INFLUENCE OF WATER VELOCITY UPON ORIENTATION AND PERFORMANCE OF ADULT MIGRATING SALMONIDS

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ABSTRACT

During the months of August and September 1957 a series of experiments were conducted at Bonneville Dam, to determine (1) how adult migrating salmonids respond to differences in flow velocity, (2) how they perform in two relatively high-velocity flows, and (3) how the velocity of flow influences their rate of movement.

Given a choice of entering either of two parallel channels carrying flows of different velocities, steelhead trout (*Salmo gairdneri*), chinook salmon (*Oncorhynchus tshawytscha*), and silver salmon (*O. kisutch*) generally demonstrated a preference for the channel with the higher velocity flow. The magnitude of the response varied between species and with velocities of the choice condition.

The performances of steelhead trout and chinook salmon were examined in flow velocities of 13.4 and 15.8 feet per second by determining the distance they could achieve in an 85-foot channel. Although there was considerable variation in the distances attained by individual fish at each velocity, steelhead trout were generally more successful in negotiating these velocities than chinook salmon. Larger fish of both species were more successful in negotiating the two flows than smaller fish. Both species performed better in the 13.4 feet per second flow than in the 15.8 f.p.s. flow.

Rates of movement of steelhead trout, chinook salmon, and silver salmon were measured in velocities ranging from 2 to 15.8 f.p.s. Rates of movement varied with species, size of fish, and velocity. Maximum observed swimming speeds are given for each species and various factors affecting rate of movement are discussed.

The increasing demand for greater utilization of water resources in the Pacific Northwest has resulted in plans for the construction of many new dams on the Columbia River and its tributaries. One of the major problems arising from these dams is that of preserving the valuable anadromous fish populations indigenous to these waters. Although there are several important aspects to the problem, one which is of primary concern is ensuring that the adult fish, migrating from the ocean to their fresh-water spawning grounds, are provided safe passage over these obstacles. In view of the number of dams which these fish will eventually have to surmount before reaching their destinations, it is extremely important to ensure that the passage facilities provided at each dam (including temporary passage during construction) are designed to operate as efficiently as possible. The cumulative effect of even minor losses or delays at each dam could seriously jeopardize the perpetuation of this valuable fishery resource. The material reported upon in this paper represents one phase of a research program being conducted by the Bureau of Commercial Fisheries (reviewed by Collins and Elling, 1961) under contract to the U.S. Army Corps of Engineers,[1] to gain more precise knowledge of the principles involved in adult fish passage.

Although fish passage requirements may vary with the nature of the obstacle to be bypassed, the basic problems entailed in achieving efficient passage are: (1) attracting the migrating fish into the fishway entrance without delay and (2) providing conditions which will promote a normal rate of movement through the facility without taxing the physical capacities of the fish. The

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[1] Research financed by the U.S. Army Corps of Engineers as part of a broad program of research to provide design criteria for more economical and more efficient fish-passage facilities at Corps projects on the Columbia River.

purpose of these experiments was to acquire a better understanding of how the velocities of fishway flows may be related to these problems. The following three types of experiments were conducted: velocity-preference, high-velocity, and rate-of-movement. The objectives were (1) to examine the orientative influence of water velocity upon adult migrating salmonids to determine how the relative attractiveness of fishway entrances may be influenced by the velocities of adjacent flows, (2) to examine the performance of these fish at two relatively high-velocity flows to gain a better idea of the maximum water velocities which might be tolerated in fishways or passage channels, and (3) to measure the rate of movement of the fish in flows of various velocities to determine which velocities might be more conducive to a uniform rate of passage through fishway channels.

The work was conducted at the Fisheries-Engineering Research Laboratory at Bonneville Dam on the Columbia River during the months of August and September 1957. Steelhead trout (*Salmo gairdneri*), fall chinook salmon (*Oncorhynchus tshawytscha*), and silver salmon (*O. kisutch*) were the salmonids used in the experiments.

RESEARCH LABORATORY

The laboratory is located immediately below the north end of the spillway section of Bonneville Dam adjacent to the Washington shore fishway (fig. 1). The laboratory and its entrance and exit fishways form a bypass around a short section of the main fishway (fig. 2). This unique feature permits fish to be collected, subjected to various types of experiments within the laboratory, and returned to the main fishway without being handled at any time.

The laboratory is composed of a collection pool where fish are collected prior to testing, an ex-

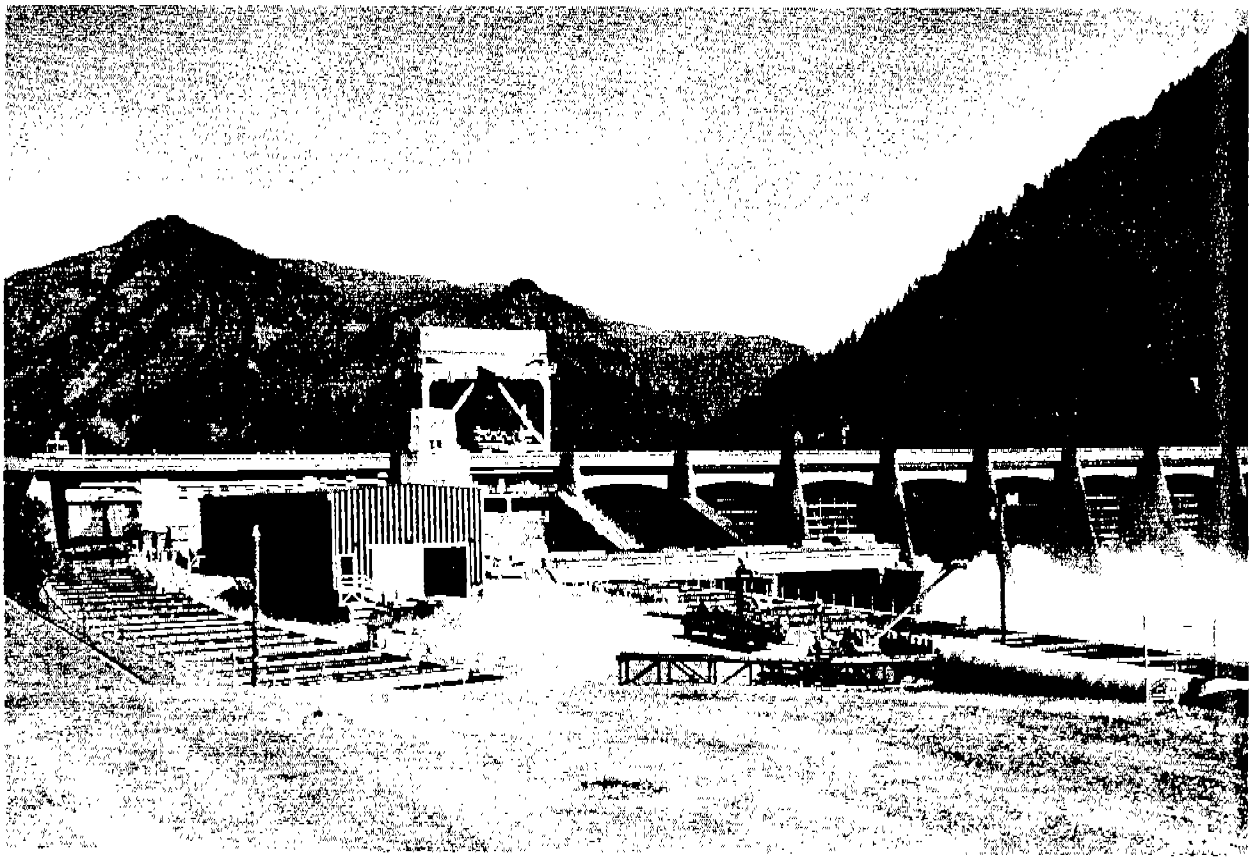

FIGURE 1.—Research laboratory showing Washington shore fishway in the foreground and section of main dam in background.

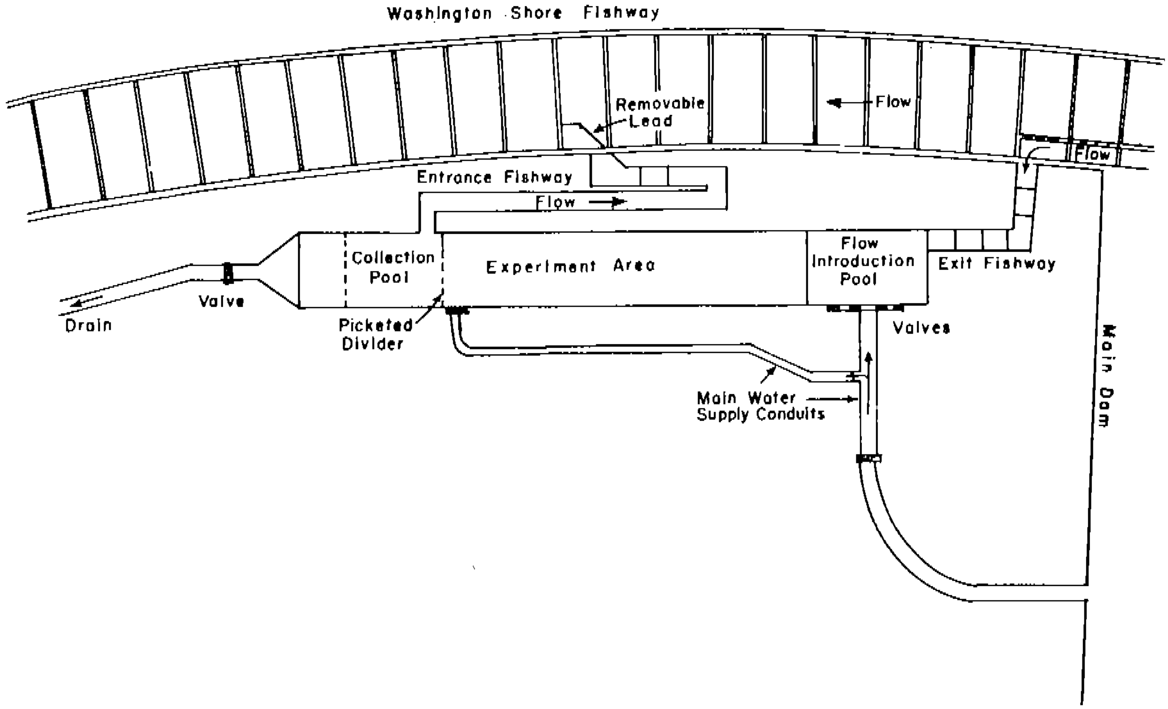

FIGURE 2.—Plan of research laboratory showing the basic components.

perimental area which can be modified to provide a variety of experimental conditions, and a flow-introduction pool where water is introduced into the laboratory. Water is supplied from two sources. The main source, capable of supplying approximately 200 cubic feet per second, comes directly from the forebay of the dam through a large conduit. The secondary source, approximately 20 c.f.s., is drawn from the Washington shore fishway to supply the facility exit fishway. The main water supply is distributed through smaller conduits to the flow-introduction pool, the collection pool, and other portions of the facility by manipulation of appropriate valves.

Water is discharged from the laboratory through a 48-inch drain conduit at the downstream end of the laboratory and through the entrance fishway. Discharge through the drain conduit is controlled by an electrically operated drain valve. Any desired water level can be maintained in the laboratory by proper adjustment of valves.

VELOCITY-PREFERENCE EXPERIMENTS

METHODS AND MATERIALS

The method employed in these experiments was patterned after the one used by Collins (1952) in his studies of factors influencing the orientation of alewives (*Alosa pseudoharengus*) and glut herring (*A. aestivalis*). As the migrating fish passed through the laboratory they were presented with a choice of entering either of two channels. During control experiments the velocities of the flows in the two channels were equal; in test experiments the velocity of the flow in one channel was always greater than the other. The responses of the fish to the various test and control conditions were measured by the number of fish entering each channel.

Experimental Area

The basic experimental area of the facility was modified for these experiments to provide a choice or introductory area, 25 feet long and 11 feet wide, joining two parallel channels each 85 feet long and 5 feet wide (figs. 3 and 4). The channels, which will be referred to hereafter as the north and south channels, were centered in the experimental area and were separated by a common center wall 1 foot thick. The downstream end of the center wall was provided with a tapered hydrofoil to converge the two channel flows smoothly as they entered the choice area.

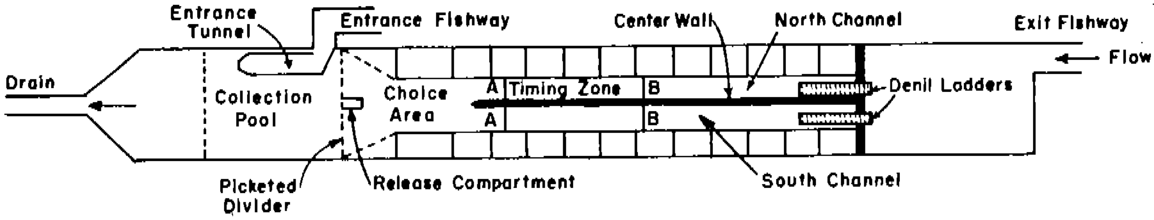

Figure 3.—Sketch of laboratory showing experimental area modified for the velocity-preference experiments.

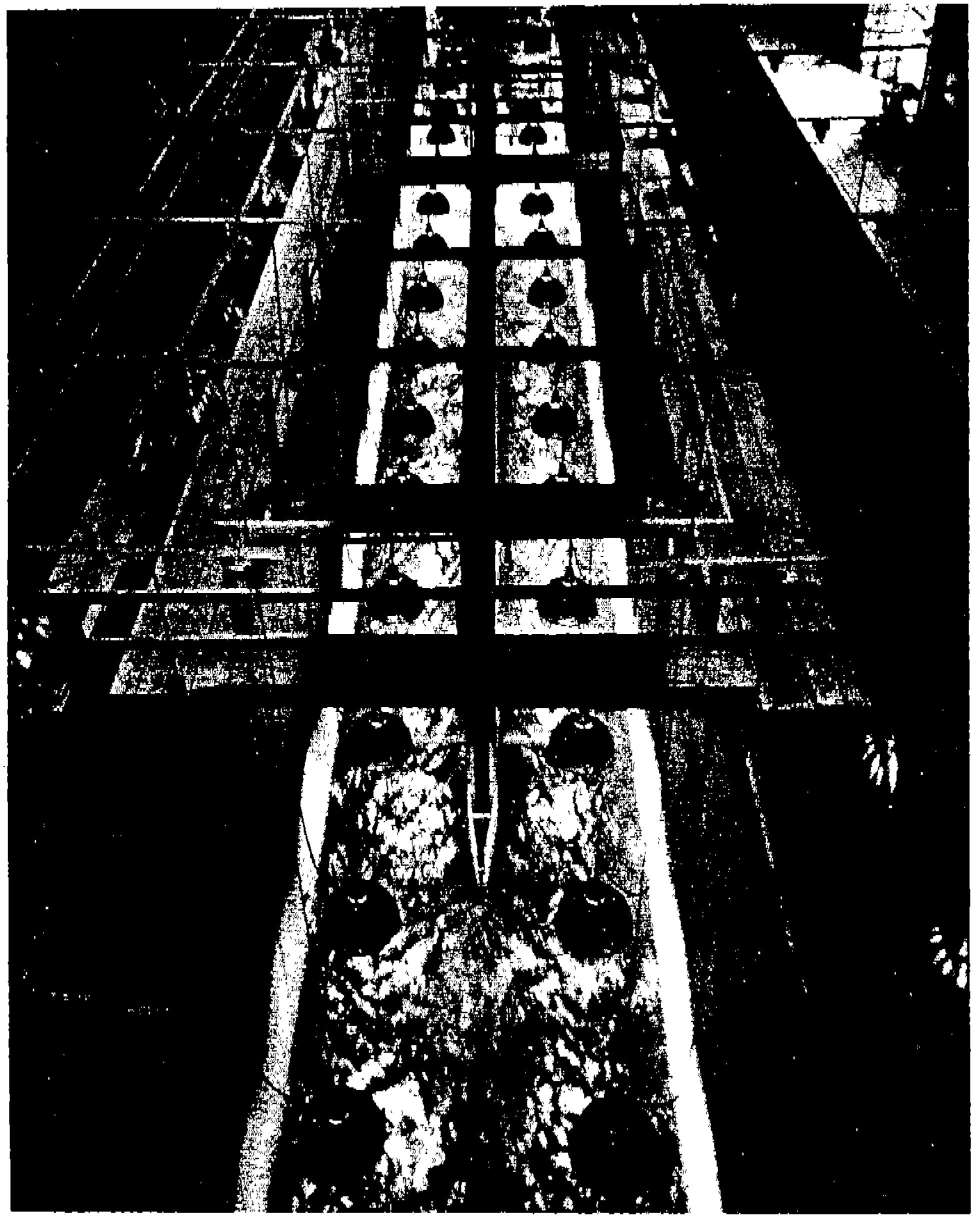

Figure 4.—View of the two channels and choice area during a control test. The velocity of flow in each channel is 4 f.p.s.

Stoplogs at the upstream end blocked the flow through the two areas outside of the channels (fig. 3). The downstream ends of these areas were open, allowing them to backfill when water was introduced into the area. Screens prevented fish from entering these areas.

The walls and floors of the channels and choice area were painted light brown to provide a uniform background throughout the experimental area.

Hydraulic Conditions

Water velocities in the two channels were controlled independently by regulating the quantity of water admitted to them from the flow introduction pool. This was accomplished by employing a prescribed arrangement of stoplogs at the upstream ends of the channels and maintaining the proper water level in the flow-introduction pool. Since the channel floors were level (zero slope) and the water at the downstream end of the two channels was maintained at nearly the same depth by regulation of the collection pool level, the ratio of the velocities of the two channels was equal to the ratio of the quantities of water flowing through the two channels. That is to say, if the velocity (f.p.s.) of one channel was twice as great as the other, then the quantity of water flowing through the channel (c.f.s.) would also be twice as great.

Velocities approximating 2, 4, 6, and 8 f.p.s. were utilized in these experiments. Table 1 lists the various combinations of these velocities which were tested and gives the actual mean water velocities and depths as they were measured at the downstream end of the channels.

Table 1.—*List of six test conditions and four control conditions utilized in the velocity-preference experiments*

Condition	Desired velocity		Actual velocity [1]		Depth of water [1]	
	High-velocity channel	Low-velocity channel	High-velocity channel	Low-velocity channel	High-velocity channel	Low-velocity channel
	F.p.s.	*F.p.s.*	*F.p.s.*	*F.p.s.*	*Feet*	*Feet*
Test	8	2	8.14	1.91	1.7	1.9
	8	4	8.03	3.96	1.7	1.8
	8	6	8.09	5.91	1.7	1.7
	6	2	6.00	1.95	1.8	1.9
	6	4	6.02	3.96	1.7	1.9
	4	2	3.98	2.00	1.9	1.9
	North channel	South channel	North channel	South channel	North channel	South channel
Control	2	2	2.03	2.01	1.9	1.9
	4	4	3.93	3.96	1.9	1.9
	6	6	5.97	6.04	1.7	1.7
	8	8	8.36	8.10	1.7	1.7

[1] Mean velocities derived from measurements taken during individual trials of each condition. Both velocities and water depths were measured at the downstream ends of the channels (fig. 5).

Hydraulic conditions within the channels and choice area varied with the velocity of the flow. At velocities of 2 and 4 f.p.s. uniform flow was maintained throughout the channels and choice area. At 6 and 8 f.p.s. velocities, standing waves were created within the channels and choice area (fig. 5). The position of these waves in relation to the channel and choice area walls remained fixed once the flows had become established. The structure shown at the upstream end of each channel in figure 5 are adjustable Denil-type ladders, which were provided to ensure that the fish would have no difficulty in negotiating the turbulent overfall created by the stoplogs.

Figure 6 illustrates the velocity gradients occurring in the choice area during the various tests at a point approximately 8 feet upstream from the release compartment. Velocities were measured with a Price current meter. Mean velocities were determined from measurements taken vertically at 4-inch intervals.

Release Compartment

Fish were introduced into the choice area through a release compartment 18 inches wide by 48 inches long by 18 inches deep. The compartment was mounted on the upstream face of the picketed divider in line with the center of the choice area (fig. 3). Fish entered the compartment through a sliding gate in the picketed divider and were released into the choice area by means of a second sliding gate at the upstream end of the compartment. The compartment was equipped with a false bottom or brail which could be raised to bring the fish near the water surface to facilitate the identification of species and estimation of length.

Efforts were made to achieve as near perfect symmetry as possible in the components of the release compartment and in the surrounding choice area to ensure that the fish would not perceive any visual stimuli which might bias their responses to the velocity test condition. The release compartment gate was operated from above and to the side to avoid frightening the fish by the motion of opening the gate, and wood panels were installed on each side of the compartment to shield the release compartment operator from the fish.

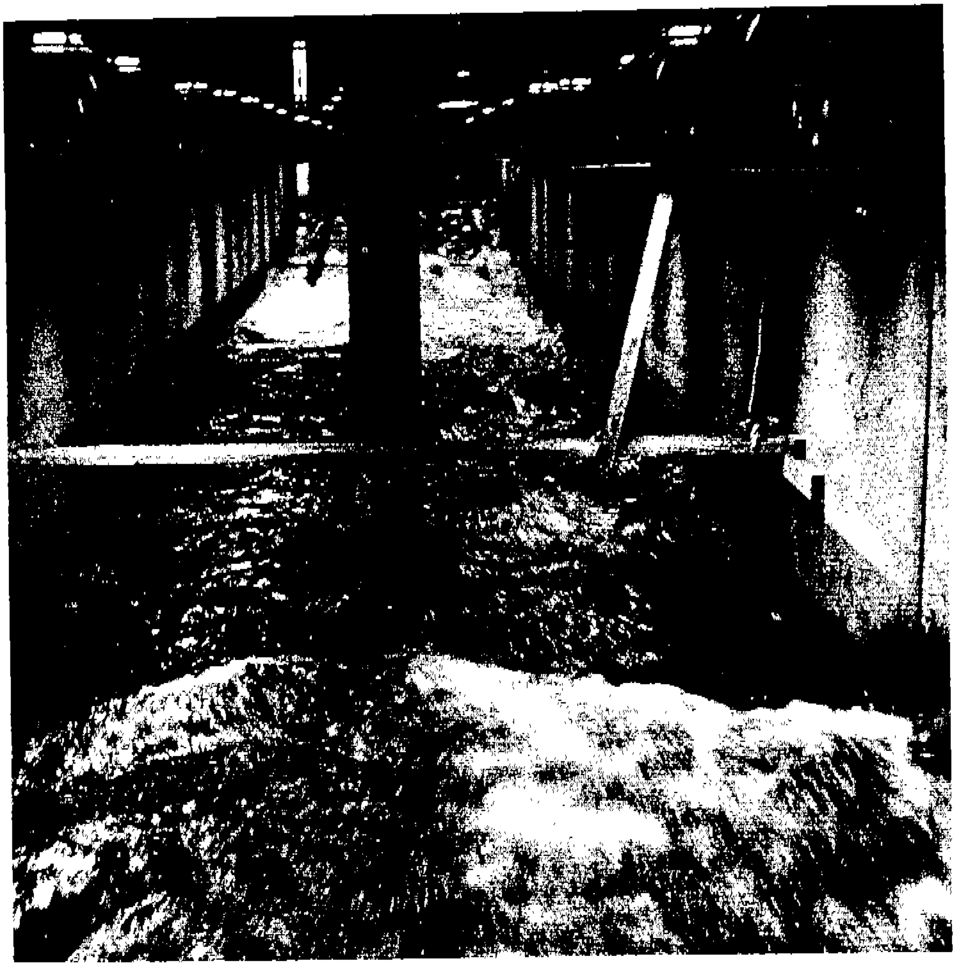

FIGURE 5.—View of choice area and channels showing 6 f.p.s. flow on left and 8 f.p.s. flow on right. Note positions of standing waves. Platform above downstream end of channels was used to check water velocities and was removed during the tests.

Lighting

Uniform lighting was maintained within the channels and choice area by use of 1,000-watt mercury-vapor lamps mounted in polished reflectors. The lamps were suspended from horizontal wall brackets spaced 6 feet apart along the walls of the building and were adjusted to hang 8 feet above the level of the floor. This placed the lamps approximately 6 feet above the surface of the water (fig. 5).

Mean incident light intensities at the water surface in the choice area and within the channels were 604 foot-candles and 746 foot-candles, respectively. This light intensity was roughly comparable to that measured in daylight on a bright overcast day.

PROCEDURE

Experimental Design

The experiments were conducted in accordance with a balanced 4 by 4 lattice-square design in five replicates (Cochran and Cox, 1950). The high velocity for the 6 test conditions was alternated between north and south channels to provide a total of 12 different test treatments (table 2, section A). These, combined with the 4 control treatments provided a total of 16 different treatments for each replicate. The rows and columns of the design were randomized, and the treatments were assigned at random to the 16 treatment numbers in each replicate (table 2, section B). The order of testing proceeded from replicate I to V, and within each replicate from left to right

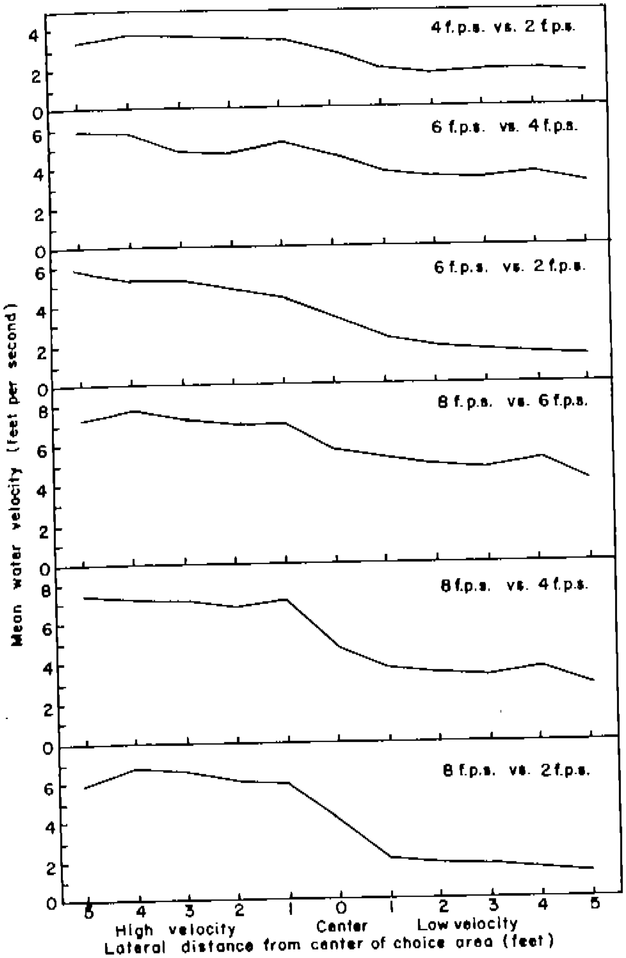

FIGURE 6.—Examples of velocity gradients occurring in cross section of choice area for each test condition.

along successive rows. The sample size for each test was set at 20 fish.

The original plan was to test both steelhead trout and chinook salmon simultaneously, continuing each test until the 20-fish sample of each species had been obtained. It became apparent, however, during several trial runs that chinook salmon were not sufficiently abundant to meet these requirements. The replicated tests, therefore, applied only to steelhead trout. Chinook salmon were tested as they presented themselves during the course of the experiments, but no effort was made to maintain consistency in the sample sizes with regard to these species. A few silver salmon were also tested during the course of the experiments.

To insure that the replicated tests would be as homogeneous as possible, the samples of 20 steelhead were restricted to fish estimated to be from 22 to 26 inches in length. Smaller and larger steelhead were tested when available; however, they were not included in the 20-fish samples.

TABLE 2.—*Outline of the 4 x 4 lattice-square design listing (A) the various test and control conditions and (B) the order of testing*

A. EXPERIMENTAL CONDITIONS (TREATMENTS)

Channel	Water velocity (feet per second)															
	Test conditions												Control conditions			
South	8	2	8	4	8	6	6	2	6	4	4	2	2	4	6	8
North	2	8	4	8	6	8	2	6	4	6	2	4	2	4	6	8

B. EXPERIMENTAL CONDITIONS (TREATMENTS) RANDOMLY FITTED TO BASIC LATTICE SQUARE DESIGN

Replicate	Treatments [1]			
I	1. $S_2 N_6$	2. $S_2 N_2$	3. $S_8 N_2$	4. $S_4 N_4$
	5. $S_2 N_2$	6. $S_6 N_4$	7. $S_6 N_8$	8. $S_2 N_8$
	9. $S_6 N_2$	10. $S_6 N_6$	11. $S_8 N_4$	12. $S_4 N_2$
	13. $S_4 N_6$	14. $S_2 N_8$	15. $S_4 N_8$	16. $S_2 N_4$
II	17. $S_6 N_8$	18. $S_6 N_6$	19. $S_4 N_6$	20. $S_4 N_4$
	21. $S_8 N_6$	22. $S_2 N_4$	23. $S_8 N_4$	24. $S_8 N_4$
	25. $S_4 N_2$	26. $S_2 N_2$	27. $S_2 N_8$	28. $S_4 N_8$
	29. $S_8 N_8$	30. $S_6 N_2$	31. $S_2 N_6$	32. $S_6 N_2$
III	33. $S_4 N_6$	34. $S_2 N_4$	35. $S_2 N_8$	36. $S_2 N_6$
	37. $S_4 N_2$	38. $S_6 N_2$	39. $S_6 N_8$	40. $S_2 N_6$
	41. $S_6 N_4$	42. $S_4 N_4$	43. $S_6 N_2$	44. $S_4 N_2$
	45. $S_8 N_2$	46. $S_2 N_2$	47. $S_2 N_4$	48. $S_6 N_6$
IV	49. $S_8 N_6$	50. $S_8 N_4$	51. $S_2 N_2$	52. $S_4 N_4$
	53. $S_4 N_8$	54. $S_4 N_2$	55. $S_6 N_4$	56. $S_8 N_2$
	57. $S_4 N_8$	58. $S_6 N_8$	59. $S_2 N_6$	60. $S_8 N_8$
	61. $S_2 N_4$	62. $S_6 N_2$	63. $S_8 N_8$	64. $S_2 N_8$
V	65. $S_4 N_6$	66. $S_6 N_2$	67. $S_8 N_4$	68. $S_8 N_2$
	69. $S_4 N_2$	70. $S_4 N_4$	71. $S_2 N_4$	72. $S_2 N_6$
	73. $S_2 N_8$	74. $S_6 N_6$	75. $S_8 N_4$	76. $S_2 N_8$
	77. $S_2 N_2$	78. $S_4 N_8$	79. $S_8 N_6$	80. $S_6 N_2$

[1] Arabic numeral indicates order of testing, letter denotes channel, (S= south, N=north) and subscript denotes velocity (f.p.s.).

Conduct of Experiments

In preparing for a given test, the predetermined stoplog arrangement was inserted at the upstream end of each channel and the water levels of the flow-introduction and collection pools were adjusted to the proper heights. A brief period was allowed for the flows to become stabilized, then water velocities were measured with a current meter at the downstream end of each channel (fig. 5).

After the velocities of each channel had been measured and the observers had taken their respective stations, the release compartment operator was signaled to start the test. The sliding gate on the picketed divider was raised, and a single fish was allowed to enter the compartment. After determining the species and estimating the length of the fish, the operator raised the sliding gate at the upstream end of the release compartment, allowing the fish to enter the choice area. An observer stationed on a walkway over the choice area followed the fish as it passed through the choice area and noted which channel was chosen. After the fish had passed through the channel a second fish was released and so on until the desired sample of 20 steelhead within the 22- to 26-inch size range had been tested.

Upon completion of a test, the main water supply entering the flow-introduction pool was shut off and the stoplog arrangement at the head of the channels was changed for the next test. The changeover could generally be accomplished within 15 minutes. However, usually several minutes elapsed before the fish would enter the release compartment after this change in hydraulic conditions.

During the course of the experiments every effort was made to keep the release technique and operation procedure as uniform as possible. The release compartment operator alternated his position in relation to the compartment after releasing each fish to minimize the chance of bias due to visual cues. If fish were noted in the upper reaches of the channels, tests were halted until these fish had moved on through the channel. This precaution was taken to ensure that the fish entering the choice area would not be affected by scent or visual perception of other fish in the channels. Rubber gloves were worn when changing the stoplogs at the head of channels to eliminate the chance of bias in response due to human scent.

An average of three to four tests were conducted each day, depending upon the availability of fish. Twenty-three days were required for the entire series of experiments.

RESULTS

A total of 80 individual tests were conducted: 60 involving a choice between a high and low velocity and 20 in which the velocities of the two flows were equal. Throughout the series of experiments a total of 2,064 steelhead trout (includes fish of all sizes), 750 chinook salmon, and 108 silver salmon were tested.

Response of Steelhead Trout

The analysis of the steelhead data was based upon the individual tests composed of 20 fish in the length range of 22 to 26 inches. The total sample consisted of 1,600 individuals, 1,200 in the test, and 400 in the control experiments. The responses of these fish to the various individual control and test experiments are presented in tables 3 and 4. The data have been grouped according to experimental conditions to facilitate comparisons between individual trials and between test conditions.

The first step in the analysis of the data was to determine whether there were differences between the five replicates of the experimental design (table 2). If not, the results of individual test and control experiments could be combined to test for differences in response for the two channels in control tests, and differences in response for the different velocity combinations in test experiments.

Since the high velocity of each test condition occurred once in the north and once in the south channel within each replicate, the percentage of fish choosing the north channel should be the same for each replicate if the nature of the response did

TABLE 3.—*Percentage of steelhead choosing north and south channels in each of the 20 control experiments*

[Samples consist of 20 fish ranging from 22–26 inches in length (estimated)]

Replicate	Water velocity							
	2 f.p.s.		4 f.p.s.		6 f.p.s.		8 f.p.s.	
	North	South	North	South	North	South	North	South
I	40	60	60	40	30	70	55	45
II	30	70	70	30	65	35	65	35
III	55	45	50	50	50	50	75	25
IV	55	45	60	40	45	55	55	45
V	55	45	55	45	50	50	45	55
Mean	47	53	59	41	48	52	59	41

TABLE 4.—*Percentage of steelhead trout choosing high velocity channel in each of the 60 test experiments*

[Each entry represents the response of 20 fish ranging from 22–26 inches in length (estimated)]

High velocity channel	Replicate	Test condition					
		8 f.p.s. vs 2 f.p.s.	8 f.p.s. vs. 4 f.p.s.	8 f.p.s. vs. 6 f.p.s.	6 f.p.s. vs. 2 f.p.s.	6 f.p.s. vs. 4 f.p.s.	4 f.p.s. vs. 2 f.p.s.
North	I	75	65	65	70	60	65
	II	90	65	55	80	50	[illegible]
	III	90	55	25	60	60	85
	IV	80	50	60	75	60	65
	V	75	50	50	55	70	[illegible]
South	I	80	50	60	75	70	85
	II	80	50	50	65	75	[illegible]
	III	80	75	55	70	90	[illegible]
	IV	95	75	60	70	60	[illegible]
	V	90	75	35	90	40	[illegible]
Pooled percentage [1] to higher velocity.		83.5	61.0	51.5	71.0	63.5	69.0

[1] Channels and replicates combined.

not differ between replicates. To test this hypothesis, data for each of the 80 trials given in table 2 were transformed to arcsin $\sqrt{\text{percentage to north channel}}$ and subject to an analysis of variance test. The results illustrate that the differences between replicates, columns, and rows were not significant (table 5).

TABLE 5.—*Analysis of variance for percentage of steelhead choosing north channel using the lattice-square design*

[Original percentages were transformed to arcsin $\sqrt{\text{percentage to north channel}}$]

Source	Sum of squares	Degrees of freedom	Mean square	F value
Replications	139.408	4	34.87	.72 N.S.
Treatments	9025.443	15		
Rows (adjusted for treatments)	597.438	15		
Rows (adjusted for treatments and columns)	550.809	15	36.72	.76 N.S.
Columns (adjusted for treatments)	1078.693	15		
Columns (adjusted for treatments and rows)	1037.063	15	69.14	1.44 N.S.
Error	1441.367	30	48.05	
Total	12235.800	70		

N.S.—Not significant.

Response in control experiments.—Since no significant differences could be detected between the five replicates of the lattice-square design, the four control tests for each replicate were combined and subjected to chi-square tests to determine whether a preference was demonstrated for either the north or south channel when the flows were of equal velocity. The results of these tests show that the disparity between the observed response and the expected 1:1 ratio was not great enough to indicate that a preference had been demonstrated for either channel in any of the combined control tests (table 6).

TABLE 6.—*Results of chi-square tests on number of steelhead choosing the north and south channels in control tests at each velocity*

[Samples are composed of fish ranging from 22–26 inches in length]

Water velocity	Sample size	Observed response		Expected response		Degree of freedom	Chi-square
		Chose north channel	Chose south channel	To north channel	To south channel		
F.p.s.							
2	100	47	53	50	50	1	.36 N.S.
4	100	59	41	50	50	1	3.24 N.S.
6	100	48	52	50	50	1	.16 N.S.
8	100	59	41	50	50	1	3.24 N.S.
Sum of chi-squares						4	7.00 N.S.

N.S.—Not significant, p>.05].

Response in test experiments

As no preference was shown for either the north or south channel in control tests and no significant differences between replicates were apparent, the data in table 4 (transformed to arcsin $\sqrt{\text{percentage to higher velocity}}$) were subjected to a two-way analysis of variance to test the effects of channel and velocity differences in the 60 trials involving a choice between a high and low velocity. The results of the analysis of variance (table 7) illustrate that: (1) there were significant differences between the responses of the fish to the different test conditions, (2) these differences were independent of channel effects, i.e., they were evident when the higher velocity was in either the north or south channel and, (3) there was no preference indicated for either the north or south channels independent of velocity effects.

TABLE 7.—*Analysis of variance of the responses of steelhead trout to differences in water velocity for the six test conditions*

Variation due to—	Degrees of freedom	Mean square	Variance ratio
Differences between test conditions	5	482.958	**9.89
Differences between channels	1	156.558	3.21 N.S.
Interaction	5	6.937	.14 N.S.
Error	48	53.167	
Error (main effects)	53	48.805	

** Significant at .01 level.
N.S.—Not significant.

Although the preceding analysis of variance demonstrated that the responses for the higher velocity differed between test conditions, it does not reveal whether each test condition differed from all the rest or whether some were undifferentiated. A test devised by Tukey (Snedecor 1956) was employed in examining these differences. The results of the test demonstrate that the response for the higher velocity in the 8 vs. 2 f.p.s. choice condition was significantly greater than that exhibited in any of the other five test conditions, and the responses in the 6 vs. 2 and 4 vs. 2 f.p.s. test conditions were significantly greater than that in the 8 vs. 6 f.p.s. condition (table 8). Other differences were not significant. The mean percentages to the higher velocity listed in this table are transformed data and should not be confused with the actual percentages to the higher velocity given in table 4.

TABLE 8.—*Tests of differences between mean percentages of steelhead choosing the higher velocity*

[Data are arcsin $\sqrt{\text{percentage to higher velocity}}$]

Test condition		Mean percentage choosing higher velocity	Differences between mean percentages to higher velocity				
High velocity	Low velocity		$\bar{X}-$ 45.80	$\bar{X}-$ 51.53	$\bar{X}-$ 53.24	$\bar{X}-$ 55.89	$\bar{X}-$ 57.77
F.p.s.	*F.p.s.*	$\bar{X}$					
8	2	66.55	*20.75	*15.02	*13.31	*10.00	*8.78
6	2	57.77	*11.97	0.24	4.53	1.88	
4	2	55.89	*10.09	4.36	2.65		
6	4	53.24	7.44	1.71			
8	4	51.53	5.73				
8	6	45.80					

* Differences greater than 7.80 are significant at .05 level.

Since there were no significant differences between replicates and no preference (independent of the effects of velocity) was shown for either channel during control or test experiments, all trials of each test condition were combined to determine whether there was a significant response to the higher velocity. The results of chi-square tests performed on these data illustrate that the proportion of steelhead selecting the higher velocity is significantly greater than that choosing the low velocity in all except the 8 vs. 6 f.p.s. choice condition (table 9).

Response in relation to fish size.—A thorough examination of the relationship between fish size and response was not possible as the steelhead tested during the course of the experiments were of nearly the same size, 80 percent ranging from 22 to 26 inches (fig. 7). Gross comparisons were made, however, by dividing all of the steelhead tested at each test condition into two size categories, small fish less than 25 inches and large fish 25 inches and greater in length, and comparing the percentages choosing the high velocity for each of the 6 test conditions (table 10). No significant differences could be detected between the percentage of small and large fish choosing the high velocity.

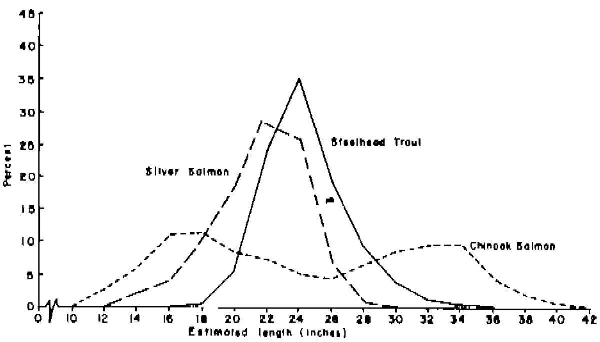

FIGURE 7.—Length composition of samples of steelhead trout, chinook salmon, and silver salmon tested in the velocity-preference experiments.

TABLE 9.—*Chi-square tests on results of choice experiments*

[Data are for steelhead estimated to be 22–26 inches in length.]

Test condition		Sample size	Observed response		Expected response		Chi-square
High velocity	Low velocity		Chose high velocity	Chose low velocity	To high velocity	To low velocity	
F.p.s.	*F.p.s.*	*Number of fish*	*Number of fish*	*Number of fish*			
8	2	200	167	33	100	100	**89.78
8	4	200	122	78	100	100	**9.68
8	6	200	103	97	100	100	.18 N.S.
6	2	200	142	58	100	100	**35.28
6	4	200	127	73	100	100	**14.58
4	2	200	136	64	100	100	**25.92

**Significant at .01 level.
N.S.—Not significant.

TABLE 10.—*Comparison between the responses of small (less than 25 inches) and large (25 inches and larger) steelhead for the high-velocity flow*

[Entries are percentage choosing high-velocity flow]

Length group	Test condition					
	8 f.p.s. vs. 2 f.p.s.	8 f.p.s. vs. 4 f.p.s.	8 f.p.s. vs. 6 f.p.s.	6 f.p.s. vs. 4 f.p.s.	6 f.p.s. vs. 2 f.p.s.	4 f.p.s. vs. 2 f.p.s.
Small	81	58	50	66	72	67
Large	75	62	56	59	75	68

Response of Chinook Salmon

It has been stated that testing of chinook and silver salmon was considered as an incidental phase of the experiments, each test being terminated when the desired sample of steelhead trout had been tested. Samples of chinook salmon in individual tests ranged from 0 to 27 fish.

Control experiments.—In order to provide sample sizes large enough to test the hypothesis of random choice of channels in control experiments, it was necessary to combine the data for the four control tests (2 vs. 2, 4 vs. 4, 6 vs. 6, and 8 vs. 8 f.p.s.) within each replicate. Results of chi-square tests on these data demonstrate that a random choice of channels was exhibited when the flows were of equal velocity (table 11).

Test experiments.—As in control tests the data for individual experiments were combined in order to examine the response of chinook salmon to the various test conditions. Since there was a pronounced variation in the sizes of fish tested during the experiments it was appropriate to examine first the response in relation to fish size.

TABLE 11.—*Response of chinook salmon to control tests for each of the five replicates*

[Responses in each replicate represent grouped data for four individual tests. Chi-square values test the hypothesis that equal numbers entered the two channels]

Replicate	Number of fish	Observed response: Number of fish to— North channel	Observed response: Number of fish to— South channel	Expected response: Number of fish to— North channel	Expected response: Number of fish to— South channel	Chi-square	Degrees of freedom
I	25	11	14	12.5	12.5	0.36 N.S.	1
II	34	19	15	17	17	.47 N.S.	1
III	43	26	17	21.5	21.5	1.88 N.S.	1
IV	19	7	12	9.5	9.5	1.32 N.S.	1
V	51	21	30	25.5	25.5	1.59 N.S.	1
Pooled	172	84	88	86	86	.09 N.S.	1
Sum of chi-squares						5.62 N.S.	4
Heterogeneity (difference)						5.53 N.S.	3

N.S.—Not significant.

The length frequency curve was bimodal and the fish could be conveniently divided into two general size groups; one composed of fish less than 25 inches and the other composed of fish 25 inches and greater in length (fig. 7). Chi-square tests on these data indicate that there was a significant difference in the responses of small and large fish in only one out of the six test conditions (table 12). In the 8 vs. 4 f.p.s. test a significantly greater proportion of large fish chose the higher velocity.

Since the response of large and small fish did not differ significantly in the majority of the tests, sizes were combined to examine the group response of chinook to the different test conditions (table 13). Chi-square values illustrate that a significantly greater proportion of chinook chose the high velocity in all except the 6 vs. 8 f.p.s. test

TABLE 12.—*Comparison between the responses of small (less than 25 inches) and large (25 inches and larger) chinook for each test condition*

Test condition: High velocity	Test condition: Low velocity	Number of fish: Small	Number of fish: Large	Chose high velocity channel: Small	Chose high velocity channel: Large	Chi-square
F.p.s.	*F.p.s.*			*Percent*	*Percent*	
8	2	37	63	91.9	93.6	0.00 N.S.
8	4	38	42	52.6	80.9	**7.19
8	6	35	31	45.7	45.2	.08 N.S.
6	2	74	65	86.5	87.7	.70 N.S.
6	4	42	27	57.1	70.4	1.24 N.S.
4	2	64	60	71.9	75.0	.16 N.S.

**Significant difference between responses, p< .01.
N.S.—Not significant.

TABLE 13.—*Chi-square tests on responses of chinook salmon to the higher velocity in the six different test conditions*

Test condition: High velocity	Test condition: Low velocity	Number of fish	Observed response: Chose high velocity	Observed response: Chose low velocity	Expected response: To high velocity	Expected response: To low velocity	Chi-square
F.p.s.	*F.p.s.*						
8	2	100	93	7	50	50	***73.96
8	4	80	54	26	40	40	**9.80
8	6	66	30	36	33	33	.54 N.S.
6	2	139	121	18	69.5	69.5	***76.32
6	4	69	43	26	34.5	34.5	*4.19
4	2	124	91	33	62	62	***27.13

N.S.—Not significant.
*Significant difference, p< .05.
**Significant difference, p<.01.
***Significant difference, p<.001.

condition. In this instance a larger proportion (not significant) of the fish chose the 6 f.p.s. velocity.

Response of Silver Salmon

Comparatively few silver salmon were tested during the course of the experiments. The combined data in table 14 illustrate that silver salmon, like steelhead trout and chinook salmon, demonstrated a preference for the higher velocity in all except the 8 vs. 6 f.p.s. choice condition. Of the 18 fish tested during the control experiments, 8 chose the north channel and 10 chose the south channel.

TABLE 14.—*Velocity preference of silver salmon in six test conditions*

Water velocity: High-velocity channel	Water velocity: Low-velocity channel	Number of fish	Chose high-velocity channel
F.p.s.	*F.p.s.*		*Percent*
8	2	12	83.3
8	4	14	85.7
8	6	13	46.1
6	2	24	83.3
6	4	22	68.2
4	2	5	100.0

Comparison Between Responses of Chinook Salmon and Steelhead Trout

Although a basic similarity in the response of steelhead trout and chinook salmon has been demonstrated, it is of interest to know whether the magnitude of the response varied between the two species. Chinook salmon demonstrated a stronger response for the higher velocity in four (8 vs. 2, 8 vs. 4, 6 vs. 2, and 4 vs. 2 f.p.s.) choice conditions (table 15). Chi-square values indicate that the response was significantly stronger in the 6 vs. 2 and 8 vs. 2 f.p.s. choice conditions. In the 8 vs. 6 and 6 vs. 4 f.p.s. choice conditions, steelhead trout demonstrated a stronger response for the higher velocity; however, chi-square values were not significant in either case. The data in table 15 include all steelhead trout and chinook salmon tested regardless of fish size.

Table 15.—*Comparison between the responses of steelhead trout and chinook salmon in the six test conditions*

[Chi-square values test the hypothesis that there was no difference in the response of the two species]

Test condition		Number of fish [1]		Chose high-velocity channel		Chi-square
High-velocity channel	Low-velocity channel	Steelhead trout	Chinook salmon	Steelhead trout	Chinook salmon	
F.p.s.	*F.p.s.*			*Percent*	*Percent*	
8	2	258	100	79.4	93.0	*9.47
8	4	240	80	50.0	67.5	1.55
8	6	206	66	52.2	45.4	.63
6	2	264	139	73.1	87.1	*10.80
6	4	257	69	63.8	62.3	.09
4	2	253	124	67.2	73.4	1.98

[1] Includes all sizes.
*Significant difference $p<.01$.

Response of Steelhead Trout and Chinook Salmon to a 12.9 vs. 2.7 f.p.s. Choice Condition

Upon completion of the high-velocity tests, exploratory experiments were conducted to examine the response of steelhead and chinook when presented with a choice between flows averaging 12.9 and 2.7 f.p.s. Velocities were measured at the downstream ends of the two channels. Average water depths were 1.8 feet in the 12.9 f.p.s. channel and 3.4 feet in the 2.7 f.p.s. channel. Water temperature remained a constant 66° F. during these tests.

The two channels and a portion of the introductory area are shown in figure 8. Fish were released individually into the introductory area by means of a release compartment mounted on the entrance tunnel (fig. 9). Experiments were conducted for only 2 days, September 18–19, and observations were made on 41 steelhead trout and 57 chinook salmon.

Results of these tests were quite similar to the preceding choice experiments, for both steelhead trout and chinook salmon demonstrated a preference for the higher velocity. Choosing the higher velocity were 75.6 and 89.5 percent, respectively. Of the 51 chinook entering the 12.9 f.p.s. velocity channel only 26 were able to swim the entire distance (85 feet) to the flow-introduction pool. The remaining 25 fish negotiated varying distances up the channels but were eventually swept back downstream to the introductory area. There was evidence that some of these fish even made second attempts at the high-velocity channel. Steelhead trout demonstrated a superior performance: 29 out of the 31 fish choosing the high velocity were able to negotiate the entire length of the channel.

HIGH-VELOCITY EXPERIMENTS

METHODS AND MATERIALS

The method employed in measuring the performance or swimming ability of salmonids at relatively high velocities, like the choice experiments, relied entirely on the natural drives or instincts which motivate the fish to migrate upstream. These experiments differed from the choice experiments in that the migrating fish passing through the facility had no alternative but to pass through a channel carrying the test flow. The fish were permitted to enter the channel of their own volition, and if they failed to negotiate the entire channel and were swept back downstream they were allowed to remain in the introductory pool. Performance was measured by the distance which the fish could negotiate in the channel before becoming exhausted or discouraged. Velocities approximating 13 and 16 f.p.s. were tested. Tests were conducted during the period September 5–15. Water temperatures ranged from 66° to 67° F.

Experimental Area

The experimental area was modified for these experiments so that only the south channel was utilized (fig. 9). The north channel was blocked with stoplogs at the upstream end and screened at the downstream end to prevent fish from entering. Gray section markers painted on the channel floor at 5-foot intervals were used to measure the distance and fish were able to negotiate through the channel. Lighting was the same as was employed in the choice experiments.

Hydraulic Conditions

The two experimental flows were created by adjusting the slope of the channel floor and regulating the head (difference between the water level in flow-introduction pool and fish-intro-

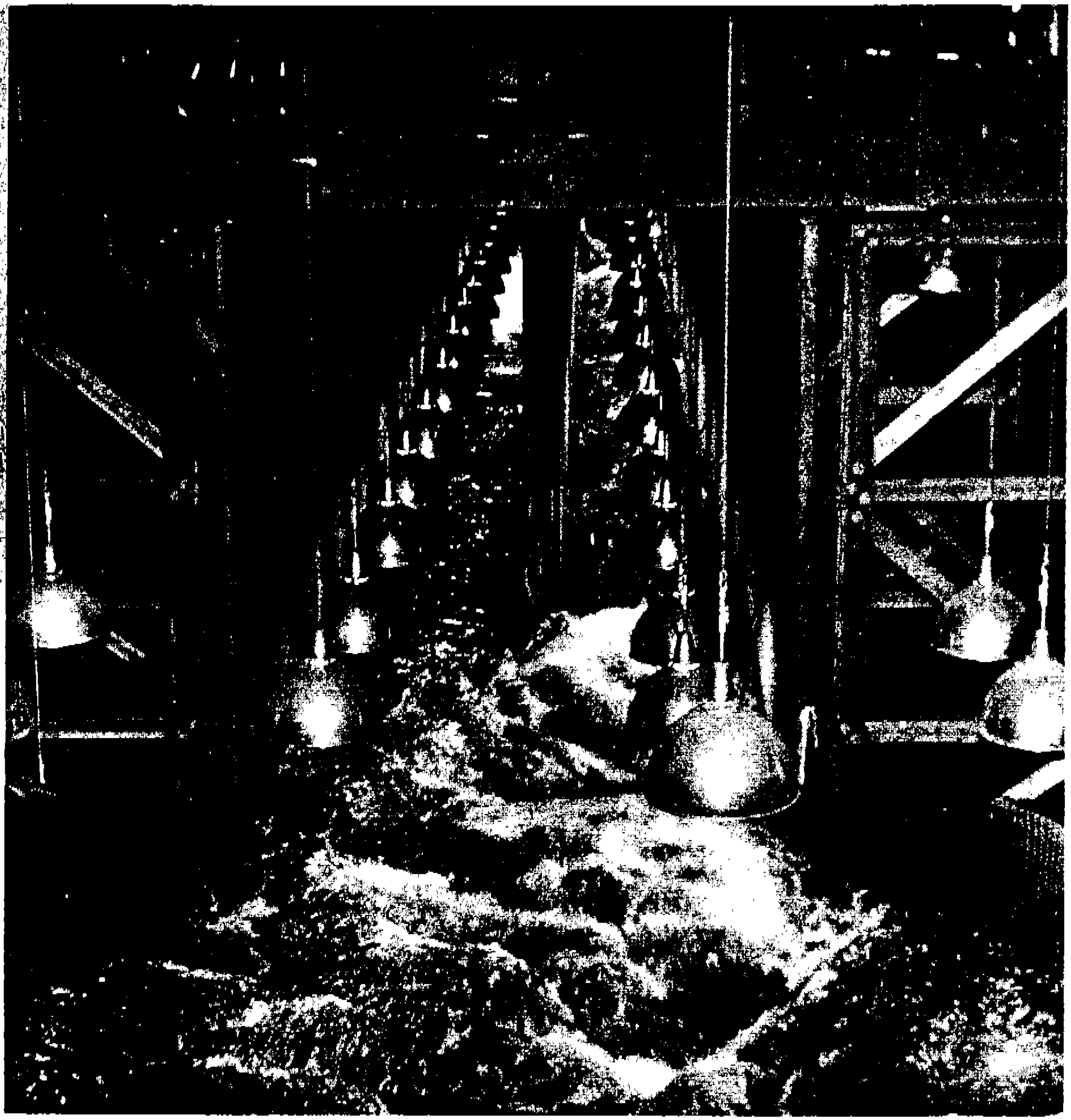

FIGURE 8.—View of two channels and introductory area during a choice experiment involving water velocities of 12.9 f.p.s. on the right and 2.7 f.p.s. on the left.

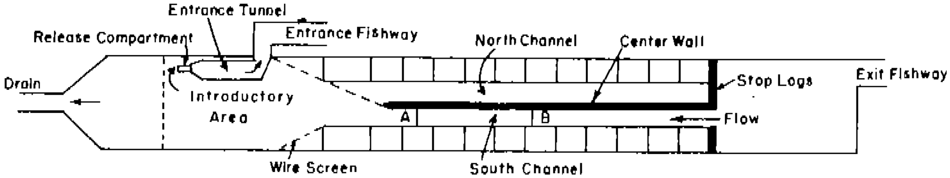

FIGURE 9.—-Sketch of laboratory showing experimental area modified for the high-velocity experiments.

ductory pool) on the channel. The total rise in floor level from the downstream end to the upstream end of the channel ranged from 1.4 feet at 13 f.p.s. to 2.5 feet at 16 f.p.s. The head on the channel ranged from 2.5 feet to 5.3 feet, respectively.

The mean water velocity and depth of flow for the two test conditions determined from rather extensive measurements in the first 35 feet of the channel before the experiments were begun, were 13.4 f.p.s. and 1.8 feet, and 15.8 f.p.s. and 1.8 feet, respectively. Velocities were measured with a current meter vertically at 4-inch intervals from the floor and horizontally at 1-foot intervals from the center of the channel at five different stations within the 35-foot reach. Examples of the distribution of velocities within the channel derived from these measurements are given in appendix figure 1 for each test condition. Velocities ranged from 11.8 to 14.4 f.p.s. in the 13.4 f.p.s. test condition and from 14.9 to 16.7 f.p.s. in the 15.8 f.p.s. test condition. The lowest velocities occurred near the floor next to the channel walls; the highest occurred just below the surface. During the course of the experiments velocities were checked only at the downstream end of the channel. Measurements at this point were made with a current meter at 1-foot intervals across the channel at 0.6 of the depth from the water surface.

With exception of the rather turbulent area at the upstream end, flows through the channel were nearly uniform for both test conditions. Although standing waves were created just below the channel entrance at both velocities, the

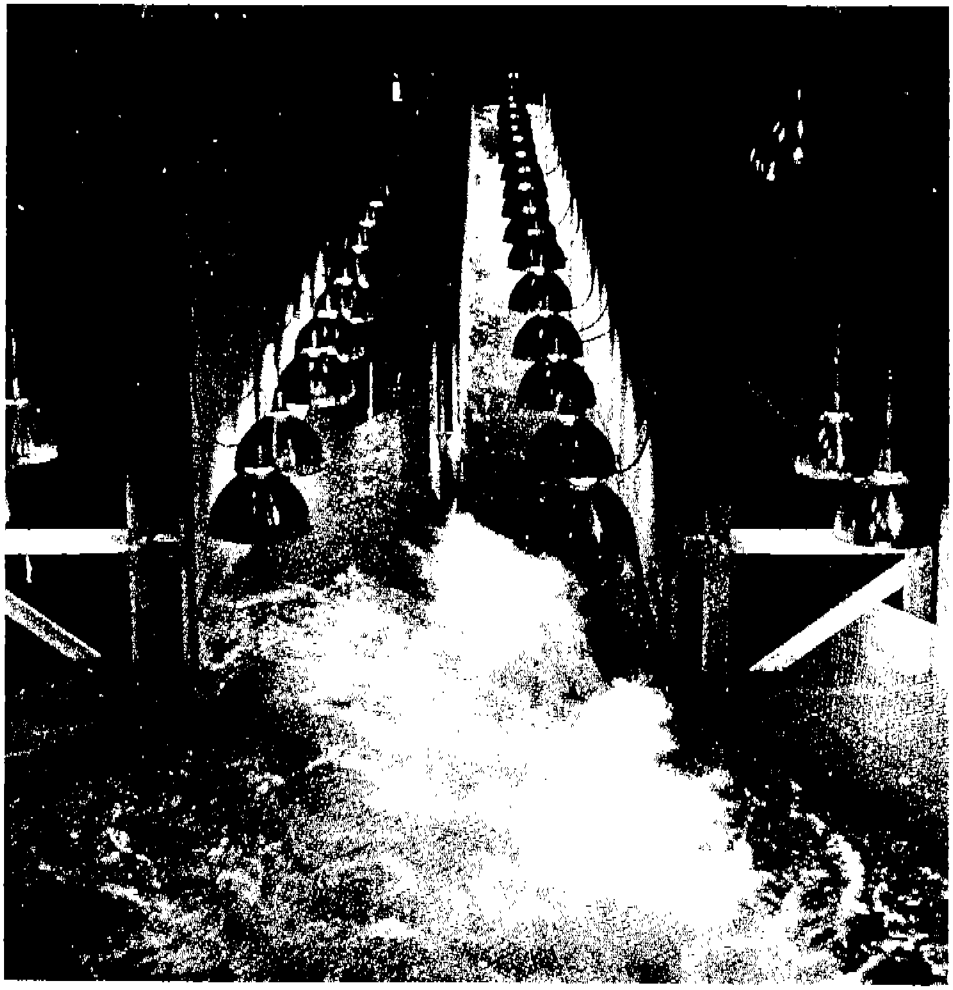

FIGURE 10.—View of south channel with 15.8 f.p.s. flow. A screen (barely visible) blocks entrance to north (left) channel.

position of the wave and its effect on the flow in the approach area were quite different at the two velocity levels. At 13.4 f.p.s. the wave was positioned at the end of the hydrofoil and at right angles to the channel flow (fig. 8). As a result, the water velocity within the approach area was greatly reduced. At 15.8 f.p.s. the standing wave extended diagonally across the entrance to approximately the center of the channel. In this instance a high-velocity jet was created along the south wall of the approach area (fig. 10). Velocities as high as 17.8 f.p.s. were measured at the end of the south wall. Although the flow through the introductory area was turbulent at both velocities, there were areas near both walls where fish could rest in relatively calm water.

PROCEDURE

The fish utilized in these experiments were collected daily from the Washington Shore fishway. They swam into the entrance fishway channel (fig. 2) where they were held until tested. They were released individually by means of a release compartment mounted on the end of the entrance tunnel (fig. 11). Prior to release, the release compartment operator ascertained the species and estimated the length of each fish. Upon releasing the fish, he alerted an observer stationed on a walkway above the entrance to the test channel. When the fish entered the channel, this observer followed its movements from the walkway above the channel and noted the maximum distance which the fish attained.

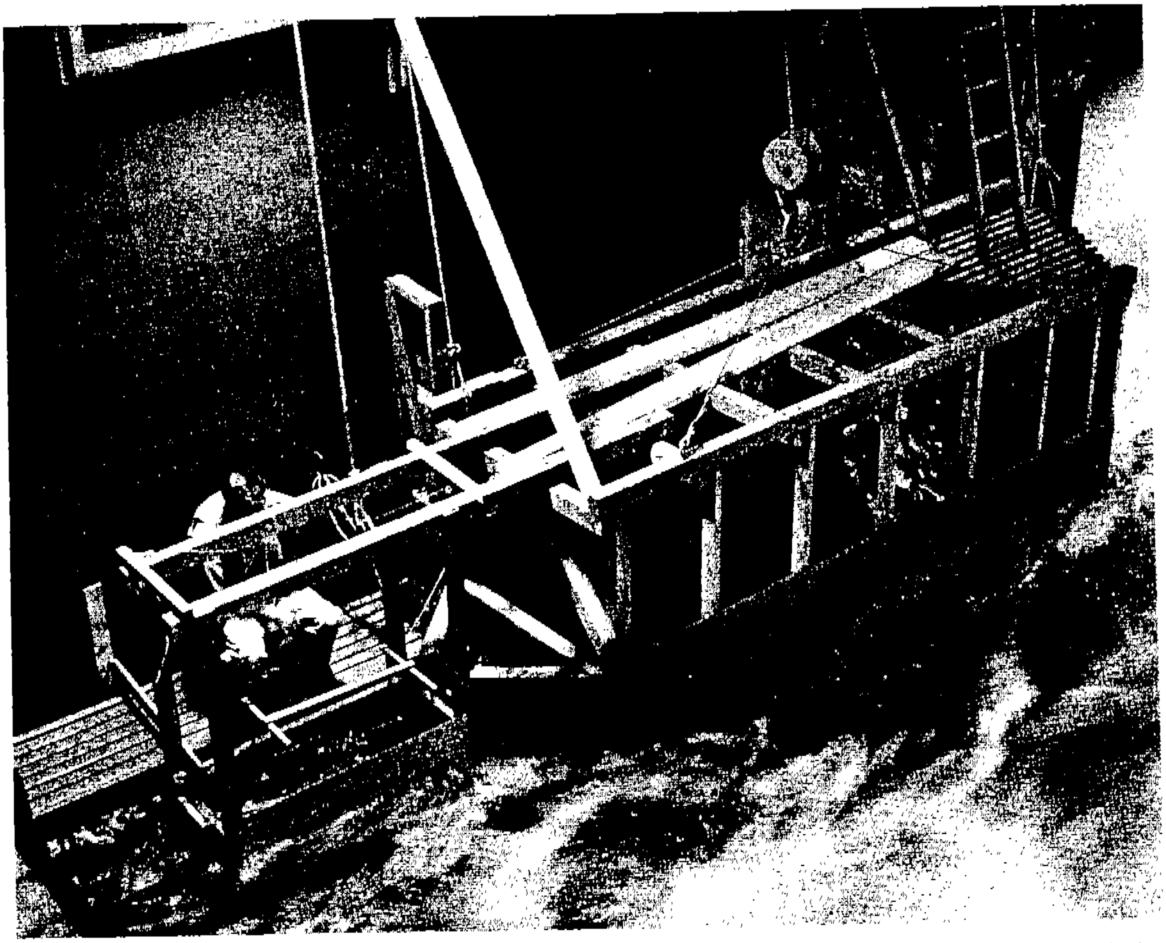

Figure 11.—View of entrance tunnel and release compartment utilized in the 13.4 and 15.8 f.p.s. velocity experiments.

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Throughout the course of the experiments (especially in the 15.8 f.p.s. tests) fish that failed to pass through the channel and were swept back downstream often reentered and attempted to negotiate the channel again. Generally when this occurred, testing was merely delayed until the fish either passed through the channel or was again swept back downstream to the introductory area; the distance negotiated was recorded, and testing was resumed. If, however, these reentries became so numerous as to pose difficulty is distinguishing the fresh fish being introduced from the release compartment, the test was terminated or at least delayed until the fish could be cleared from the introductory area by reducing the channel velocity.

As many fish as possible were tested each day. The number varied from 30 to 60 fish depending upon availability. At the end of each day the channel velocity was reduced so that the fish which had accumulated in the introductory area could pass through the laboratory during the night.

RESULTS

The 13.4 f.p.s. velocity tests were conducted on September 5, 6, and 7, and the 15.8 f.p.s. tests were made on September 9, 10, 14, and 15. A total of 47 steelhead trout and 91 chinook salmon were tested in the 13.4 f.p.s. velocity flow, and 67 steelhead and 130 chinook, in the 15.8 f.p.s. flow.

A cursory examination of the data revealed that there was considerable variation in the swimming abilities of the fish tested in the two velocities. The distances attained by individual steelhead trout ranged from 10 to 85 feet (total length of channel) in the 13.4 f.p.s. velocity and from 14 to 85 feet in the 15.8 f.p.s. velocity. Chinook salmon ranged from 15 to 85 feet in the 13.4 f.p.s. velocity and from 0 feet (one fish failed to reach the channel entrance) to 85 feet in the 15.8 f.p.s.

The performances of the two species tested on different days are compared in table 16. The only consistent variation in performance between days occurred with the chinook tested in the 15.8 f.p.s. velocity. In this instance there was a decline in the median distance negotiated by the four groups of fish tested during the 7-day period. Since there were only slight differences in the mean lengths of the fish in the four tests, a real decline in the swimming ability of the chinook salmon tested during the 7-day period is indicated.

The pooled data from the individual tests at each velocity are presented graphically to show the respective distances negotiated by the two species in the 85-foot channel (fig. 12). Each species has been divided into two general-size groups (small fish consisting of individuals estimated to be less than 25 inches in length and large fish consisting of individuals 25 inches and larger) to indicate the relationships between performance and fish size. These data clearly illustrate that

TABLE 16.—*Median distances attained by chinook salmo[n] and steelhead trout tested on different days in velocities [o]f 13.4 and 15.8 f.p.s.*

Velocity	Date	Number of fish		Mean length [1]		Median distan[ce] negotiated in 85-foot channel	
		Chinook salmon	Steelhead trout	Chinook salmon	Steelhead trout	Chinook salmon	Steelhead trout
F.p.s.				*Inches*	*Inches*	*Feet*	*Feet*
13.4	Sept. 5	16	12	30.5	27.3	75	85
	Sept. 6	40	14	27.6	26.0	85	85
	Sept. 7	29	21	29.8	24.1	70	85
15.8	Sept. 9	44	13	27.3	25.1	30	7[illegible]
	Sept. 10	40	25	27.4	26.1	28	8[illegible]
	Sept. 14	21	9	26.0	24.0	21	7[illegible]
	Sept. 15	25	20	26.6	24.9	19	7[illegible]

[1] Based on estimated lengths.
[2] Values of 85 foot represent a minimum estimate of median as length o[f] channel was only 85 feet.

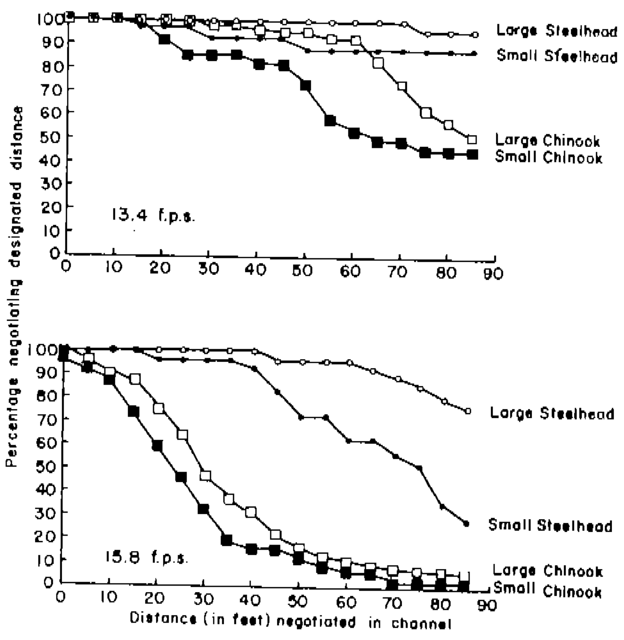

FIGURE 12.—Performances of small (estimated to be less than 25 inches in length) and large (25 inches and larger) steelhead trout and chinook salmon in velocities of 13.4 and 15.8 feet per second.

steelhead trout were more successful than chinook salmon in negotiating the two test flows and larger fish of both species were more successful than smaller fish. In the 13.4 f.p.s. tests 92 percent of the steelhead negotiated the entire 85-foot channel. In comparison, only 51 percent of the chinook salmon traveled this distance. The performances of both species declined significantly in the 15.8 f.p.s. velocity. Only 51 percent of the steelhead and 5 percent of the chinook negotiated the entire length of the channel. In comparing the performances of the two size groups it is interesting to note that the decline in the performance of steelhead between the 13.4 and 15.8 f.p.s. velocity tests was due largely to the influence of the smaller fish. The proportion of large steelhead negotiating the entire 85-foot channel was reduced by only 20 percent while that of the smaller fish was reduced by 66 percent. In comparison, the proportions of large and small chinook salmon negotiating the channel were reduced by nearly the same proportion (90 and 95 percent, respectively) between the 13.4 and 15.8 f.p.s. velocity tests.

In considering the performance curves in figure 12 we should bear in mind that: (1) the velocities of 13.4 and 15.8 f.p.s. are mean values, (2) the distances given apply only to measurements made within the confines of the channel and, (3) the performance curves are based upon the distances attained by the fish in their first attempt to negotiate the channel.

Reference to appendix (fig. 1) illustrates that fish may have encountered velocities somewhat higher or lower than 13.4 and 15.8 f.p.s. as they ascended the channel depending upon the course they followed. Observations made during the course of the experiments indicated that although some fish traversed back and forth across the channel they generally ascended the channel near the walls and were posited near the floor or at least below middepth. The performance curves in figure 12, therefore, are probably associated with velocities slightly lower than the mean values given.

On the other hand the distances given in figure 12 may be somewhat less than the actual distances which the fish negotiated in the two velocities, especially in the 15.8 f.p.s. tests. In these tests the flow was not dissipated upon entering the approach area to the extent that it was in the 13.4 f.p.s. tests, and a high-velocity jet continued through the approach area to the introduction pool (fig. 10). A number of fish followed this jet as they approached the channel and were subjected to velocities of 15.8 f.p.s. or greater for distances up to 20 feet before entering the channel. The distances given in figure 12 apply only to the distance attained after entering the channel and may lead to an underestimation of the performance of the fish in this velocity.

It has been mentioned that fish which failed to negotiate the entire channel in their first attempt and were swept back downstream to the introductory area frequently reentered and attempted to negotiate the channel again. Although the mean distance negotiated by both steelhead trout and chinook salmon reentering the channel was slightly less than the mean distance achieved by the two species in their first attempts in both velocities, there was evidence that at least some of the fish were capable of achieving greater distances in the two velocities than they demonstrated in their first attempt. The maximum distances which all (100 percent) steelhead trout and chinook salmon were capable of negotiating in the two velocities may, therefore, be somewhat greater than is indicated in figure 12.

RATE OF MOVEMENT EXPERIMENTS

METHODS AND MATERIALS

These experiments were conducted concurrently with the choice and high-velocity experiments and utilized the same fish. Rates of movement were determined by simply recording the time required for the fish to pass through a 30-foot timing zone in the lower portion of the channels. Gray lines on the floor of the channels marked the boundaries of these zones. The downstream boundary or "start" line and the upstream or "finish" line are designated as points *A* and *B*, respectively, in figures 3 and 9.

Rates of movement in water velocities of 2, 4, 6, and 8 f.p.s. were measured during the velocity-preference experiments and in velocities of 13.4 and 15.8 f.p.s. during the high-velocity experiments. In the high-velocity experiments the upper end of the channel was not obstructed with the Denil ladder or stoplogs as it was in the choice experiments. It was possible, therefore, to obtain an additional measure of the rate of movement

TABLE 17.—*Distribution of times required by steelhead trout to negotiate the 30-foot timing zone in water velocities approximating 2, 4, 6, 8, 13, and 16 f.p.s.*

Time interval in seconds	Water velocity											
	2 f.p.s.		4 f.p.s.		6 f.p.s.		8 f.p.s.		13.4 f.p.s.		15.8 f.p.s.	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number [1]	Percent	Number [1]	Percent
0–0.9												
1.0–1.9					2	.3	1	.2				
2.0–2.9	8	2.5	11	2.3	17	2.9	18	3.1				
3.0–3.9	37	11.4	37	7.8	61	10.5	89	15.4			1	1.
4.0–4.9	38	11.7	63	13.3	114	19.6	140	24.2	2	4.9	5	7.
5.0–5.9	34	10.5	66	14.0	80	13.7	108	18.6	13	31.7	15	23.
6.0–6.9	36	11.1	63	13.3	56	9.6	93	16.1	8	19.5	22	34.
7.0–7.9	31	9.6	40	10.4	31	5.3	58	10.0	8	19.5	10	15.
8.0–8.9	25	7.7	51	10.8	34	5.8	29	5.0	5	12.2	7	10.
9.0–9.9	21	6.5	28	5.9	21	3.6	11	1.9	2	4.9	1	1.
10.0–10.9	16	4.9	23	4.9	15	2.6	10	1.7				
11.0–11.9	8	2.5	21	4.4	16	2.7	5	.8	3	7.3	1	1.
12.0–12.9	12	3.7	17	3.6	13	2.2					2	3.
13.0–13.9	7	2.2	6	1.3	8	1.4	1	.2				
14.0–14.9	11	3.4	6	1.3	7	1.2	2	.3				
15.0–15.9	11	3.4	5	1.1	6	1.0	1	.2				
16.0–16.9	4	1.2	5	1.1	3	.5	1	.2				
17.0–17.9	4	1.2	5	1.1	4	.7						
18.0–18.9	2	.6	3	.6	3	.5	1	.2				
19.0–19.9	4	1.2	3	.6	2	.3	1	.2				
20.0–20.9	2	.6			3	.5						
21.0–21.9	1	.3	1	.2								
22.0–22.9	1	.3	1	.2	3	.5	1	.2				
23.0–23.9	2	.6			1	.2						
24.0–24.9			1	.2	1	.2						
25.0–25.9							1	.2				
26.0–26.9			2	.4	2	.3						
27.0–27.9	3	.9										
28.0–28.9					1	.2						
29.0–29.9	1	.3	2	.4								
30.0+	5	1.5	3	.6	79	13.6	8	1.4				
Total number of fish	324		472		583		579		41		64	

[1] Represents only fish which were able to negotiate timing zone.

(from point B to the upstream end of the channel) for those fish which negotiated the entire length of the channel.

PROCEDURE

Fish were timed through the 30-foot zone with stopwatches by an observer stationed on the catwalk above the entrances of the channels. During the choice experiments a single watch was used. It was started as the fish crossed point *A* and stopped when the fish crossed point *B*.

During the high-velocity studies two watches were employed. One was used as above to record the time required to negotiate the 30-foot zone. The second watch was started as the fish crossed point *B* at the end of the 30-foot zone and stopped when the fish reached the upstream end of the channel. If the fish failed to negotiate the entire channel, the watch was stopped when the fish started to fall back downstream.

RESULTS

The distributions of individual times required by steelhead trout, chinook, and silver salmon to negotiate the 30-foot timing zone in the various water velocities tested are given in tables 17, 18, and 19. Passage times listed for velocities from 2 to 8 f.p.s. were measured during the choice experiments and include all fish tested at a given velocity regardless of choice condition. Passage times listed for water velocities of 13.4 and 15.8 f.p.s. were measured during the high-velocity experiments and include only those fish which were able to negotiate the timing zone.

Relationship Between Water Velocity and Rate of Movement by Species

Since the passage times do not conform to a normal type distribution in all instances, a nonparametric method was considered appropriate in comparing passage times between species and water velocities. The median passage time with 95-percent confidence limits was selected as the test statistic. These values for each species and velocity are presented in table 20. Rates of movement in each velocity, calculated by dividing the length of the timing zone (30 feet) by the median times in table 20, are compared in figure 13. Rates of movement ranged from 3.1 to 6.9 f.p.s., varying with species and water velocity.

A comparison of median times in table 20 reveals the following with respect to differences between

Table 18.—*Distribution of times required by chinook salmon to negotiate the 30-foot timing zone in water velocities approximating 2, 4, 6, 8, 13, and 16 f.p.s.*

Time interval in seconds	Water velocity											
	2 f.p.s.		4 f.p.s.		6 f.p.s.		8 f.p.s.		13.4 f.p.s.		15.8 f.p.s.	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent	Number [1]	Percent	Number [1]	Percent
0-0.9												
1.0-1.9	1	1.1										
2.0-2.9	14	15.2	20	10.9	20	9.1	7	3.5				
3.0-3.9	24	26.1	41	22.4	35	16.0	19	9.6				
4.0-4.9	18	19.6	39	21.3	44	20.1	41	20.7			1	2.6
5.0-5.9	14	15.2	25	13.7	57	26.0	50	25.2	2	2.3	4	10.2
6.0-6.9	7	7.6	19	10.4	14	6.4	37	18.7	9	10.7	4	10.2
7.0-7.9	3	3.3	10	5.5	14	6.4	18	9.1	17	20.2	10	25.6
8.0-8.9	5	5.4	4	2.2	7	3.2	14	7.1	23	27.4	9	23.1
9.0-9.9	2	2.2	6	3.3	5	2.3	5	2.5	21	25.0	6	15.4
10.0-10.9	3	3.3	7	3.8	5	2.3	1	.5	10	11.9	4	10.2
11.0-11.9			4	2.2	2	.9	3	1.5	1	1.2	1	2.6
12.0-12.9			1	.5			1	.5				
13.0-13.9			2	1.1					1	1.2		
14.0-14.9	1	1.1			2	.9						
15.0-15.9			3	1.6			1	.5				
16.0-16.9												
17.0-17.9					2	.9						
18.0-18.9					1	.5	1	.5				
19.0-19.9					1	.5						
20.0-20.9			1	.5								
21.0-21.9												
22.0-22.9					2	.9						
23.0-23.9					1	.5						
24.0-24.9					2	.9						
25.0-25.9												
26.0-26.9			1	.5								
27.0-27.9												
28.0-28.9					1	.5						
29.0-29.9												
30.0+					4	1.8						
Total number of fish	92		183		219		198		84		39	

[1] Represents only fish which were able to negotiate timing zone.

Table 19.—*Distribution of times required by silver salmon to negotiate the 30-foot timing zone in water velocities approximating 2, 4, 6, and 8 f.p.s.*

Time interval in seconds	Water velocity							
	2 f.p.s.		4 f.p.s.		6 f.p.s.		8 f.p.s.	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
0-0.9								
1.0-1.9								
2.0-2.9					1	2.6		
3.0-3.9					2	5.3	1	3.1
4.0-4.9	1	11.1	2	12.5	3	7.9	6	18.7
5.0-5.9	1	11.1	5	31.3	4	10.5	11	34.4
6.0-6.9			1	6.2	7	18.4	5	15.6
7.0-7.9	1	11.1	2	12.5	4	10.5	7	21.9
8.0-8.9	1	11.1			6	15.8	1	3.1
9.0-9.9	1	11.1					1	3.1
10.0-10.9	1	11.1	2	12.5	1	2.6		
11.0-11.9			1	6.2	1	2.6		
12.0-12.9			1	6.2	1	2.6		
13.0-13.9	1	11.1						
14.0-14.9					1	2.6		
15.0-15.9								
16.0-16.9								
17.0-17.9								
18.0-18.9								
19.0-19.9	1	11.1						
20.0-20.9					1	2.6		
21.0-21.9					1	2.6		
22.0-22.9								
23.0-23.9								
24.0-24.9					1	2.6		
25.0-25.9								
26.0-26.9								
27.0-27.9								
28.0-28.9			1	6.2				
29.0-29.9								
30.0+	1	11.1	1	6.2	4	10.5		
Total number of fish	9		16		38		32	

species: (1) chinook salmon moved significantly faster (required less time to negotiate the 30-foot timing zone) than steelhead trout or silver salmon in velocities of 2, 4, and 6 f.p.s., (2) the rates of movement of the three species were approximately equal at 8 f.p.s., and (3) chinook salmon were

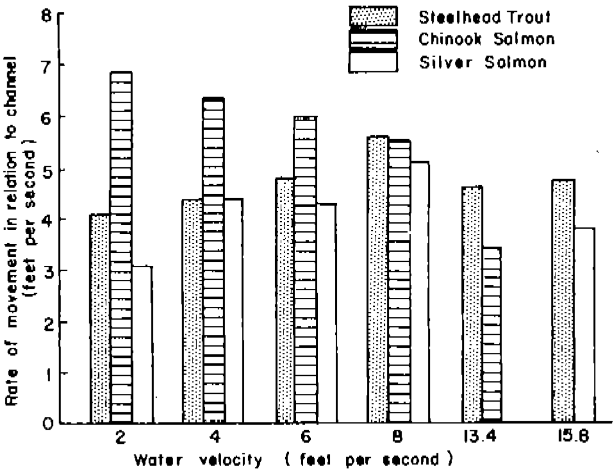

Figure 13.—Average rates of movement maintained through the 30-foot timing zone by steelhead trout, chinook salmon, and silver salmon in the six velocities tested. Rates are based on the median time required to negotiate the timing zone.

TABLE 20.—*Median passage times of steelhead trout, chinook and silver salmon through the 30-foot timing zone in water velociti[es] approximating 2, 4, 6, 8, 13, and 16 f.p.s.*

Species	Median and[1] 95% confidence limits	Passage time in seconds						Sample size					
		Water velocity (f.p.s.)						Water velocity (f.p.s.)					
		2	4	6	8	13.4	15.8	2	4	6	8	13.4	15.8
Steelhead trout	Lower limit	6.6	6.4	5.7	5.0	5.8	5.9						
	Median	7.4	6.8	6.2	5.4	6.5	6.3	324	179	583	579	41	
	Upper limit	8.0	7.5	6.7	6.6	7.0	6.6						
Chinook salmon	Lower limit	3.7	4.2	4.6	5.1	8.0	7.0						
	Median	4.3	4.7	5.0	5.5	8.7	8.0	92	183	279	108	84	
	Upper limit	5.2	5.5	5.3	6.0	9.0	8.9						
Silver salmon	Lower limit	5.8	5.4	6.4	5.4	----	----						
	Median	9.7	6.8	7.0	5.8	----	----	0	16	38	32	0	
	Upper limit	10.2	11.0	8.3	6.9	----	----						

[1] If the median passage time listed for a given species and velocity does not lie between the lower and upper limits listed for another velocity or sp[ecies], t[he] two passage times are considered to be significantly different.

significantly slower than steelhead trout in water velocities of 13.4 and 15.8 f.p.s.

Definite trends are noted when rates of movement and water velocities are compared (fig. 13). Steelhead moved progressively faster as the water velocity increased from 2 to 8 f.p.s.; then slowed down somewhat in velocities of 13.4 and 15.8 f.p.s. The rate of movement at 8 f.p.s. was significantly faster than at any other velocity (table 20). Silver salmon, although slightly slower than steelhead, also moved faster as the water velocity increased

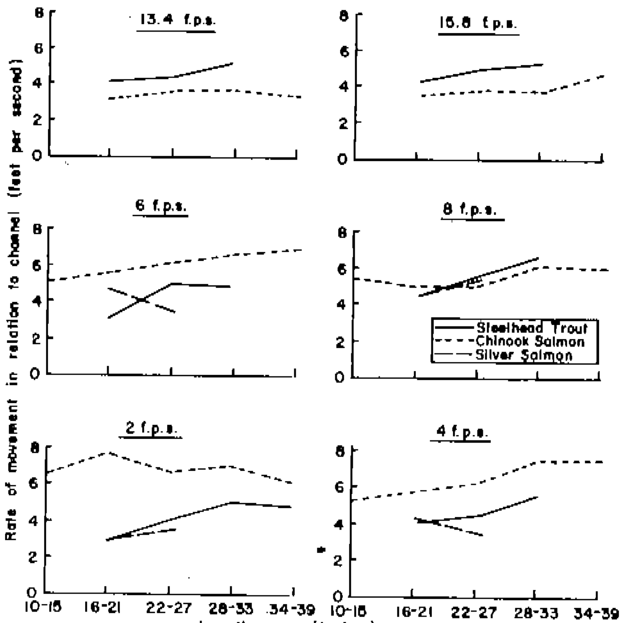

FIGURE 14.—Relationship between fish size and rate of movement. Rates are based on the median passage time of each length group. Lengths of individual fish were estimated. Underscored headings represent water velocities.

from 2 to 8 f.p.s. Chinook salmon differed ...co[m] steelhead trout and silver salmon in th... hei[r] rate of movement decreased with an incr... i[n] water velocity; the fastest rate of movemen... [w]in achieved in the 2 f.p.s. velocity.

Examination of the relationship betwe... fis[h] size and rate of movement illustrates t... dif[-] ferences previously noted in the rate of mov...en[t] between species cannot be attributed to diffe...nce[s] in size of the fish (fig. 14). Comparisons ... th[e] rates of movement between species b... [len]gt[h] groups agrees closely with the ... i[n] figure 13. A direct relationship betwee... siz[e] and rate of movement is also indicated. ...ee[l-] head were consistent in this respect thro...ou[t] the various velocities tested. With the exc...io[n] of the fish tested at 2 f.p.s., chinook demons...ate[d] a similar consistency. Silver salmon were ...t a[s] consistent. At 2 and 8 f.p.s. the larger fish ...ov[ed] fastest, while at velocities of 4 and 6 f.p.s. th[e] smaller fish moved fastest. It should be noted however, that the silver salmon data represen[t] comparatively small sample sizes and thus ma[y] not be reliable.

Maximum Observed Swimming Speeds

The preceding rates of movement were ...se[d] upon the speed of the fish in relation to th[e] channel and did not take into account the w...te[r] velocity in which they were measured. S...m[-] ming speeds may be calculated by adding ...h[e] velocity of the flow to these rates of movem...nt.

Maximum observed swimming speeds for s...e[el-] head trout, chinook, and silver salmon at ... a velocity are given in table 21. The fastest ... timed was a 24-inch steelhead which mainta... e an average swimming speed of 26.8 f.p.s. while passing through the 30-foot timing zone. Maximum observed swimming speeds for chinook and silver salmon were 21.9 and 17.5 f.p.s.. respectively.

Here again the water velocities given are mean values and may be somewhat lower or higher than the actual velocities which the fish encountered depending upon the course they followed ascending the channel (appendix fig. 1). The maximum swimming speeds based on these values, therefore, are subject to an unknown degree of error depending upon the distribution of velocities within the channel and the course the fish followed.

TABLE 21.—*Maximum observed swimming speeds of steelhead trout, chinook, and silver salmon timed through the 30-foot timing zone in water velocities ranging from 2 to 15.8 f.p.s.*

Species	Water velocity	Water temperature	Estimated length	Rate of movement through timing zone	Swimming speed[1]	
	F.p.s.	° *F*	*Inches*	*F.p.s.*	*F.p.s.*	*M.p.h.*
Steelhead trout	2.0	66.5	24	12.0	14.0	9.5
	4.0	66.5	28	13.6	17.6	12.0
	6.0	66.5	30	18.7	24.7	16.8
	8.1	66.5	24	18.7	26.8	18.3
	13.4	67.0	32	6.5	19.9	13.6
	15.8	66.5	24	7.7	23.5	16.0
Chinook salmon	2.0	66.0	20	15.8	17.8	12.1
	3.9	66.5	28	14.3	18.2	12.4
	5.9	66.0	32	14.3	20.2	13.8
	7.9	65.5	32	13.6	21.5	14.7
	13.4	67.0	28	5.8	19.2	13.1
	15.8	67.0	38	6.1	21.9	14.9
Silver salmon	2.1	66.0	18	7.3	9.4	6.4
	3.9	66.0	14	7.0	10.9	7.4
	5.9	66.5	24	11.5	17.4	11.9
	8.4	66.5	24	9.1	17.5	11.9

[1] Swimming speed equals rate of movement maintained through 30-foot timing zone plus the velocity of flow in which the rate was measured.

Other Factors Related to Rate of Movement

Effect of nonuniform flow upon rate of movement.—At a water velocity of 6 f.p.s. a standing wave was created in the channel. Although the position of the wave varied somewhat in relation to the channel during the different test conditions, it was generally posited within the limits of the timing zone. During the course of the experiments it became apparent that this wave was affecting the rate at which fish swam through the timing zone. Some of the fish would stop when they reached the wave and remain for periods ranging from a few seconds to several minutes. This accounts for the comparatively greater percentages of steelhead, chinook, and silver salmon requiring 30 seconds or more to negotiate the timing zone in the 6 f.p.s. velocity tests. A comparison of the distributions of passage times in tables 17, 18, and 19 indicates that the occurrence of the wave affected steelhead trout and silver salmon more than it did chinook salmon; 13.6 percent of the steelhead trout and 10.5 percent of the silver salmon required 30 seconds or longer to negotiate the timing zone in contrast to 1.8 percent of the chinook salmon.

Relationship between swimming ability and rate of movement.—Data on samples of fish tested at water velocities of 13.4 and 15.8 f.p.s. were examined to determine whether there were significant differences in time required to negotiate the timing zone between fish which were able to negotiate the entire channel and those that failed to do so. The distribution of sample sizes restricted the comparisons to chinook salmon at 13.4 f.p.s. and steelhead trout at 15.8 f.p.s. Passage times were obtained for only three steelhead trout which failed to negotiate the channel at 13.4 f.p.s. velocity and for only six chinook salmon which were able to negotiate the entire channel at 15.8 f.p.s. The limited data indicate that the ability of the fish to negotiate the channel was not reflected in the passage time through the timing zone (table 22).

The data for steelhead trout and chinook salmon which were able to negotiate the entire channel in the 13.4 and 15.8 f.p.s. tests were further examined to determine whether the rates of movement decreased as the fish ascended the channel. A comparison was made of rates of movement measured through the first 30 feet of the channel and those measured through the next 50 feet of the channel (table 23). By inspection, no decrease in the rate

TABLE 22.—*Differences between mean passage times of fish which negotiated entire channel and those which failed to do so*

[Data are for chinook in 13.4 f.p.s. velocity and steelhead in 15.8 f.p.s. velocity]

Water velocity	Species	Size[1] group	Mean time required to negotiate 30-foot timing zone: A Negotiated entire channel	Mean time required to negotiate 30-foot timing zone: B Failed to negotiate entire channel	Difference (B−A)	Sample size: A	Sample size: B
F.p.s.			*Seconds*	*Seconds*	*Seconds*		
13.4	Chinook salmon.	small	9.03	9.14	+.11 N.S.	7	12
		large	8.48	8.31	−.17 N.S.	32	33
15.8	Steelhead trout.	small	7.29	6.84	−.45 N.S.	10	25
		large	5.95	7.36	+1.41 N.S.	22	7

[1] Small fish consist of individuals 24 inches and less in length, large fish consist of individuals 25 inches and greater in length.
N.S.—Not significant.

TABLE 23.—*Comparison of steelhead and chinook rates of passage through the lower and upper sections of the channel in water velocities of 13.4 and 15.8 f.p.s.*

Water velocity	Species	Size group	Sample size	Mean rate of movement through	
				First 30 feet	Next 50 feet
F.p.s.				*F.p.s.*	*F.p.s.*
13.4	Steelhead trout	small	15	4.0	3.8
		large	21	4.7	4.7
	Chinook salmon	small	6	3.2	3.3
		large	31	3.5	3.6
15.8	Steelhead trout	small	7	4.4	3.3
		large	20	5.0	4.0
	Chinook salmon	small	---	---	---
		large	4	5.2	4.6

of movement is apparent among either steelhead trout or chinook salmon at 13.4 f.p.s. At 15.8 f.p.s. both steelhead and chinook showed a declining rate of movement as they ascended the channel.

DISCUSSION AND CONCLUSIONS

The results of the preceding experiments clearly demonstrate that water velocity is an important consideration in the design and operation of fishways.

The general response for the high-velocity flow in the choice experiments emphasizes the importance of maintaining adequate attraction flows at fishway entrances. The variation in the response for a given flow velocity among the different experimental conditions suggests that the relative attractiveness of a fishway entrance may vary with the magnitude of the flows adjacent to the entrance, and if these contrasting flows are strong enough, a significant proportion of the fish approaching the fishway might be diverted from the entrance. This may be especially true at low head dams on the Columbia River where entrance flows must often compete with comparatively strong spillway or turbine discharges. The results of the two exploratory tests involving a choice between velocities of 2.7 and 12.9 indicate that at least some fish might repeatedly enter and attempt to negotiate velocities beyond their swimming ability even though a low-velocity passage was near at hand.

Admittedly the responses demonstrated in the laboratory may not be directly applicable to conditions normally existing at fishway entrances. The interaction of other factors such as turbulence; turbidity; differences in water quality, temperature, or light intensity; and possibly tendency of the fish to follow the shoreline might influence the response to flow differences in the vicinity of fishway entrances. We have no assurance, therefore, that the relative attractiveness of a fishway could be greatly improved by striving to maintain the entrance velocity at a higher level than adjacent flows from spillway or turbine discharges. Furthermore, since the high-velocity channel in these experiments always carried a proportionally greater quantity of water, we have not definitely established that the fish were responding solely to velocity differences. Additional studies should be conducted to determine the relative importance of flows in attracting adult salmonids.

The results of the high-velocity experiments demonstrate that the maximum water velocity which may be employed at the entrance or within a fishway will be governed by the species and size of fish involved and the distance which the fish are required to negotiate. When a fishway is designed to pass several species simultaneously the maximum allowable velocities should be determined by the swimming ability of the weakest species. It is evident that velocities of 13 and 16 feet per second could not be utilized in passage facilities designed for both steelhead trout and chinook salmon unless relatively short distances are involved (fig. 12). From the performances of the two species in the choice experiments we would conclude that the maximum velocity which could be employed for distances of approximately 85 feet would lie somewhere between 8 and 13 f.p.s. It is recognized that determination of a maximum velocity which may be safely utilized in passage facilities must not rely solely on the demonstrated ability of the fish to negotiate a required distance. The latent effects of the strenuous effort which may be required to negotiate the passage must also be considered. Paulik, DeLacy, and Stacy (1957) have demonstrated that salmonids may require a period of several hours to recover from exhausting swimming efforts, and Black (1958) has discussed the possible lethal effects and reduction of swimming ability brought about by sustained severe muscular exertion.

The recent findings of Paulik and DeLacy (1958) indicating that the swimming ability of adult salmonids may vary as the fish proceed up the river suggest that caution must be exercised in applying the results of the Bonneville experiments to situations farther up the river.

The results of the rate of movement experiments demonstrate that certain water velocities may be more conducive to passing fish through channels than others. The differences in the rate of movement between species in these experiments preclude a definite decision as to which velocity would be most effective in passing these fish through channels. Chinook salmon demonstrated the fastest rate of movement in the 2 f.p.s. velocity while steelhead trout and silver salmon moved fastest in the 8 f.p.s. velocity. Perhaps the present standard (Bureau of Commercial Fisheries, 1958) of 2 f.p.s. is adequate when dealing with the species utilized in these experiments. This velocity appears strong enough to keep the fish orientated and moving through the channel at a satisfactory rate and would certainly require the least effort of the various velocities tested. It is significant to note, however, that our observations were made in a shallow, well-lighted, relatively narrow channel; somewhat different patterns of movement might be demonstrated in deeper, wider, and often darker passage channels frequently encountered at dams.

The fact that some fish were observed to hesitate in the standing wave created by the 6 f.p.s. velocity suggests a laminar-type flow might be more conducive to a uniform rate of passage through channels.

SUMMARY

The purpose of these experiments was to examine the influence of water velocity upon the orientation, performance, and rate of movement of adult migrating salmonids of the Columbia River. Experiments were conducted at the Fisheries-Engineering Research Laboratory, Bonneville Dam, during the months of August and September 1957. Steelhead trout and chinook salmon were the principal species involved in these experiments. A few silver salmon were also tested. The various experiments which were conducted and their results are outlined below.

Velocity-preference experiments

The orientative influence of water velocity was examined by offering the fish a choice of two channels carrying flows of different velocities. The following six velocity combinations were tested: 8 vs. 2, 8 vs. 4, 8 vs. 6, 6 vs. 2, 6 vs. 4, and 4 vs. 2 feet per second. The response for the high or low velocity in each test condition was measured by the number of fish selecting each channel. The responses of 2,064 steelhead trout, 750 chinook salmon, and 108 silver salmon were observed during the period August 8–30. The following results were obtained:

1. The percentages of steelhead choosing the high-velocity channel in order of the choice conditions listed above were 79.4, 59.0, 52.2, 73.1, 63.8, and 67.2, respectively. This preference for the high velocity was statistically significant for all except the 8 vs. 6 f.p.s. choice condition.

2. The percentages of chinook choosing the high-velocity channel for the above choice conditions were 93.0, 67.5, 45.4, 87.1, 62.3, and 73.4, respectively. Again, as in the case of steelhead, the preference for the higher velocity was statistically significant for all except the 8 vs. 6 f.p.s. choice condition. Chinook demonstrated a more positive response than steelhead for the high velocity in four (8 vs. 2, 8 vs. 4, 6 vs. 2, and 4 vs. 2 f.p.s.) out of the six test conditions. The response was significantly greater at 8 vs. 2, and 6 vs. 2 f.p.s. No significant difference could be demonstrated between the response of large (25 inches and larger) and small (less than 25 inches) fish except in the 8 vs. 4 f.p.s. test condition. Here a greater proportion of large fish chose the higher velocity channel.

3. The limited number of silver salmon tested during these experiments indicated that this species generally preferred the higher velocity channel.

4. Results of an exploratory test in which 41 steelhead and 57 chinook were presented with a choice between water velocities of approximately 3 and 13 f.p.s. were similar to the preceding test in that 75.6 percent of the steelhead and 89.5 percent of the chinook chose the high-velocity channel.

High-velocity experiments

The performances of steelhead and chinook were measured in water velocities of 13.4 and 15.8 f.p.s. by determining the distance which the fish were able to negotiate through an 85-foot channel. The 13.4 f.p.s. tests were conducted from September 5–7, and the 15.8 f.p.s. tests were conducted on September 9, 10, 14, and 15. A total of 47

steelhead and 91 chinook were tested in the 13.4 f.p.s. flow and 67 steelhead and 130 chinook were tested in the 15.8 f.p.s. flow. The following results were obtained.

1. The performance of steelhead surpassed that of chinook in both 13.4 and 15.8 f.p.s. velocities. At a water velocity of 13.4 f.p.s., 92 percent of the steelhead negotiated the entire length of the channel whereas only 51 percent of the chinook achieved this distance. The performance of both steelhead and chinook declined at 15.8 f.p.s. velocity. Only 51 percent of the steelhead and 5 percent of the chinook negotiated the entire 85-foot channel. A decline in the swimming ability of chinook was noted during the experimental period.

2. Large fish of both species performed better than small fish in both 13.4 and 15.8 f.p.s. velocities.

Rate-of-Movement Experiments

The influence of water velocity upon rate of movement was measured by timing the fish through a 30-foot distance within the channels. Rates were determined at water velocities approximating 2, 4, 6, 8, 13, and 16 f.p.s. These experiments were conducted concurrently with the velocity-preference experiments and high-velocity experiments and utilized the same fish. The following results were obtained:

1. Rates of passage through the channels varied with species and water velocity. Based on median passage times required to negotiate 30 feet, both steelhead trout and silver salmon increased their rate of movement as the water velocity increased from 2 to 8 f.p.s.; steelhead from 4.1 to 5.6 f.p.s. and silver salmon from 3.1 to 5.1 f.p.s. In contrast the rate of movement of chinook salmon decreased from 6.9 f.p.s. in the 2 f.p.s. flow to 5.5 f.p.s. in the 8 f.p.s. flow.

The rates of movement of steelhead and chinook, based on median passage times of the fish which were able to negotiate the 30-foot timing zone, were 4.6 and 3.4 f.p.s., respectively, in the 13.4 f.p.s. velocity and 4.7 and 3.8 f.p.s., respectively in the 15.8 f.p.s. velocity.

3. A standing wave which occurred within the timing zone at a velocity of 6 f.p.s. tended to stop some of the fish for periods ranging from several seconds to several minutes. Steelhead were more affected by this wave than chinook.

4. Large steelhead and chinook were generally faster than small steelhead and chinook at each velocity tested.

5. Maximum observed swimming speeds (rate of movement in relation to the channel plus the water velocity in which the rate was measured) for each species were as follows: steelhead 26. f.p.s., chinook 21.9 f.p.s., and silver salmon 17. f.p.s. These rates are equivalent to 18.3, 14.9 11.9 miles per hour, respectively.

6. There was no evidence that the distance which steelhead and chinook were able to negotiate in flows of 13.4 and 15.8 f.p.s. influenced their rates of movement at these velocities. Rates of movement of fish which were unable to negotiate the entire channel at these velocities did not differ significantly from those fish which negotiated the entire channel.

7. There was no apparent difference in the rates of movement maintained by steelhead and chinook through the first 30 feet and last 50 feet of the channel in the 13.4 f.p.s. flow. At 15.8 f.p.s. velocity the rates of movement of both steelhead and chinook decreased somewhat through the last 50 feet of the channel.

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APPENDIX A

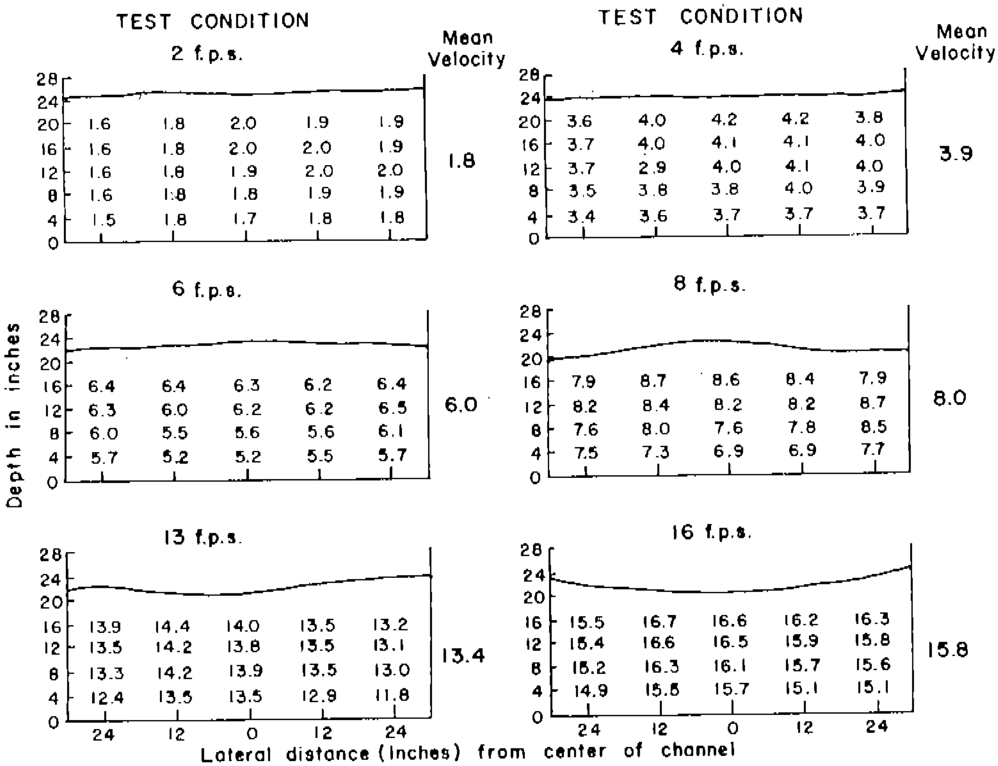

Figure A-1.—Examples of the distribution of water velocities in the channel for each of the six test conditions. Entries for each measuring point (depth and distance from the center of the channel) are mean values derived from measurements taken at these points at five different stations between the downstream end of the channel and the upstream limit of the timing zone. (point B, figs. 3 and 9). Line at top indicates water surface.