Passage of Adult Salmon and Trout through an Inclined Pipe[1]

EMIL SLATICK
National Marine Fisheries Service, Biological Laboratory
2725 Montlake Boulevard East
Seattle, Washington 98102

ABSTRACT

This research was designed to determine if migrating adult salmon and trout at Bonneville Dam on the Columbia River would use as a passageway an inclined pipe that required them to make a descent and an ascent before they reached the upstream end of the pipe. Chinook salmon (*Oncorhynchus tshawytscha*), sockeye salmon (*O. nerka*), coho salmon (*O. kisutch*), and steelhead trout (*Salmo gairdneri*) were tested with water velocities of about 0.30, 0.76, and 1.22 m/sec in a pipe that was 0.61 m in diameter and 31.4 m long. From 64 to 100% of the fish passed through the inclined pipe during a 45-min period. Median passage times ranged from 3 to 23 min. Chinook salmon passed through the pipe most rapidly at the 0.76 m/sec flow; coho salmon and steelhead trout passed through in the least time at 1.22 m/sec. Sockeye salmon passed through equally well at flows of 0.76 and 1.22 m/sec.

INTRODUCTION

Transportation channels are an integral part of fish-passage facilities at many large dams on the Columbia River (Gauley, 1967). They provide passageways to or from fishways or other passage facilities. The two types of transportation channels used are: (1) a multiple-entrance collection channel on the downstream side of a powerhouse and (2) an independent channel that passes fish on a level plane between two distant points. The Dalles Dam on the Columbia River is equipped with both types of channels (U. S. Army Corps of Engineers, 1957).

The use of pipes for fish passageways could substantially reduce costs of constructing and operating fishways at dams and facilitate the transportation and handling of fish at other passage or trapping sites. Recent studies have indicated that migrating adult salmon and trout would pass through level pipes ranging from 0.61 to 0.91 m in diameter (Slatick, 1970), and travel for distances of over a kilometer (Trefethen, 1968).

Because a pipe transportation system may be required to pass fish beneath a navigation lock or some other structure at a dam site, an experiment was made in 1966 to determine if salmon and trout would pass through an inclined pipe that made a descent and an ascent necessary to reach the upstream end. This paper reports on the influence of water velocity on fish passage through the inclined pipe and on the relation between performance and length of fish.

RESEARCH AREA

All tests were made in the Fisheries-Engineering Research Laboratory at Bonneville Dam on the Columbia River (see Collins and Elling, 1960). Basically the laboratory is a large enclosed rectangular tank about 54.9 m long, 7.3 m wide, and 7.3 m deep. It is located adjacent to the Washington shore fish ladder on the right bank of the river. Fish are diverted from the ladder, enter and pass through the laboratory on their own volition, and re-enter the ladder to continue their ascent. They are not handled at any time.

EXPERIMENTAL EQUIPMENT AND METHODS

A 0.61-m-diameter steel pipe 31.4 m long (Figure 1) emerged from a head box, or pool, at the upstream end; after traveling horizontally for about 1.8 m it dipped down at a 45° angle to a depth of about 5.2 m (Figure 2). It continued horizontally at this level for about 12.2 m, rose (again at a 45° angle) to about 0.3 m below the starting elevation, and leveled off for the last 1.8 m before entering the down-

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

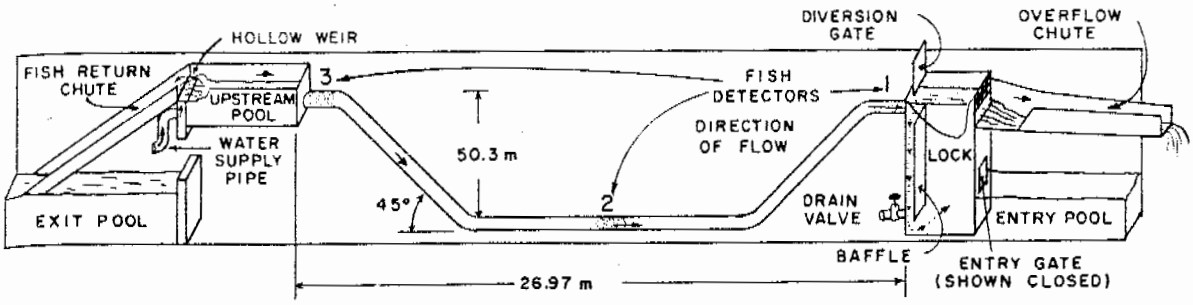

FIGURE 1.—Plan of the inclined pipe and appurtenant structures. Electronic detectors used to monitor fish passage are designated by the numbers 1 to 3.

stream pool, or lock. The pipe was dark except for incidental light that entered each end.

Water for the pipe system entered a hollow weir (Figure 1) from a supply pipe, passed through the weir to enter the upstream pool, flowed through the inclined pipe, and was discharged at the downstream end of the fish lock into an overflow chute (when the lock was full) or into the entry pool (when the lock was drained). Water velocities in the inclined pipe were regulated by a valve in the supply pipe and by stop logs at the downstream end of the lock.

Fish entered the laboratory from the Washington shore fishway via a short auxiliary fishway. Before each fish was released into the test area, it passed through a release compartment where an observer ascertained its size and species.

Fish were tested individually. The downstream pool, or lock, was drained and the flow was adjusted to provide a suitable overflow from the lock into the entry pool. After a fish entered the lock, the entry gate was closed, the lock was filled, and a diversion gate in front of the pipe was opened to allow the fish to enter the pipe.

Passage of the fish through the pipe was monitored by three pairs of electronic detectors, one at the center and one at each end of the pipe (Figure 1). Each of these paired detectors activated two separate pens on a time-event recorder. When a fish passed a detector, a relay was tripped, causing a pen to make a mark on a time-scaled chart. The sequence of marks between each pair of detectors indicated the direction the fish was moving, and the distance between the marks indicated the length of time the fish remained in the various sections of the pipe.

Fish emerging from the upstream end of the pipe eventually swam over the hollow weir, slid down the chute to a pool, and then continued on their way out of the laboratory. If a fish failed to enter or pass through the pipe

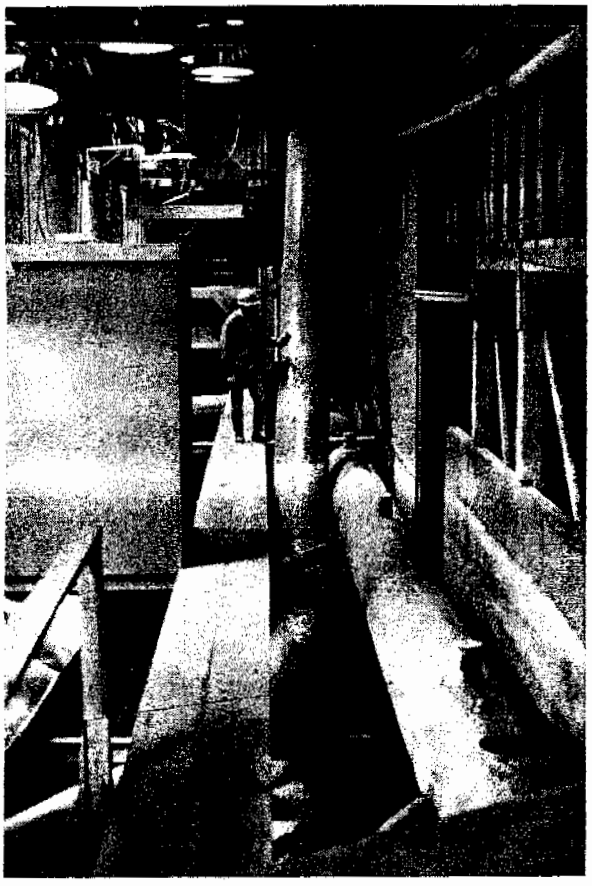

FIGURE 2.—Upstream rise of the inclined pipe. The pipe is inclined at a 45° angle and rises about 5.2 m. The horizontal pipe on the right is a part of another pipe system.

TABLE 1.—*Distribution of times required by individual chinook salmon, sockeye salmon, and coho salmon to pass through the 31.4-m-long inclined pipe at water velocities of 0.30, 0.76, and 1.22 m/sec, June–October 1966*

Time interval (min)	Number of summer chinook salmon 23 June to 1 August Velocity (m/sec)			Number of fall chinook salmon 24 August to 10 September Velocity (m/sec)			Number of sockeye salmon 23 June to 14 July Velocity (m/sec)			Number of coho salmon 6 September to 2 October Velocity (m/sec)		
	0.30	0.76	1.22	0.30	0.76	1.22	0.30	0.76	1.22	0.30	0.76	1.22
0–1.9	1	3	4	1	–	3	6	5	5	–	–	1
2.0–3.9	2	1	6	5	4	–	3	14	13	1	–	2
4.0–5.9	3	8	5	4	3	6	3	5	7	2	1	5
6.0–7.9	–	5	2	3	5	3	4	3	2	4	3	2
8.0–9.9	1	4	1	3	3	1	2	–	1	6	3	4
10.0–11.9	1	1	1	2	4	1	1	–	–	3	–	5
12.0–13.9	–	–	1	3	2	1	3	–	–	1	3	1
14.0–15.9	–	1	1	2	–	–	1	–	–	2	3	3
16.0–17.9	1	–	2	–	–	–	1	3	–	2	3	1
18.0–19.9	1	–	–	2	1	–	2	–	–	3	–	5
20.0–21.9	–	–	1	1	1	–	–	–	–	2	1	1
22.0–23.9	–	–	–	1	1	–	2	–	–	–	–	–
24.0–25.9	–	–	1	–	–	–	–	–	–	–	3	–
26.0–27.9	–	–	–	–	2	–	–	–	–	2	1	1
28.0–29.9	–	–	–	–	1	3	–	–	–	–	1	1
30.0–31.9	–	–	1	–	–	–	–	–	–	1	–	–
32.0–33.9	–	–	1	1	–	1	–	–	–	–	1	–
34.0–35.9	–	–	–	–	–	–	–	–	–	1	–	–
36.0–37.9	–	–	–	–	1	–	–	–	–	1	–	1
38.0–39.9	1	–	–	–	1	–	–	–	1	1	–	1
40.0–41.9	–	–	–	–	–	–	–	–	–	–	–	1
42.0–43.9	–	–	1	–	–	2	–	–	–	–	2	1
44.0–44.9	–	–	–	–	–	–	–	–	–	–	–	–
45+	4	1	3	5	4	6	1	–	–	7	9	5
Total number of fish	15	24	31	33	33	27	29	30	29	39	34	41
Percent completing passage	73	96	90	85	88	78	97	100	100	82	74	88
Median passage time	11.0	5.9	6.8	10.8	10.5	11.2	7.0	3.5	3.0	17.2	22.3	12.9

within 45 min after entering the facility, it was removed from the system and another fish was started. Tests were conducted with water velocities in the pipe of about 0.30, 0.76, and 1.22 m/sec.

INFLUENCE OF WATER VELOCITY ON FISH PASSAGE

The influence of water velocity on fish passage was measured by comparing the times required for the fish to pass through the inclined pipe at different flows. A nonparametric three-sample Kolmogorov-Smirnov test (Fisz, 1963) was applied to determine the significance of differences between the passage times at three velocities.

Chinook salmon (*Oncorhynchus tshawytscha*), sockeye salmon (*O. nerka*), coho salmon (*O. kisutch*), and steelhead trout (*Salmo gairdneri*) were used in the tests. Chinook salmon and steelhead trout were tested during two periods, or runs; they are designated as summer-run and fall-run fish. Summer-run chinook salmon were tested from 23 June to 1 August, and fall-run chinook salmon were tested from 24 August to 10 September. Summer- and fall-run steelhead trout were tested from 15 July to 10 August and from 11 to 28 September, respectively.

Chinook Salmon

The responses of summer and fall chinook salmon to different flows in the inclined pipe were similar. Median times required by the fish to complete passage through the inclined pipe at water velocities of 0.30, 0.76, and 1.22 m/sec were 11.0, 5.9, and 6.8 min, respectively, for summer chinook salmon and 10.8, 10.5, and 11.2 min, respectively, for fall chinook salmon (Table 1). Kolmogorov-Smirnov tests of these data indicated that differences between passage times at the three water velocities were not significant for either summer or fall chinook salmon (Table 2).

Summer chinook salmon completing passage through the pipe ranged from 96% at the 0.76-m/sec flow to 73% at the 0.30-m/sec flow. Fall chinook completing passage ranged from 88% at the 0.76-m/sec flow to 78% at the 1.22-m/sec flow.

TABLE 2.—*Kolmogorov-Smirnov test for significance of difference between passage times through the inclined pipe at water velocities of 0.30, 0.76, and 1.22 m/sec for chinook salmon, sockeye salmon, coho salmon, and steelhead trout, 1966*

Species	Velocity tested (m/sec)	Symbol	$D_{[i,j]}$	K	Conclusion at $\alpha = 0.05$
Summer chinook	0.30 vs. 0.76	X11/X12	0.425	0.440	X11 ≡ X12
	0.30 vs. 1.22	X11/X13	0.144	0.420	X11 ≡ X13
	0.76 vs. 1.22	X12/X13	0.303	0.350	X12 ≡ X13
Fall chinook	0.30 vs. 0.76	X21/X22	0.091	0.320	X21 ≡ X22
	0.30 vs. 1.22	X21/X23	0.203	0.345	X21 ≡ X23
	0.76 vs. 1.22	X22/X23	0.175	0.345	X22 ≡ X23
Sockeye	0.30 vs. 0.76	X31/X32	0.386	0.345	X31 ≢ X32*
	0.30 vs. 1.22	X31/X33	0.448	0.345	X31 ≢ X33*
	0.76 vs. 1.22	X32/X33	0.062	0.345	X32 ≡ X33
Coho	0.30 vs. 0.76	X41/X42	0.204	0.310	X41 ≡ X42
	0.30 vs. 1.22	X41/X43	0.118	0.300	X41 ≡ X43
	0.76 vs. 1.22	X42/X43	0.257	0.305	X42 ≡ X43
Summer steelhead	0.30 vs. 0.76	X51/X52	0.370	0.350	X51 ≢ X52*
	0.30 vs. 1.22	X51/X53	0.536	0.345	X51 ≢ X53*
	0.76 vs. 1.22	X52/X53	0.189	0.305	X52 ≡ X53
Fall steelhead	0.30 vs. 0.76	X61/X62	0.328	0.520	X61 ≡ X62
	0.30 vs. 1.22	X61/X63	0.409	0.565	X61 ≡ X63
	0.76 vs. 1.22	X62/X63	0.215	0.520	X62 ≡ X63

* Significant difference (95% level).

Considering passage times and the percentages of fish completing passage, I conclude that the 0.76-m/sec flow provided the best passage condition of the three velocities tested for chinook salmon.

Sockeye Salmon

Median passage times of sockeye salmon at flows of 0.30, 0.76, and 1.22 m/sec were 7.0, 3.5, and 3.0 min, respectively (Table 1). Passage by individual sockeye salmon through the pipe was significantly faster at 0.76 and 1.22 m/sec than at 0.30 m/sec, but the difference between the passage times at flows of 0.76 and 1.22 m/sec was not significant (Table 2).

Percentages of sockeye salmon completing passage through the inclined pipe were the highest of all species tested. All of the sockeye salmon successfully negotiated the pipe at velocities of 0.76 and 1.22 m/sec, and only one failed to do so at 0.30 m/sec.

Coho Salmon

Median passage times of coho salmon ranged from 12.9 min at the 1.22-m/sec flow to 22.3 min at the 0.76-m/sec flow (Table 1). Kolmogorov-Smirnov tests on passage times through the pipe indicated, however, that differences between passage times at the three velocities were not significant (Table 2). Coho salmon completing passage through the pipe ranged from 88% at 1.22 m/sec to 74% at 0.76 m/sec. These data indicate that the 1.22-m/sec flow was better than the 0.30- or 0.76-m/sec flow for passage of coho salmon.

TABLE 3.—*Distribution of times required by individual steelhead trout to pass through the 31.4-m-long inclined pipe at water velocities of 0.30, 0.76, and 1.22 m/sec, July–September 1966*

Time interval (min)	Number of summer steelhead trout 15 July to 10 August Velocity (m/sec)			Number of fall steelhead trout 11–28 September Velocity (m/sec)		
	0.30	0.76	1.22	0.30	0.76	1.22
0–1.9	1	3	7	–	2	1
2.0–3.9	1	7	4	1	1	2
4.0–5.9	1	7	8	–	1	2
6.0–7.9	–	2	7	1	–	–
8.0–9.9	3	4	3	–	1	1
10.0–11.9	4	1	3	–	–	–
12.0–13.9	–	2	2	–	1	–
14.0–15.9	1	–	–	–	–	–
16.0–17.9	1	1	–	2	3	–
18.0–19.9	–	2	1	–	–	–
20.0–21.9	1	–	1	1	–	–
22.0–23.9	4	3	–	1	–	–
24.0–25.9	–	1	–	–	–	2
26.0–27.9	1	–	–	–	–	–
28.0–29.9	1	–	–	–	–	–
30.0–31.9	1	–	–	–	–	–
32.0–33.9	1	–	–	–	–	–
34.0–35.9	–	–	–	–	–	–
36.0–37.9	–	1	–	–	1	–
38.0–39.9	–	–	1	–	–	–
40.0–41.9	–	–	–	–	–	1
42.0–43.9	–	–	–	1	–	–
44.0–44.9	–	–	–	–	–	–
45+	2	4	2	4	3	1
Total number of fish	23	38	39	11	13	10
Percent completing passage	91	89	95	64	77	90
Median passage time	16.5	8.3	6.2	23.0	17.1	6.9

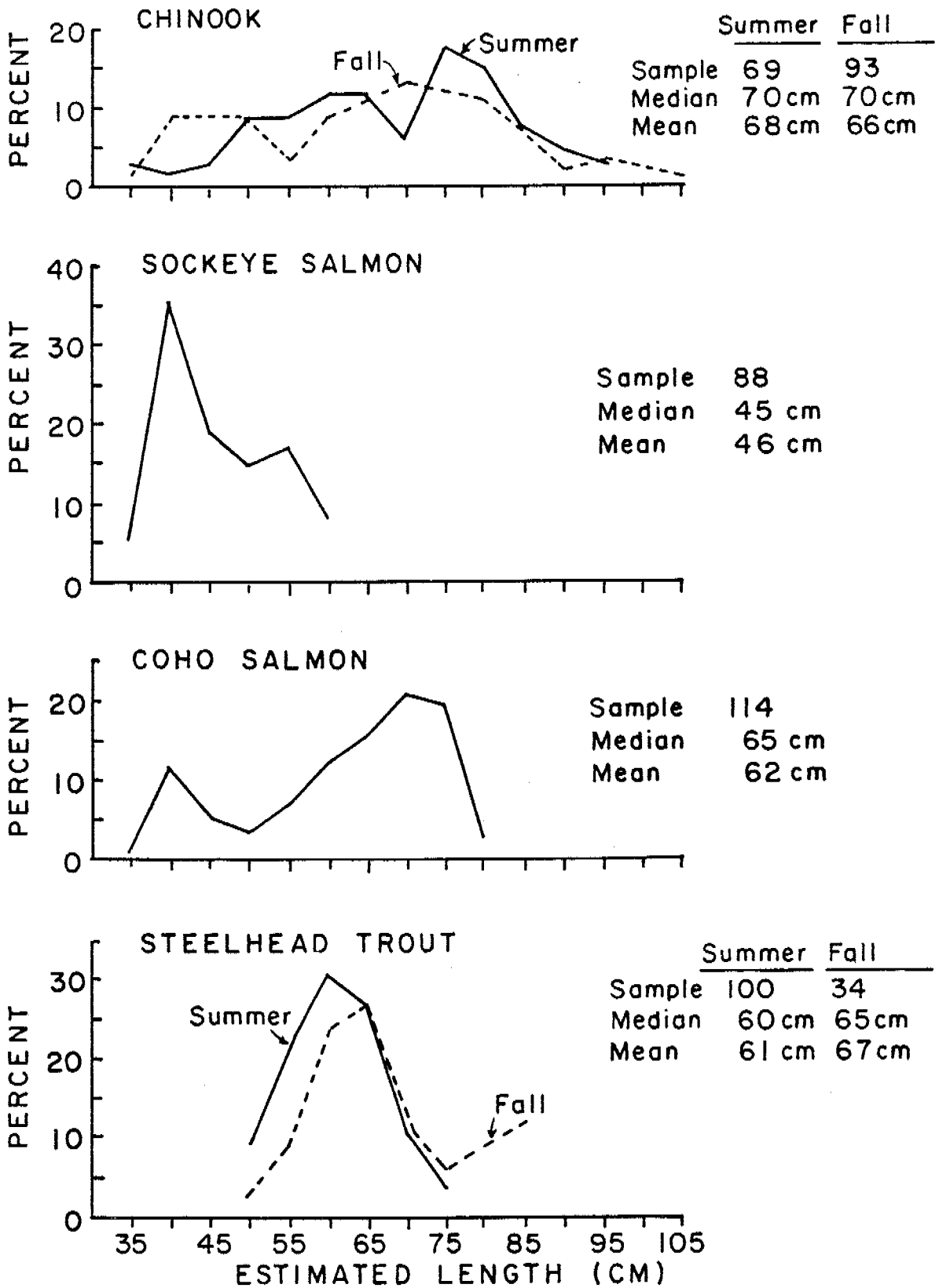

FIGURE 3.—Length composition, median length, and mean length of chinook salmon, sockeye salmon, coho salmon, and steelhead trout tested in the inclined-pipe experiments.

TABLE 4.—*Median and mean passage times of small (less than median length) and large (median length and larger) chinook salmon and coho salmon passing through a 31.4-m-long inclined pipe in water velocities of 0.30, 0.76, and 1.22 m/sec, June–October 1966*

Species and size	Passage time by velocity in pipe[1]						Confidence interval	
	0.30 m/sec		0.76 m/sec		1.22 m/sec		Lower limit Median[3]	Upper limit Median[3]
	Mean[2]	Median	Mean[2]	Median	Mean[2]	Median		
Summer chinook								
Small (under 70 cm)	11.9(8)	11.0(9)	–	–	–	–	2.1	39.5
Large (70 cm and over)	10.5(4)	13.2(5)	–	–	–	–	–	–
Small	–	–	6.2(10)	6.5(10)	–	–	1.8	8.9
Large	–	–	6.3(13)	5.7(14)	–	–	4.4	9.8
Small	–	–	–	–	10.5(11)	10.1(14)	3.5	45+
Large	–	–	–	–	10.6(17)	4.3(17)	3.6	15.9
Fall chinook								
Small (under 70 cm)	9.7(10)	12.5(13)	–	–	–	–	4.2	45+
Large (70 cm and over)	10.6(18)	10.8(20)	–	–	–	–	5.6	15.6
Small	–	–	13.5(15)	10.7(17)	–	–	5.8	26.9
Large	–	–	12.6(14)	9.7(16)	–	–	7.0	27.4
Small	–	–	–	–	13.5(12)	11.0(16)	5.7	45+
Large	–	–	–	–	14.5(9)	11.2(11)	0.7	45+
Coho								
Small (under 65 cm)	14.1(14)	15.0(19)	–	–	–	–	9.1	45+
Large (65 cm and over)	16.7(18)	18.0(20)	–	–	–	–	8.4	27.8
Small	–	–	17.5(10)	21.0(14)	–	–	13.3	45+
Large	–	–	18.8(15)	22.6(20)	–	–	12.9	43.0
Small	–	–	–	–	14.2(12)	11.7(13)	3.9	26.4
Large	–	–	–	–	15.8(24)	15.0(28)	8.9	21.7

[1] Number of minutes and (in parentheses) number of fish that passed through the pipe.
[2] Based on fish which completed passage within the 45-min limit.
[3] 95% confidence intervals about the median.

Steelhead Trout

Median passage times of summer steelhead trout ranged from 6.2 min at the 1.22-m/sec flow to 16.5 min at the 0.30-m/sec flow, and those of fall steelhead trout ranged from 6.9 min at the 1.22-m/sec flow to 23.0 min at the 0.30-m/sec flow (Table 3). The data indicated that of the three velocities tested 1.22 m/sec provided the best passage condition for steelhead trout.

Passage times of summer steelhead trout were significantly less at flows of 0.76 and 1.22 m/sec than at 0.30 m/sec, but the difference between the passage times at 0.76 and 1.22 m/sec was not significant (Table 2). Although median passage times of fall steelhead trout differed by as much as 16.1 min, sample sizes were small and no significant difference between passage times could be demonstrated.

Summer steelhead trout completing passage ranged from 95% in the 1.22 m/sec flow to 89% at 0.76 m/sec. Fall steelhead trout completing passage ranged from 90% at 1.22 m/sec to 64% at 0.30 m/sec.

RELATION BETWEEN PERFORMANCE AND LENGTH OF FISH

The median passage times of large and small fish of each species under each test condition were compared to determine if performance in the inclined pipe was related to length of fish. This possibility was suggested by the better performance of sockeye salmon, which were smaller than the other species. A table of confidence intervals was used to test the significance of observed differences between these median passage times (Dixon and Massey, 1957).

Chinook salmon ranged in fork length from 35 to 105 cm; sockeye salmon, 35 to 60 cm; coho salmon, 35 to 80 cm; and steelhead trout, 40 to 85 cm (Figure 3). The median length of each species was used to divide the fish into two size groups. Fish less than the median length were designated as small fish, and those of median length and larger were classified as large fish.

Comparison of the median passage times of the two size groups showed no significant differences between the performance of large

TABLE 5.—*Median and mean passage times of small (less than median length) and large (median length and larger) sockeye salmon and steelhead trout passing through a 31.4-m-long inclined pipe in water velocities of 0.30, 0.76, and 1.22 m/sec, June–October 1966*

	Passage time by velocity in pipe[1]						Confidence interval	
	0.30 m/sec		0.76 m/sec		1.22 m/sec		Lower limit	Upper limit
Species and size	Mean[2]	Median	Mean[2]	Median	Mean[2]	Median	Median[3]	Median[3]
Sockeye								
Small (under 45 cm)	6.8(11)	3.1(12)	–	–	–	–	1.3	19.0
Large (45 cm and over)	9.7(17)	8.6(17)	–	–	–	–	5.4	13.3
Small	–	–	3.4(11)	3.0(11)	–	–	2.0	6.4
Large	–	–	5.8(19)	3.5(19)	–	–	3.0	5.2
Small	–	–	–	–	5.6(13)	2.3(13)	1.4	4.8
Large	–	–	–	–	3.9(16)	3.0(16)	2.1	5.0
Summer steelhead								
Small (under 60 cm)	14.2(7)	11.0(7)	–	–	–	–	1.7	28.5
Large (60 cm and over)	17.5(14)	22.5(17)	–	–	–	–	10.6	31.5
Small	–	–	9.6(9)	6.7(10)	–	–	3.2	25.9
Large	–	–	10.0(25)	7.9(27)	–	–	3.8	17.7
Small	–	–	–	–	6.2(14)	6.0(14)	2.9	9.7
Large	–	–	–	–	8.4(23)	7.3(25)	3.7	11.1
Fall steelhead								
Small (under 65 cm)	16.4(2)	16.4(2)	–	–	–	–	–	–
Large (65 cm and over)	19.6(5)	43.8(9)	–	–	–	–	6.6	45+
Small	–	–	6.3(6)	7.3(8)	–	–	1.2	45+
Large	–	–	21.1(4)	17.1(5)	–	–	–	–
Small	–	–	–	–	22.9(2)	22.9(2)	–	–
Large	–	–	–	–	10.4(7)	6.9(8)	1.5	45+

[1] Number of minutes and (in parentheses) number of fish that passed through pipe.
[2] Based on fish which completed passage within the 45-min limit.
[3] 95% confidence intervals about the median.

and small fish under the water velocities tested (Tables 4 and 5). Under the best passage conditions (0.76 m/sec for chinook salmon and 1.22 m/sec for sockeye salmon, coho salmon, and steelhead trout), the difference between the median passage times was 1 min or less for chinook salmon, sockeye salmon, and steelhead trout and about 3 min for coho salmon. The small sample size of fall steelhead trout at 0.30, 0.76, and 1.22-m/sec flows and of summer chinook salmon at 0.30 m/sec precluded testing for statistical significance of the difference in passage times.

SUMMARY AND CONCLUSIONS

An experiment was made at Bonneville Dam on the Columbia River in 1966 to determine if migrating adult salmon and trout would use as a passageway an inclined pipe that required them to make a descent and an ascent before they reached the upstream end. The influence of water velocity on fish passage through the pipe was measured, and the relation between performance and length of fish was determined by comparing median passage times of large and small fish.

Of the water velocities tested, the best for passing fish through the inclined pipe were 0.76 m/sec for chinook salmon and 1.22 m/sec for coho salmon and steelhead trout. Sockeye salmon passed through the inclined pipe equally well at either the 0.76- or the 1.22-m/sec flow.

No significant differences were demonstrated between the median passage times of small and large chinook salmon, sockeye salmon, coho salmon, or summer steelhead trout. The samples of summer chinook salmon tested at 0.30 m/sec and of fall steelhead trout at 0.30, 0.76, and 1.22 m/sec were too small to be tested for statistically significant differences.

Results of this experiment indicate that if proper conditions of flow are provided, a large percentage of migrating adult salmon and steelhead trout will pass through an inclined pipe requiring a descent and ascent of about 5.2 m. If more time is allowed (only 45 min in this experiment), an even larger percentage will probably complete passage.

LITERATURE CITED

COLLINS, GERALD B., AND CARL H. ELLING. 1960. Fishway research at the Fisheries-Engineering

Research Laboratory. U. S. Fish Wildl. Serv., Circ. 98, 17 pp.

DIXON, WILFRID J., AND FRANK J. MASSEY, JR. 1957. Introduction to statistical analysis. 2d ed. McGraw-Hill Book Company, Inc., New York, 488 pp.

FISZ, MAREK. 1963. Probability theory and mathematical statistics. John Wiley and Sons, Inc., New York, 677 pp.

GAULEY, JOSEPH R. 1967. Effect of water velocity on passage of salmonids in a transportation channel. U. S. Fish Wildl. Serv., Fish. Bull. 66: 59–63.

SLATICK, EMIL. 1970. Passage of adult salmon and trout through pipes. U. S. Fish Wildl. Serv., Spec. Sci. Rept. Fish. 592, 18 pp.

TREFETHEN, PARKER S. 1968. Fish-passage research: Review of progress, 1961–66. U. S. Fish Wildl. Serv., Circ. 254, 24 pp.

U. S. ARMY CORPS OF ENGINEERS. 1957. Annual fish passage report, North Pacific Division; Bonneville, The Dalles, and McNary Dams, Columbia River, Oregon and Washington. U. S. Army Corps of Engineers, Portland and Walla Walla Districts, 49 pp. text, 101 tables, 40 pl., 3 maps.