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GAULEY, J. R.
ELLING, C. H.

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Ability of Salmonids to Ascend High Fishways[1]

GERALD B. COLLINS, JOSEPH R. GAULEY, AND CARL H. ELLING

U. S. Bureau of Commercial Fisheries
Seattle, Washington

ABSTRACT

The ability and persistence of salmonids in ascending pool-and-overfall fishways was measured in experimental "endless" fishway structures in which fishways of any height could be simulated. Six chinook salmon (*Oncorhynchus tshawytscha*), four sockeye salmon (*O. nerka*), and four steelhead trout (*Salmo gairdneri*) were permitted to ascend 1,000 feet in the experimental fishways. One sockeye salmon was allowed to ascend an endless fishway for over 5 days, climbing 6,648 feet, a vertical ascent of more than a mile, before the test was discontinued. Rate of ascent of all fish tested increased following an initial period of experience in the fishway. The level of blood lactate in the exercised fish showed no evidence of fatigue. Practical significance of the data in relation to fishway design is discussed.

INTRODUCTION

The large-scale development of water resources on the Columbia River system, with construction of numerous large dams on the main river and tributary streams, poses many special problems for agencies responsible for providing safe passage for migrant anadromous fish. One of these problems is the design of fishways for adult migrants at high dams. Experience on the Columbia River has been confined to fishways requiring a total vertical ascent of less than 100 feet. McNary Dam, the highest dam with fishways on the Columbia, requires an ascent of 92 feet. Pelton Dam on the Deschutes River, a tributary of the Columbia, has fishways requiring a total ascent of 188 feet, although this height is attained gradually over a distance of almost 3 miles. Several dams now proposed, however, would require that fish ascend much greater heights. The question arises as to whether the pool-and-overfall fishways now conventional on the Columbia River would be practical with dams 300, 400, or 500 feet high, or whether the migrating fish would tire after a few hours and fail to complete passage through such fishways.

Another concern is the possibility that migrating fish might become fatigued because the effects of ascending fishways at many dams accumulated. In the Columbia River adult migrants may have to ascend as many as 10 major dams before reaching their spawning areas. Whether or not a total ascent of as much as 1,000 feet in pool-and-overfall fishways would fatigue fish to the degree that they might be unable to reach spawning areas or to reproduce successfully has been a matter of apprehensive speculation.

In an attempt to provide at least partial answers to these and other questions related to the behavior and performance of migrating fish in pool-and-overfall fishways, a series of tests was made in specially designed experimental structures in which fishways of great height could be simulated.

MATERIALS AND METHODS

The experiments were conducted in the Fisheries-Engineering Research Laboratory at Bonneville Dam on the Columbia River using a pair of "endless" fishways. These experimental fishways were pool-and-overfall types constructed so that each made a complete circuit (Figure 1), with the highest pool con-

[1] Research financed by the U. S. Army Corps of Engineers as a part of a broad program of Fisheries-Engineering Research for the purpose of providing design criteria for fish-passage facilities at Corps projects on the Columbia River.

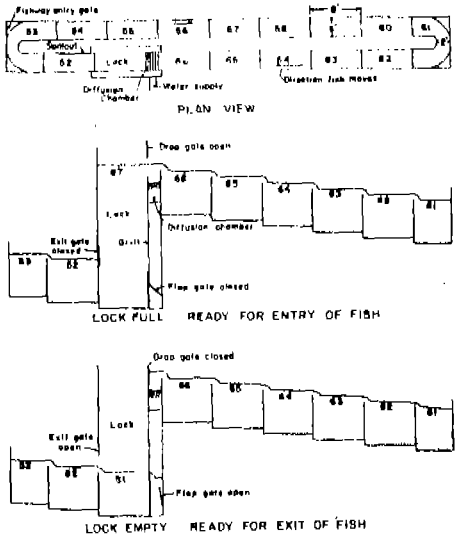

FIGURE 1.—Diagram of the 1-on-8-slope endless fishway showing plan and side views of two phases of lock operation. Numbers 51 through 67 are pool elevations in feet above mean sea level.

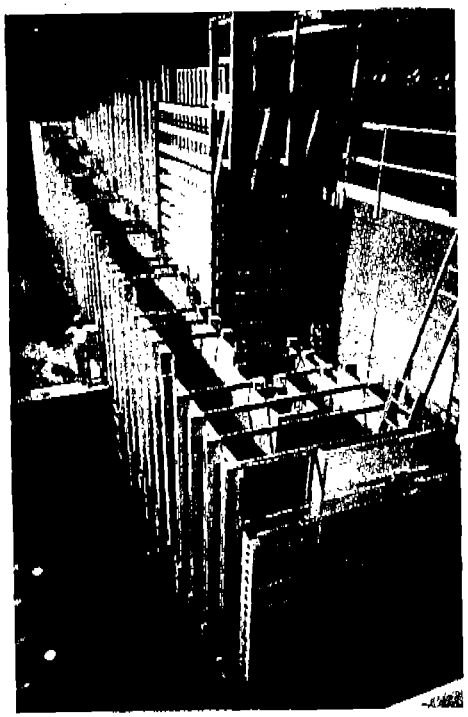

FIGURE 2.—The 1-on-8-slope endless fishway shown during construction. Locking unit for lowering and recycling fish appears in center. Entry gate (shown closed) is visible in foreground.

nected to the lowest pool by means of a lock. When a test fish had ascended to the top of one of these fishways it was rapidly locked to the lowest pool to begin its ascent again. By repeating the procedure, fishways of any desired height could be simulated. Two endless fishways were constructed in order to study the effect of fishway slope on the performance and biochemistry of the ascending fish. Results of that study, with related observations on the effects of pool hydraulics on patterns of ascent, will be reported elsewhere.[2] This report is confined to the aspect of extended ascents of 1,000 or more feet.

One of the endless fishways had a slope of 1 on 8 (Figure 2) with pools 8 feet long, 3 feet wide, 6.8 feet deep and with overfalls of 1 foot between pools. The other fishway, with a 1-on-16 slope (Figure 3), was similar except that the pools were 16 feet in length. The locks in both fishways were 8 feet long, 3 feet wide, and 23 feet deep when filled and 7 feet deep when drained (Figure 1). Weirs in both fishways were 6 feet high, 2 inches thick, with flat crests and were without orifices through which fish might pass. Water flow over the weirs was maintained by 0.8 foot of head measured 2.5 feet upstream from the weir crest. Turn pools were larger in volume than the other pools in the fishway (Figure 1) since pool length in the turn pools was measured on the straight sections of the inside wall. During the initial test in 1958, a wooden grill was placed in each turn pool to restrict fish movements to the upper 2 feet in order to reduce the tendency of fish to linger in these pools. In the second year the grills were covered with plywood, and turbulence-creating baffles were installed to make the turn pools unsuitable as resting areas. In order to modify the hydraulic conditions in the pools of the 1-on-8-slope fishway, weir crests were reduced in width from 36 inches to 26 inches during the second year, reducing pool turbulence and introducing lateral eddies in the pools. The differences in pool hydraulic pattern, in fishway slopes, in weir crests, and in turn pools

[2] Collins, Gerald B., Carl H. Elling, Joseph R. Gauley, and Clark S. Thompson. Effect of fishway slope on the performance and biochemistry of salmonids. (Manuscript in preparation.)

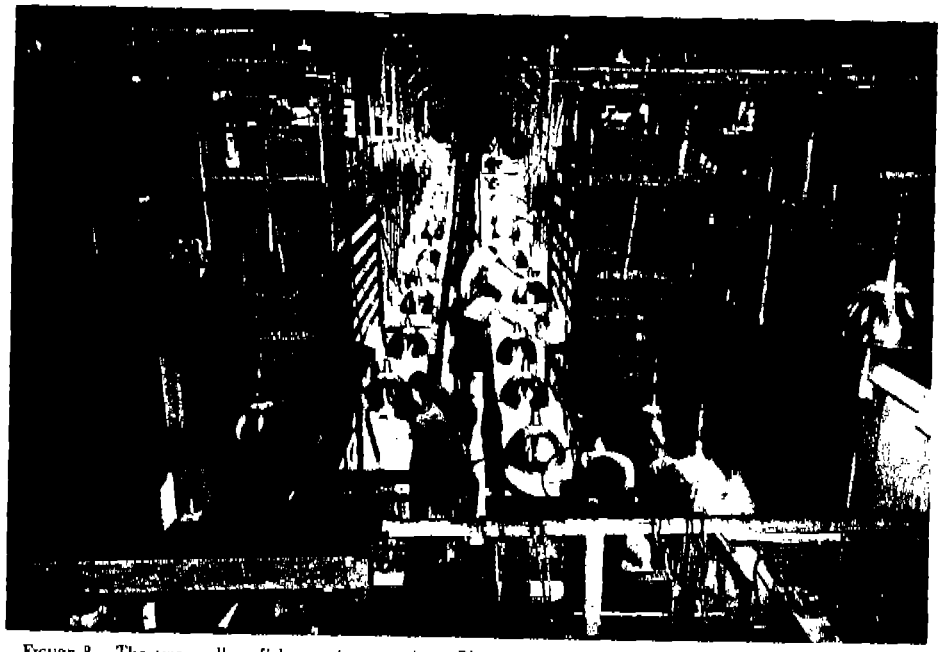

FIGURE 3.—The two endless fishways in operation. Observers on walkways record progress of fish.

are called to attention to emphasize the variety of conditions under which the extended ascents were made. Throughout each individual test, however, constant conditions were maintained.

Light was supplied by 1,000-watt mercury-vapor lamps suspended 6 feet above the water surface and 6 feet apart along the fishway. These lights were on day and night, producing an average light intensity of 800 foot candles at the water surface.

PROCEDURE

As in all of the experiments conducted at the Fisheries-Engineering Research Laboratory (Collins and Elling, 1960), the experimental fish were not handled in any way prior to testing. Fish were permitted to swim into the laboratory from the adjoining fishway and into a small collection pool. Then, when an entrance gate (Figure 2) was opened, fish swam from the collection pool into one of the endless fishways to begin the ascent. Once a fish had entered an experimental fishway, the entrance gate was closed and the fishway was operated as a closed system until the completion of the test. Observers followed the progress of each test fish at all times (Figure 3), recording the time each weir was crossed, and in this way obtained a detailed record of the time spent in each pool throughout the entire test. Because of the necessity for synchronizing locking with the movements of the fish, all tests were made with individual fish. Upon completion of a test, water flow was shut off, the fish was netted, and blood and tissue samples were taken for biochemical studies. Sex, weight, and length were then determined.

RESULTS

The first attempt to measure the maximum height that a salmon would ascend in a pool-and-overfall fishway was made in 1958 with a sockeye salmon (*Oncorhynchus nerka*). That fish, a 20-inch male weighing 3 pounds 4 ounces, was allowed to ascend the 1-on-8-slope endless fishway for over 5 days. It ascended day and night, climbing 6,648 feet in 7,947 minutes, an average of 1.2 minutes per pool. It completed 415 circuits in the endless fishway, traveling slightly more than 10 miles horizontally while ascending more than a mile vertically, and it was still actively ascending the fishway when the test had to be discon-

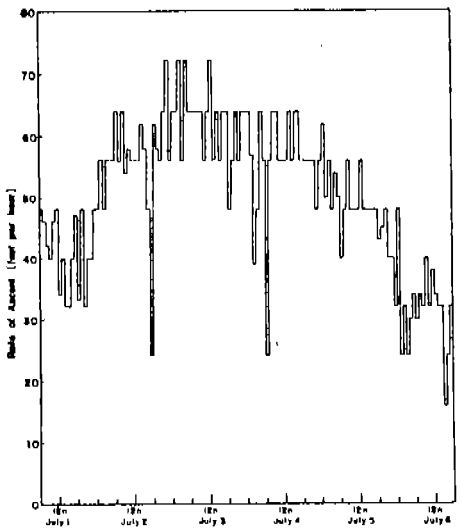

FIGURE 4.—Performance of a sockeye salmon (*O. nerka*) ascending the 1-on-8-slope endless fishway during July 1-6, 1958. The fish was still actively ascending when the test was terminated.

tinued because of other experimental commitments.

An examination of the rate of ascent during the test (Figure 4) reveals that performance actually increased the first 2 days and that it was not until the fifth day, after the fish had ascended more than 6,000 feet, that the rate of ascent dropped below that of the first day. The increased rate of ascent in the first couple of days could probably be attributed to learning. McLeod and Nemenyi (1940) state that in their experimental fishways trout apparently learned to climb fish ladders. The gradual decline in the rate of ascent in the last 2 days of the test might be ascribed either to a gradual loss of interest in the often-repeated cycle of events or to changes in the physical condition of the fish.

Blood-lactate level, frequently used as an index of muscular fatigue (Black, 1958), however, was only 32.88 milligrams percent in the sockeye salmon after its long ascent of more than 6,000 feet. This level is well below the 125 milligrams percent that Parker and Black (1959) found to be minimum for lethal effects in troll-caught salmon. It is also less than the mean lactate level (63.5 milligrams percent)[3]

[3] Details of data, sampling techniques, and chemical methods are reported elsewhere. See footnote 2.

FIGURE 5.—Sockeye salmon after an ascent of 6,648 feet in the 1-on-8-slope endless fishway. Note fungus on head and abrasions on the side.

of all the sockeye salmon that were tested with an ascent of 104 feet in the 1-on-8-slope fishway during 1958.

Water temperature in the endless fishway increased from 64° F. at the start of the test to 67° F. on the final day. Whether or not this rise in temperature affected the rate of ascent in any way is not known.

During the prolonged ascent several changes in the external appearance of the fish were noted. No marks, abrasions, or fungus were apparent when the fish was first admitted to the fishway nor were they apparent during the first 2 days of the ascent. However, on the third day two small white spots were seen on the top of the head and another on the left side of the fish near the adipose fin. On the fourth day these had grown in size and a fungus growth was beginning to show near the insertion of the dorsal fin. Lesions had appeared on the right side of the fish by the fifth day and by the final day the top of the head was covered with fungus, the tail had become frayed and the lesions on the side of the fish had grown in size (Figure 5). Such injuries give evidence of physical contact with the fishway structure, possibly the result of the tendency of individual fish to cross weirs next to a wall (Collins, 1958). Irritation from these injuries could have been a contributing factor in the decline in the rate of ascent noted in the final days of the test.

To determine whether the ability and persistence shown by the first salmon given an opportunity for a prolonged ascent in an endless fishway were characteristic of salmonids in the Columbia River, a series of extended ascent tests was made during the migration of 1959. These tests were arbitrarily limited to 1,000 feet in order to conserve time and allow testing of a larger number of fish. The ex-

Fungus forming after day 3

TABLE 1.—*Ascent time and lactate level of whole blood (milligrams percent) for chinook salmon* (O. tshawytscha), *sockeye salmon* (O. nerka), *and steelhead trout* (S. gairdneri) *ascending 1,000 feet in experimental endless fishways, 1959*

Date	Species	Sex	Weight (pounds)	Gonad weight as percentage of body weight	Fishway slope	Water temperature (° F.)	Ascent time (minutes)	Lactate whole blood (milligrams percent)
June 15, 16	Chinook	F	22	5.63	1 : 8	58	1,885	26.7
June 29, 30	Chinook	F	23	6.31	1 : 8	60	1,877	28.6
July 14, 15	Sockeye	F	3	3.96	1 : 16	65	925	20.7
July 15, 16	Sockeye	M	3	2.04	1 : 8	66	1,210	21.8
July 24	Sockeye	F	3	5.05	1 : 8	68	1,041	28.9
July 24, 25	Sockeye	M	3	1.46	1 : 16	68	1,319	7.8
August 3	Steelhead	F	4	0.63	1 : 8	66	922	13.3
August 7	Steelhead	M	4	0.55	1 : 16	68	693	8.4
August 17	Steelhead	M	5	0.15	1 : 16	68	558	19.7
August 18	Steelhead	F	7	0.88	1 : 16	68	757	9.8
August 31–September 1	Chinook	F	21	7.33	1 : 16	66	1,726	30.3
September 14, 15	Chinook	M	25	—[1]	1 : 16	66	1,387	—[1]
September 17	Chinook	M	6	—[1]	1 : 8	66	924	—[1]
September 21, 22	Chinook	M	5	—[1]	1 : 8	64	1,061	—[1]

[1] Fish released. No samples taken. External features of all fish indicated they were approaching sexual maturity.

periments were made with spring- and fall-run chinook salmon (*Oncorhynchus tshawytscha*), with sockeye salmon, and with steelhead trout (*Salmo gairdneri*). The results are shown in Table 1. All 14 fish were actively ascending at the time the tests were discontinued. There is no reason to believe that most of these fish could not have equaled or even exceeded the performance of the original sockeye salmon. The single sockeye tested in 1958 required 1,377 minutes to ascend the first 1,000 feet. The four sockeye salmon tested in 1959 were actually faster (Table 1) in both fishways.

Throughout the 1,000-pool ascent a general increase in the hourly rate of ascent similar to the pattern of the initial day of the 1958 test (July 1, Figure 4) was discernible for all fish. Blood-lactate levels of the fish that had ascended 1,000 feet (Table 1) were either equal to or less than the mean blood-lactate levels of fish that had been tested with ascents of only 104 feet during 1959 (Table 2).

The abrasions that were so conspicuous on the single sockeye salmon that had ascended 6,648 feet were not in evidence on the fish that made 1,000-pool ascents in 1959.

DISCUSSION

Considering the apparent ease with which the 15 fish in these experiments made ascents of 1,000 feet, and the absence of any evidence of fatigue either in the performance of the fish or in the blood-lactate levels, it would appear that the ascent of a properly designed pool-and-overfall fishway is only a moderate exercise for chinook salmon, sockeye salmon, and steelhead trout.

The long ascents were made at two different fishway slopes, under a variety of pool hydraulic conditions, with differences in weir crests and turn pool design, and with water temperature that ranged from 58° to 68° F. Despite this, all groups were successful and rates of ascent for 1,000 feet seemed to be characteristic for each species, conforming to the pattern noted in studies of rates of ascent for 6 feet (Elling, 1960). Steelhead trout were the fastest in ascent and chinook salmon were slower than sockeye salmon.

Concern has been expressed (Andrew and Geen, 1960) that fish that fail to complete a long fishway during daylight hours might migrate back downstream out of the fishway at night causing delay and possibly resulting in the complete failure of some fish to ever reach the top of the fishway. This type of behavior, however, was never observed during the tests made with endless fishways. Under the constant lighting conditions used in the experiments, rates of ascent generally were uniform throughout the 24-hour day. Whether or not

TABLE 2.—*Mean blood-lactate levels (milligrams percent) of salmonids ascending 104 pools in endless fishways with slopes of 1 on 8 and 1 on 16, 1959*[1]

Species	1-on-8 slope		1-on-16 slope	
	n	Blood lactate	n	Blood lactate
Chinook	33	31.9	34	30.6
Sockeye	18	42.4	18	31.2
Steelhead	35	20.8	36	20.4

[1] Progress Report No. 52 for the month of November 1959. Research on fishway problems conducted at the Fisheries-Engineering Research Laboratory at Bonneville Dam under contract No. DA-33-026-25142 with the U. S. Fish and Wildlife Service, U. S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

a diurnal pattern of movement would exist under natural light conditions is not known.

Apprehensions that the hourly rate of fish ascent might decrease in the upper end of a long fishway and result in dangerous crowding or delay appear to be without factual foundation. Similarly, the possibility of cumulative fatigue effects resulting from ascending fishways at a series of low dams seems to be remote in view of the data from the 1,000-foot ascent tests.

The experiments with the endless fishways actually did not suggest any upper limit for the height of pool-and-overfall fishways. It would seem probable, however, that economic factors would limit the use of this type of fishway to something considerably less than 1,000 feet in height. Fishways of this type several hundred feet in height would not seem to be an excessive extrapolation of our present experience with fishways approximately 100 feet high, particularly in view of the recent experimental data. Pool-and-overfall fishways up to 1,000 feet in height may be equally feasible from the standpoint of fish behavior and ability; before accepting such an extreme view, however, several factors should be considered. One of these is the effect of water temperature on the ability and willingness of fish to ascend high fishways. The experiments at the Fisheries-Engineering Research Laboratory were made within a range of relatively moderate water temperatures (58°–68° F.). The degree to which higher water temperatures or marked changes in water temperatures might affect this aspect of fish behavior should be known.

A second consideration is the possible effect of sexual maturity on the performance of fish in fishways. Paulik and DeLacy (1958) found that the swimming ability of sockeye salmon changed as the fish migrated upstream through the Columbia River and that there was a measurable decline in swimming ability as the fish neared the spawning ground. Swimming ability was measured in terms of swimming endurance in a horizontal flume at fixed water velocities. The degree to which this measure of swimming ability can be applied to the ability to ascend pool-and-overfall fishways is difficult to assess. The fish tested in the horizontal flume were compelled to swim at arbitrarily selected velocities and exhaustion occurred within a matter of minutes, whereas fish tested in the ascent of an endless fishway selected their own pace and were able to continue for days without evidence of exhaustion. Collins *et al.*[4] were unable to find any correlation between sexual maturity and performance in pool-and-overfall fishways in fall chinook salmon using the weight of gonads expressed as percentage of body weight as an index of maturity. The success of mature fall chinook salmon in completing 1,000-pool ascents would appear to confirm this. More information on this relationship is needed, however, in view of the fact that the high dams proposed on the Columbia River system are largely in upper tributaries near spawning areas and that the experiments with endless fishways were made on the lower Columbia River at the early stage of migration for upper river fish.

Experience with fish behavior at a wide variety of fishways on the Columbia River system suggests that other factors such as water turbidity and odors may affect the willingness of fish to enter and to ascend fishways. These factors probably affect fish movement generally, whether in fishways or in the river. Until their nature is understood, however, the possibility that they might have a greater effect in a long fishway should be considered.

CONCLUSIONS

The ascent of a properly designed pool-and-overfall fishway is only a moderate exercise for chinook and sockeye salmon and steelhead trout. Salmonids could ascend such fishways even if several hundred feet in height. Under certain conditions these fish will ascend fishways continuously day and night, and for all practical purposes their rate of ascent will not decrease in the upper end of a long fishway. Fatigue effects from the fishways of a series of low dams such as those on the Columbia River appear to be very unlikely. Pool-and-overfall fishways up to 1,000 feet in height may be practical for these salmonids, at least from the standpoint of fish behavior and ability; however, a greater knowledge of the effects of sexual maturity, water temperature, and other water qualities upon the ability of salmonids to ascend high fishways should be obtained.

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[4] See footnote 2.

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