EFFECTS OF FLOW AND WEIR DESIGN ON THE BEHAVIOR OF AMERICAN SHAD AND SALMONIDS IN AN EXPERIMENTAL FISH LADDER

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ABSTRACT

This research was conducted to determine methods of improving American shad (_Alosa sapidissima_) passage through flow control regulating sections of fish ladders at Columbia River dams without hindering the passage of anadromous salmonids, e.g., chinook salmon (_Oncorhynchus tshawytscha_), sockeye salmon (_O. nerka_), and steelhead (_Salmo gairdneri_). In 1969 and 1970, various weir configurations at two flow regimes were tested at the Fisheries Engineering and Research Laboratory located at Bonneville Dam on the Columbia River. American shad passage through the test section was significantly increased when an overflow slot and submerged orifice were provided. Velocities in the overflow slots were found to be critical to American shad passage. Passage through the ladder system for the three species of salmonids tested was not adversely affected by the overflow slot. Other tests were conducted in 1978 and 1979 at the same facility to determine the feasibility of using the American shad's preference for overflow slots to separate them from the salmonid species within the ladder system.

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INTRODUCTION

The spread and increase of American shad (Alosa sapidissima) along the Pacific coast of America has been one of the most remarkable in all cases of introduced species (Welander 1940). The successful establishment of shad in the Pacific Northwest is attributed to 1885-1886 plants in the Columbia River at its confluence with the Snake River, in the Willamette River, a tributary to the Columbia River, and to adult migrations from other river systems south of the Columbia River (Parks 1978). The first commercial landings of American shad in the Columbia River were reported in 1889 and their abundance depressed the market value as early as 1893 (Craig and Hacker 1940). Since the early 1900's there has also been a steady increase in the American shad's migratory range, which according to Stainbrook (1982), now extends to Grand Coulee Dam on the Columbia River and past Lower Granite Dam on the Snake River [639 and 695 km respectively, from the mouth of the Columbia River (Fig. 1)]. American shad count at Ice Harbor Dam on the Snake River have increased from 253 in 1962 (the first year of operation of the dam) to a high of 19,337 in 1982. At Priest Rapids Dam on the Columbia River, also completed and operating in 1962, the counts have increased from 839 to a high of 95,840 in 1983. Counts for 1985 were 8,102 at Ice Harbor Dam and 44,093 at Priest Rapids Dam [U.S. Army Corps of Engineers (COE) 1962-1985].

As American shad have extended their range far up the Columbia River, counts at Bonneville Dam (the first dam on the Columbia River) have gone from 6,720 in 1959 to 1.3 million in 1985. Wendler (1967) states that these large increases may be attributable to: "(1) construction of dams with fish passage facilities making it possible to pass natural barriers now inundated, (2) a warming temperature and regulated flow resulting from dam construction, and (3) the availability and use of spawning and rearing areas in the forebays of these structures." He also notes that prior to 1960, all major spawning areas for American shad were below Bonneville Dam. Record returns began occurring at Bonneville, The Dalles, and McNary Dams in 1961, 4 years after the completion of The Dalles Dam and the resulting inundation of a natural barrier at Celilo Falls (U.S. Army Corps of Engineers 1966). Since 58.5% of adult returns consist of 4-year-old fish (Stainbrook 1982), these returns seem to coincide with the completion of The Dalles Dam and the subsequent availability of new spawning areas.

As the dams on the Columbia and Snake Rivers went into operation, it became apparent that American shad were reluctant to pass through certain sections of the ladders, causing large accumulations of fish in these sections. This created a serious maintenance problem at dams where fish counting stations were located in the ladders downstream of the shad obstruction because the American shad ultimately died in the ladder, drifted downstream, were caught against the fish-barrier screens at the counting stations and eventually had to be removed.

During the first year of operation of John Day Dam (1968), the flow control sections of the two fish ladders were not passing American shad satisfactorily. These sections comprised the last or uppermost 19 pools of each ladder which were separated by non-overflow weirs with submerged orifices for the passage of fish and water. These sections were designed to control flow in the fish ladder over a wide range of forebay levels (3.3 m from minimum to maximum). Many American shad were either reluctant or unable to pass through the submerged orifices in the weirs of these sections, thus creating the problem previously described. The weirs separating all the other pools in the ladder had submerged orifices, but water also flowed over the top of the weirs providing both a surface and submerged passage for fish.

In 1969, full-scale model tests began at the COE Fisheries-Engineering Research Laboratory at Bonneville Dam to evaluate various methods of modifying these weirs to improve American shad passage through the flow control sections of the fish ladders without decreasing the capability of regulating flows and without impeding the passage of other species. These studies were conducted by the National Marine Fisheries Service (NMFS) and funded by the COE. During the first year, three types of regulating weirs were tested and information was obtained regarding the effectiveness of slot-type and orifice-type weirs in passing fish. This information was incorporated in two designs of flow control sections that were tested in the Bonneville Fisheries-Engineering and Research Laboratory during 1970 (Plan C and Plan E). Both of these plans were similar in that they incorporated slot-type weirs for fish passage and regulation of flows, but Plan E contained twice as many pools (in the same distance) so that the head drop per pool was reduced to one-half.

In 1978, similar problems with American shad passage were encountered at Ice Harbor Dam when the fish counting station was moved from the upper end of the ladder to about mid-ladder (below the flow control regulating section). During the peak of the American shad migration, the problem became so severe that COE personnel were required to haul two truck loads of dead American shad a day from the the barrier screens located at the fish counting station. Therefore, the COE wanted to replace the existing non-overflow weirs in the flow control section with slot-type weirs which would not impede shad passage. This was opposed by the Washington Department of Game and the Idaho Fish and Game Department because these agencies did not want to open up new spawning and rearing areas to American shad and further increase both the population size and migratory range of this introduced species.[1/]

With Ice Harbor Dam's problems in mind, tests were undertaken by NMFS at the COE Fisheries-Engineering and Research Laboratory at Bonneville Dam in 1978 and 1979 to determine the feasibility of further ladder modifications which would either completely block American shad passage into the ladder system without impeding passage of other migrating fish, or divert American shad into a separate ladder system which would shunt them around regulating sections and fish barrier screens in the existing ladder. The latter proposal would also benefit salmon (*Oncorhynchus* spp.) and steelhead (*Salmo gairdneri*) trapping facilities operated by NMFS and located in some fishways on the Columbia River dams, where American shad cause similar problems.

The objective of this paper is to document the results of these two sets of tests (1969 and 1970; 1978 and 1979) and provide additional information on the behavior of both salmonids and American shad in various types of fishways. The salmonids tested were summer chinook salmon (*O. tshawytscha*), sockeye salmon (*O. nerka*), and steelhead.

[1/] J. McKern, Walla Walla District CofE. Bldg. 602, City-County Airport, Walla Walla, WA 99362. Pers. Commun., March 1984.

METHODS AND MATERIALS

1969 and 1970 Tests

Test facilities at the Fisheries-Engineering and Research Laboratory consisted of a 43-m long by 7-m wide by 5-m deep channel located parallel to the north shore fish ladder (Fig. 2). Test fish were diverted from the fish ladder into the introductory pool by means of picketed leads and an entrance fishway. After passing through the test area, fish could return to the ladder via the fish exit (Collins and Elling 1960). Inside the channel a full-scale model (49 m by 7 m) of the first six orifice control pools in the John Day Dam north shore ladder (between Elevations 249 and 255)[2] were constructed, and three different weir configurations tested. As shown in Fig. 3, these were the original John Day Dam orifice type weir (W_1), the original weir modified by enlarging the center orifice so there would be surface passage between pools at all forebay levels (W_2), and a further modification of W_1 in which the 0.46-m wide center orifice was replaced by two 0.23-m wide side slots (W_3). Each pool in the experimental ladders was 6 m wide by 4.9 m long, making the overall length of the 6-pool section over 29 m. The floor of the ladder was built on a 1 on 32 slope, but hydraulic slopes varied between test conditions depending upon head loss between pools. Pool depths ranged from 2.1 m at the downstream end to 9.5 m at the upstream end when the ladder was operated with a 0.3-m head loss between pools. Each weir configuration was tested at 0.23 and 0.30 m of head, and each test was repeated two or three times.

Using information from the 1969 tests, two types of control sections (Plan C and Plan E) were built in the Fisheries-Engineering and Research

Laboratory and tested in the spring and summer of 1970 (Fig. 4). Both of these plans incorporated slot-type weirs and were designed to occupy the existing orifice control section and provide the same flow regulation throughout the normal range of forebay levels (from elevation 257 to elevation 268).[2] The Plan C control section consisted of a series of seven pools separated by weirs placed at 4.9-m centers, each having a vertical slot near the center and an 0.46-x 0.46-m orifice on the bottom left side for the passage of fish and water. Slot widths and heights were designed to provide a drop between pools of 0.30 m under conditions simulating maximum forebay elevation at John Day Dam. The Plan E fishway was created by inserting additional slot-type baffles along the center line of the Plan C pools and eliminating the orifice. This increased the number of pools to 12 in the experimental section and reduced the maximum head drop between pools to 0.15 m. The Plan C design was tested with the orifice opened and closed at 0.30 m and 0.15 m of head differential (four seperate test conditions). The Plan E tests were run with average head drop between pools of 0.03, 0.08, and 0.15 m, simulating conditions at John Day Dam at minimum, intermediate, and maximum forebay elevations.

Except for the difference in weir configurations, the procedures for the tests in 1969 and 1970 were basically the same. The ladder sections were lighted by an array of 1000-watt mercury lamps producing 700 footcandles of illumination at the surface. Each test lasted 7 hours during which the upward or downward movement of fish past underwater observatory chambers was recorded on time-scaled chart recorders with eight pens (a separate pen was used for the upward and downward movement of each species). At the final weir, an underwater chamber was situated at the

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[2] Elevations are feet above mean sea level.

orifices and slots so that the number of fish choosing any of the three available exits could be tallied. Fish were allowed to enter the facility continuously for a 6-hour period (5 hours in 1970). The entry gates were then closed, but counts at the upstream or exit stations continued for 1 additional hour in 1969, and 2 additional hours in 1970 so that the tests ran for a total of 7 hours. After the counting was terminated, the facility was drained, and fish that remained in the facility were counted and removed.

A two-way analysis of variance with replication was performed on total percent passage (P) for each test in 1969 [for chinook and sockeye salmon and steelhead P was transformed to arcsine P (Sokal and Rohlf 1981)].

In 1970, to compare the effect of head drop and weir configuration on fish passage, we computed P, the median elasped time (MET) for each species, and the average time per pool. The MET was calculated by subtracting the time at which one-half of the fish had entered the system from the time at which one-half of the fish had left. The average time per pool was determined by dividing the MET by the number of pools (7 or 12). In these tests, the number of American shad swimming back through the final weir was considerably reduced by placing screens around the upstream side of the slots and thereby narrowing the upstream opening; so the MET was considered to be an accurate measurement of passage times. Student's t tests on the differences in the MET were used to compare: (1) the effects of varying head drops (0.30 and 0.15 m in Plan C; and 0.15, 0.08, and 0.03 m in Plan E), (2) the effect of opening versus closing the orifice in Plan C, and (3) the effects of the two weir configurations (C and E).

1978 and 1979 Tests

The procedures for the 1978 and 1979 tests were similar to the earlier tests, with some changes. Fig. 5 shows an overhead view of the test area. The three overflow slots were 0.23 m wide by 0.61 m high and were placed 3.0 m apart (center to center). The orifices were 0.61 m wide by 0.46 m high, 1.5 m apart (inside to inside), and submerged 1.5 m at maximum upstream water level. A 0.3-m head drop was maintained between the upstream and downstream sides of the overflow orifice. The lighting in the building was the same as in 1969 and 1970, except that during the 1979 tests, the submerged orifices were backlighted by hanging a 1000-watt mercury vapor light within 0.3 m of the water surface directly upstream from the weir so that the submerged orifices emitted approximately 4 footcandles of light. This was set up to model the best conditions for salmon passage, as discovered in 1967 orifice tests[3/]. Counting stations were placed over the entry and exit weirs and over the overflow slot (or slots) used for a particular test. Since there was no counting station at either of the submerged orifices, a fish that exited from one of the submerged orifices also had to exit out the final weir to be tallied out. Again, a time-scaled chart recorder was activated from these stations so that upstream or downstream movement could be timed.

We tested each one of the slots separately to determine the effect of the position of the overflow slot on passage. In some of the tests, we attempted to block American shad passage upstream to the submerged orifices by placing an adjustable panel in the center of the test area perpendicular

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[3/] Emil Slatick, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, NOAA, 2725 Montlake Blvd. E., Seattle, WA 98112, per. commun., March 1984.

to the flow with the bottom edge set 0.9 m below the water level. Other tests were run to determine the effects of backlighting the slots and orifices or lighting either upstream or downstream from the center panel. ? In the last three tests, we attempted to straighten out the flow over the overflow slot and possibly provide better orientation for the American shad by attaching a 0.3 m plywood apron, the same width as the slot and parallel to the flow, to the front side of the weir crest. The last two tests incorporated a vertical fillet under this apron in the downstream corner to keep the American shad out from under the apron. In all tests, a head of 0.3 m was maintained between the upstream and downstream water levels.

Counts of fish passing through the submerged orifices were not recorded but counts of fish exiting at Station V were taken, and each test was terminated after 2 hours. The proportions of American shad or salmonids using the slot was computed by dividing the total number in the system by the number using the slot. These proportions were then used to judge the relative efficiencies of the various slot/orifice configurations.

RESULTS

1969 Tests

Measurement of passage times of American shad under the various test conditions was complicated in 1969 by a fallback problem at the final weir. After exiting the test section of the ladder, the American shad entered a large pool, (6 m wide, 10.8 m long, and x 3.3 m deep) and tended to accumulate instead of leaving via the fish exit. As the numbers of fish accumulated in this pool during a test, increasing numbers would either swim or be swept downstream over the final weir and back into the test area. The number of American shad falling back during various tests ranged from 0 to 317, and since observers recording upstream passage at the last weir were unable to distinguish between reascents of fallbacks and ascents of fish released at the downstream end of the ladder, it was impossible to accurately measure passage time within the ladder. Therefore, the relative efficiencies of the various weir configurations used in the 1969 tests were judged by comparing the total percent passage (P) for each species, which was determined by dividing the number of fish exiting the system by the total number of fish entering the system (sum of number released at downstream end plus fallbacks from the upper pool).

The averaged percent passages (through the various orifices at the last weir and overall) for each species tested in 1969 are shown in Tables 1 and 2. The effects of weir design and flow on American shad passage are clear. The overflow or slot-type weirs (surface passage) were much more effective than the orifice-type weirs (submerged passage) and the 0.22 m of head was more effective than the 0.30 m of head. The smallest percent passage (17.2%) occurred with the original John Day Dam design (W_1) operating with 0.30 m of head, whereas the most effective passage (79.7%) was obtained with the W_3 design operating at 0.23 m of head.

Passageways used by the American shad at the last weir varied between test conditions, but when given the choice, the American shad preferred exits with surface flow (Orifice C in W_2 design and Slots C and D in W_3 design). In W_1 tests, there was a large difference between the routes chosen by the American shad when the ladder was operated at different flow conditions. With 0.30 m of head on the weirs, only 1.5% of the American shad (8.6% of the total passage) used the center orifice (C). When the head was reduced to 0.23 m 27.5% (53% of the total) selected the center orifice. However, differences between the passage routes were not as great when the other two weir configurations were operated with 0.23 or 0.30 m of head. The 0.30 m head drop through the shallow orifice in the W_1 configuration apparently created a flow large enough to almost completely block American shad passage, whereas the flows created by the same head drop through the overflow orifice (slots) in W_2 or W_3 were not large enough to impede the American shad.

In both W_1 and W_2 designs, the discharges through the submerged orifices created strong reverse surface flows in the corners of the pools to which the American shad would orient for a considerable amount of time before finding the orifice passage to the next pool. In the W_3 design, however, the overflow weirs produced surface flows that directed shad upstream to the next pool.

The results of the two-way analysis of variance (with replication) performed on P for each test are shown in Table 3. The main effects of flow and weir design on American shad passage were highly significant; however, the interaction mean square was also significant, implying that the effects of flow varied for each of the three designs. The lower flow increased shad passage through the ladder sections in all three designs, but the effect was not as great in the W_2 tests, as shown by the response curves in Fig. 6. Without interaction, the curves for the two head drops would be parallel to each other.

The effects of flow on total passage were not significant for the three species of salmonids tested, and variations in weir design were significant only for chinook salmon. Percent passage of all three species ranged from 93.3 to 100%. In all of the W_1 and W_2 tests, except W_2 at 0.30 M, the percent passage for chinook salmon, sockeye salmon, and steelhead through either of the submerged orifices (A or B) was greater than that through the shallow orifice. Although percent passage was over 99% for sockeye and chinook salmon during the W_2 test at 0.30 M tests, both species showed a preference for the shallow orifice (C) instead of the submerged orifices. At the lower flow condition there was a shift back to the submerged orifices.

1970 Tests

The percent passage through the various Plan C conditions ranged from 95.9 to 100% for salmonids, and from 84.2 to 97.4% for American shad. At the last weir, a larger percentage of all species used the slot over the orifice in Plan C tests in which both were available (Table 4). Under Plan E conditions, the average percent passage ranged from 96.4 to 99.9% for salmonids and from 81.2 to 100% for American shad (Table 5).

As expected from the 1969 tests, the lesser head drops in both designs significantly decreased the MET for all species and markedly so for American shad. Lowering the head in both wier designs also decreased the MET for all the salmonid species (Table 6). During Plan E tests with minimum head differential (0.03 m), American shad passed through the test section as fast as the sockeye and faster than chinook or steelhead but were slower than the other species at the intermediate and high flow conditions.

Opening the orifice in the Plan C tests did not significantly affect the MET for any species at the high flow conditions (Table 7). However, at the low flows the the MET for American shad was significantly less with the orifice closed. American shad was the only species for which the MET was consistently less with the orifice closed. The MET for steelhead was significantly decreased by opening the orifice at the low flow but there was no significant difference at the high flow. It is possible that the orifice created better attraction currents for the steelhead at the lower flows.

As stated earlier, both the Plan C and Plan E ladders were designed to occupy the existing orifice control sections at John Day Dam and provide the same flow regulation throughout the normal range of forebay levels. Therefore, to test the relative efficiencies of the two ladder designs we compared the MET's of the various species at flow conditions approximating a maximum and intermediate forebay level at John Day Dam (elevations 268 and 263, respectively).2/ Under the former conditions, the fish ascended a 2.13-m rise in 7 pools in the Plan C ladder and a 1.86-m rise in 12 pools in the Plan E ladders. At intermediate forebay levels, the fish ascended a 1.07-m rise in 7 pools in the Plan C ladder and a 0.91-m rise in 12 pools in the Plan E ladder.

Fig. 7 shows a comparison of the MET's of Plan C and Plan E for all four species. The MET for American shad in the Plan E design was less than in either of the two Plan C designs at both forebay levels. Although the t-values were not significant, American shad were the only species for which the MET for one design was lower at both forebay levels (Table 8). There were no species for which statistically significant differences in the METs between the two plans held true at both forebay levels. For example, at the intermediate forebay level the MET for chinook salmon in the Plan E design was significantly faster than in either of the two Plan C designs; whereas, at the maximum forebay level, this was reversed and the METs for both the Plan C designs were less than in Plan E. The t-value's for 16 different comparisons between Plan C and Plan E tests (4 species x 2 forebay levels x 2 Plan C designs). As shown, only five of these comparisons are significant (P = 0.05), yet in all five of these cases it is the Plan E design that is significantly better than one or the other of the two Plan C designs. The decrease in head drop per pools apparently compensated for the increase in the number of pools which had to be negotiated.

1978 and 1979 Tests

The tests done in 1978 and 1979 were meant to give preliminary results which could be used to ascertain what configurations of slots and orifices held the most potential for success in separating American shad from salmonids. In 1979, by the time we were able to initiate these tests, the number of American shad migrating through the Bonneville ladder was rapidly decreasing. Since we wanted to try as many different configurations and conditions as possible in 2 weeks, none of the tests were replicated and the results indicate only the direction future tests should pursue. In the winter of 1979-80, the Fisheries Engineering and Research Laboratory at Bonneville Dam collapsed under a large snow load and was not rebuilt, so it has been impossible to repeat the tests which showed some success or to try further modifications of the basic designs.

Fig. 8 shows the results of the nine tests run in 1978 and 1979 (refer to Fig. 5 for location of center panel, slots, and orifices). The only tests in which a large percentage of the American shad (87 to 95%) and a fairly small percentage of salmonids passed out of the overflow slot were

Tests 4, 5, and 6 (in all of these tests, 100% of the salmonids counted into the test area exited past counting Station V therefore, when exiting those not using the overflow slot passed through one of the submerged orifices). As expected, these tests again indicated American shad were more willing to pass through overflow slots than submerged orifices. Here again, currents and eddies created by water flowing through the submerged orifices seemed to orient the American shad away from the center slot and greatly reduce passage, and the downstream slot (with directional flow along the downstream wall) seemed to provide the best passage for American shad. The best results were obtained in Tests 4 and 6 in which only the downstream slot was open. Although good results were obtained when the center panel was down (at 0.9 m), its overall effectiveness was not clear. In all of the tests with the panel down, large numbers of American shad could be seen on the upstream side of the wall--even in Tests 4 and 6 when ultimately a large percentage of the American shad did pass out the overflow slot (downstream of panel). Apparently, because of the velocities involved, the submerged orifices impeded American shad passage, but the large submerged horizontal slot created by the panel did not.

Neither the weir crest apron (used in Test 6, 7, 8, and 9) nor the corner fillet (used in Tests 8 and 9) produced the desired effects. Although the apron did straighten the flow out, the American shad were reluctant to swim the extra distance to negotiate the crest and tended to congregate under the apron. The fillet was then installed under the apron to remove this santuary, but passage through the slot was still not improved. We had hoped that the apron would provide a shallow stream of water directly in front of the weir crest would impede sockeye salmon passage, but in Test 9 (with the apron), P for sockeye increased.

DISCUSSION AND CONCLUSIONS

The reluctance of American shad to pass through the submerged orifices in the flow control section of the John Day Dam fish ladders necessitated the redesign of the facilities. The 1969 and 1970 tests were initiated to develop a satisfactory model of these sections which could be incorporated into this new design. These studies showed the following: (1) American shad orient towards the surface flow in a ladder system, and in the original John Day design the submerged orifices created a rather strong reverse surface current which directed the American shad into a blind corner; (2) American shad passage could be increased many fold by providing overflow or slot-type passage with directional flows along a wall; (3) velocities in the overflow slots were also critical to passage times for shad--doubling the head drop between weirs (from 0.15 m to 0.30 m) more than doubled the median elapsed time in the 1970 tests; (4) passage through the ladder system for the three species of salmonids tested (chinook and sockeye salmon and steelhead) was not adversly affected by the slot-overflow type orifice with or without the submerged orifice. On the basis of the 1970 tests, we concluded that installation of either a Plan C or Plan E control section would resolve the passage problem with American shad at John Day Dam.

While these fish behavior studies were being conducted, the COE Portland Division ran tests on the hydraulic aspects of the new designs at the Bonneville Hydraulic Laboratory indicating that a slot type weir design (specifically Plan E) would provide satisfactory flow regulation. Therefore, with the concurrence of state and federal fisheries agencies the Plan E design was installed in the flow control section of the south fish ladder at John Day Dam in 1970. An evaluation study was made by NMFS under contract with the COE during the 1971 fish runs (Weaver et al. 1972). In these tests, the slot-type section passed an average of 94.4% of the salmonids [chinook, sockeye, and coho salmon (*O. kisutch*) and steelhead]; 73.1% of the American shad; and 91.7% of other species [suckers (*Catostomus* spp), northern squawfish (*Ptyhocheilus oregonenis*), common carp (*Cyprinus carpio*), chiselmouth (*Acrocheilus alutaceus*), etc.] that were counted at a COE counting station located at the lower end of the ladder. The MET for all species of salmonids and American shad was less in the new regulating section than in the unmodified overflow section.

Although installation of slot-type weirs in the regulating section of John Day Dam greatly increased American shad passage and therefore alleviated most of the accumulation problems, there are other situations where the almost complete elimination of American shad from the ladder system would be desirable (i.e., in the counting sections of fish ladders, in ladders used for trapping other species for egg bank or tagging studies, or in entries to salmon hatcheries). In a few of the 1978 and 1979 tests, we were able to partially accomplish this through an overflow slot by shunting between 85 and 95% of the American shad into a separate ladder; unfortunately, under some conditions salmonid species (especially sockeye salmon) also had a propensity to use the overflow slot. During the tests, sockeye salmon made up 50% of the total salmonids using the north shore ladder, and of the three species of salmonids tested in 1970 tests, sockeye salmon were the most willing to use an overflow slot when given a choice between it and a submerged orifice. Because of time delays, we were not able to run the 1979 tests at lower velocities, which likely would have achieved better separation.

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The next possible step in achieving separation would seem to be a series of pools set up as in Tests 4 or 6, with all of the submerged orifices leading to one pool. If separation was similar to that achieved in the 1980 tests, by the fourth pool at least 96% of the salmonids would be separated from the American shad. It is obvious that further tests along these lines need to be done before conclusive statements can be made, yet the methods we employed in these tests do indicate a potential for almost complete separation of American shad from salmonids within a fish ladder.

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Table 1.--Percent passage through each orifice, total percent passage (P) with the standard deviation (SD, n-1) at the final weir in 1969 tests (W_1 and W_2 designs). Weighted means of two or three replicates.

Head drop (m)	Species	No.	Orifice A (submerged) %	Orifice B (submerged) %	Total (A+B)	Orifice C[a/] (shallow) %	Total passage (P) (A+B+C) %	SD (n-1)
W_1 - Original John Day design								
0.23[b/]	Chinook	140	51.8	31.7	83.5	15.8	99.3	1.1
	Sockeye	345	50.7	41.0	91.7	7.7	99.4	0.3
	Steelhead	110	45.5	41.8	87.2	11.8	99.1	1.7
	Shad	807	9.5	14.9	24.4	27.5	51.9	10.4
0.30[c/]	Chinook	345	43.4	36.7	80.1	19.0	99.1	1.0
	Sockeye	732	36.2	33.5	69.7	29.8	99.5	3.1
	Steelhead	125	44.4	34.9	79.3	18.3	97.6	1.5
	Shad	550	9.0	6.7	15.7	1.5	17.2	5.2
W_2 - Center orifice enlarged								
0.23[b/]	Chinook	182	61.6	25.8	87.4	12.6	100.0	0.0
	Sockeye	42	57.1	26.2	83.3	16.7	100.0	0.0
	Steelhead	687	62.7	35.4	98.1	1.6	99.7	0.5
	Shad	131	19.7	6.8	26.5	25.8	52.3	1.1
0.30[c/]	Chinook	285	27.0	21.1	48.1	51.5	99.6	0.6
	Sockeye	112	17.9	26.8	44.7	54.4	99.1	7.0
	Steelhead	449	52.3	43.0	95.3	4.0	99.3	0.6
	Shad	116	11.9	2.5	14.4	26.3	40.7	1.9

[a/] Orifice C was completely submerged (1.5 and 0.05 m, respectively) in the W design at both head drops; and was partially exposed (overflow condition) in the W_2 design at both head drops.

[b/] Two replicates.

[c/] Three replicates.

Table 2.--Percent passage through each orifice and slot, and total percent passage (P) with standard deviation (SD, n-1) at the final weir in 1969 tests (W_3 - Orifice-side slot combination). Weighted means of two replicates.

Head (m)	Species	No.	Orifice A (submerged) %	Orifice B (submerged) %	Total (A+B)	Slot C %	Slot D %	Total (C+D)	Total passage (P) (A+B+C+D) %	SD (n-1)
0.23	Chinook	268	39.3	35.9	75.2	18.5	4.1	22.6	97.8	0.0
	Sockeye	206	40.1	36.7	76.8	13.0	9.7	22.7	99.5	0.0
	Steelhead	461	54.6	38.1	92.7	3.9	3.0	6.9	99.6	0.9
	Shad	528	4.7	5.4	10.1	39.7	29.9	69.6	79.7	2.4
0.30	Chinook	148	32.9	38.3	71.2	22.1	0.0	22.1	93.3	4.0
	Sockeye	138	34.8	30.4	65.2	22.5	11.6	34.1	99.3	0.6
	Steelhead	256	47.8	33.3	81.1	14.9	1.6	16.5	97.6	1.1
	Shad	813	5.0	4.2	9.2	34.8	16.7	51.5	60.7	12.3

Table 3. Results of two-way analysis of variance on total percent passage (P) for each species in 1969 tests. Asterisks denote $P < 0.01$* or $P < 0.001$**.

Source of variation (d.f.)	Shad[a]		Chinook [b]		Sockeye[b]		Steelhead[b]	
	M.S.	F	M.S.	F	M.S.	F	M.S.	F
Flow (1,12)	0.22	52.38**	15.44	0.83	62.09	2.39	27.53	1.83
Weir (2,12)	0.18	42.86**	88.22	4.73*	3.96	0.15	18.90	1.25
Interaction (2,12)	0.03	7.14*	0.455	0.24	9.96	0.38	14.26	0.95
Error	0.0042		18.66		25.98		15.08	

[a] Without transformation of P

[b] P transformation = arcsin P

[c] M.S. designates mean square value.

Table 4.--Percent passage, median elapsed time (MET)and average time per pool for chinook and sockeye salmon, steelhead, and American shad tested in 7-Pool Plan C tests (weighted means of two replicates).

Head drop per pool (m)		Species	No. of fish tested	Percent passage (P)	MET (minutes)	MET SD	Time/pools (minutes)	SD	Percent of passage using slot (at last exit)
Orifice & slot	0.15	Chinook	69	100.0	23.0	5.0	3.3	0.7	71.3
		Sockeye	455	99.6	17.5	6.5	2.3	0.9	57.7
		Steelhead	54	100.0	10.4	3.1	1.5	0.5	85.4
		Shad	1,211	96.9	42.0	2.0	6.0	0.3	99.9
	0.30	Chinook	146	98.3	29.0	10.0	4.1	1.4	77.2
		Sockeye	408	98.0	39.5	13.5	5.6	1.9	87.7
		Steelhead	63	100.0	76.0	-	10.9	-	97.4
		Shad	1,615	84.2	100.0	12.0	14.3	1.7	100.0
Slot only	0.15	Chinook	53	100.0	16.0	0.5	2.3	0.1	
		Sockeye	317	99.7	15.5	7.5	2.2	1.1	
		Steelhead	41	100.0	49.0	-	7.0	-	
		Shad	910	97.4	35.3	0.2	5.04	0.0	
	0.30	Chinook	66	98.5	23.5	0.5	3.4	0.1	
		Sockeye	470	96.4	64.0	10.0	9.14	1.4	
		Steelhead	49	95.9	64.5	14.5	9.2	2.1	
		Shad	1,789	90.6	89.5	20.5	12.8	2.9	

Table 5.--Percent passage, median elapsed time (MET), and average time per pool for chinook and sockeye salmon, steelhead, and American shad tested in 12-Pool Plan E tests under three flow conditions (weighted means of four or five replicates). Standard deviations (SD) are also shown.

Head drop per pool (m)	Species	No. of fish tested	Percent passage (P)	MET (minutes)	SD	Time/pool (minutes)	SD
0.03[a]	Chinook	176	99.4	22.2	12.6	1.85	1.05
	Sockeye	557	99.6	14.4	6.2	1.20	0.52
	Steelhead	224	96.9	17.9	2.2	1.49	0.18
	Shad	266	100.0	14.9	12.6	1.24	1.05
0.08[a]	Chinook	306	98.4	9.8	3.2	0.82	0.26
	Sockeye	1,126	99.9	21.0	8.7	1.75	0.72
	Steelhead	250	98.4	19.4	11.1	1.62	0.92
	Shad	318	96.9	33.0	6.74	2.75	0.56
0.15[b]	Chinook	437	97.3	40.9	10.8	3.41	0.89
	Sockeye	1,295	99.2	43.8	7.6	3.65	0.63
	Steelhead	332	96.4	26.5	7.8	2.21	0.65
	Shad	597	81.2	87.6	18.8	7.30	1.56

[a] Four replicates.

[b] Five replicates.

Table 6.--Pooled t-tests for significant differences in median elapsed times (MET) for two head differentials in Plan C and Plan E tests. Asterisks denote P < 0.05* or P < 0.01**.

Plan C (0.15 m vs 0.30 m)				Plan E (0.08 vs 0.15 m)			
Species	d.f.	t[a]	1-tail probability	Species	d.f.	t[a]	1-tail probability
Chin	6	-1.29	0.122	Chin	7	-4.92	0.001**
Sockeye	6	-3.30	0.008**	Sockeye	7	-3.71	0.004**
Steelhead	4	-2.83	0.024*	Steelhead	7	-0.98	0.180
Shad	6	-4.74	0.002**	Shad	7	-4.88	0.001**

[a] Negative values mean faster MET at the lesser head drop.

Table 7.--Pooled t-tests for significant differences in median elapsed times (MET) for slot and orifice versus slot only at 2 head drops in Plan C. Asterisks denote $P < 0.05$* or $P < 0.01$**.

	0.30 m head drop			0.15 m head drop		
Species	d.f.	t[a]	1-tail probability	d.f.	t[a]	1-tail probability
Chinook	2	-0.55	0.319	2	-1.37	0.152
Sockeye	2	1.46	0.859	2	-0.20	0.430
Steelhead	1	-0.46	0.363	2	7.19	0.991**
Shad	2	-0.44	0.351	2	-3.34	0.040*

[a] Positive t value denotes a faster MET for slot and orifice design, negative t value denotes a faster MET for slot only design.

Table 8.--Pooled t-tests for significant differences in median elapsed times (MET) for Plan C tests versus Plan E tests at flows that would be generated by maximum (268 ft above mean sea level) and intermediate (263 ft above mean sea level) forebay levels at John Day Dam. Asterisks denote $P < 0.05$* or $P < 0.01$**.

Forebay water level	Species	Plan C (Slot only) vs. Plan E			Plan C (slot and orifice) vs. Plan E		
		d.f.	t[a]	1-tail probability	d.f.	t[a]	1-tail probability
Maximum							
	Chinook	5	-1.92	0.056	5	-1.14	0.153
	Sockeye	5	2.44	0.971*	5	-0.45	0.336
	Steelhead	5	3.77	0.993**	4	5.18	0.997**
	Shad	5	-0.10	0.538	5	0.73	0.751
Intermediate							
	Chinook	4	2.22	0.954*	4	3.16	0.983*
	Sockeye	4	-0.62	0.284	4	-0.41	0.351
	Steelhead	3	2.07	0.935	4	-0.93	0.203
	Shad	4	0.39	0.642	4	1.51	0.897

[a] Negative t values denote a faster MET for Plan C, positive t values denote a faster MET for Plan E.

FIGURE CAPTIONS

Figure 1.--Maps of Columbia and Snake Rivers.

Figure 2.--Relationship of the U.S. Army Corps of Engineers Fisheries-Engineering and Research Laboratory to the north shore fish ladders at Bonneville Dam.

Figure 3.--The three weir configurations used in the 1969 tests. Letters A through D designate the various orifices or slots.

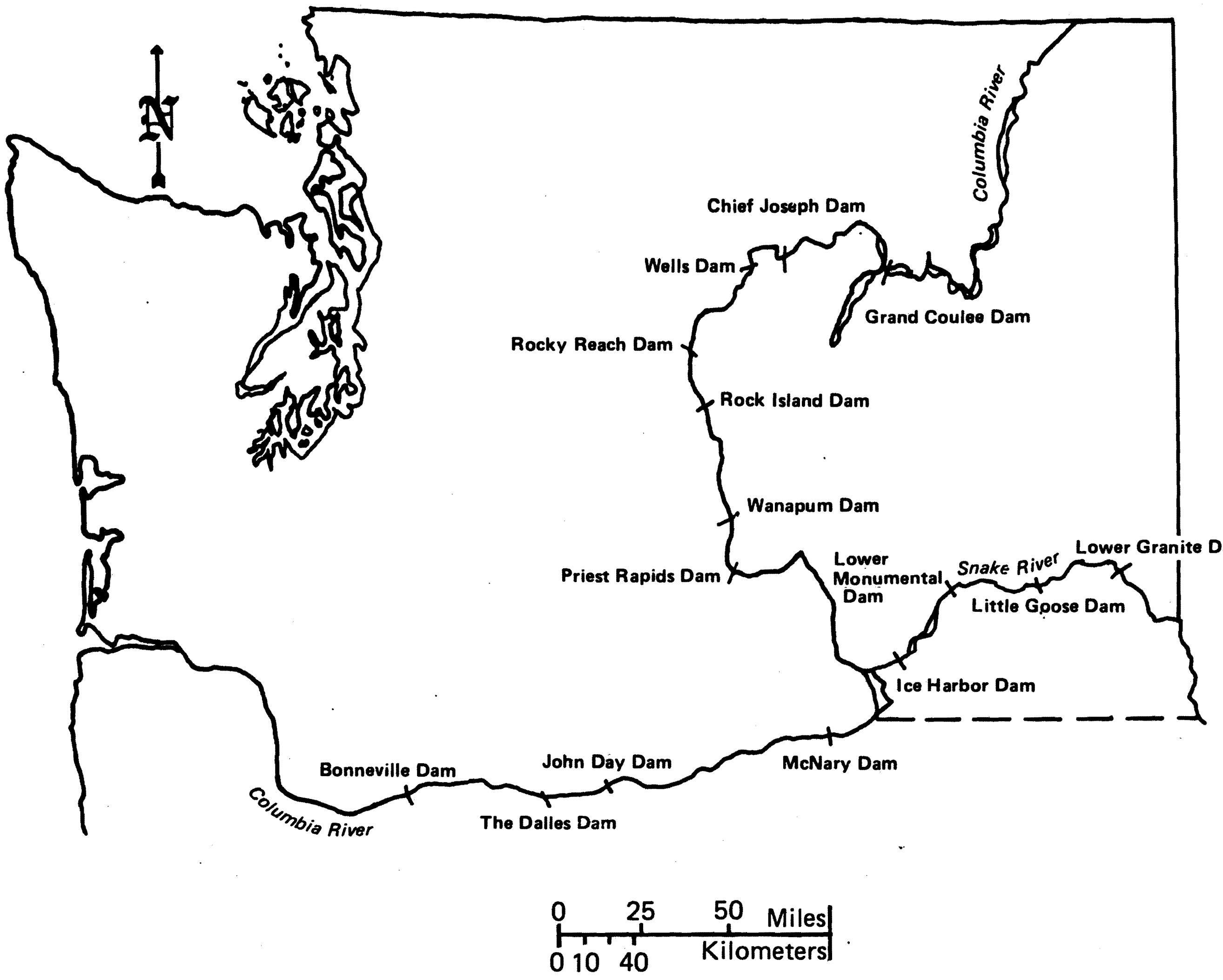
Figure 4.--Overhead views of the Plan C and Plan E fish ladders tested in 1970.

Figure 5.--Overhead view of test area used for 1978 and 1979 tests. Roman numerals I through V designate counting stations.

Figure 6.--Percent passage (P) of American shad through the three weir designs (W_1, W_2, and W_3) at two head drops during 1969 tests.

Figure 7.--Comparisons of averaged median elapsed times (MET) required by the various species to negotiate the Plan C (7 pools) and Plan E (12 pools) test sections under simulated maximum and intermediate forebay levels.

Figure 8.--Bar graph of percent of shad and salmonids (chinook and sockeye salmon, and steelhead) exiting overfall slots and the test conditions used in 1979. Head drop of 0.30 M was maintained for all tests.



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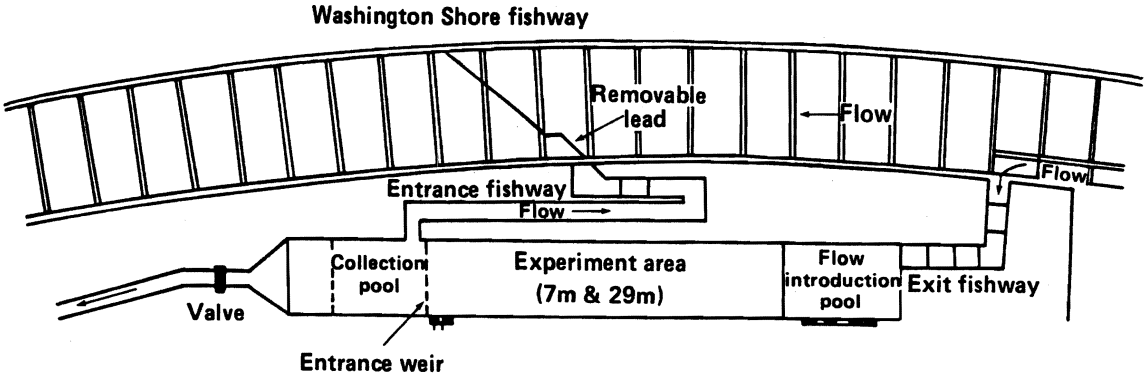

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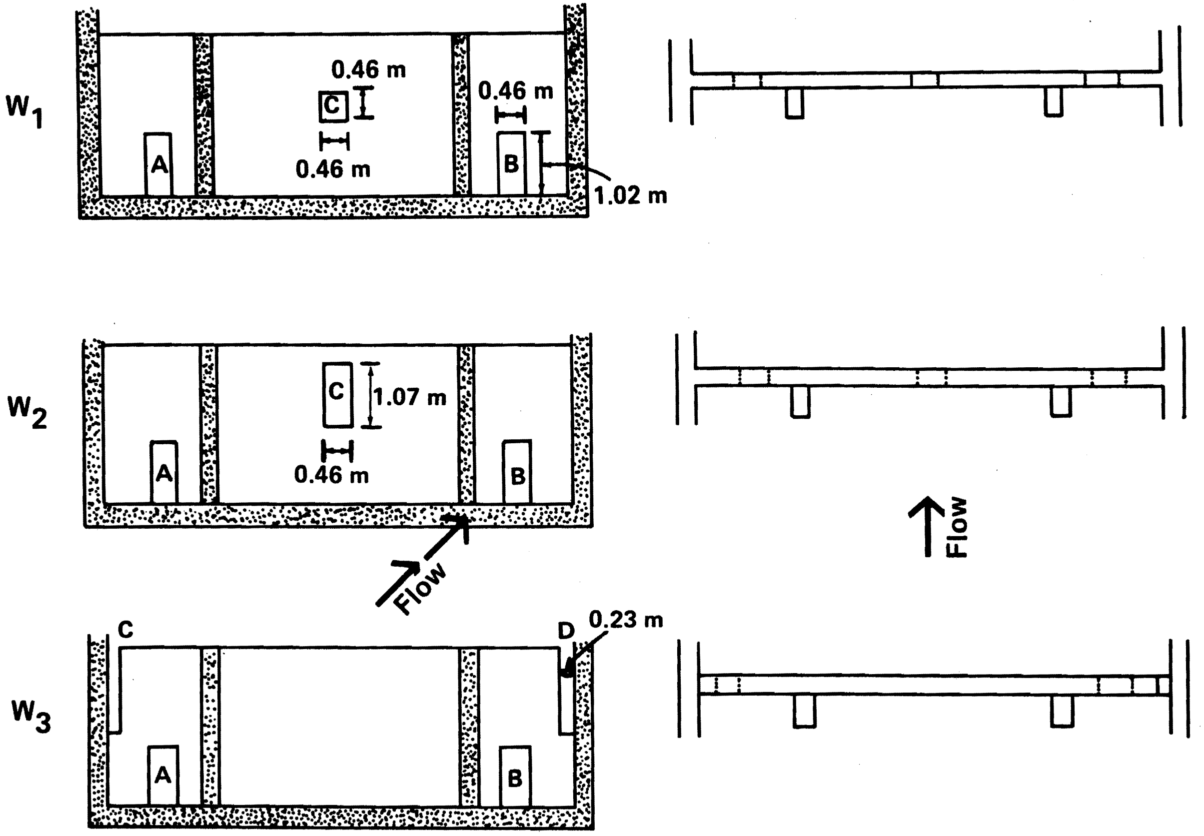

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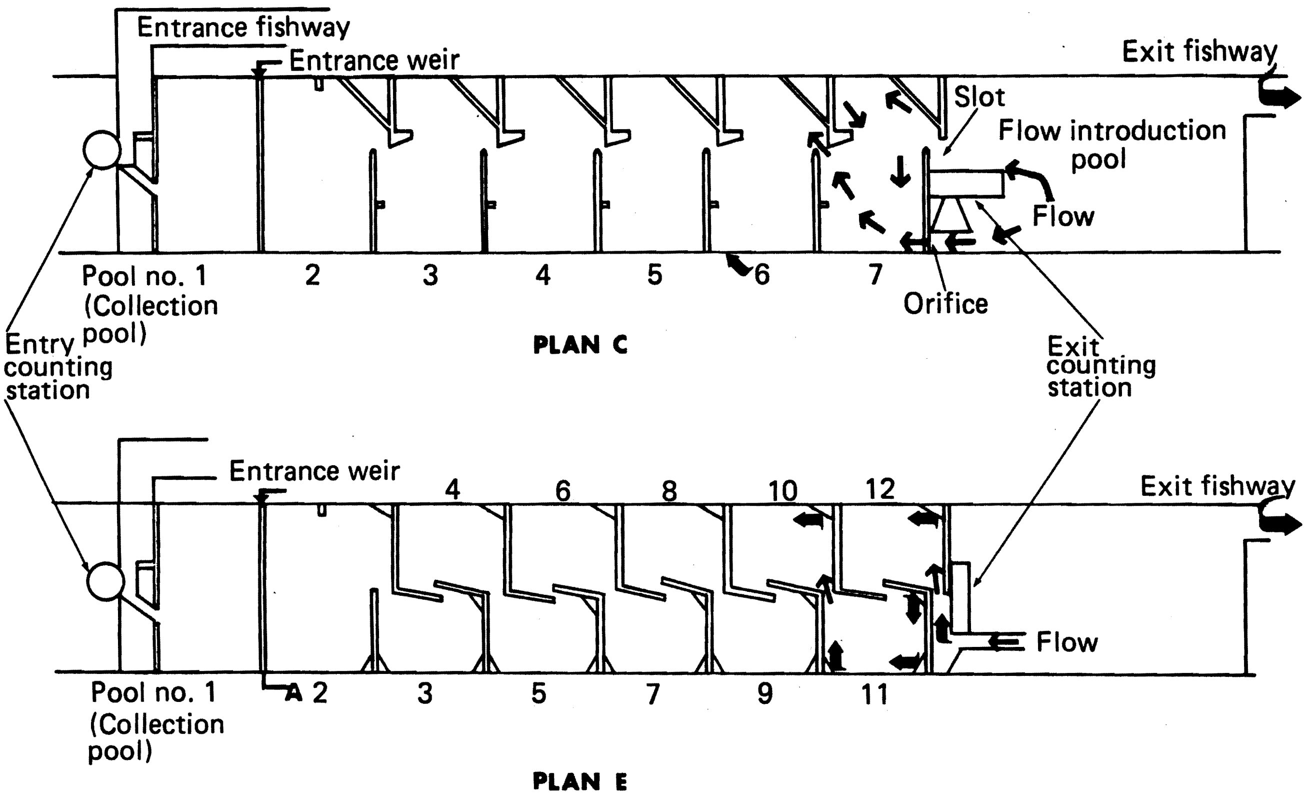

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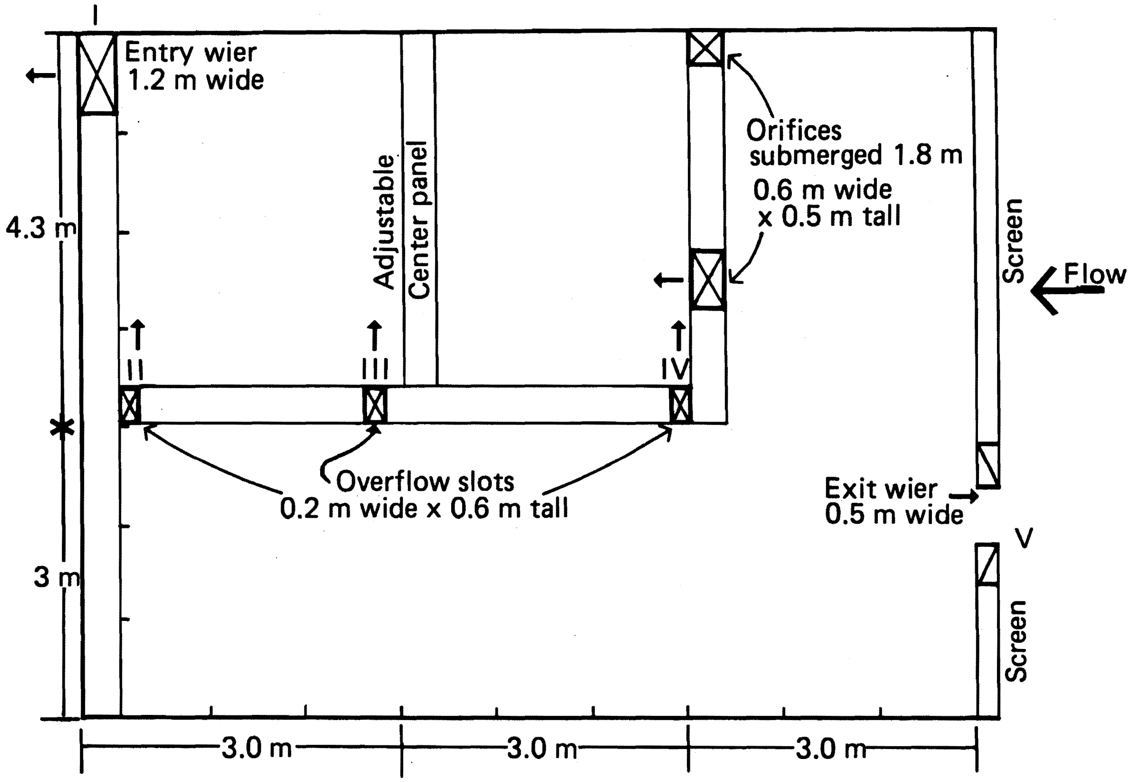

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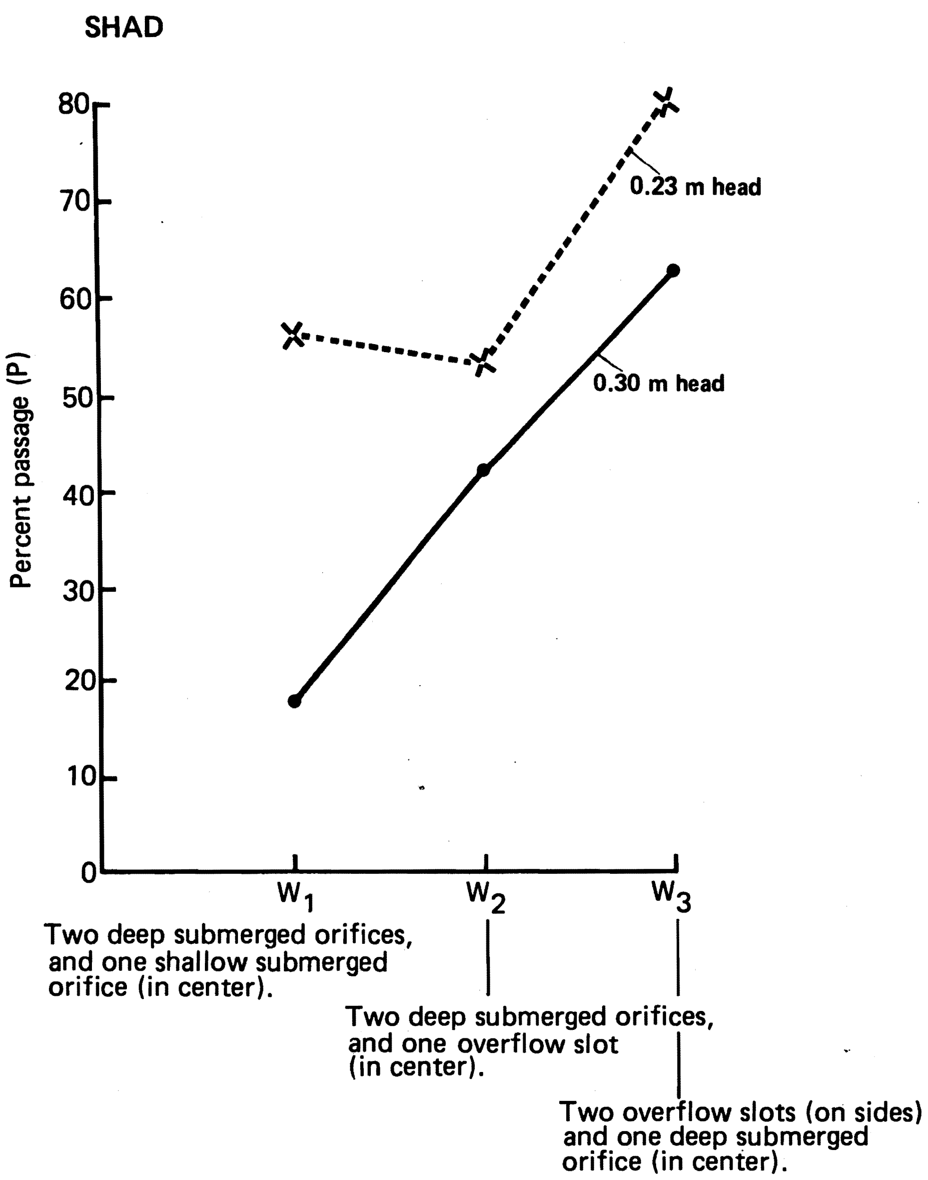

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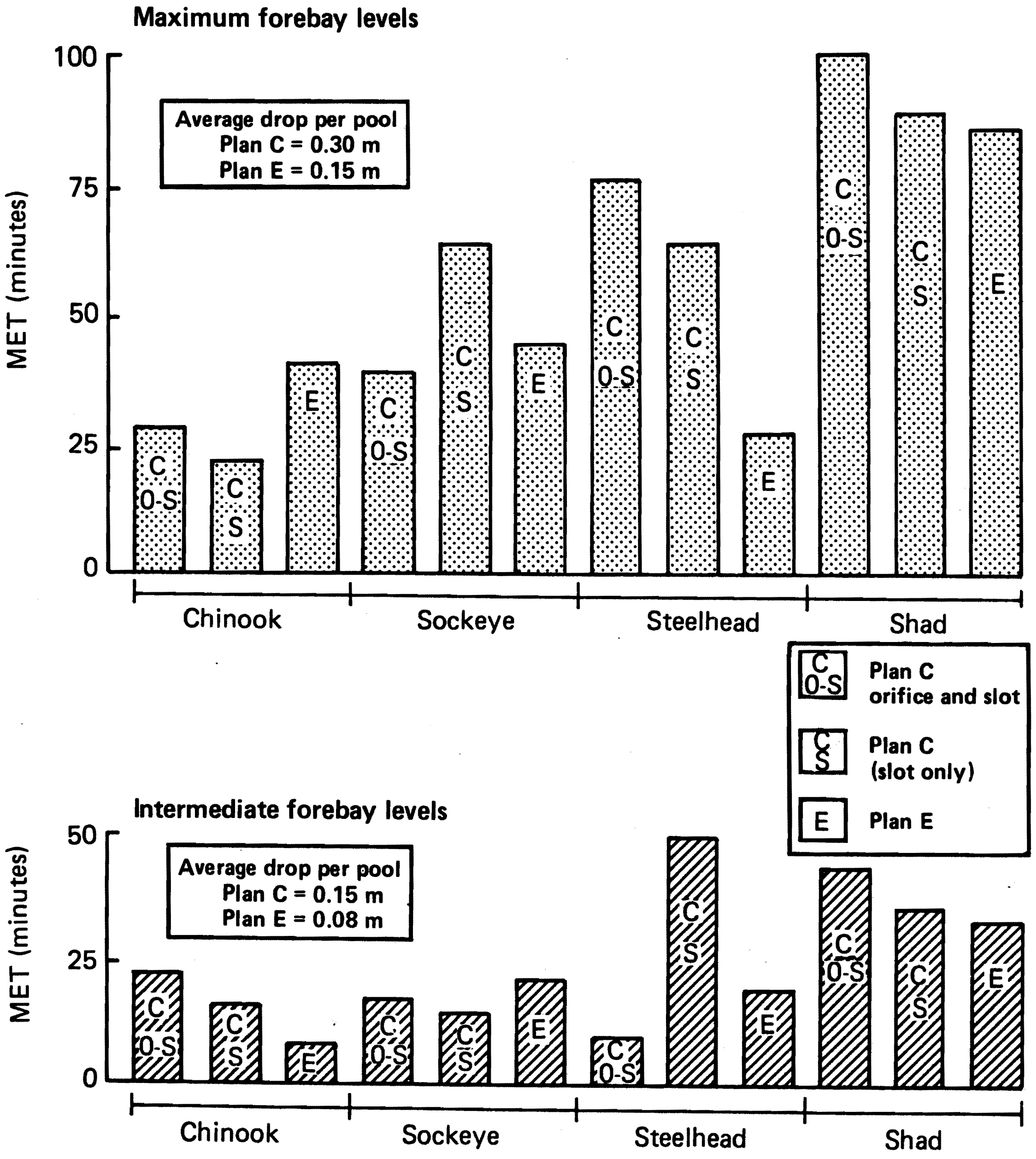

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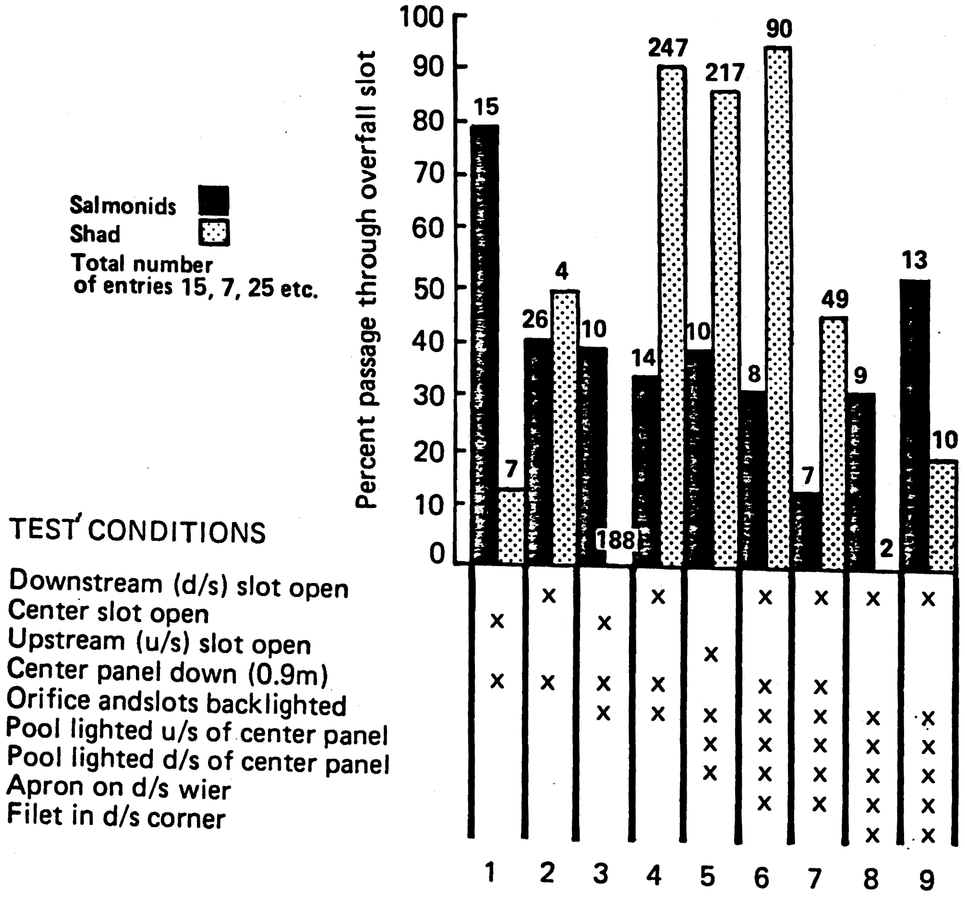

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