TRIAL OF DENIL-TYPE FISH LADDER ON PACIFIC SALMON

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Explanatory Note

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United States Department of the Interior, Douglas McKay, Secretary
Fish and Wildlife Service, Albert M. Day, Director

TRIAL OF DENIL-TYPE FISH LADDER ON PACIFIC SALMON

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ILLUSTRATIONS

In the Pacific Northwest the problem of safeguarding the passage of upstream migrating fish at hydroelectric and irrigation developments is becoming increasingly important.

New types of fishways are being considered in the hope that more efficient ones will be found. A design known as the Denil-type fishway, used to some extent in Europe, has had favorable comment as an economical yet efficient means of enabling fish to surmount barriers. New interest was stimulated by an article by Valter Furuskog (1945) of Stockholm, Sweden, concerning the design and construction of a "fish pass" for the Herting power dam on the Atran River, near Falkenburg, Sweden. As a result of this interest, an experiment was designed to compare the effectiveness of the pool-type and Denil-type ladders as fish-passage devices.

Observations were made in a side-by-side installation at Dryden Dam on the Wenatchee River approximately 17 miles above the confluence of the Wenatchee and Columbia Rivers.

HISTORY OF THE DENIL-TYPE LADDER

The Denil-type fish ladder, "counter-current" in principle, was developed by G. Denil of Brussels, Belgium who devised a system of baffles in a channel which by nature of their shape and position impart a secondary outward circulation of flow, producing a momentum transfer from the central portion of the channel toward the walls. In a publication concerning "fish-pass" installations at the Meuse and Orthe Dams on the Rhine River, Denil (1909) presented his fish-ladder design in its original form, explained the ideas which served as the basis of his design, and described in detail the first fish ladders constructed with his principles. Work initiated by Denil in 1907 was continued over a period of 30 years. In his endeavor to develop a rational basis for fish-ladder design, Denil (1936-38) conducted numerous experiments on the hydraulics of "counter-current" fish ladders, the nature and magnitude of resistance encountered by fish in various types of ladders, and the ability of fish to overcome those resistances.

Denil's principles were further investigated by the Committee on Fish Passes, British Institution of Civil Engineers, who during the period 1936-38 carried out hydraulic experiments at the Imperial College of Science and Technology to confirm Denil's results and, by application of his principles, to develop a simpler design of baffle than the somewhat complicated cup-shaped baffle utilized by Denil in his experiments. The type of baffle selected by the British investigators as the most practical was a single-plane baffle (see Figure 1) which is more readily constructed than the cup-shaped baffle used by Denil.

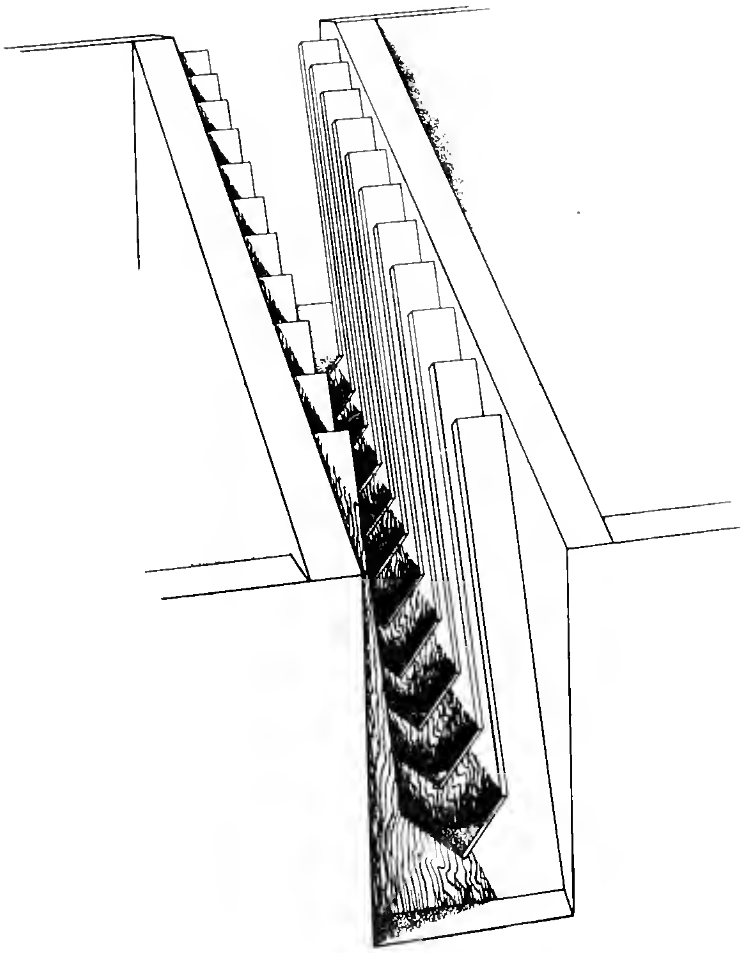

Figure 1.-- Perspective of Denil-type fish ladder with single-plane baffles

In March 1943, further investigations were made by Swedish fishery interests at Stockholm, of experimental fish ladders constructed in accordance with the recommendations of the Committee on Fish Passes. Based on the results of these experiments, a Denil-type ladder was designed by Furuskog for the Herting power dam in Sweden. Furuskog's design represented a modification of the design recommended by the Committee on Fish Passes, involving an increase in linear dimensions and a decrease in bottom slope of the channel.

Further comparative experiments of models of the Herting fish ladder were undertaken in May 1943 under the guidance of Professor Hellstrom of the Royal Technical University of Stockholm. One of the models was sawed down the middle, and one of the halves was placed against the glass wall of a test flume, so that observations could be made of currents inside the fish-ladder model. By use of a wire with thread banderoles attached, it was found that the currents near the bottom of the channel were nearly vertically upward with the higher velocities in a longitudinal direction occurring near the water surface (see Figure 2). The baffles being placed at an angle with the floor of the channel catch the faster-flowing water near the water surface, forcing the flow downward to the floor where it is directed upward in such a manner that it slows down the current in a longitudinal direction. Experiments utilizing small fish gave no indication of their being disturbed by the vertical currents.

The Herting fish ladder was completed in May, 1945, and counting observations were initiated in September of the same year. According to Furuskog (1945), 54 Atlantic salmon weighing up to 20 pounds and 6 sea-run trout negotiated the new fish ladder during one 3-hour period. The success of the Denil-type ladder at the Herting power dam was considered proved, although the information furnished by Furuskog gives no indication of the size of run involved.

DESIGN DEVELOPMENTS OF THE DENIL-TYPE LADDER

Based on experiments conducted by the British investigators during the period 1936-38, a practical Denil-type fish ladder as defined by the Committee on Fish Passes (1942) would have a channel width of 3 feet, with single-plane baffles spaced at a distance of two-thirds the channel width and laid sloping upstream at a 45-degree angle with the channel floor. As further defined by the Committee, a practical Denil-type fish ladder would have a clear opening between the upright portions of the individual baffles of 1 foot 9 inches, the channel would have a bottom-slope not exceeding 1 on 4, and resting pools would be provided at vertical intervals of 6 to 8 feet. A bottom slope of 1 on 5 was, however, recommended where a channel length of 30 feet is provided between resting pools.

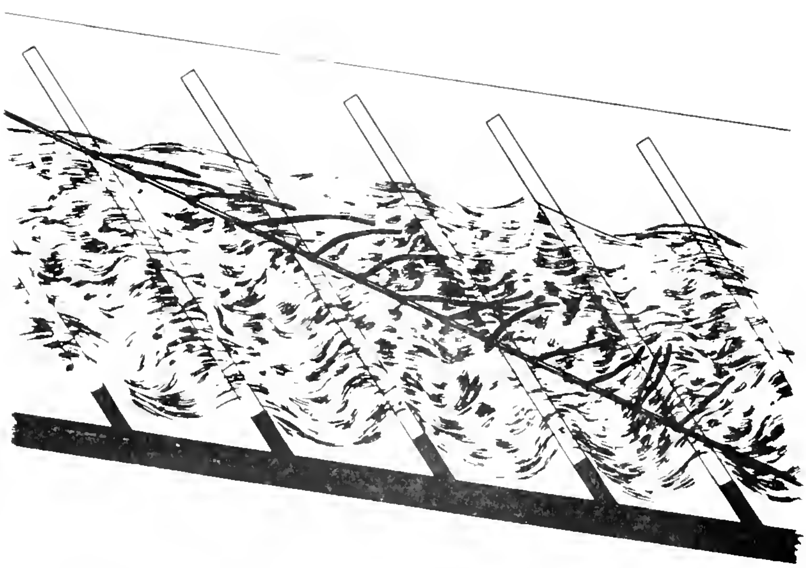

Figure 2.-- Pictorial representation of flow conditions in Denil-type fish ladder, with direction of flow at the various depths shown by position of thread banderoles. (Redrawn from Furuskog 1945).

Effective operating depth, as recommended by the Committee, varies between the limits of 2 to 3 feet above the floor of the channel. At a depth of 2 feet, approximately 10 second-feet (cubic feet per second) of flow would be required for operation of the defined practical Denil-type ladder, and at a 3-foot depth, flow requirements would be increased to about 21 second-feet.

As described by Furuskog (1945), the Denil-type ladder at the Herting power dam represents a modification of the design recommended by the Committee on Fish Passes, involving a linear enlargement of about 142 percent and a decrease in bottom slope of the channel to 1 on 6. The channel width was increased to 1.30 meters (4 feet 3-1/4 inches), with a clear opening between the upright portions of the individual baffles of 0.76 meters (2 feet 6 inches). The slope of the baffles was maintained at 45 degrees with respect to the floor of the channel, and the spacing of baffles was maintained at two-thirds the channel width. The greatest channel distance between successive resting pools in 9.02 meters (29 feet 7-1/8 inches)

Flow requirements of the Denil-type fish ladder at the Herting power dam was reported by Furuskog to be normally 1.4 cubic meters per second (49 second-feet), although the figure is not particularly significant in that the operating depth within the channel was not specified.

GENERAL DESIGN FEATURES OF THE DENIL-TYPE LADDER AT DRYDEN DAM

The apparent success of the Herting fish-ladder installation designed by Furuskog, encouraged the Fish and Wildlife Service to construct a Denil-type ladder side by side with an overflow weir pool-type ladder. In this way the efficiency of the two types could be compared under similar operating conditions and with the same species of fish. The site at Dryden Dam (see Figure 3) on the Wenatchee River was selected, inasmuch as it was a relatively low dam where concentrations of salmon could be assured. The location was particularly advantageous, since, as the result of reconstruction work at Dryden Dam to replace sections of the dam damaged by high water in the spring of 1948, a temporary earthfill cofferdam made it possible to construct the Denil fish-ladder in the existing pool-type ladder while the latter was unwatered. The work was thus facilitated and resulted in a more economical installation than otherwise could have been effected.

Construction of the Denil-type ladder reduced the width of the pool-type ladder to approximately one-half of its original width of 10 feet as shown in Figures 4 and 5. The two ladders could then be compared to determine which was preferred by the fish. Work on the Denil-type installation was initiated during the fall of 1948 and was completed in the spring of 1949.

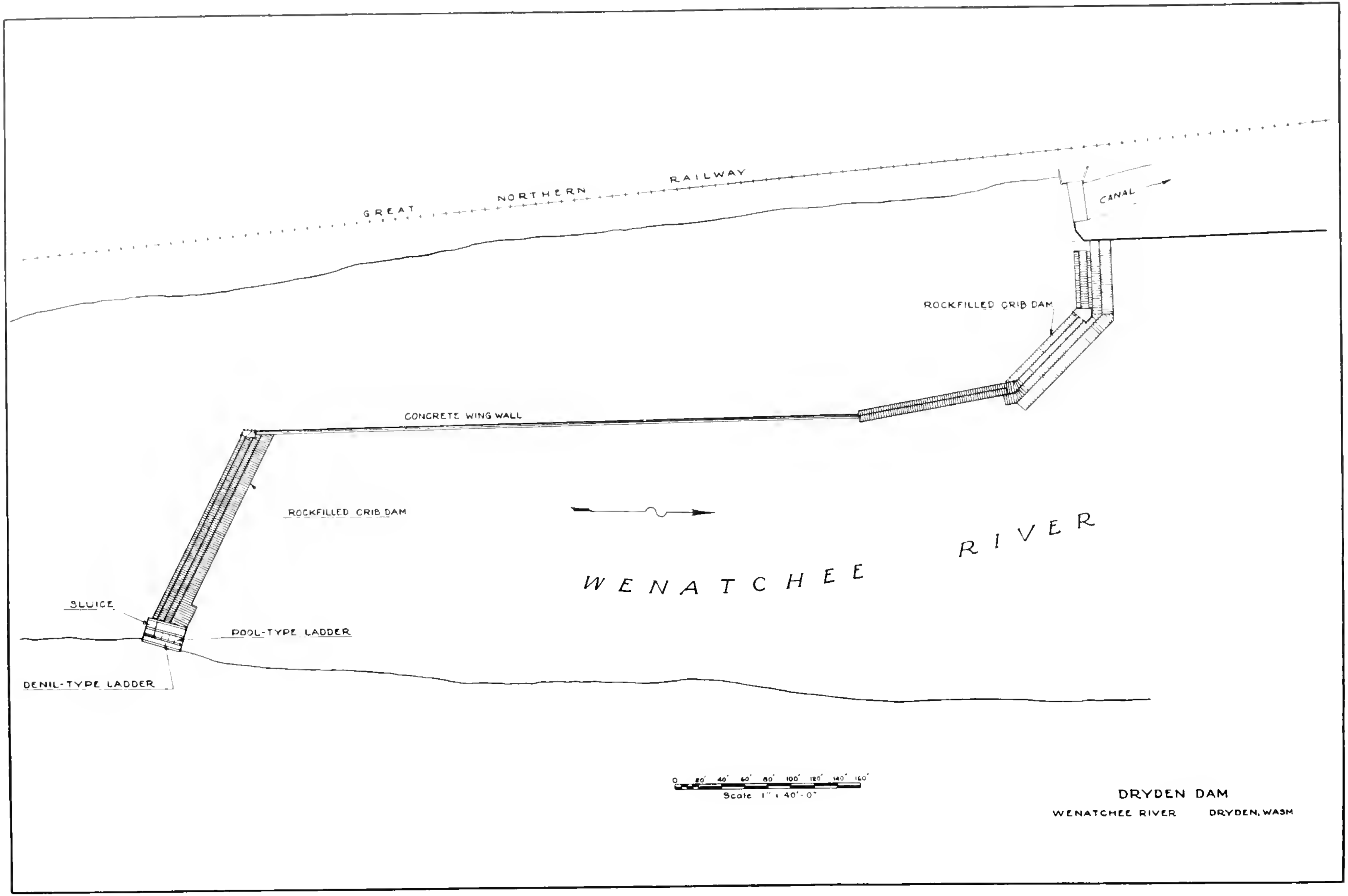

Figure 3.--Arrangement of structures at Dryden Dam.

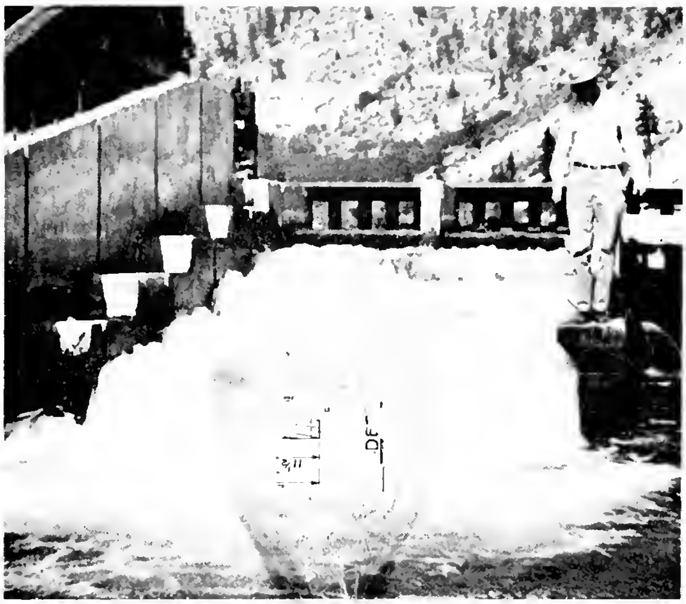

Figure 4.--Pool-type fish ladder in 1948 prior to construction of the Denil-type ladder.

Figure 5.--The Denil and pool-type fish ladders in operation in 1949.

Design of the Denil-type ladder at Dryden Dam was patterned after the Herting installation and varied therefrom only to the extent that no weirs were provided at the upper end for regulation of ladder flows with accompanying forebay fluctuations. However, flow regulation can be effected to a small degree by the insertion of one or more stop-logs in the guides provided at the upper end of the ladder for unwatering purposes. The Dryden installation (see Figure 6) consists of a channel 4 feet 3 inches in width, with 10 U-shaped wooden baffles spaced 2 feet 10 inches on centers along the floor of the channel and set at a 45-degree angle thereto. Clear opening between the upright portions of the individual baffles is 1 foot 9 inches, and the bottom slope of the channel is 1 on 6. The ladder is designed for a maximum difference in elevation between forebay and tail[illegible] of approximately 5 feet 9 inches.

Flow through the ladder was experimentally adjusted between 20 and 30 second-feet during the tests. According to the British Committee on Fish Passes, minimum operating depth for the Denil-type ladder with a channel 3 feet in width was indicated to be 2 feet above the channel floor. Observations made at Dryden Dam showed that fish could readily negotiate the ladder at a lesser depth.

The maximum operating depth was based on the assumption that the maximum depth (3 feet) prescribed by the Committee on Fish Passes for the channel 3 feet in width could be increased by 42 percent. The 42 percent represents the increase in linear dimensions of the Denil-type ladder at Dryden Dam over that recommended by the Committee on Fish Passes. From actual observations, the most suitable operating depth appeared to be 3 feet. At this depth flow through the Dryden installation was computed from current-meter readings to be approximately 30 second-feet.

GENERAL DESIGN FEATURES OF THE POOL-TYPE LADDER AT DRYDEN DAM

As previously mentioned, the width of the pool-type ladder was reduced to about one-half of the original width (10 feet) as a result of construction of the Denil-type ladder. The pool-type ladder consisted of 4 pools each 5 feet wide and 6 feet long. This made 5 steps of approximately 1 foot drop. Flows were regulated at from 9 to 12 second-feet.

The pool-type ladder was damaged by high water in the spring of 1950 when the lowest weir supports were washed out. This reduced the number of ladder pools to three and created a short entrance channel to the ladder from the tailwater area below the dam. This change in the number of pools apparently did not affect fish passage. More fish ascended the ladder in 1951 than in 1949.

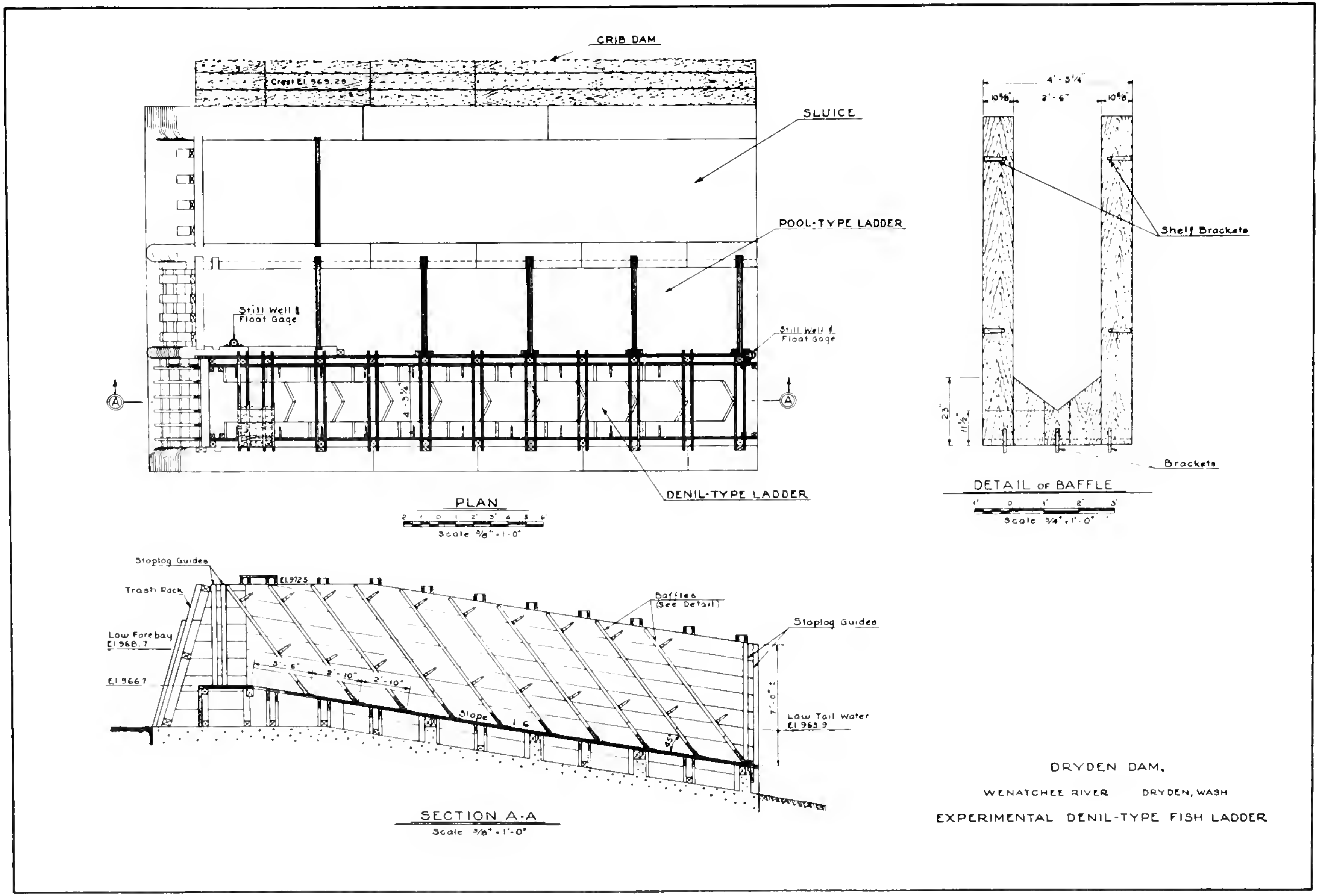

Figure 6.--General design of Denil-type fish ladder at Dryden Dam.

The average depth of water in the pools of the ladder was calculated to be 5.5 feet for the 4 pools in 1949 and 4.4 feet for the 3 pools as operated during 1951.

THE EXPERIMENT

With the completion of the Denil-type ladder at Dryden Dam in the spring of 1949, plans were formulated for fish-passage observations at both the Denil-type and pool-type ladders, in connection with the migration of blueback salmon (Oncorhynchus nerka) and chinook salmon (Oncorhynchus tshawytscha) on their way to their spawning grounds.

The method used for making comparative counts of fish utilizing the individual ladders was for the observer to alternate his attention from one ladder to the other for approximately equal periods. When two observers were available, fish were counted simultaneously in both ladders.

During the 1949 migration, 114 hours 20 minutes of observations were made, with a total of 260 fish being counted through the ladders. However, not as many fish were tallied as had been anticipated, since, as the result of flow conditions over this relatively low dam, a great many were able to negotiate the dam without using the ladders. Fish other than salmon seen ascending the Dryden ladders were rainbow or steehead trout (Salmo gairdenrii), Dolly Varden trout (Salvelinus malma), suckers (Catostomus sp.) and Squawfish (Ptychocheilus oregonensis).

In 1949, a total of 259 fish was counted through the Denil-type ladder in 64 hours and 5 minutes, while only one fish was observed passing through the pool-type ladder in 50 hours 15 minutes of observation. Data concerning these observations are listed in Table 1. The observations were extended to the 1950 season, but were soon abandoned after no fish were seen using the ladders over a period of several days. High water conditions resulted in the fish finding other means of negotiating the dam than by the ladders.

From the standpoint of the experimental observations, water levels during the 1951 season were more satisfactory and salmon used the fish ladders to a greater extent. Both the Denil-type and pool-type ladders were observed for a total of 46 hours 40 minutes during which time 1,569 fish ascended the Denil-type ladder and 225 fish were counted through the pool-type ladder. The data on 1951 observations can be found in Table 2. Thus in the total time that counting was conducted in 1949 and 1951 (207 hours 40 minutes, 89 percent of the fish used the Denil-type ladder and 11 percent used the pool-type ladder. As will be noted from Tables 1 and 2, a larger percentage of fish negotiated the dam in 1951 by use of the pool-type than in 1949.

TABLE 1.—FISH COUNTS AT DRYDEN DAM FISH LADDERS

1949

Date	Elevations		Denil-type Ladder						Pool-type Ladder					
	Fore-bay	Tail-water	Time Obser. in Min.	Blueb. Salmon	Chin. Salmon	Trout 1/	Others 2/	Total	Time Obser. in Min.	Blueb. Salmon	Chin. Salmon	Trout 1/	Others 2/	Total
Jul. 28	970.50	965.62	160	2	1	3	0	6	160	0	0	0	0	0
" 29	970.40	965.67	120	60	9	0	4	73	120	0	0	0	0	0
" 30	970.38	965.70	225	32	2	0	7	41	105	0	0	0	0	0
" 31	970.40	965.75	280	10	4	2	2	18	280	0	0	0	0	0
Aug. 1	970.40	965.73	365	8	1	0	6	15	305	1	0	0	0	1
" 2	970.42	965.73	120	7	0	0	0	7	85	0	0	0	0	0
" 3	970.40	965.75	200	4	3	0	0	7	200	0	0	0	0	0
" 4	970.35	965.60	120	2	0	1	3	6	90	0	0	0	0	0
" 5	970.20	965.26	150	0	0	1	0	1	90	0	0	0	0	0
" 6	970.20	965.27	120	2	0	1	0	3	120	0	0	0	0	0
" 7	970.18	965.30	150	4	3	2	0	9	90	0	0	0	0	0
" 8	970.10	965.20	120	0	0	0	1	1	120	0	0	0	0	0
" 9	970.05	965.04	95	0	1	0	2	3	50	0	0	0	0	0
" 10	970.03	964.97	240	7	1	0	2	10	180	0	0	0	0	0
" 11	970.00	964.90	360	18	4	0	4	26	240	0	0	0	0	0
" 12	969.95	964.75	420	13	3	0	5	21	180	0	0	0	0	0
" 13	969.95	964.65	420	8	2	0	1	11	420	0	0	0	0	0
" 14	969.90	964.50	180	0	1	0	0	1	180	0	0	0	0	0
Totals:			3845	177	35	10	37	259	3015	1	0	0	0	1
Percentage:								99.6						0.4

1/ Eight rainbow and two Dolly Varden trout.

2/ Mainly suckers and squawfish.

TABLE 2 - FISH COUNTS AT DRYDEN DAM FISH LADDERS

1951

Date	Elevations		Denil-type ladder						Pool-type ladder					
	Forebay	Tailwater	Time Ob. in Min.	Blueb. Salmon	Chinook Salmon	1/ Trout	2/ Others	Total	Time Ob. in Min.	Blueb. Salmon	Chinook Salmon	1/ Trout	2/ Others	Total
Aug. 6	970.02	964.79	100	0	0	0	1	1	100	0	0	0	0	0
" 7	970.00	964.75	300	41	1	1	4	47	300	2	1	0	0	3
" 8	969.96	964.68	265	330	4	0	2	336	265	76	2	0	0	78
" 9	969.95	964.64	280	93	4	0	1	98	280	19	0	0	0	19
" 10	969.94	964.63	100	61	5	0	0	66	100	18	3	0	0	21
" 11	969.94	964.62	140	39	2	0	0	41	140	12	1	0	0	13
" 12	969.92	964.59	205	38	1	0	0	39	205	0	0	0	0	0
" 13	969.91	964.43	165	19	0	0	0	19	165	3	0	0	0	3
" 14	969.83	964.29	155	30	2	0	0	32	155	0	0	0	0	0
" 15	969.79	964.13	315	122	9	1	0	132	315	3	1	0	0	4
" 16	969.76	964.06	290	96	3	0	0	99	290	15	3	0	0	18
" 17	969.73	964.07	325	407	18	0	0	425	325	41	1	0	0	42
" 18	969.74	963.91	160	222	12	0	0	234	160	22	2	0	0	24
Totals:			2800	1498	61	2	8	1569	2800	211	14	0	0	225
Percentage								87.5						12.5

1/ One rainbow and one steelhead trout.

2/ Mainly suckers and squawfish.

DISCUSSION

In an experiment of this type, it is difficult to eliminate all influences which might have an effect on the final outcome. Results of the experiment would have been more conclusive, had it been possible to alternate the position of the two ladders. However, the importance of position is minimized to a degree at least by two conditions: (1) the small flow requirement for each of the ladders as compared to the total flow over the dam gave both ladders a relatively equal attraction to salmon approaching from either shore, and (2) despite the fact that salmon are sometimes known to follow the shorelines in their upstream migration, our experience at other dams, such as Tumwater Dam further upstream, indicates that the greatest numbers of fish do not always use the entrance situated nearest the shore.

Another question which arises is whether or not the pool-type ladder at Dryden Dam was a good example of that type. That is, were the pools of adequate dimensions and was the entrance most suitably located with respect to the downstream face of the dam? Also, might not the pool-type ladder have been more effective had it been possible to provide submerged orifices in the weirs? Short ladder pools (6 feet) precluded the use of submerged orifices. While the pool-type ladder at Dryden Dam is not suggested as being the best example of that type ladder, it is a typical example of the ladders constructed at low-head dams on the tributary streams throughout the Columbia River basin.

It appeared from observations made in connection with the experiment that the foremost advantage of the Denil-type ladder is the attractive entrance condition created by the nozzle-like flow from the ladder entrance. In the case of the pool-type ladder, the effect of the nappe of flow over the entrance weir is quickly dissipated as it plunges into the deeper water below the dam, whereas the effect of the jet of flow from the Denil-type ladder extends downstream a considerable distance from the ladder entrance horizontally along the water surface. This fact, it was concluded, was the chief reason why most of the fish selected the Denil-type over the pool-type ladder.

In addition to providing what appears to be a better attraction to fish, the Denil-type proved to be superior with regard to facilitation of fish passage. Salmon and fish of several other species, including squawfish, suckers and certain less active fish, appeared to arrive at the upper end of the ladder with little effort. The ease with which fish appeared to negotiate the ladder is attributed to the dissipation of energy by the baffles. Part of this dissipation of energy produces upward currents which were demonstrated by Furuskog in a model, as shown in Figure 2.

It was not always possible to see fish entering the two ladders, hence the length of time it took fish to negotiate the two types was not measured. However, there were a few occasions when the water was clear so that individual fish could be seen entering the ladders and later crossing the counting board. The short time required for a salmon to pass upstream through the Denil-type never failed to startle the observers, and was especially in contrast to the slow progress through the pool-type ladder.

During short periods of observation, fish passed through the Denil-type at an average of 24 second intervals. (On August 18, 1951, in 100 minutes of observation, 247 fish passed through). On numerous occasions several bluebacks passed through the ladder simultaneously, or in rapid succession. However, it would be desirable to make an additional study at a location where there is a greater concentration of fish and other species of salmon present. The apparently more attractive entrance flow of the Denil-type could be a deciding factor in preventing delay or accumulation of salmon such as now occurs below pool-type ladders.

From the standpoint of flow and number of fish concerned, the Denil-type ladder conveyed more fish per second-foot of flow than the pool-type ladder. That is, 89 percent of the fish used the Denil-type ladder, although it carried only 40 percent more flow.

A saving in space can be an important factor where there is limited room for construction. Fishery engineers in Sweden are convinced that the Denil-type ladder, with a width of approximately that of the Dryden Dam installation (4 feet 3-1/4 inches), will replace the pool-type ladder with a width of 10 feet, commonly used in Sweden. In addition, the steep gradient of the Denil-type ladder would result in a somewhat shorter over-all length than for a pool-type ladder with pools of normal length, thereby conserving space.

Some difficulty was experienced in keeping the pool-type ladder continually adjusted to produce optimum flow conditions for upstream passage of fish. The removal or addition of stop-logs or for that matter, even minor changes in water level, will alter the hydraulic conditions within the pool to influence to some degree the response of fish to the fishway. A distinct advantage in the Denil-type structure is the automatic adjustment for changes in water level obtained from use of the vertical baffles. Although the optimum conditions for salmon have never been adequately determined, the accepted operational procedure for pool-type ladders was followed to even a greater degree than would be done in normal operational practice.

Although it might at first appear that there would be considerable savings affected--due to the smaller size of the Denil-type ladder, size alone does not necessarily control cost. The Denil-type ladder requires higher walls, and numerous specially constructed baffles which increase the cost. Therefore, it is the opinion of the authors that the Denil-type ladder would not represent any savings in construction cost over the pool-type ladder.

SUMMARY AND CONCLUSIONS

Interest in the Denil-type fish ladder constructed at the Herting power dam in Sweden led to the construction at Dryden Dam of one patterned after the Swedish installation. Comparison of the Denil-type and pool-type ladders was facilitated because it was possible to construct a Denil-type ladder in one-half of the existing pool-type ladder at Dryden Dam.

During the actual time that counting observations were conducted in 1949 and 1951, the Denil-type was preferred by fish utilizing the ladders. In 110 hours 45 minutes, 1,828 fish used the Denil-type ladder, and in 96 hours 55 minutes a total of 226 fish were counted through the pool-type ladder.

The Denil-type ladder at Dryden Dam occupies essentially the same amount of space as the pool-type ladder. There is, therefore, some advantage in the Denil construction in conservation of space, both from the standpoint of its narrowness, and shorter length made possible by a steeper slope.

It was concluded, because of the baffles and higher flume wall construction of the Denil-type ladder, that there is no substantial saving in cost of construction over the standard pool-type ladder.

With regard to flow requirements, the data collected revealed that the Denil-type ladder passed a greater number of fish per second-foot of flow and required less attention. With only 40 percent more flow than in the pool-type ladder, the Denil-type was utilized by 89 percent of the fish counted through the ladders.

Probably the most desirable feature of the Denil-type was the attraction flow it presented to fish.

The study undertaken at Dryden Dam was somewhat limited in scope, and it is hoped that the encouraging results may stimulate further research into the possibilities of the Denil-type ladder. One possibility for adoption of the Denil-type which should be investigated is its installation at the downstream end of a pool-type ladder, since, on the basis of observations at Dryden Dam, the Denil-type fish ladder is apparently more effective in attracting fish than the small pool-type ladder common to the Pacific Northwest. Additional studies also should be undertaken to determine the height of dam that different species of fish can negotiate by a continuous baffled channel without resting pools, and investigations should be carried out to determine the practicability of the Denil-type ladder at higher dams.

ACKNOWLEDGEMENTS

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