SWIMMING SPEEDS OF JUVENILE ESTUARINE FISH IN A CIRCULAR FLUME[a]

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Abstract: Sustained voluntary swimming speeds of 5 species of juvenile estuarine fish were determined in a laboratory circular flume, 2.5 m in mean circumference. Successful tests depended on the fish's ability to avoid downstream displacement through positive rheotaxis. The following swimming speeds, in body lengths (BL/sec, were measured: 3 to 6 cm Atlantic menhaden (*Brevoortia tyrannus*), the species of primary interest, swam 5 (at 13 C) to 11 (at 30 C) BL/sec; striped mullet (*Mugil cephalus*), 3 cm, swam 8 (at 15 C) to 12 (at 25 C) BL/sec; pinfish (*Lagodon rhomboides*), 4 cm, swam 11 BL/sec (27 C); spot (*Leiostomus xanthurus*), 4 cm, swam 6 BL/sec (25 C); Atlantic croaker (*Micropogon undulatus*), 7 cm, swam 5 BL/sec (30 C). An evaluation of the apparatus and implications of the data for predicting impingement of juveniles on power plant intake screens are included.

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Once-through cooling systems used at most steam electric generating stations may entrain and kill small aquatic organisms passing through pumps and heat exchangers, or impinge and kill larger organisms on the intake screens. Fish that are positively rheotactic and can swim faster than the intake approach velocity may be able to avoid impingement or entrapment. The key environmental variables that influence impingement or entrapment of fish were listed by Bibko et al. (1974) as: water temperature, water velocity, illumination, fish concentration and species-specific behavioral patterns. Low dissolved oxygen concentrations, the presence of toxicants, and poor fish condition can also limit swimming performance (Kutty 1968, Peterson 1974, Brett et al. 1958) and increase impingement.

To design a station intake so that the fewest animals are overcome by intake velocities, it is necessary to know their swimming speeds under expected environmental conditions. The literature on burst and endurance speeds for a number of marine fish families was reviewed by Blaxter (1968). Although it is difficult to generalize from the literature on the endurance speed of fishes of similar body shape, maximum values up to 5-10 BL/sec may be approximated from published data for pelagic species up to 1 m in length (Bainbridge 1958) as well as small freshwater fish (Gray 1957). This means that typical approach velocities of 30 cm/sec for intakes without fish guidance systems (Barnes 1976) may impinge or entrain fish smaller than 6 cm.

Although there are many references to swimming studies on fish, no data were available on the sustained swimming speeds of fish likely to be affected by power stations located on estuaries or coasts of the southeastern United States. In the Beaufort Laboratory, several species of common estuarine fish were tested for their maximum sustained voluntary swimming speeds in a circular flume. Only sustained speed (one that can be maintained for minutes, e.g., passage through difficult areas) was measured; cruising speed (capable of being maintained one or more hours, e.g. migration) or burst speed (a single, non-sustainable effort, e.g. feeding or escape) were not determined. The main species was Atlantic menhaden because of its notoriety in causing serious impingement problems in several northeastern U.S. power stations (Young 1974). Other species tested were: striped mullet, pinfish, spot, and Atlantic croaker. Only small fish were tested, because most adult fish can exceed 30 cm/sec under favorable conditions.

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METHODS

Juveniles tested were seined from local estuaries and held in the laboratory under controlled conditions of salinity, temperature, and photoperiod in an open-flow seawater system (Hettler et al. 1971, Hettler 1974). In the acclimation tanks, the water intake was directed to generate water currents up to 20 cm/sec around the circumference of the 100-1 tanks, giving fish the opportunity to exercise voluntarily in the current during acclimation. A quiet-water refuge existed in the center of each tank. Acclimation salinities were uncontrolled, but usually were above 30 ppt, except when acclimating Atlantic menhaden for a few tests at 5 ppt. The photoperiod was maintained at 12 hr of light per day. Fish were acclimated in the laboratory for a minimum of 2 weeks before use. All species were fed twice a day on weekdays and once a day on weekends, but were not fed for 16 hr before testing. Experiments were conducted during spring and summer when small juveniles were available.

The 0.9 m diameter circular flume used in the tests (Fig. 1) is a modification

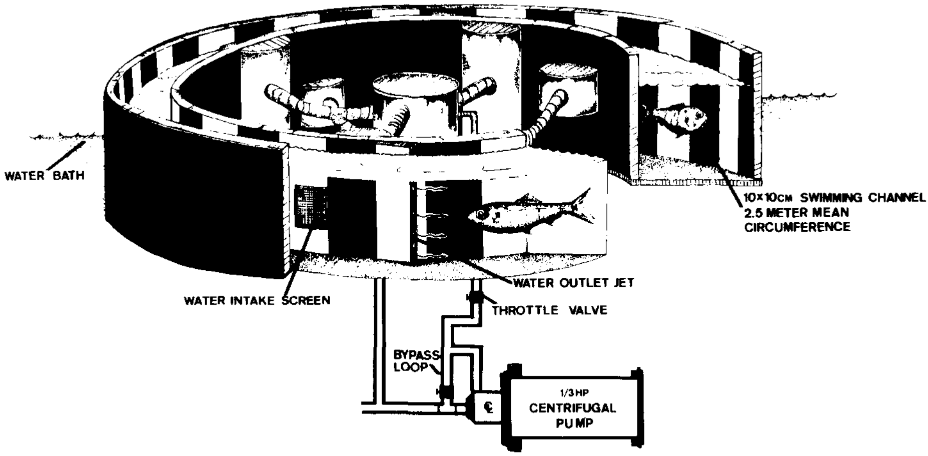

Fig. 1. Circular flume used to generate water velocities up to 70 cm/sec. Pump piping connects to center distribution manifold. Overflow sump, overhead lighting, and water bath not shown.

of an apparatus described by MacLeod (1967). Water was driven through the flume by a ⅓-hp centrifugal pump. All flume components were nonmetallic. Four vertical-slit inlet jets located equidistant on the inner wall forced water around the flume at speeds up to 70 cm/sec. Four screened outlets, also located along the inner wall, pulled water back to the pump. New sea water was added to the pump system at 5 l/min, and excess water was discharged via a screened overflow pump (not illustrated), also located on the inner wall. The flume was partially immersed in a water bath to control temperatures during each test within $\pm$ 0.1 C. The flume was illuminated from above by four 60 W incandescent bulbs with reflectors. Water speed was adjusted with throttle and bypass values.

The procedure for measuring swimming speeds depends on the ability of test fish to orient into the water flow and to remain stationary relative to visual references (alternating black and white bars). In each test, groups of 5 fish of the same species, closely matched in size, were placed in the flume from an acclimation tank. After a brief adjustment period with a slight current (6 cm/sec), the current speed was increased quickly to a level such that all fish were slowly displaced downstream. Three consecutive 2 min counts were made on each 5 fish group. The number of times fish passed a fixed reference mark was tallied during each 2 min test. The water speed was then measured by counting the number of laps that a small, neutrally buoyant marker (piece of sponge) traveled in 1 min and converting that to a cm/sec rate. Fish fork lengths were measured after the tests. The maximum swimming speed (S_{max}) was calculated using the following formula (from King 1969):

$$S\ max = V - \frac{LC}{TN}$$

where,

S max	=	maximum swimming speed (cm/sec)
V	=	current velocity (cm/sec)
L	=	cumulative total number of laps lost by all fish in test group
C	=	midline circumference (cm)
T	=	time duration of test (sec)
N	=	number of fish in test group

The problem of uncooperative individuals within a group was recognized in preliminary tests. A decision was made to use all 5 fish selected, even if during testing one or more fish became passive, failed to actively swim into the current, and, as a result, drifted during the remainder of the test. It was felt that these fish probably represent a portion of a normal population of differently motivated individuals, and consequently they should not be removed from the test group.

RESULTS

The data from 127 five-fish Atlatic m enhaden groups (3.2 to 5.6 cm fork length) are expressed in BL/sec (Fig. 2). Individual data points represent the mean value for

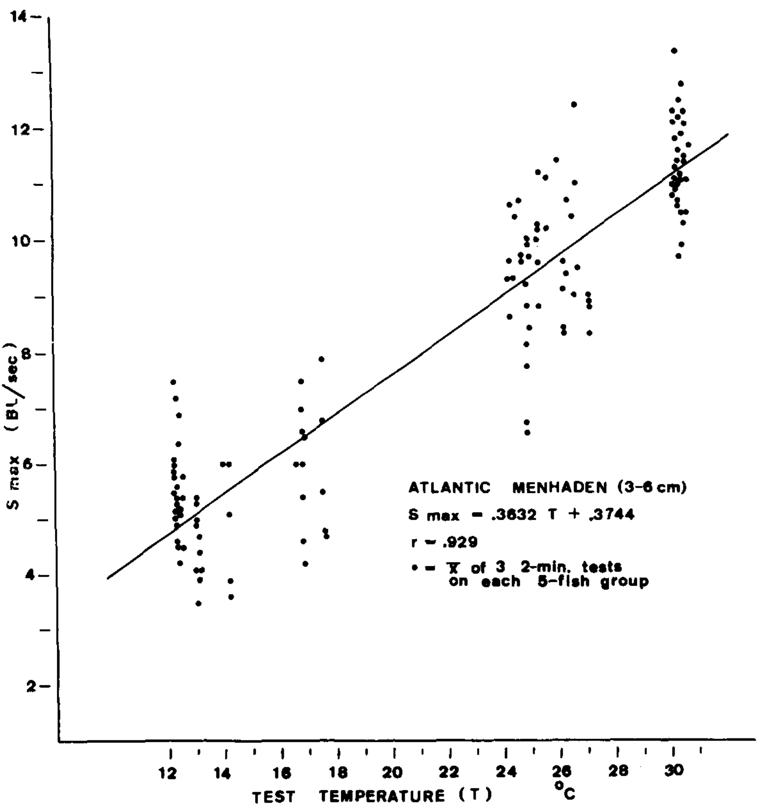

Fig. 2. Maximum sustained voluntary swimming speeds (S_{max}) for Atlantic menhaden.

each group for the 3 consecutive 2-min tests. The regression of maximum swimming speed on temperature was: $S_{max} = 0.3744 + 0.3632\ T$ in BL/sec, where T is the test temperature, with a correlation coefficient (r) value of 0.929. The actual speed can be found by multiplying the BL/sec value by a given fork length. For example, at 25 C, a 4 cm Atlantic menhaden can sustain an average speed of 38 cm/sec for 6 min, whereas the same-size fish at 15 C can only sustain 23 cm/sec.

Low salinity (5 ppt) did not (at the 0.05 level) significantly influence swimming speed of Atlantic menhaden when compared with salinities greater than 30 ppt (Table 1).

Table 1. Effect of salinity on maximum sustained speed of Atlantic menhaden juveniles.

Salinity (*ppt*)	*No. tests*	*Mean water temp.* (°C)	*Mean size* (*cm*)	*BL/sec*	*Standard deviation*
>30	9	30.3	4.8	11.8	0.582
5	6	30.2	4.7	12.3	0.808

Striped mullet, like Atlantic menhaden, increased swimming speed with temperature (Fig. 3). For 39 tests, $S_{max} = 1.2865 + 0.4292\ T$, with an r of 0.717. All striped mullet tested were the same size (2.8 to 3.4 cm), and at test temperatures (15 to 25 C) could swim 8 to 12 BL/sec, (24 to 36 cm/ sec), or about the same rate as 4 cm Atlantic menhaden.

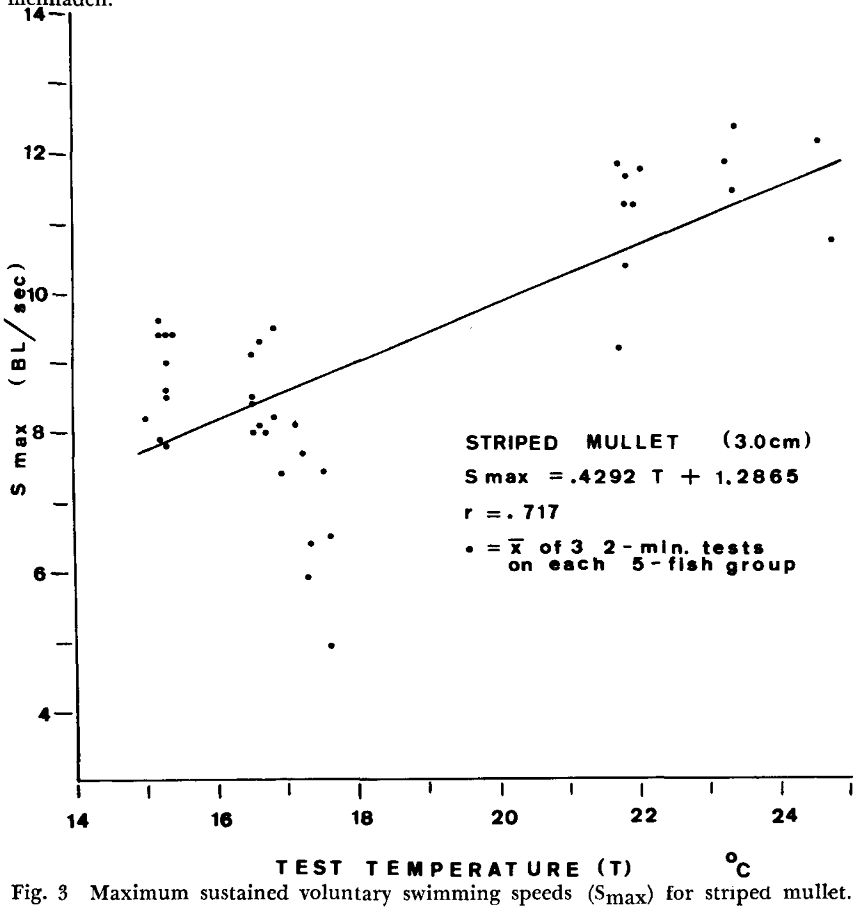

Fig. 3 Maximum sustained voluntary swimming speeds (S_{max}) for striped mullet.

For all species, each test comprised three 2-min measuring intervals, rather than one 6 min measuring interval, to determine if maximum voluntary speed would decrease during the test interval. A comparison of the means of the first, second, and third readings from a number of randomly chosen data sets for striped mullet and Atlantic menhaden illustrates the general pattern of all the data for these 2 species, i.e., their speed during the first 2 min was not significantly different (0.05 level) than their speed during the last 2 min (Table 2).

Juveniles of 3 other species were tested (Table 3). Although quite similar in body form and size, pinfish could sustain a speed nearly twice as fast as spot. No temperature effect can be shown as each species was run at 1 temperature.

Table 2. Comparison of means of the 3 consecutive readings in each test for striped mullet and Atlantic menhaden. Data sets were randomly chosen.

Species	*No. tests sampled*	*Mean BL/sec rate of each 2-min period*		
		1st	*2nd*	*3rd*
Atlantic menhaden	18	10.1	9.7	9.8
Striped mullet	22	9.8	9.2	9.2

Table 3. Maximum sustained swimming speeds for pinfish, spot and Atlantic croaker juveniles.

Species	*No. tests*	*Mean fork length (cm)*	*Mean water temp. (°C)*	*BL/sec*
pinfish	14	3.7	27 ± 0.5	10.8
spot	23	4.3	25 ± 1.5	5.8
Atlantic croaker	3	7.3	30 ± 0.5	5.1

DISCUSSION

Evaluation of Methods

Most references to swimming speed data disclose that the apparatus employed was designed for purposes other than fish impingement studies, i.e., for measuring metabolic rates at various swimming speeds or measuring effects of sublethal stress on swimming performance. The methodology used here was derived, after modification, from a device[a] suggested for standardizing testing procedures for power plant siting studies. That device was designed for portability so experiments could be site specific, since each site would probably have different environmental features, such as temperature, turbidity, dissolved oxygen, and pollutants.

We tried the recommended design, which was an open oval flume, 2.5 m in mean circumference in which water was circulated by a centrifugal pump through two vertical inlet jets on either side of the swimming channel. Water was withdrawn through a screened opening in the bottom of the flume just ahead of one inlet jet. Preliminary testing showed that certain sections of this recommended oval flume had lower than average water velocities and even eddy currents and provided places where fish could swim at a reduced rate and rest. Because of the irregular current pattern, we abandoned the recommended flume and designed the circular flume which gave more uniform water velocity. Because the fish were unrestricted in their movements within the circular flume and the method used to measure velocity averaged out any velocity anomalies near the walls and bottom, it was not necessary to determine whether the apparatus created laminar or turbulent flow. This is a major concern in tunnel respirometers where swimming speeds have often been measured, because current velocity is measured from a fixed point in a tunnel system.

[a]American National Standard. Entrapment/impingement: Guide to steam electric power station cooling system siting, design and operation for controlling damage to aquatic organisms at intake structures, N19. X-1975. (Proposed for acceptance as an ANSI Standard).

Fish of various sizes were tested in the circular flume from larvae less than 2 cm in fork length to adults up to 16 cm in fork length. Small larvae (pinfish, spot, Atlantic croaker, and Atlantic menhaden) usually failed to orient into the current and would merely drift, or would often become negatively rheotactic. Adult pinfish were always positively rheotactic, but could easily overcome the maximum flow of the flume; thus their maximum speed could not be determined. The apparatus seems most suitable for fish 3 to 6 cm long. For larger fish up to 18 cm the circular channel described by MacPhee and Watts (1975) may be more appropriate.

Sustained Voluntary Swimming Speeds

The relative importance of 2 variables, temperature and body length, cannot be precisely separated in the menhaden data. Menhaden size increased during the season concurrently with the normal increase in ambient water temperature so that, usually, smaller fish (3-4 cm) were tested at cooler temperatures and larger fish (4-6 cm) were tested at warmer temperatures. However, when absolute speed is reduced to body length per unit of time, size effect is essentially eliminated. Blaxter and Dickson (1959) determined that speed was independent of body size in 2 to 26 cm *Clupea harengus* and was $V = 7.6L^{0.04}$, where L is body length and V is actual speed (note that the exponent is almost 1.0). Similarly, Boyar (1961) found a maximum speed for 6-8 cm *C. harengus* of 9.5 BL/sec for 30 sec, and for all lengths averaged 6 to 9 BL/sec. *Clupea* has similar body form to *Brevoortia,* and it was assumed for my tests that fish length differences were less important than having temperatures correspond to appropriate seasonal levels for the particular size tested. Atlantic menhaden are unlikely to inhabit warm water as 3 cm fish or cool water as 6 cm fish in the southeastern United States.

Although low salinity increases respiration and growth rates of young Atlantic menhaden (Hettler 1975), it had no significant effect on maximum voluntary speeds in this study. It may be surmised that low salinity tends to increase spontaneous locomotor activity in menhaden, but does not increase their maximum swimming performance.

Because data for striped mullet were all from similarly-sized fish, body length did not affect results. The slopes of regressions of test temperature on body lengths per second were 0.43 for mullet ($Q_{10} = 1.62$) and 0.36 for menhaden ($Q_{10} = 1.56$), indicating similar temperature effects. Otto and Rice (1974) also found that yellow perch (*Perca flavescens*) initial swimming speeds were temperature dependent, with a Q_{10} of 1.6 from 10 to 20 C. Rulifson (in press) found that temperature had a highly significant effect for mullet, spot, and pinfish. For test periods equal to mine (6 min) Rulifson measured the following approximate rates: mullet—12 BL/sec (similar to mine); pinfish—9 BL/sec (lower); spot—8 BL/sec (higher). The slight differences in our data may be explained by the fact that his test fish were forced to swim to avoid an electrified grid, whereas in my experiments fish swam voluntarily.

Implications for Intake Structures

Assuming average approach velocities of 30 cm/sec at the trash rack/intake traveling screen locations of power plants, Atlantic menhaden, striped mullet, and pinfish, should be able to avoid being overcome by the current when they are at a body size large enough to be impinged on intake screen (normally 0.95 cm^2), except at cooler temperatures (less than 16 C for 4.5-cm menhaden, for example).

Of perhaps more concern than swimming speeds should be factors which affect orientation, particularly light. During preliminary tests, I observed that, in the absence of light, fish would drift in the flume. However, this loss of orientation occurred at a light level below which counts could be made by the unaided human eye as fish circulated in the flume, so the point at which orientation failed could not be determined. Other factors that would temporarily disrupt a school from otherwise successfully maintaining itself ahead of the intake may be more important in causing impingement than simple fatigue.

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