in white perch, striped bass and Atlantic tomcod in the test cage. Observations of the behavior of the test fish in the absence of introduced sound served as control observations for comparison with their behavior in response to introduced sound. Upon introduction to the cage, all 3 species of fish sounded to the bottom of the cage and exhibited quick, erratic, and apparently random movements for approximately 10-20 minutes as they moved through the new surroundings.

3.1.1 White Perch

Following the 10-20 minute period immediately after introduction, white perch were generally randomly distributed between the mid-point and the bottom of the cage during the day. White perch were oriented with their dorsal side towards the surface which indicated good buoyancy control and normal orientation. White perch moved slowly and apparently randomly, usually in the same horizontal plane. Schooling

into tight groups generally did not occur, and white perch did not move in unison. At night white perch exhibited different behavior. They were generally distributed within the top 15-30 cm of the test cage, and showed very little movement. What little movement that did occur was apparently random and generally in a horizontal plane. As during day conditions, white perch generally did not school into tight groups or move in unison.

White perch shifted from night to day behavior when exposed to constant artificial light at night. The behavior shift consisted of increased activity and movement to the lower half of the test cage. Generally the night to day behavior shift started after 5 seconds of exposure to artificial light and was complete within 10 minutes. Because white perch shifted their behavior from a night to day mode after 5 seconds exposure to artificial light, experimentation was conducted to determine the shortest duration of light that would not cause a behavior shift. Repeated experiments in which white perch were exposed to brief flashes of light of 1 second or less duration indicated that this method of observation did not appear to cause a shift from night to day behavior, and most closely modeled actual night behavior.

3.1.2 Striped Bass

During the day, striped bass behaved in a similar manner as white perch, except movements were more rapid and resulted from sudden spurts of swimming. At night, striped bass behavior was virtually identical to white perch. The reactions of striped bass to artificial light at night were also virtually identical to those of white perch with the possible exception that the night to day behavior shift was completed in less time. Striped bass started to shift their behavior from the night to day modes in less than 5 seconds when exposed to constant low level light, and the shift was completed within 10 minutes.

3.1.3 Atlantic Tomcod

Atlantic tomcod behaved very differently from white perch and striped bass during the day. Atlantic tomcod were oriented with their ventral surfaces to the bottom or sides of the test cage. Their movements were constant, quick, apparently random, and generally along the bottom and side surfaces of the test cage. Atlantic tomcod did not exhibit schooling behavior. No observations were made of Atlantic tomcod behavior at night because testing of this species did not occur at night.

3.2 RECORDED SOUNDS

During the course of the study it was observed that rocks thrown into the water near the experimental enclosure elicited a strong avoidance response from white perch and striped bass. The sound of a rock entering the water was recorded, amplified and played back to assess its fish deterrence potential.

3.2.1 White Perch - Recorded Sounds

White perch displayed an active avoidance response to the recorded sound of a rock entering the water under both day and night conditions (Table 3-1). Out of a total of 96 day tests, an avoidance response was obtained in 76 tests (79%). The general lower activity level of white perch at night in the absence of introduced sound was reflected in the reactions to the recorded rock sound at night. White perch appeared to be less reactive to the recorded rock noise at night when 17 tests with active avoidance responses were observed out of a total of 34 tests (50%). During both day and night testing amplitudes ranged from 133.3-157.8 dB//μPa/Hz at 1 m.

TABLE 3-1. RESPONSE OF AGE-0 WHITE PERCH TO THE RECORDED ROCK SOUND UNDER DAY AND NIGHT CONDITIONS.

AMPLITUDE dB//µPa/HZ AT 1 M	PERCENT RESPONDING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSER-VATIONS[f]	NUMBER OF FISH
133.3	75	DIAGONAL	2	9	A	21DEC88	16:09	DAY	6	4		75
133.3	75	DIAGONAL	2	10	A	21DEC88	16:10	DAY	6	4		75
133.3	75	DIAGONAL	2	11	A	21DEC88	16:11	DAY	6	4		75
133.3	75	DIAGONAL	1	13	A	21DEC88	16:13	DAY	6	4		75
133.3	50	DIAGONAL	2	15	A	21DEC88	16:15	DAY	6	3		75
133.3	50	DIAGONAL	1	16	A	21DEC88	16:16	DAY	6	3		75
133.3	25	SOUNDING	1	19	A	21DEC88	16:19	DAY	6	3		75
133.3	50	SOUNDING	1	26	A	21DEC88	16:26	DAY	6	2		75
133.3	50	DIAGONAL	1	29	A	21DEC88	16:29	DAY	6	2		75
133.3	0	NO RESPONSE	.	32	A	21DEC88	16:32	DAY	6	2		75
133.3	75	LATERAL	1	39	A	21DEC88	16:39	DAY	6	2		75
133.3	100	DIAGONAL	2	940	A	22DEC88	7:40	DAY	6	5		75
133.3	100	STARTLE	.	943	A	22DEC88	7:43	DAY	6	5		75
138.3	75	LATERAL	3	944	A	22DEC88	7:44	DAY	6	5		75
138.3	100	DIAGONAL	2	948	A	22DEC88	7:48	DAY	6	5		75
138.3	100	STARTLE	.	950	A	22DEC88	7:50	DAY	6	5		75
133.3	75	DIAGONAL	2	11	B	22DEC88	9:16	DAY	6	5		75
133.3	100	DIAGONAL	2	14	B	22DEC88	9:19	DAY	6	5		75
133.3	75	DIAGONAL	1	24	B	22DEC88	9:29	DAY	6	5		75
133.3	75	DIAGONAL	1	42	B	22DEC88	9:47	DAY	6	5		75
138.3	75	DIAGONAL	1	47	B	22DEC88	9:52	DAY	6	5		75
142.3	50	LATERAL	2	58	B	22DEC88	10:03	DAY	6	5		75
142.3	50	LATERAL	1	66	B	22DEC88	10:11	DAY	6	5		75
142.3	75	DIAGONAL	1	113	B	22DEC88	10:58	DAY	6	5		75

(CONTINUED)

TABLE 3-1. (CONTINUED)

AMPLITUDE dB//μPa/Hz AT 1 M	PERCENT RESPONDING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSERVATIONS[f]	NUMBER OF FISH
133.3	75	DIAGONAL	3	15	C	22DEC88	12:15	DAY	6	5		75
133.3	75	DIAGONAL	2	17	C	22DEC88	12:17	DAY	6	5		75
133.3	50	DIAGONAL	2	21	C	22DEC88	12:21	DAY	6	5		75
133.3	50	DIAGONAL	2	22	C	22DEC88	12:22	DAY	6	5		75
133.3	50	DIAGONAL	2	23	C	22DEC88	12:23	DAY	6	5		75
133.3	50	DIAGONAL	2	24	C	22DEC88	12:24	DAY	6	5		75
133.3	50	DIAGONAL	2	25	C	22DEC88	12:25	DAY	6	5		75
133.3	0	NO RESPONSE	.	26	C	22DEC88	12:26	DAY	6	5		75
133.3	25	DIAGONAL	1	26	C	22DEC88	12:26	DAY	6	5		75
133.3	25	DIAGONAL	1	27	C	22DEC88	12:27	DAY	6	5		75
133.3	50	DIAGONAL	2	28	C	22DEC88	12:28	DAY	6	5		75
133.3	25	DIAGONAL	1	29	C	22DEC88	12:29	DAY	6	5		75
133.3	0	NO RESPONSE	.	34	C	22DEC88	12:34	DAY	6	5		75
133.3	50	DIAGONAL	2	38	C	22DEC88	12:38	DAY	6	5		75
133.3	25	DIAGONAL	1	40	C	22DEC88	12:40	DAY	6	5		75
133.3	25	SOUNDING	1	41	C	22DEC88	12:41	DAY	6	5		75
133.3	50	DIAGONAL	2	42	C	22DEC88	12:42	DAY	6	5		75
133.3	25	SOUNDING	1	44	C	22DEC88	12:44	DAY	6	5		75
133.3	0	NO RESPONSE	.	45	C	22DEC88	12:45	DAY	6	5		75
133.3	0	NO RESPONSE	.	46	C	22DEC88	12:46	DAY	6	5		75
133.3	25	DIAGONAL	1	63	D	22DEC88	14:03	DAY	6	5		75
133.3	25	DIAGONAL	1	65	D	22DEC88	14:05	DAY	6	5		75
133.3	25	LATERAL	1	66	D	22DEC88	14:06	DAY	6	5		75

(CONTINUED)

TABLE 3-1. (CONTINUED)

AMPLITUDE dB//μPa/Hz AT 1 M	PERCENT RESPONDING	RESPONSE[a]	RESPONSE STRENGTH[ba]	HOLDING TIME (MINUTES)	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSER-VATIONS[f]	NUMBER OF FISH
133.3	0	NO RESPONSE	.	18	E	22DEC88	15:48	DAY	6	4		200
138.3	0	NO RESPONSE	.	20	E	22DEC88	15:50	DAY	6	4		200
138.3	0	NO RESPONSE	.	22	E	22DEC88	15:52	DAY	6	3		200
138.3	50	DIAGONAL	1	30	E	22DEC88	16:00	DAY	6	3		200
142.3	100	DIAGONAL	3	34	E	22DEC88	16:04	DAY	6.0	3		200
142.3	75	DIAGONAL	3	36	E	22DEC88	16:06	DAY	6.0	3		200
142.3	75	DIAGONAL	2	40	E	22DEC88	16:10	DAY	6.0	3		200
142.3	100	DIAGONAL	3	43	E	22DEC88	16:13	DAY	6.0	3		200
142.3	75	DIAGONAL	3	45	E	22DEC88	16:15	DAY	6.0	3		200
142.3	50	DIAGONAL	2	49	E	22DEC88	16:19	DAY	6.0	3		200
142.3	25	DIAGONAL	1	52	E	22DEC88	16:22	DAY	6.0	3		200
142.3	25	DIAGONAL	1	90	E	22DEC88	16:30	DAY	6.0	3		200
142.3	0	NO RESPONSE	.	64	E	22DEC88	16:34	DAY	6.0	3		200
142.3	75	DIAGONAL	2	68	E	22DEC88	16:38	DAY	6.0	2		200
142.3	25	DIAGONAL	1	72	E	22DEC88	16:42	DAY	6.0	2		200
138.8	0	NO RESPONSE	.	6171	F	03JAN89	15:30	DAY	5.5	5		200
138.8	0	NO RESPONSE	.	6172	F	03JAN89	15:31	DAY	5.5	5		200
143.8	75	DIAGONAL	2	6173	F	03JAN89	15:32	DAY	5.5	5		200
143.8	50	SOUNDING	1	6177	F	03JAN89	15:36	DAY	5.5	5		200
143.8	0	NO RESPONSE	.	6178	F	03JAN89	15:37	DAY	5.5	5		200
143.8	75	SOUNDING	1	6181	F	03JAN89	15:40	DAY	5.5	5		200
147.8	75	SOUNDING	1	6188	F	03JAN89	15:47	DAY	5.5	5		200
147.8	75	DIAGONAL	2	6191	F	03JAN89	15:50	DAY	5.5	5		200
147.8	0	NO RESPONSE	.	6194	F	03JAN89	15:53	DAY	5.5	5		200
147.8	0	NO RESPONSE	.	6198	F	03JAN89	15:57	DAY	5.5	5		200
147.8	75	SOUNDING	1	6207	F	03JAN89	16:06	DAY	5.5	5		200
147.8	0	NO RESPONSE	.	6212	F	03JAN89	16:11	DAY	5.5	5		200

(CONTINUED)

TABLE 3-1. (CONTINUED)

AMPLITUDE dB//μPa/Hz AT 1 M	PERCENT RESPONDING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSERVATIONS[f]	NUMBER OF FISH
138.8	75	SOUNDING	1	7243	F	04JAN89	9:22	DAY	5.5	5		200
138.8	75	SOUNDING	1	7245	F	04JAN89	9:24	DAY	5.5	5		200
143.8	75	LATERAL	1	7263	F	04JAN89	9:42	DAY	5.5	5		200
143.8	75	LATERAL	2	7278	F	04JAN89	9:57	DAY	5.5	5		200
138.8	0	NO RESPONSE	.	7341	F	04JAN89	11:00	DAY	5.5	5		200
143.8	0	NO RESPONSE	.	7342	F	04JAN89	11:01	DAY	5.5	5		200
147.8	50	DIAGONAL	1	7344	F	04JAN89	11:03	DAY	5.5	5		200
147.8	0	NO RESPONSE	.	7353	F	04JAN89	11:12	DAY	5.5	5		200
147.8	0	NO RESPONSE	.	7367	F	04JAN89	11:26	DAY	5.5	5		200
147.8	100	SOUNDING	1	7376	F	04JAN89	11:35	DAY	5.5	5		200
147.8	0	NO RESPONSE	.	7378	F	04JAN89	11:37	DAY	5.5	5		200
147.8	75	SOUNDING	1	7516	F	04JAN89	13:55	DAY	5.5	5		200
147.8	0	NO RESPONSE	.	7518	F	04JAN89	13:57	DAY	5.5	5		200
147.8	0	NO RESPONSE	.	7709	F	04JAN89	17:08	NIGHT	5.5		2RL 1WL	200
147.8	100	SOUNDING	1	7710	F	04JAN89	17:09	NIGHT	5.5		2RL 1WL	200
147.8	0	NO RESPONSE	.	7711	F	04JAN89	17:10	NIGHT	5.5		2RL 1WL	200
147.8	0	NO RESPONSE	.	7712	F	04JAN89	17:11	NIGHT	5.5		2RL 1WL	200
147.8	75	DIAGONAL	2	7813	F	04JAN89	18:52	NIGHT	5.5		2RL 1WL	200
142.3	0	NO RESPONSE	.	70	G	05JAN89	18:10	NIGHT	5.0		BF	200
142.3	100	SOUNDING	1	107	G	05JAN89	18:47	NIGHT	5.0		2RL	200
142.3	100	SOUNDING	1	114	G	05JAN89	18:54	NIGHT	5.0		2RL	200
142.3	100	SOUNDING	1	150	G	05JAN89	19:30	NIGHT	5.0		2RL	200
142.3	100	LATERAL	2	156	G	05JAN89	19:36	NIGHT	5.0		2RL	200
142.3	0	NO RESPONSE	.	170	G	05JAN89	19:50	NIGHT	5.0		2RL 1WL	200
142.3	100	DIAGONAL	1	172	G	05JAN89	19:52	NIGHT	5.0		2RL 1WL	200
142.3	0	NO RESPONSE	.	176	G	05JAN89	19:56	NIGHT	5.0		2RL 1WL	200

(CONTINUED)

TABLE 3-1. (CONTINUED)

AMPLITUDE dB//μPa/Hz AT 1 M	PERCENT RESPONDING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSERVATIONS[f]	NUMBER OF FISH
142.3	75	DIAGONAL	2	225	G	05JAN89	20:45	NIGHT	5.0		1RL	200
142.3	0	NO RESPONSE	.	226	G	05JAN89	20:46	NIGHT	5.0		1RL	200
142.3	75	LATERAL	1	241	G	05JAN89	21:01	NIGHT	5.0		2RL	200
142.3	100	SOUNDING	3	1132	G	06JAN89	11:52	DAY	4.5	4		200
142.3	100	DIAGONAL	3	1134	G	06JAN89	11:54	DAY	4.5	4		200
142.3	100	LATERAL	3	1135	G	06JAN89	11:55	DAY	4.5	4		200
146.0	0	NO RESPONSE	.	1543	G	06JAN89	18:43	NIGHT	4.5		BF	200
146.0	75	DIAGONAL	3	1565	G	06JAN89	19:05	NIGHT	4.5		BF	200
146.0	75	DIAGONAL	1	1586	G	06JAN89	19:26	NIGHT	4.5		BF	200
146.0	100	SOUNDING	3	18846	G	18JAN89	19:06	NIGHT	4.0		BF	200
146.0	75	SOUNDING	2	18855	G	18JAN89	19:15	NIGHT	4.0		BF	200
146.0	75	SOUNDING	1	18863	G	18JAN89	19:23	NIGHT	4.0		BF	200
146.0	100	DIAGONAL	3	19775	G	19JAN89	10:35	DAY	4.0	4		200
146.0	100	DIAGONAL	3	19778	G	19JAN89	10:38	DAY	4.0	4		200
146.0	100	LATERAL	3	19780	G	19JAN89	10:40	DAY	4.0	4		200
146.0	100	DIAGONAL	3	19785	G	19JAN89	10:45	DAY	4.0	4		200
146.0	25	SOUNDING	1	1382	H	19JAN89	11:02	DAY	4.0	4		300
146.0	50	SOUNDING	1	1392	H	19JAN89	11:12	DAY	4.0	4		300
146.0	0	NO RESPONSE	.	1799	H	19JAN89	17:59	NIGHT	4.0		BF	300
146.0	0	NO RESPONSE	.	1803	H	19JAN89	18:03	NIGHT	4.0		BF	300
146.0	0	NO RESPONSE	.	1805	H	19JAN89	18:05	NIGHT	4.0		BF	300

(CONTINUED)

TABLE 3-1. (CONTINUED)

AMPLITUDE dB//μPa/Hz AT 1 M	PERCENT RESPONDING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSERVATIONS[f]	NUMBER OF FISH
146.0	0	NO RESPONSE	.	1830	H	19JAN89	18:30	NIGHT	4.0		BF	300
146.0	0	NO RESPONSE	.	1861	H	19JAN89	19:01	NIGHT	4.0		BF	300
146.0	0	NO RESPONSE	.	1868	H	19JAN89	19:08	NIGHT	4.0		BF	300
146.0	50	SOUNDING	1	1900	H	19JAN89	19:40	NIGHT	4.0		2RL	300
157.8	0	NO RESPONSE	.	356	I	20JAN89	18:56	NIGHT	4.0		BF	300
157.8	0	NO RESPONSE	.	369	I	20JAN89	19:09	NIGHT	4.0		BF	300
157.8	100	DIAGONAL	2	410	I	20JAN89	19:50	NIGHT	4.0		BF	300
157.8	25	STARTLE	.	436	I	20JAN89	20:16	NIGHT	4.0		BF	300
157.8	25	DIAGONAL	1	477	I	20JAN89	20:57	NIGHT	4.0		BF	300

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

[f] Method of Night Observation RL = Red Light
WL = White Light
BF = Brief Flash

White perch acclimated to the recorded rock sound during the day after 20 consecutive tests conducted over approximately 30 minutes (Table 3-1). On 22 December 1988 between 1215 and 1246 hours a series of 20 consecutive tests were conducted on Group C of white perch specifically to determine if they acclimated to the recorded rock sound and the time interval after which acclimation occurred. The strength of active avoidance response and the percentage of white perch responding decreased steadily when Group C of white perch were subjected to 20 consecutive tests of the recorded rock sound at constant amplitude and light level (Table 3-1). From this series of tests it appeared that white perch became acclimated to the recorded rock sound during the day within 30 minutes when the sound was repeated an average of every 1.5 minutes.

A similar series of 11 consecutive tests were conducted on Group A of fish on 21 December 1988 between 1609 and 1639 hours. These tests were conducted during the late afternoon and light level was decreasing during the series which introduced a possible confounding variable. During these tests, both the strength of the active avoidance responses and percentage of white perch responding generally decreased. However, in the last test in this series, 75% of the white perch responded weakly which was an increase over the preceding test. During this series of tests, the recorded rock sound was repeated an average of every 2.7 minutes. The slower average repetition rate in this series of tests may account for the lack of a clear acclimation response.

No constant decrease in strength of active avoidance responses or the percentage responding occurred in any series of tests at night (Table 3-1). However, unlike day testing, there were no series of tests at night in which white perch were subjected to repeated consecutive, or near consecutive tests of the recorded rock sound under similar conditions. Therefore, it was difficult to tell from these data if white perch acclimate to the recorded rock sound at night.

It was also difficult to separate the influence of relative light level and acclimation on the responses of white perch to the recorded rock sound during the day due to the experimental design. Strength of active avoidance responses in Group A of white perch decreased as relative light level decreased from 4 to 2 on 21 December 1988 between 1609 and 1639 hours (Table 3-1). However, the decrease in strength of response could also be attributed to acclimation, as this group of white perch were subjected to the recorded rock sound 11 times in 30 mintues. No consistent decrease in strength of active avoidance responses was evident on 22 December 1988 between 1548 and 1642 hours when a new group of white perch were exposed to the recorded rock sound and relative light levels decreased from 4 to 2 (Table 3-1). From these data it cannot be conclusively determined if light level during the day consistently influenced the strength of the avoidance response in white perch.

White perch were slightly more reactive to the recorded rock sound at night under constant low level light than when they were observed under brief flashes (Table 3-1). When observed under various combinations of constant low level red and white light, 9 active avoidance reactions were observed out of 16 tests (56%). When white perch were observed through brief flashes, 8 active avoidance responses were observed out of 18 tests (44%).

A series of 12 tests were conducted on 22 December 1988 between 1530 and 1611 hours on Group F of white perch to determine if there is an amplitude threshold below which white perch did not react to the recorded rock sound. Amplitude increased during these tests from 138.8 dB//μPa/Hz at 1 m on the first 2 tests of the series, to 143.8 dB//μPa/Hz at 1 m on the third test, to 147.8 dB//μPa/Hz at 1 m on tests 4 through 12 (Table 3-1). No active avoidance responses were observed in the first 2 tests but an active avoidance response did occur on the

third test when amplitude was 143.8 dB//μPa/Hz at 1 m, and at subsequent tests when amplitude was 147.8 dB//μPa/Hz at 1 m. The strength of the active avoidance response and the percentage of fish reacting decreased in tests 9-12 which may be due to acclimation. From this series of tests it appears that an amplitude threshold for active avoidance in white perch occurred between 138.8 and 147.8 dB//μPa/Hz at 1 m. However, active avoidance responses did occur in other groups of fish at other times at amplitudes below 138.8 dB//μPa/Hz at 1 m. On 21 and 22 December 1988, active avoidance responses occurred in Groups A and B of white perch at amplitudes of 133.3 dB//μPa/Hz at 1 m.

Water temperature did not vary enough (4-6°C) to determine the realtionship between water temperature and the responses of white perch to sound.

3.2.2 Striped Bass - Recorded Rock Sound

Striped bass displayed an avoidance response to the recorded sound of a rock entering the water (Table 3-2). Striped bass exhibited active avoidance responses to the recorded rock sound in 10 out of 16 tests (63%) conducted during the day, and in all 3 tests conducted at night (Table 3-2). Amplitudes ranged from 142.3-147.8 dB//μPa/Hz at 1 m. Striped bass may acclimate to the recorded rock sound. Percentage of fish reacting to the sound decreased during a series of 6 tests between 1530 and 1542 hours on 30 January 1989 when Group J of striped bass were exposed to the recorded rock sound an average of every 1.7 minutes. The trend of decreasing percentage of striped bass reacting during this period was overcome at 1540 hours when a strong sounding reaction was exhibited by all the striped bass in response to a real rock thrown in the water (Appendix B).

TABLE 3-2. RESPONSE OF AGE-0 STRIPED BASS TO THE RECORDED ROCK SOUND UNDER DAY AND NIGHT CONDITIONS.

AMPLITUDE dB//μPa/Hz AT 1 M	PERCENT RESPONDING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSERVATIONS[f]	NUMBER OF FISH
142.3	25	SOUNDING	1	30	J	30JAN89	15:30	DAY	3	5		100
142.3	50	SOUNDING	1	32	J	30JAN89	15:32	DAY	3	5		100
142.3	0	NO RESPONSE	.	34	J	30JAN89	15:34	DAY	3	5		100
142.3	50	SOUNDING	1	37	J	30JAN89	15:37	DAY	3	5		100
142.3	50	SOUNDING	1	39	J	30JAN89	15:39	DAY	3	5		100
142.3	0	NO RESPONSE	.	42	J	30JAN89	15:42	DAY	3	5		100
142.3	0	NO RESPONSE	.	75	J	30JAN89	16:15	DAY	3	2		100
147.8	75	SOUNDING	3	111	J	30JAN89	16:51	DAY	3	4		100
147.8	75	DIAGONAL	2	121	J	30JAN89	17:01	DAY	3	3		100
147.8	75	SOUNDING	1	134	J	30JAN89	17:14	DAY	3	2		100
147.8	50	SOUNDING	1	268	J	30JAN89	19:28	NIGHT	3		BF	100
147.8	50	SOUNDING	1	285	J	30JAN89	19:45	NIGHT	3		BF	100
147.8	25	SOUNDING	1	305	J	30JAN89	20:05	NIGHT	3		BF	100
147.8	0	NO RESPONSE	.	1233	J	31JAN89	11:33	DAY	3	5		100
147.8	0	NO RESPONSE	.	1235	J	31JAN89	11:35	DAY	3	5		100
147.8	100	DIAGONAL	3	1497	J	31JAN89	15:57	DAY	3	4		100
147.8	75	DIAGONAL	2	1501	J	31JAN89	16:01	DAY	3	4		100
147.8	0	NO RESPONSE	.	1505	J	31JAN89	16:05	DAY	3	4		100
147.8	25	DIAGONAL	1	1518	J	31JAN89	16:18	DAY	3	4		100

TABLE 3-2. (CONTINUED)

FOOTNOTES

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

[f] Method of Night Observation RL = Red Light
WL = White Light
BF = Brief Flash

Relative light levels during the day did not appear related to the responses of striped bass to the recorded rock sound (Table 3-2). Active avoidance responses were observed at all light levels tested. Only brief flashes were used in the 3 night tests to observe the responses of striped bass to the recorded rock sound, and active avoidance responses occurred in all 3 tests.

Striped bass were exposed to amplitudes of 142.3 and 147.8 dB//μPa/Hz at 1 m. Although active avoidance reactions occurred at both amplitudes, strong and moderate active avoidance reactions only occurred at an amplitude of 147.8 dB//μPa/Hz at 1 m.

Water temperature for all tests did not vary from 3°C. Any water temperature threshold below which striped bass will not react to the recorded rock sound must be below 3°C.

3.2.3 Atlantic Tomcod - Recorded Rock Sound

Only 2 tests of the reactions of Atlantic tomcod to the recorded rock sound were conducted (Table 3-3). During both of these tests, a weak lateral reaction was elicited from 75% of the fish. A lateral movement was the only response observed because Atlantic tomcod are demersal fish and the bottom of the cage prevented any sounding or diagonal movement. Relative light level and water temperature were constant during all of these tests.

TABLE 3-3. RESPONSE OF AGE-1 ATLANTIC TOMCOD TO THE RECORDED ROCK SOUND UNDER DAY AND NIGHT CONDITIONS.

AMPLITUDE dB//μPa/Hz AT 1 M	PERCENT RESPONDING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	NUMBER OF FISH
142.3	75	LATERAL	1	13	K	22DEC88	14:33	DAY	6	5	100
142.3	75	LATERAL	1	15	K	22DEC88	14:35	DAY	6	5	100

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

3.3 ANALYSIS OF RECORDED ROCK SOUND

The sound of a rock entering the water consistently elicited a strong avoidance response. The waterborne part of the rock splash sound was recorded using the receive hydrophone input to a magnetic tape recorder. It was then played back into the amplifier and ultimately into the transducer via the power amplifier to electronically reproduce the sound as desired.

Figures 3-1 and 3-2 illustrate the time and frequency plots of the rock sound, respectively. The time plot illustrates the two components of the rock splash. The first component is the rock hitting the surface at time zero on the plot. The energy from this part is of short duration, decaying within 40 ms. After the surface entry event (approximately 200 ms), the void created by the rock collapses. This collapse generates a longer duration and higher source level measured at the hydrophone (and experienced by the fish) then the actual splash.

The spectrum plot of the actual rock sound in Figure 3-2 contains an amplitude-versus-frequency plot. The spectral predominant frequency is 76 Hz. The source level at 76 Hz is 128.2 dB//μPa/Hz at 1 m, which is significantly (20 dB) lower than the maximum level achievable with the EFSS prototype. Maximum levels for tones and band limited noise were 160 dB//μPa/Hz/m or 148 dB//μPa/Hz/m, respectively. The band-limited noise is similar to the "rock sound" in that each covers a span of frequencies.

The signal to noise ratio (SNR) for the real rock splash was calculated as the rock spectrum level at 100 Hz (128.2 dB//μPa/Hz) minus the quarry background level (67.7 dB//μPa/Hz) or 60.5 dB (Figure 3-3). The sound level for the recorded rock sound was between 140 and 150 dB//μPa/Hz at 1 m. This equals a SNR near the source of about 145-67.7 or 77.3 dB. Therefore, the recorded rock SNR was approximately 77 minus 60 or 17 dB higher than the real rock at frequencies greater than 100 Hz.

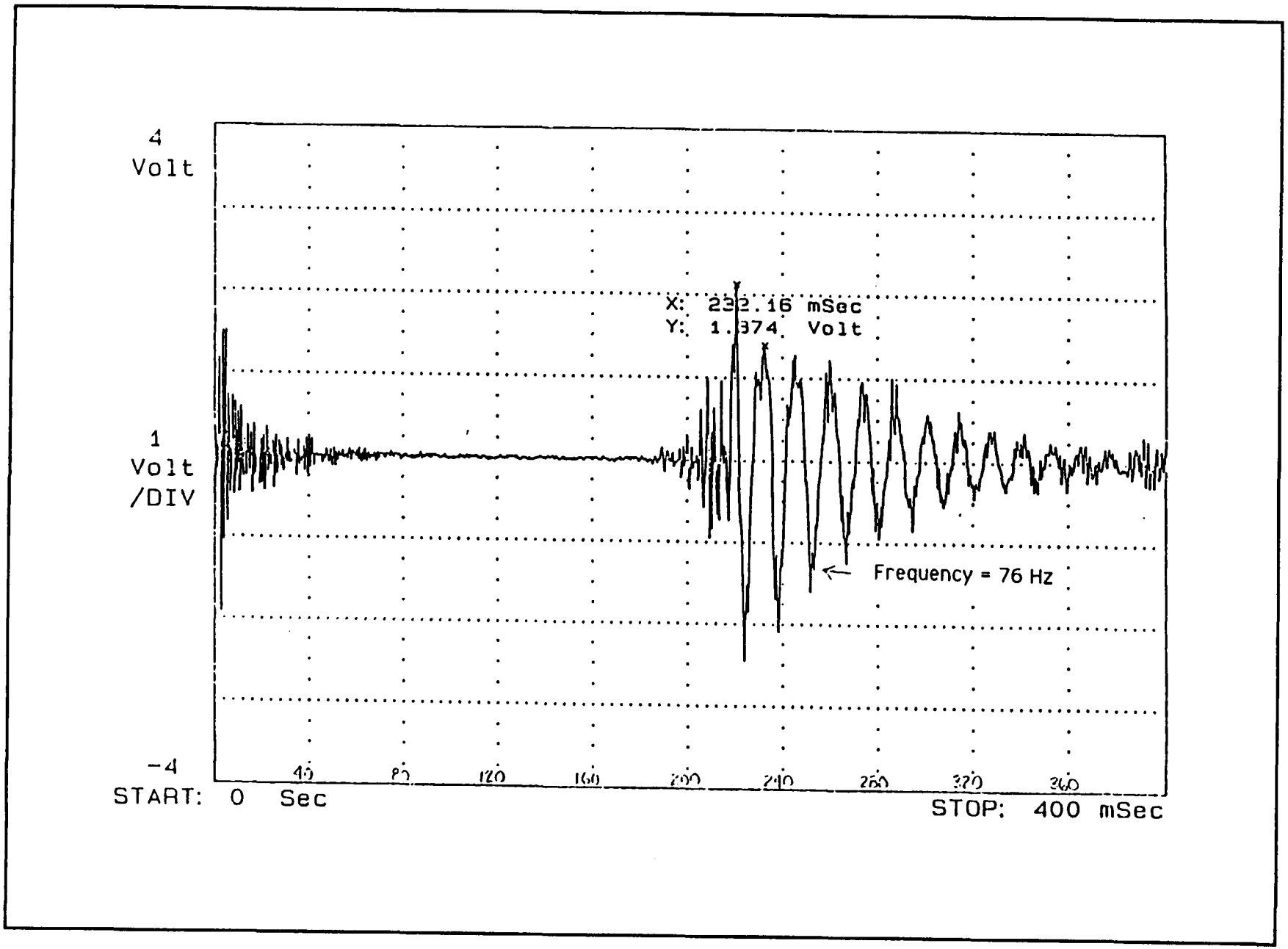


Figure 3-1. Time Plot of Rock Sound used in the 1988-89 Fish Deterrence Studies.

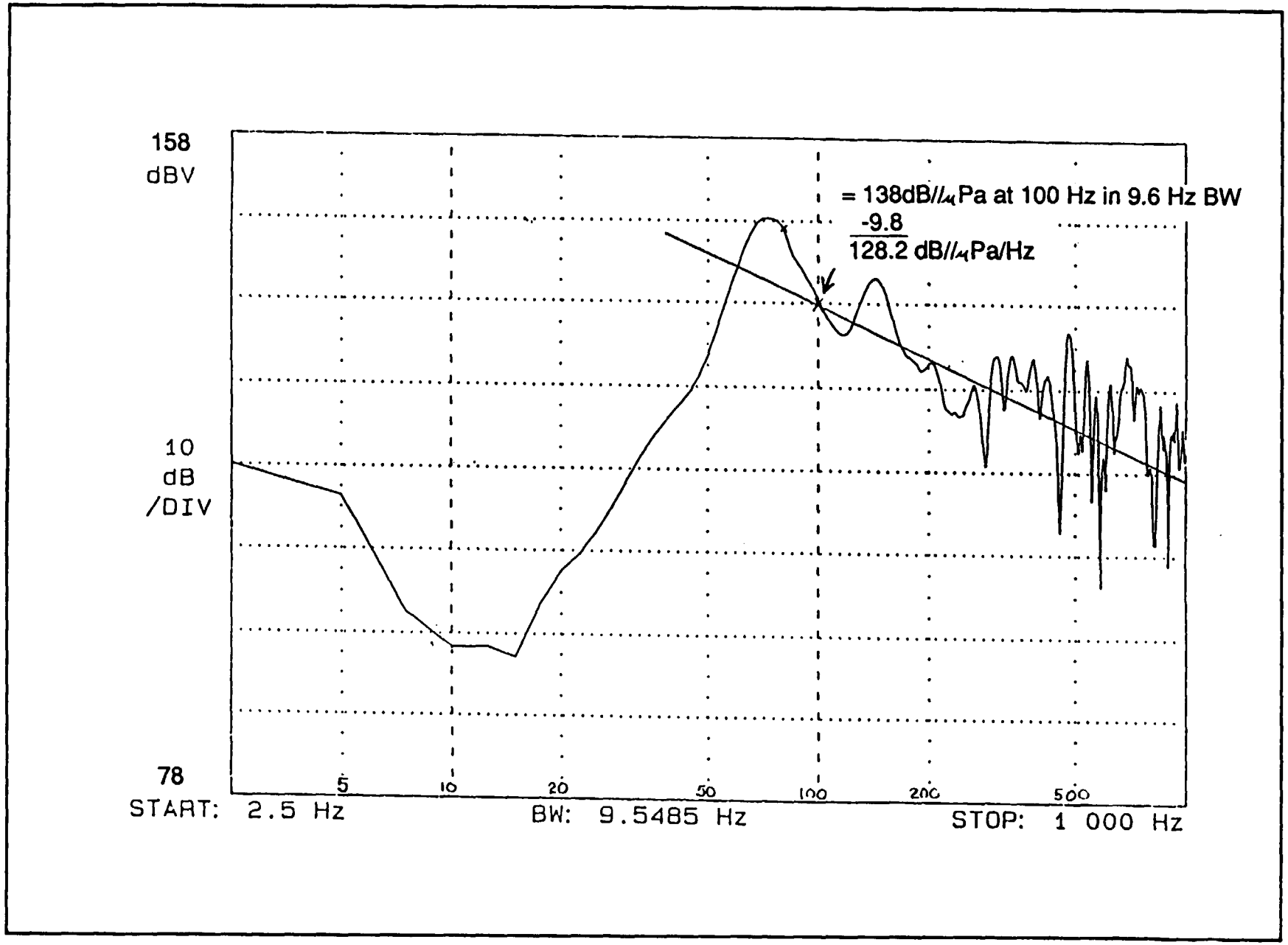


Figure 3-2. Frequency Plot of Rock Sound used in the 1988-89 Fish Deterrence Studies.

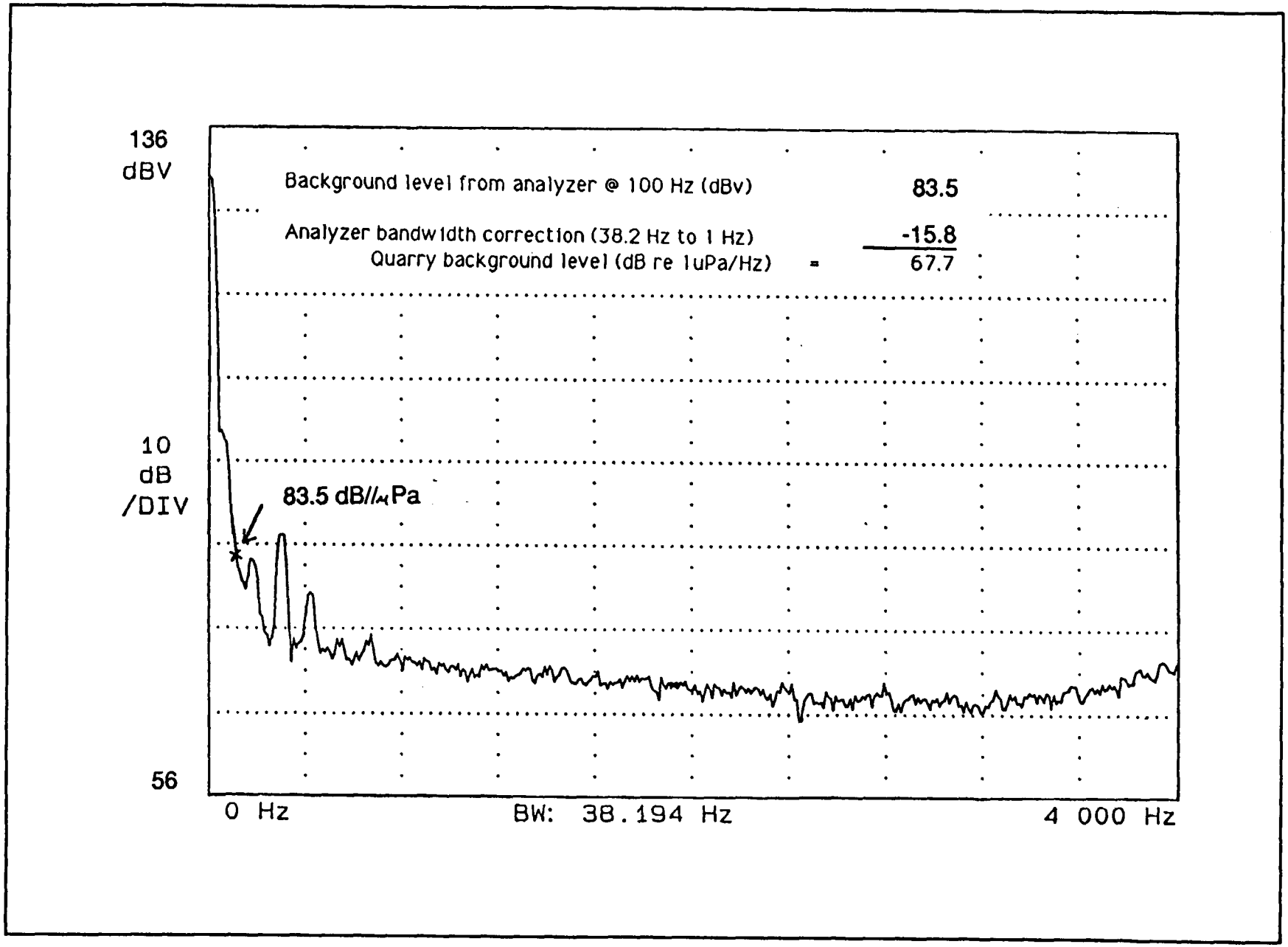


Figure 3-3. Verplanck Quarry Background Noise Plot during the 1988-89 Fish Deterrence Studies.

3.4 SINGLE TONES

3.4.1 White Perch - Single Tones

White perch reacted to single tones during both day and night testing. The strongest active avoidance reactions to single tones were obtained in response to frequencies less than 150 Hz at night (Table 3-4). Active avoidance responses were elicited in 9 out of 21 tests (43%) during the day, and 14 out of 31 tests (45%) at night.

During day testing there were 8 slight and 1 moderate active avoidance reactions (Table 3-4). The 8 slight reactions consisted of 6 sounding reactions and 2 slight diagonal reactions. Five slight sounding reactions occurred at a frequency of 150 Hz and at an amplitude of 128.8 dB//μPa/Hz at 1 m, and pulse lengths ranging from 60-100 ms. One slight sounding reaction occurred at a frequency of 220 Hz, an amplitude of 142.8 dB//μPa/Hz at 1 m and a pulse length of 100 ms. The 2 slight diagonal reactions occurred at frequencies of 100 Hz, amplitudes of 138.5 dB//μPa/Hz at 1 m and pulse lengths of 200 ms. The moderate diagonal reaction occurred at a frequency of 100 Hz, an amplitude of 138.5 dB//μPa/Hz at 1 m, and a pulse length of 200 ms.

Most (81%) of the night testing occurred at frequencies less than or equal to 100 Hz. Out of 31 night tests, 8 resulted in slight sounding responses, 2 resulted in strong sounding responses, 1 resulted in a moderate diagonal response, and 3 resulted in strong diagonal responses (Table 3-4). The 8 slight sounding reactions occurred at frequencies of 50-100 Hz, amplitudes of 122.8-138.5 dB//μPa/Hz at 1 m and pulse lengths of 100-200 ms. The 2 strong sounding responses occurred at a frequency of 50 Hz, amplitude of 128.3 dB//μPa/Hz at 1 m and a pulse length of 100 ms. The moderate and strong diagonal responses occurred at a frequency of 100 Hz, amplitude of 140.3-145.0 dB//μPa/Hz at 1 m and a pulse length of 100 ms.

TABLE 3-4. RESPONSE OF AGE-0 WHITE PERCH TO SINGLE TONES UNDER DAY AND NIGHT CONDITIONS.

FREQUENCY (HZ)	AMPLITUDE dB//μPa/Hz AT 1 M	PULSE LENGTH (MS)	PERCENT RESPOND-ING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSER-VATIONS[f]	NUMBER OF FISH
112	114.8	20	0	NO RESPONSE	.	958	A	22DEC88	7:58	DAY	6.0	5		75
112	114.8	20	0	NO RESPONSE	.	961	A	22DEC88	8:01	DAY	6.0	5		75
220	142.8	.	0	NO RESPONSE	.	77	B	22DEC88	10:22	DAY	6.0	5		75
220	142.8	100	75	SOUNDING	1	79	B	22DEC88	10:24	DAY	6.0	5		75
220	142.8	.	0	NO RESPONSE	.	85	B	22DEC88	10:30	DAY	6.0	5		75
150	138.8	.	0	NO RESPONSE	.	89	B	22DEC88	10:34	DAY	6.0	5		75
150	134.8	100	0	NO RESPONSE	.	93	B	22DEC88	10:38	DAY	6.0	5		75
250	141.8	100	0	NO RESPONSE	.	95	B	22DEC88	10:40	DAY	6.0	5		75
150	128.8	60	25	SOUNDING	1	20	D	22DEC88	13:20	DAY	6.0	5		75
150	128.8	60	25	SOUNDING	1	21	D	22DEC88	13:21	DAY	6.0	5		75
150	128.8	60	50	SOUNDING	1	23	D	22DEC88	13:23	DAY	6.0	5		75
150	128.8	60	25	SOUNDING	1	26	D	22DEC88	13:26	DAY	6.0	5		75
150	128.8	100	50	SOUNDING	1	28	D	22DEC88	13:28	DAY	6.0	5		75
150	128.8	100	0	NO RESPONSE	.	30	D	22DEC88	13:30	DAY	6.0	5		75
150	122.8	100	0	NO RESPONSE	.	33	D	22DEC88	13:33	DAY	6.0	5		75
150	122.8	100	0	NO RESPONSE	.	34	D	22DEC88	13:34	DAY	6.0	5		75
150	128.8	1000	0	NO RESPONSE	.	39	D	22DEC88	13:39	DAY	6.0	5		75
100	145.0	100	100	DIAGONAL	3	7825	F	04JAN89	19:04	NIGHT	5.5		2RL	200
100	140.3	100	100	DIAGONAL	3	7833	F	04JAN89	19:12	NIGHT	5.5		2RL	200
150	140.3	100	50	SOUNDING	1	7837	F	04JAN89	19:16	NIGHT	5.5		2RL	200
100	140.3	100	75	DIAGONAL	2	7838	F	04JAN89	19:17	NIGHT	5.5		2RL	200
50	128.3	100	100	SOUNDING	3	7841	F	04JAN89	19:20	NIGHT	5.5		2RL	200
50	128.3	100	100	SOUNDING	3	7845	F	04JAN89	19:24	NIGHT	5.5		2RL	200
50	128.3	100	0		.	7853	F	04JAN89	19:32	NIGHT	5.5		2RL	200
100	140.3	100	0		.	7865	F	04JAN89	19:44	NIGHT	5.5		BF	200
100	140.3	100	0		.	7866	F	04JAN89	19:45	NIGHT	5.5		BF	200
100	140.3	100	100	DIAGONAL	3	7871	F	04JAN89	19:50	NIGHT	5.5		2RL	200

(CONTINUED)

TABLE 3-4. (CONTINUED)

FREQUENCY (HZ)	AMPLITUDE dB//µPa/Hz AT 1 M	PULSE LENGTH (MS)	PERCENT RESPOND-ING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSER-VATIONS[f]	NUMBER OF FISH
100	134.8	100	0	NO RESPONSE	.	80	G	05JAN89	18:20	NIGHT	5.0		BF	200
50	122.8	100	0	NO RESPONSE	.	82	G	05JAN89	18:22	NIGHT	5.0		BF	200
100	134.8	100	100	SOUNDING	1	130	G	05JAN89	19:10	NIGHT	5.0		2RL	200
50	122.8	100	100	SOUNDING	1	134	G	05JAN89	19:14	NIGHT	5.0		2RL	200
100	134.8	100	100	SOUNDING	1	229	G	05JAN89	20:49	NIGHT	5.0		2RL	200
100	140.8	100	0	NO RESPONSE	.	230	G	05JAN89	20:50	NIGHT	5.0		2RL	200
100	140.8	100	0	NO RESPONSE	.	231	G	05JAN89	20:51	NIGHT	5.0		2RL 1WL	200
100	137.8	100	100	SOUNDING	1	232	G	05JAN89	20:52	NIGHT	5.0		2RL 1WL	200
100	138.5	100	75	SOUNDING	1	1605	G	06JAN89	19:45	NIGHT	4.5		BF	200
100	138.5	100	75	SOUNDING	1	1627	G	06JAN89	20:07	NIGHT	4.5		BF	200
150	135.5	200	0	NO RESPONSE	.	18947	G	18JAN89	20:47	NIGHT	4.0		BF	200
150	135.5	200	0	NO RESPONSE	.	18949	G	18JAN89	20:49	NIGHT	4.0		BF	200
100	135.5	200	0	NO RESPONSE	.	18951	G	18JAN89	20:51	NIGHT	4.0		BF	200
100	135.5	200	0	NO RESPONSE	.	18955	G	18JAN89	20:55	NIGHT	4.0		BF	200
100	139.5	200	25	SOUNDING	1	18958	G	18JAN89	20:58	NIGHT	4.0		BF	200
100	139.5	20	0	NO RESPONSE	.	18961	G	18JAN89	21:01	NIGHT	4.0		BF	200
100	138.5	200	75	DIAGONAL	2	1377	H	19JAN89	10:57	DAY	4.0	4		300
100	138.5	200	50	DIAGONAL	1	1379	H	19JAN89	10:59	DAY	4.0	4		300
100	138.5	200	0	NO RESPONSE	.	1380	H	19JAN89	11:00	DAY	4.0	4		300
100	138.5	200	50	DIAGONAL	1	1390	H	19JAN89	11:10	DAY	4.0	4		300

(CONTINUED)

TABLE 3-4. (CONTINUED)

FREQUENCY (HZ)	AMPLITUDE dB//μPa/Hz AT 1 M	PULSE LENGTH (MS)	PERCENT RESPOND-ING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSER-VATIONS[f]	NUMBER OF FISH
100	138.5	200	0	NO RESPONSE	.	1890	H	19JAN89	19:30	NIGHT	4.0		BF	300
100	138.5	200	0	NO RESPONSE	.	1895	H	19JAN89	19:35	NIGHT	4.0		BF	300
5000	139.5	200	0	NO RESPONSE	.	454	I	20JAN89	20:34	NIGHT	4.0		BF	300
5000	139.5	200	0	NO RESPONSE	.	468	I	20JAN89	20:48	NIGHT	4.0		BF	300
10000	139.5	200	0	NO RESPONSE	.	473	I	20JAN89	20:53	NIGHT	4.0		BF	300

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

[f] Method of Night Observation RL = Red Light
WL = White Light
BF = Brief Flash

During both day and night testing, repetition of the same or similar experimental conditions did not consistently result in the same reaction. The lack of replicability may be due to acclimation. The percentage of fish in Group D exhibiting active avoidance decreased from 50% to 0 after 5 tests during a series of 9 tests conducted on average every 2 minutes between 1320 and 1339 hours on 22 December 1989 at a frequency of 150 Hz (Table 3-4). This reduction in percentage responding in a series of test conducted under similar conditions may be an acclimation response. However, pulse length varied from 60 ms to 1 second during the series which may have confounded the results. There was no series of tests at night during which test conditions, particularly light level, remained constant. Therefore it cannot be determined if white perch acclimate to single tones at night.

Light level appeared to influence the responses of white perch to single tones at night. During day testing, relative light level did not vary enough to determine if it affected the responses of white perch to single tones. During the night of 4 January 1989 between 1904 and 1950 hours, Group F of white perch were exposed to frequencies ranging from 50-150 Hz and amplitudes ranging from 128.3 to 145.0 dB//μPa/Hz at 1 m (Table 3-4). White perch displayed active avoidance reactions in 7 out of 8 tests when observed under constant low level light, but did not react at all during the 2 tests when observed through brief flashes of light. Similar observations were made during night testing on 5, 6, and 18 January 1989. On 5 January between 1820 and 2052 hours, Group G of white perch were exposed to a frequency of 100 Hz at amplitudes ranging from 122.8 to 140.8 dB//μPa/Hz at 1 m. Active avoidance responses occurred in 4 out of 5 tests when the white perch were observed under constant low level light and no responses were observed in the 2 tests where the fish were observed using brief flashes of light. The only active avoidance responses observed with brief flashes of light occurred in both tests conducted on 6 January 1989 and in 1 test out of 6 conducted on 18 January 1989. On 6 January 1989, white perch displayed slight

active avoidance reactions to 2 tests when observed with brief flashes of light and exposed to a frequency of 100 Hz and an amplitude of 138.5 dB//μPa/Hz at 1 m. On 18 January 1989 between 2047 and 2101 hours, white perch displayed a slight active avoidance response in 1 test out of 6 when the fish were observed using brief flashes of light and exposed to frequencies of 100 and 150 Hz at amplitudes of 135.5 and 139.5 dB//μPa/Hz at 1 m.

White perch were exposed to single tone frequencies of 100, 112, 150, 220 and 250 Hz during day testing and single tone frequencies of 50, 100, 150, 5,000 and 10,000 Hz during night testing (Table 3-4). During day testing, white perch exhibited active avoidance responses in 6 out of 21 tests (29%). Active avoidance responses occurred at frequencies of 100 Hz and 150-220 Hz. No active avoidance responses occurred during both tests conducted at 112 Hz and the one test conducted at 250 Hz. The 2 tests conducted at 112 Hz were at a relatively low amplitude (114.8 dB//μPa/Hz at 1 m). It is possible that active avoidance reactions could be elicited if these frequencies were further investigated at higher amplitudes. The other test with no active avoidance response took place at 250 Hz at an amplitude of 141.8 dB//μPa/Hz at 1 m. From these data, a frequency threshold above which active avoidance responses during the day do not occur was probably greater than 220 Hz. During night testing active avoidance responses were elicited in 14 out of 31 tests (45%). The active avoidance responses occurred at frequencies between 50-150 Hz. However, only 3 tests took place at frequencies greater than 150 Hz: 5,000 and 10,000 Hz. From these data, a frequency threshold at night above which active avoidance responses did not occur is probably greater than 150 Hz when observed with constant low level light, and greater than 100 Hz when observed with brief flashes. There were very few replicate tests during both day and night and testing and variation in other variables such as amplitude may have confounded interpretation of the results.

During day testing, amplitudes ranged from 114.8-142.8 dB//μPa/Hz at 1 m, and active avoidance reactions were only observed at amplitudes greater than 128.8 dB//μPa/Hz at 1 m (Table 3-4). However, only 2 tests occurred at amplitudes below 128.8 dB//μPa/Hz at 1 m and the frequency used in these 2 tests (112 Hz) was not replicated at higher amplitudes. During night testing, excluding the 3 tests at frequencies of 5000 and 10,000 Hz, active avoidance reactions were obtained at amplitudes greater than 122.8 dB//μPa/Hz at 1 m when the fish were observed under constant low level light. When fish were observed with brief flashes of light, active avoidance responses only occurred at amplitudes of 138.5 dB//μPa/Hz at 1 m or greater. Since observations made with brief flashes of light more closely modeled night conditions, an amplitude threshold for active avoidance responses in white perch at night was about 138.5 dB//μPa/Hz at 1 m.

Water temperature ranged from 4-6°C during testing of single tones and appeared to have no relationship to the reactions of white perch to single tones. However, this variation in water temperature was probably not great enough to determine if water temperature was related to the responses of white perch to single tones.

3.4.2 Striped Bass - Single Tones

Striped bass were not reactive to single tones during the day, and they were not exposed to single tones at night. No active avoidance responses were elicited at single tone frequencies ranging from 100-2000 Hz and at amplitudes ranging from 134.3-146.3 dB//μPa/Hz at 1 m (Table 3-5). Water temperature was constant (3°C) during the testing and its relationship to the responses of striped bass to single tones cannot be determined.

TABLE 3-5. RESPONSE OF AGE-0 STRIPED BASS TO SINGLE TONES UNDER DAY CONDITIONS.

FREQUENCY (HZ)	AMPLITUDE dB//μPa/Hz AT 1 M	PULSE LENGTH (MS)	PERCENT RESPOND-ING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	NUMBER OF FISH
100	140.3	200	0	NO RESPONSE	.	130	J	30JAN89	17:10	DAY	3	2	100
100	146.3	200	0	NO RESPONSE	.	132	J	30JAN89	17:12	DAY	3	2	100
100	134.3	200	0	NO RESPONSE	.	1123	J	31JAN89	9:43	DAY	3	5	100
100	134.3	200	0	NO RESPONSE	.	1125	J	31JAN89	9:45	DAY	3	5	100
150	134.3	200	0	NO RESPONSE	.	1128	J	31JAN89	9:48	DAY	3	5	100
150	140.3	200	0	NO RESPONSE	.	1130	J	31JAN89	9:50	DAY	3	5	100
150	140.3	200	0	NO RESPONSE	.	1133	J	31JAN89	9:53	DAY	3	5	100
150	140.3	200	0	NO RESPONSE	.	1135	J	31JAN89	9:55	DAY	3	5	100
500	144.3	200	0	NO RESPONSE	.	1158	J	31JAN89	10:18	DAY	3	5	100
1000	145.3	200	0	NO RESPONSE	.	1165	J	31JAN89	10:25	DAY	3	5	100
2000	139.0	200	0	NO RESPONSE	.	1188	J	31JAN89	10:48	DAY	3	5	100

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

3.4.3 Atlantic Tomcod - Single Tones

Atlantic tomcod were not reactive to single tones during the day, and they were not exposed to single tones at night. No active avoidance responses were elicited at single tone frequencies ranging from 150-758 Hz and at amplitudes ranging from 128.8-138.8 dB//μPa/Hz at 1 m (Table 3-6). Relative light level and water temperature were constant during the testing and their relationship to the responses of Atlantic tomcod cannot be determined.

3.5 BROADBAND SOUND

3.5.1 White Perch - Broadband Sound

White perch did not react strongly to broadband sound between 100-500 Hz and 1300-3300 Hz during the day. Amplitudes for these tests ranged from 110.6 to 160.0 dB//μPa/Hz at 1 m. During day testing, only 5 out of 13 tests (38%) resulted in active avoidance reactions (Table 3-7). These active avoidance reactions occurred at frequency ranges of 100-500, and 1300-3300, and amplitudes of 142.1, 143.8, and 146.0 dB//μPa/Hz at 1 m. During night testing, white perch were exposed to recorded background noise from Indian Point Station between 100-800 Hz, and one test of broadband sound between 1300-3300 Hz (Table 3-7). Weak active avoidance responses were elicited in 2 of the 3 Indian Point Station background noise tests when amplitudes were 110.6 and 135.8 dB//μPa/Hz at 1 m.

Most of the testing with broadband sound occurred on groups of white perch that had been previously subjected to other sounds on the same day (Appendix A). The prior exposure of white perch to other sounds may have diminished the reactions of white perch to broadband sound. Group B of white perch were subjected to broadband sound starting at 10:48 on 22 December 1988. Prior to 1048 hours on 22 December, Group B of white perch exhibited active avoidance responses to

TABLE 3-6. RESPONSE OF AGE-1 ATLANTIC TOMCOD TO SINGLE TONES UNDER DAY CONDITIONS.

FREQUENCY (HZ)	AMPLITUDE dB//μPa/Hz AT 1 M	PULSE LENGTH (MS)	PERCENT RESPOND-ING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	NUMBER OF FISH
150	128.8	1	0	NO RESPONSE	.	32	K	22DEC88	15:02	DAY	6	5	100
500	132.8	1	0	NO RESPONSE	.	36	K	22DEC88	15:06	DAY	6	5	100
500	132.8	3	0	NO RESPONSE	.	41	K	22DEC88	15:11	DAY	6	5	100
758	138.8	1	0	NO RESPONSE	.	45	K	22DEC88	15:15	DAY	6	5	100

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

TABLE 3-7. RESPONSE OF AGE-0 WHITE PERCH TO BROADBAND SOUND UNDER DAY AND NIGHT CONDITIONS.

FREQUENCY (HZ)	AMPLITUDE dB//µPa/Hz AT 1 M	PULSE LENGTH (MS)	PERCENT RESPOND-ING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	METHOD OF NIGHT OBSER-VATIONS[f]	NUMBER OF FISH
100-500	118.1	1	0	NO RESPONSE	.	4	A	21DEC88	16:04	DAY	6.0	4		75
100-500	142.1	100	50	DIAGONAL	1	103	B	22DEC88	10:48	DAY	6.0	5		75
1300-3300	146.0	100	50	SOUNDING	1	104	B	22DEC88	10:49	DAY	6.0	5		75
1300-3300	146.0	100	50	SOUNDING	1	106	B	22DEC88	10:51	DAY	6.0	5		75
100-500	142.1	100	50	SOUNDING	1	108	B	22DEC88	10:53	DAY	6.0	5		75
100-500	142.1	100	0	NO RESPONSE	.	43	D	22DEC88	13:43	DAY	6.0	5		75
100-500	142.1	100	0	NO RESPONSE	.	46	D	22DEC88	13:46	DAY	6.0	5		75
100-500	142.1	100	0	NO RESPONSE	.	46	D	22DEC88	13:46	DAY	6.0	5		75
1300-3300	148.0	100	0	NO RESPONSE	.	54	D	22DEC88	13:54	DAY	6.0	5		75
1300-3300	.	100	0	NO RESPONSE	.	55	D	22DEC88	13:55	DAY	6.0	5		75
1300-3300	160.0	100	0	NO RESPONSE	.	60	D	22DEC88	14:00	DAY	6.0	5		75
100-800	110.6	.	0	NO RESPONSE	.	7348	F	04JAN89	11:07	DAY	5.5	5		200
100-800	110.6	.	75	SOUNDING	1	7742	F	04JAN89	17:41	NIGHT	5.5		2RL 1WL	200
100-800	105.1	.	0	NO RESPONSE	.	144	G	05JAN89	19:24	NIGHT	5.0		BF	200
100-800	135.8	.	100	LATERAL	1	192	G	05JAN89	20:12	NIGHT	5.0		1RL	200
1300-3300	151.7	20	0	NO RESPONSE	.	18965	G	18JAN89	21:05	NIGHT	4.0		BF	200
100-500	143.8	200	50	SOUNDING	1	1387	H	19JAN89	11:07	DAY	4.0	4		300

(CONTINUED)

TABLE 3-7. (CONTINUED)

FOOTNOTES

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

[f] Method of Night Observation RL = Red Light
WL = White Light
BF = Brief Flash

the recorded rock sound and single tones in 9 out of 12 tests (75%)-(Appendix A). Similarly, prior to the start of broadband sound testing at 13:43 on 22 December, Group D of white perch exhibited active avoidance responses to single tones in 5 out of 9 tests between 1320 and 1339 hours. Despite the possibility of diminished responses due to prior exposure to other sounds, broadband sound in the frequencies tested does not appear to have great potential as a deterrence to white perch. On 22 December 1988, Group D of white perch exhibited an active avoidance response to the recorded rock sound in 3 consecutive tests after exhibiting no reaction to 6 consecutive tests of the broadband sound (Appendix A). This test suggested that any diminished response due to previous exposure was overcome by a recorded rock sound of approximately the same amplitude.

The effect of relative light level during the day on the reactions of white perch to broadband sound could not be determined because light levels were similar among all tests (Table 3-7). Light level did appear related to the responses of white perch to broadband sound at night, with constant low level light resulting in increased active avoidance reactions. The 2 night tests conducted with constant low level light resulted in slight active avoidance responses, while no active avoidance responses were observed in the 2 tests conducted while using brief flashes of low level light to observe the fish.

Frequency range of broadband sound was not related to the responses of white perch during the day (Table 3-7). Active avoidance responses occurred at frequency ranges of 100-500 Hz and 1300-3300 Hz. An amplitude threshold for response by white perch to broadband noise may exist between 118.1 and 142.1 dB//μPa/Hz at 1 m. No active avoidance responses were observed at amplitudes below 142.1 dB//μPa/Hz at 1 m. However, other experimental conditions such as pulse length and repetition rate varied greatly among amplitudes tested.

Any possible relationship between amplitude or frequency range on the reactions of white perch to broadband sound at night may have been obscured by variations in light level. Tests of the simulated background noise from Indian Point Station between 100 and 800 Hz elicited weak active avoidance reactions at 135.8 and 110.6 dB//μPa/Hz at 1 m but not at 105.1 dB//μPa/Hz at 1 m (Table 3-7). A threshold for response may exist between 105.1 and 110.6 dB//μPa/Hz at 1, however the test at the 105.1 dB//μPa/Hz at 1 m was observed using brief flashes of light while the other 2 tests were observed with constant low level light. No active avoidance response occurred in the one test conducted at a frequency range of 1300-3000 Hz.

3.5.2 Striped Bass - Broadband Sound

Striped bass did not react at all or only reacted slightly to broadband sound during the 6 tests conducted during the day (Table 3-8). No tests were conducted at night. Replicate exposures of striped bass to pulses of broadband sound between 1300-3300 Hz at an amplitude of 147.5 dB//μPa/Hz at 1 m, and a pulse length of 200 ms resulted in a slight sounding reaction. Striped bass did not exhibit further avoidance responses after these 2 tests, possibly due to acclimation as amplitude increased and all other experimental conditions remained constant.

Striped bass were exposed to 5 tests in the 1300-3300 Hz range and 1 test in the 100-500 Hz range (Table 3-8). Active avoidance responses were observed in 2 tests in the 1300-3300 Hz range and no active avoidance responses were observed in 100-500 Hz range. Striped bass may not be reactive to broadband sound in the 100-500 Hz frequency range, however, with the lack of replication it is difficult to draw conclusions. Active avoidance responses were only observed at amplitudes of 147.5 dB//μPa/Hz at 1 m, and not at greater amplitudes. This leads to the counter-intuitive conclusion that striped bass react only

TABLE 3-8. RESPONSE OF AGE-0 STRIPED BASS TO BROADBAND SOUND UNDER DAY CONDITIONS.

FREQUENCY (HZ)	AMPLITUDE dB//μPa/Hz AT 1 M	PULSE LENGTH (MS)	PERCENT RESPOND-ING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	NUMBER OF FISH
1300-3300	147.5	200	50	SOUNDING	1	1110	J	31JAN89	9:30	DAY	3	5	100
1300-3300	147.5	200	50	SOUNDING	1	1112	J	31JAN89	9:32	DAY	3	5	100
1300-3300	153.5	200	0	NO RESPONSE	.	1114	J	31JAN89	9:34	DAY	3	5	100
1300-3300	159.5	200	0	NO RESPONSE	.	1115	J	31JAN89	9:35	DAY	3	5	100
100-500	147.6	200	0	NO RESPONSE	.	1230	J	31JAN89	11:30	DAY	3	5	100
1300-3300	167.5	200	0	NO RESPONSE	.	1231	J	31JAN89	11:31	DAY	3	5	100

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

to broadband sound of lower amplitudes. From our data a more likely conclusion is that other factors such as acclimation have a greater effect on the active avoidance reactions of striped bass than frequency and amplitude within the ranges tested.

Relative light level and water temperature remained constant throughout the testing so it was not possible to draw conclusions regarding the relationship between these factors and the responses of striped bass to broadband sound.

3.5.3 Atlantic Tomcod - Broadband Sound

Atlantic tomcod actively avoided broadband sound in 1 out of 5 tests (20%) during the day (Table 3-9); no testing was conducted at night. The 1 test in which an active avoidance response was observed was in response to a continuous duration broadband sound between 1300-3300 Hz at an amplitude of 148.0 dB//μPa/Hz at 1 m. Atlantic tomcod may have acclimated to this sound as the next test of the same conditions did not elicit a response. There were not enough data to draw reasonable conclusions regarding the relationship between amplitude and frequency range and the responses of Atlantic tomcod to broadband sound.

Relative light level and water temperature remained constant throughout the testing so it was not possible to draw conclusions regarding the relationship between these factors and the responses of Atlantic tomcod to broadband sound.

TABLE 3-9. RESPONSE OF AGE-1 ATLANTIC TOMCOD TO BROADBAND SOUND UNDER DAY CONDITIONS.

FREQUENCY (HZ)	AMPLITUDE dB//μPa/Hz AT 1 M	PULSE LENGTH (MS)	PERCENT RESPOND-ING	RESPONSE[a]	RESPONSE STRENGTH[b]	HOLDING TIME (MINUTES)[c]	FISH GROUP[d]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[e]	NUMBER OF FISH
1300-3300	148.0	15	0	NO RESPONSE	.	17	K	22DEC88	14:47	DAY	6	5	100
100-500	144.1	15	0	NO RESPONSE	.	19	K	22DEC88	14:49	DAY	6	5	100
1300-3300	142.0	5	0	NO RESPONSE	.	23	K	22DEC88	14:53	DAY	6	5	100
1300-3300	148.0	CONT.[f]	100	SOUNDING	1	25	K	22DEC88	14:55	DAY	6	5	100
1300-3300	148.0	CONT.[f]	0	NO RESPONSE	.	28	K	22DEC88	14:58	DAY	6	5	100

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

[f] CONT. = Continuous

3.6 FM LOG SWEEPS

3.6.1 White Perch - FM Log Sweeps

White perch exhibited active avoidance to FM log sweeps at night in all tests (Table 3-10). White perch were not exposed to FM sweeps during the day. White perch did not appear to acclimate to the FM log sweeps. However, each group of fish was exposed to only 2 tests each which was probably not enough tests to observe acclimation. Frequency range and amplitude did not vary enough to determine the relationship between these variables and the responses of white perch. However, 75% of the white perch reacted moderately during the 2 tests at the higher amplitude of 141.3 dB//μPa/Hz at 1 m and 100% of the fish reacted slightly at the the 2 tests at the lower amplitude of 135.8 dB//μPa/Hz at 1 m.

There was not enough variability in light level and water temperature to determine if these variables were related to the responses of white perch to FM log sweeps.

3.6.2 Striped Bass - FM Log Sweeps

Striped bass were not exposed to FM log sweeps.

3.6.3 Atlantic Tomcod - FM Log Sweeps

Atlantic tomcod were not exposed to FM log sweeps.

TABLE 3-10. RESPONSE OF AGE-0 WHITE PERCH TO FM LOG SWEEPS UNDER NIGHT CONDITIONS.

FREQUENCY (HZ)	AMPLITUDE dB//μPa/Hz AT 1 M	PULSE LENGTH (MS)	PERCENT RESPOND-ING	RESPONSE	RESPONSE STRENGTH	HOLDING TIME (MINUTES)	FISH GROUP	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELA-TIVE DAY LIGHT LEVEL[e]	NUMBER OF FISH
200-800	141.3	100	75	DIAGONAL	2	7818	F	04JAN89	18:57	NIGHT	5.5	4	200
100-800	141.3	.	75	DIAGONAL	2	7824	F	04JAN89	19:03	NIGHT	5.5	4	200
800-100	135.8	100	100	SOUNDING	1	122	G	05JAN89	19:02	NIGHT	5.0	4	200
100-800	135.8	100	100	SOUNDING	1	126	G	05JAN89	19:06	NIGHT	5.0	4	200

[a] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[b] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[c] Holding time = time in minutes between introduction to test cage and time of testing

[d] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[e] Relative Day Light Level 1 = low light
Level 5 = bright light

3.7 INCIDENTAL SOUNDS

During the course of the study it was observed that the fish displayed avoidance responses to various incidental sounds. These incidental sounds included noise generated by personnel walking on the catwalk from shore to the quarry building, noise generated by the door of the shelter in the quarry building scraping on the floor as it opened and closed, and the live sound generated by a real rock entering the water. The live sound generated by a real rock entering the water was recorded and the reactions of fish to this sound are discussed in Section 3.2. Incidental sounds resulted in few active avoidance responses by white perch, striped bass and Atlantic tomcod, with the exception of sounds generated by the door and sound generated by a real rock entering the water. Fish occasionally reacted to the door and rock incidental sounds when they were unreactive to sounds generated by the EFSS. Tests in which fish reacted to incidental sounds after they were unreactive to sounds generated by the EFSS are discussed in this section in their chronological context.

3.7.1 White Perch - Incidental Sounds

White perch exhibited active avoidance reactions to a rock thrown in the water in 6 out of 7 tests (86%) during the day and 18 out of 23 tests (78%) at night. During night testing, active avoidance reactions were obtained in 7 out of 9 tests (78%) when observed under constant low level light and 11 out of 14 tests (79%) when observed with brief flashes. White perch were reactive to the sounds of a rock entering the water 6 times following a series of tests in which they were not reactive to sounds produced by the EFSS, such as the recorded rock sound, single tones, broadband sound and FM log sweeps (Table 3-11; Appendix A). Increased reactivity was demonstrated by either an increase in the strength of an active avoidance response, or an increase in the percentage of fish responding to the sound. On 22 December 1988 at 1631 hours, 100% of the white perch in the test cage exhibited a

Table 3-11. ACTIVE AVOIDANCE RESPONSES OF WHITE PERCH TO THE SOUND OF A ROCK ENTERING THE WATER FOLLOWING SERIES OF TESTS WHEN WHITE PERCH WERE NOT RESPONSIVE TO SOUNDS GENERATED BY THE EFSS.

DATE	TIME	PERCENT RESPONDING	RESPONSE	RESPONSE STRENGTH	NUMBER OF PRECEDING TESTS WITH LESSER RESPONSE
22 December 1988	16:31	100	Diagonal	3	9
22 December 1988	16:43	75	Diagonal	3	3
3 January 1989	16:10	100	Diagonal	3	9
4 January 1989	14:49	100	Lateral	2	18
18 January 1989	19:47	100	Sounding	3	2
18 January	20:00	100	Sounding	3	2

strong diagonal reaction to a rock thrown in the water following a series of 9 tests in which white perch were exposed to the recorded rock sound and the percentage of fish responding and the strength of the active avoidance response was diminished (Appendix A). Similar tests where a rock thrown in the water elicited a stronger response than preceding tests in which sounds were generated by the EFSS occurred on 22 December 1988 at 1643 hours, 3 January 1989 at 1610 hours, 4 January 1989 at 1449 hours, 18 January 1989 at 1947 and 2000 hours (Appendix A).

White perch also exhibited active avoidance to the door sound, although the response was not as strong as to the rock. Active avoidance reactions to the door sound were obtained in all 3 tests during the day and 2 out of 9 tests (22%) at night. During night testing active avoidance reactions were obtained in 2 out of 6 tests (33%) when observed under constant low level light. Only 1 test was observed with brief flashes and an active avoidance reaction did not occur. Four tests were conducted where the EFSS was used to expose white perch to a recorded door sound. One active avoidance reaction occurred at night when observed with constant low level light. When observed with brief flashes, 1 active avoidance reaction occurred in 3 tests.

3.7.2 Striped Bass - Incidental Sounds

Six tests were conducted in which striped bass were exposed to incidental sounds (Appendix B). Striped bass exhibited active avoidance reactions in 3 out of 4 tests during the day in response to a real rock thrown in the water. Striped bass did not exhibit active avoidance responses to the door sound in the 2 tests conducted during the day.

3.7.3 Atlantic Tomcod - Incidental Sounds

Atlantic tomcod were not exposed to incidental sounds.

4.0 DISCUSSION

4.1 EFFECTIVENESS OF ELECTRONICALLY PRODUCED SOUND

The EFSS elicited strong active avoidance responses in young-of-the-year white perch and striped bass. Moderate and weak active avoidance responses were elicited in adult Atlantic tomcod by the EFSS. The sound produced by the EFSS that was the most effective in all species was a recorded rock sound followed in order of effectiveness by FM log sweeps, single tones and broadband sound, although little testing was done with FM log sweeps. The sound produced by an actual rock being thrown in the water was an even more effective deterrence than a recording of the same sound produced by the EFSS because the acoustic equipment used during this study was not capable of measuring, recording, and reproducing the real rock sound over its full frequency spectrum, particularly at frequencies less than 100 Hz. Frequency ranges of the equipment used in this study were:

Component	Frequency Range (Hz)
Receive Hydrophone	50 - 40,000
Signal Analyzer	0 - 40,000
Tape Recorder	20 - 18,000 (estimated)
Transducer	100 - 800

It appears that sound generated by a real rock entering the water produces significant sound components below 50 Hz that were not accurately recorded, analyzed or reproduced by the system used in this study. The significant decrease in amplitude below 76 Hz in the frequency analysis of the sounds of a rock entering the water (Figure 3-2) may be due in part to the decreased sensitivity in system components below 100 Hz. When the real rock hits the surface of the water, there is a sharp compression or displacement of water that is analogous to a DC (non-oscillating) signal. This brief, direct increase in pressure can probably be sensed by the fish but is not detectable or reproducible by the EFSS as an acoustic oscillation. This event occurs in the

microseconds before the first oscillation shown on the left side of Figure 3-1. The greater active avoidance reactions obtained by the sound of a rock entering the water compared to the recorded rock sound is probably due to the poor reproduction of sounds less than 100 Hz.

Among sounds produced by the EFSS, the recorded rock sound was the most effective sound deterrence tested for white perch followed by FM log sweeps, single tones and broadband sound (Table 4-1). The recorded rock sound received extensive testing with white perch and active avoidance reactions were obtained in 79% of the 96 tests during the day and 50% of the 34 tests at night. However, under night conditions white perch exhibited active avoidance reactions in only 44% of the 18 tests when they were observed through brief flashes of light, which was the experimental condition that most closely modelled actual night conditions. Active avoidance reactions were observed in all 4 tests in which white perch were exposed to FM log sweeps. These tests occurred at night under constant low level illumination which may be more similar to day conditions than night. More testing is needed to fully evaluate the deterrence potential of FM log sweeps. White perch exhibited active avoidance reactions to single tones in less than 50% of the 52 tests conducted under both day and night conditions. Only 2 night tests were conducted under brief flashes and no active avoidance reactions occurred in either test. White perch exhibited active avoidance reactions to the broadband sound in less than 50% of the 17 tests conducted under both day and night conditions. No active avoidance reactions were observed during night testing using brief flashes of light.

For striped bass, as with white perch, the recorded rock sound was the most effective deterrence to striped bass produced by the EFSS. However, striped bass did not receive as extensive testing as white perch, particularly at night. Active avoidance reactions were observed in 63% of the 16 day tests and in all 3 night tests (Table 4-1). All night tests were observed with brief flashes of light, the method of observation that was considered to most closely model actual night

TABLE 4-1. PERCENTAGE OF TESTS CONDUCTED WITH SOUND PRODUCED BY THE ELECTRONIC FISH STARTLE SYSTEM IN WHICH AN ACTIVE AVOIDANCE RESPONSE WAS OBSERVED (% OF TESTS) AND NUMBER OF TESTS CONDUCTED (n) ON WHITE PERCH, STRIPED BASS, AND ATLANTIC TOMCOD.

		INTRODUCED SOUND TYPE							
		RECORDED ROCK SOUND		SINGLE TONES		FM LOG SWEEPS		BROADBAND SOUND	
SPECIES	TIME PERIOD	% OF TESTS	n	% OF TESTS	n	% OF TESTS	n	% OF TESTS	n
White Perch	Day	79	96	43	21		0	38	13
	Night	50	34	45	31	100	4	50	4
Striped Bass	Day	63	16	0	11		0	33	6
	Night	100	3		0		0		0
Atlantic Tomcod	Day	100	2	0	4		0	20	5
	Night		0		0		0		0

conditions, and active avoidance reactions were observed in all tests. In contrast to white perch, striped bass did not react at all to single tones, and exhibited active avoidance responses to broad band sound in 33% of the day tests.

Atlantic tomcod did not react strongly to any of the sounds tested (Table 4-1). Although active avoidance reactions were elicited in both tests with the recorded rock sound, and one test with broad band sound, the reactions were weak.

The greatest success in using sound as a fish deterrence has occurred with members of the herring family, Clupeidae (Haymes and Patrick 1986). Clupeids have anterior vesicles of their swimbladders that are in close articulation with the inner ear, which probably function to improve hearing (Alexander 1974). None of the fishes tested in this study posses any connections between the swimbladder and the ear and probably are less sensitive to sound than members of the clupeid family. If white perch, striped bass and Atlantic tomcod are less sensitive to sound, it may be necessary to produce sounds of higher amplitude to elicit a strong, consistent avoidance response in field applications.

4.2 ACCLIMATION

White perch appeared to acclimate to the recorded rock sound and single tones. Acclimation to the recorded rock sound occurred after white perch had been exposed to the sound every 1.5 minutes on average for approximately 30 minutes. White perch acclimated to a single tone of 150 Hz after being exposed to the sound every 2.0 minutes on average for 19 minutes. Striped bass also appeared to acclimate to the recorded rock sound after being exposed to the sound every 1.7 minutes on average for 12 minutes. The acclimation response appeared to be transitory as fish that were acclimated to one sound would respond to a different

sound, or would be responsive to the same sound the next day. Acclimation to recorded sounds may be an artifact of observing the fish in a test cage which prevented movement by the fish out of the ensonified area. Fish would be free to move beyond the ensonified area in an unconstrained environment and the acclimation response might be reduced or nonexistent because fish would not be constantly exposed to sound. Acclimation to sound may not be an important factor in a field application of the EFSS at Indian Point Station. Most high impingement episodes of white perch at Indian Point Station occur on ebb tides during the winter (NYPA et al. in prep.). Hydroacoustic data indicates that during winter ebb tides, white perch are moving passively with the current (Ross et al. 1987). Maximum and average ebb tide currents at mid-depth 30 m in front of the Indian Point Unit 3 intake structure are 25.6 and 20.1 m/minute respectively (Parkinson and Goulet 1976). The intake structures for Indian Point Units 2 and 3 each are 40 m long and white perch would only be vulnerable to impingement for approximately 1.6 minutes during maximum ebb tide and 2.0 minutes during average ebb tide at each unit. During this study, acclimation to introduced sound occurred only after exposure for approximately 30 minutes which is much greater than the approximate 2.0 minute period of white perch vulnerability to impingement during winter ebb tides.

4.3 RELATIONSHIP OF AVOIDANCE RESPONSE TO WATER TEMPERATURE AND LIGHT

Behavior of white perch and striped bass was significantly different between night and day. Control observations in the absence of recorded sound indicated that white perch and striped bass were much more active during the day than at night. This difference in behavior was reflected in the reactions of the fish to recorded sounds. During the day white perch and striped bass were more reactive to recorded sound (Table 4-1). Responses were generally diminished at night when the behavior of white perch and striped bass shifted from an active day behavior to a more inactive night behavior.

Light level used to observe the results of night testing was strongly related to the responses of fish to recorded sound, but did not appear related to the reactions of the fish to recorded sound during the day. However, most day tests in low light levels occurred late in the afternoon and any possible reduction in active avoidance responses may have been confounded by acclimation of the test group. During night testing fish were more reactive during tests made under constant low level light compared to tests observed with brief flashes of light. Nocturnal behavior and reactions to sound by white perch and striped bass observed with brief flashes probably reflected actual nocturnal reactions better than any other method of observation used. Future testing at night should use a method of observation such as hydroacoustics or low light level photography that does not increase perceived light above ambient levels.

The shift in behavior by white perch and striped bass between day and night was not anticipated. The computerized literature search failed to turn up any references to this shift in behavior. Sheridan and Power (1969) reported that the diel depth distribution of white perch was influenced by light level. During the night, catch per unit effort (CPUE) in fish traps was greatest at depths of 2.4 m. At night the depth distribution of white perch was modified when the fish traps were illuminated from the surface with a 100 watt light bulb. Under these conditions the greatest CPUE in the fish traps occurred at 6.1 m and decreased at shallower depths. Day catches of white perch were too small to provide meaningful data regarding depth distribution. Leach (1962) reported that white perch in the Bay of Quinte, Ontario, from May through September had a diel pattern to feeding activity with peak feeding activity occurring at midnight and noon.

The behavior of white perch can be influenced by light level (Leach 1962; Sheridan and Power 1969). The increased activity levels of white perch observed during the day in the quarry may have resulted from increased light level. During this study, light level in the Hudson

River measured during the day at 3 m at Indian Point Station was near darkness (less than 0.1 watts/cm^2/ nm). Ross *et al.* (1987) reported that during the winter, white perch in the vicinity of Indian Point Station are found at depths of 6-10 m. Due to low light levels at depths greater than 3 m, white perch activity level during the day in the Hudson River may be similar to that observed in the quarry at night.

Water temperature ranged from 3.0-6.0°C during the study. Although active avoidance responses occurred at all temperatures, there was not enough variation in water temperature to determine if water temperature and the responses of fish to sound were related.

4.4 RELATIONSHIP OF AVOIDANCE RESPONSE TO SOUND AMPLITUDE

It was difficult to determine if a threshold in amplitude exists for an active avoidance response in white perch, striped bass and Atlantic tomcod exists. Not enough tests were conducted under controlled conditions with striped bass and Atlantic tomcod to determine if an amplitude threshold exists. Furthermore, the testing of white perch for an amplitude threshold was confounded by uncontrolled variation in other factors such as light level. The best data to evaluate an amplitude threshold are a series of tests with the recorded rock sound in which amplitude of the recorded rock sound was progressively increased. These data indicated that the response was positive in relation to increasing amplitude and an amplitude threshold for active avoidance reactions of white perch to the recorded rock sound was between 138.8 and 147.8 dB//μPa/Hz at 1 m. The limited data available indicated that an amplitude threshold for an active avoidance response in white perch to single tones occurred at less than 128.8 and less than 138.8 dB//uPa/Hz at 1 m during day and night testing respectively. A similar amplitude threshold for an active avoidance response to broad band sound occurred at less than 142.1 and less than 110.6 dB//uPa/Hz at 1 m during day and night testing respectively.

The lack of a clear cut amplitude threshold for active avoidance responses in test fish is not explained by variations in SNR. SNR expresses the relative relationship between a generated signal and any background "noise" that may be present in a system. For our purposes, the amplitude of the sounds generated by the EFSS can be considered the signal, and the amplitude of the background noise present in the quarry can be considered the "noise". If the amplitude of the background noise is high relative to the signal generated by the EFSS, than the SNR will be low and the background noise may mask the signal generated by the EFSS. During testing in the quarry background noise in the quarry averaged 67.7 dB//μPa/Hz with little variation. The primary source of the background noise was wind and waves, but wave height was generally less than 0.3 m during testing. For comparison, open ocean ambient noise levels generally increase only 10 dB//μPa/Hz from flat calm conditions to wave heights of 1.2 to 2.0 m. Therefore, the variation in wave height observed in the quarry would result in an increase in background noise of much less than 10 dB//μPa/Hz which is negligible in the context of the tests conducted.

4.5 RELATIONSHIP OF AVOIDANCE RESPONSE TO SOUND FREQUENCY

It was clear that frequencies below 500 Hz have the greatest potential as a fish deterrence for YOY white perch and YOY striped bass. However, due to the presence of confounding variables it was difficult to determine if active avoidance response was dependent upon a single frequency, or a narrow range of frequencies. The recorded rock sound was the most effective deterrence test produced by the EFSS and most of the acoustic energy in this complex sound was below 500 Hz. White perch were most responsive to single tones below 220 Hz, and to broad band sound between 100-500 Hz.

The mechanical fishpulser developed by Ontario Hydro was found to be an effective deterrence for clupeids at the Pickering Nuclear Generating Station on Lake Ontario (Haymes and Patrick 1986). Although

not as reliable or as flexible as the system used in this study, it produced sound of a greater amplitude at frequencies less than 100 Hz. Additional testing of sound as a fish deterrence should include system components capable of recording and reproducing sounds below 100 Hz at amplitudes greater than 110.6 dB//μPa/Hz at 1 m, the lower threshold for eliciting an active avoidance response by broad band sound. The amplitude needed to elicit active avoidance responses from fish in front of a power plant is higher than that required in the Verplanck Quarry due to the higher background noise level at a power plant. The amplitude required can be estimated from data collected during this study and background noise levels at Indian Point Nuclear Generating Station (Appendix D). The estimated amplitude required at Indian Point to elicit an active avoidance response is 208.9 dB//μPa.

5.0 CONCLUSIONS

1.0 The EFSS elicited active avoidance responses in 142 out of 239 tests (62%) with YOY white perch and striped bass.

2.0 Based on the percentage of tests in which active avoidance responses were observed, the sound produced by the EFSS that was the most effective among the three fish species tested was the recorded rock sound, followed in order of effectiveness by FM log sweeps, single tones and broad band sound, although little testing was conducted with FM log sweeps.

3.0 White perch and striped bass appeared to acclimate to the recorded rock sound in approximately 30 minutes, although this acclimation may be an artifact of confining the fish to a test cage, and did not appear to be a long lived effect.

4.0 White perch and striped bass were more active during the day and exhibited more active avoidance responses to sounds produced by the EFSS during the day. Within day testing, it was not possible to determine if light level affected the strength of active avoidance responses due to the acclimation response. During night testing the level of artificial light used for observation appeared related to the strength of active avoidance responses. White perch and striped bass were more reactive at night when observed under constant low level light then when observed with brief flashes of light. Future testing at night should use a method of observation such as hydroacoustics or low light level photography that does not increase light above ambient levels.

5.0 The range of water temperatures encountered during the study (3.0-6.0°C) did not vary enough to determine the realtionship between water temperature and the response of fish to sound produced by the EFSS.

6.0 It was not possible to determine if the active avoidance response was dependent on a particular frequency or range of frequencies due to confounding variables, but sounds at frequencies less than 500 Hz were most effective. In particular, sound at frequencies less than 100 Hz produced by a real rock entering the water had the greatest deterrence effect on fish tested. Sounds at frequencies less than 100 Hz could not be efficiently reproduced by the EFSS, which may account for the lesser deterrence effect of the recorded rock sound compared with the actual rock sound.

7.0 The active avoidance response in the recorded rock sound appeared to be a positive function of of sound amplitude. Recorded rock sound at amplitudes greater than 138.8 dB//μPa/Hz at 1 m were most effective.

8.0 Further testing should focus on sounds less than 500 Hz at amplitudes greater than 110 dB//μPa/Hz at 1 m.

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APPENDIX A

APPENDIX A. RESPONSE OF AGE 0 WHITE PERCH TO INTRODUCED SOUNDS UNDER DAY AND NIGHT CONDITIONS.

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAYLIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
BAND	901	100-500	118.1	1	0	NO RESPONSE	.	4	A	21DEC88	16:04	DAY	6	4		75
RECORDED	902	.	133.3	.	75	DIAGONAL	2	9	A	21DEC88	16:09	DAY	6	4		75
RECORDED	903	.	133.3	.	75	DIAGONAL	2	10	A	21DEC88	16:10	DAY	6	4		75
RECORDED	904	.	133.3	.	75	DIAGONAL	2	11	A	21DEC88	16:11	DAY	6	4		75
RECORDED	905	.	133.3	.	75	DIAGONAL	1	13	A	21DEC88	16:13	DAY	6	4		75
RECORDED	906	.	133.3	.	50	DIAGONAL	2	15	A	21DEC88	16:15	DAY	6	3		75
RECORDED	907	.	133.3	.	50	DIAGONAL	1	16	A	21DEC88	16:16	DAY	6	3		75
RECORDED	908	.	133.3	.	25	SOUNDING	1	19	A	21DEC88	16:19	DAY	6	3		75
RECORDED	909	.	133.3	.	50	SOUNDING	1	26	A	21DEC88	16:26	DAY	6	2		75
RECORDED	910	.	133.3	.	50	DIAGONAL	1	29	A	21DEC88	16:29	DAY	6	2		75
RECORDED	911	.	133.3	.	0	NO RESPONSE	.	32	A	21DEC88	16:32	DAY	6	2		75
RECORDED	912	.	133.3	.	75	LATERAL	1	39	A	21DEC88	16:39	DAY	6	2		75
DOOR	913	.	.	.	75	DIAGONAL	3	927	A	22DEC88	7:27	DAY	6	5		75
RECORDED	914	.	133.3	.	100	DIAGONAL	2	940	A	22DEC88	7:40	DAY	6	5		75
RECORDED	915	.	133.3	.	100	STARTLE	.	943	A	22DEC88	7:43	DAY	6	5		75
RECORDED	916	.	138.3	.	75	LATERAL	3	944	A	22DEC88	7:44	DAY	6	5		75
REAL	917	.	.	.	100	STARTLE	.	945	A	22DEC88	7:45	DAY	6	5		75
RECORDED	918	.	138.3	.	100	DIAGONAL	2	948	A	22DEC88	7:48	DAY	6	5		75
RECORDED	919	.	138.3	.	100	STARTLE	.	950	A	22DEC88	7:50	DAY	6	5		75
TONE	920	112	114.8	20	0	NO RESPONSE	.	958	A	22DEC88	7:58	DAY	6	5		75
TONE	921	112	114.8	20	0	NO RESPONSE	.	961	A	22DEC88	8:01	DAY	6	5		75
RECORDED	1001	.	133.3	.	75	DIAGONAL	2	11	B	22DEC88	9:16	DAY	6	5		75
RECORDED	1002	.	133.3	.	100	DIAGONAL	2	14	B	22DEC88	9:19	DAY	6	5		75
RECORDED	1003	.	133.3	.	75	DIAGONAL	1	24	B	22DEC88	9:29	DAY	6	5		75
RECORDED	1004	.	133.3	.	75	DIAGONAL	1	42	B	22DEC88	9:47	DAY	6	5		75
RECORDED	1005	.	138.3	.	75	DIAGONAL	1	47	B	22DEC88	9:52	DAY	6	5		75
REAL	1006	.	.	.	75	DIAGONAL	3	49	B	22DEC88	9:54	DAY	6	5		75

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
RECORDED	1007	.	142.3	.	50	LATERAL	2	58	B	22DEC88	10:03	DAY	6	5		75
RECORDED	1008	.	142.3	.	50	LATERAL	1	66	B	22DEC88	10:11	DAY	6	5		75
TONE	1009	220	142.8	.	0	NO RESPONSE	.	77	B	22DEC88	10:22	DAY	6	5		75
TONE	1010	220	142.8	100	75	SOUNDING	1	79	B	22DEC88	10:24	DAY	6	5		75
TONE	1011	220	142.8	.	0	NO RESPONSE	.	85	B	22DEC88	10:30	DAY	6	5		75
TONE	1012	150	138.8	.	0	NO RESPONSE	.	89	B	22DEC88	10:34	DAY	6	5		75
TONE	1013	150	134.8	100	0	NO RESPONSE	.	93	B	22DEC88	10:38	DAY	6	5		75
TONE	1014	250	141.8	100	0	NO RESPONSE	.	95	B	22DEC88	10:40	DAY	6	5		75
BAND	1015	100-500	142.1	100	50	DIAGONAL	1	103	B	22DEC88	10:48	DAY	6	5		75
BAND	1016	1300-3300	146.0	100	50	SOUNDING	1	104	B	22DEC88	10:49	DAY	6	5		75
BAND	1017	1300-3300	146.0	100	50	SOUNDING	1	106	B	22DEC88	10:51	DAY	6	5		75
BAND	1018	100-500	142.1	100	50	SOUNDING	1	108	B	22DEC88	10:53	DAY	6	5		75
RECORDED	1019	.	142.3	.	75	DIAGONAL	1	113	B	22DEC88	10:58	DAY	6	5		75
REAL	1020	.	.	.	0	NO RESPONSE	.	114	B	22DEC88	10:59	DAY	6	5		75
RECORDED	1101	.	133.3	.	75	DIAGONAL	3	15	C	22DEC88	12:15	DAY	6	5		75
RECORDED	1102	.	133.3	.	75	DIAGONAL	2	17	C	22DEC88	12:17	DAY	6	5		75
RECORDED	1103	.	133.3	.	50	DIAGONAL	2	21	C	22DEC88	12:21	DAY	6	5		75
RECORDED	1104	.	133.3	.	50	DIAGONAL	2	22	C	22DEC88	12:22	DAY	6	5		75
RECORDED	1105	.	133.3	.	50	DIAGONAL	2	23	C	22DEC88	12:23	DAY	6	5		75
RECORDED	1106	.	133.3	.	50	DIAGONAL	2	24	C	22DEC88	12:24	DAY	6	5		75
RECORDED	1107	.	133.3	.	50	DIAGONAL	2	25	C	22DEC88	12:25	DAY	6	5		75
RECORDED	1108	.	133.3	.	0	NO RESPONSE	.	26	C	22DEC88	12:26	DAY	6	5		75
RECORDED	1109	.	133.3	.	25	DIAGONAL	1	26	C	22DEC88	12:26	DAY	6	5		75
RECORDED	1110	.	133.3	.	25	DIAGONAL	1	27	C	22DEC88	12:27	DAY	6	5		75
RECORDED	1111	.	133.3	.	50	DIAGONAL	2	28	C	22DEC88	12:28	DAY	6.0	5		75
RECORDED	1112	.	133.3	.	25	DIAGONAL	1	29	C	22DEC88	12:29	DAY	6.0	5		75
RECORDED	1113	.	133.3	.	0	NO RESPONSE	.	34	C	22DEC88	12:34	DAY	6.0	5		75

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
RECORDED	1114	.	133.3	.	50	DIAGONAL	2	38	C	22DEC88	12:38	DAY	6.0	5		75
RECORDED	1115	.	133.3	.	25	DIAGONAL	1	40	C	22DEC88	12:40	DAY	6.0	5		75
RECORDED	1116	.	133.3	.	25	SOUNDING	1	41	C	22DEC88	12:41	DAY	6.0	5		75
RECORDED	1117	.	133.3	.	50	DIAGONAL	2	42	C	22DEC88	12:42	DAY	6.0	5		75
RECORDED	1118	.	133.3	.	25	SOUNDING	1	44	C	22DEC88	12:44	DAY	6.0	5		75
RECORDED	1119	.	133.3	.	0	NO RESPONSE	.	45	C	22DEC88	12:45	DAY	6.0	5		75
RECORDED	1120	.	133.3	.	0	NO RESPONSE	.	46	C	22DEC88	12:46	DAY	6.0	5		75
TONE	1121	150	128.8	60	25	SOUNDING	1	20	D	22DEC88	13:20	DAY	6.0	5		75
TONE	1122	150	128.8	60	25	SOUNDING	1	21	D	22DEC88	13:21	DAY	6.0	5		75
TONE	1123	150	128.8	60	50	SOUNDING	1	23	D	22DEC88	13:23	DAY	6.0	5		75
TONE	1124	150	128.8	60	25	SOUNDING	1	26	D	22DEC88	13:26	DAY	6.0	5		75
TONE	1125	150	128.8	100	50	SOUNDING	1	28	D	22DEC88	13:28	DAY	6.0	5		75
TONE	1126	150	128.8	100	0	NO RESPONSE	.	30	D	22DEC88	13:30	DAY	6.0	5		75
TONE	1127	150	122.8	100	0	NO RESPONSE	.	33	D	22DEC88	13:33	DAY	6.0	5		75
TONE	1128	150	122.8	100	0	NO RESPONSE	.	34	D	22DEC88	13:34	DAY	6.0	5		75
TONE	1129	150	128.8	1	0	NO RESPONSE	.	39	D	22DEC88	13:39	DAY	6.0	5		75
BAND	1130	100-500	142.1	100	0	NO RESPONSE	.	43	D	22DEC88	13:43	DAY	6.0	5		75
BAND	1131	100-500	142.1	100	0	NO RESPONSE	.	46	D	22DEC88	13:46	DAY	6.0	5		75
BAND	1132	100-500	142.1	100	0	NO RESPONSE	.	46	D	22DEC88	13:46	DAY	6.0	5		75
BAND	1133	1300-3300	148.0	100	0	NO RESPONSE	.	54	D	22DEC88	13:54	DAY	6.0	5		75
BAND	1134	1300-3300	.	100	0	NO RESPONSE	.	55	D	22DEC88	13:55	DAY	6.0	5		75
BAND	1135	1300-3300	160.0	100	0	NO RESPONSE	.	60	D	22DEC88	14:00	DAY	6.0	5		75
RECORDED	1136	.	133.3	.	25	DIAGONAL	1	63	D	22DEC88	14:03	DAY	6.0	5		75
RECORDED	1137	.	133.3	.	25	DIAGONAL	1	65	D	22DEC88	14:05	DAY	6.0	5		75
RECORDED	1138	.	133.3	.	25	LATERAL	1	66	D	22DEC88	14:06	DAY	6.0	5		75
RECORDED	1210	.	133.3	.	0	NO RESPONSE	.	18	E	22DEC88	15:48	DAY	6.0	4		200
RECORDED	1211	.	138.3	.	0	NO RESPONSE	.	20	E	22DEC88	15:50	DAY	6.0	4		200

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
RECORDED	1212	.	138.3	.	0	NO RESPONSE	.	22	E	22DEC88	15:52	DAY	6.0	3		200
RECORDED	1213	.	138.3	.	50	DIAGONAL	1	30	E	22DEC88	16:00	DAY	6.0	3		200
RECORDED	1214	.	142.3	.	100	DIAGONAL	3	34	E	22DEC88	16:04	DAY	6.0	3		200
RECORDED	1215	.	142.3	.	75	DIAGONAL	3	36	E	22DEC88	16:06	DAY	6.0	3		200
RECORDED	1216	.	142.3	.	75	DIAGONAL	2	40	E	22DEC88	16:10	DAY	6.0	3		200
RECORDED	1217	.	142.3	.	100	DIAGONAL	3	43	E	22DEC88	16:13	DAY	6.0	3		200
RECORDED	1218	.	142.3	.	75	DIAGONAL	3	45	E	22DEC88	16:15	DAY	6.0	3		200
RECORDED	1219	.	142.3	.	50	DIAGONAL	2	49	E	22DEC88	16:19	DAY	6.0	3		200
RECORDED	1220	.	142.3	.	25	DIAGONAL	1	52	E	22DEC88	16:22	DAY	6.0	3		200
RECORDED	1221	.	142.3	.	25	DIAGONAL	1	60	E	22DEC88	16:30	DAY	6.0	3		200
REAL	1222	.	.	.	100	DIAGONAL	3	61	E	22DEC88	16:31	DAY	6.0	3		200
RECORDED	1223	.	142.3	.	0	NO RESPONSE	.	64	E	22DEC88	16:34	DAY	6.0	3		200
RECORDED	1224	.	142.3	.	75	DIAGONAL	2	68	E	22DEC88	16:38	DAY	6.0	2		200
RECORDED	1225	.	142.3	.	25	DIAGONAL	1	72	E	22DEC88	16:42	DAY	6.0	2		200
REAL	1226	.	.	.	75	DIAGONAL	3	73	E	22DEC88	16:43	DAY	6.0	2		200
RECORDED	1301	.	138.8	.	0	NO RESPONSE	.	6171	F	03JAN89	15:30	DAY	5.5	5		200
RECORDED	1302	.	138.8	.	0	NO RESPONSE	.	6172	F	03JAN89	15:31	DAY	5.5	5		200
RECORDED	1303	.	143.8	.	75	DIAGONAL	2	6173	F	03JAN89	15:32	DAY	5.5	5		200
RECORDED	1304	.	143.8	.	50	SOUNDING	1	6177	F	03JAN89	15:36	DAY	5.5	5		200
RECORDED	1305	.	143.8	.	0	NO RESPONSE	.	6178	F	03JAN89	15:37	DAY	5.5	5		200
RECORDED	1306	.	143.8	.	75	SOUNDING	1	6181	F	03JAN89	15:40	DAY	5.5	5		200
RECORDED	1307	.	147.8	.	75	SOUNDING	1	6188	F	03JAN89	15:47	DAY	5.5	5		200
RECORDED	1308	.	147.8	.	75	DIAGONAL	2	6191	F	03JAN89	15:50	DAY	5.5	5		200
RECORDED	1309	.	147.8	.	0	NO RESPONSE	.	6194	F	03JAN89	15:53	DAY	5.5	5		200
RECORDED	1310	.	147.8	.	0	NO RESPONSE	.	6198	F	03JAN89	15:57	DAY	5.5	5		200
RECORDED	1311	.	147.8	.	75	SOUNDING	1	6207	F	03JAN89	16:06	DAY	5.5	5		200
REAL	1312	.	.	.	100	DIAGONAL	3	6211	F	03JAN89	16:10	DAY	5.5	5		200

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
RECORDED	1313	.	147.8	.	0	NO RESPONSE	.	6212	F	03JAN89	16:11	DAY	5.5	5		200
DOOR	1401	.	.	.	100	SOUNDING	2	7229	F	04JAN89	9:08	DAY	5.5	5		200
DOOR	1402	.	.	.	75	SOUNDING	1	7231	F	04JAN89	9:10	DAY	5.5	5		200
RECORDED	1403	.	138.8	.	75	SOUNDING	1	7243	F	04JAN89	9:22	DAY	5.5	5		200
RECORDED	1404	.	138.8	.	75	SOUNDING	1	7245	F	04JAN89	9:24	DAY	5.5	5		200
RECORDED	1405	.	143.8	.	75	LATERAL	1	7263	F	04JAN89	9:42	DAY	5.5	5		200
RECORDED	1406	.	143.8	.	75	LATERAL	2	7278	F	04JAN89	9:57	DAY	5.5	5		200
DOOR	1407	100-800	.	.	75	SOUNDING	1	7313	F	04JAN89	10:32	DAY	5.5	5		200
DOOR	1408	100-800	.	.	0	NO RESPONSE	.	7318	F	04JAN89	10:37	DAY	5.5	5		200
DOOR	1409	100-800	.	.	0	NO RESPONSE	.	7319	F	04JAN89	10:38	DAY	5.5	5		200
DOOR	1410	100-800	110.6	.	100	DIAGONAL	2	7329	F	04JAN89	10:48	DAY	5.5	5		200
RECORDED	1501	.	138.8	.	0	NO RESPONSE	.	7341	F	04JAN89	11:00	DAY	5.5	5		200
RECORDED	1502	.	143.8	.	0	NO RESPONSE	.	7342	F	04JAN89	11:01	DAY	5.5	5		200
RECORDED	1503	.	147.8	.	50	DIAGONAL	1	7344	F	04JAN89	11:03	DAY	5.5	5		200
DOOR	1504	100-800	110.6	.	0	NO RESPONSE	.	7346	F	04JAN89	11:05	DAY	5.5	5		200
BAND	1505	100-800	110.6	.	0	NO RESPONSE	.	7348	F	04JAN89	11:07	DAY	5.5	5		200
RECORDED	1506	.	147.8	.	0	NO RESPONSE	.	7353	F	04JAN89	11:12	DAY	5.5	5		200
DOOR	1507	100-800	100.6	.	0	NO RESPONSE	.	7356	F	04JAN89	11:15	DAY	5.5	5		200
DOOR	1508	100-800	100.6	.	0	NO RESPONSE	.	7358	F	04JAN89	11:17	DAY	5.5	5		200
RECORDED	1509	.	147.8	.	0	NO RESPONSE	.	7367	F	04JAN89	11:26	DAY	5.5	5		200
RECORDED	1510	.	147.8	.	100	SOUNDING	1	7376	F	04JAN89	11:35	DAY	5.5	5		200
RECORDED	1511	.	147.8	.	0	NO RESPONSE	.	7378	F	04JAN89	11:37	DAY	5.5	5		200
DOOR	1512	100-800	89.6	.	0	NO RESPONSE	.	7381	F	04JAN89	11:40	DAY	5.5	5		200
RECORDED	1513	.	147.8	.	75	SOUNDING	1	7516	F	04JAN89	13:55	DAY	5.5	5		200
RECORDED	1514	.	147.8	.	0	NO RESPONSE	.	7518	F	04JAN89	13:57	DAY	5.5	5		200
DOOR	1515	100-800	110.6	.	75	SOUNDING	1	7561	F	04JAN89	14:40	DAY	5.5	5		200
DOOR	1516	100-800	116.6	.	75	SOUNDING	1	7563	F	04JAN89	14:42	DAY	5.5	5		200

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
DOOR	1517	100-800	116.6	.	75	SOUNDING	1	7567	F	04JAN89	14:46	DAY	5.5	5		200
REAL	1518	.	.	.	100	LATERAL	2	7570	F	04JAN89	14:49	DAY	5.5	5		200
DOOR	1601	.	.	.	100	DIAGONAL	1	7699	F	04JAN89	16:58	NIGHT	5.5		2RL 1WL	200
DOOR	1602	.	.	.	0	NO RESPONSE	.	7708	F	04JAN89	17:07	NIGHT	5.5		2RL 1WL	200
RECORDED	1603	.	147.8	.	0	NO RESPONSE	.	7709	F	04JAN89	17:08	NIGHT	5.5		2RL 1WL	200
RECORDED	1604	.	147.8	.	100	SOUNDING	1	7710	F	04JAN89	17:09	NIGHT	5.5		2RL 1WL	200
RECORDED	1605	.	147.8	.	0	NO RESPONSE	.	7711	F	04JAN89	17:10	NIGHT	5.5		2RL 1WL	200
RECORDED	1606	.	147.8	.	0	NO RESPONSE	.	7712	F	04JAN89	17:11	NIGHT	5.5		2RL 1WL	200
DOOR	1607	.	.	.	0	NO RESPONSE	.	7741	F	04JAN89	17:40	NIGHT	5.5		2RL 1WL	200
BAND	1608	100-800	110.6	.	75	SOUNDING	1	7742	F	04JAN89	17:41	NIGHT	5.5		2RL 1WL	200
DOOR	1609	100-800	110.6	.	75	SOUNDING	2	7772	F	04JAN89	18:11	NIGHT	5.5		2RL 1WL	200
DOOR	1610	100-800	110.6	.	0	NO RESPONSE	.	7774	F	04JAN89	18:13	NIGHT	5.5		2RL 1WL	200
DOOR	1611	100-800	116.6	.	75	DIAGONAL	1	7781	F	04JAN89	18:20	NIGHT	5.5		2RL 2WL	200
DOOR	1612	.	.	.	0	NO RESPONSE	.	7787	F	04JAN89	18:26	NIGHT	5.5		2RL 2WL	200
DOOR	1613	.	.	.	0	NO RESPONSE	.	7800	F	04JAN89	18:39	NIGHT	5.5		2RL	200
REAL	1614	.	.	.	75	DIAGONAL	3	7802	F	04JAN89	18:41	NIGHT	5.5		2RL 1WL	200
DOOR	1615	.	.	.	75	SOUNDING	2	7805	F	04JAN89	18:44	NIGHT	5.5		2RL 1WL	200
RECORDED	1616	.	147.8	.	75	DIAGONAL	2	7813	F	04JAN89	18:52	NIGHT	5.5		2RL	200
FM SWEEP	1617	200-800	141.3	100	75	DIAGONAL	2	7818	F	04JAN89	18:57	NIGHT	5.5		2RL	200
FM SWEEP	1618	100-800	141.3	.	75	DIAGONAL	2	7824	F	04JAN89	19:03	NIGHT	5.5		2RL	200
TONE	1619	100	145.0	100	100	DIAGONAL	3	7825	F	04JAN89	19:04	NIGHT	5.5		2RL	200
TONE	1701	100	140.3	100	100	DIAGONAL	3	7833	F	04JAN89	19:12	NIGHT	5.5		2RL	200
TONE	1702	150	140.3	100	50	SOUNDING	1	7837	F	04JAN89	19:16	NIGHT	5.5		2RL	200
TONE	1703	100	140.3	100	75	DIAGONAL	2	7838	F	04JAN89	19:17	NIGHT	5.5		2RL	200
TONE	1704	50	128.3	100	100	SOUNDING	3	7841	F	04JAN89	19:20	NIGHT	5.5		2RL	200
TONE	1705	50	128.3	100	100	SOUNDING	3	7845	F	04JAN89	19:24	NIGHT	5.5		2RL	200
TONE	1706	50	128.3	100	0	NO RESPONSE	.	7853	F	04JAN89	19:32	NIGHT	5.5		BF	200

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
TONE	1707	100	140.3	100	0	NO RESPONSE	.	7865	F	04JAN89	19:44	NIGHT	5.5		BF	200
TONE	1708	100	140.3	100	0	NO RESPONSE	.	7866	F	04JAN89	19:45	NIGHT	5.5		2RL	200
TONE	1709	100	140.3	100	100	DIAGONAL	3	7871	F	04JAN89	19:50	NIGHT	5.5		2RL	200
REAL	1710	.	.	.	75	SOUNDING	1	7874	F	04JAN89	19:53	NIGHT	5.5		BF	200
REAL	1711	.	.	.	75	DIAGONAL	2	7877	F	04JAN89	19:56	NIGHT	5.5		BF	200
OTHER	1712	.	.	.	100	DIAGONAL	2	7885	F	04JAN89	20:04	NIGHT	5.5		2RL	200
REAL	1713	.	.	.	75	DIAGONAL	1	7892	F	04JAN89	20:11	NIGHT	5.5		BF	200
REAL	1714	.	.	.	0	NO RESPONSE	.	7896	F	04JAN89	20:15	NIGHT	5.5		BF	200
OTHER	1715	.	.	.	0	NO RESPONSE	.	60	G	05JAN89	18:00	NIGHT	5.0		BF	200
RECORDED	1716	.	142.3	.	0	NO RESPONSE	.	70	G	05JAN89	18:10	NIGHT	5.0		BF	200
TONE	1717	100	134.8	100	0	NO RESPONSE	.	80	G	05JAN89	18:20	NIGHT	5.0		BF	200
TONE	1718	50	122.8	100	0	NO RESPONSE	.	82	G	05JAN89	18:22	NIGHT	5.0		BF	200
OTHER	1719	.	.	100	0	NO RESPONSE	.	89	G	05JAN89	18:29	NIGHT	5.0		BF	200
OTHER	1720	.	.	100	0	NO RESPONSE	.	92	G	05JAN89	18:32	NIGHT	5.0		BF	200
DOOR	1721	.	142.3	.	0	NO RESPONSE	.	97	G	05JAN89	18:37	NIGHT	5.0		BF	200
REAL	1722	.	.	.	0	NO REPONSE	.	100	G	05JAN89	18:40	NIGHT	5.0		BF	200
REAL	1723	.	.	.	0	NO RESPONSE	.	102	G	05JAN89	18:42	NIGHT	5.0		BF	200
RECORDED	1724	.	142.3	.	100	SOUNDING	1	107	G	05JAN89	18:47	NIGHT	5.0		2RL	200
RECORDED	1726	.	142.3	.	100	SOUNDING	1	114	G	05JAN89	18:54	NIGHT	5.0		2RL	200
DOOR	1727	.	142.3	.	100	SOUNDING	1	118	G	05JAN89	18:58	NIGHT	5.0		2RL	200
FM SWEEP	1728	800-100	135.8	100	100	SOUNDING	1	122	G	05JAN89	19:02	NIGHT	5.0		2RL	200
FM SWEEP	1729	100-800	135.8	100	100	SOUNDING	1	126	G	05JAN89	19:06	NIGHT	5.0		2RL	200
TONE	1730	100	134.8	100	100	SOUNDING	1	130	G	05JAN89	19:10	NIGHT	5.0		2RL	200
TONE	1731	50	122.8	100	100	SOUNDING	1	134	G	05JAN89	19:14	NIGHT	5.0		2RL	200

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
BAND	1734	100-800	105.1	.	0	NO RESPONSE	.	144	G	05JAN89	19:24	NIGHT	5.0		BF	200
RECORDED	1735	.	142.3	.	100	SOUNDING	1	150	G	05JAN89	19:30	NIGHT	5.0		2RL	200
REAL	1736	.	.	.	100	SOUNDING	1	155	G	05JAN89	19:35	NIGHT	5.0		2RL	200
RECORDED	1737	.	142.3	.	100	LATERAL	2	156	G	05JAN89	19:36	NIGHT	5.0		2RL	200
REAL	1738	.	.	.	0	NO RESPONSE	.	168	G	05JAN89	19:48	NIGHT	5.0		2RL	200
DOOR	1739	.	.	.	0	NO RESPONSE	.	169	G	05JAN89	19:49	NIGHT	5.0		2RL	200
RECORDED	1740	.	142.3	.	0	NO REPONSE	.	170	G	05JAN89	19:50	NIGHT	5.0		2RL 1WL	200
RECORDED	1741	.	142.3	.	100	DIAGONAL	1	172	G	05JAN89	19:52	NIGHT	5.0		2RL 1WL	200
REAL	1742	.	.	.	100	DIAGONAL	2	173	G	05JAN89	19:53	NIGHT	5.0		2RL 1WL	200
RECORDED	1743	.	142.3	.	0	NO RESPONSE	.	176	G	05JAN89	19:56	NIGHT	5.0		2RL 1WL	200
REAL	1744	.	.	.	25	DIAGONAL	1	186	G	05JAN89	20:06	NIGHT	5.0		2RL	200
BAND	1801	100-800	135.8	.	100	LATERAL	1	192	G	05JAN89	20:12	NIGHT	5.0		2RL	200
REAL	1802	.	.	.	100	DIAGONAL	3	206	G	05JAN89	20:26	NIGHT	5.0		2RL	200
REAL	1803	.	.	.	100	DIAGONAL	2	214	G	05JAN89	20:34	NIGHT	5.0		2RL	200
REAL	1804	.	.	.	100	DIAGONAL	1	217	G	05JAN89	20:37	NIGHT	5.0		2RL	200
REAL	1805	.	.	.	0	NO RESPONSE	.	220	G	05JAN89	20:40	NIGHT	5.0		2RL	200
RECORDED	1806	.	142.3	.	75	DIAGONAL	2	225	G	05JAN89	20:45	NIGHT	5.0		2RL	200
RECORDED	1807	.	142.3	.	0	NO RESPONSE	.	226	G	05JAN89	20:46	NIGHT	5.0		2RL	200
TONE	1808	100	134.8	100	100	SOUNDING	1	229	G	05JAN89	20:49	NIGHT	5.0		2RL	200
TONE	1809	100	140.8	100	0	NO RESPONSE	.	230	G	05JAN89	20:50	NIGHT	5.0		2RL	200
TONE	1810	100	140.8	100	0	NO RESPONSE	.	231	G	05JAN89	20:51	NIGHT	5.0		2RL 1WL	200
TONE	1811	100	137.8	100	100	SOUNDING	1	232	G	05JAN89	20:52	NIGHT	5.0		2RL 1WL	200
REAL	1812	.	.	.	0	NO RESPONSE	.	233	G	05JAN89	20:53	NIGHT	5.0		2RL 1WL	200
DOOR	1813	.	.	.	0	NO RESPONSE	.	236	G	05JAN89	20:56	NIGHT	5.0		2RL	200
RECORDED	1814	.	142.3	.	75	LATERAL	1	241	G	05JAN89	21:01	NIGHT	5.0		2RL	200
RECORDED	1815	.	142.3	.	100	SOUNDING	3	1132	G	06JAN89	11:52	DAY	4.5	4		200
RECORDED	1816	.	142.3	.	100	DIAGONAL	3	1134	G	06JAN89	11:54	DAY	4.5	4		200

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//μPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAYLIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
RECORDED	1817	.	142.3	.	100	LATERAL	3	1135	G	06JAN89	11:55	DAY	4.5	4		200
RECORDED	1818	.	146.0	.	0	NO RESPONSE	.	1543	G	06JAN89	18:43	NIGHT	4.5		BF	200
REAL	1819	.	.	.	100	SOUNDING	3	1548	G	06JAN89	18:48	NIGHT	4.5		BF	200
RECORDED	1820	.	146.0	.	75	DIAGONAL	3	1565	G	06JAN89	19:05	NIGHT	4.5		BF	200
RECORDED	1821	.	146.0	.	75	DIAGONAL	1	1586	G	06JAN89	19:26	NIGHT	4.5		BF	200
TONE	1822	100	138.5	100	75	SOUNDING	1	1605	G	06JAN89	19:45	NIGHT	4.5		BF	200
TONE	1823	100	138.5	100	75	SOUNDING	1	1627	G	06JAN89	20:07	NIGHT	4.5		BF	200
DOOR	1826	.	146.0	.	100	SOUNDING	1	1644	G	06JAN89	20:24	NIGHT	4.5		BF	200
DOOR	1827	.	146.0	.	0	NO RESPONSE	.	1653	G	06JAN89	20:33	NIGHT	45.0		BF	200
OTHER	1828	.	.	.	0	NO RESPONSE	.	1660	G	06JAN89	20:40	NIGHT	4.5		BF	200
REAL	1829	.	.	.	100	DIAGONAL	3	1670	G	06JAN89	20:50	NIGHT	4.5		BF	200
REAL	2001	.	.	.	100	SOUNDING	3	18800	G	18JAN89	18:20	NIGHT	4.0		BF	200
REAL	2002	.	.	.	100	SOUNDING	3	18820	G	18JAN89	18:40	NIGHT	4.0		BF	200
RECORDED	2003	.	146.0	.	100	SOUNDING	3	18846	G	18JAN89	19:06	NIGHT	4.0		BF	200
RECORDED	2004	.	146.0	.	75	SOUNDING	2	18855	G	18JAN89	19:15	NIGHT	4.0		BF	200
RECORDED	2005	.	146.0	.	75	SOUNDING	1	18863	G	18JAN89	19:23	NIGHT	4.0		BF	200
REAL	2006	.	.	.	100	SOUNDING	3	18887	G	18JAN89	19:47	NIGHT	4.0		BF	200
REAL	2007	.	.	.	100	SOUNDING	3	18900	G	18JAN89	20:00	NIGHT	4.0		BF	200
TONE	2008	150	135.5	200	0	NO RESPONSE	.	18947	G	18JAN89	20:47	NIGHT	4.0		BF	200
TONE	2009	150	135.5	200	0	NO RESPONSE	.	18949	G	18JAN89	20:49	NIGHT	4.0		BF	200
TONE	2010	100	135.5	200	0	NO RESPONSE	.	18951	G	18JAN89	20:51	NIGHT	4.0		BF	200
TONE	2011	100	135.5	200	0	NO RESPONSE	.	18955	G	18JAN89	20:55	NIGHT	4.0		BF	200
TONE	2012	100	139.5	200	25	SOUNDING	1	18958	G	18JAN89	20:58	NIGHT	4.0		BF	200
TONE	2013	100	139.5	20	0	NO RESPONSE	.	18961	G	18JAN89	21:01	NIGHT	4.0		BF	200
BAND	2014	1300-3300	151.7	20	0	NO RESPONSE	.	18965	G	18JAN89	21:05	NIGHT	4.0		BF	200

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
REAL	2015	.	.	.	50	SOUNDING	2	18970	G	18JAN89	21:10	NIGHT	4.0		BF	200
RECORDED	2016	.	146.0	.	100	DIAGONAL	3	19775	G	19JAN89	10:35	DAY	4.0	4		200
RECORDED	2017	.	146.0	.	100	DIAGONAL	3	19778	G	19JAN89	10:38	DAY	4.0	4		200
RECORDED	2018	.	146.0	.	100	LATERAL	3	19780	G	19JAN89	10:40	DAY	4.0	4		200
RECORDED	2019	.	146.0	.	100	DIAGONAL	3	19785	G	19JAN89	10:45	DAY	4.0	4		200
TONE	2020	100	138.5	200	75	DIAGONAL	2	1377	H	19JAN89	10:57	DAY	4.0	4		200
TONE	2021	100	138.5	200	50	DIAGONAL	1	1379	H	19JAN89	10:59	DAY	4.0	4		200
TONE	2022	100	138.5	200	0	NO RESPONSE	.	1380	H	19JAN89	11:00	DAY	4.0	4		200
RECORDED	2023	.	146.0	.	25	SOUNDING	1	1382	H	19JAN89	11:02	DAY	4	4		200
BAND	2024	100-500	143.8	200	50	SOUNDING	1	1387	H	19JAN89	11:07	DAY	4	4		200
TONE	2025	100	138.5	200	50	DIAGONAL	1	1390	H	19JAN89	11:10	DAY	4	4		200
RECORDED	2026	.	146.0	.	50	SOUNDING	1	1392	H	19JAN89	11:12	DAY	4	4		200
RECORDED	2027	.	146.0	.	0	NO RESPONSE	.	1799	H	19JAN89	17:59	NIGHT	4		BF	300
RECORDED	2028	.	146.0	.	0	NO RESPONSE	.	1803	H	19JAN89	18:03	NIGHT	4		BF	300
RECORDED	2029	.	146.0	.	0	NO RESPONSE	.	1805	H	19JAN89	18:05	NIGHT	4		BF	300
OTHER	2030	.	.	.	0	NO RESPONSE	.	1813	H	19JAN89	18:13	NIGHT	4		BF	300
OTHER	2031	.	.	.	0	NO RESPONSE	.	1820	H	19JAN89	18:20	NIGHT	4		BF	300
RECORDED	2032	.	146.0	.	0	NO RESPONSE	.	1830	H	19JAN89	18:30	NIGHT	4		BF	300
OTHER	2033	.	.	.	0	NO RESPONSE	.	1848	H	19JAN89	18:48	NIGHT	4		BF	300
OTHER	2034	.	.	.	0	NO RESPONSE	.	1855	H	19JAN89	18:55	NIGHT	4		BF	300
REAL	2035	.	.	.	50	SOUNDING	1	1858	H	19JAN89	18:58	NIGHT	4		BF	300
RECORDED	2036	.	146.0	.	0	NO RESPONSE	.	1861	H	19JAN89	19:01	NIGHT	4		BF	300
RECORDED	2037	.	146.0	.	0	NO REPONSE	.	1868	H	19JAN89	19:08	NIGHT	4		BF	300
DOOR	2038	.	.	.	0	NO RESPONSE	.	1870	H	19JAN89	19.10	NIGHT	4		BF	300
OTHER	2039	.	.	.	0	NO RESPONSE	.	1873	H	19JAN89	19:13	NIGHT	4		BF	300
OTHER	2040	.	.	.	25	SOUNDING	1	1879	H	19JAN89	19:19	NIGHT	4		BF	300
OTHER	2041	.	.	.	0	NO RESPONSE	.	1885	H	19JAN89	19:25	NIGHT	4		BF	300

(CONTINUED)

APPENDIX TABLE A. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
TONE	2042	100	138.5	200	0	NO RESPONSE	.	1890	H	19JAN89	19:30	NIGHT	4		BF	300
TONE	2043	100	138.5	200	0	NO RESPONSE	.	1895	H	19JAN89	19:35	NIGHT	4		BF	300
RECORDED	2044	.	146.0	.	50	SOUNDING	1	1900	H	19JAN89	19:40	NIGHT	4		2RL	300
REAL	2045	.	.	.	100	DIAGONAL	3	1905	H	19JAN89	19:45	NIGHT	4		2RL	300
OTHER	2046	.	.	.	100	SOUNDING	2	163	I	20JAN89	15:43	DAY	4	5		300
OTHER	2047	.	.	.	100	DIAGONAL	2	168	I	20JAN89	15:48	DAY	4	5		300
OTHER	2048	.	.	.	75	DIAGONAL	1	292	I	20JAN89	17:52	NIGHT	4		BF	300
OTHER	2049	.	.	.	75	DIAGONAL	1	305	I	20JAN89	18:05	NIGHT	4		BF	300
OTHER	2050	.	.	.	75	DIAGONAL	1	330	I	20JAN89	18:30	NIGHT	4		BF	300
RECORDED	2101	.	157.8	.	0	NO RESPONSE	.	356	I	20JAN89	18:56	NIGHT	4		BF	300
RECORDED	2102	.	157.8	.	0	NO RESPONSE	.	369	I	20JAN89	19:09	NIGHT	4		BF	300
RECORDED	2103	.	157.8	.	100	DIAGONAL	2	410	I	20JAN89	19:50	NIGHT	4		BF	300
RECORDED	2104	.	157.8	.	25	STARTLE	.	436	I	20JAN89	20:16	NIGHT	4		BF	300
TONE	2105	5000	139.5	200	0	NO RESPONSE	.	454	I	20JAN89	20:34	NIGHT	4		BF	300
TONE	2106	5000	139.5	200	0	NO RESPONSE	.	468	I	20JAN89	20:48	NIGHT	4		BF	300
TONE	2107	10000	139.5	200	0	NO RESPONSE	.	473	I	20JAN89	20:53	NIGHT	4		BF	300
RECORDED	2108	.	157.8	.	25	DIAGONAL	1	477	I	20JAN89	20:57	NIGHT	4		BF	300

APPENDIX TABLE A. (CONTINUED)

FOOTNOTES

[a] Sound
- Band = broadband sound
- Recorded = recorded rock sound
- Door = door sound
- Real = sound generated by a real rock entering the water
- Tone = single frequency
- FM Sweep = FM log sweep
- Other = incidental sounds

[b] Response
- Diagonal = movement down and away from sound source
- Lateral = movement horizontally away from sound source
- Sounding = movement down from sound source
- Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
- No Response = no apparent reaction to sound

[c] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[d] Holding time = time in minutes between introduction to test cage and time of testing

[e] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[f] Relative Day Light Level 1 = low light
Level 5 = bright light

[g] Method of Night Observation RL = Red Light
WL = White Light
BF = Brief Flash

APPENDIX B

APPENDIX B. RESPONSES OF AGE 0 STRIPED BASS TO INTRODUCED SOUNDS UNDER DAY AND NIGHT CONDITIONS.

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
RECORDED	2109	.	142.3	.	25	SOUNDING	1	30	J	30JAN89	15:30	DAY	3	5		100
RECORDED	2110	.	142.3	.	50	SOUNDING	1	32	J	30JAN89	15:32	DAY	3	5		100
RECORDED	2111	.	142.3	.	0	NO RESPONSE	.	34	J	30JAN89	15:34	DAY	3	5		100
RECORDED	2112	.	142.3	.	50	SOUNDING	1	37	J	30JAN89	15:37	DAY	3	5		100
RECORDED	2113	.	142.3	.	50	SOUNDING	1	39	J	30JAN89	15:39	DAY	3	5		100
REAL	2114	.	.	.	100	SOUNDING	3	40	J	30JAN89	15:40	DAY	3	5		100
RECORDED	2115	.	142.3	.	0	NO RESPONSE	.	42	J	30JAN89	15:42	DAY	3	5		100
RECORDED	2116	.	142.3	.	0	NO RESPONSE	.	75	J	30JAN89	16:15	DAY	3	2		100
RECORDED	2117	.	147.8	.	75	SOUNDING	3	111	J	30JAN89	16:51	DAY	3	4		100
RECORDED	2118	.	147.8	.	75	DIAGONAL	2	121	J	30JAN89	17:01	DAY	3	3		100
TONE	2119	100	140.3	200	0	NO RESPONSE	.	130	J	30JAN89	17:10	DAY	3	2		100
TONE	2120	100	146.3	200	0	NO RESPONSE	.	132	J	30JAN89	17:12	DAY	3	2		100
RECORDED	2121	.	147.8	.	75	SOUNDING	1	134	J	30JAN89	17:14	DAY	3	2		100
DOOR	2122	.	.	.	0	NO RESPONSE	.	134	J	30JAN89	17:14	DAY	2	2		100
REAL	2123	.	.	.	0	NO RESPONSE	.	135	J	30JAN89	17:15	DAY	3	2		100
RECORDED	2124	.	147.8	.	50	SOUNDING	1	268	J	30JAN89	19:28	NIGHT	3		BF	100
RECORDED	2125	.	147.8	.	50	SOUNDING	1	285	J	30JAN89	19:45	NIGHT	3		BF	100
.	2126	.	.	.	50	SOUNDING	1	285	J	30JAN89	19:45	NIGHT	3		BF	100
RECORDED	2127	.	147.8	.	25	SOUNDING	1	305	J	30JAN89	20:05	NIGHT	3		BF	100
OTHER	2128	.	.	.	25	SOUNDING	3	350	J	30JAN89	20:50	NIGHT	3		BF	100
BAND	2129	1300-3300	147.5	200	50	SOUNDING	1	1110	J	31JAN89	9:30	DAY	3	5		100
BAND	2130	1300-3300	147.5	200	50	SOUNDING	1	1112	J	31JAN89	9:32	DAY	3	5		100
BAND	2131	1300-3300	153.5	200	0	NO RESPONSE	.	1114	J	31JAN89	9:34	DAY	3	5		100
BAND	2132	1300-3300	159.5	200	0	NO RESPONSE	.	1115	J	31JAN89	9:35	DAY	3	5		100
TONE	2133	100	134.3	200	0	NO RESPONSE	.	1123	J	31JAN89	9:43	DAY	3	5		100
TONE	2134	100	134.3	200	0	NO RESPONSE	.	1125	J	31JAN89	9:45	DAY	3	5		100
TONE	2135	150	134.3	200	0	NO RESPONSE	.	1128	J	31JAN89	9:48	DAY	3	5		100

(CONTINUED)

APPENDIX TABLE B. (CONTINUED)

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAYLIGHT LEVEL[f]	METHOD OF NIGHT OBSERVATION[g]	NUMBER OF FISH
TONE	2136	150	140.3	200	0	NO RESPONSE	.	1130	J	31JAN89	9:50	DAY	3	5		100
TONE	2137	150	140.3	200	0	NO RESPONSE	.	1133	J	31JAN89	9:53	DAY	3	5		100
TONE	2138	150	140.3	200	0	NO RESPONSE	.	1135	J	31JAN89	9:55	DAY	3	5		100
TONE	2139	500	144.3	200	0	NO RESPONSE	.	1158	J	31JAN89	10:18	DAY	3	5		100
TONE	2140	1000	145.3	200	0	NO RESPONSE	.	1165	J	31JAN89	10:25	DAY	3	5		100
TONE	2141	2000	139.0	200	0	NO RESPONSE	.	1188	J	31JAN89	10:48	DAY	3	5		100
DOOR	2142	.	.	.	0	NO RESPONSE	.	1193	J	31JAN89	10:53	DAY	3	5		100
BAND	2201	100-500	147.6	200	0	NO RESPONSE	.	1230	J	31JAN89	11:30	DAY	3	5		100
BAND	2202	1300-3300	167.5	200	0	NO RESPONSE	.	1231	J	31JAN89	11:31	DAY	3	5		100
RECORDED	2203	.	147.8	.	0	NO RESPONSE	.	1233	J	31JAN89	11:33	DAY	3	5		100
RECORDED	2204	.	147.8	.	0	NO RESPONSE	.	1235	J	31JAN89	11:35	DAY	3	5		100
REAL	2205	.	.	.	50	DIAGONAL	1	1240	J	31JAN89	11:40	DAY	3	5		100
RECORDED	2206	.	147.8	.	100	DIAGONAL	3	1497	J	31JAN89	15:57	DAY	3	4		100
RECORDED	2207	.	147.8	.	75	DIAGONAL	2	1501	J	31JAN89	16:01	DAY	3	4		100
RECORDED	2208	.	147.8	.	0	NO RESPONSE	.	1505	J	31JAN89	16:05	DAY	3	4		100
REAL	2209	.	.	.	100	DIAGONAL	2	1506	J	31JAN89	16:06	DAY	3	4		100
RECORDED	2210	.	147.8	.	25	DIAGONAL	1	1518	J	31JAN89	16:18	DAY	3	4		100
DOOR	2211	.	.	.	0	NO RESPONSE	.	1520	J	31JAN89	16:20	DAY	3	4		100

APPENDIX TABLE B. (CONTINUED)

FOOTNOTES

[a] Sound

Band = broadband sound
Recorded = recorded rock sound
Door = door sound
Real = sound generated by a real rock entering the water
Tone = single frequency
FM Sweep = FM log sweep
Other = incidental sounds

[b] Response

Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[c] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[d] Holding time = time in minutes between introduction to test cage and time of testing

[e] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

[f] Relative Day Light Level 1 = low light
Level 5 = bright light

[g] Method of Night Observation RL = Red Light
WL = White Light
BF = Brief Flash

APPENDIX C

APPENDIX TABLE C. RESPONSE OF AGE-1 ATLANTIC TOMCOD TO INTRODUCED SOUNDS UNDER DAY CONDITIONS.

SOUND[a]	TEST NO.	FREQUENCY (HZ)	AMPLITUDE (dB//µPa/ Hz AT 1 M)	PULSE LENGTH (MS)	PERCENT RESPONDING	RESPONSE[b]	RESPONSE STRENGTH[c]	HOLDING TIME[d] (MIN)	FISH GROUP[e]	DATE	TIME	TEST PERIOD	WATER TEMPERATURE (°C)	RELATIVE DAY LIGHT LEVEL[f]	NUMBER OF FISH
RECORDED	1139	.	142.3	.	75	LATERAL	1	13	K	22DEC88	14:33	DAY	6	5	100
RECORDED	1140	.	142.3	.	75	LATERAL	1	15	K	22DEC88	14:35	DAY	6	5	100
REAL	1141	.	.	.	75	LATERAL	1	17	K	22DEC88	14:37	DAY	6	5	100
REAL	1142	.	.	.	50	LATERAL	1	18	K	22DEC88	14:38	DAY	6	5	100
BAND	1201	1300-3300	148.0	15	0	NO RESPONSE	.	17	K	22DEC88	14:47	DAY	6	5	100
BAND	1202	100-500	144.1	15	0	NO RESPONSE	.	19	K	22DEC88	14:49	DAY	6	5	100
BAND	1203	1300-3300	142.0	5	0	NO RESPONSE	.	23	K	22DEC88	14:53	DAY	6	5	100
BAND	1204	1300-3300	148.0	CONT.[g]	100	SOUNDING	1	25	K	22DEC88	14:55	DAY	6	5	100
BAND	1205	1300-3300	148.0	CONT.[g]	0	NO RESPONSE	.	28	K	22DEC88	14:58	DAY	6	5	100
TONE	1206	150	128.8	1	0	NO RESPONSE	.	32	K	22DEC88	15:02	DAY	6	5	100
TONE	1207	500	132.8	1	0	NO RESPONSE	.	36	K	22DEC88	15:06	DAY	6	5	100
TONE	1208	500	132.8	3	0	NO RESPONCE	.	41	K	22DEC88	15:11	DAY	6	5	100
TONE	1209	758	138.8	1	0	NO RESPONSE	.	45	K	22DEC88	15:15	DAY	6	5	100

APPENDIX TABLE C. (CONTINUED)

[a] Sound
Band = broadband sound
Recorded = recorded rock sound
Door = door sound
Real = sound generated by a real rock entering the water
Tone = single frequency
FM Sweep = FM log sweep
Other = incidental sounds

[b] Response
Diagonal = movement down and away from sound source
Lateral = movement horizontally away from sound source
Sounding = movement down from sound source
Startle = momentary non-directed departure from normal movements or decrease in inter-fish distance
No Response = no apparent reaction to sound

[c] Response strength 1 = fish swim 1-3 ft in 10 seconds (slight reaction)
2 = fish swim 3-7 ft in 10 seconds (moderate reaction)
3 = fish swim length of cage (10 ft) in 10 seconds (strong reaction)

[d] Holding time = time in minutes between introduction to test cage and time of testing

[e] Fish Group = each letter identifies a batch of fish that were subjected to sequential testing

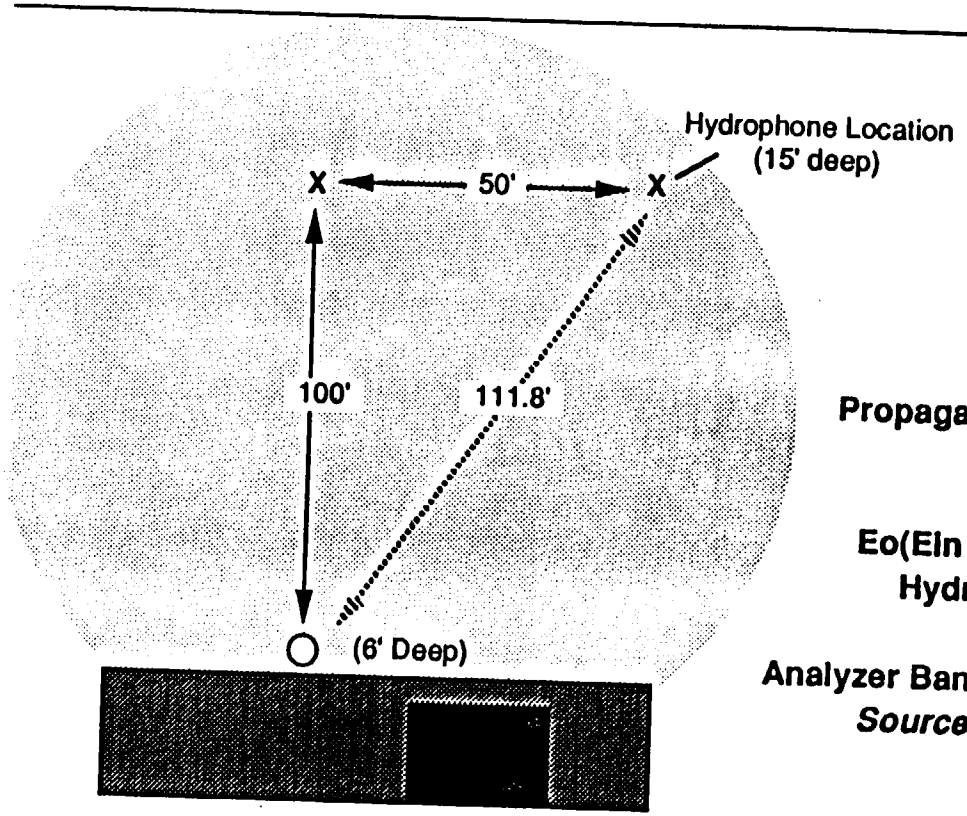
[f] Relative Day Light Level 1 = low light
Level 5 = bright light

[g] CONT. = Continuous

APPENDIX D

CALCULATION OF REQUIRED SOURCE LEVEL TO MAINTAIN SAME SIGNAL TO NOISE RATIO AT INDIAN POINT GENERATING STATION AS IN QUARRY

TEST GEOMETRY



Propagation Loss =10 log range (yds)

10 log (111.8/3) = 15.7

Eo(Ein to Amp = -12dBV) =	**- 77.0**	
Hydrophone Response	**-(-196.0)**	
Propagation Loss	**+15.7**	
Analyzer Bandwidth Correction	**- 11.9**	dB // uPa/Hz
Source Level @ -12 dBV =	***122.8***	

		dB // uPa/Hz
Source Level =	**122.8**	dB
(to refer to Ein = 0 dBV)	**+ 12.0**	dB // uPa/Hz
Level for noise (400 Hz band)	**134.8**	dB
Band level correction (10 log (500-100))	**+ 26.0**	dB // uPa
Power in Band	**160.8**	

(or level for tone required to be equivalent to the energy in the band)

REAL ROCK SOURCE LEVEL AND SIGNAL TO NOISE RATIO (SNR) IN QUARRY

REASON:

- PROVEN RESULTS OBTAINED WITH REAL ROCK
- DATA POINT FOR DETERMINING DESIGN REQUIREMENTS

ROCK SPECTRUM LEVEL:

LEVEL FROM ANALYZER @ 100 Hz	-20.0 dBV
RECEIVE SENSITIVITY OF HYDROPHONE dB //1V/uPa (Includes tape recorder gain correction)	-(-158.0)
ANALYZER BANDWIDTH CORRECTION (from 9.55 Hz to 1 Hz band)	-9.8
(a) ROCK SPECTRUM LEVEL =	*128.2 dB //uPa/Hz*

SNR IN QUARRY:

BACKGROUND LEVEL FROM ANALYZER @ 100 Hz	-112.5 dBV
RECEIVE SENSITIVITY OF HYDROPHONE (no recorder)	-(-196.0)
ANALYZER BANDWIDTH CORRECTION (from 38.2 Hz to 1 Hz band)	15.8
(b) QUARRY BACKGROUND LEVEL =	67.7 dB // uPa/Hz

SNR= ROCK SPECTRUM LEVEL (a) minus BACKGROUND (b)

128.2 - 67.7 = 60.5 dB

REQUIRED LEVEL TO MAINTAIN SAME SNR AT INDIAN POINT AS IN QUARRY

BACKGROUND:		
INDIAN POINT LEVEL FROM ANALYZER	- 79.4	@ 100 Hz
HYDROPHONE RESPONSE	-(-196.0)	dB // uPa/V
ANALYZER BANDWIDTH CORRECTION (2.5 Hz to 1 Hz)	- 4.0	dB
INDIAN POINT BACKGROUND LEVEL:	*112.6*	*dB // uPa/Hz*
INDIAN POINT SOURCE LEVEL REQUIRED TO MAINTAIN SAME SNR AS QUARRY (REAL ROCK):		
INDIAN POINT BACKGROUND LEVEL (@ 100 Hz)	112.6	dB // uPa/Hz
REAL ROCK SNR MEASURED IN QUARRY	± 60.5	dB
REQUIRED LEVEL:	*173.1*	*dB // uPa/Hz*
SOURCE LEVEL REQUIRED TO PROVIDE 100' EFFECTIVE STANDOFF RANGE:		
INDIAN POINT SOURCE LEVEL AT 1 METER	173.1	dB // uPa/Hz
PROPAGATION LOSS FACTOR	± 15.0	dB
SOURCE LEVEL FOR 100' RANGE :	*188.1*	*dB // uPa/Hz*
EQUIVALENT BAND LEVEL REQUIRED FOR 100' RANGE:		
SOURCE LEVEL IN 1 Hz BAND	188.1	dB // uPa/Hz
BAND LEVEL CORRECTION	± 20.8	dB
TONE OR BAND LEVEL SOURCE LEVEL:	*208.9*	*dB // uPa*

ASA Analysis & Communication, Inc.

FINAL REPORT:

PHYSIOLOGY INVESTIGATIONS OF THE ATLANTIC TOMCOD

Submitted by:

Martin P. Schreibman, Ph.D.
Director, Aquatic Research and Environmental Assessment Center (AREAC)
Brooklyn College, City University of New York

John R. Young, Ph.D.
Senior Scientist
ASA Analysis & Communication, Inc.

September 2002

Funded by:

Central Hudson Gas & Electric Corporation
Consolidated Edison Company of New York
New York Power Authority
Orange & Rockland Utilities, Inc.
Dynegy Northeast Generation
Entergy Nuclear Indian Point 2, LLC.
Entergy Nuclear Indian Point 3, LLC.
Mirant Bowline, LLC.

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Entergy Nuclear Indian Point 3, LLC.
Mirant Bowline, LLC.

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I. INTRODUCTION

The Atlantic tomcod, *Microgadus tomcod* (Waldbaum), an anadromous euryhaline species of the family Gadidae, inhabits the Atlantic coast from Canada to Virginia (Peterson et al, 1980). In the Hudson River they occur as far upriver as the Albany Region, but are uncommon above the Kingston Region, approximately river mile (RM) 100. Young of the year (YOY) move down river in the fall as the salinity drops in the mid-estuary (Klauda et al., 1988). Adult tomcod, including the young-of-year, move back upriver to the freshwater portion of the estuary in November and December to spawn.

The Hudson River represents the southernmost range of the reproductive distribution for this species. Considerable attention has been given to the Hudson River Atlantic tomcod because of its high rate of liver cancer (Dey et al., 1993) and its involvement with power plant intakes (McLaren et al. 1988). These two factors have stimulated a considerable amount of research on the population (e.g. Grabe 1978, 1980; Smith et al. 1979; Cormier 1986; Watson 1987; Cormier et al. 1989; Wirgin et al. 1989; Kreamer et al. 1991;Dew and Hecht 1994a and 1994b;Dew 1995).

For most of the 25 years that the Hudson River utilities have been studying Atlantic tomcod, three facts have formed the core of the views on the species' population dynamics: 1) tomcod spawn in mid-winter when few other fish species are active predators or competitors; 2) both sexes reach reproductive maturity at one year of age; 3) the spawning stock is composed primarily of 1-year old fish (McLaren et al. 1988). Although winter spawning is found in all known populations, more northern populations may mature later and/or live longer than the Hudson population, although there is some question whether ageing methods have been consistent for different populations (McLaren et al 1988).

The truncated age structure of the Hudson River population, which is apparently not heavily fished, indicates a very high adult mortality rate. High adult mortality could be due to a recent change in adult mortality factors, such as pollution-induced cancer, increase in abundance of predators of adult fish, or power plant impingement. It could also be a result of the population developing a semelparous life history in which individuals make such a large commitment of resources to reproduction that they seldom survive to spawn again. The environment of the Hudson estuary, which is the southernmost limit of successful spawning, may present unique challenges to the species, resulting in this possibly unique (for tomcod) life history pattern.

A recent analysis of tomcod abundance patterns suggests that the factors modulating survival rates have changed within the last decade (Central Hudson et al. 1999). A fluctuating pattern of abundance has appeared since 1990 in which a small number of age 1 and age 2 spawners one year, is followed by a considerably higher number the next year, followed by another low spawning stock the next. The mean level of abundance since 1990 also appears lower than it was previously. Extrinsic factors which have changed significantly over the last decade include improved water quality in the lower river and harbor as the input of raw sewage was drastically reduced, lower rates of impingement mortality at mid-Hudson power plants,

lessened incidence of liver cancer (suggested by data from 1995-1996 spawning season), and a substantial increase in the number of striped bass (a known predator) in the estuary.

One possible explanation of what appears to be strongly density-dependant survival in both YOY and adult tomcod, as evidenced by the alternating abundance pattern, is that the water pollution control programs completed in the late 1980s significantly improved survival potential, but also increased the potential for intraspecific competition. The reduced sewage inputs resulted in better water quality and, perhaps most importantly, higher dissolved oxygen during the summer (Brosnan and O'Shea 1996) and a reduced input of fine particulate organic carbon, which may be a prime food source for the populations of invertebrate organisms upon which both YOY and age 1 tomcod feed (Central Hudson et al. 1999). Thus, the ultimate effect of the sewage treatment program could be high summer competition for food and eventually poor survival of YOY when tomcod are abundant at the beginning of the summer. When abundance is low at the beginning of the summer, food may be sufficient to allow good survival through the high-temperature summer period

The research being reported herein represents an attempt to examine some of the potential factors that affect Atlantic tomcod population dynamics. Some of the specific questions for which answers were sought were:

- How do food levels and temperatures interact to affect survival and growth of Atlantic tomcod juveniles and adults?
- Do all fish mature at 1 year of age?
- Has the Hudson population evolved a semelparous life history strategy? (i.e. are fish pre-programmed to die after spawning?)
- What role does liver cancer play in the current life history pattern?

To obtain answers to these questions, a dedicated experimental facility that would allow holding tomcod for long periods in controlled environmental conditions was constructed at Brooklyn College of the City University of New York. By holding fish under controlled laboratory conditions, some potential sources of mortality (predation, fishing, impingement) can be removed, which facilitated examination of the importance of food level and temperature. Unfortunately, delays in construction and several equipment malfunctions seriously affected the efforts to answer these questions and forced major modifications of the intended scope of work. However, the study was nevertheless able to provide useful information that should aid in interpretation of the population dynamics of Atlantic tomcod.

II. METHODS

All experiments were conducted at the Aquatic Research and Environmental Assessment Center (AREAC) at Brooklyn College. During 1997, the dedicated laboratory facilities for these experiments were under construction, therefore some of the initial experiments were conducted in smaller facilities already in existence at AREAC. These facilities are described in the sections pertaining to those studies.

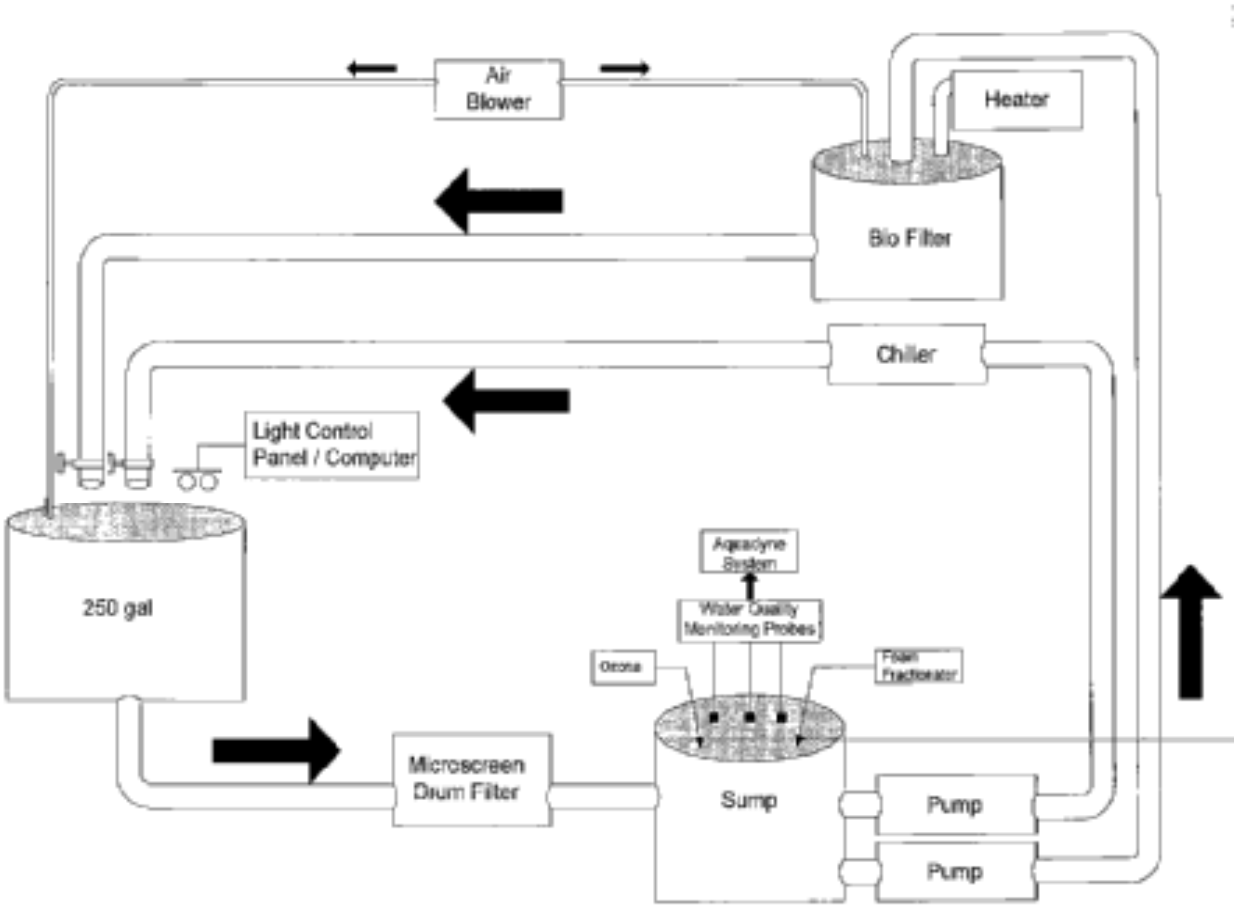
The dedicated facilities constructed for the tomcod studies were a set of eight round fiberglass tanks of approximately 450 gal capacity (5 ft diameter, 3 ft deep) with an accompanying recirculating water system (Figure 1). Inflow to the tanks (up to 80 gpm) was provided by a flow delivery system, with a center outflow through a slotted standpipe. Outflow from the tanks went to a pump (Serfilco LTD, # SE2HLD3.OC pumps for 100gpm at 60'), biofilter (4' x 32" (200 gal plastic sump filled with small plastic "wagon wheel macaroni" disks - home made describe and then to the chiller (Filtrine recirculating loop chiller, model PCP or POC-3; 40 degrees to 96 deg F) before going back to the tanks. The tanks were covered with hinged covers and were illuminated by a variable illumination 75 W incandescent bulbs light.

Conditions within the system were monitored continuously with an Aquadyne Monitoring system for temperature, pH, salinity, dissolved oxygen. Ammonia levels and other chemical determinations were done manually at least once daily.

Parameters that may be controlled and monitored to induce desired natural environmental conditions include salinity, temperature (4 to 30 degrees Celsius), photoperiod and light intensity, dissolved oxygen and pH.

The Atlantic tomcod studied were gathered by several methods: box trap, beam trawl, otter trawl, and beach seining primarily during normal sampling for the utility monitoring program. In some instances additional sampling effort was expended entirely to collect fish for these studies. For some studies, ripe adults were captured and spawned in the field or laboratory. In all field acquisitions, animals were returned to the laboratory by motor vehicle, in oxygenated, insulated coolers in less than two hours after returning to the dock. Slow temperature acclimatization of the fish over three to four hours preceded their placement into the larger tanks.

Figure 1. Schematic of Hudson River System used for holding and rearing Atlantic tomcod. System included 8 large 450 gallon tanks for holding the fish.

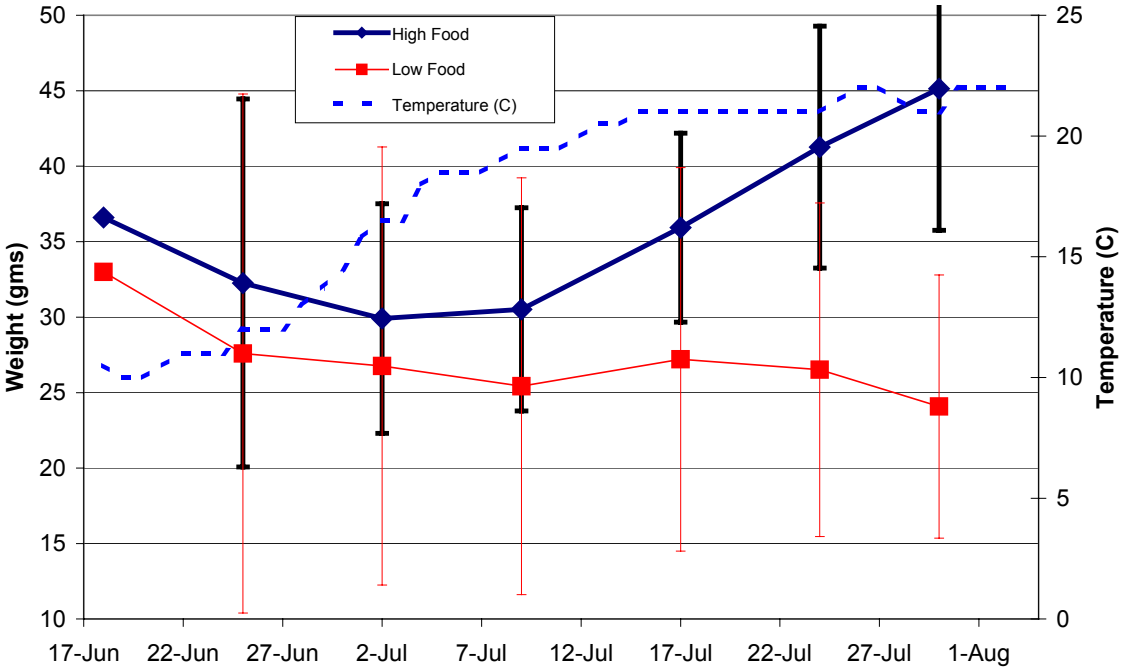


III. RESULTS

Experiment 1. Effects of Temperature and Ration on Survival and Growth of Adult Tomcod.

Fish for this experiment were captured in box traps set at Garrison, NY, during the annual winter adult spawning stock study. The fish were held in square, 40-gal glass tanks from capture in January and February until the experiment began on June 16, 1997. The prolonged holding period was used to ensure that all fish beginning the experiment were healthy and apparently physiologically capable of living to spawn again. Initial temperature on June 16 was 10.5 C, and temperature was gradually increased until it reached approximately 22C (Figure 2). The equipment did not permit precise control of temperature, however it was used because the Hudson River facility was not complete and operational.

Figure 2. Mean weight (+/- standard deviation), and temperature for Atlantic tomcod in initial ration experiment, 1997.



Fish were divided into two groups in separate tanks, "high food" (3 feedings daily at initially 1% body weight) and "low food" (2 feedings daily at initially 0.5% body weight) consumption. The high food group initially had 15 fish, and the low food group had 16. From June 16 to June 25, food was chopped frozen squid obtained from a local bait dealer. After June 25, chopped fresh or frozen and thawed clams were used. All surviving fish were weighed and measured weekly until the experiment was ended on August 1. Ventilation rates were determined by counting movements of the opercula (gill covers) of 10 fish daily. Only those fish

that appeared to be behaving normally were used for ventilation rate observations.

Food rations were increased part-way through the experiment because both high and low food groups were initially losing weight. When ration was increased (Table 1), and clams were used instead of squid, the high food group began to gain weight (Figure 2), and the low food group appeared to stabilize. Mortalities occurred in both groups, primarily near the end of the experiment at temperatures of approximately 22C.

Table 1. Results of Experiment 1.

	High Ration Treatment				Low Ration Treatment			
Date	Number of Fish Surviving	Mean Weight	Std. Dev.	Mean Daily Ration (% of Biomass)	Number of Fish Surviving	Mean Weight	Std. Dev.	Mean Daily Ration (% of Biomass)
6/18/1997	15	36.6		2%	16	33.0		1%
6/25/1997	15	32.3	12.2	4%	16	27.6	17.2	1%
7/2/1997	14	29.9	7.6	4%	15	26.8	14.5	1%
7/9/1997	14	30.5	6.7	5%	14	25.4	13.8	1%
7/17/1997	13	35.9	6.3	11%	12	27.2	12.7	3%
7/24/1997	11	41.3	8.0	9%	11	26.5	11.0	2%
7/30/1997	11	45.1	9.4		10	24.1	8.7	

[Due to methods used to record and summarize the ventilation data, meaningful presentation of ventilation results was not possible.]

Experiment 2. Post-spawning survival of adult fish – 1997-1998 Spawning Season

In January 1998, more than 325 feral adult fish were captured by box trap and net in Garrison NY by box trap and brought to the AREAC facility. On February 24, 1998, 310 fish were tagged with a 1mm x 3 mm plastic tag with bright florescent code numbers printed on them (VI Alpha tags, Northwest Marine Technologies). Tags were inserted into the fleshy part of their gill cover (operculum). In this position, the code numbers were clearly visible through the epidermis by gross inspection. The fish were divided evenly into four, 450 gal insulated, covered fiberglass tanks. Water was maintained at 5 C, and 5 ppt salinity. Illumination was dim and in concert with the natural photoperiod. The average weight of all the fish at the time of tagging was 42.8 gm and the average length was 17.1 cm (Appendix A).

On February 28, 1998 (four days after implanting tags) a chiller unit failed and water temperature rose to 15 C in less than 24 hours (Figure 3), resulting in the death of 159 fish between February 28 and March 5. The length frequency of the fish that died during this temperature excursion indicated that small fish were more likely to die than were larger fish (Figure 4). Mean length at tagging of fish that died during this event was 16.0 cm and mean weight was 32.9 gm. However, both length and weight distributions were highly skewed with

the majority of fish smaller than the means. Based on the initial length-weight data collected at time of tagging, it would not appear that the length-weight relationship (one indicator of physical condition) for fish that died during the first temperature event differed from that of fish that survived (Figure 5).

Figure 3. Water quality parameters during first chiller failure event on February 28, 1998.

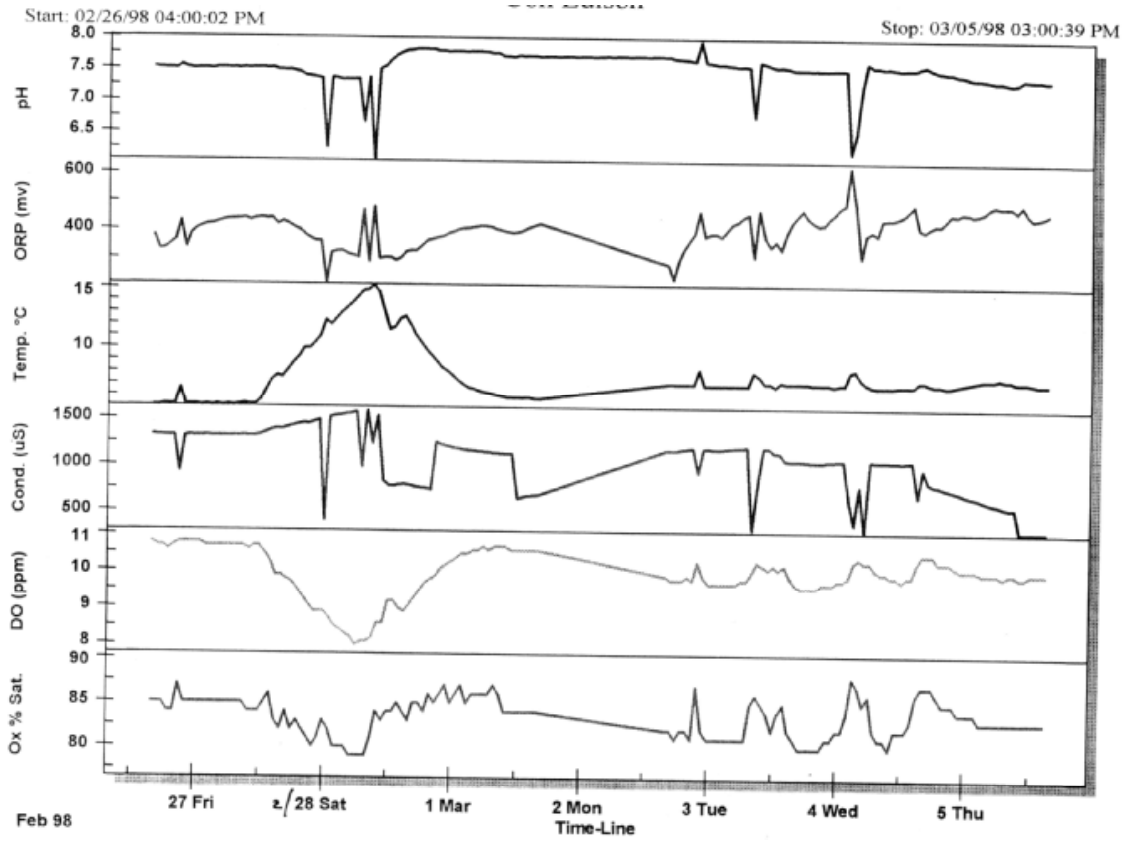


Figure 4. Length frequency of adult tomcod that died in two temperature excursion events, and of those that survived both events..

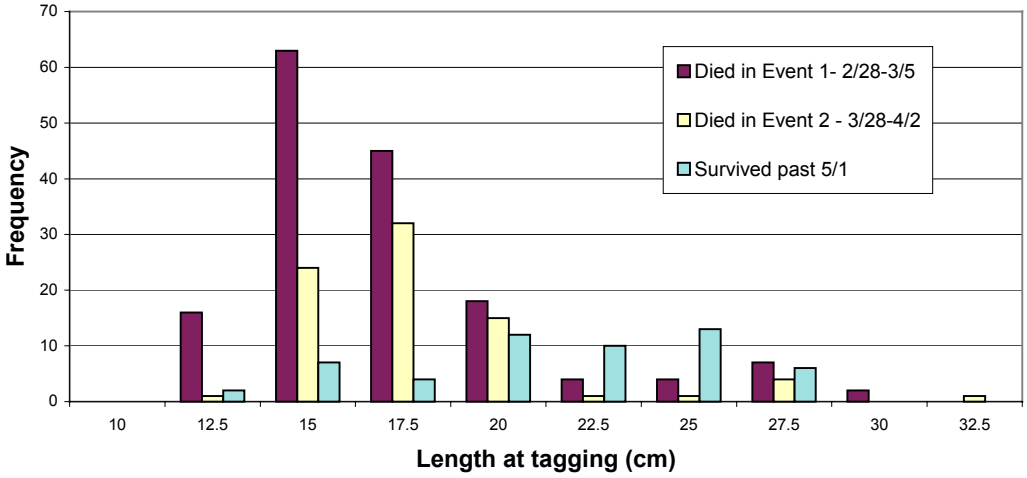
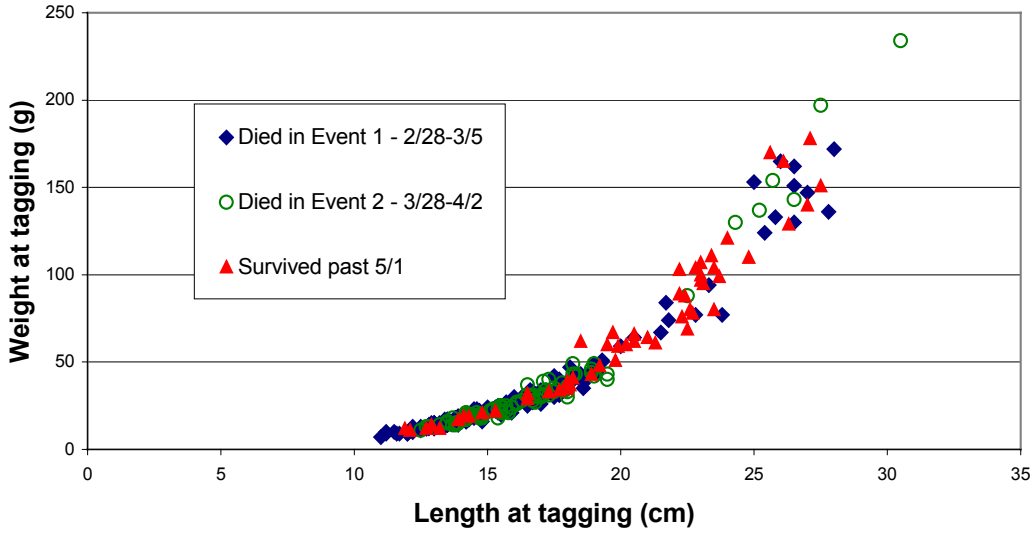


Figure 5. Length-weight of Atlantic tomcod at time of tagging 2/24.



The 159 dead fish consisted of 92 males, 56 females, and 11 fish of undetermined gender. The prevalence of male fish in those that died may indicate that the thermal stress was somewhat sex-selective instead of size-selective since male fish are on average smaller than females (McLaren et al. 1988). Livers were classified as to the presence of abnormality associated with cancers according to the methods of Dey et al. (1993). Most of the dead fish (101) had normal appearing livers, 51 were classified as category 2 (clear nodules present), 5 were category 3 (gross pathology obvious), and 2 were undetermined. Fifty-six percent were infected with round worm (Acanthocephalan) parasites.

During the weekend from Friday March 27 to Sunday March 29 a second chiller failure occurred. Water temperature rose from 7 C to 25 C over a period of approximately 48 hours (Figure 6). Seventy-nine fish died between March 28 and April 2. Similar to the fish that died during the first high-temperature excursion, smaller fish appeared more likely to die than larger fish (Figure 4), although the initial condition of the fish that died did not appear to be different from those that survived (Figure 5). Mean length and weight for the fish dying during this event were 16.8 cm and 37.9 gm. Based on the length and weight measurements at time of tagging, and those collected again at death, it appeared that the fish were typically in slightly poorer condition than they were at the time of tagging (Figure 7).

Figure 6. Water quality parameters during second chiller failure event on March 28-29, 1998.

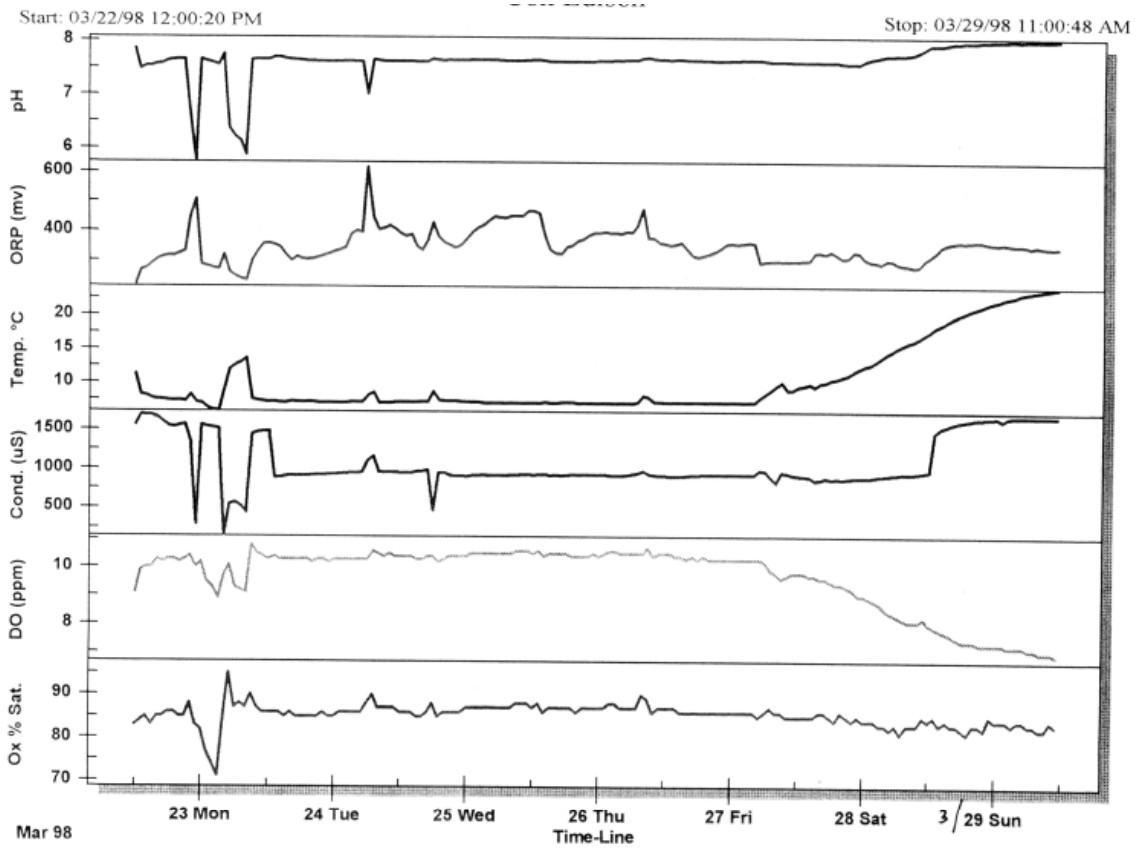
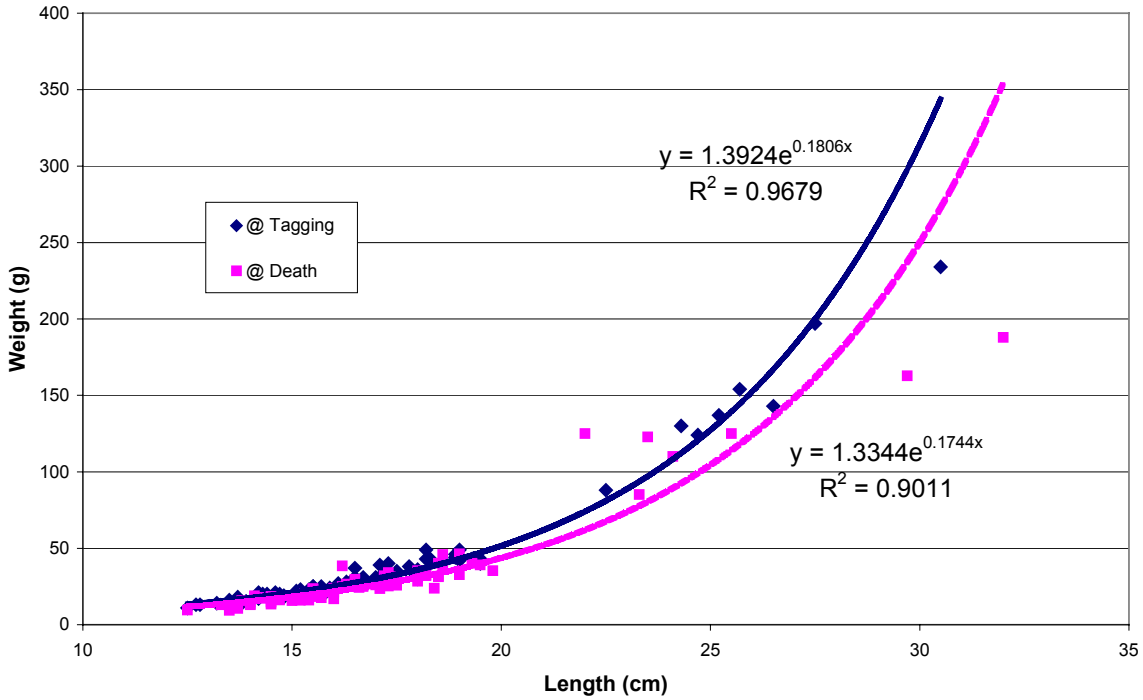


Figure 7. Length-weight relationship for fish that died in 2nd temperature event, March 28-29, 1998.



Of the 79 dead fish from event 2, 6 fish were males, 4 fish were females, and 69 fish were of undetermined gender. Livers were classified as to the presence of abnormality associated with cancers according to the methods of Dey et al. (1993). Most of the dead fish (68) had normal appearing livers, 6 were classified as category 2, and 1 was category 3, and 4 were undetermined. Thirty-eight percent were infected with parasitic worms.

Logistic regression was used to model influence of size on the probability of dying during the high temperature excursions:

$$Pr(Die) = [1 + \exp(\beta_0 + \beta_S \times S)]^{-1}$$

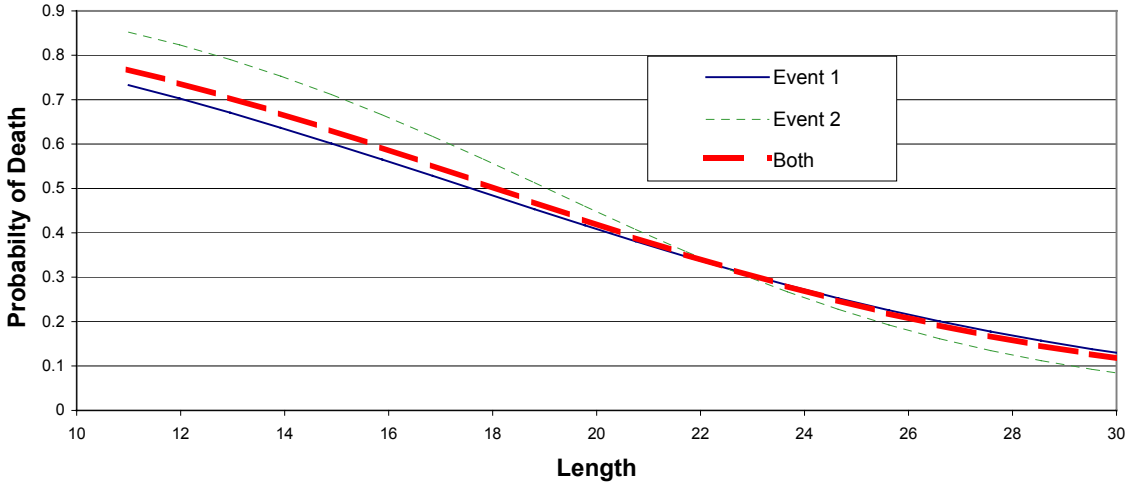
Where
β_0 = intercept
β_S = coefficient of effect of fish size
S = measure of fish size; length, weight, and Fulton's condition factor (weight/length^3) were examined

The regression was fitted by the method of maximum likelihood.

Length proved to be the best predictor of the effect of size on probability of dying, and

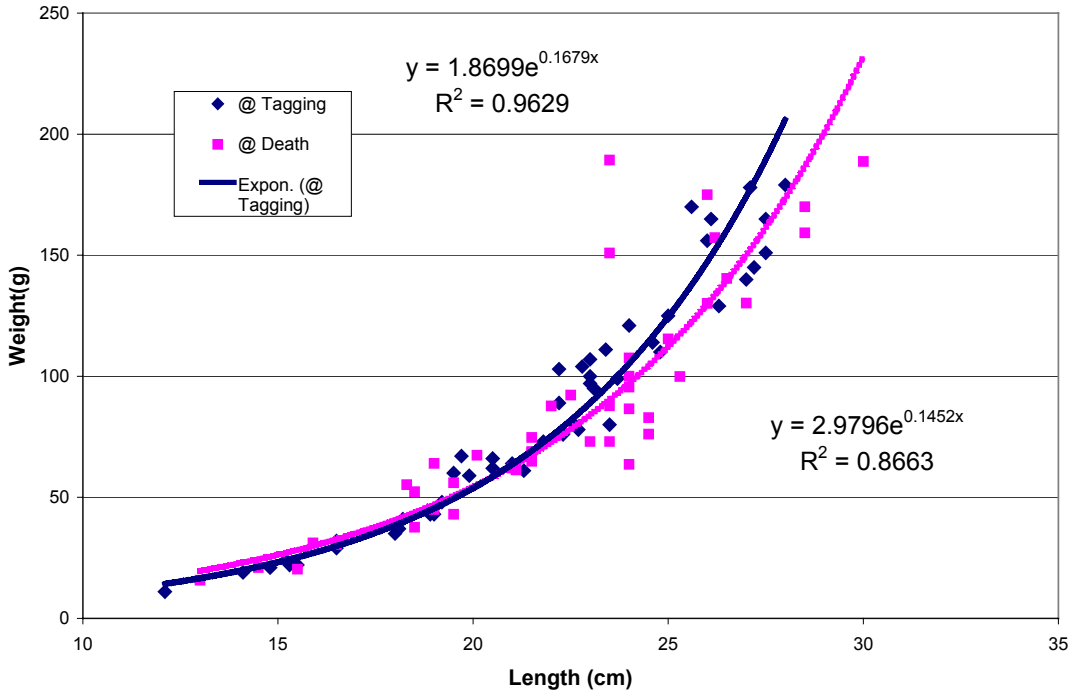
the regression curves for the two events were not significantly different. Negative log of the likelihood for two curves was 288.01; negative log of the likelihood for a single composite curve was 289.65. The difference between the likelihoods (1.64) was less than the critical χ^2 for two degrees of freedom. For the combined curve, probability of dying declined from 0.77 for an 11 cm fish, to 0.12 for a 30 cm fish (Figure 8). The similarity of the regression curves for the two events was somewhat surprising in that the maximum temperature reached during the second event was substantially higher (25 C vs 15 C).

Figure 8. Logistic regression to predict probability of death in temperature excursion events.



After these two equipment failures, fish died only sporadically through July 17, 1998 (see Appendix A). Of the fish that survived to at least May 1, the mean length and weight at time of tagging were 20.2 cm and 70.1 gm, substantially larger than the means for fish that died during the chiller failures. The condition at time of death did not appear to be substantially different from condition at time of tagging, as indicated by the length-weight curves for the two time periods (Figure 9). Of the fish that died by July 17, 25 had category 1 livers, 10 category 2, 2 category 3, and the rest undetermined.

Figure 9. Length-weight relationships for fish that died after the 2 two high temperature excursion events.



Experiment 3. Post-spawning survival of adult fish – 1998-1999 Spawning Season

Pre-spawning adults were captured in box traps set in the lower Hudson River in proximity to "The River Project" and in box traps set in Irvington and Garrison New York. Fish were transported by vehicle, as described in the "Methods" section, with minimal fatality. The majority of feral adults that came into the laboratory by January 1999 were from 7 box trap field collections in Garrison, NY (162 fish) and Irvington NY (11 fish). Of the fish that were collected, 25 died between 1/18/99 and 1/31/00. Six were males, 14 females and 5 could not be identified. All had category 1 livers. Forty percent were infected with parasites; several were extremely heavily infested with the parasites extending from their body surface so that fish appeared like porcupines (Fig. 10). However, no parasites were seen in animals that died between 5/18/99 to 1/3/00. This suggests that the occurrence of adult parasites may coincide with the reproductive spawning of the tomcod.

Figure 10. Adult tomcod with external parasites.

Once fish had survived through the summer, they were brought to water temperature and photoperiod conditions simulating spawning conditions in nature gradually, with temperature decreasing from 17 C on August 6 to 4 C on September 27. The final conditions (September 27, 1999) that the fish were subjected to were 4 C, 4.5 ppt salinity, and 9 hours of subdued artificial light. Animals received 0.24cc/kgm injections of 36 mgm of carp pituitary extract (Stoller Fisheries, Iowa) in 3.87ml distilled water into the dorsal posterior quadrant musculature on alternate days. Injections began on 12/4/99 and ended 12/27/99. Eggs and milt were stripped on 12/28 and 12/30/99. Fertilized eggs were stored at 4 C (household refrigerator) in 5 ppt saline water.

Egg hatching times were quite variable -from 28 to 40 days post-fertilization. When larvae were in the yolk sac stage, but freely swimming, they were transferred to 4 gal black plastic tubs that contained 5 ppt saline and that were suspended in 80 gal long recirculating troughs maintained at 6-7 C and 5 ppt salinity. When yolk sacs were almost fully resorbed, a commercial preparation of algae consisting of *Isochrysis* and *Nannochloropsis* ("Instant Algae", Reed Mariculture Inc., San Jose, CA) as well as live rotifers (Florida Aqua Farms, Dade City, FL.) were fed to the fry.

Larvae survived for a short period of time and then began to die. All were dead by 2/15/2000. (Note: We deeply appreciate the technical information and assistance provided by Dr. Chris Chambers and his staff of NMFS in Sandy Hook, NJ)

Experiment 4. Effects of temperature on growth, survival and maturity of juvenile tomcod.

Due to poor success in earlier efforts to obtain wild juveniles through beam trawl collections in the Hudson River, it was necessary to obtain wild juveniles through beach seining on the north shore of Long Island (Little Neck Bay). Eighty-one YOY were captured by beach seine in Little Neck Bay of Long Island Sound in Bayshore, NY (South of Willets Point) on May 23, 1999 (n = 55) and on May 27, 1999 (n = 26). They were maintained in 80 gal, fiberglass, trough tanks at 18 C, 22 ppt salinity and natural daylight, the same conditions that they were experiencing in nature at the time of capture. Twenty-five fish died between the collection date and 7/6/99. After this date there was minimal mortality. Fish were divided equally into the two 80 gal tanks, A & B. Fish were fed omega-enriched adult brine shrimp and later augmented with chopped fresh or frozen clams. Tank water temperatures approximated reported natural temperatures. On July 10 water temperature was 15 C and salinity was 15 ppt. Dissolved oxygen and ammonia levels were determined at least once each day.

On 7/26/99, the mean length (cm) and weight (g) were:

	TL	SD	Range	W	SD	Range
Tank A:	9.59	1.10	7.50 - 12.20	6.83	2.36	2.80 - 12.60
Tank B:	9.37	1.02	7.40 - 12.00	6.46	2.22	3.30 - 13.40

Beginning 8/17/99 water temperature was increased 1 C each week until temperatures were 21^0 C (tank A) and 18^0 C (tank B). This was achieved by 9/14/99 and maintained until 12/30/99. There were no fatalities during this period and fish showed no significant difference in feeding behavior during this period.

Total length (TL) and weight (W) were determined approximately every month for each fish. Growth in length was approximately 1 cm per month for both temperature regimes (Figure 11). At the beginning of the temperature experiment, juveniles in the experiment were slightly larger than wild fish found in the Hudson River, but were within the range of natural variation. Growth in weight was also similar for the two temperature treatments (Figure 12).

On 12/27/99, the final length and weights were:

	TL	SD	Range	W	SD	Range
Tank A:	14.77	2.19	10.70 - 19.00	31.95	14.48	9.60 - 63.30
Tank B:	15.21	2.52	11.00 - 21.00	36.62	19.82	11.00 - 88.90

Figure 11. Growth in length of captive young-of-year Atlantic tomcod under Low (18 C) and High (21 C) temperature conditions in the laboratory, 1999. Sizes of the wild young-of-year shown for comparison.

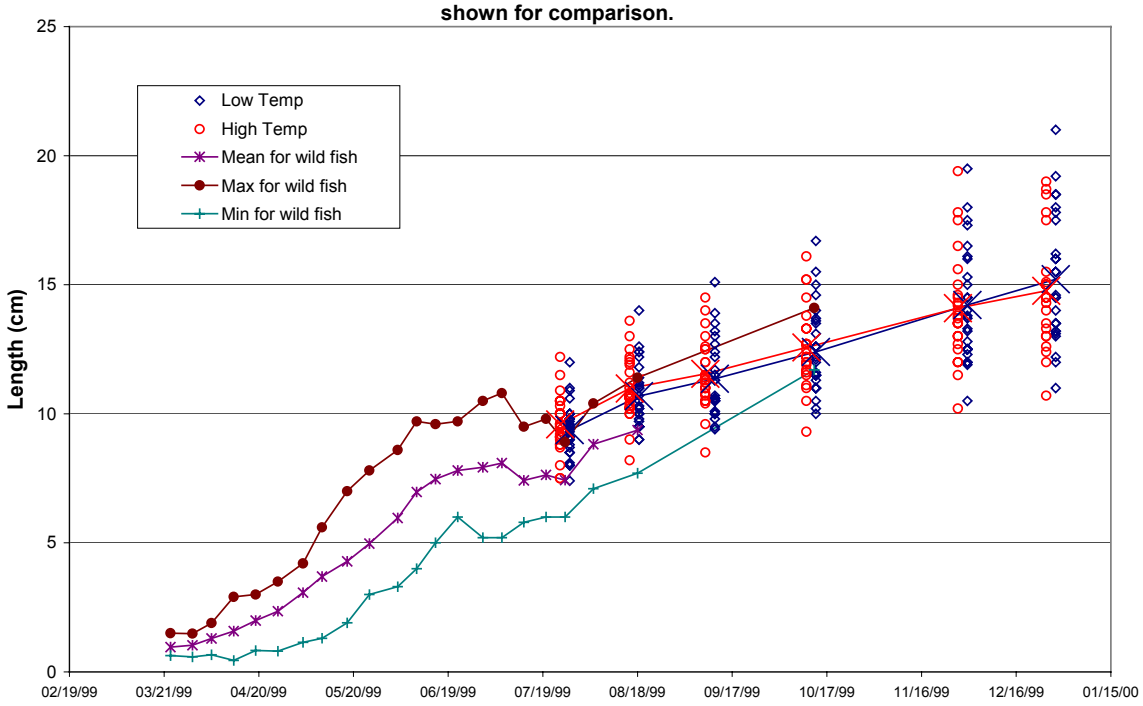
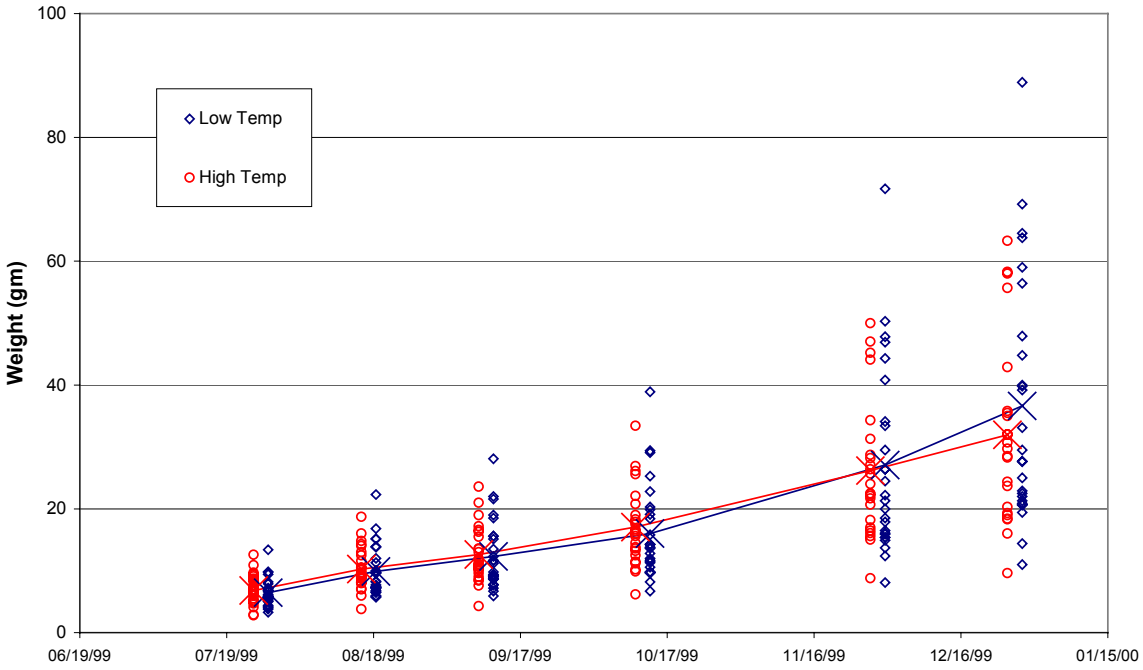


Figure 12. Growth in weight of captive young-of-year Atlantic tomcod under Low (18 C) and High (21 C) temperature conditions in the laboratory, 1999.



Experiment 5. Maturity and post-spawning survival of young-of-year

On 1/21/00 and 1/31/00 YOY from the above temperature tolerance experiment were placed in equal numbers into two 450 gal Hudson River System tanks. Temperature and daylight were reduced between 12/30/99 (still in 80 gal troughs) and 2/14/00 to simulate natural winter spawning conditions (i.e., 4 C, 9 hrs daylight, 3 ppt salinity).

On April 1, 2000 seven of the remaining 31YOY (now one year old) tomcod received implants of slow-release polymer compounds containing 50 ug of GnRH (courtesy of Dr. Y. Zohar, COMB, University of Maryland) in their upper dorsal musculature. On April 14, 2000, 13 days later, fish that received the GnRH implants and as well as a large number of fish that did not, but were maintained at water conditions favoring spawning in nature, were stripped of their gametes. Fertilized eggs were maintained at 5 C in a household type refrigerator where they completed their embryonic development. On May 18, 2000, 34 days after fertilization, animals began to hatch out of their egg membranes. (Note: There was also considerable variability in hatch out times in this experiment that ranged between 30 and 45 days in animals kept under identical conditions.) Free-swimming fish were placed in 10 liter black plastic buckets that floated in the 80 gal trough tanks at 7 C. When yolk sacs were almost completely resorted, rotifers and shrimp naupli were provided. (Note: As of the end of the study [6/26/00] approximately 15 fry were alive and doing well.)

Beginning on May 5, 2000, the water temperature was raised one degree on each day. On May 10, 2000, 30 remaining tomcod, now one year old, were moved from the 400 gal (Con Ed) tanks (11 C) to 80 gal long troughs with similar water temperature. The water temperature continued to be raised one degree each day until it reached 16 C (5/15/00). As the temperature reached 13 C, fish began to die in relatively large numbers (Table 2). The temperature was 16 C on 5/15. The temperature was decreased to 14 C by May 18. It is interesting to note that all of the dead animals were females with many eggs in their ovary (recall that these animals were brought to spawning condition). It is also interesting to note that although tomcod continued to die, catfish, white perch, and eels in the same tank and under the same conditions showed no deaths or signs of marked stress during this period. (Note: On June 26, 2000, nine [one year old] tomcod were alive and are being maintained at 18 C and 10 ppt (going to 15 ppt salinity)

Table 2. Results of temperature challenge experiment for wild adult Atlantic tomcod, 2000.		
Date	Temperature (C)	Number Die
May 5	6	0
May 5	7	0
May 7	8	0
May 8	9	0
May 9	10	0
May 11	12	0
May 12	13	1
May 13	14	4
May 14	15	0
May 15	16	5
May 18	14	3

IV. **DISCUSSION**

The experiments conducted during this project have provided information on temperature tolerance, growth, and life history of Hudson River Atlantic tomcod.

- Growth and feeding occur at temperatures up to 22.5 C.

  Atlantic tomcod young of year and adults both grew in the laboratory at temperatures up to 21 C. Growth of young-of-year was rapid and appeared similar to growth of wild fish of the same age. Yearling fish also fed normally and grew at temperatures up to 22.5 C.

- Temperature tolerance is size related.

  The two unplanned temperature challenges, one to 15 C and the second to 25 C, provided information on the thermal tolerance. Although the second challenge event subjected fish to a temperature much closer to the upper incipient lethal temperature (26.5 C), the mortality associated with both events was very similar. In both events, smaller fish had significantly higher probability of death than larger fish.

- Hudson River tomcod are not semelparous.

  The maintenance of post-spawning adult fish in the laboratory for periods approaching 12 months demonstrated that the Hudson River population is not semelparous. In the laboratory, fish were able to recover from the physiological stress of migration and spawning, regain growth, and prepare to spawn again when appropriate

environmental conditions were achieved.

- All fish appear to mature at age 1.

  Regardless of growth conditions during the first year of life, we saw no evidence that Hudson River tomcod would delay maturation under adverse conditions.

- Liver cancers appear much less prevalent than in past, and not evidently a cause of mortality.

  In all of the experiments conducted, the majority of fish had normal appearing livers (category 1), with category 2 and 3 livers accounting only 23% and 3% respectively of all livers for which condition was determined. As was seen by Dey et al. (1993), older fish exhibited a higher frequency of stage 2 and 3 livers than did Age 1 fish, although the frequencies are substantially lower. In experiment 2, the percentages of category 2 and 3 livers was higher for fish greater than 20 cm (approximately the cutoff between Age 1 and Age 2), than for smaller fish.

	Liver Category			
Size	1	2	3	Undetermined
<= 20 cm	71%	21%	2%	6%
>20 cm	50%	27%	8%	15%
Combined	67%	22%	3%	7%

- The population exhibits high rates of parasitic infestations, which may affect population dynamics.

  During the course of the study, a very high incidence of parasitic infection was observed in the population. Parasites would appear to be possibly of two types: an internal Acanthocephalan worm that infests the reproductive tract, and an external parasite that attaches to the body musculature, possibly a parasitic copepod (*Lerneae* sp.) commonly known as "anchor worms". An EPA (Gulf Breeze, Florida) parasitologist suggested, following an examination of specimens that we provided to him, that the internal worms belong to the Class Palaeacanthocephala and the Genus *Acanthocephalus*. According to a search of the USDA National Parasite collection (http://www.anri.barc.usda.gov/bnpcu/parasrch.htm), Acanthocephalans (*Echinorhynchus gadi* and *Paratenuisentis ambiguus*) have been previously reported in Atlantic tomcod.

  Acanthocephalans, or spiny-headed worms, are parasites of vertebrate intestinal systems, particularly of freshwater fish. Species that affect fish may have intermediate stages that use amphipods or copepods as hosts, and can also involve a paratenic (transport) host. Williams and Johnson (1994) list *Paratenuisentis ambiguus* as a species that uses *Gammarus tigrinus* (a common amphipod found in the lower part of the Hudson

estuary, and an important part of the tomcod diet) as an intermediate host, the American eel (Anguilla rostrata) as a final host, and can use Atlantic tomcod as a paratenic host. Acanthocephalans are unsegmented and usually recognized because of their proboscis, which has prominent chitinoid hooks and which may become withdrawn when the worms are removed from the host. The acanthocephalan life cycle is very simple and generally involves the shedding of eggs by the adult worm in the intestine. After passing out of the intestine, eggs are then eaten by the intermediate host, a copepod, ostracod, amphipod or isopod. Typically the intermediate or final fish becomes infected by eating the crustacean (Hoffman, 1999). If acanthocephalans are numerous, their armed proboscides may cause serious damage as they retract and reinsert the proboscis in different parts of the intestinal wall (Bullock, 1963a; Chubb et al., 1964; Hammond, 1967).

We have most frequently observed these parasites in feral spawning adults (December, January and February). The worms occur in large numbers in the upper third of the coelom (in the region of the intestine and liver). Adult worms are observed to have their probosci inserted into the wall of the intestine with the body portion extending into the body cavity. No round worms were observed in the 19 feral young of the year (less than one year of age) that died between 7/29/99 and 5/9/00. In feral adults and YOY that were brought into the laboratory during their first spring, parasites at any stage of development were not seen. We first observed worms in a limited number of animals when one year old and when brought to spawning condition by altering water quality conditions to simulate the natural (spawning) conditions and/or given implants of GnRH.

During the winter spawning season, the external parasites, probably anchor worms (*Lernaea* sp.), are also frequently seen protruding from the outer body wall of the fish in such frequency that one is inclined to describe the appearance to that of a pin cushion or porcupine (Fig. 10). Although the parasites do not have the two characteristic egg sacs typical of anchor worms, in the temperate zone they are known to pass the winter months as attached juvenile adults (Hoffman 1999).

It is quite apparent from the sheer number and anatomical location, that parasitic infections of the kind we have described could have a profound influence on the physiology of the animals, possibly contributing to the relatively short life cycle. The specific physiological processes affected by these roundworm parasites cannot be determined from these studies. We suggest that this is an important area of research that needs to be pursued. One particular aspect of this phenomenon is the relationship of the occurrence of the worms, the reproductive cycle and the age classes found in the natural environment. We hypothesize based on limited and inconsistent data derived form our studies of laboratory-reared YOY, that reproductive hormones, or the physiological state brought about by the preparation for spawning, may be contributing factors to the severity of parasitic infection. That parasites may rely on the hormonal milieu of their hosts has been previously reported in the literature for mammals.

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