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RESPONSES OF JUVENILE CHINOOK SALMON, *ONCORHYNCHUS TSHAWYTSCHA*, AND AMERICAN SHAD, *ALOSA SAPIDISSIMA*, TO LONG TERM EXPOSURE TO TWO-VECTOR VELOCITY FLOWS

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CALIFORNIA DEPARTMENT OF WATER RESOURCES
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RESPONSES OF JUVENILE CHINOOK SALMON, *ONCORHYNCHUS TSHAWYTSCHA* AND AMERICAN SHAD, *ALOSA SAPIDISSIMA*, TO LONG TERM EXPOSURE TO TWO-VECTOR VELOCITY FLOWS[1/]

by

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ABSTRACT

The responses of young-of-the-year chinook salmon and American shad to two-vector flow conditions were studied in a rotating treadmill apparatus that simulated velocities near stationary vertical and sloped fish screens. Responses were measured by determining:

1. survival of fish for 6 h duration tests under light or dark conditions, where approach velocities of up to 10.7 cm/s (0.35 ft/s) were combined with past-screen velocities of up to 28.9 cm/s (0.95 ft/s), and

2. delayed effects of test conditions as reflected by mortality within 24 h.

Salmon successfully withstood 6 h exposure to all velocities along both vertical and sloped screen orientations. No significant difference in survival occurred between tests conducted in light or dark. Mortality caused by delayed effects of the tests was not appreciable.

Survival of shad during 6 h lighted tests was very high. However, their ability to withstand increasing velocities decreased in dark tests, with greater mortality along the sloped screen than the vertical screen. The greater part of mortality was due to 6 h exposure rather than 24 h delayed effects.

1/ Interagency Ecological Study Program for the Sacramento-San Joaquin Estuary, Technical Report No. 4. September, 1982.

INTRODUCTION

The proposed Peripheral Canal intake site on the Sacramento River is located on the downstream migration route of juvenile chinook salmon and American shad. The magnitude of water diversions, and the need to minimize fish loss into the canal, requires a fish screening facility of unprecedented size. Concepts for a "positive barrier, low velocity" fish screen include a stationary perforated plate structure on the river bank which may be up to a mile long.

Fish entrained to the vicinity of the screen will encounter water velocities caused primarily by two flow vectors. Water diversion from the river into the canal will produce an approach velocity toward the fish screen, and may cause impingement of fish on the screen. The second vector, a screen passing velocity, is comprised of water remaining in the river channel, and may act as a guidance flow for fish along the screen. With the fish screen located directly "on-river," a passing velocity with a net downstream flow will guide fish away from the screen. However, in the event of tidal reversals, an upstream flow could delay passage of fish, increasing exposure time to as much as 6 h. The study presented here was part of investigations into the "on-river" screen concept, and particularly examines the effects that prolonged exposure to water velocities near the screen will have on juvenile salmon and shad.

Swimming ability in relation to impingement velocities has been studied for chinook salmon by Kerr (1953), Greenland and Thomas (1972), and Sazaki et al. (1972) for short test durations (6-10 min.). Katz, Pritchard, and Warren (1959), and Davis et al. (1963) examined swimming endurance over periods of up to two days. Similar swimming performance evaluations of juvenile American shad for periods ranging from 6 min. to 6 h also have been conducted (Fisher 1976, 1981).

The above investigations involved the testing of fish in water flow of a single vector. My study was concerned with the reaction of salmon and shad to a two-vector flow, combined approach and passing velocities. Tests under both light and dark conditions were run along vertical and sloped screen surfaces to determine survival for a 6 h exposure, and 24 h post-test mortality. Results will be used to develop Peripheral Canal fish screen design and operational criteria.

METHODS

Test Apparatus

A variety of techniques has been used to determine swimming performance of fish (Blaxter 1969). Methods involving flumes, tunnels, or circular troughs have utilized paddle wheels (MacLeod 1967), pumps (Thomas et al. 1964, Brett 1967), or rotational momentum (Brett et al. 1958, Bainbridge 1960) and water jets (Hettler 1978) to produce test velocities primarily of unidirectional flow. Heuer and Tomljanovich (1979) evaluated the screen avoidance response of larval fish in a flume using a limited two-vector flow.

A swimming ability treadmill (Figure 1) was designed for this study to subject fish to simulated two-vector flow conditions envisioned at the fish screen. A velocity component approaching a stationary screen (V_A), and a vector passing along the same screen (V_P) were simultaneously produced in a circular channel 0.3 m (1.0 ft) wide and 8.6 m (28.3 ft) in median circumference. The channel was formed by two concentric vertical cylinders made of 16 gauge aluminum plate, performated with 3.97 mm (5/32 in.) holes on 5.56 mm (7/32 in.) centers. Each cylinder was 0.7 m (2.3 ft) tall and had diameters of 3.0 m (10.0 ft) and 2.4 m (8.0 ft), respectively, resulting in a 0.3 m (1.0 ft) test space. The larger diameter cylinder, comprising the outer channel wall, represented the stationary test screen. The smaller cylinder was mounted on a turntable, forming the channel's inner wall and floor. A drive shaft connected the turntable to a rheostatically controlled 3 hp electric motor which allowed variable speed rotation. The entire treadmill was enclosed in a steel tank (test chamber) 3.7 m (12.0 ft) in diameter and 2.7 m (9.0 ft) tall. Water was introduced from a constant head tank into the test chamber through a 0.6 m (2.0 ft) diameter inlet in the floor of the chamber centered within the treadmill. A 2.4 m (8.0 ft) long rectangular weir was located across a draining bay in the side of the chamber.

Operation of the apparatus was started by filling the chamber and submerging the treadmill to a depth of 0.3 m (1.0 ft) in the test channel. Water level was manually adjusted by a gate valve and point gauge. A flow of water radiated from the inlet through the treadmill and drained over the weir.

The velocity of each flow vector could be controlled independently from the other. Approach velocity to the stationary channel wall depended on withdrawal of water from the channel. Withdrawal rates were regulated by adjusting the discharge weir height while maintaining a constant water depth in the channel. Velocity of the second flow vector passing along the stationary screen was controlled by the speed of turntable rotation. A stopwatch was used to set rotation speed, with one revolution in 55 s equivalent to a linear speed of 0.15 m/s (0.5 ft/s). Flow in the test channel was imparted by circular momentum, thus slippage occurring between turntable and water resulted in the actual water velocity being lower than rotational velocity (Figure 2).

Test Fish

Swimming tests were conducted during 1977-1979 using juvenile wild fish collected with a 15.2 X 1.2 m (50 X 4 ft) beach seine. The testing schedule corresponded to the seasons of natural occurrence of each species. Chinook salmon were caught in the Sacramento River above Red Bluff Dam and from the American River near Sacramento between February and June. An exception was one group of salmon taken from the artificial spawning channel of the Tehama-Colusa Canal at Red Bluff. American shad were gathered during July through October from various locations along the Sacramento River between Rio Vista and Sacramento.

Fish were transported in aerated containers to the testing facility at Hood, California, where they were transferred to stainless steel holding tanks. Unfiltered Sacramento River water was pumped directly into holding areas for once through circulation. Velocities through the tanks were erratic but generally less than 0.6 cm/s (0.02 ft/s).

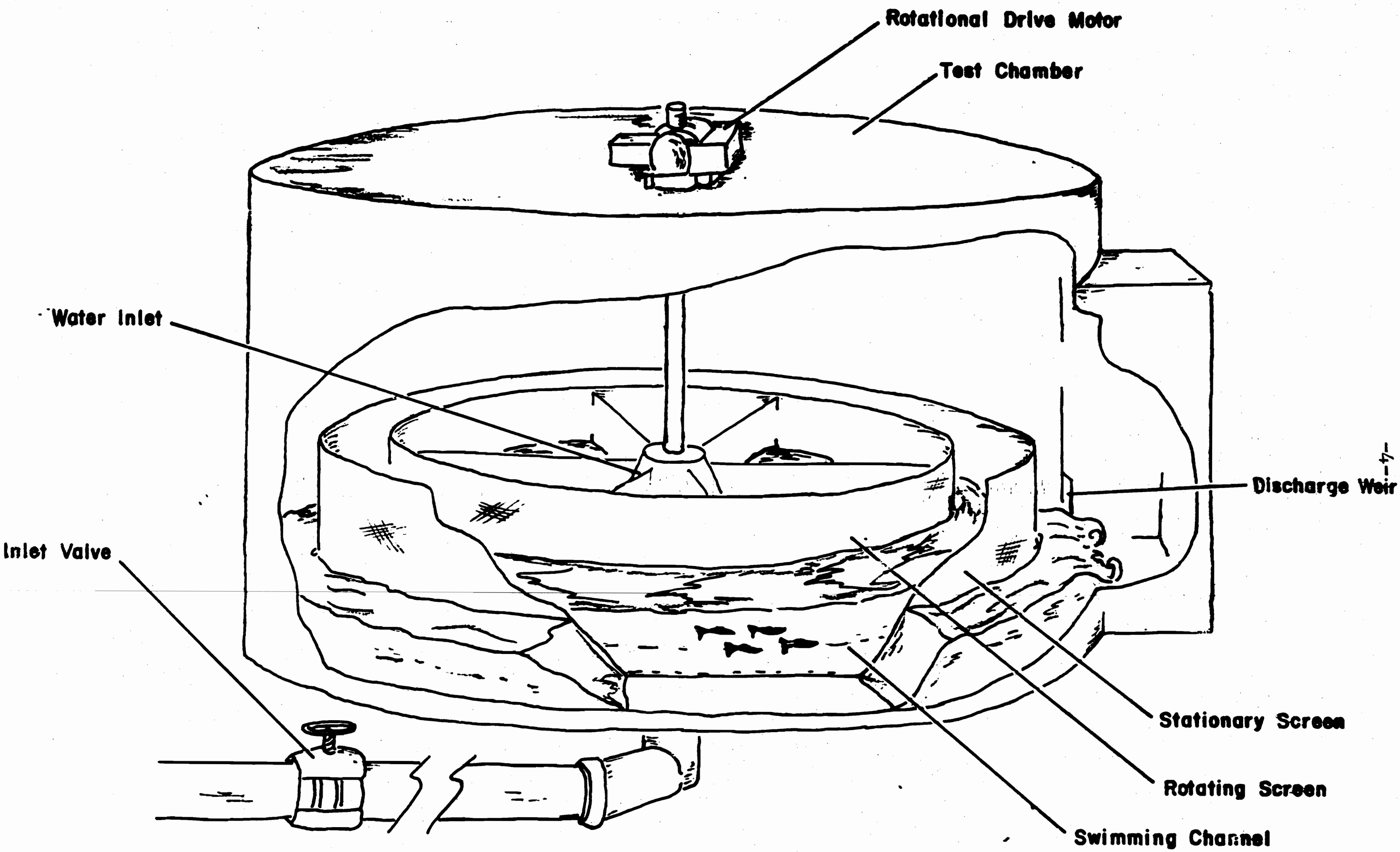
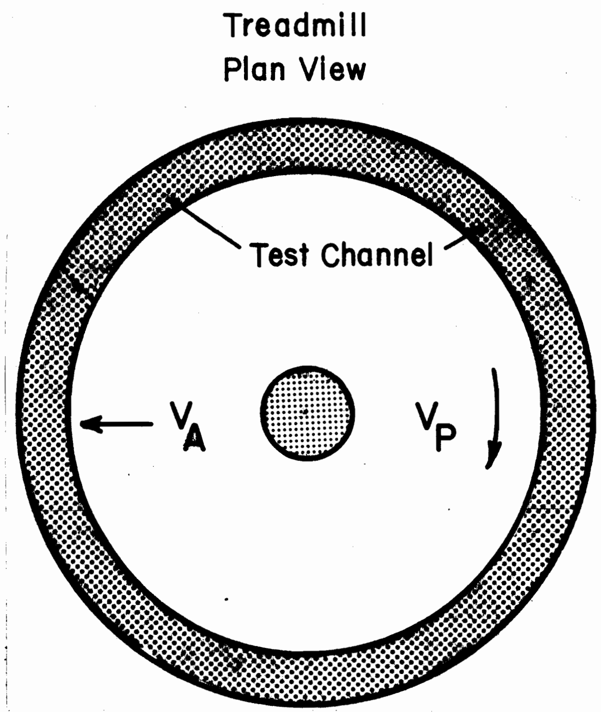
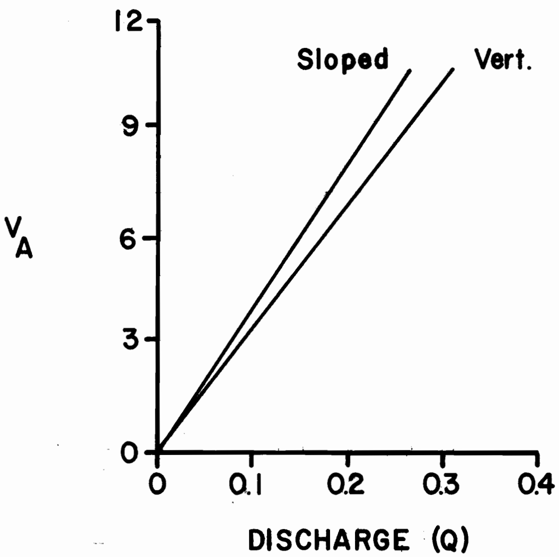


FIGURE 1. DIAGRAM OF LONG TERM SWIMMING ABILITY TEST DEVICE (TREADMILL).

	Q (m^3/s)	V_A (cm/s)
Sloped Screen	0.08	3.0
	0.15	6.1
	0.27	10.7
Vertical Screen	0.09	3.0
	0.18	6.1
	0.31	10.7



ROT.	V_P (cm/s)
0	0
15.2	4.9
30.5	11.3
45.7	[illegible]
61.0	23.5
76.2	28.9



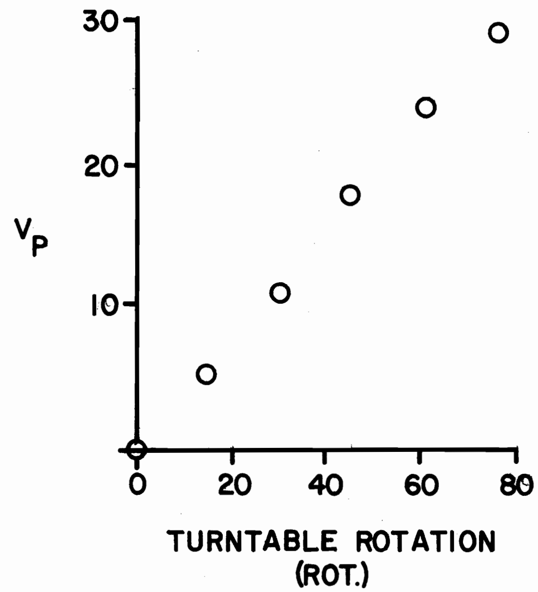


FIGURE 2. WATER VELOCITIES OF SCREEN APPROACH VECTOR (V_A) AND SCREEN PASSING VECTOR (V_P) PRODUCED IN THE TREADMILL.

Both species were held at least 24 h prior to testing under average illumination of 3.5 ft candles and fed three times daily with Oregon Moist Pellets (OMP). Food was withheld at least 6 h before testing.

Test Parameters

Screen Angle

Two stationary screen orientations were tested in the treadmill. A series of tests was conducted with the outer wall of the test channel positioned as previously described, in a vertical position essentially perpendicular to the approach velocity. In a second series of tests, the stationary screen was sloped at a 45^{o} angle away from the approach vector. This configuration reduced the test space by approximately 50% (Figure 3).

Velocities

Flow conditions used in the swimming tests were produced using combinations of the approach and passing screen velocities. Approach velocities of 3.0, 6.1, or 10.7 cm/s (0.1, 0.2, or 0.35 ft/s) were used, together with passing velocities of 4.9, 11.3, 17.4, 23.5, or 28.9 cm/s (0.16, 0.37, 0.57, 0.77, or 0.95 ft/s).

Light

Four 200 watt incandescent lamps suspended above the treadmill provided an average illumination of 6.33 foot-candles at the water surface during tests conducted in the light. For tests under dark conditions, lamps were gradually dimmed over a period of thirty minutes to produce a condition with less than 1×10^{-3} foot candles.

Testing Procedure

The treadmill, like the holding facilities, was supplied with unfiltered water pumped from the Sacramento River. Test water conditions therefore approximated those found in the river during each season. Mean temperature and secchi disc measurements were 15.3 C (59.5 F) and 30.5 cm (12.0 in.), respectively during chinook salmon tests in the spring, and 21.2 C (70.2 F) and 51.4 cm (20.2 in.) in the summer when American shad were tested.

Immediately preceding a swimming test, fish were selected from the holding area and placed in plastic buckets for introduction to the treadmill. Fish which were diseased or obviously in poor physical condition were discarded. Tests were not intended to differentiate the responses of fish according to size. However, as fish were selected for a test, they were visually sorted into a 20 mm size range. Tests were replicated throughout the seasonal occurrence

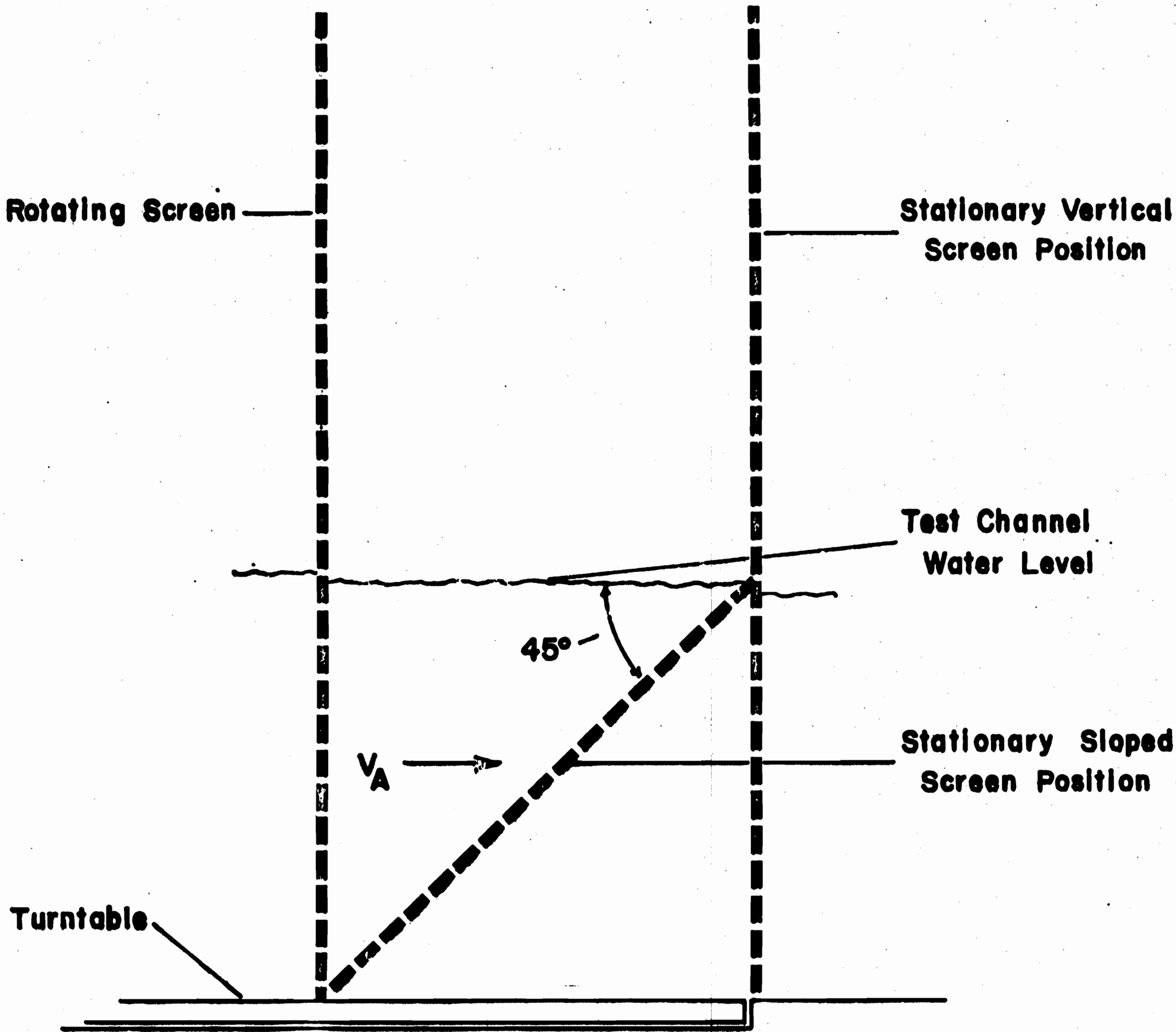


FIGURE 3. SCHEMATIC CROSS-SECTION OF TREADMILL TEST CHANNEL, SHOWING ORIENTATION OF VERTICAL AND SLOPED STATIONARY SCREEN.

of a species to cover the size range within the population. Salmon were tested in groups of 100 fish, while twenty shad were used per test. An equivalent number of fish was chosen for an accompanying control group to determine effects of handling. This group was placed in the treadmill and immediately removed into a holding area. American shad tests included an additional control group for holding effects. These groups were simply moved from one holding area to another.

Groups of fish were placed in the treadmill with test velocity conditions operating. Release was accomplished by immersing the bucket and allowing fish to swim out. Aside from a gradual reduction of light level for dark tests, no acclimation period was allowed.

Test duration was 6 h. Attempts were made to record swimming behavior throughout the tests, but water turbidity and surface turbulence made consistent observations difficult. At the conclusion of the 6 h period, fish were recovered from the treadmill. Those still swimming were considered to have survived test conditions, and were held for an additional 24 h at which time delayed mortality was recorded. All fish were measured to the nearest mm fork length (FL) at the end of a test.

Results of 6 h survival were analyzed using a multiple regression (Steel and Torrie 1960) for the relationship of approach velocity, passing velocity, and light conditions. Partial correlation coefficients were calculated to determine the relative importance of each test variable to survival.

Results of 24 h delayed mortality and test-end instantaneous mortality were regressed on passing velocity for each approach velocity-light condition. Differences between regressions for instantaneous and 24 h mortality were analyzed by a test of the equality of slopes (Sokal and Rohlf 1969). Data used in the analyses were in the form of arc sine transformations of percent swimming or mortality.

RESULTS

Chinook Salmon

Vertical Screen Tests

The vertical screen orientation was used to test 5,011 juvenile salmon ranging in size from 30.0 to 89.0 mm (1.2 to 3.5 in.) FL, with a mean size of 51.6 mm (2.0 in.) FL. Multiple regression for the relationship of light, approach velocity, and passing velocity to $\sin^{-1}\sqrt{\%\ \text{swimming}}$ at the end of a 6 h test, accounted for 57% of the variation in survival. Partial correlations ranked approach velocity ($r = -0.7$, $p < 0.05$) and passing velocity ($r = -0.4$, $p < 0.05$) in respective order of their effect on salmon survival. Light condition ($r = 0.35$, $p > 0.1$) did not show a significant effect on survival.

Since light was not a significant factor in the ability of salmon to survive 6 h exposures, the data for light and dark tests was averaged, and subsequently analyzed for the multiple regression of approach and passing velocities on survival (Figure 4). This analysis produced a significant relationship ($F = 16.35$, $p < 0.001$), accounting for 73% of the variability. Partial correlations indicated that both velocity variables had significant effects, with V_A ($r = -0.82$, $p < 0.01$) ranked above V_P ($r = -0.65$, $p < 0.01$). Twenty-four h mortality as a result of delayed test effects was not determined for the vertical screen tests on salmon.

Sloped Screen Tests

Sloping screen tests were accomplished with 8,012 salmon. Sizes of fish ranged from 30.0 to 89.0 mm (1.2 to 3.5 in.) FL, with a mean size of 54.2 mm (2.1 in.) FL. Multiple regression of light condition, approach velocity, and passing velocity versus survival accounted for 36% of the variation. Partial correlation coefficients for approach velocity ($r = -0.37$, $p < 0.05$), and passing velocity ($r = -0.49$, $p < 0.01$) were both significant, while the effect of the light variable was not significant ($r = 0.24$, $p > 0.3$).

The relationship between salmon 6 h survival along the sloped screen and velocity was further analyzed by averaging the results of light and dark tests, and calculating the multiple regression of approach and passing velocities on $\text{sine}^{-1}\sqrt{\%\text{ swimming}}$ (Figure 5). The analysis accounted for 60% of the variability in survival ($F = 8.9$, $p < 0.005$). Partial correlations indicated that salmon were less able to withstand 6 h exposure as velocity increased, with V_P having more of an effect ($r = -0.71$, $p < 0.01$), than V_A ($r = -0.55$, $p < 0.05$).

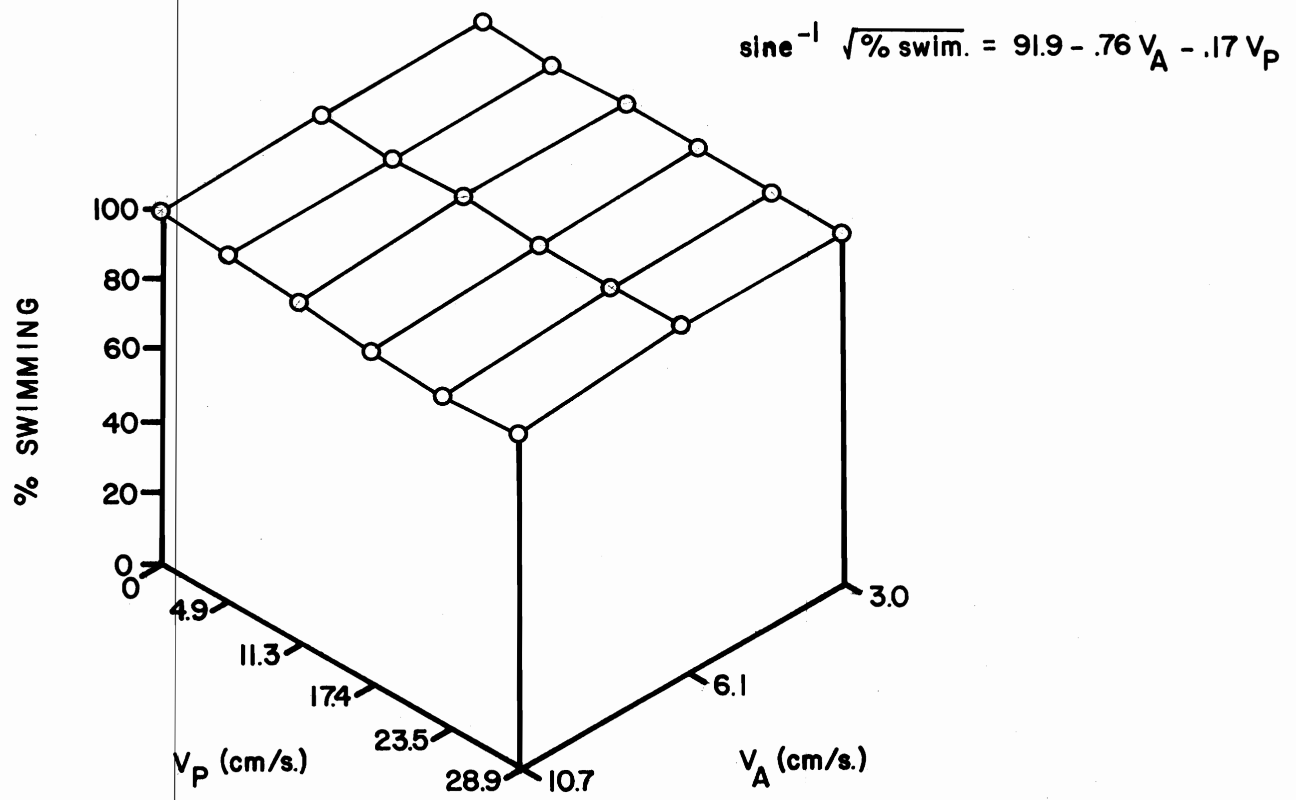
Delayed effects of test conditions on salmon were analyzed by comparing 24 h post-test mortality to test-end mortality. A linear regression of 24 h delayed mortality on passing velocity was statistically homogenous to the regression of test-end instantaneous mortality for all approach velocities under both light and dark conditions. The analysis indicates that the variation between 24 h and test-end mortality over the range of passing velocities was not significant. Delayed mortality was generally less than instantaneous mortality and contributed little to total mortality (Table 1).

American Shad

Vertical Screen Tests

Along the vertical screen configuration, I tested 1,403 shad of mean size 65.6 mm (2.6 in.) FL, ranging 31.0 to 104.0 mm (1.2 to 4.1 in.) FL. Analysis of light, approach velocity, and passing velocity vs. $\text{sine}^{-1}\sqrt{\%\text{ swimming}}$) produced a multiple regression accounting for 84% of the variation in survival. Partial correlation coefficients indicated that all independent variables were significant. Light was the most important test variable affecting the ability of shad to survive 6 h exposures ($r = 0.75$, $p < 0.001$). Approach velocity ($r = -0.68$, $p < 0.001$) and passing velocity ($r = -0.37$, $p < 0.05$) were next in order of their effect on survival.

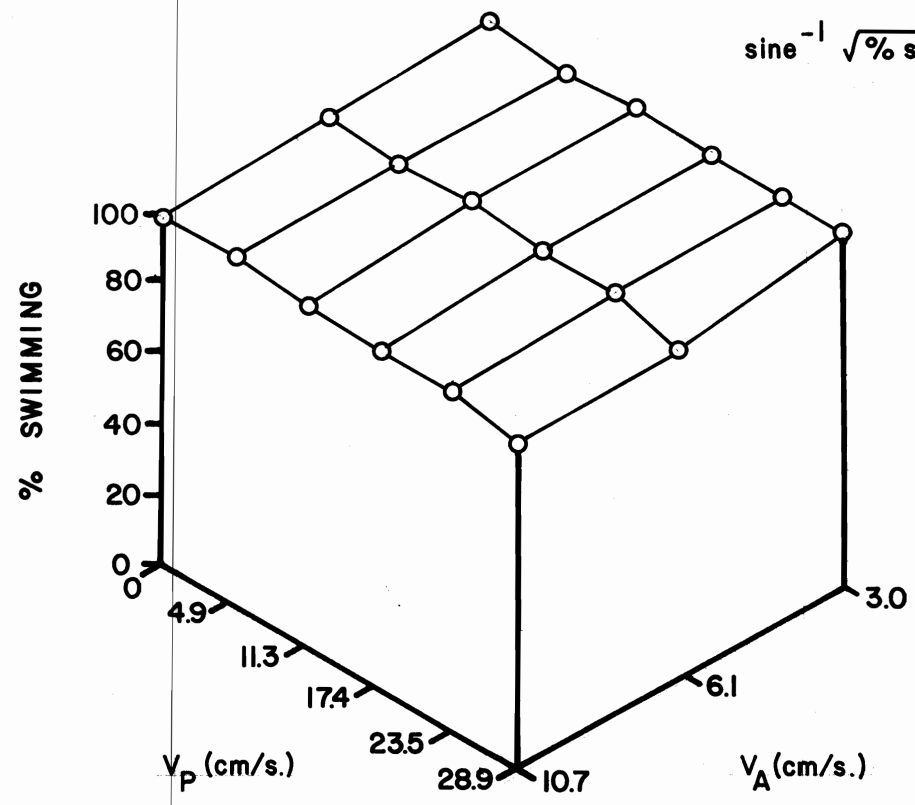
Due to the dramatic difference in the survival of shad between light and dark tests (Figure 6), analyses of velocity effects for each light condition were made. For tests conducted in the light, the multiple regression of approach and passing velocity on survival accounted for 64% of the variability ($F = 10.76$,



% Swimming @ 6 H.

V_A \ V_P	0	4.9	11.3	17.4	23.5	28.9
3.0	100	99.5	100	99.5	99.5	99.0
6.1	100	99.5	99.8	99.2	97.9	98.9
10.7	99.5	99.4	97.7	95.8	95.6	97.1

FIGURE 4. SWIMMING ABILITY OF CHINOOK SALMON IN RELATION TO APPROACH VELOCITY (V_A) AND PASSING VELOCITY (V_P) IN VERTICAL SCREEN TESTS.



$$\sin^{-1}\sqrt{\%\ \text{swim.}} = 93.5 - .61\,V_A - .35\,V_P$$

% Swimming @ 6 H.

V_P	0	4.9	11.3	17.4	23.5	28.9
3.0	100	99.4	100	99.5	99.0	99.2
6.1	99.7	99.0	100	98.1	98.9	93.4
10.7	99.5	100	98.3	96.2	97.0	93.6

FIGURE 5. SWIMMING ABILITY OF CHINOOK SALMON IN RELATION TO APPROACH VELOCITY (V_A) AND PASSING VELOCITY (V_P) IN SLOPED SCREEN TESTS.

TABLE 1. Comparison between test-end instantaneous mortality and 24 h delayed mortality of chinook salmon in sloped screen tests.

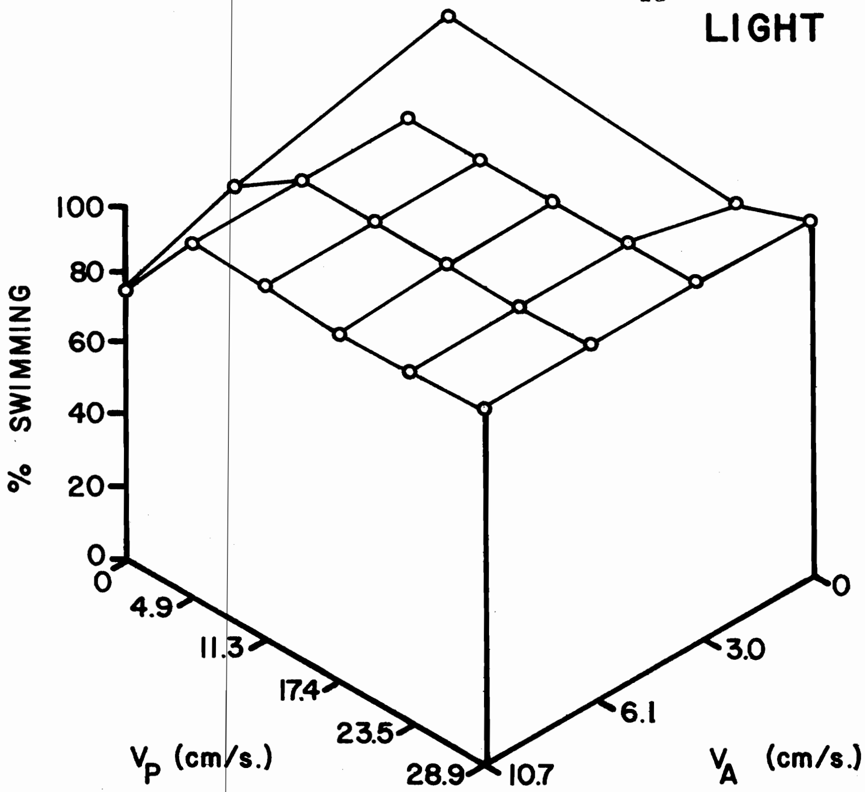
LIGHT TESTS

V_A	V_P	% Mortality Test End	24 h	Total	
3.0	4.9	0	0.1	0.1	$\sin^{-1}\sqrt{\%\text{ end mort.}} = 0.37 - 2.2\ V_P$
	11.3	0	0.5	0.5	$\sin^{-1}\sqrt{\%\text{ 24 h mort.}} = 0.13 + 1.7\ V_P$
	17.4	1.0	0.5	1.5	F 4.97 $p > 0.1$
	23.5	1.2	0.5	1.7	
	28.9	1.5	1.0	2.5	
6.1	4.9	0.5	0	0.5	$\sin^{-1}\sqrt{\%\text{ end mort.}} = 0.15 + 0.36\ V_P$
	11.3	0	0	0	$\sin^{-1}\sqrt{\%\text{ 24 h mort.}} = .003 + 1.09\ V_P$
	17.4	0	1.0	1.0	$F = 0.51$ $p > 0.5$
	23.5	0.5	0	0.5	
	28.9	1.4	0	1.4	
10.7	4.9	0	0.5	0.5	$\sin^{-1}\sqrt{\%\text{ end mort.}} = .09 + 1.92\ V_P$
	11.3	1.0	1.0	2.0	$\sin^{-1}\sqrt{\%\text{ 24 h mort.}} = .02 + 4.57\ V_P$
	17.4	1.0	0.5	1.5	$F = 0.1$ $p > 0.5$
	23.5	0	1.5	0.5	
	28.9	0.9	0.5	1.4	

DARK TESTS

V_A	V_P	% Mortality Test End	24 h	Total	
3.0	4.9	0	1.0	1.0	$\sin^{-1}\sqrt{\%\text{ end mort.}} = 0$
	11.3	0	1.0	1.0	$\sin^{-1}\sqrt{\%\text{ 24 h mort.}} = .04 + 5.53\ V_P$
	17.4	0	1.5	1.5	$F = 1.56$ $p > 0.1$
	23.5	0	1.0	1.0	
	28.9	0	1.5	1.5	
6.1	4.9	1.5	0.4	1.9	$\sin^{-1}\sqrt{\%\text{ end mort.}} = 0.2 + 11.5\ V_P$
	11.3	1.0	0.2	1.2	$\sin^{-1}\sqrt{\%\text{ 24 h mort.}} = 0.8 + 2.83\ V_P$
	17.4	2.8	1.0	3.8	$F = 0.24$ $p > 0.5$
	23.5	2.4	0.5	2.9	
	28.9	4.0	0.9	4.9	
10.7	4.9	0	0	0	$\sin^{-1}\sqrt{\%\text{ end mort.}} = .63 - 0.29\ V_P$
	11.3	2.5	1.0	3.5	$\sin^{-1}\sqrt{\%\text{ 24 h mort.}} = .42 - 0.56\ V_P$
	17.4	5.3	2.0	7.3	$F = 1.49$ $p > 0.1$
	23.5	5.5	2.1	7.6	
	28.9	8.1	3.9	12.0	

LIGHT

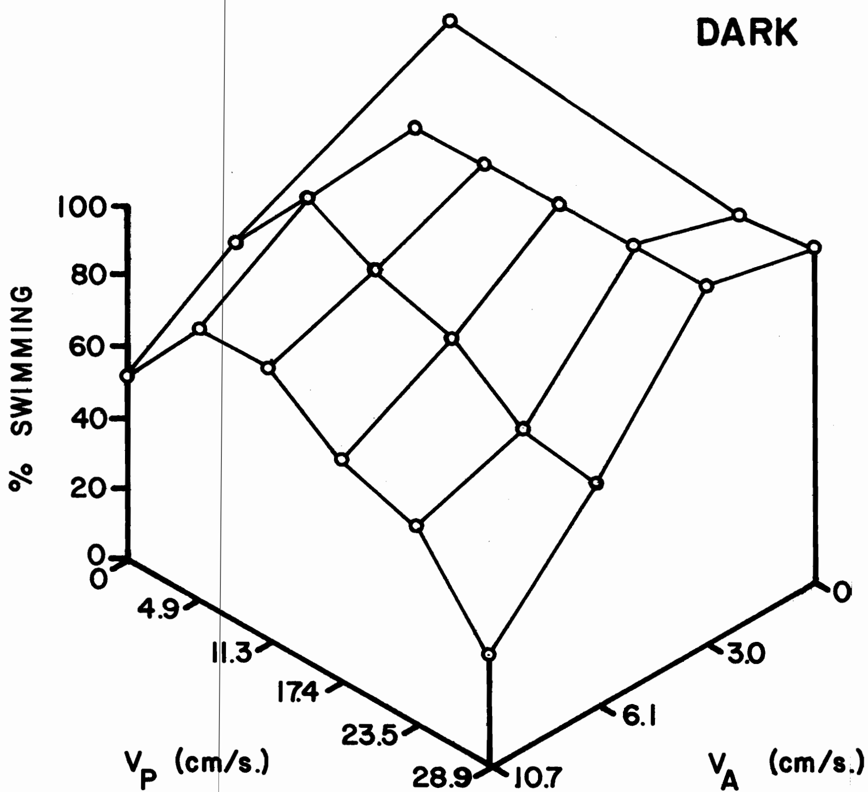


% Swimming @ 6 H.

V_A \ V_P	0	4.9	11.3	17.4	23.5	28.9
0	100	-	-	-	93.1	89.7
3.0	-	100	100	100	100	100
6.1	88.1	100	100	99.7	99.4	99.4
10.7	77.8	100	100	98.7	98.5	99

$$\sin^{-1}\sqrt{\%\ \text{swim.}} = 94.2 - .49V_A - .17V_P$$

DARK



% Swimming @ 6 H.

V_A \ V_P	0	4.9	11.3	17.4	23.5	28.9
0	100	-	-	-	93	90
3.0	-	98.5	100	100	100	100
6.1	74.2	96.2	87.5	81.9	69.1	65.2
10.7	55.3	78	78.9	64	58.8	35.7

$$\sin^{-1}\sqrt{\%\ \text{swim.}} = 108.7 - 4.5V_A - .62V_P$$

FIGURE 6. SWIMMING ABILITY OF AMERICAN SHAD IN RELATION TO APPROACH VELOCITY (V_A) AND PASSING VELOCITY (V_P) IN VERTICAL SCREEN TESTS.

$p < 0.005$). Partial correlation coefficients attributed equivalent effects to both V_A ($r = -0.69$, $p < 0.01$) and V_P ($r = -0.68$, $p < 0.01$). For the dark tests the relationship of survival to approach and passing velocities was also significant ($F = 25.7$, $p < 0.001$), covering 81% of the variability in survival. Partial correlation ranked increased approach velocity as more important in decreasing survival ($r = -0.89$, $p < 0.001$) than was the effect of passing velocity ($r = -0.58$, $p < 0.05$).

The mortality of shad in vertical screen tests was analyzed to determine if mortality occurring during the 6 h test period was different than that which occurred 24 h post-test, as a result of delay effects. Regressions of 24 h mortality on passing velocity and regressions of test-end mortality on passing velocity were statistically homogenous at all approach velocities in light tests, and at V_A = 3.0 cm/s (0.1 ft/s) under dark conditions. Comparison of the regression slopes of 24 h and test-end mortality for dark tests at approach veloiities of 6.1 and 10.7 cm/s (0.2 and 0.35 ft/s), showed that delayed mortality varied significantly from instantaneous mortality (Table 2). For these conditions, increased passing velocity caused higher mortality during the 6 h test than during the following 24 h period.

<u>Sloped Screen Tests</u>

The mean size of 1,800 American shad tested in sloped screen tests was 45.3 mm (1.8 in.) FL, ranging from 23.0 to 85.0 mm (0.9 to 3.3 in.) FL. The multiple regression for light, approach velocity, and passing velocity versus $\sin^{-1}\sqrt{\%\ \text{swimming}}$ accounted for 82.5% of the variability in survival. Partial correlations ranked the light condition as the most important factor ($r = 0.88$, $p < 0.001$) determining shad survival. Approach velocity ($r = -0.61$, $p < 0.001$) and passing velocity ($r = -0.62$, $p < 0.001$) also had significant effects.

The effect of velocity on survival was further analyzed for both the light and dark condition (Figure 7). Multiple regression of approach and passing velocity on survival for light tests did not show a significant relationship ($F = 2.17$, $p > 0.1$). The regression for survival to both velocities for darkened conditions, however, was highly significant ($F = 75.54$, $p < 0.001$) and accounted for 93% of the variation. Increases in each velocity vector contributed equally to decreasing survival as indicated by a partial correlation coefficient of -0.93 for V_A and for V_P, both of which were significant ($p < 0.001$).

Analysis of the mortality of shad along the sloped screen showed that the linear regressions of 24 h delayed mortality and test-end mortality on passing velocity were not statistically different under light conditions. A significant difference was present between 24 h and test-end results for dark tests, with higher mortality occurring during 6 h exposure than as a result of delayed effects 24 h post-test (Table 3).

DISCUSSION

The responses of chinook salmon to the treadmill tests indicate that the species can be successful in withstanding long term exposure to a fish screen under two-vector flows within the range of velocities tested. More than 90% of the fish

TABLE 2. Comparison between test-end instantaneous mortality and 24 h delayed mortality of American shad in vertical screen tests.

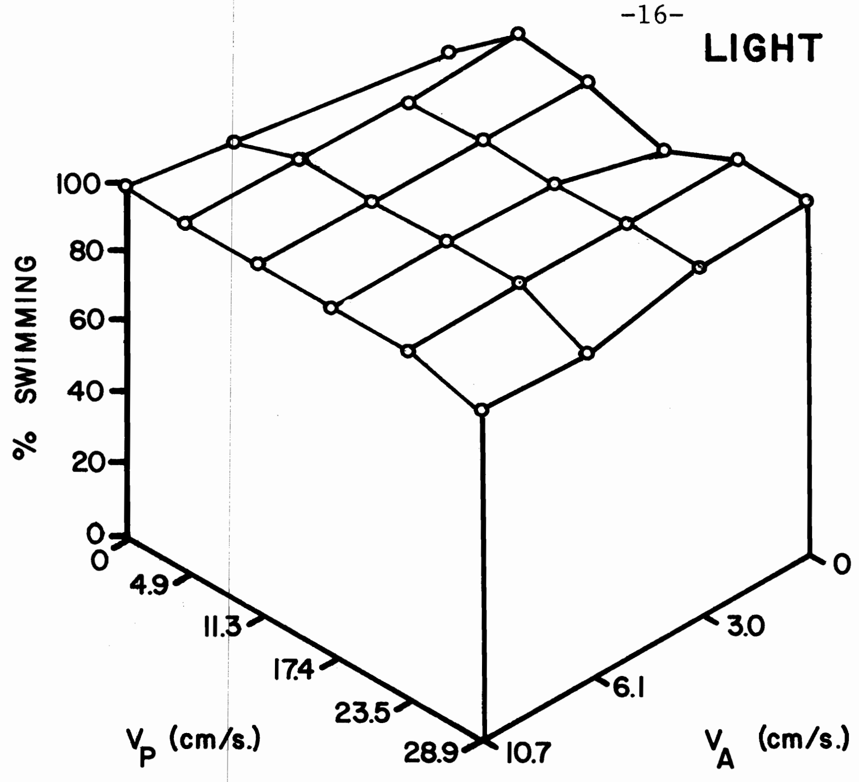
LIGHT TESTS

V_A	V_P	% Mortality Test End	24 h	Total	
3.0	4.9	0	0	0	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = 0$
	11.3	0	0.07	0.07	$\sin^{-1}\sqrt{\%\ \text{24 h mort.}} - 0.3 + 2.07\ V_P$
	17.4	0	2.6	2.6	$F = 0.65 \quad p > 0.25$
	23.5	0	13.6	13.6	
	28.9	0	0	0	
6.1	4.9	0	17.0	17.0	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = .23 - 1.54\ V_P$
	11.3	0	2.2	2.2	$\sin^{-1}\sqrt{\%\ \text{24 h mort.}} = .31 + 16.2\ V_P$
	17.4	0.3	17.4	17.7	$F = 0.03 \quad p > 0.5$
	23.5	0.6	16.5	17.1	
	28.9	0.7	19.2	19.9	
10.7	4.9	0	5.8	5.8	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = .32 - 1.58\ V_P$
	11.3	0	1.9	1.9	$\sin^{-1}\sqrt{\%\ \text{24 h mort.}} = .52 + 6.07\ V_P$
	17.4	1.3	4.3	5.6	$F = 0.39 \quad p > 0.5$
	23.5	1.5	6.5	8.0	
	28.9	1.1	20.1	21.2	

DARK TESTS

V_A	V_P	% Mortality Test End	24 h	Total	
3.0	4.9	1.5	4.2	5.7	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = -.24 + 5.51\ V_P$
	11.3	0	2.5	2.5	$\sin^{-1}\sqrt{\%\ \text{24 h mort.}} = .11 + 10.14\ V_P$
	17.4	0	5.2	5.2	$F = 4.83 \quad p < 0.1$
	23.5	0	4.6	4.6	
	28.9	0	5.4	5.4	
6.1	4.9	3.8	0	3.8	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = 1.05 + 7.36\ V_P$
	11.3	12.5	3.9	16.4	$\sin^{-1}\sqrt{\%\ \text{24 h mort.}} = .44 + 1.44\ V_P$
	17.4	18.1	6.4	24.5	$F = 7.66 \quad p < 0.05$
	23.5	30.9	0	30.9	
	28.9	34.8	10.8	45.6	
10.7	4.9	22.0	11.5	33.5	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = 1.04 + 19.21\ V_P$
	11.3	21.0	16.8	37.8	$\sin^{-1}\sqrt{\%\ \text{24 h mort.}} = .18 + 19.34\ V_P$
	17.4	36.0	10.4	46.4	$F = 9.87 \quad p < 0.05$
	23.5	41.2	17.2	58.4	
	28.9	64.3	18.1	82.4	

LIGHT

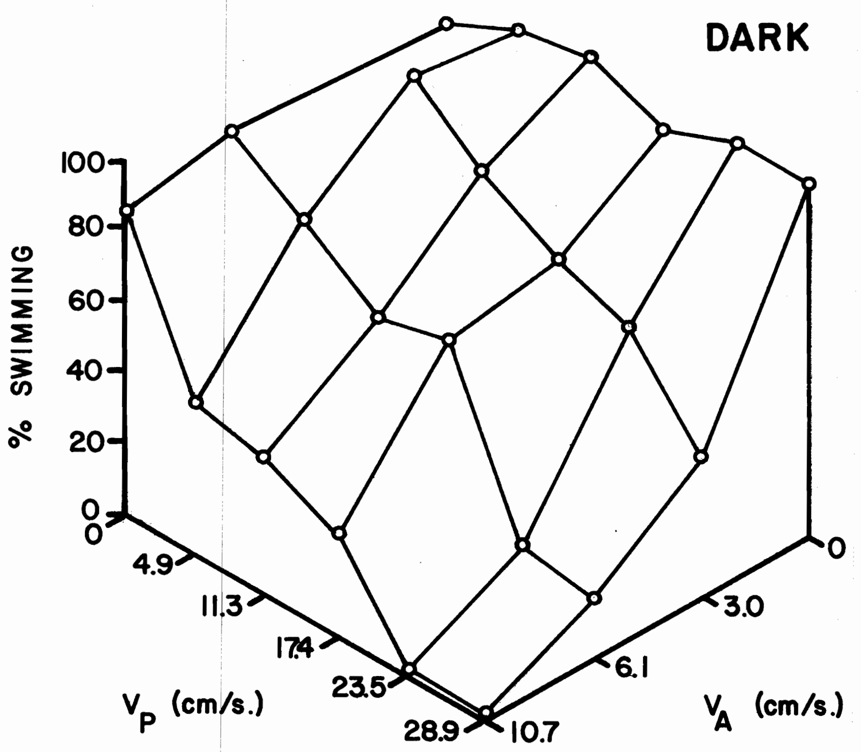


% Swimming @ 6 H.

V_A \ V_P	0	4.9	11.3	17.4	23.5	28.9
0	94.1	100	98	91.8	100	100
3.0	-	98.4	99.6	98.4	99.6	98.3
6.1	94	100	99.1	100	100	92.4
10.7	98.4	98.4	98.4	98.4	98.4	93.5

$\text{sine}^{-1}\sqrt{\%\text{swim.}}$ = [redacted] - [redacted] - [redacted]

DARK



% Swimming @ 6 H.

V_A \ V_P	0	4.9	11.3	17.4	23.5	28.9
0	88	96.1	100	92	100	100
3.0	-	100	85.8	72.4	66.4	43
6.1	90.3	77.5	62.5	68.5	24.7	21.9
10.7	86.3	45.7	42.5	33.1	1.1	1.1

$\text{sine}^{-1}\sqrt{\%\text{ swim.}}$ = [redacted] - 4.7V_A - [redacted]

FIGURE 7. SWIMMING ABILITY OF AMERICAN SHAD IN RELATION TO APPROACH VELOCITY (V_A) AND PASSING VELOCITY (V_P) IN SLOPED SCREEN TESTS.

TABLE 3. Comparison between test-end instantaneous mortality and 24 h delayed mortality of American shad in sloped screen tests.

LIGHT TESTS

V_A	V_P	% Mortality Test End	24 h	Total	
3.0	4.9	1.6	0	1.6	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = -.004 + 4.48\ V_P$
	11.3	0.4	1.8	2.2	$\sin^{-1}\sqrt{\%\ 24\ \text{h mort.}} = .06 + 2.65\ V_P$
	17.4	1.6	0	1.6	$F = 0.03 \quad p > 0.5$
	23.5	0.4	3.4	3.8	
	28.9	1.7	0	1.7	
6.1	4.9	0	0.1	0.1	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = .43 - 3.04\ V_P$
	11.3	0.9	1.8	2.7	$\sin^{-1}\sqrt{\%\ 24\ \text{h mort.}} = .52 - 1.67\ V_P$
	17.4	0	0	0	$F = 0.04 \quad p > 0.5$
	23.5	0	3.3	3.3	
	28.9	7.6	7.8	15.4	
10.7	4.9	1.6	0	1.6	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = .24 + 4.64\ V_P$
	11.3	1.6	1.8	3.4	$\sin^{-1}\sqrt{\%\ 24\ \text{h mort.}} = .14 + 0.81\ V_P$
	17.4	1.6	0	1.6	$F = 0.13 \quad p > 0.5$
	23.5	1.6	0	1.6	
	28.9	6.5	2.0	8.5	

DARK TESTS

V_A	V_P	% Mortality Test End	24 h	Total	
3.0	4.9	0	0	0	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = 1.85 - 4.23\ V_P$
	11.3	14.2	0	14.2	$\sin^{-1}\sqrt{\%\ 24\ \text{h mort.}} = .46 - 4.16\ V_P$
	17.4	27.6	0	27.6	$F = 19.41 \quad p < 0.01$
	23.5	33.6	2.7	36.3	
	28.9	57.0	2.5	59.5	
6.1	4.9	22.5	4.5	27.0	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = 1.49 + 18.84\ V_P$
	11.3	37.6	9.7	47.3	$\sin^{-1}\sqrt{\%\ 24\ \text{h mort.}} = .32 + 10.37\ V_P$
	17.4	31.5	1.6	33.1	$F = 5.65 \quad p < 0.05$
	23.5	75.4	13.1	88.5	
	28.9	78.1	12.1	90.2	
10.7	4.9	54.3	14.7	69.0	$\sin^{-1}\sqrt{\%\ \text{end mort.}} = 1.78 + 33.23\ V_P$
	11.3	57.5	0	57.5	$\sin^{-1}\sqrt{\%\ 24\ \text{h mort.}} = -.46 + 16.22\ V_P$
	17.4	66.9	1.4	68.3	$F = 13.06 \quad p < 0.01$
	23.5	98.9	1.1	100	
	28.9	98.9	1.1	100	

tested were still swimming after 6 h, even with an approach velocity of 10.7 cm/s (0.35 ft/s) and a passing velocity of 28.9 cm/s (0.95 ft/s). The difference between the two light levels tested (6.33 ft candles and 1 X 10^{-3} ft candles) was not a significant factor in determining the ability of salmon to survive with both vertical and sloped screens. Swimming failure that did occur was related to increases in velocity.

In vertical screen tests the approach velocity had the predominant effect on survival. My results along the vertical screen are consistent with those reported by Fisher (1981) for salmon swimming ability at single vector approach velocities less than 12.2 cm/s (0.4 ft/s). He noticed that small salmon were able to "rest" on vertical retaining screens in his test chamber without damage resulting in better than 90% swimming performance. Salmon in the treadmill were also observed to withstand impingement on the vertical screen for short periods and swim off. The presence of the passing velocity vector did not modify the "resting behavior."

In tests conducted with the sloped screen salmon were not observed on the screen face under the water. Impinged fish were found at the top of the incline near the water surface. The passing velocity was statistically the greater influence in this series of tests. Its effect may have been to reduce the ability of salmon to rest on the sloped screen, and may have forced them to the surface. Increased mortality of chinook salmon at an inclined fish screen was observed by Coots (1956).

Mortality that occurred within 24 h after salmon were removed from test conditions was less than 4%. In general, test effects seemed to carry over to the post-test period with delayed mortality increasing with higher velocities. The resulting mortality may be attributed to the latent effects of impingement as well as velocity.

American shad were able to survive two-vector flows for 6 h under lighted conditions. Better than 98% of the fish were still swimming at the end of vertical screen tests, and more than 92% along the sloped screen. The results reflect a difference in their behavior from that demonstrated by salmon. While salmon can survive impingement upon a screen, shad cannot withstand physical contact, but avoid impingement through strong swimming ability. In the treadmill during lighted tests, shad were seen maintaining a position centrally within the swimming channel and oriented into the passing velocity vector. Even at higher passing velocities, upstream movement was observed. The survival of shad during tests under darkened conditions was significantly lower than for light tests. The numbers of fish still swimming after 6 h decreased with increased velocities. At the highest velocity combination, survival was only 35% for the vertical screen tests, and almost complete failure was observed along the sloped screen. Apparently, the species relies heavily on visual cues to maintain its school formation and to avoid the fish screen (Fisher 1976, 1981). Reduction in light produces a disorientation and a lowering in ability to endure increasing velocities.

In summary, chinook salmon could withstand long term exposure to screen approach velocities as high as 10.7 cm/s (0.35 ft/s) and passing velocities of 28.9 cm/s (0.95 ft/s) in both light and dark conditions. American shad showed the ability to survive similar velocities, but only in the light. In dark tests, the survival of shad greatly decreased with increased velocities. Design of a fish screen, utilizing the upper limits of approach and passing velocities that I tested, should attempt to minimize the length of time that fish are exposed to the screen. Further testing would be required to determine responses to two-vector flows for periods less than 6 h.

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