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Laboratory Studies of Screens for Diverting Juvenile Salmon and Trout from Turbine Intakes

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ABSTRACT

Fish-guiding screens of different porosities were tested with juvenile spring chinook salmon (*Oncorhynchus tshawytscha*) in a laboratory model that simulated a turbine intake and gatewell (a vertical shaft in a dam that extends from the forebay deck to the ceiling of the intake). The study was part of a program to develop methods for preventing mortality of juvenile salmon and steelhead trout (*Salmo gairdneri*) in Kaplan turbines of low-head dams on the Columbia and Snake Rivers. If large numbers of juvenile fish could be guided into gatewells, a method of safely bypassing them around turbines might be devised.

Three types of screens (wood, and single and double layers of spiral-weave conveyor belt) were attached to the intake ceiling at an angle of 45° to the flow; their lengths were adjusted to intercept one-third or two-thirds of the total flow into the intake. The screen with the greatest porosity (constructed of a single layer of belting) gave the highest guiding efficiency; 87% of the test fish were diverted into the gatewell. We believed that water deflected under the screen carried fish with it, but our tests indicated that some fish swam upwards out of the flow and into the gatewell.

Diversion of 3% of the intake flow up through a gatewell with a single opening into the intake increased the guiding efficiency of only the double-layer screen. Diversion of flow through a gatewell with two openings caused a significant percentage of the guided fish to leave the gatewell and reenter the intake.

INTRODUCTION

The loss of juvenile salmon (genus *Oncorhynchus*) and steelhead trout (*Salmo gairdneri*) in the Columbia and Snake Rivers is increasing each year as the number of dams continues to increase. Eventually, when all river flow is controlled by dams, offspring of some important runs will have to pass through or around the turbines of 8 to 10 low-head dams to reach the Pacific Ocean. The loss of juvenile fish passing through turbines at a dam may be as great as 11% (Schoeneman, Pressey, and Junge, 1961; Long and Marquette, 1967).

One solution to the problem is to provide the fish with safe bypasses around the turbines. The general approach pursued by the NMFS (National Marine Fisheries Service) was proposed by Long (1961), after he showed that 70% of the downstream migrants were concentrated within 4.6 m of the ceilings of the turbine intakes (Long, 1968). Interception of a small portion of the river flow with a device for guiding fish might result, therefore, in the diversion of a large percentage of the fish into intake gatewells (vertical shafts that extend from the forebay deck of the dam to the ceiling of the intake; the shafts are slotted to receive gates that stop the flow while turbines are being inspected or repaired). Fish then would be passed through an orifice into ice sluices or special bypasses for transport to the tailrace (Figure 1).

Long and Marquette (1967) proposed the use of a traveling screen to divert fish from turbine intakes into gatewells. To obtain basic information for the design of a suitable fish-guiding device, the NMFS constructed a model to simulate a segment of a turbine intake and gatewell and placed it in the Fisheries-Engineering Research Laboratory at Bonneville Dam on the Columbia River. Diversion equipment tested in this structure included baffles and expanded metal plates to modify flows and fish behavior (Weaver, Slatick, and Thompson, 1966; Weaver, Marquette, and VanDerwalker, 1967; VanDerwalker, 1970), lights to attract fish (Weaver, Slatick, and Thompson, 1966), and screens to separate fish from intake flows by forcing them to enter a gatewell (Weaver, Marquette, and VanDerwalker, 1967). The present paper reports on tests with stationary screens installed in the model. We measured the guiding efficiency of screens as

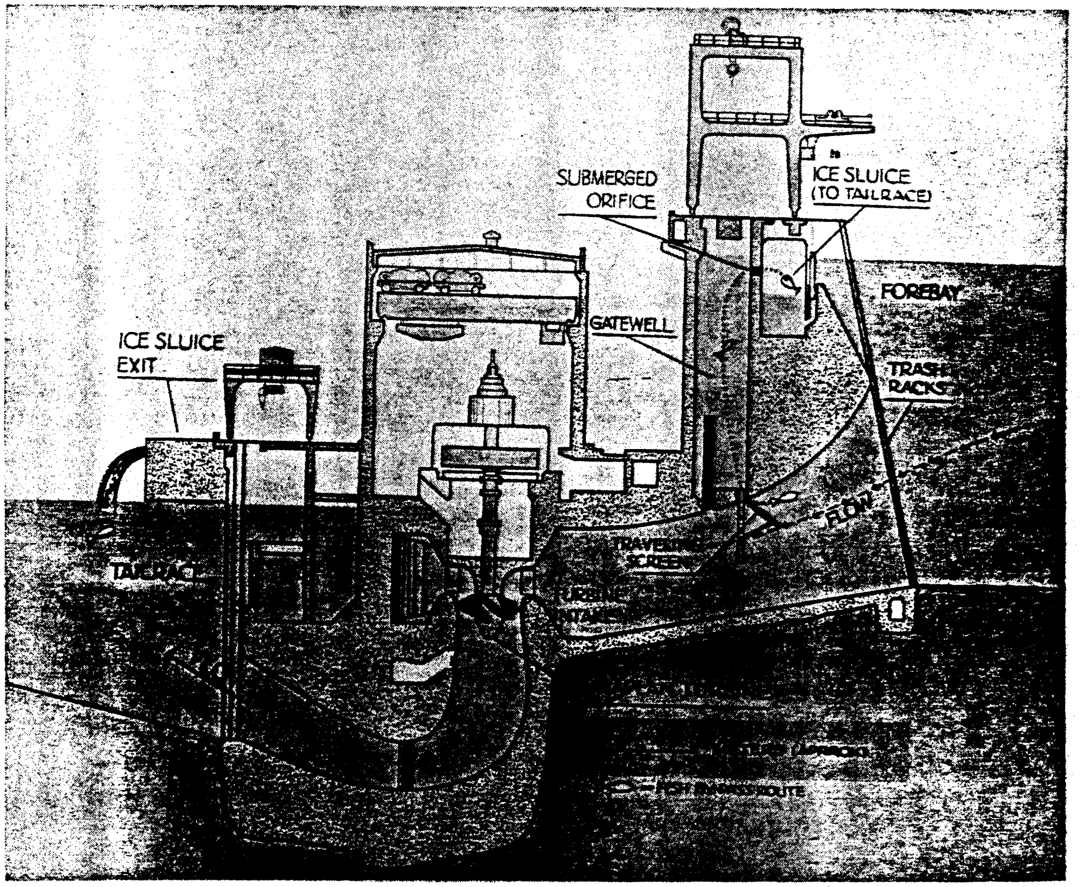

FIGURE 1.—Typical low-head dam with proposed traveling screen for guiding downstream-migrating juvenile salmon and trout into gatewells.

affected by: (1) screen porosity, (2) fish behavior, and (3) gatewell design. We also determined the percentage of fish that re-entered the turbine intake from one type of gatewell.

FACTORS IN PROTOTYPE TURBINE INTAKES AND GATEWELLS THAT MAY AFFECT FISH GUIDANCE

The test structure, or model, simulated three important features common to prototype intakes and gatewells: (1) the general design, (2) illumination and water pressure near the entrance to the gatewells, and (3) water velocities in the turbine intakes and flow patterns in the intakes and in the gatewells. The possible effects of these conditions on fish behavior in the prototype structure and the reasons for their consideration in the design of the model are reviewed below. In these experiments, we examined: (1) the potential changes in guiding efficiency of screens caused by hypothetical changes in the normal flow patterns that accompany changes in screen porosity, and (2) the potential increase in guiding efficiency of screens due to (a) the behavior of migrating fish subjected to increased pressure within intakes, and (b) the deliberate diversion of flow through the gatewell.

Factors Influencing Design of Model

Five factors that could influence the behavior of fish were considered in the design of the model: (1) general design, (2) design of intake gatewells, (3) light, (4) pressure, and (5) velocity and pattern of flow.

1. General design of the turbine intakes. The curvature of the ceiling controls the rate

of increase in pressure that fish are subjected to (and to which they may react) as they travel through the intakes. Although turbine intakes of low-head dams on the Columbia and Snake Rivers vary in overall dimensions, all intake ceilings have a curvature similar to that shown in Figures 1 and 2.

2. The design of intake gatewells. Because the gatewell is the area into which fish are to be guided, the hydraulics at the entrance of the gatewell could influence the behavior of fish. Two types of gatewells are commonly used in low-head dams. One type has a single opening in the ceiling of the intake (type 1, Figure 2) and a second type has two openings (type 2, Figure 2).

3. Illumination. Light near the entrance to the gatewell may affect the diversion of fish from the intake into the gatewell. At all low-head dams on the Columbia and Snake Rivers, the opening is downstream from the mouth of the intake at water depths of 8.7 to 29.8 m. The transmission of light is poor in these two rivers during the period of migration of juvenile salmon and trout. At McNary Dam, on the main Columbia River 51 km below the confluence of the Snake and Columbia Rivers, average Secchi disc readings (1963–67) ranged from 0.4 to 1.2 m. Because of the depth and location of the opening and the natural turbidity of the water, we assume the fish near the entrance of the gatewells are in almost total darkness.

4. Pressure. The pressure near the entrance to the gatewell is higher than that to which most migrating fish are acclimated and may cause fish to seek lower pressures by swimming upwards. Tarrant (1964) showed in the laboratory that juvenile chinook salmon respond to increases in pressure as small as 0.07 kg/cm^2 by swimming upward. He suggested that this response to pressure may account for the large numbers of juvenile fish that enter intake gatewells of low-head dams (as demonstrated by Bentley and Raymond, 1968). Fish acclimated to the surface flows in the forebays of dams are presumably subjected to increases in pressure as great as 2.95 kg/cm^2 (comparable to 29.8 m of depth) by the time they reach the entrance to the gatewells. Although fish in deep water in the forebay undergo much less change in depth

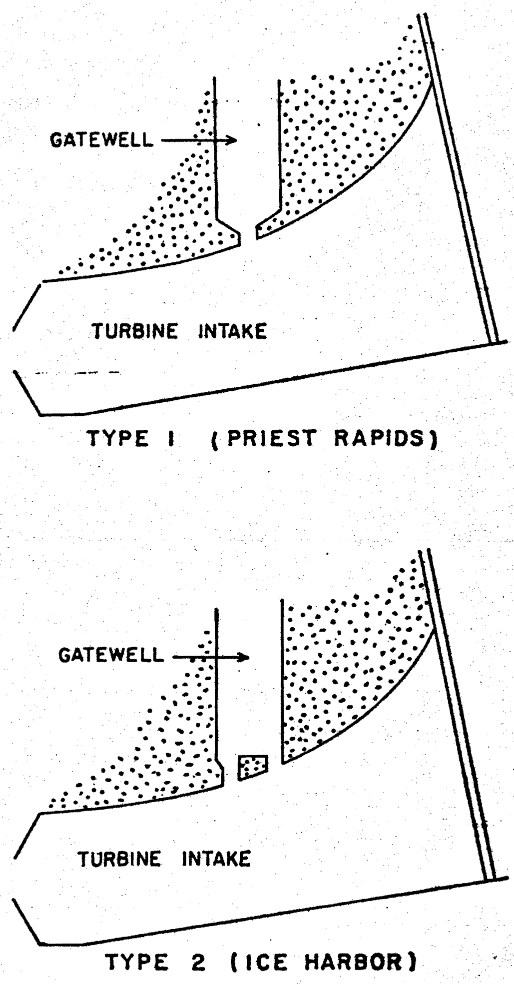

FIGURE 2.—Gatewells in low-head dams commonly have one opening (type 1, as exemplified by Priest Rapids Dam on the Columbia River) or two openings (type 2, as in Ice Harbor Dam on the Snake River) into the turbine intake.

and pressure as they enter the intake, most of the fish probably are in the upper few meters of water in the forebay (Rees, 1957; Erho, 1964; Smith, Pugh, and Monan, 1968; Long, 1968).

5. Velocity and pattern of flow within turbine intakes. Water velocity near the entrance to the gatewell varies from dam to dam and fluctuates with the turbine load. At Ice Harbor Dam, it averages 1.8 m/sec when the units are operated at 115% of rated capacity (overload) at the mean operating head (29.3 m). Flows within turbine intakes are well ordered

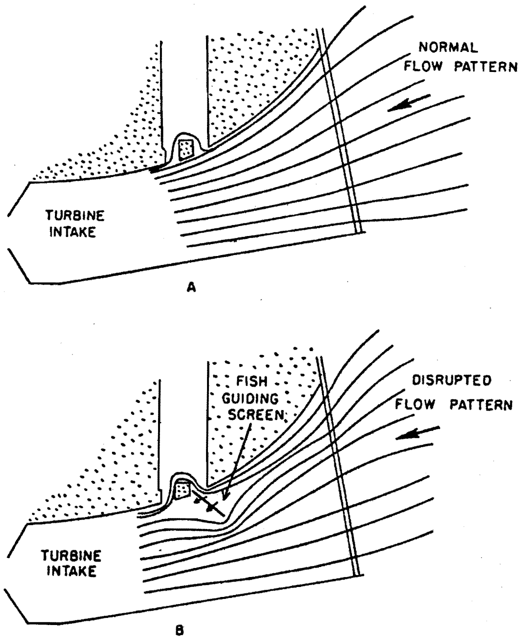

FIGURE 3.—Patterns of flow in a turbine intake with a type 2 gatewell. Pattern A shows the normal flow; pattern B shows the hypothetical change in flow with a fish-guiding screen.

and predictable and have a pattern similar to that shown in Figure 3A.

Factors Influencing Experiments in Model

A fish-guiding screen for diverting fish from turbine intakes into gatewells will cause changes in normal flow patterns that may affect guiding efficiency of the screen. The flow pattern probably will change immediately upstream from the screen and in the opening to the gatewell, immediately above the screen.

A screen presumably will disrupt the normal pattern of flow (Figure 3A) in the intake upstream from the screen and cause a pattern that approaches the exaggerated, or hypothetical, one shown in Figure 3B. Discounting the behavior of fish, one would expect fish in the deflected water to be carried under the screen with it. All of the fish, however, may not pass under the screen; some of them, subjected to higher pressure than that to which they have been acclimated, may swim upwards instead of being swept under the screen with the deflected water. The effects of downward deflection of the water and upward movement of the fish must be considered in attempting to determine the length of screen that will be most effective.

A screen also will increase the flow entering a gatewell. Guiding efficiency of the screen would be increased because flows deflected under the screen would be reduced by an amount equal to the flow deflected upwards into the gatewell, thus presumably reducing the number of fish deflected beneath the screen. We anticipate that the amount of water exchanged between the turbine intake and a type 1 gatewell will not be increased significantly by the presence of a screen but that the increase in water passed through type 2 gatewells may be significant. Normally, about 3% of the total flow in the turbine intake passes into the upstream opening of type 2 gatewells and out of the downstream opening (Winston E. Farr, pers. comm.). Installation of a screen should increase this flow. Increased guiding efficiency may be neutralized, however, by the escape of fish through the downstream opening of the type 2 gatewell. Thus, to realize this potential advantage, we may have to devise a method of retaining fish within the gatewell.

EXPERIMENTAL EQUIPMENT

The experimental equipment consisted of a test structure that simulated a turbine intake and gatewell that incorporated: (1) a compartment for holding the test fish, and from which they could be released into the structure, (2) traps to recover the test fish, and (3) screens attached to the ceiling of the simulated intake to guide test fish into the simulated gatewell.

Simulated Turbine Intake and Gatewell

The test structure, or simulated turbine intake (Figure 4), resembled a segment of an intake at Ice Harbor Dam (Figure 5). A rectangular conduit (0.6 m wide, 0.8 m high, and 14.6 m long) was constructed with the same curvature as that of the ceiling of the prototype intake. The opening into the gatewell extended the full width of the conduit (0.6 m). The length of the opening was 1.2 m —about the same as that of the single opening into prototype gatewells of the type 1 design and of the upstream opening of prototype

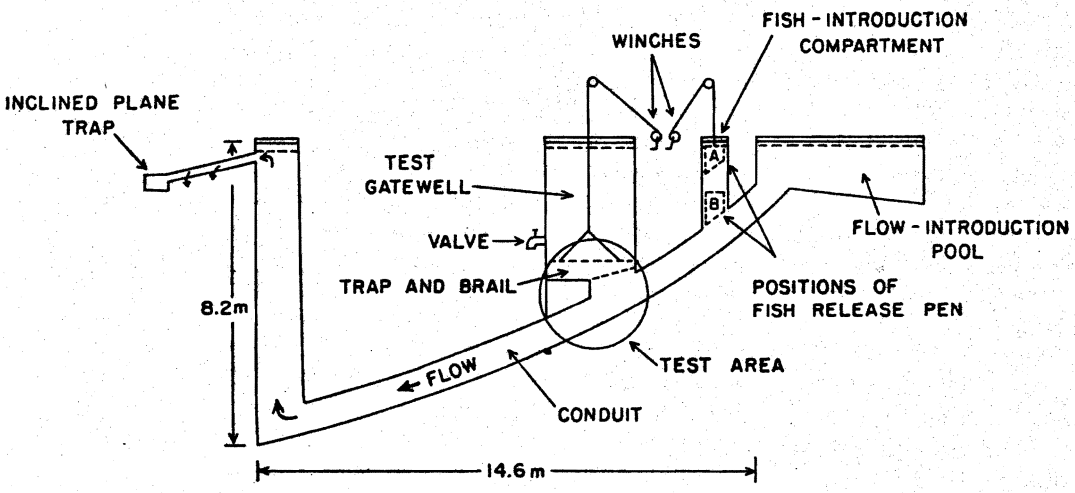

FIGURE 4.—Test structure designed to simulate a turbine intake.

gatewells of the type 2 design. The structure in the downstream portion of the gatewell entrance (Figure 4) had an opening that could be covered to simulate a type 1 gatewell. For tests of a type 2 gatewell, the opening was either: (1) uncovered to permit water and fish to pass through the opening from the gatewell into the intake or (2) uncovered but screened to permit water but exclude fish from passing through the opening into the intake. Water in the gatewell was 3.0 m deep. Fish equilibrated to a shallow depth (20 cm) and passed through the intake were subjected to 0.28 kg/cm^2 of increased pressure when they reached the opening during the tests.

Water from the forebay of Bonneville Dam was supplied to the flow-introduction pool of the model at a specific rate. The flow-introduction pool provided a uniform flow of water through the conduit at an average velocity of 1.8 m/sec.

The type 1 gatewell was equipped with a valve so that a flow through the gatewell could be created for comparison with the standard no-flow condition. The valve, installed in the gatewell wall and screened to exclude fish, could divert 3% of the total intake flow through the gatewell.

The type 2 gatewell had a natural flow into the upstream opening of the gatewell. Although we did not measure the quantity of this flow, we presumed that a screen diverting water upward toward the opening would cause more than the normal 3% of the intake flow to pass through the gatewell. We determined the retention of guided fish within the gatewell by tests with and without a screen over the downstream opening.

Apparatus for Releasing and Recovering Fish

Operation of the main features of the test structure can best be described by showing how they were used during a test. The structure was equipped to release fish into the simulated turbine intake, or conduit, and

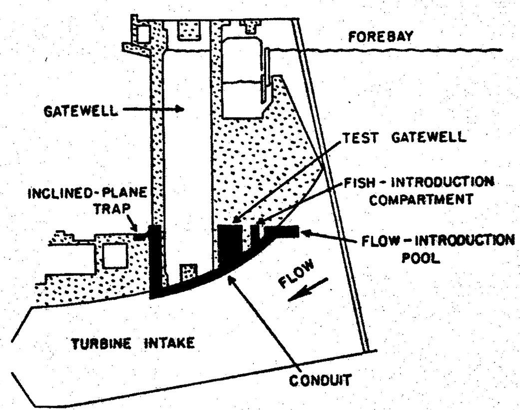

FIGURE 5.—Size of test structure (dark area) compared with that of turbine intake and gatewell at Ice Harbor Dam.

recover them from the test gatewell and the terminal end of the intake. A release pen suspended within a fish-introduction compartment introduced fish into the turbine intake. The bottom of the pen was hinged to open downward. At the beginning of a test, the pen was placed in position A (Figure 4), and the bottom was opened by remote control to release the fish. After they were released, the bottom was closed and the pen was lowered to position B, which forced the remaining fish out of the introduction compartment and into the intake.

After release, most of the fish either entered the test gatewell or passed through the intake and entered a trap. Fish that entered the gatewell were trapped in a specially designed holding pen. The bottom of the pen was formed by two screen doors that remained open to allow fish to enter and were closed by remote control to trap the fish. When the doors were closed, the pen served as a brail to remove the fish. Fish that passed through the intake were captured in an inclined-plane trap at the lower end of the structure. Some fish did not enter either trap but remained in the system until the structure was dewatered at the end of each series of three tests.

Screens for Guiding Fish

Three screens of different porosities were used in the tests. One (the most porous) consisted of a single layer, conveyor belting with an equalized spiral weave.[1] Another screen consisted of two layers of conveyor belting and the third (nonporous) was a wooden baffle. The screens were placed at an angle of 45° to the flow in the simulated turbine intake and adjusted in length to intercept either one-third or two-thirds of the total flow.

EXPERIMENTAL DESIGN AND PROCEDURES

The effects of screen porosity and fish behavior on the guiding efficiency of the three screens were tested in two series of experiments. One series measured the effect of flow through a type 1 gatewell on the guiding efficiency of the screens and the second (performed with a single-layer screen) determined the effect of flow through a type 2 gatewell on retention of fish within the gatewell. In the latter series, the total number of fish in the gatewell when the downstream opening was screened, which prevented escapement of fish, was compared with the number remaining when the opening was unscreened, which allowed the escape of fish from the gatewell.

The tests were conducted from December 5 to 28, 1967. Water temperatures fell from 8.3 C at the beginning of the test period to 5.0 C at the end. In all tests, light was excluded from the gatewell. The average water velocity was 1.8 m/sec in the intake. Three replicate tests were run for each set of experimental conditions. Control tests were conducted for each test condition before fish-guiding screens were installed.

Spring chinook salmon (*O. tshawytscha*), averaging 85 mm fork length, were transported from the Carson National Fish Hatchery near Carson, Washington, to the laboratory 1 day before the tests began. A new group of fish was used for each test. The fish were held in covered troughs supplied with water from the same source that supplied the test structure. Water in the troughs was 20 cm deep. The fish were transferred without being removed from the water to reduce stress from handling.

Fifty fish were used in each test. A test was begun by placing the fish in the release pen and covering all openings into the test structure to exclude light. The fish were left undisturbed in the dark for the first 30 min and then released for dispersal in the intake. The test was terminated 20 min later. Fish that had entered the gatewell and the inclined-plane trap were removed and counted. Fish remaining in the structure after each series of three replicate tests were removed when the facility was drained in preparation for the next series of replicate tests.

It was recognized that fish remaining within the test structure could have influenced the results by entering the gatewell during the second or third replicate tests. Preliminary observations made under lighted conditions showed, however, that most of the fish passed downstream immediately after release and

[1] Similar to 9.5-mm mesh designated by Catalogue No. E-30-30-16, Cyclone Metal Conveyor Belts, United States Steel, 1968. Reference to trade names in this publication does not imply endorsement of commercial products by the National Marine Fisheries Service.

TABLE 1.—*Number and average percentage[1] (in parentheses) of fish captured in a simulated type 1 gatewell and from the trap during tests with different types of screens, with and without flow of water through the gatewell (50 fish were released for each test)*

Type of screen, with and without flow	None[2]	Proportion of intake flow intercepted: One-third Gatewell	One-third Trap	Two-thirds Gatewell	Two-thirds Trap
None					
Without flow	(6.6)	–	–	–	–
With flow	(7.4)	–	–	–	–
Solid baffle					
Without flow	–	8	34	3	18
	–	7	39	5	14
	–	8	40	4	8
	–	(15.3)	–	(8.0)	–
With flow	–	11	33	6	19
	–	4	41	9	20
	–	7	43	10	16
	–	(14.7)	–	(16.7)	–
Two-layer screen					
Without flow	–	22	13	21	10
	–	32	11	40	7
	–	24	16	38	8
	–	(52.0)	–	(66.0)	–
With flow	–	39	3	34	5
	–	33	4	29	5
	–	39	8	36	12
	–	(74.0)	–	(66.0)	–
One-layer screen					
Without flow	–	36	7	34	4
	–	51	3	37	10
	–	44	3	41	7
	–	(87.3)	–	(74.6)	–
With flow	–	28	9	44	3
	–	39	7	43	3
	–	33	8	42	4
	–	(66.7)	–	(86.0)	–

[1] The percentages were calculated by dividing the number of fish that entered the gatewell by the number that were released for each test and then computing the arithmetic average for the three replicates for each test condition. This procedure assumes that the few fish remaining in the system after each test were not available to enter the gatewell.
[2] Percentage of fish captured within the gatewell only.

TABLE 2.—*Analysis of variance on the catch of fish entering the type 1 simulated gatewell to determine the effects of: (1) flow through the gatewell, (2) porosity (or type) of screen, and (3) proportion of intake flow intercepted by the screen[1]*

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F values[2]
F	1	0.081	0.081	0.316
P	2	58.780	29.390	114.670**
I	1	0.008	0.008	0.031
FXP	2	0.970	0.485	1.892
FXI	1	0.444	0.444	1.732
PXI	2	0.185	0.093	0.363
FXPXI	2	2.886	1.443	5.630**
Error	24	6.153	0.256	
Total	35	69.507		

F = Flow through gatewell (with and without flow).
P = Type of screen (solid baffle, one-layer, and two-layer screens).
I = Proportion of intake flow intercepted by screen (one-third and two-thirds of flow).
** Significant effect at 0.99 probability level.
[1] The basic data from Table 1 on the number of fish entering the gatewell were transformed to stabilize the variance by using the Anscombe transformation (Laubscher, 1961). All computations were performed using the transformed values.
[2] All tests were made using a null hypothesis of no treatment effects.

either entered the gatewell or passed under the test screen and into the lower section of the structure. After initial dispersal of the test fish, none were observed to enter the gatewell.

Even though a few of the residual fish may have entered the gatewell during the second or third replicates, any such bias would be directional and tend only to reduce the difference in guiding efficiencies between the test screens. That is, since the percentage of these residual fish was larger during tests with the least efficient guiding device than during those with the most efficient device, tests with the least efficient device were subject to a greater degree of bias. The test results reported here are conservative, therefore, and the differences in guiding efficiencies between the screens tested may actually be slightly higher than indicated by our data.

EFFECT OF SCREEN POROSITY AND FISH BEHAVIOR ON GUIDING EFFICIENCY

The results of tests with the type 1 gatewell are itemized in Table 1. The table shows that more fish were guided into the gatewell with the single- than with the double-layer screen and that more fish were guided with the double-layer screen than with the solid baffle. Analysis of variance of these data (Table 2) shows the importance of porosity (or type) of screen compared to the small increase in guidance obtained with changes in flow through the gatewell and length of screen (proportion of intake flow intercepted). Figure 6 shows the effect of porosity when no flow was diverted through the gatewell and the screen was placed to intercept the upper one-third of the flow in the intake; fish-guiding efficiency varied directly with porosity of the screen.

Although the percentage of fish swept under a fish-guiding screen may be directly related to the porosity of the screen (or the amount of water deflected under it), tests showed that this relation may be counteracted to some degree by the behavior of the fish. For example, even though all of the water in the intake had to pass under the solid baffle, the

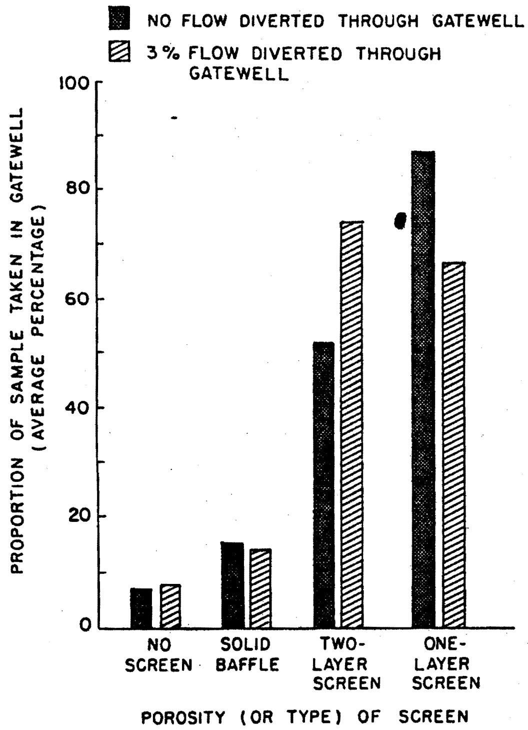

FIGURE 6.—Fish captured within the simulated type 1 gatewell, with and without flow through the gatewell, by porosity (or type) of screen. The screens intercepted one-third of the flow in the intake.

guiding efficiency of this device ranged from 8.0 to 16.7% (Table 1)—which showed that some fish swam toward the ceiling and into the gatewell instead of passing under the screen.

EFFECT OF FLOWS THROUGH GATEWELLS ON GUIDING EFFICIENCY

The effect of gatewell flows on the guiding efficiency of the screens was tested with a type 1 gatewell. Statistical analysis of the data (Table 2) showed that guiding efficiency of all screens combined was not significantly increased by allowing 3% of the flow in the intake to pass through the gatewell. Our tests did show, however, that the guiding efficiency of the double-layer screen was increased significantly (22%) by a flow through the gatewell (Figure 6).

A 3% flow diverted through the gatewell did not improve the guiding efficiency of either the single-layer screen or the solid baffle (Figure 6). When a single-layer screen was used, the percentage of fish guided with no flow through the gatewell (87.3%) presumably was nearly all of the fish available for guiding. Thus, no increase in efficiency could be expected. When a solid baffle was used, however, guiding efficiency was expected to increase with water diverted through the gatewell, but it did not. Perhaps the amount of water diverted through the gatewell was too small in comparison with the amount deflected beneath the solid baffle to influence the fish.

TABLE 3.—*Percentages of fish released in the test structure that were captured within the simulated type 2 gatewell, with and without a screen blocking the downstream opening*

Type of screen	Percentage of test fish taken in gatewell: Downstream opening unscreened	Downstream opening screened
None	7.4	–
Single-layer screen	39.1	66.7

The effect of gatewell flows on the retention of fish was tested with a type 2 gatewell. The single-layer screen, placed to intercept one-third of the total flow in the intake, was used as the guiding device. Table 3 shows that screening the downstream opening of the gatewell (to block fish from leaving the gatewell) increased the captured fish from 39.1 to 66.7% of the total number released. Evidently, nearly 28% of the fish had been guided into the gatewell and then had reentered the turbine intake through the unscreened downstream opening.

APPLICATION OF RESEARCH TO PROTOTYPE TRAVELING SCREENS

A prototype traveling screen is now being developed at Ice Harbor Dam as a component of a system proposed by the NMFS for safely bypassing juvenile fish around low-head dams (Figure 1). Initial testing of the prototype will by necessity be concerned with two primary problems: (1) protection of the turbine and (2) mechanical operation of the guiding device. After these two problems have been resolved, modifications of the device can be considered that will maximize guiding efficiency of the screen.

According to this experiment the most important design factor affecting guiding efficiency is porosity. Although our study indicated that reduced guiding efficiencies should be expected with screens of low porosity, the efficiency of such screens may be higher in the prototype than was observed in these tests. The fish will probably have more time in the prototype—where dimensions of the screen, turbine intake, and associated patterns of flow are greater—to swim upwards out of the flow that is diverted under the screen. Furthermore, fish entering prototype intakes will be subjected to higher increases in pressure than were test fish used in the simulated intake. The reaction of fish to pressure may therefore be greater in the prototype than in the simulated intake.

If the fish-guiding efficiency of a screen is below an acceptable level for a specific situation, guiding efficiency may possibly be increased by lengthening the screen or diverting more water through the gatewell. In type 1 gatewells, lengthening the screen may be more economical than modifying the gatewell to divert more water through it. In type 2 gatewells, however, flow through the gatewell will probably increase when a screen is installed in the intake. If increased flow through the gatewell is necessary to achieve maximum guiding efficiency, retention of fish within the gatewell may become a problem, and a method must be developed to prevent fish from reentering the turbine intake. If the flow is not desired, it can be easily reduced or stopped.

In developing a prototype traveling screen, high porosity should be emphasized. If porosity is great enough, additional methods for increasing guiding efficiency may not be necessary. After initial engineering studies of the prototype traveling screen are completed, we recommend studies with hydraulic models to determine patterns of intake flows upstream from the traveling screen. More precise knowledge of the changes in pattern of flow will help determine the optimum length of screen required to divert juvenile salmon and trout from turbine intakes into gatewells.

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