FISHWAY RESEARCH AT THE FISHERIES-ENGINEERING RESEARCH LABORATORY

UNITED STATES DEPARTMENT OF THE INTERIOR

FISH AND WILDLIFE SERVICE

BUREAU OF COMMERCIAL FISHERIES

CIRCULAR 98

Cover: Bonneville Dam, Bradford Island fishway in the foreground. Fisheries-Engineering Research Laboratory may be seen at the far end of the spillway.

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ABSTRACT

Results of 4 years of research on fishway problems, data on rates of movement of salmonids ascending fishways, and of spatial requirements of fish are given and experiments to measure fishway capacity are described. The effect of fishway slope and fishway length on fish performance and biochemical state were measured in "endless" fishways. No evidence of fatigue was found when proper hydraulic conditions were obtained. One salmon ascended over 6,600 feet vertically. Experiments to measure swimming abilities of salmon indicated that the critical velocity was between 8 and 13 feet per second. Maximum observed swimming speed was 26.7 feet per second. Preferences of salmonids for water velocities and light conditions revealed marked differences between species. Effects of light and water velocity on rates of passage through channels and fishways are described. Experiments involving fingerling passage problems and the testing of fullscale prototype fishway designs are illustrated. Reports and publications on laboratory research are listed.

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Gerald B. Collins and Carl H. Elling

Fishway problems are many and complex on the Columbia River system where a long series of major dams interrupts the migration of several species of anadromous fishes. Adult fish returning to the Columbia from the sea may have to ascend as many as nine dams to reach their spawning areas. Young fish must pass downstream over all of these dams on their journey to the sea. Even small losses, injuries, or delays in the passage over each dam could threaten the entire fishery resource because of the cumulative effects of many dams. Similarly, the costs involved in providing adequate fishways to pass fish safely over a large dam must be multiplied by the increasing number of dams. It is therefore highly important that fish passage facilities be designed with both a maximum of safety for fish and also a maximum of economy in construction and operation costs. To accomplish these goals obviously requires a sound basic knowledge of the behavior, abilities, and requirements of migratory fish, particularly in relation to fishways.

To supply precise information on the behavior and performance of migrating fish, a special type of laboratory was constructed [1] in which it is possible to measure the reactions of fish under controlled experimental conditions while the fish are actually migrating. The Fisheries-Engineering Research Laboratory adjoining one of the major fishways at Bonneville Dam (fig. 1) is the only laboratory of its kind in the world. Fish diverted (fig. 2) from the Washington-shore fishway at Bonneville Dam swim into this laboratory (fig. 3) where their responses to full-scale fishway situations are observed and recorded. Fish then swim out of the laboratory and re-enter the main fishway to continue their migration upstream.

The laboratory basically consists of a level experimental flume (fig. 4) with a fish collection pool at the downstream end that is connected to the main fishway by a small entrance fishway ("B" in fig. 2), and with a flow introduction pool at the upstream end that is connected to the main fishway by an exit fishway ("F" in fig. 2). Various types of fishway structures are erected (fig. 5) in the experimental area while it is dry, then water is introduced and the gates to the main fishway are opened to permit the entry of fish. A water supply and discharge system is independent of the main fishway and is capable of delivering and discharging up to 200 cubic feet of water per second without disturbing the flow pattern of the main fishway outside. Light control is provided by a completely covered building and eighty 1,000-watt mercury-vapor lamps (fig. 6) that under standard operating conditions produce illumination equivalent to a cloudy bright day. The ability to control large flows, water levels, structures, and light makes it possible to create a wide variety of test conditions. Adult migrating fish are available to the laboratory for approximately 6 months of the year. Migrants include chinook salmon (*Oncorhynchus tshawytscha*), blueback salmon (*O. nerka*), silver salmon (*O. kisutch*), steelhead trout (*Salmo gairdneri*), shad (*Alosa sapidissima*), and also the Pacific lamprey (*Lampetra tridentata*).

NOTE.—Gerald B. Collins and Carl H. Elling, Fishery Research Biologists, Bureau of Commercial Fisheries, U.S. Fish and Wildlife Service, Seattle, Washington.

[1] Financed by the U.S. Army Corps of Engineers as a part of their Fisheries-Engineering Research Program for the purpose of providing design criteria for more economical and more efficient fish-passage facilities at the Corps' projects on the Columbia River.

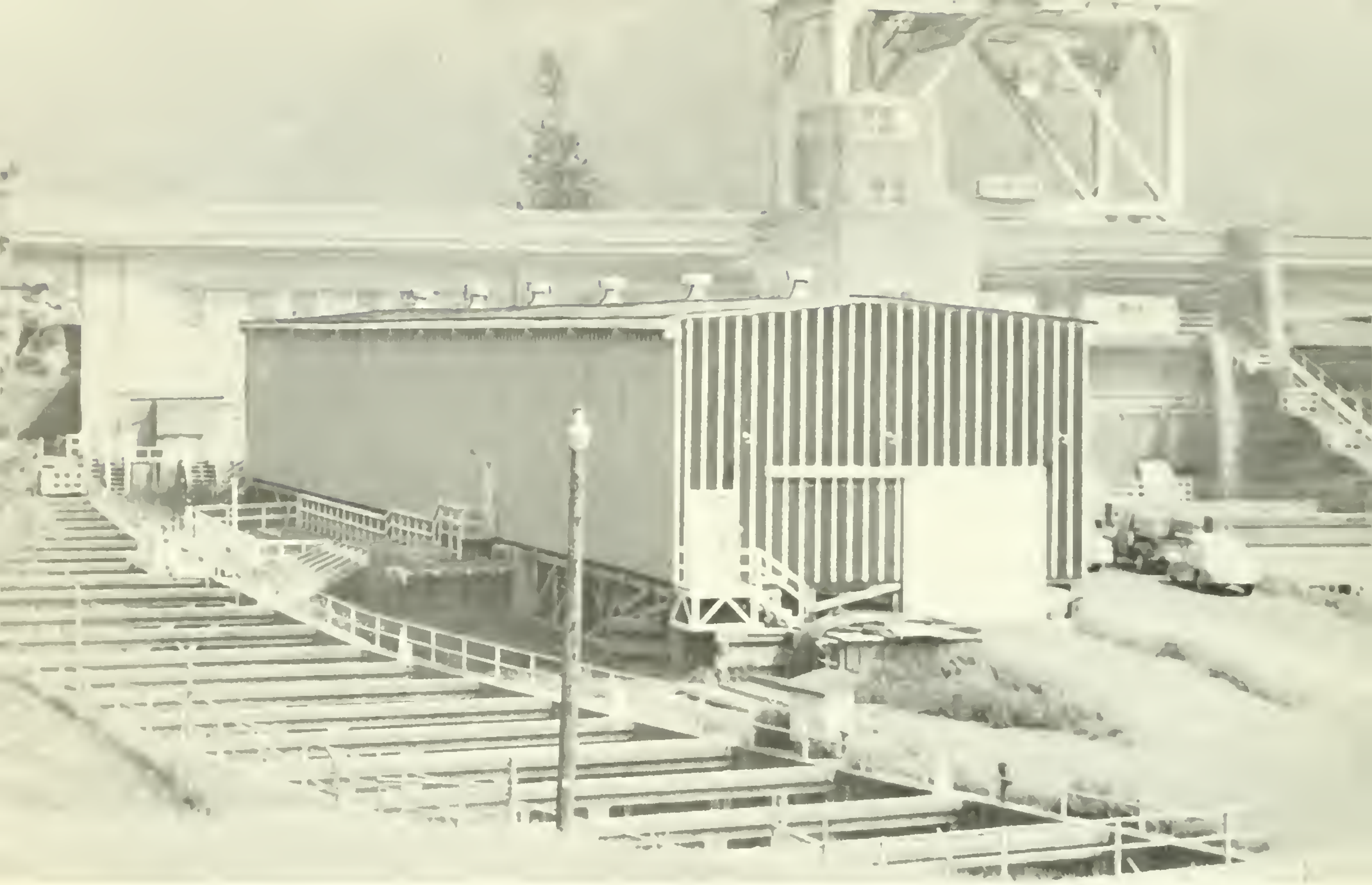
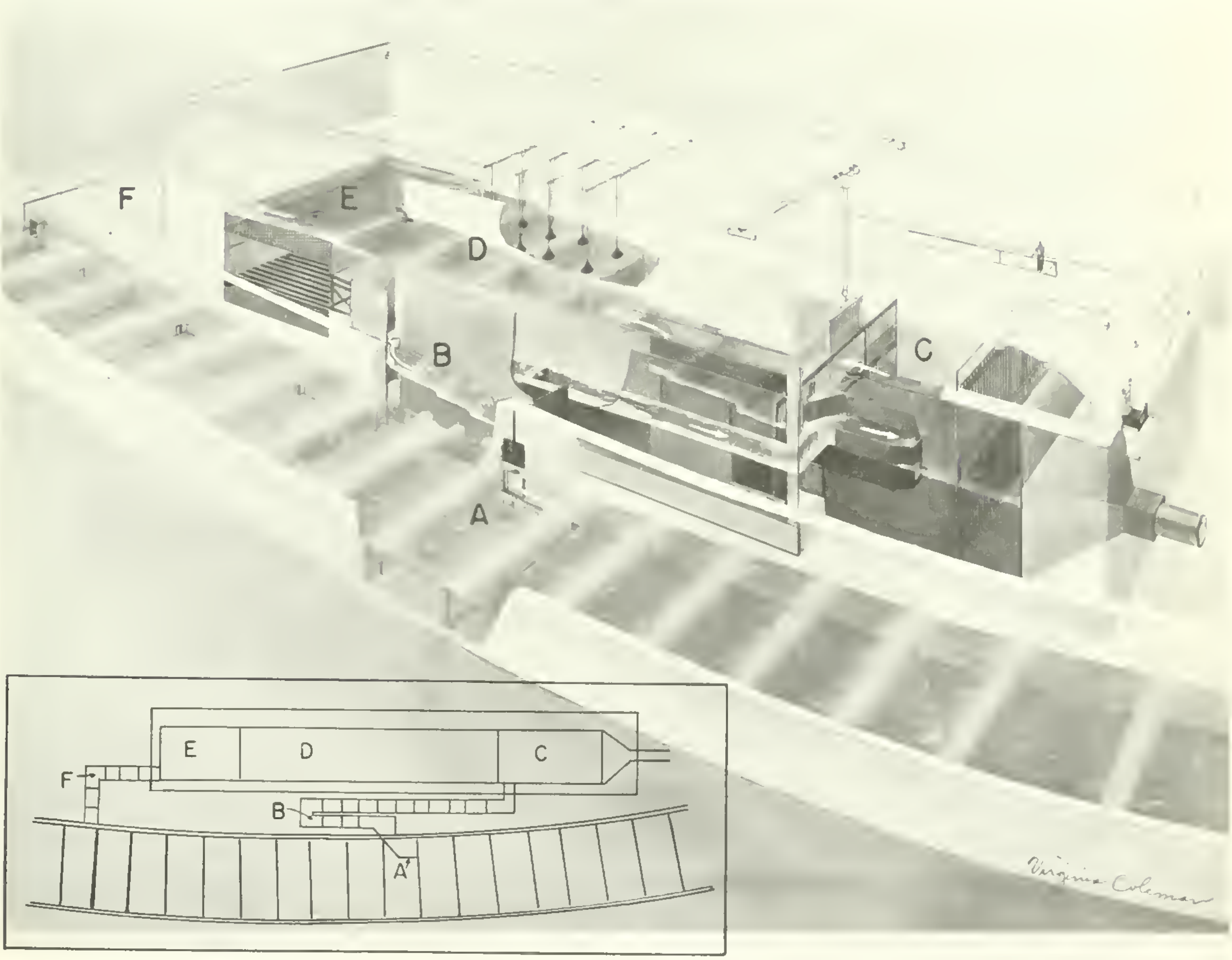


Figure 2.—Sketch of Fisheries-Engineering Research Laboratory showing its relationship to the Washington-shore fishway. Fish are diverted from the main fishway by a picketed lead (A) and ascend the entrance fishway (B) to a collection pool (C) in the laboratory. After release, they pass through an experimental area (D) to the flow introduction pool (E) and then out the exit fishway (F) where they return to the main fishway. Insert shows plan view of laboratory.

Figure 1.—Fisheries-Engineering Research Laboratory adjoining Washington-shore fishway at Bonneville Dam. The dam is on the Columbia River 140 river-miles from the sea.



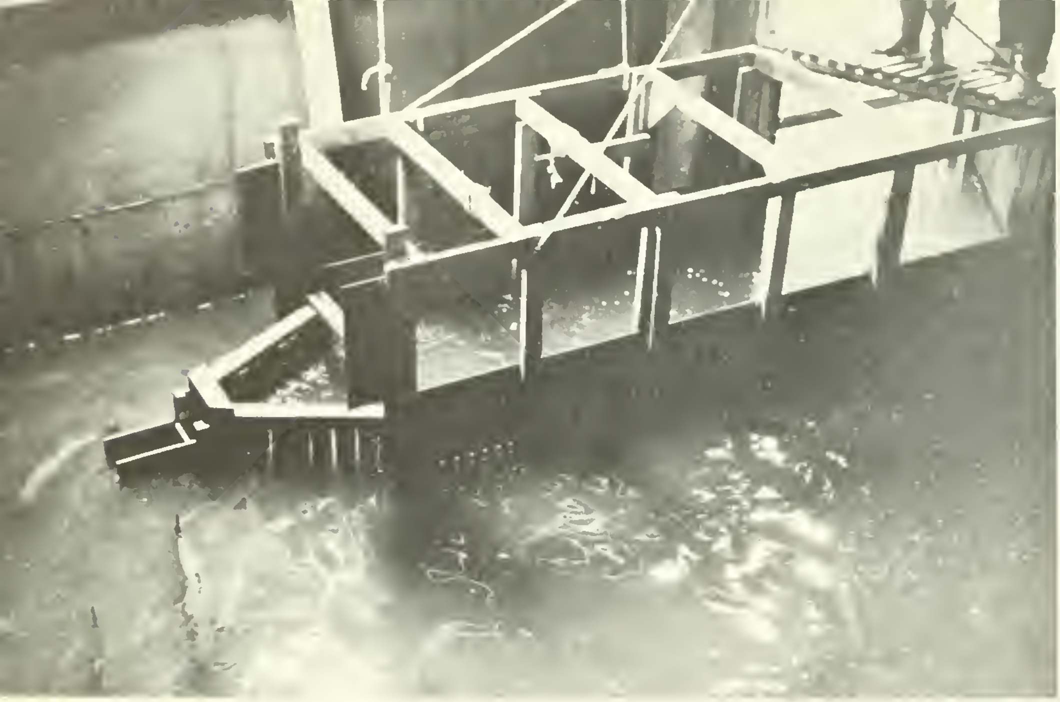


Figure 3.—Entrance to the fish collection pool. Fish swim into the laboratory through a narrowing funnel that prevents them from leaving.

Figure 4.—Interior of Fisheries-Engineering Research Laboratory when empty and unwatered. Experimental area (center) is 104 feet long, 24 feet wide, and 17 feet deep. Fish collection pool at far end is 50 feet long and 24 feet deep.

Figure 5.—Experimental fishways under construction. Careful planning and great ingenuity are required in building temporary structures capable of supporting and controlling large volumes of water.

Figure 6.—Full-scale experimental fishways in operation. Standard lighting conditions are created by mercury-vapor lamps. Picketed barriers and release gates for the control of fish have yet to be erected.

The Fisheries-Engineering Research Laboratory is now (1960) in its fifth year of full-scale operation. The following is a review intended only as a brief summary of research to show the scope and general progress of the studies at the laboratory. Listed in Appendix A are the proposals, reports, and publications that describe in detail the major aims and objectives of the project, the experimental designs and procedures followed, complete observations and results with the limitations and qualifications of the data and conclusions. Research at the laboratory is planned and conducted as a team effort, with the task of reporting divided among the staff by assignment. Selection of major research items to be assigned priority or studied in greatest detail follow the recommendations of the Corps of Engineers with the advice of the Technical Advisory Committee for the Corps' Fisheries-Engineering Research Program composed of representatives of State and Federal fishery agencies.

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Figure 7.—The 4-foot wide, 1-on-16-slope fishway used for fishway capacity tests. Passage of 3,000 salmonids per hour was demonstrated in this fishway.

FISHWAY CAPACITY

In a pool-type fishway, "capacity" (i.e., the maximum number of fish of a given size that a fishway of specified design and dimensions can pass per unit time) is controlled by the rate of fish movement from pool to pool and the space required for each fish. Examples of laboratory data on rates of movement for chinook salmon, blueback salmon, and steelhead trout obtained from a wide variety of experiments are shown in table 1. Examination shows that although rates vary with species and time of year there is considerable consistency in the average rates of movement under a wide range of experimental

Table 1.—Passage times per pool of individual and groups of salmonids ascending experimental fishways [1] of Bonneville laboratory

Time per pool by species and source [2] of data							
Spring chinook		Blueback		Steelhead		Fall chinook	
Minutes	*Source*	*Minutes*	*Source*	*Minutes*	*Source*	*Minutes*	*Source*
2.2	5, table 1	1.7	5, table 1	1.6	6, page 1	1.6	10, No. 38
2.7	5, table 1	1.6	5, table 1	2.2	6, page 1	1.5	10, No. 38
3.0	10, No. 22	1.3	10, No. 11	1.0	10, No. 11	2.0	10, No. 40
3.2	10, No. 22	2.8	10, No. 24	2.0	10, No. 13	1.1	10, No. 14
2.0	10, No. 46	1.2	10, No. 24	1.6	10, No. 13	1.1	10, No. 14
2.4	10, No. 46	1.2	10, No. 36	2.4	24, table 3	----	-
1.9	10, No. 47	----	----------	1.7	24, table 3	----	----------
1.9	10, No. 47	----	----------	1.4	24, table 2	----	----------
3.0	16, table 1			1.3	24, table 2		----------

[1] Pool-and-overfall-type fishways with slopes of 1 on 8 and 1 on 16, varying in width from 3 to 11.5 feet. No orifices in fishways, pool depth approximately 6.5 feet, rise between pools 1 foot and head on weirs 0.8 foot. Total rise varying from 6 to 6,600 feet.

[2] See Appendix A.

Figure 8.—The 16-pool, 1-on-8-slope endless fishway nearing completion. Worker stands in fish entry gate. Locking unit for lowering and recycling fish appears in center.

conditions. A basis for estimating spatial requirements is provided by data (table 2) from a series of capacity experiments in 1957. In these experiments large numbers of fish were collected over a 48-hour period and then released in a 1-hour test. During one such experiment, fish averaging 9.2 pounds in weight were passed through a 1-on-16-slope fishway (a fishway that rises 1 foot for every 16 feet of fishway length) only 4 feet wide (fig. 7) at a rate of 3,000 fish per hour without any indication that capacity had been reached. Experiments in the Washington-shore fishway at Bonneville examining possible effects of the collection-and-release technique upon fish performance, although not yet completed, appear to confirm the laboratory data shown.

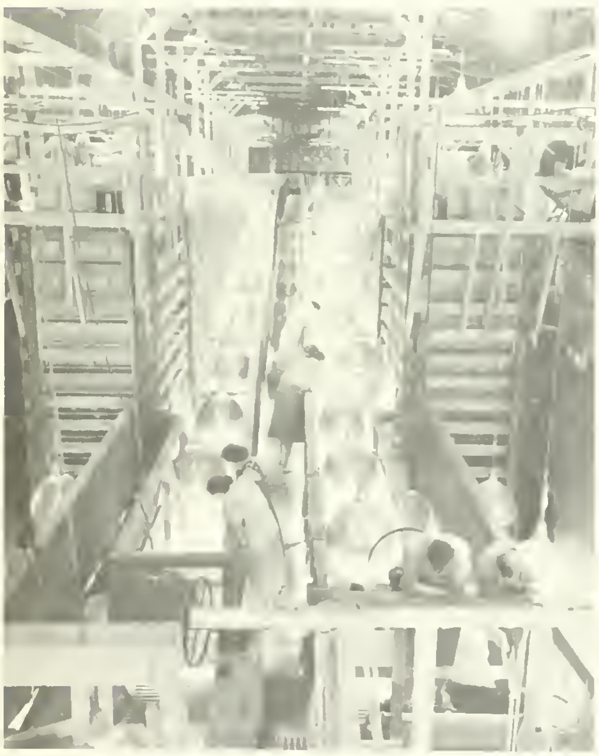

Figure 9.—The two endless fishways, 1-on-16 slope on left and 1-on-8 slope on right. Observers along walkways record progress of fish in the respective fishways.

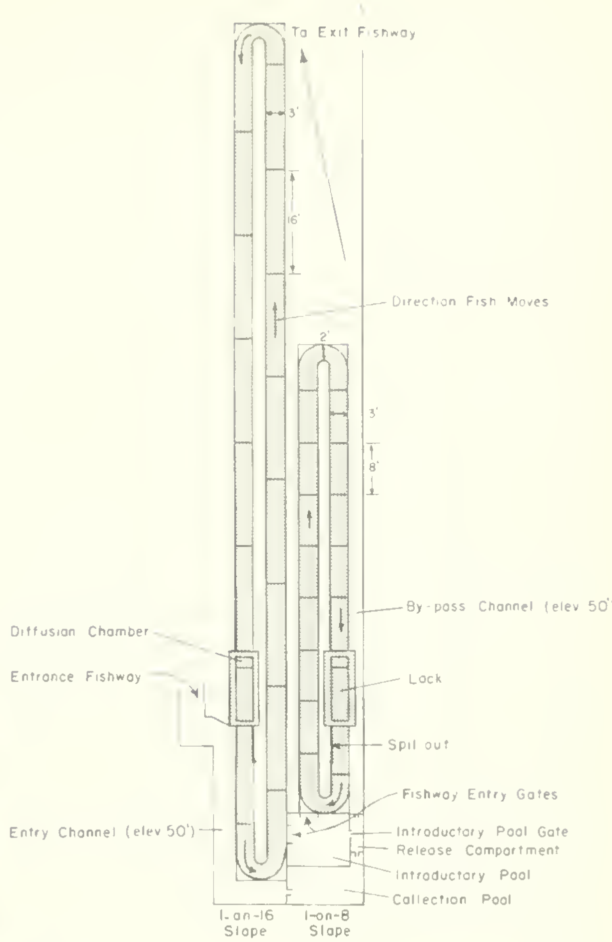

Figure 10.—Plan view of the 1-on-16- and 1-on-8-slope endless fishways with auxiliary approach channels and pools.

Table 2.—Observed space utilization in two fishway capacity tests, 1957

Species	Estimated weight-pounds	Cubic feet per fish in first pool	Source[1]
Chinook	14.0	2.6	16, table 3.
Chinook, steelhead, blueback	9.2	2.2	16, table 3.

[1] See Appendix A

FISHWAY SLOPE AND FISHWAY LENGTH

Initial experiments comparing the performance of salmonids in fishways with slopes of 1 on 8 and 1 on 16 indicated a higher rate of passage in the steeper slope fishway. However, the tests were conducted in short segments of fishways and the possibility that the increased rate was the result of turbulence and lack of resting area had to be considered. To make a further comparison of the effect of slope upon rates of fish movement and to measure the effect of length of fishway on fish performance, experiments were undertaken using a pair of "endless" fishways with slopes of 1 on 8 and 1 on 16. These endless fishways (figs. 8 and 9) were pool-and-overfall fishways constructed so that each made a complete circuit (fig. 10), with the highest pool connected 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 lowered by lock to the lowest pool to ascend again. By repeating this procedure, fishways of any desired length could be simulated. Comparisons were made on the basis of fish performance and also on the basis of biochemical indices of fatigue such as lactate and inorganic phosphate of the blood (fig. 11) and muscle.

Figure 11.—Biologist extracting a sample of blood from a fish exercised in one of the endless fishways. Blood samples were analyzed for lactate and inorganic phosphate to determine if the fish was fatigued.

No evidence of fatigue was found in either fishway when the proper pool flow conditions prevailed. Blood lactates, the most sensitive of the biochemical measurements, showed (fig. 12) a moderate increase (lactate levels above 125 mg. percent may be lethal to fish under certain circumstances) during active ascent and were back to the control level in both fishways within 1 hour. Most of the fish were tested with an ascent of approximately 100 pools. However, a limited number were permitted to make extended ascents exceeding several hundred pools and at least four of each species were allowed to ascend more than 1,000 pools. One blueback salmon was permitted to ascend for over 5 days, climbing continuously over 6,600 pools before the test was terminated. This was a vertical ascent of more than a mile in a 1-on-8-slope fishway. The conclusion drawn is that ascent of a properly designed fishway is only a moderate exercise for the fish, possibly similar to swimming at a "cruising" speed that can be maintained over long periods of time.

The exaggerated pattern of work-and-rest that appeared in the 1-on-8 endless fishway resulted in the fish spending about 70 percent of the time resting in the turn pools (fig. 13). In an actual fishway this would result in about 70 percent of the fish being in resting pools at any given time. To avoid this impractical condition, the hydraulic pattern in the 1-on-8 fishway was changed by modifying the weirs. This changed the pattern of movement so that the fish rested in each pool (fig. 14), clearly demonstrating the importance of pool flow pattern to fishway design. The steeper

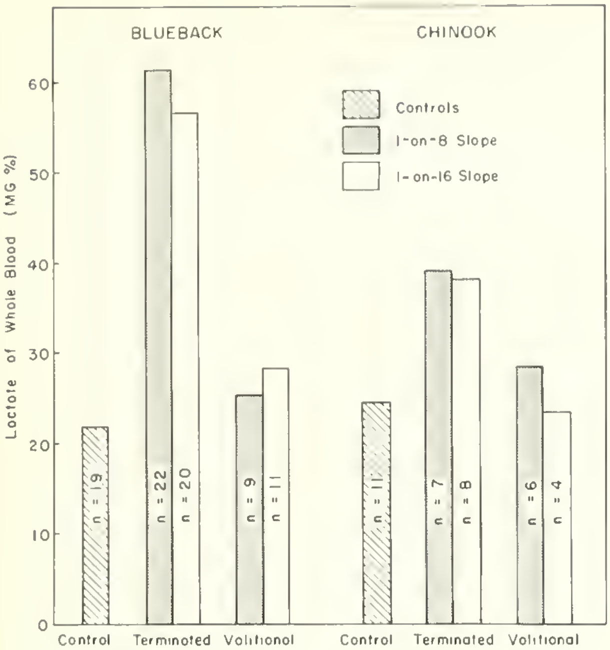

Figure 12.—Comparison of blood lactate levels of blueback and chinook salmon ascending 1-on-8- and 1-on-16-slope endless fishways. Note that fish actively ascending ("Terminated") show an increase in lactate levels typical for each species, and that lactate levels of fish that have stopped for 60 minutes of their own volition ("Volitional") are not significantly different from levels of fish that have not been exercised in a fishway ("Controls").

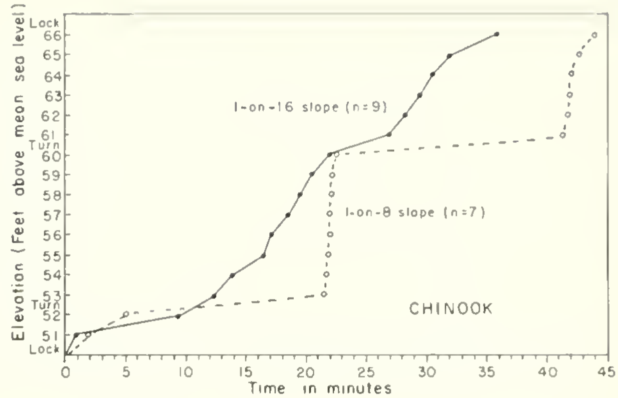

Figure 13.—Pattern of ascent in the 1-on-8- and 1-on-16-slope endless fishways when full overfall weirs and resting turn pools were in use. Note exaggerated "work-rest" pattern in 1-on-8-slope fishway.

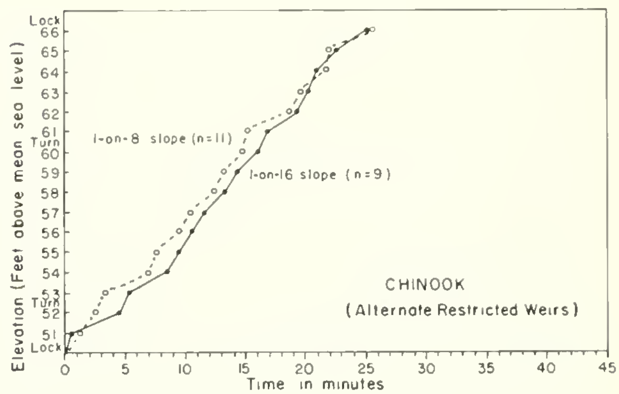

Figure 14.—Pattern of ascent in the 1-on-8- and 1-on-16-slope endless fishways after rest areas were removed from turn pools and with restricted overfalls in the 1-on-8-slope fishway.

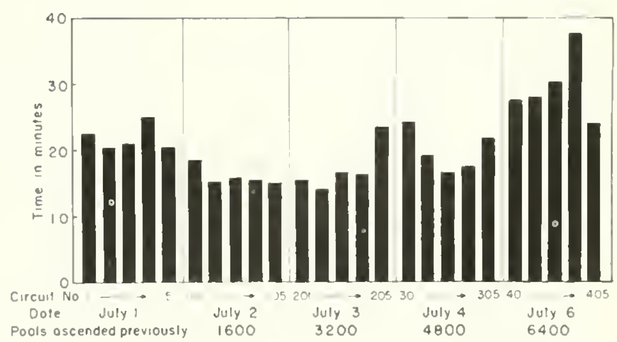

Figure 15.—Passage time per circuit (16 pools) of a blueback salmon that ascended over 6,000 feet in the 1-on-8-slope endless fishway.

1-on-8 slope was shown to be as suitable for the passage of salmonids as the 1-on-16 slope when the proper hydraulic conditions were provided. As to the effect of fishway length on the rate of fish movement, the evidence shows that rates of movement tend to increase slightly in the initial stages of a prolonged ascent, probably due to learning, and then become quite consistent. An example is given in figure 15. Note that the blueback salmon had ascended over 5,000 feet before slowing down to its initial rate of movement. This means that for all practical purposes the rate of movement of ascending fish will not decrease in the upper end of a long fishway and so result in crowding or delay.

Experiments at the laboratory support two further generalizations on the rate of fish movement in fishways. The first is that ascending fish show a tendency to do a certain amount of work in a given amount of time regardless of the slope of the fishway. The rate of ascent in a 1-on-8-slope fishway of proper hydraulic design is approximately the same as in a 1-on-16-slope fishway. The second is that for practical purposes the rate of fish movement in fishways is independent of the numbers of fish. Groups of fish in the laboratory tests moved as fast as individual fish. This behavior pattern reduces the concern that the rate of fish movement might drop suddenly if a fishway became crowded.

FISH SWIMMING ABILITIES

Tests with adult chinook salmon and steelhead trout have shown that all fish negotiated an 85-foot flume when velocities were approximately 8 feet per second. When the velocity was increased to 13 f.p.s. approximately 50 percent of the chinook and 9 percent of the steelhead failed to pass the flume. Thus, somewhere in the range of 8-13 f.p.s., we can expect some of the fish of these species to be blocked when the distance to be negotiated approaches 100 feet.

Figure 16.—Experimental channel with a water velocity of 16 feet per second appears on right. Entrance to channel on left is screened to prevent access during swimming ability tests.

Table 3.—Response of chinook and silver salmon and steelhead trout presented with a choice between entering a high- or a low-velocity channel

Test condition		Number of fish tested [1]			Chose high-velocity channel		
High-velocity channel	Low-velocity channel	Steelhead trout	Chinook salmon	Silver salmon	Steelhead trout	Chinook salmon	Silver salmon
F.p.s.	*F.p.s.*				*Percent*	*Percent*	*Percent*
8	2	258	100	12	79.4	93.0	83.3
8	4	249	80	14	59.0	67.5	85.7
8	6	266	66	13	52.2	45.4	46.1
6	2	264	139	24	73.1	87.1	83.3
4	2	253	134	5	67.2	73.4	100.0
6	4	257	69	22	63.8	62.3	68.2

[1] Includes all size groups.

Additional tests were conducted in which salmonids were subjected to a velocity of approximately 16 f.p.s. (fig. 16). Marked declines in performance were noted. About 95 percent of the chinook salmon and approximately 50 percent of the steelhead failed to negotiate the 85-foot flume.

Differences in performance with respect to size were also noted. Two size groups were considered (1) fish estimated at 24 inches and under, and (2) fish over 24 inches. Respective performance (distance negotiated) of the two groups in velocities of approximately 13 and 16 f.p.s. are shown in figure 17. Clearly, "large" fish were capable of greater performance than "small" fish.

Measurements of the rate at which salmonids travel in a channel under a variety of water velocities suggest that a velocity of 2 f.p.s. may be most satisfactory for transportation purposes. These experiments utilized fall chinook salmon, silver salmon, and steelhead trout which were subjected to water velocities ranging from 2 to 16 f.p.s. Rate of movement in relation to the channel is shown in figure 18. Chinook salmon made their fastest progress at 2 f.p.s. and exhibited a progressive decline in rate of movement up to 13 f.p.s. Conversely, steelhead trout and silver salmon indicated an increase in performance as the water velocity increased up to 8 f.p.s. The three species tested registered approximately equal median rates of movement (5+ f.p.s.) in a water velocity of 8 f.p.s. Any slight advantages the higher flows may have in expediting the movement of certain species are minimized by the fact that considerably more water would be required

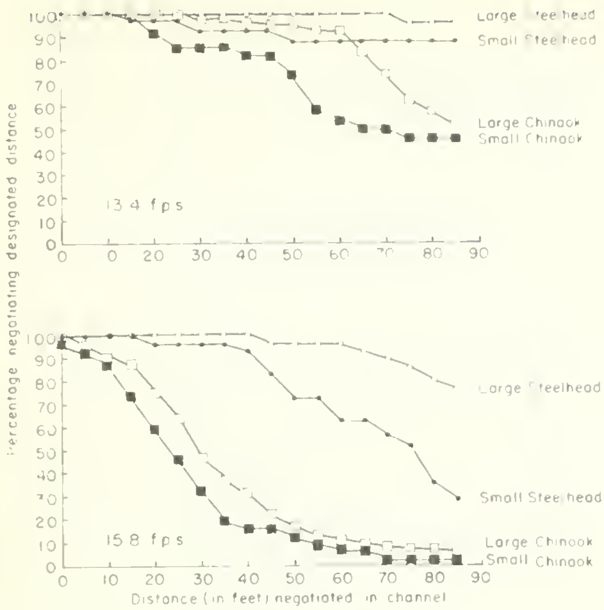

Figure 17.—Swimming performances of chinook salmon and steelhead trout by size in water velocities of approximately 13 and 16 feet per second.

for transport. It might also be expected that fish would have to expend more energy in passing through the higher velocities. Maximum swimming speeds in relation to the water were 26.7 f.p.s. for steelhead trout and 22.1 f.p.s. for chinook salmon measured over a distance of 30 feet.

ATTRACTION OF FISH

Chinook and silver salmon and steelhead trout presented with a choice between entering channels carrying either a "high" or a "low" water velocity demonstrated a significant preference for the high-velocity channel in virtually every test. The response to the high velocity is given in table 3.

Following these tests an additional experiment was conducted in which a sample of chinook salmon and steelhead trout were presented with a choice between flows of approximately 3 and 13 f.p.s. The high-velocity channel was chosen by 89.5 percent of the chinook and by 75.6 percent of the steelhead. The choice of the high-velocity channels by the chinook salmon is of particular interest since approximately half of the total sample of 51 fish failed to negotiate the channel after entry. Fish swept back after failing to pass the flume again selected the higher velocity on their second attempt.

Responses of the nature indicated in these tests suggest the possibility that upstream migrating salmonids may actually be diverted from fishway entrance flows into those of the spillway or even into the turbine discharges under certain hydraulic conditions.

Experiments at Bonneville exploring the preference of adult migrating salmonids for light conditions have demonstrated that pronounced species differences prevail. Steelhead presented with a choice of entering a light or dark channel exhibited a marked preference (80 percent) for the dark channel. In contrast, chinook salmon entered the light and dark flumes in nearly equal proportions, indicating no particular preference for either condition. In both instances, fish were light adapted prior to exposure to the test condition.

FISHWAY HYDRAULICS

The importance of controlling hydraulic conditions in fishway pools and channels has been brought to light in several experiments at the Bonneville laboratory. A change in fishway flow from a plunging to a streaming condition was found to halt temporarily almost all movement for a period of several minutes. Such information indicated that unstable flow conditions could seriously interfere with fish movement in fishways.

Demonstration of the importance of maintaining a uniform flow in fishway channels was evidenced in a series of tests in which fish were passed through an open channel approximately 2 feet deep.

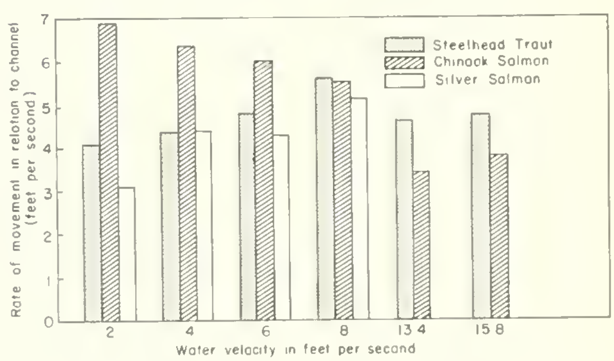

Figure 18.—Salmonid rate of movement in an open channel with water velocities ranging from 2 to 16 feet per second.

When flows were uniform, evidence of interrupted passage of fish was lacking. When hydraulic jumps were established in the channel a number of fish were observed to linger in the low-velocity areas created by these jumps. Occasionally fish remained in these areas for several minutes before continuing their movement through the channel. Improper design and operation of diffusion chambers conceivably may create similar disturbances in the flows of collection and entrance channels, giving rise to delays in fish movement comparable to those occasioned by the hydraulic jumps in these tests.

Tests examining the performance of fall chinook salmon in a fishway under a uniform plunging or streaming flow indicated there was no significant difference between the rate of ascent in the two flow conditions. Respective rates of ascent under plunging and streaming flows were 37 and 34 pools per hour.

Figure 19.—Covered fishway used in darkened passage experiments. All laboratory lights were turned off during dark tests.

Table 4.—Chinook salmon and steelhead trout rate of movement in light and dark channels. Water velocity—4 feet/second, distance measured—30 feet

Channel condition	Rate (feet per second) in relation to floor					
	Steelhead			Chinook		
	n	Mean	Median	n	Mean	Median
		F.p.s.	*F.p.s.*		*F.p.s.*	*F.p.s.*
Dark	22	0.6	0.6	20	0.5	0.7
Light	37	3.8	4.3	20	5.2	5.3

The influence of hydraulic conditions in the pools on the pattern of ascent in the endless fishways was previously noted. The change in pool hydraulics brought about by restricting the length of the weirs in the 1-on-8-slope fishway was sufficient to correct the pattern of movement to that desired, i.e., encourage fish to utilize each pool for resting (figs. 13 and 14).

EFFECT OF LIGHT ON FISH MOVEMENT

Measurement of the swimming performances of chinook salmon and steelhead trout in light and dark channels indicated that the movement of both species was significantly slower in the dark channel (table 4). In these tests the fish were light adapted before they entered the channels. Light intensities averaged approximately 750 foot-candles in the "light" channel and 0.3 foot-candle in the "dark" channel.

In contrast to the foregoing channel experiments, a series of passage trials in light and dark fishways (fig. 19) indicated that faster movement occurred under the dark condition (table 5). These data apply principally to steelhead trout (98 percent steelhead and 2 percent chinook salmon). Before entering the fishway, fish were light adapted under the "light" condition and dark adapted under the "dark" condition. Prevailing light intensities in the fishways were about 800 foot-candles in the light and less than .01 foot-candle in the dark. Further research will be necessary to explain why the fish moved so securely and effectively through the fishway pools in the dark, apparently oriented by the patterns of jets, eddies, and turbulences, while in a straight, level channel with a uniform laminar-type flow they appeared to move only with great caution in the dark.

Figure 20.—Chinook salmon jumping over a weir. Salmon usually swim over an overfall of this height. Proximity to the wall is characteristic.

Table 5.—Comparison of passage times in "light" and "dark" fishways [1]

Test number	Passage time for 6 pools					
	Light fishway			Dark fishway		
	n	Median elapsed time	Mean time	n	Median elapsed time	Mean time
		Minutes	*Minutes*		*Minutes*	*Minutes*
1	30	6.1	10.5	22	1.3	6.4
2	24	7.3	6.6	19	2.2	4.6
3	23	11.9	12.2	20	2.8	5.9
4	26	8.5	7.9	22	1.8	8.0
Summary	103	8.3	9.3	83	2.1	6.2

[1] Six-pool fishway, 1-on-16 slope, 4 feet wide, 6.3 feet deep and 1-foot rise between pools.

Tests involving around-the-clock passage of salmonids have indicated that rate of ascent during the night in a lighted fishway compared favorably with ascent in daytime hours. A blueback salmon that ascended over a mile in height during a 5½-day period averaged 52 pools per hour between 6:00 p.m. and 6:00 a.m. and 53 pools per hour from 6:00 a.m. to 6:00 p.m. Lighting in the fishway was constant throughout the test period, ranging from 700 to 1,000 foot-candles at the surface of the pools. Similar trends in day and night movement were exhibited by steelhead trout and chinook salmon when constant light prevailed.

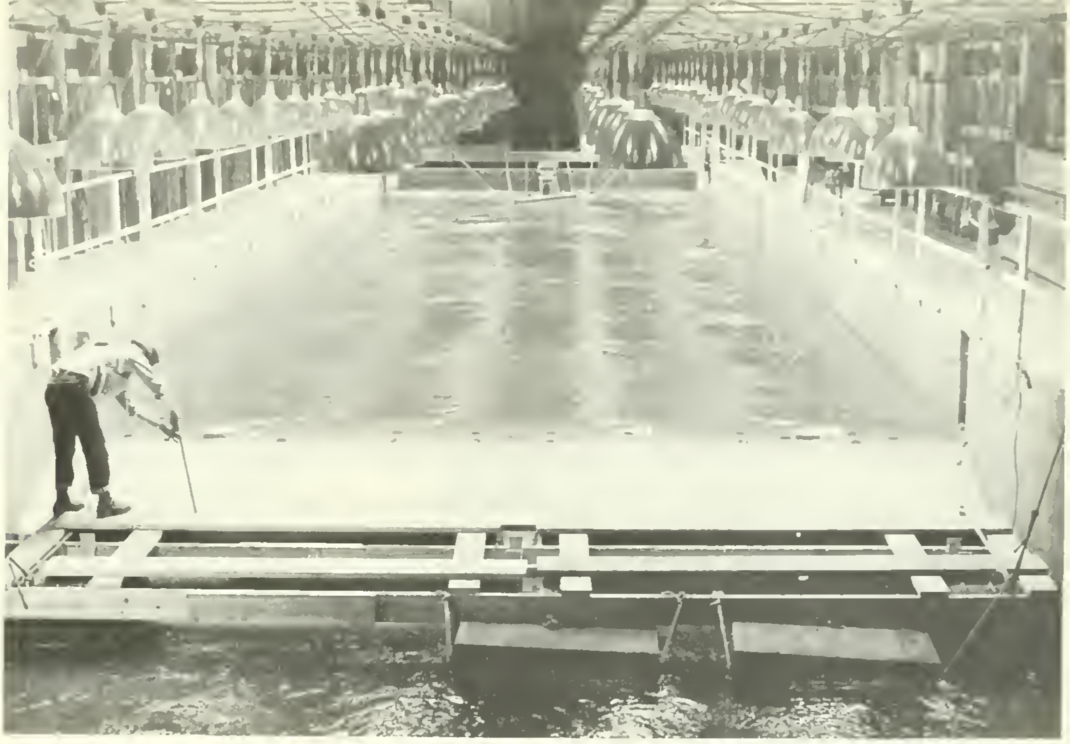

Figure 21.—Experimental arrangement for examining reactions of salmon fingerlings. to overfalls and orifices. Approach channel is 24 feet wide and 15 feet deep. Release box may be seen at the far end of the channel. Inclined plane screen trap is visible in the foreground.

GENERAL OBSERVATIONS

The effect of human odors on fish behavior has been quite conspicuous during laboratory experiments. Fish near the surface rapidly sounded on detecting the odor and activity was suppressed for as long as 20 minutes. This re-emphasizes that in the operation of fishways, effort should be made to avoid physical contact with equipment that will be immersed in the water.

Fish movement through auxiliary pools and channels can be expedited by restricting these channels to less than 4 feet of depth. The tendency for salmon to linger and accumulate in deeper pools and channels at the laboratory was effectively discouraged by the use of wire-mesh grills at shallow depths.

Figure 22.—Ice Harbor prototype fishway with 1-on-10 slope now undergoing tests at Bonneville laboratory. Temporary divider walls have been inserted in each pool. Note paired orifices in each weir. Large numbers of fish use these ports in ascending the fishway.

Figure 23.—Ice Harbor design fishway in operation.

Transitions in spatial relationships, water velocities, and particularly light affect the movement of fish into, through, and out of the laboratory. The effect of an abrupt change in conditions is usually hesitancy and delay.

The ability of all species of salmonids to negotiate overfalls up to 3 feet was frequently demonstrated in the laboratory (fig. 20). However, it was generally observed that the fish would swim easily over a 1-foot overfall but that it usually had to resort to jumping over higher overfalls. The additional energy expended, the delays and the increased probability of minor injuries that would make the fish more susceptible to disease suggests that overfalls greater than 1 foot are undesirable for standard fishways.

Research directed toward the passage problems of downstream migrants was largely postponed because of the priority given to adult passage problems.

Exploratory experiments conducted to test the reactions of chinook fingerlings to an overfall, an orifice, and a siphon are illustrated in figure 21. A 3.5-inch orifice at a depth of 7 feet was far more effective (80 percent) in attracting and collecting fingerlings than a 7-inch overfall of comparable width. The siphon with an intake 18 inches below the surface was also more effective than the overfall.

CURRENT RESEARCH

Experiments now in progress at the laboratory are centered around a full-scale model (figs. 22 and 23) of the 1-on-10-slope fishway designed for the north shore of Ice Harbor Dam, now under construction on the lower Snake River, a major tributary of the Columbia. Pattern and rate of fish movement, space utilization, and capacity potential are being examined in the 6-pool section of the fishway.

The experiments this year demonstrate a special function of the Fisheries-Engineering Research Laboratory—that of providing the means by which new fish passage devices and new features of fishway design may be biologically tested and proven to have merit before being permanently cast in concrete.

APPENDIX A

Proposals, Reports, and Publications Related to Research at the Fisheries-Engineering Research Laboratory

UNPUBLISHED REPORTS

(Distributed to state and federal agencies and universities participating in the research program.)

1. COLLINS, GERALD B.
   1950. Outline of proposed program of research on orientation in migrating fish. U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries, Biological Laboratory, Seattle, Wash. 9 pp., typewritten.

2. 1952. Proposed research on fishway problems, Proposal submitted to North Pacific Division, Corps of Engineers, U.S. Army, Portland, Oregon, by U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries, Biological Laboratory, Seattle, Wash., 36 pp., typewritten.

3. 1953. A special type of laboratory for research on fish orientation. U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries, Biological Laboratory, Seattle, Wash., 6 pp., ditto process.

4. 1954. Explanatory notes on the Fish and Wildlife Service proposal for research on fishway problems. U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries, Biological Laboratory, Seattle, Wash., 9 pp., ditto process.

5. COLLINS, GERALD B., and CARL H. ELLING.
   1958. Performance of salmon in experimental "endless" fishways with slopes of 1 on 8 and 1 on 16. U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries, Biological Laboratory, Seattle, Wash., 19 pp., ditto process.

6. 1958. Supplement I to performance of salmon in experimental "endless" fishways with slopes of 1 on 8 and 1 on 16. U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries, Biological Laboratory, Seattle, Wash., 3 pp., ditto process.

7. COLLINS, GERALD B., CARL H. ELLING, and EDGAR C. BLACK (with technical assistance of Arthur Hanslip)
   1958. II. Blood lactates and performance of salmon and trout in experimental "endless" fishways. *In:* Summary report from Edgar C. Black on "Further studies on the effects of muscular fatigue on fish." Department of Physiology, University of British Columbia, N.R.C. Grant TR-7, November 1, 1958, p. 3, mimeographed.

8. COLLINS, GERALD B., CARL H. ELLING, EDGAR C. BLACK, and ANNE C. ROBERTSON (with technical assistance from Edward Trevor-Smith)
   1959. II. Lactate and glycogen in relation to the performance of salmon and trout in experimental "endless" fishways. *In:* Summary report from Edgar C. Black on "Further studies on the effects of muscular fatigue on fish." Department of Physiology, University of British Columbia, N.R.C. Grant TR-7, November 1, 1959, p. 3 mimeographed.

9. ELLING, CARL H.
   1958. The effect of water velocity on the response and performance of adult salmonids. U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries, Biological Laboratory, Seattle, Wash., 13 pp., typewritten.

10. ELLING, CARL H., and others.
    1955-1960. Monthly progress reports on research on fishway problems. Nos. 1 to 58. Prepared by U.S. Fish and Wildlife Service under Contract No. DA-35-026-25142 for North Pacific Division, Corps of Engineers, U.S. Army, Portland, Oreg. Irregular paging including tables, graphs, and photos.

PUBLICATIONS

11. BLACK, EDGAR C., ANNE C. ROBERTSON, and ROBERT R. PARKER.
    Some aspects of carbohydrate metabolism in fish. University of Washington Press, Seattle, Wash. In press, expected 1960.

12. COLLINS, GERALD B.
    1954. Research on anadromous fish passage at dams. Transactions of the Nineteenth North American Wildlife Conference, pp. 418-423.

13. COLLINS, GERALD B.
    1956. Research on fishway problems. *In:* Report on Fisheries Engineering Research Program. North Pacific Division, Corps of Engineers, U.S. Army, Portland, Oreg., pp. 118-125.

14. Collins, Gerald B.
1958. The measurement of performance of salmon in fishways. *In:* H. R. MacMillan Lectures in Fisheries, a symposium held at the University of British Columbia, April 29 and 30, 1957. Edited by P. A. Larkin. Institute of Fisheries, University of British Columbia, Vancouver, B.C., pp. 85–91.

15. Elling, Carl H., and Howard L. Raymond.
1959. Fishway capacity experiment, 1956. U.S. Fish and Wildlife Service, Special Scientific Report—Fisheries No. 299, 26 pp.

16. Elling, Carl H.
1960. Further experiments in fishway capacity, 1957. U.S. Fish and Wildlife Service, Special Scientific Report—Fisheries No. 340, 16 pp.

17. Lander, Robert H.
1959. The problem of fishway capacity. U.S. Fish and Wildlife Service, Special Scientific Report—Fisheries No. 301, 5 pp.

18. Long, Clifford W.
1959. Passage of salmonids through a darkened fishway. U.S. Fish and Wildlife Service, Special Scientific Report—Fisheries No. 300, 9 pp.

19. vanHaagen, Richard H.
1956. Audio in salmon research. Journal of the Audio Engineering Society, vol. 4, no. 4, October, pp. 151–158.

MANUSCRIPTS

(Reports by the staff of the Biological Laboratory, Seattle, Wash., except as noted, in various stages of preparation and review for future publication.)

20. Collins, Gerald B.
Research in fish passage problems.

21. Collins, Gerald B., and Carl H. Elling.
Progress in fishway research Bonneville Dam.

22. Collins, Gerald B., Carl H. Elling, Joseph R. Gauley, and Clark S. Thompson.
Effect of slope on performance of salmonids in experimental "endless" fishways.

23. Collins, Gerald B., and Joseph R. Gauley.
Ability of salmon to ascend long fishways.

24. Gauley, Joseph R.
Effect of fishway slope on rate of passage of salmonids.

25. Gauley, Joseph R., and Clark S. Thompson.
Further studies on fishway slope and its effect on rate of passage of salmonids.

26. Long, Clifford W.
Effect of light on orientation and rate of movement of adult salmonids in a channel.

27. Thompson, Clark S.
Influence of flow patterns on performance of chinook salmon in pool-type fishways.

28. Trefethen, Parker S.
Effect of sonic tags on fish movement.

29. Trevor-Smith, Edward.
Changes in carbohydrate in salmon and trout in experimental "endless" fishways. M.D. thesis. University of British Columbia, Vancouver, B.C.

30. Weaver, Charles R.
Influence of water velocity upon orientation and performance of adult migrating salmonids.

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