Reprinted from:
Proceedings of the Second Entrainment and Intake Screening Workshop. 1974.
L. D. Jensen (ed.). The Johns Hopkins University Cooling Water Research Project, Report No. 15.

A Functional Evaluation of a Large Louver Screen Installation and Fish Facilities Research on California Water Diversion Projects

JOHN E. SKINNER

CALIFORNIA DEPARTMENT OF FISH AND GAME

INTRODUCTION

My presentation this morning will be given in two parts: the first will be a review of some of the biological data we are in the process of developing to provide engineers with design criteria for what may be the largest fish salvage installation in the world; the second will be a report on the results of a functional evaluation of a large louver installation.

This workshop is both relevant and timely. I think it is safe to say that the use and abuse of water is going to increase in the future and that the demand to minimize or prevent the diversion and entrainment of aquatic organisms will continue to escalate.

When one realizes the gamut through which water is put the outlook for aquatic life seems very dim. We divert water, spread it on fields for irrigation where we enrich it and load it with salts; we spread it over the ground for waste treatment and into streams for percolation; we draw it through industrial systems where we heat it, beat it, boil it, saturate it with chemicals, evaporate it, centrifuge it and evacuate it. We disrupt the land so that we change our water to mud. We treat huge quantities in our water supply systems and use it for sewage disposal where we frequently treat it again. We raise it, then drop it from dizzying heights; spin it through turbines and pumps and shuttle it back and forth in our reservoirs and export it into foreign environments.

I recognize that animals are adaptive, most are tolerant, and many have amazing powers of resiliency. I submit, however; they are hardly up to the changes that man subjects them to. Obviously, we who are concerned, have a tremendous job ahead of us if we are going to maintain the traditional forms of aquatic life in our environment.

BACKGROUND

Our primary purpose and objectives are aimed at the development of design criteria for a fish screen concept, and related facilities for the so-called Peripheral Canal. This will be a facility with an ultimate capacity of 617 to 792 m^3/sec (21,800 to 28,000 ft^3/sec). The canal will divert the water from the Sacramento River about 40.3 km (25 mi) south of the City of Sacramento and convey it about 69.2 km (43 mi) around the Sacramento-San Joaquin Delta to the State and Federal pumping facilities in the south Delta (Fig. 1). Enroute, the water will pass through several major siphons. Provisions are also being made to release up to 141.5 m^3/sec (5,000 ft^3/sec) at various turnouts to improve water quality in the Delta for agricultural and environmental purposes.

Several important anadromous fish species will encounter the diversion as well as a variety of resident river fishes. The fish will encounter the diversion in several life history stages. These range from the eggs and larvae of striped bass and American shad through the fingerlings and smolts of salmon and steelhead to postspawning adult striped bass, shad and white sturgeon.

The present program on fish facilities design is being carried out under a quadripartite agreement among the California Departments of Water Resources and Fish and Game and the U. S. Bureaus of Reclamation, and Sport Fisheries and Wildlife. The research is being performed by Fish and Game under contract to the water development agencies.

PART I

FISH FACILITIES RESEARCH FOR CALIFORNIA WATER PROJECTS

Fundamentally, our objectives under this program are to: (1) develop biological design criteria for required fish facilities associated with the Peripheral Canal; and (2) develop operating criteria for the facilities. Our foremost concern is to develop an appropriate fish screen and other measures to minimize losses of fish, eggs and larvae from the Sacramento River.

Roughly, one-half to two-thirds of the anadromous fish of the state spawn in the Sacramento River or its tributaries. About two-thirds of the striped bass, and perhaps as much as 90% of the salmon, steelhead, American shad and

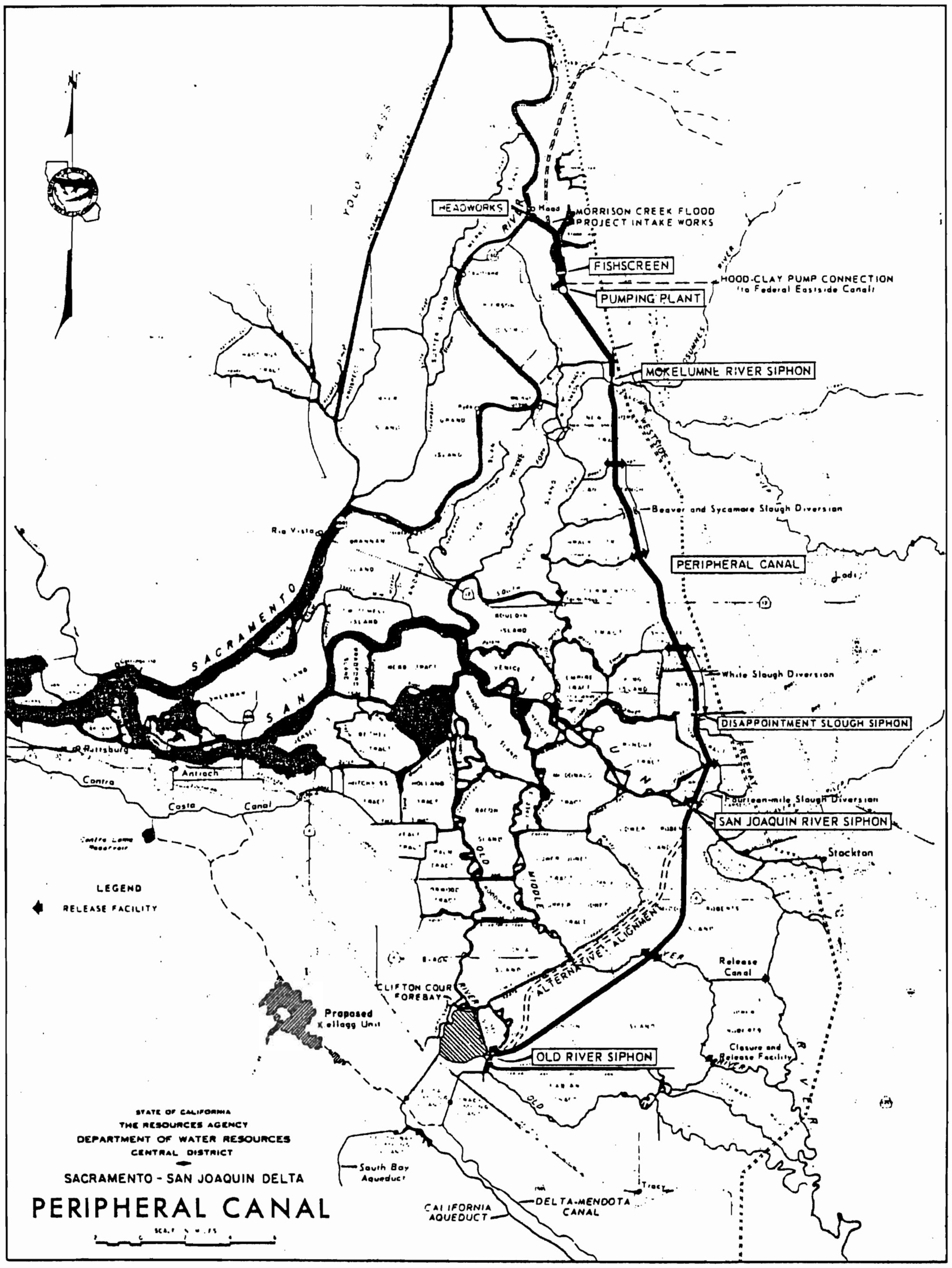


FIG. 1. Location and features of Peripheral Canal.

white sturgeon of California's Central Valley originate in the Sacramento River System with the remainder being contributed by the San Joaquin River and its tributaries.

It is evident from the literature on fish screens that most have evolved from the mechanical approach. Ideas are converted to mechanical structures which usually are then modified to improve their effectiveness. Most fish screen development has been oriented toward salmonids and more specifically toward those of the Pacific states and British Columbia.

Basic research on the fundamental guidance mechanisms and physiological capacities of fish has been rather limited. For example, fish screens have been constructed for over 50 years to prevent the loss of salmon, steelhead and trout. Yet as late as 1970, we had no good measure of either the swimming capabilities or the impingement tolerance of fingerling salmon relative to fish screens.

Generally, the research that has been done has been in response to a specific need. Bates, Vinsonhaler and Sutherland (1964), for example, did a substantial amount of applied research in developing the louver concept in connection with the 141.5 m^3/sec (5,000 ft^3/sec) diversion for the Central Valley Project. Although Kerr (1953) was trying to solve a particular problem at the Antioch steam plant of the Pacific Gas and Electric Company, he was curious enough to venture into the more basic elements of the problem and astute enough to translate the results into general observations about fish behavior that have application to fish screen development. More recently, Greenland and Thomas (1972) reported the results of their research on the swimming speed of fall chinook salmon. Numerous investigators have studied the swimming speeds and motions of fish. However, little of this work has, as yet, been of direct benefit to fish screen design. Perhaps the greatest void has been the lack of research on juvenile fish.

Our approach to the problem of developing a fish screen installation for the Peripheral Canal was to: (1) develop conceptual ideas of a system; (2) determine the principal components to establish the critical links in the system; and (3) conduct the necessary research to develop design criteria and to evaluate the critical links in the system.

Since astronomical numbers of eggs and larvae as well as fry, juveniles, subadult and adult fish will be encountered at the diversion, we have concentrated on developing a screen concept and related criteria. However, we are also considering problems associated with a settling basin, collecting facilities, pumps, a return conduit up to 8 Km (5 mi) in length and terminal release facilities.

Because we are unsure of the screen concept that will ultimately be adopted we have emphasized research on the swimming performance and/or impingement tolerance of eggs, larvae and juvenile fish. We believe this approach will be effective since it will produce design criteria that should be useful irrespective of the concept ultimately adopted.

We have been doing this research since 1966. The first several years were spent in developing the equipment and techniques to handle and hold the eggs, larvae and small fish. Hardly a testing season goes by without significant modification of the equipment, holding facilities, handling techniques or experimental design. Thus, we have experienced rather substantial differences from year to year.

We have learned that research of this nature must be planned carefully and implemented expeditiously. Eggs and larvae are only available for a few weeks each year. Normal growth is such that a desired size must be tested quickly and efficiently. It usually takes either a massive effort when the fish are available or several seasons of testing in order to obtain meaningful results. This gets extremely expensive when it is necessary to collect specimens in the field.

Test Equipment, Procedures and Methods

The details of the test equipment, procedures and methods are too lengthy to deal with here. They can be obtained on request and will be included in subsequent publications.

We initiated our research with a simple velocity chamber, modified after Beamish (1966). Very simply, it was a 20.3-cm (8-in.) Plexiglas tube inserted in a water bath with a dry well in the center so that the reactions of the fish could be observed. A propeller attached to a variable speed motor was used to obtain the desired water velocities through the tube (Fig. 2). For most tests, we used a cylindrical tube with the retainer screen placed perpendicular to the flow of water. The retainer screen is fixed at the end of a removable extension to the plastic tube which we refer to as the test chamber. This removable chamber greatly simplifies the insertion and removal of test fish. The angled screens, with a bypass and collector attachment, were used for special experiments which will not be discussed here.

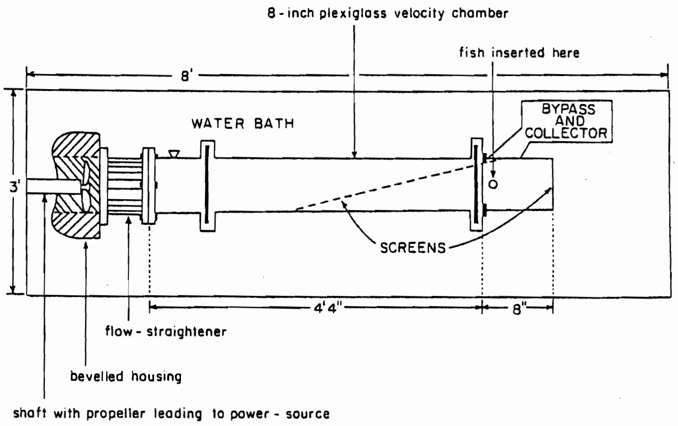


FIG. 2. Schematic diagram of velocity chamber.

Over the years the velocity chamber has evolved to the extent that our latest facility uses hydraulic head rather than a propeller to regulate the velocity. This system results in much more uniform hydraulic conditions in the test chamber. It was just completed and will be used extensively for the first time this year (1973).

Our holding and handling techniques have gone through a similar process. We originally held the fish in screened plastic buckets placed in a water bath. This was later modified to a sinuous trough provided with a continuous flow. Presently, we use a rack and canister system which greatly increases efficiency while reducing the physical handling and resultant stress of the fish. In the latter system, the fish are put in a screened canister which is then placed in the holding trough prior to testing. The fish are tested in the same canister without being removed and are returned to the trough for post-test holding.

As a rule, all larvae and test fish were held 24 hr before and after testing. This procedure eliminated most handling mortality prior to testing and permitted an assessment of delayed mortality. Eggs were usually tested shortly after they were obtained; otherwise most would hatch before testing.

Most testing was done at the Delta Fish Protective Facility, although much of the salmon and steelhead research was carried on at the Department's Mokelumne River Fish Installation, a combination hatchery and artificial spawning channel facility. The test schedule was governed by the natural occurrence of each species. Salmon and steelhead were tested from the middle of January to the middle of April and striped bass were tested from May to September.

Swimming performance was measured in terms of the percentage of fish in a free-swimming position at a given velocity at the end of selected time intervals. Impingement tolerance is defined as the proportion of fish surviving impingement for a given velocity and time period. Because of inherent differences between fish and some peculiarities of the test equipment not all fish are impinged uniformly. Therefore, these tests are often a measure of tolerance to the combination of swimming and impingement. At marginal impingement velocities, some fish which were impinged were later able to free themselves.

Before testing, the fish were carefully segregated into similar length groups. Because of the critical relationships between fish length and swimming performance particular care was given to measuring the fish to reduce the variability of the results attributed to this source. Each test lot normally consisted of 20 fish. After the fish were introduced into the test chamber, a velocity of about 0.03 m/sec (0.1 ft/sec) was provided to allow the fish to orient themselves with respect to the current. When the fish were oriented, the velocity was raised quickly to the desired test level. The holding water and test water was generally kept within 1.1 deg. C (2 deg. F) of each other.

These tests involved several thousand fish and hundreds of individual tests. In 1971 for example, 280 separate tests were conducted involving 5400 fingerling salmon.

RESULTS

Salmon and Steelhead

The typical results of our swimming performance tests are shown in Fig. 3. The figure shows the percentage of 39 mm king salmon swimming up to 6 min at velocities ranging from 0.15 to 0.76 m/sec (0.5 to 2.5 ft/sec). In general, swimming performance varies directly with size and inversely with velocity. This relationship is rather critical for the smallest fish but diminishes as the fish get larger.

The composite results of 36 to 56-mm king salmon are shown in Fig. 4. These tests ranged from 1 to 6 min in length. Time within this range was much less important than velocity. To attain a success level of 90% or more, the water velocity for 36 to 56-mm king salmon should not exceed 0.21 m/sec (0.7 ft/sec) based on these tests.

Because swimming performance varies so greatly with size and velocity it is rather difficult to illustrate the results. However, Fig. 5 shows the apparent relationship between king salmon fry body length, and swimming performance for 4 min based on our 1971 data. Comparable results for steelhead fry are depicted in Fig. 6. We expect to analyze these relationships in greater detail at a later date and eventually develop the mathematical equations to express them.

We learned that impingement at moderate velocities for short time intervals presented no immediate hazard to salmon and steelhead. Numerous tests at velocities up to 0.76 m/sec (2.5 ft/sec) and for 6 min or less showed virtually no mortality. Consequently, we ran a series of tests to assess the effects of longer-term impingement. The results of the latter tests are shown in Fig. 7. The survival of 22 to 36-mm steelhead did not drop below 90% until the fish had been impinged over 50 min at 0.46 m/sec (1.5 ft/sec). The critical relationship between time and velocity for impinged fish is illustrated at 0.76 m/sec (2.5 ft/sec). Survival decreases rapidly after 10 min of impingement at the higher velocity.

Striped Bass

The swimming performance of striped bass is similar to salmon and steelhead in terms of the effect of size and velocity. Striped bass generally perform better at any given size up to 50 mm. It should be noted however, that such a comparison has little meaning since there is a great difference in the embryology and development of the two species. Salmon are on the order of 25 to 30 mm when they

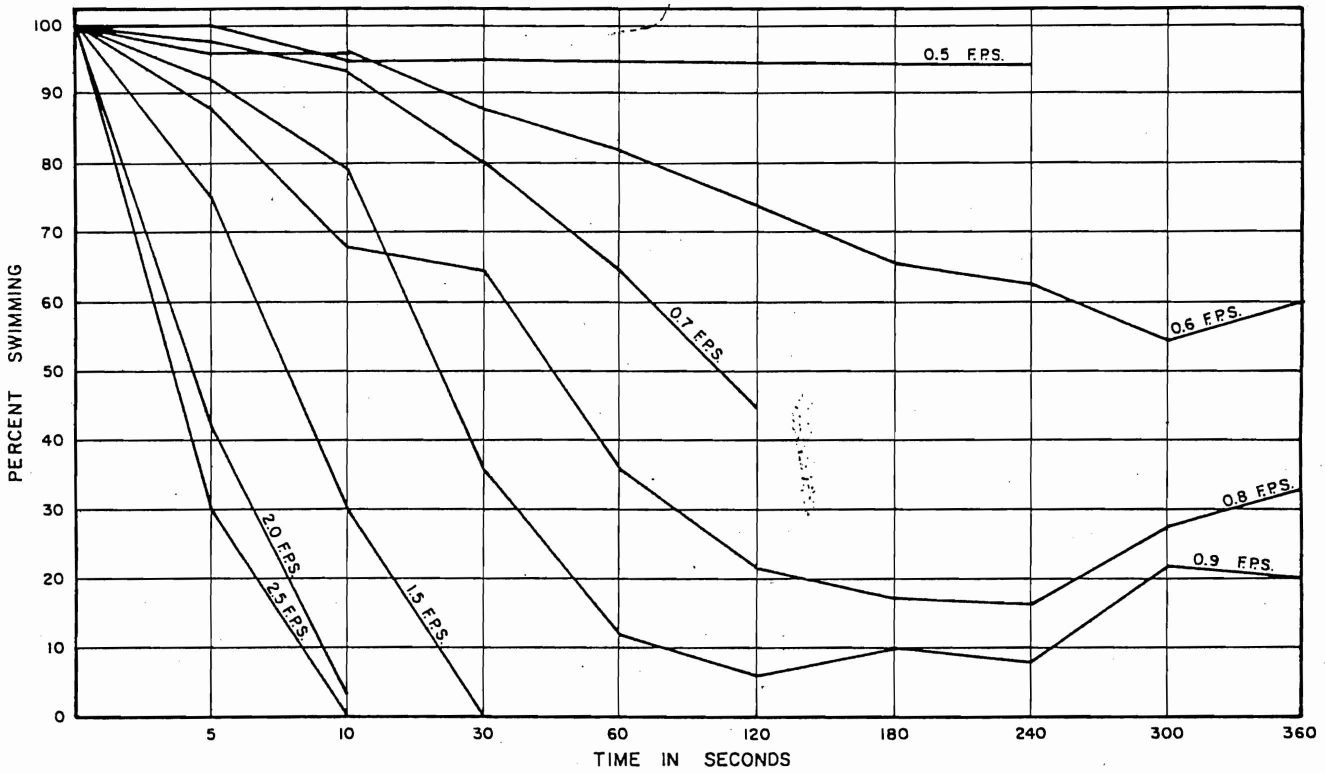


FIG. 3. Swimming endurance of 39-mm king salmon.

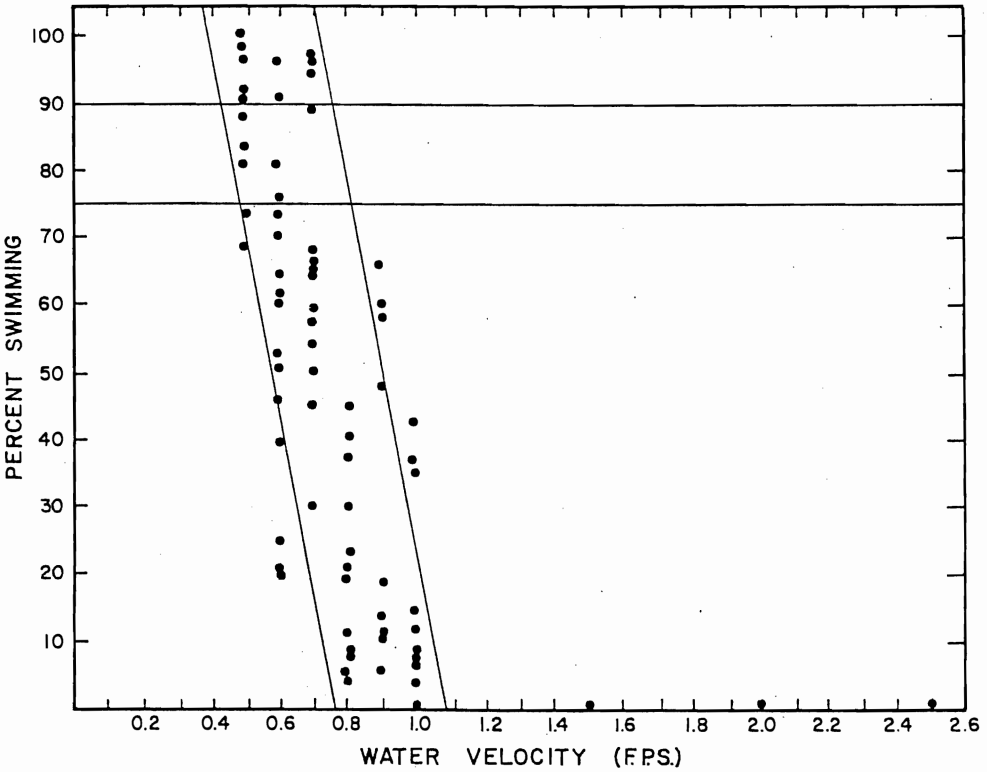


FIG. 4. Swimming ability of 36 to 56-mm king salmon for 1, 2, 4 and 6 min.

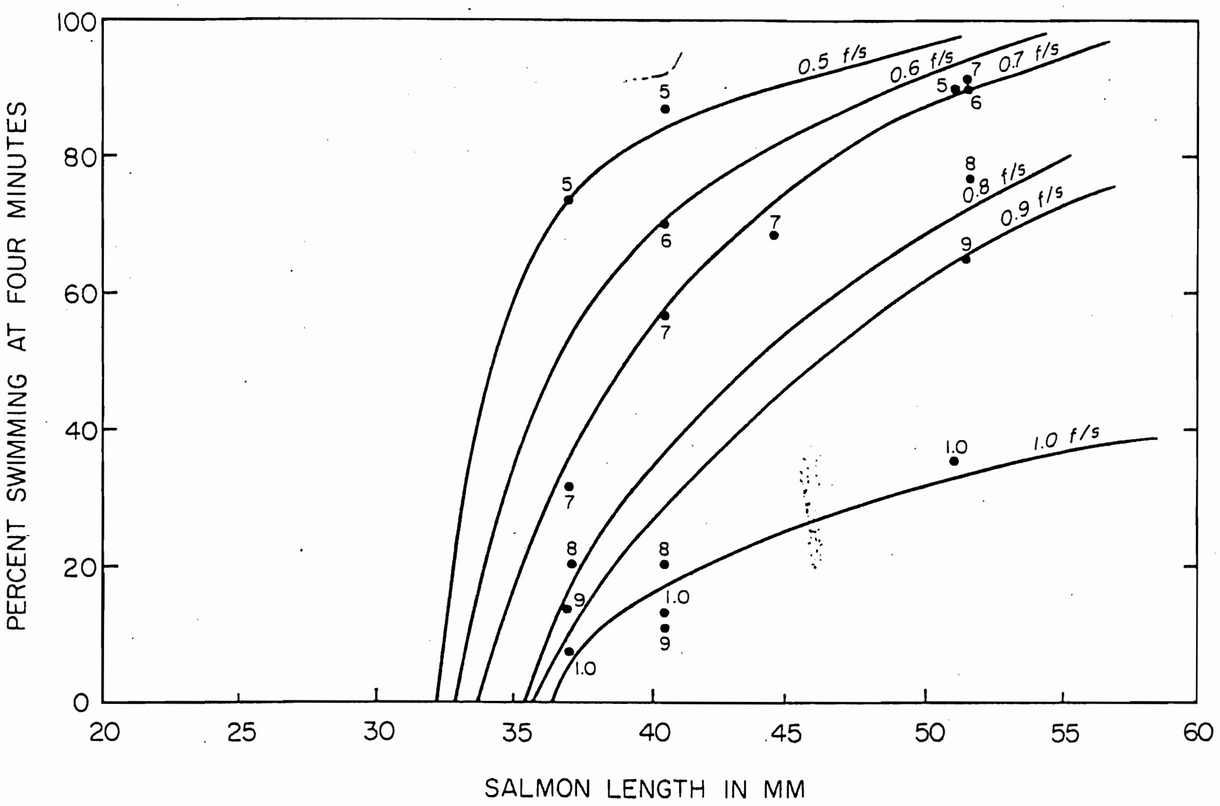


FIG. 5. Apparent relationship between king salmon fry body length and swimming performance for 4 min. (Data are for 1971 and curves fitted by eye.)

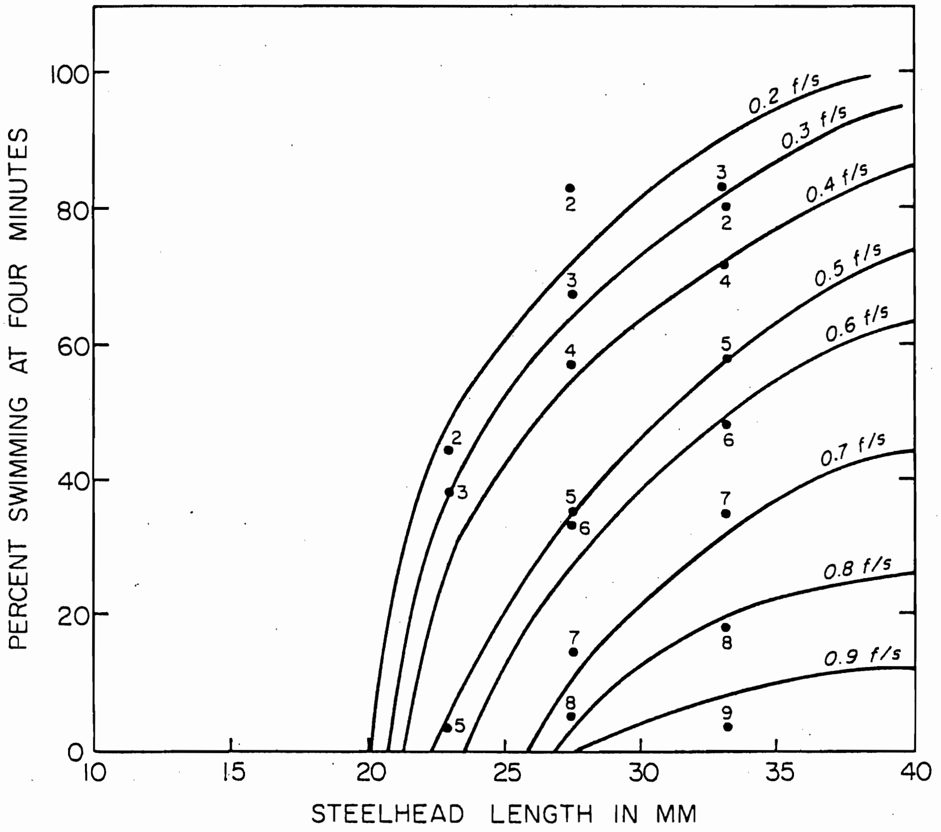


FIG. 6. Apparent relationship between steelhead fry body length and swimming performance for 4 min. (Data are for 1971 and curves fitted by eye.)

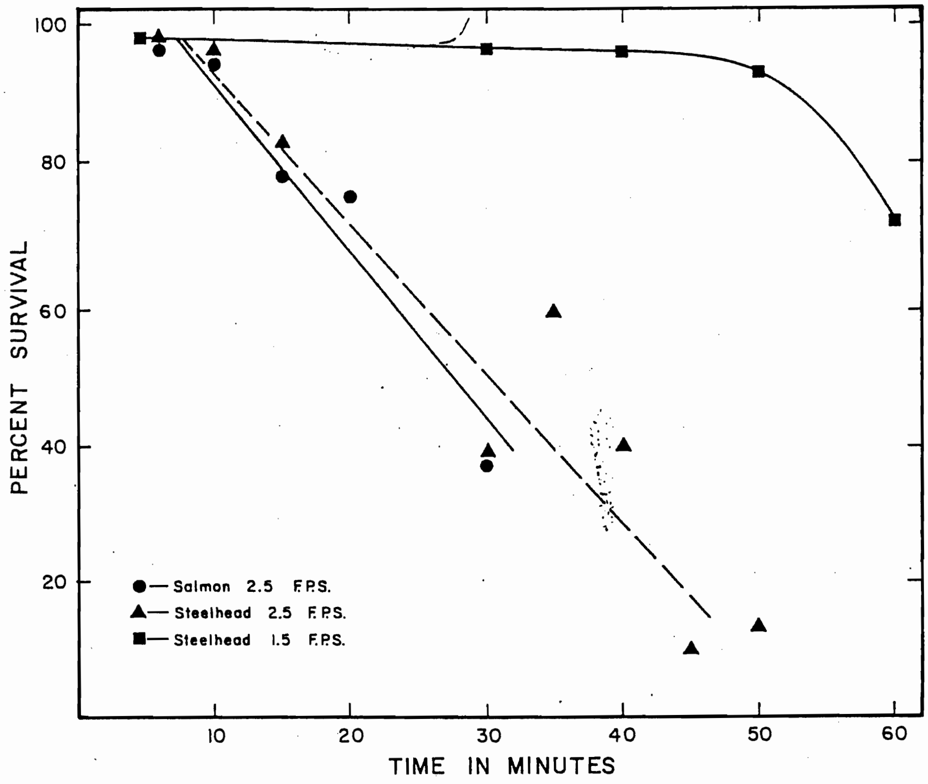


FIG. 7. Survival of salmon (36 to 56-mm) and steelhead (22 to 36-mm) impinged for extended periods of time (lines fitted by eye).

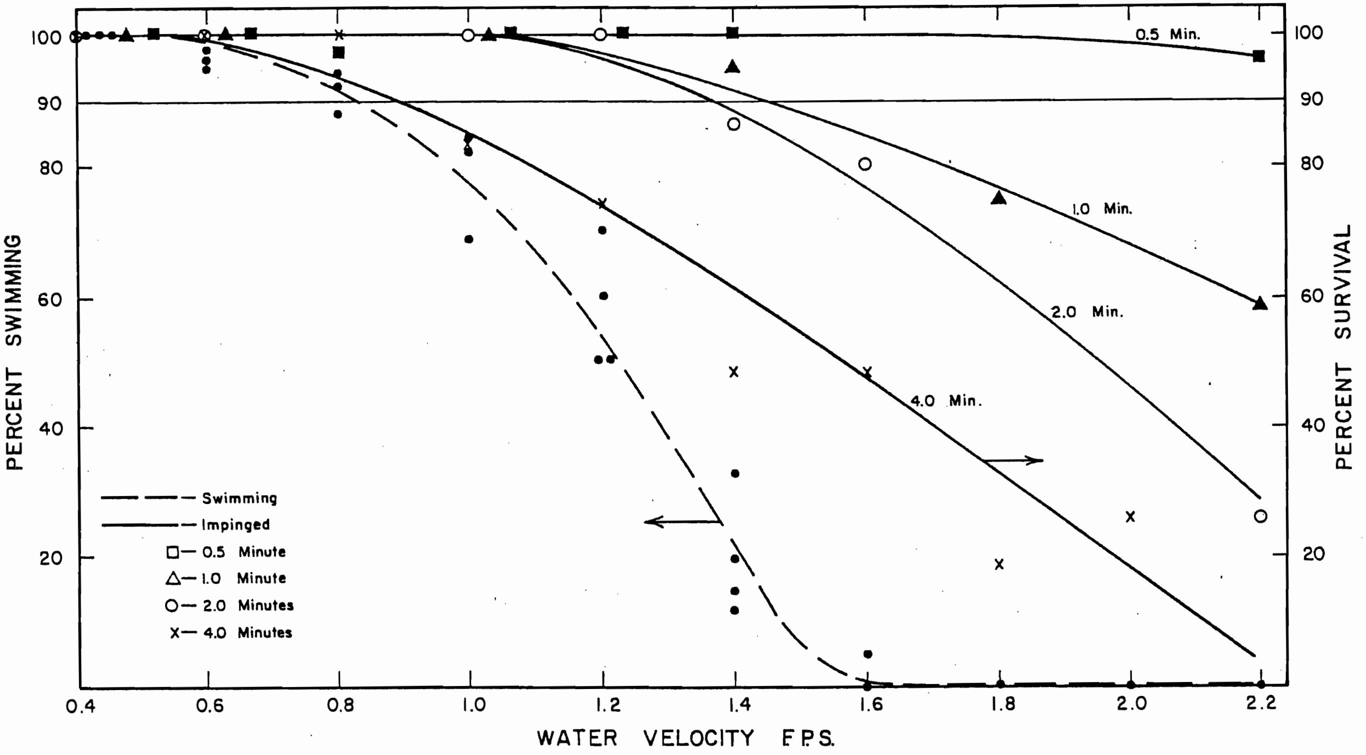


FIG. 8. Swimming ability and impingement survival of striped bass 40 to 50-mm, 1970, (curves fitted by eye).

hatch and carry a yolk sac until they are 40 mm or larger. Striped bass are approximately 3 mm in length at hatching. Also, there is a substantial difference in the temperature of the water during the early development of the two.

The 1970 results of our tests for 40 to 50-mm striped bass are shown in Fig. 8. Swimming performance is delineated by the dashed line. Essentially, 90% were able to swim at velocities up to 0.24 m/sec (0.8 ft/sec) for 6 min or less and almost all were impinged by velocities over 0.49 m/sec (1.6 ft/sec). The dots are the results of tests at 1, 2, 4 and 6 min. Generally, performance was best for the shortest test period and worst at the longest. The curve was fitted by eye and is intended to reflect the general relationship. Velocity is a more important determinant of swimming performance than time. The impingement tolerance of 40 to 50-mm striped bass is reflected by the solid lines. These results quite clearly indicate that survival is related to the length of time impinged as well as the velocity of the water.

The general relationship between swimming performance, water velocity, and fish length is shown in Fig. 9. Attainment of the 90% level of success for 6 min depends on velocities ranging from 0.06 m/sec (0.2 ft/sec) for 12 to 15-mm bass to less than 0.21 m/sec (0.7 ft/sec) for bass greater than 35 mm.

The general relationship between impingement tolerance, velocity and size is seen from Fig. 10 for bass between 20 and 50 mm in length. Survival obviously is related to both size and water velocity in these 6-min tests.

It was stated earlier, that the variables become less important as fish size increases. This is also apparent from Fig. 10. In general, survival is less than 90% for fish smaller than 40 mm at all velocities over 0.15 m/sec (0.5 ft/sec). The notable exception is the 100% survival for 20 to 25-mm fish at 0.24 m/sec (0.8 ft/sec).

To assess the feasibility of salvaging striped bass eggs by an impingement device we tested substantial numbers of eggs over a 2-year period. The results of our 1972 tests are shown in Fig. 11. The data suggest that it may be feasible to impinge eggs up to 6 min at velocities up to 0.24 m/sec (0.8 ft/sec). Survival was generally related to the length of time impinged but gross differences are apparent. Survival as measured by immediate survival (clear, intact eggs) and 24-hr survival (hatched eggs, i.e. larvae) were not greatly different, but the mortality after 24 hr is greater than mortality immediately following the tests.

DISCUSSION

Our tests and those of other investigators have demonstrated that swimming performance varies directly with fish length and inversely with water velocity. A comparison of our results will, in most cases, show that the performance of fish in these tests is somewhat lower than the results obtained by other investigators. Most of the difference

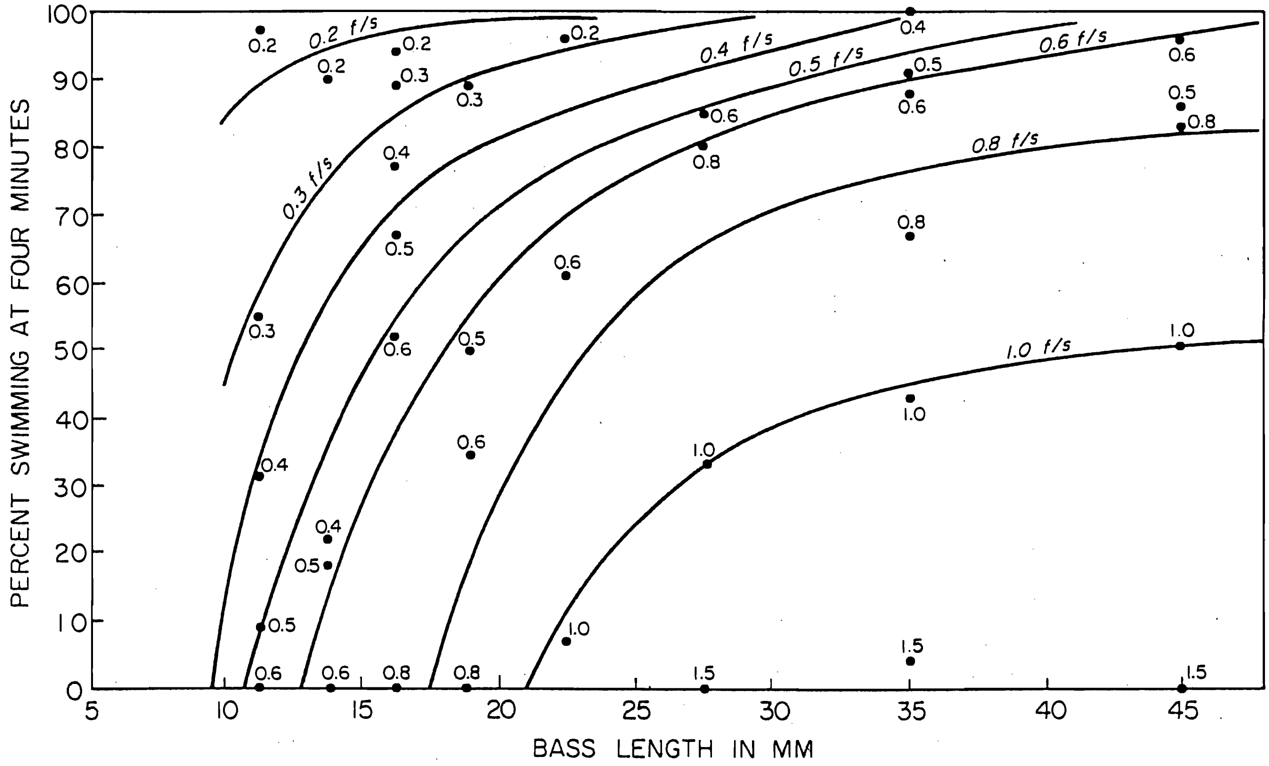


FIG. 9. Apparent relationship between the length of young striped bass and swimming performance for 4 min. (Data are for 1971 and curves fitted by eye.)

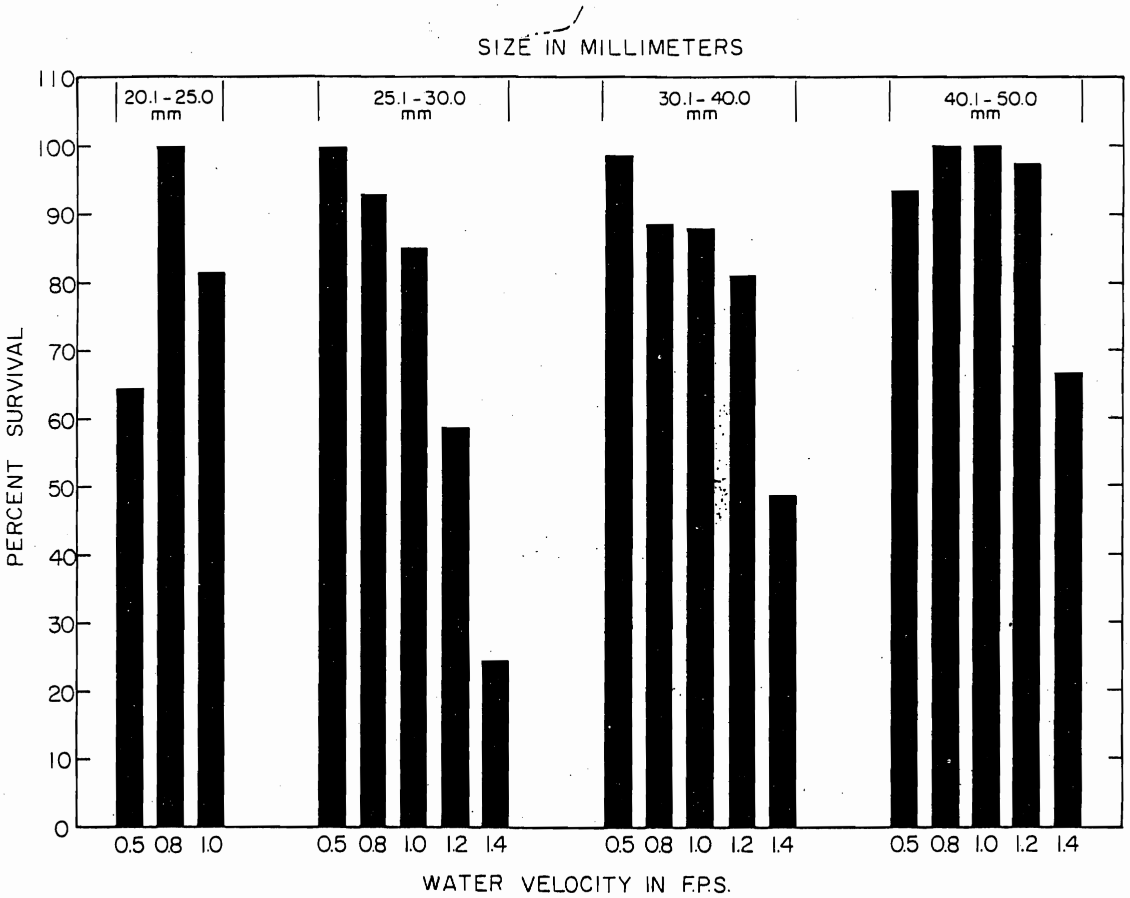


FIG. 10. Survival of striped bass impinged at various velocities for 6 min. (Data for 1972.)

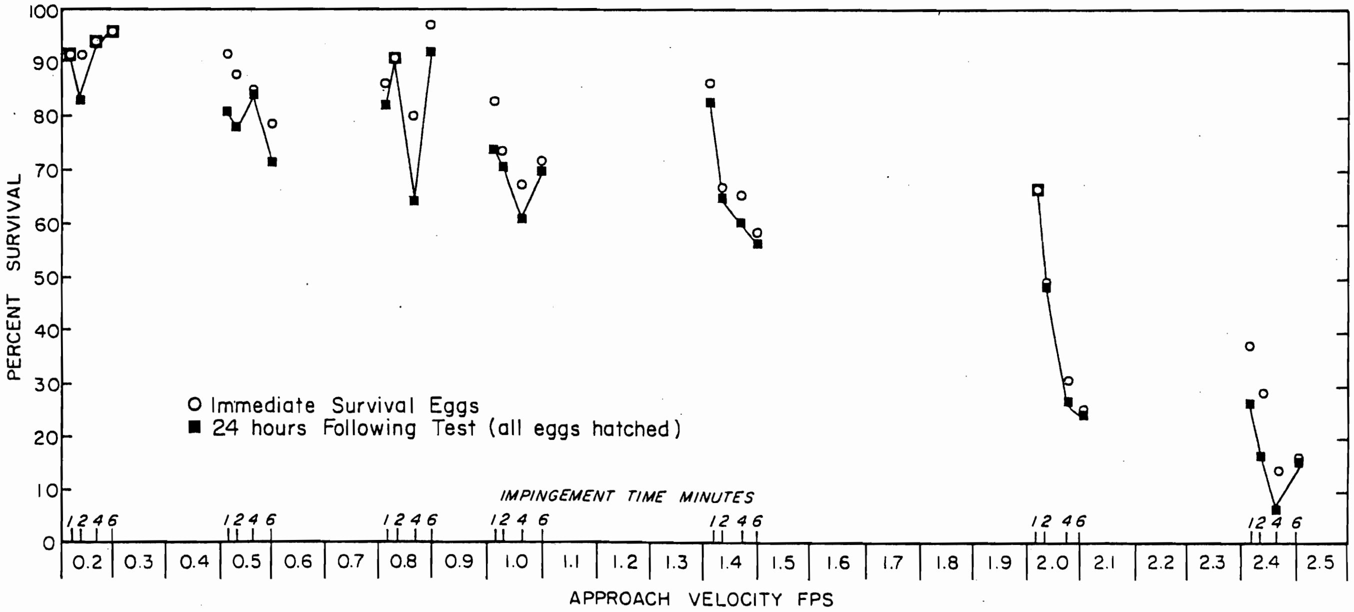


FIG. 11. Survival of striped bass eggs impinged at various velocities and durations of time. Screen size, 16 mesh/inch. (Data for 1972.)

can be ascribed to differences in the holding and testing procedures and facilities.

We were able to demonstrate substantial differences in the level of performance simply by altering the holding and handling techniques and test facilities. For example, we were able to increase performance up to 30% for small salmon simply by changing the 24-hr pretest holding environment. We changed from screened buckets held in a circulating water bath to holding the fish in a series of compartments in a sinuous trough supplied with running water. We assume the latter situation kept the fish in a more exercised and naturally oriented condition with respect to current. Although the screens on the buckets allowed for adequate aeration and replacement of the water, they contained a large area of essentially dead water near the bottom. This condition apparently did not require the fish to exercise continuously. We observed that fish in the trough regularly oriented themselves into the current, whereas those in the buckets simply swam at random. We assumed that the trough best simulated the conditions that the fish would encounter in a stream and at a fish screen. Hence, we changed our holding facilities to provide the continuous current.

We also observed differences in performance from year to year that were significant among the smaller fish. For this purpose, we compared fish of the same size from the same installation at identical velocities. Performance varied as much as 40% or more. Such differences are to be expected, but they are pointed out here because they create real problems in attempting to establish useful criteria. The variability caused by such differences affect the reliability and treatment of the data. A specific test parameter may easily be masked by such gross differences.

In 1970 we found that anesthetizing striped bass fry, so that they could be measured, resulted in a rather serious bias. In this case the mortality from impingement was substantially less with anesthetized fish than with unanesthetized fish. The results apparently depend upon the elapsed time between anesthetization and testing. We were unable to establish any significant difference between salmon anesthetized 24 hr before testing and a control group. Consequently, we anesthetized our salmon before measuring them, but this was always done 24 hr or more before testing them.

Another matter that should be given increasing attention is the test chamber itself. Most investigators have used a cylindrical tube of some type or other. Usually these have been over 0.31 m (1 ft) in length. Our initial unit contained a test chamber over 0.92 m (3 ft) long. Due to the difficulty of removing fish and to the stress induced in removing them, we designed a chamber that was simply a 10.2-cm (4-in.) extension of the Plexiglas tube.

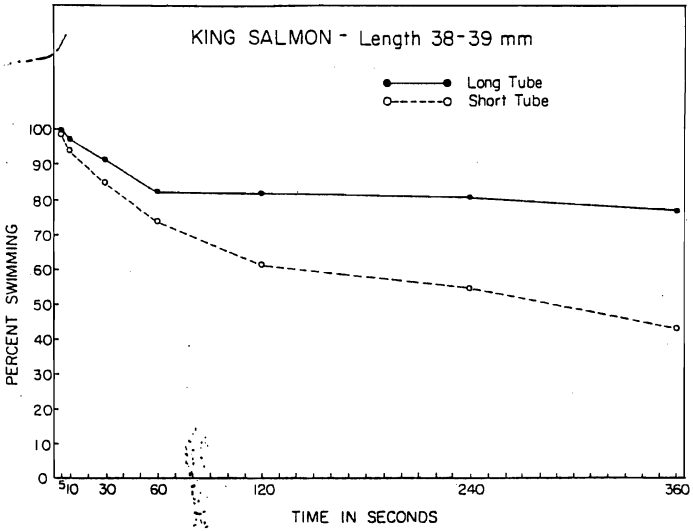


FIG. 12. Comparative performance of 38 to 39-mm king salmon fry tested in 10.2-cm (4-in.) cannister and 1.5-m (5-ft) velocity tube at 0.18 m/sec (0.6 ft/sec).

Upon comparing the results of the 10.2-cm (4-in.) test chamber with the longer chamber, we found that the short chamber generally resulted in poorer performance. Figure 12 shows the results for 38 to 39-mm salmon. There is a difference of more than 30% for the 6-min test period.

There is an obvious need to standardize test procedures and facilities if we expect to compare results among investigators. Standard procedures appear particularly relevant where the consequences may involve substantial costs or result in inadequate protection of the resource for overdesigned or underdesigned facilities, respectively.

The case of test chamber design may be used to illustrate the point. In our case, we are attempting to develop realistic design criteria for a very large fish screen installation. Figure 12 shows a difference of more than 30% between the two test chambers in the performance of 38 to 39-mm king salmon at a velocity of 0.18 m/sec (0.6 ft/sec). If we were to accept a performance level of 80%, based on the long tube, we could design a facility having a maximum velocity of 0.18 m/sec (0.6 ft/sec) and an exposure time of at least 6 min. With the short tube, the same performance level would probably require a reduction in velocity and/or exposure time. Reference to Figs. 3 and 5 suggests that the velocity may need to be reduced from 0.18 to 0.15 m/sec (0.6 to 0.5 ft/sec) to achieve the same level of performance. This would necessitate a 20% increase in the screen structure. Considering the potential consequences, it is apparent that we must decide which results are most appropriate to our situation.

In the longer test module, it was apparent that the fish were able to find areas of reduced velocity. They were observed to move upstream, drift back, and often assume a relatively stable position, usually along the bottom of the tube. Such a condition may be presumed to be more similar to the natural environment of a free flowing stream inhabited by downstream migrant fish. Although fish may passively move downstream with the flow of water at a given velocity, they nevertheless have substantial opportunity for lateral movement to avoid obstacles and to take advantage of irregularities in the flow pattern.

Fish tested in the short module were required to exert themselves much more to maintain a free swimming position and avoid impingement. This condition may be more typical of the situation fish would encounter in approaching a fish screen.

The short module, due to the screen immediately in front of it presumably provides a more uniform velocity profile to the fish than the long test tube. Thus, the short test module obviously provides a better measure of the maximum swimming performance of fish than the long module.

I assume therefore, that the short test module yields design data that are somewhat more restrictive than may be necessary in the natural environment, but I also feel it is a better measure of conditions a fish will encounter at a fish screen. A significant factor in its favor, at least from the biologist's point of view, is that it probably provides a realistic "built-in" margin of safety which the long tube does not.

The above arguments of course would become moot if the test module provides fully uniform velocity conditions irrespective of length or shape. The results of our studies suggest that it is feasible to employ impingement screen concepts, even for the eggs and larvae of some fish. However, practical application of the idea would necessitate careful design in terms of allowable velocities and length of impingement. As a general observation, solutions to the problem of screening planktonic and immature forms of aquatic life will require much more innovation and effort. For example, preliminary studies, performed at our request, indicate that a filter bed having a matrix of uniform particle size may be promising. We need much more fundamental knowledge about hydraulic patterns and fish behavior to aid in the location and designs of intakes to minimize entrainment. Finally, I believe, one of the most important and profitable areas for future effort lies in the investigation of the behavior of aquatic organisms and associated physiological mechanisms. For example, knowledge that a zooplankter responds to light could be extremely helpful in designing a facility to preclude entrainment.

PART II

A FUNCTIONAL EVALUATION OF A LARGE LOUVER FACILITY

We undertook a 2-year evaluation of the State's Delta Fish Protective Facility for the following purposes:

1. To verify the extent to which the installation met the original design criteria.
2. To develop operating criteria for the installation.
3. To assess the applicability of the louver concept to the proposed Peripheral Canal.

Description of the Delta Fish Protective Facility

The Delta Fish Protective Facility is a large louver facility which was completed in 1968. Its present capacity is 170 m^3/sec (6000 ft^3/sec) with provision for 283 m^3/sec (10,000 ft^3/sec) ultimately. The basic design is patterned after the neighboring federal Tracy Fish Collecting Facility which preceded the state facility by 12 or so years. However, several significant features were incorporated into the state facility. A general layout of the primary system is shown in Fig. 13.

The most significant differences include:

1. A 3.6×10^7 m^3 (2.9×10^4acre-foot) forebay into which water is admitted on flood tides only rather than by direct diversion from Old River, the natural channel on which both the state and federal intake systems are located. The forebay was constructed to permit off-peak pumping. However, it serves to eliminate the velocity fluctuations which would otherwise occur because of tidal influence.
2. A sawtooth or Vee arrangement of the louvers instead of a single oblique line across the channel.
3. Division of the intake channel into a series of bays with control gates. This feature permits the regulation of channel approach velocity when the installation is not operating at peak capacity.
4. A center or guide wall in one bay which bisects the Vee louver arrangement.

Each functional primary bay is 12.2 m (40 ft) wide and 7.6 m (25 ft) deep, although the bay with the center wall is again reduced to two channels, each 6.1 m (20 ft) wide. The louvers lead directly into 30.5-cm (12-in.) wide bypasses at their apex. The bypasses extend the full depth of the channel. However, due to extension of the terminal end of the centerwall to the very entrance of the bypass in the bisected bay, the bypass is effectively reduced to 15.2 cm (6 in.) for each half of the bay.

Each louver panel is 2.4 m (8 ft) in length by 4 m (13 ft) in depth. The panels are stacked two deep, to extend the full depth of the channel. Each line of louvers crosses the channel at 15 degrees to the flow. The louver slats are 2.5 cm (1 in.) apart and at 90 degrees to the flow. Each eighth louver is curved and extends behind the panel to form a flow straightener. The primary bypasses undergo immediate transition to 122-cm (48-in.) circular pipes leading through a system of control values to the secondary channel. Here the pipes undergo retran-

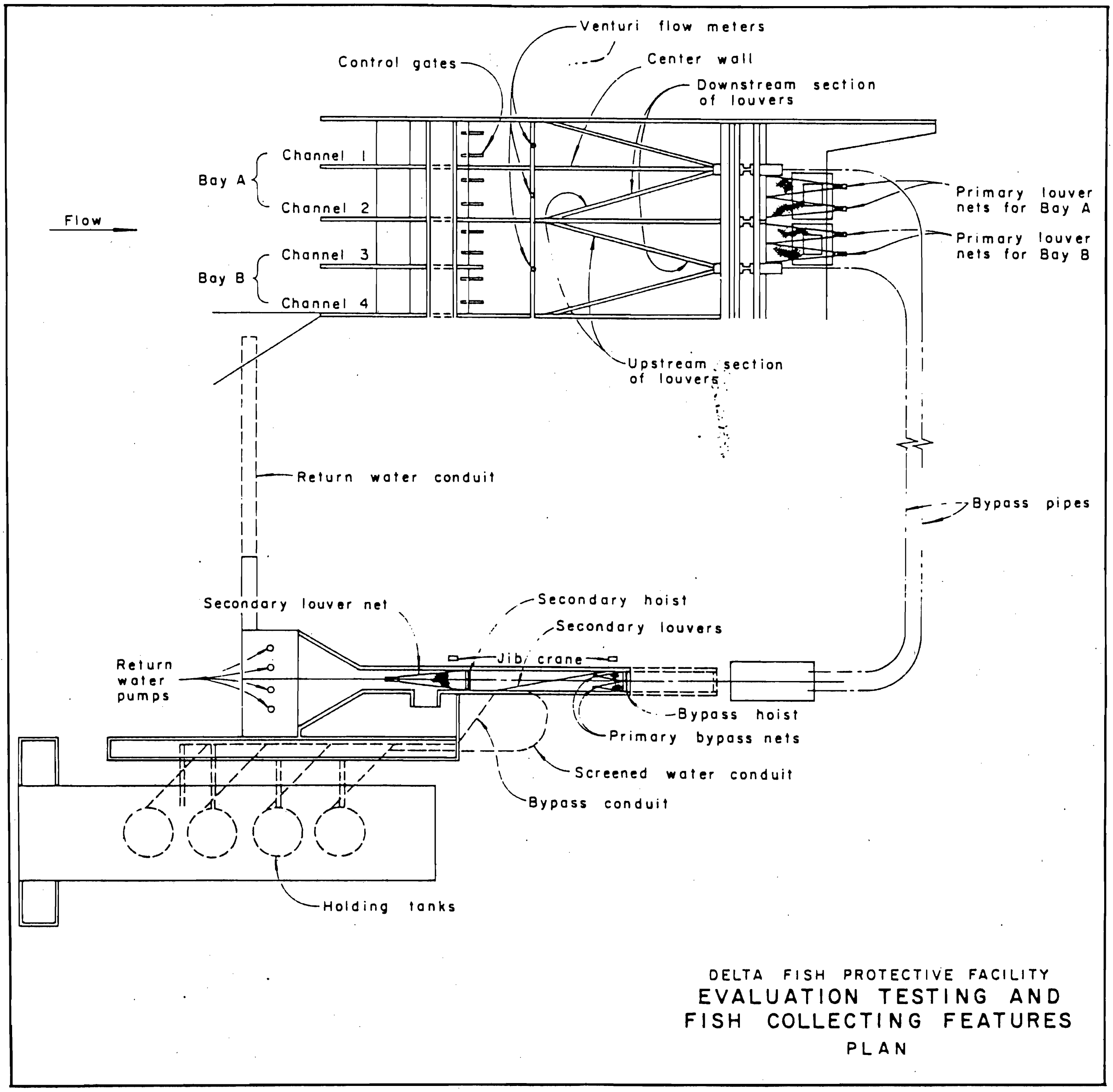


FIG. 13. A schematic of the primary system.

sition to 1.5- X 3.1-m (5- X 10-ft) rectangular conduits as they enter the secondary where they discharge side by side.

The secondary louvers further concentrate the fish. Those which are louvered are bypassed to the holding tank building where they are held until a sufficient number has been collected to be hauled away by truck to the release sites. The excess water in the secondary channel collects in a sump where it is pumped back into the intake channel ahead of the primary louver system. To minimize the amount of debris and detritus in the holding tanks, clean, screened water is injected into the secondary bypass system.

Test Facilities and Features

It is not possible here to describe the details of the testing equipment nor the assumptions and methods of the study. Hence, I will only describe the most essential features. In order to determine the proportions of fish successfully louvered and those which failed to be louvered, we used fine mesh nets to capture the fish. Nets were hung from a specially designed frame and hoist system to capture those entering the secondary system from the primary bypasses. Six large nets, each 2.8 X 3.1 m (9 X 10 ft) at the mouth and 19.2 m (63 ft) in length were hung from a single frame to collect fish which were not successfully deflected by the primary louvers. The net frame was raised and lowered from a 10-ton hoist mounted on a large gantry. Only one line of louvers was tested in each of the two primary channels. The secondary louvers consist of a single line crossing the channel at 15 degrees to the flow. The 15.2-cm (6-in.) bypass is located at the downstream end. To test the secondary system, a large net of the same size mesh was suspended from a hoist situated behind the secondary louvers to capture fish which passed through the louvers. Fish which were successfully deflected were collected in a selected tank in the holding tank building.

All nets were specifically designed for the evaluation program, taking into consideration the volume of water to be passed, its velocity and debris conditions. The nets were fabricated from Marion Textiles pattern 281 nylon bobbinet because of its unusual strength and durability. The openings of the mesh were approximately 2.5 mm X 2 mm, but more eliptical than rectangular in shape. In the primary system, the nets had to be capable of handling a total of 43 m^3/sec (1500 ft^3/sec) [7.1 m^3/sec (250 ft^3/sec) in each of the six nets] in each bay. In the secondary system the maximum capacity was on the order of 6.8 m^3/sec (240 ft^3/sec) or 1.7 m^3/sec (60 ft^3/sec) in each of the primary bypass nets. Two work platforms, each about 4.9 m (16 ft) square with a center well, were specially designed and constructed to handle the primary test nets. Each platform was equipped with pneumatic winches to raise and lower the cod ends of the nets.

Test Parameters

Some of the parameters we tested included the following:

1. *Effect of the center wall* (divided versus undivided sawtooth array).
2. *Approach velocity.* Because of the variability in a functioning system, and to simplify analytical procedures, we established the following ranges of channel approach water velocities for both the primary and secondary systems: 0.46 to 0.61 m/sec (1.5 to 2.0 ft/sec); 0.61 to 0.76 m/sec (2.0 to 2.5 ft/sec); 0.76 to 0.91 m/sec (2.5 to 3.0 ft/sec); and 0.91 to 1.07 m/sec (3.0 to 3.5 ft/sec).
3. *Bypass acceleration ratio.* This parameter is defined as the ratio of the water velocity entering the bypass to the channel approach water velocity. We established the following ranges for bypass acceleration ratio: 1.2:1.33; 1.34:1.47; 1.48:1.60.
4. *Night versus day efficiency.*
5. *Valid test.* In order for a test to be considered valid, we required a minimum of three replicates of at least 10 fish.

Methods and Analytical Procedures

Here again it is not possible to go into detail. The salmon tests usually required from 0.5 to 1 hr to obtain a valid sample. For striped bass, the sampling time varied from 5 to 15 min. At the peak of their abundance, several thousands of fish were taken in a 5-min sample. When the numbers of fish were very large it was necessary to reduce them to aliquot portions. Special lattice work trays were designed for this purpose and the samples were properly weighted to account for this procedure.

Because of the critical nature of the relationship between fish length and louver efficiency the smallest fish (5 to 15 mm) were measured and segregated into 2.5-mm class intervals. Class intervals were graduated as fish size increased until the largest fish (50 to 100 mm) were placed in 25-mm intervals. These intervals were determined statistically. Analysis of variance procedures were then used to determine how each size class was to be treated in relation to each test parameter. Where these procedures indicated no statistical difference between size classes in relation to a specific test parameter, the size classes were combined.

Because the primary and secondary systems work in series, the efficiency of the installation is the product of the efficiencies of both systems. For example, if the primary system saves 80% of the fish approaching it and these fish are then subjected to the secondary system where 90% are saved, then the combined efficiency is 0.80 X 0.90 or 72%. Efficiency as a percentage as we have used it is defined as follows:

$$\text{Primary} = \frac{B}{L+B};\ \text{Secondary} = \frac{H}{l+H};\ \text{Combined} = \frac{B}{L+B} \cdot \frac{H}{l+H}$$

where B is the number of fish taken in the primary bypass nets; L is the number of fish taken in the primary louver nets; H is the number of fish taken in the secondary holding tank and; l is the number of fish taken in the secondary louver net.

The numerator is the number of fish that were successfully louvered into the bypasses, and the denominator is the total number of fish approaching the louvers. The denominator consists of the sum of those successfully louvered plus those which went through the louvers (unsuccessful).

The net efficiency of the installation (E_n) can be defined as:

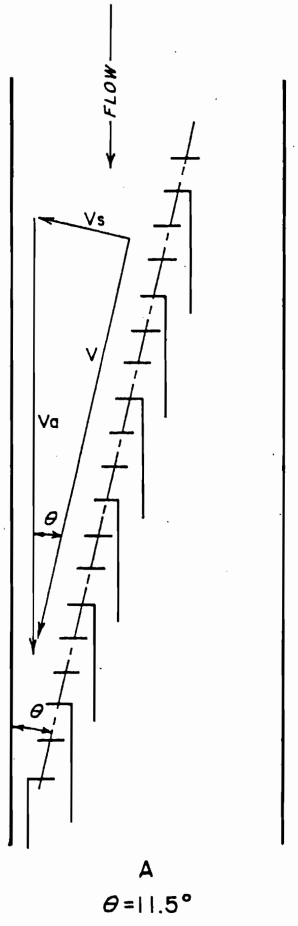
$$\sum_{i}^{n} = P_i\ S_i\ F_i$$

where Σ is the summation of size classes i to n; P is the primary efficiency of each size class; S is the secondary efficiency of each size class; F is the fraction of fish in each size class relative to the total population of fish entering the installation.

Louver Theory

No one has yet explained the underlying cause and effect relationships associated with louvers. We know they can be effective in deflecting fish. Our work has clearly established that their efficiency is related to the size of fish, and consequently to their swimming capabilities and physiological senses.

Bates and Vinsonhaler defined the relationship $V_s = V_a \sin \theta$ where V_s is the required swimming speed of the fish; V_a is the channel approach velocity and; θ is the angle of the louvers to the flow. These relationships are shown in Fig. 14 for a louver array at an angle of 11.5 degrees. This relationship suggests that, given the swimming speed of a fish and a design approach velocity, the angle of the louvers can be established. Similarly, both the approach velocity and the angle of the louver array can be compromised in design to obtain the greatest flexibility if the installation must accommodate fish of varying swimming capabilities.



Va = Approach velocity of flow in feet per second
Vs = Swimming speed of fish in feet per second
V = Resultant movement of fish in feet per second
θ = Angle of the line of louvers

FIG. 14. Diagram showing angle of louvers and vectors of force in flow and fish movement.

As a consequence of this relationship, it has been assumed that if a fish swims at V_s he will avoid being carried through the louvers. At the same time, the vector V, parallel to the line of louvers, will move the fish downstream toward the bypass. The time required to reach the bypass (the resultant) can similarly be calculated. It should be emphasized here that the above theory is simply an extension of trigonometric relationships. We hope that our program will ascertain the validity of these relationships with fish. Obviously, the presence of the screen structure itself is of some consequence.

RESULTS

King Salmon

Salmon were tested from March to June of both 1970 and 1971. The first year approximately 8300 downstream migrants, ranging in size from less than 50 mm to about 150 mm, were tested. In 1971 only 3700 salmon were involved and these fish were more restricted in size (50 to 100 mm). In 1970, the efficiency of independent primary tests ranged from 60 to 100%. Secondary louver efficiency was generally greater than 90%. For some, as yet unexplained, reason, fish from 100 to 125 mm were louvered less efficiently in the primary than smaller and larger fish. In the secondary system, efficiency was directly related to size. It is assumed therefore, that the lower efficiency of the 100 to 125 mm fish was a result of functional problems in the system and is not characteristic of the fish. In 1971 primary efficiency ranged from 85 to about 97% for fish 50 to 100 mm in length. Since 100 to 125-mm fish did not occur we could not verify the 1970 observation. The combined efficiency for salmon ranged from 65 to 84% in 1970 and from 84 to 90% in 1971. We are somewhat at a loss to explain the better overall results in the second year. We do know that the operators were better able to attain and maintain the test parameters in 1971.

Figure 15 depicts the relationships described above. The net efficiency of the installation (for king salmon in this case) is the last point on the cumulative efficiency curve. This curve permits an assessment of the relative value of a system for each size class of fish and their relationship to the total efficiency of the system. In this particular case, the curves for combined efficiency and cumulative efficiency were depressed by the low efficiency of 100 to 125-mm salmon. We concluded that efficiency is related to the length of the fish but that the importance of the relationship declines as the length of the fish increases. Similarly, velocity is much more significant for the smaller salmon. Obviously, these two variables are interrelated. As a fish grows, its swimming performance increases and velocity becomes less critical. This relationship is true of the other species also.

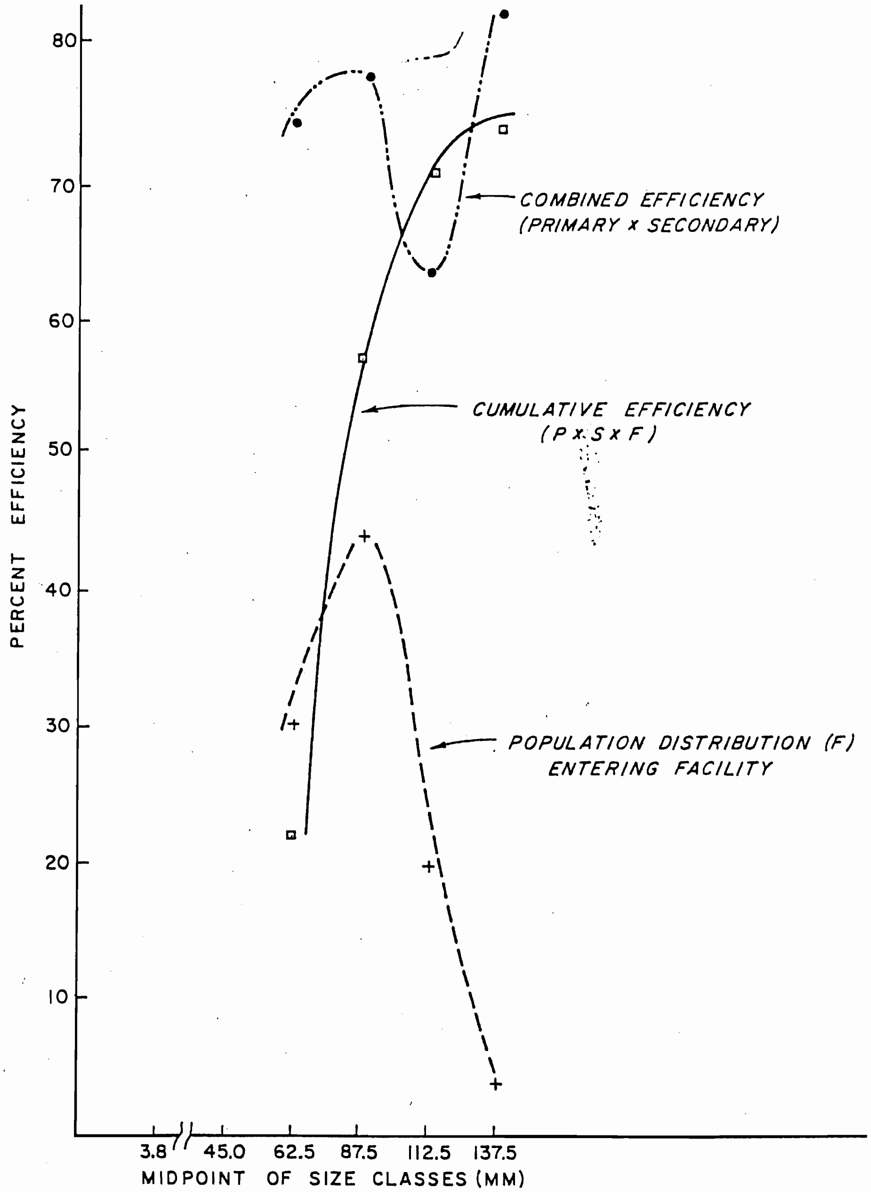


FIG. 15. Louver efficiency of the Delta Fish Protective Facility for king salmon (data for 1970-71 combined).

Striped Bass

Over 1.3 million striped bass were involved in our tests during the 2 years of the study. These fish occur in abundance at the facility from June through August. The size of fish in these tests ranged from 5 to 125 mm. Because of the importance of size, we examined the size-frequency distribution of fish entering each of the two primary bays in order to assist in evaluating potential differences between bays (Fig. 16). The examination revealed a comparatively higher proportion of small fish in Bay B and a comparatively higher proportion of large fish in Bay A. This observation could have resulted from a chronological bias in testing between bays; for example, favoring Bay B tests in the early part of the season while the smallest bass were abundant and/or favoring Bay A later when the fish were larger. However, a review of the data indicated there was not sufficient bias of this nature to account for the results observed. The distribution observed appears to be real, suggesting that the larger juveniles show a preference for the channel nearest the shore.

Fish Length

Efficiency was positively related to size in the primary system. Efficiency increased rapidly with size up to about 25 mm and thereafter the rate of increase decreased. The general relationship is shown in Fig. 17. Secondary efficiency was similar but better in relation to size.

Centerwall

The bay with the centerwall (A) was clearly superior to the bay without it (B) (Fig. 17). Presumably, the fish

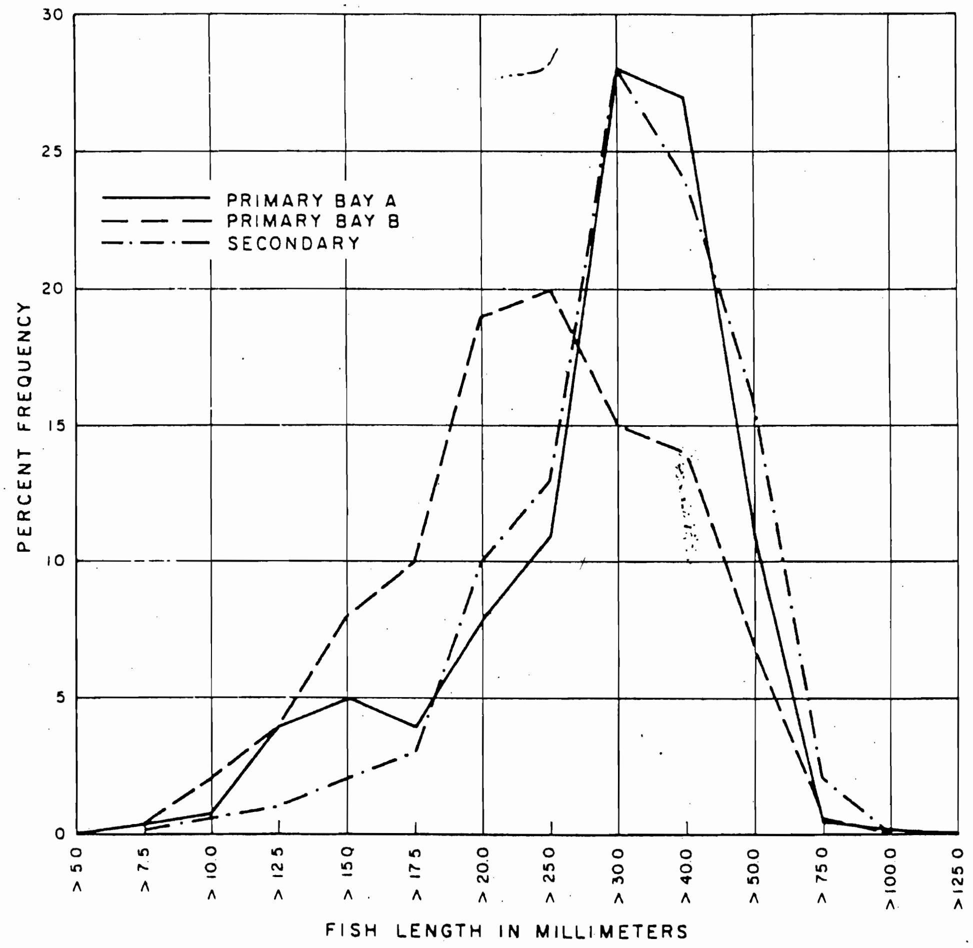


FIG. 16. Length frequency distribution of striped bass tested.

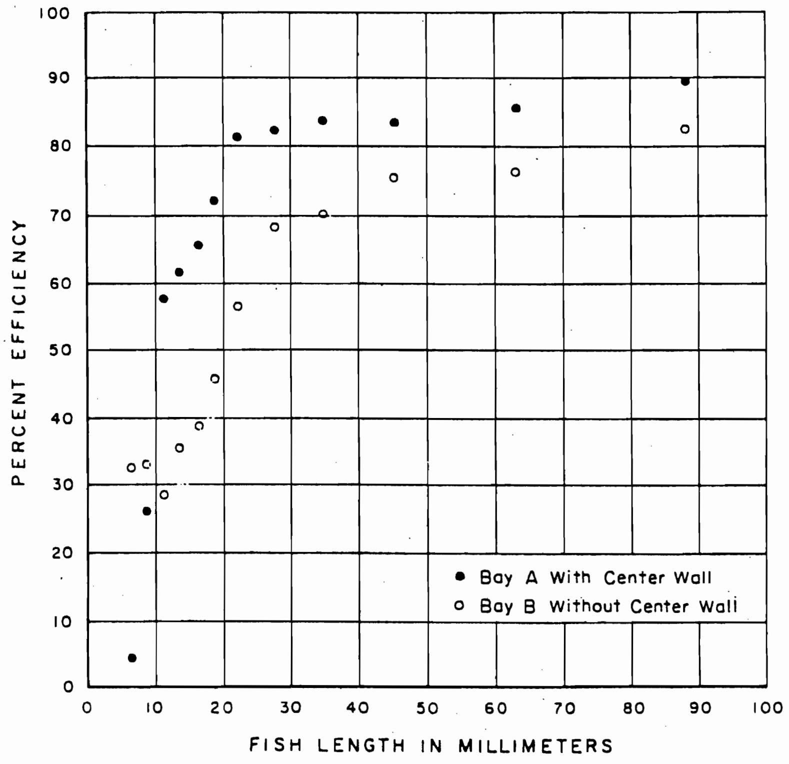


FIG. 17. Efficiency of primary louvers in relation to the length of striped bass.

are inclined to search for areas of lower velocity which are offered by the sides of a channel or, in this case, the centerwall.

Approach Velocity

As expected, there was an inverse relationship between efficiency and channel approach water velocity. This was apparent in the primary system where the composite results of all tests indicated a difference of up to 30% between the lowest and highest velocity ranges [0.46 to 0.61 versus 0.91 to 1.07 m/sec (1.5 to 2.0 versus 3.0 to 3.5 ft/sec)]. The difference was even greater in the bay without the centerwall.

Since conditions in the secondary system could be controlled better than those in the primary system the results were examined in greater detail to determine the relationship between efficiency and velocity (Fig. 18). The results clearly demonstrate that the lower velocities were the most favorable, at least for striped bass less than 30 mm in length. However, these results, for reasons that follow, are probably biased downward for fish less than 20 mm in length. A comparison of the velocity-efficiency relationship between the primary and secondary systems revealed a discrepancy for fish less than 20 mm in length (Fig. 19). The composite results for the two systems indicate that the primary system was the most efficient for fish less than 20 mm. This result was quite at odds with our intuitive expectations, particularly since conditions in the secondary can be controlled so much better.

After a thorough search for mechanisms that could have caused the discrepancy, I have tentatively concluded that a substantial proportion of the fish less than 20 mm in length escaped through the cylinder screen of the holding tank which received those fish successfully deflected by the secondary louvers. At all other points where fish were captured, nets of identical size mesh were used. In designing our test program we overlooked the possibility that the terminal holding facility might lose fish. Later investigation established the fact that the openings in the cylinder screens are about 7.5 square mm compared to 4.5 square mm for the openings in our nets. Figure 19 shows a definite loss of fish less than 20 mm in the secondary system, as compared to the primary system. Since the results are consistent for both primary bays and both points of entry into the secondary system, I believe they represent a true deficiency in the system. The obvious consequence is that the louvers are more efficient for these small fish than the results indicate. In comparing the primary and secondary systems, the secondary results show a definite downward bias for fish less than 20 mm. Put another way, the cylinder screens are a limiting factor in the efficiency of louvers for this size striped bass. The management implication is obvious. The cylinder screens in the holding tanks should be redesigned to retain the fish salvaged by the louvers.

Entry into Secondary

At the Delta Fish Protective Facility, fish from the two primary bypasses are discharged into the secondary system separately from side-by-side rectangular conduits. To complicate matters, the transition length from the point of discharge to the louvers is relatively short. As a consequence, fish discharged from the conduit on the same side as the bypass may only negotiate one-half the length of the louver. Those discharged from the other conduit, on the side opposite the bypass, not only confront the louvers sooner but also need to traverse a greater length of louver to reach the bypass. Our tests showed that fish discharged on the bypass side had a definite advantage over those discharged on the opposite side. The difference ranged from less than 5 to nearly 50%, depending on size (Fig. 20). Here also, it appears that efficiency can be improved by changes in design.

Bypass Acceleration Ratio

Bypass acceleration ratio is defined as the ratio of the velocity of water entering the bypass to the channel approach water velocity. Our tests to determine the effect of bypass ratio on efficiency were not very rewarding in terms of definitive criteria. In the bay with the centerwall, there was not a great deal of difference among bypass ratios, although ratios between 1.34 and 1.47 appeared to be best. In the bay without the centerwall, bypass ratios greater than 1.48 were best with ratios from 1.34 to 1.47 being the worst. Because the results at bypass ratios from 1.34 to 1.47 were generally contradictory between the two bays, we were unable to assess the true effect of bypass ratios. We were unable to detect a consistent relationship between secondary efficiency and bypass ratio. Efficiency varied widely among bypass ratios but there was no statistically significant difference between ratios. Although bypass acceleration ratio may be important, my analysis of results here and elsewhere leads me to conclude that other design features may need to be resolved before the effect of bypass ratio can be assessed properly.

Authorities generally agree that bypass design is critical for fish screens. This appears to be particularly true for louvers. Conventional louver design usually results in an incremental increase in approach water velocity which distorts the relationship between bypass ratio and the approach velocity. At this point I am convinced that approach velocity, bypass design and bypass acceleration ratio are so interrelated that the true effects of bypass ratio and approach velocity are confounded. Ducharme (1972), for example, observed that the relationship between approach velocity and efficiency was changed from a definitely negative to a slightly positive relationship simply by changing the bypass design.

Secondary Screened Water Ratio

The natural water passing through the fish facility

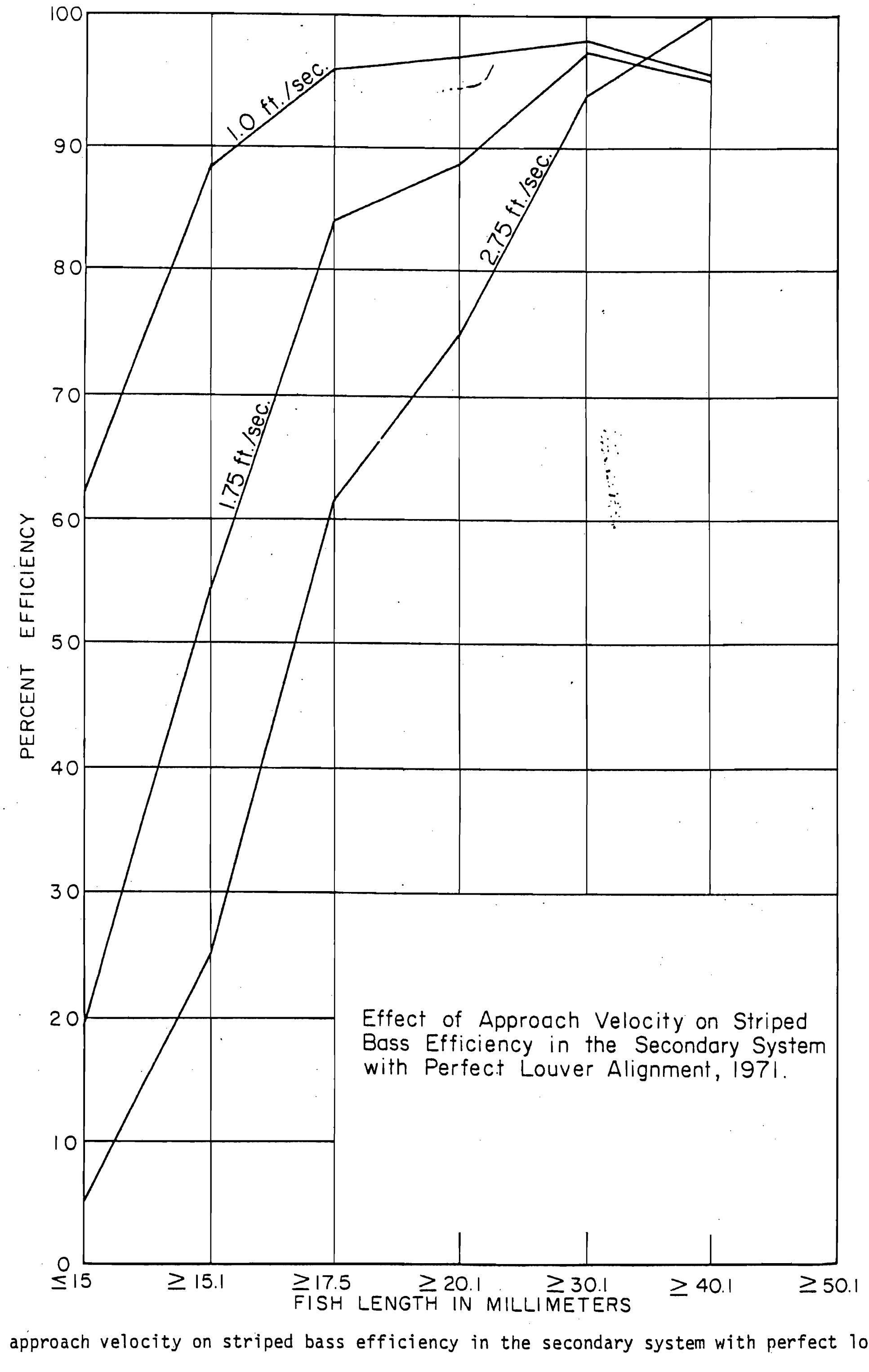


FIG. 18. Effect of approach velocity on striped bass efficiency in the secondary system with perfect louver alignment, 1971.

normally carries a heavy load of debris, particularly fibrous, vegetative material commonly called peat moss. To reduce the load of such material in the fish holding tanks an auxiliary water supply system injects clean screened water into the secondary bypass. Our program revealed that if the rate at which this screened water was injected into the bypass exceeded the approach water velocity in the secondary channel, efficiency was reduced (Fig. 21). At higher velocities apparently, the screened water deflects fish back toward and through the louver. As a result, we have recommended that the velocity of the screened water never exceed the approach velocity. This is another problem that should be considered in the design of a louver installation.

Diel Efficiency

At velocities less than 0.76 m/sec (2.5 ft/sec) there

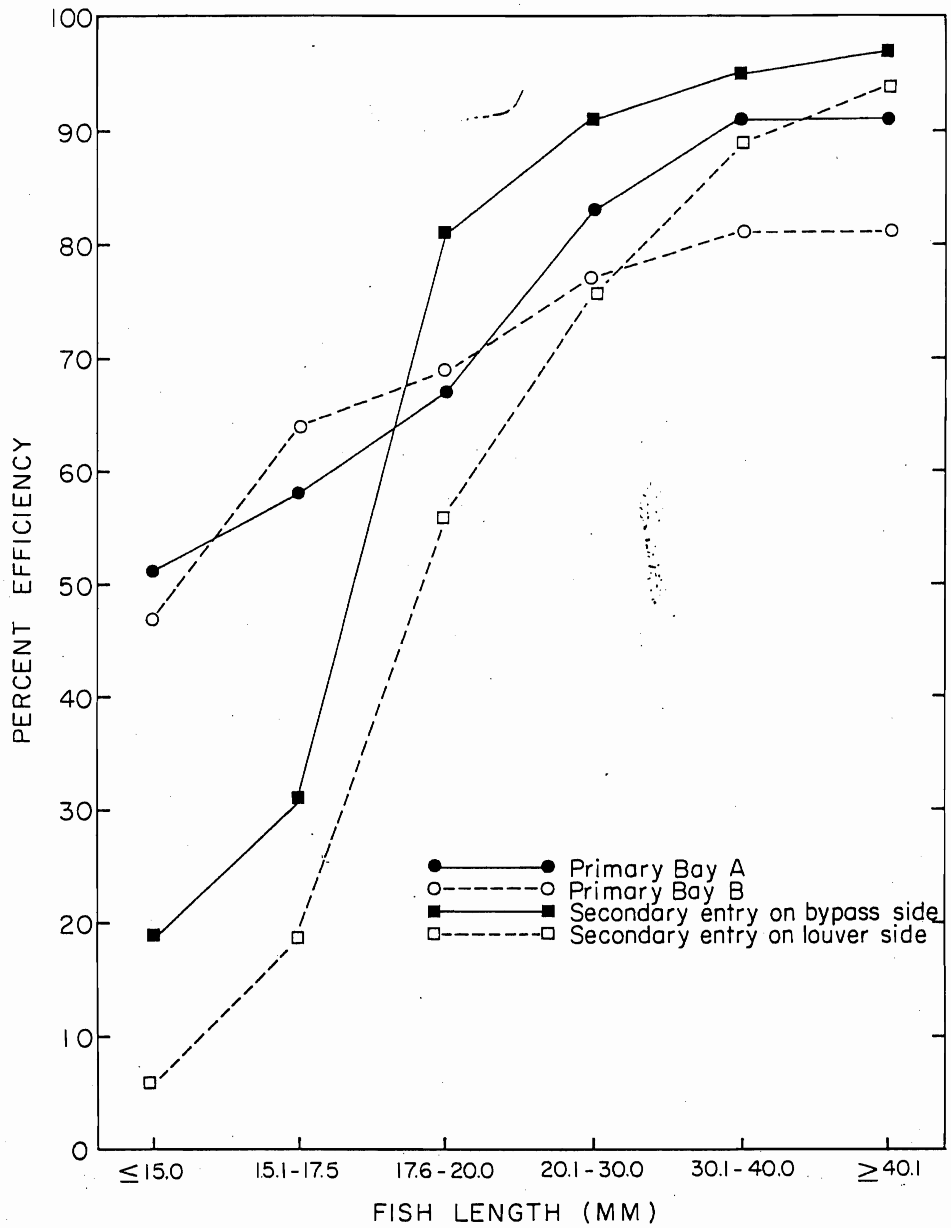


FIG. 19. Comparison of primary and secondary louver efficiency for striped bass at 0.46 to 0.61 m/sec (1.5 to 2.0 ft/sec).

was no apparent difference between night and daytime efficiencies among tests at various velocities. However, when the data were combined, efficiency was slightly superior at night. At velocities greater than 0.76 m/sec (2.5 ft/sec) efficiency was definitely better during the daytime. Such factors take on more than academic significance when a facility is operated on an off-peak basis to take advantage of reduced power costs. We have no definitive explanation for the result observed.

Net Efficiency

The net efficiency of the Delta Fish Protective Facility for striped bass for 1970 was about 69%. Figure 22 shows the length-frequency distribution of fish entering the facility, the combined (primary X secondary) efficiency and the cumulative efficiency of the facility. An inspection of the cumulative efficiency curve shows that no real gain in efficiency occurs until the fish reach 20 to 25 mm in length. Although efficiency may be relatively high for fish less than this length, they constitute a relatively small proportion of the total. This analysis suggests the possibility of incorporating a cost-effectiveness approach into louver design.

White Catfish

More than 87,000 white catfish were involved in our tests in 1970. These fish ranged in size from less than 10 mm to more than 125 mm in length. About 25% were less than 25 mm and 50% less than 40 mm in length.

Fish Length

Louver efficiency was directly related to length in both the primary and secondary systems (Fig. 23). Primary

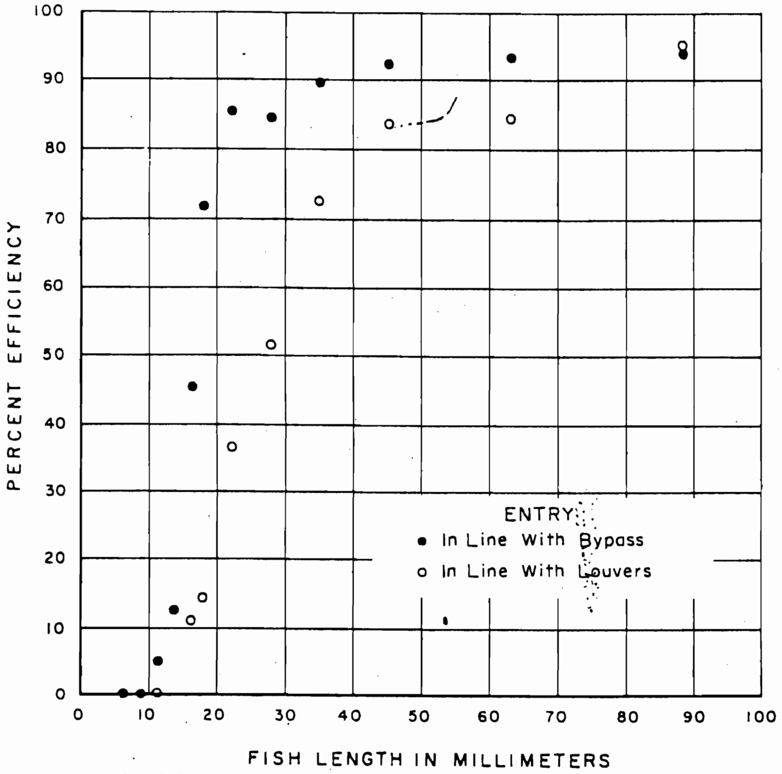


FIG. 20. Secondary efficiency of striped bass in relation to length.

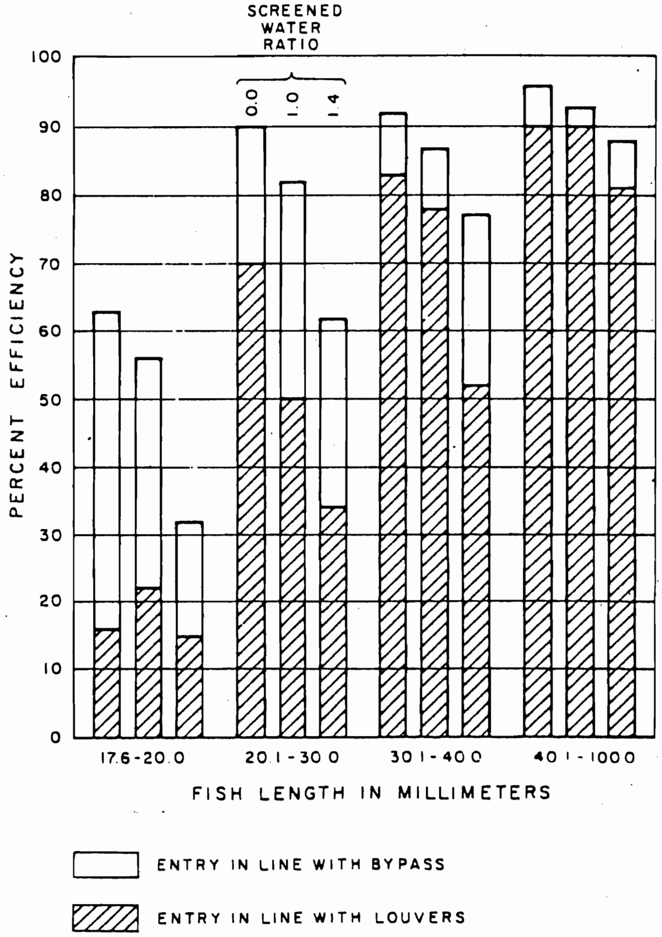


FIG. 21. Louver efficiency of striped bass in relation to the screened water ratio and entry into the secondary system.

efficiency ranged from 4% for 10 to 12.5-mm catfish to 68% for 75 to 100-mm catfish. Secondary efficiency was substantially superior to primary efficiency for fish over 20 mm in length.

It is interesting to speculate on the relative differences in efficiency between the primary and secondary systems for striped bass and white catfish. In the case of striped bass, secondary efficiency was clearly better than primary efficiency but only by a few percentage points. With white catfish secondary efficiency was most often 20 to 30% better than the primary for fish 20 mm and larger. We are clearly losing catfish in the primary system. It is possible that catfish find it difficult to negotiate the full 24.4-m (80-ft) length of the primary louvers.

Approach Velocity

Efficiency varied greatly with velocity. In both primary bays efficiency was usually best at the lowest velocity range [0.46 to 0.61 m/sec (1.5 to 2.0 ft/sec)], but it was not uncommon to attain relatively high efficiencies at the highest velocity range [0.91 to 1.07 m/sec (3.0 to 3.5 ft/sec)]. In Bay B the intermediate velocity ranges were the least efficient.

Effect of Centerwall

As in the case of striped bass, the centerwall appeared to be a distinct advantage (Fig. 23).

Entry into Secondary

Catfish entering the secondary channel on the bypass side were louvered more efficiently than those entering the opposite side. These results suggest that fish which must

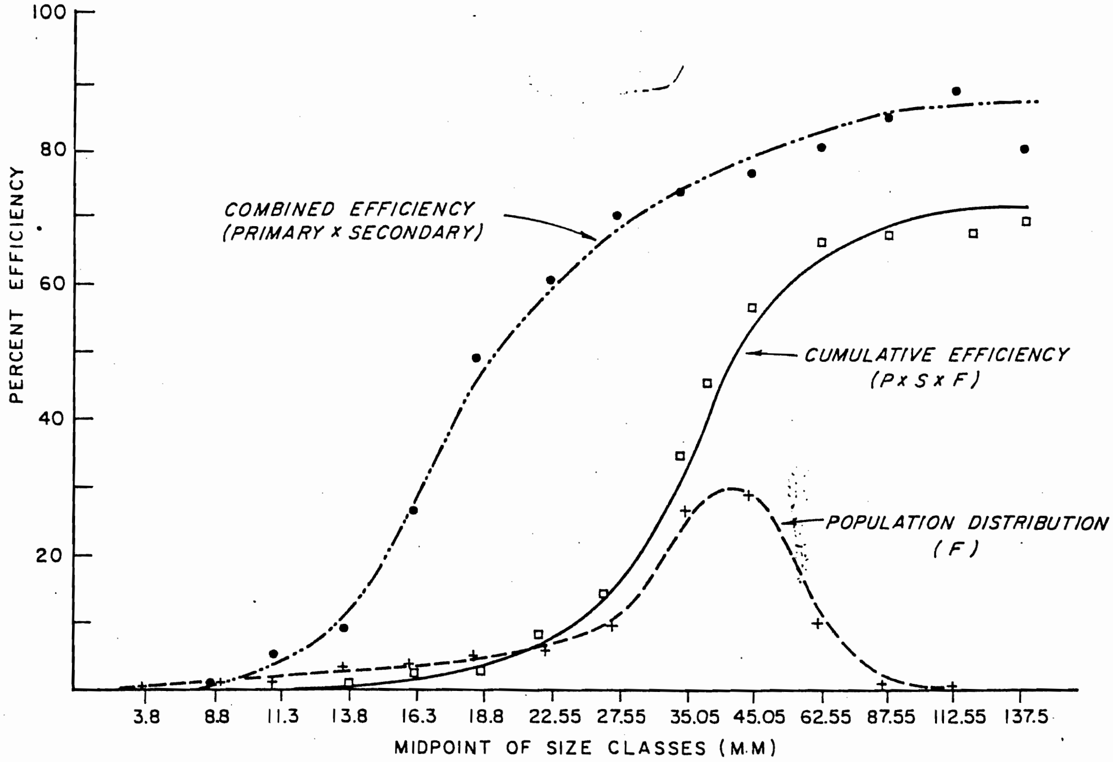


FIG. 22. Louver efficiency of the Delta Fish Protective Facility for striped bass (data for 1970).

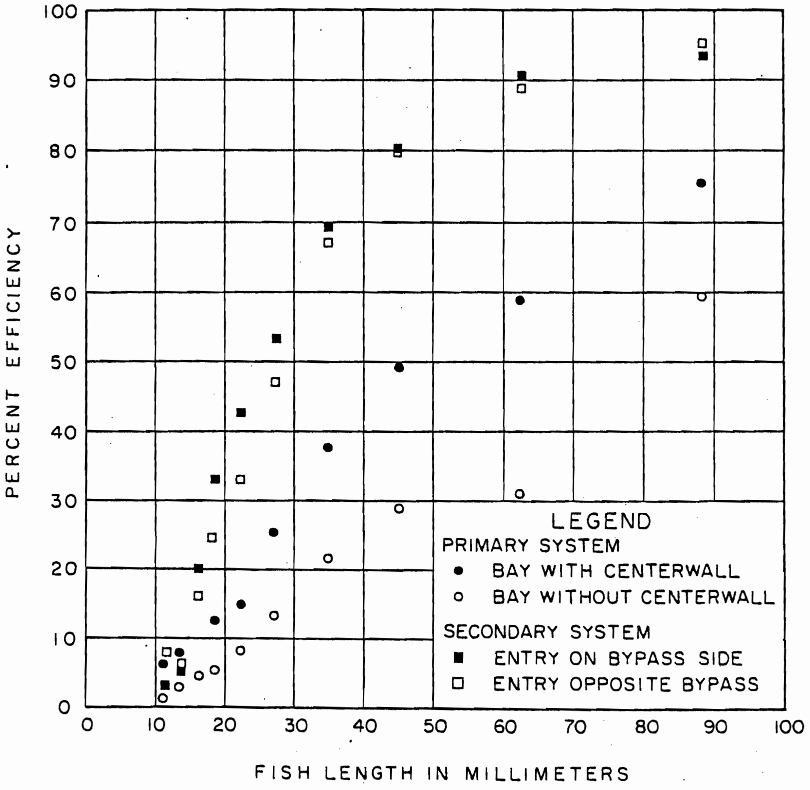


FIG. 23. Primary and secondary louver efficiency of white catfish in relation to size.

traverse the line of louvers are at a disadvantage. However, the point of entry into the secondary was not as important for catfish as it was for striped bass.

Diel Efficiency

In general, catfish response was similar to striped bass with respect to night and daytime guiding efficiency. Efficiency was greatest during the daytime when velocity exceeded 0.76 m/sec (2.5 ft/sec). The data indicate that efficiency at night decreases more rapidly than daytime efficiency under comparable increases in approach velocity.

Net Efficiency

Figure 24 shows the combined efficiency and cumulative efficiency for white catfish as well as the length-frequency distribution of catfish entering the Delta Fish Protective Facility. Even though efficiency reaches a respectable level for the larger fish the net efficiency (last point on cumulative efficiency curve) of the facility for white catfish was only 22%. Ten percent efficiency is not attained until 35- to 40-mm fish are encountered. This result is due to the combination of poor efficiency of small fish in the primary system and the large proportion of small fish. These results suggest that either louvers are not a good concept for white catfish, or the operation of the louvers may need to undergo substantial modification in order to salvage this species. The good results obtained in the secondary system favor the latter because it indicates louvers have reasonably good potential to salvage catfish.

Some General Observations About Louvers

Louver Alignment

Following construction of the Delta Fish Protective Facility, many of us were concerned about gaps of several inches between louver panels and the misalignment of adjacent louver sections. It was assumed these construction deficiencies distorted the flow pattern along the line of louvers and would therefore reduce efficiency. To assess the effect of louver alignment on efficiency, we undertook a study program using the secondary system in which the louvers could be more readily adjusted. Figure 25 shows the seven basic configurations we tested. The numbers in-

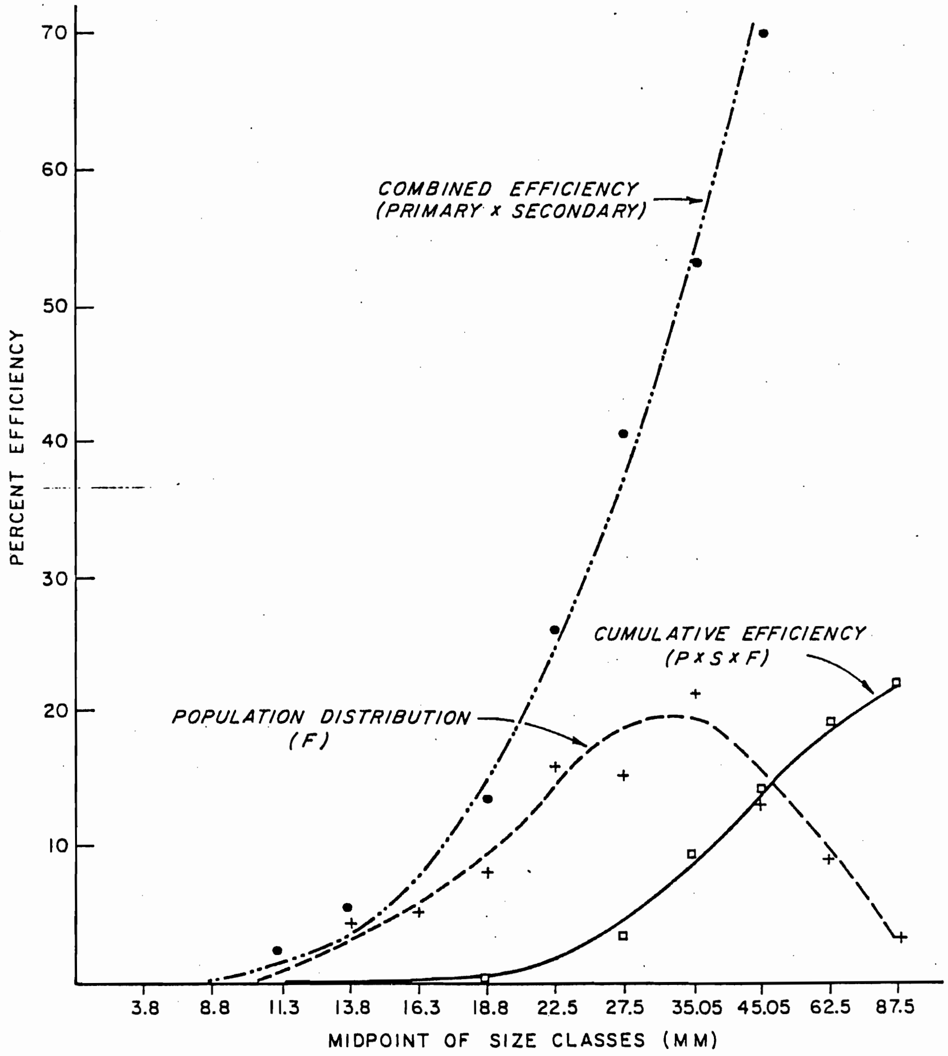


FIG. 24. Louver efficiency fo the Delta Fish Protective Facility for white catfish (data for 1970).

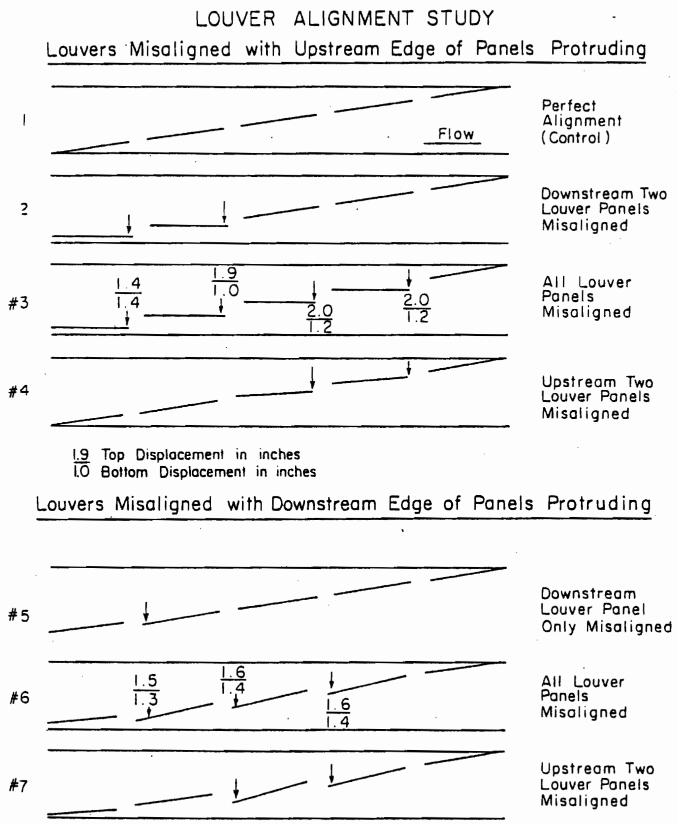


FIG. 25. Louver alignment configuration.

dicate the amount of lateral displacement achieved relative to the adjacent panel.

We ran tests at several velocities involving more than 800,000 striped bass. However, to simplify the results I will only show those obtained at 0.53 m/sec (1.75 ft/sec). The results were quite startling (Fig. 26). For fish less than 30 mm in length the conditions tested resulted in slightly superior efficiencies than the control situation (perfect alignment). The best results were achieved when the downstream ends of the panels were deflected toward the bypass. We concluded, therefore, that louver alignment and gaps are probably not critical with the range of misalignment we tested.

Approach Velocity and Fish Length

It is apparent from our tests that even very small fish can be guided quite well, given the proper conditions. The relationship between fish length and approach velocity is critical. Our tests indicate that the smallest fish achieved the highest efficiency at the lowest velocities. Although we tested very small fish our test design did not include velocities less than 0.31 m/sec (1.0 ft/sec). It is probable that higher efficiencies can be achieved at velocities less than 0.31 m/sec (1.0 ft/sec). In light of the critical relationship between efficiency and approach velocity at least two matters are paramount to louver design. First, it is essential to know the sizes of fish encountered and their swimming capabilities. Secondly, it is necessary to design the facility with sufficient capacity and adequate control structures to provide rigid velocity control.

Facility Design

Our observations suggest that louvers have immense potential but a great deal more research and development is necessary to perfect them. Perhaps those matters requiring most urgent attention are the following:

1. Hydraulic and related biological studies on bypass design including the terminal louver sections in the vicinity of the bypass.
2. Hydraulic and related model studies to develop a channel design which will provide a uniform channel approach velocity.
3. Studies to evaluate the effect of prelouver deflectors and louver array configurations.
4. Biological and physiological studies to determine the effective guidance mechanisms of fishes and the age at which such mechanisms become functional.
5. Further research to determine the transitional length of channel required between the louvers and such upstream facilities as trashracks and control structures.
6. Additional research and development on the discharge and bypasses of secondary systems including the injection of screened water.
7. Additional research on holding facilities to minimize physical injury, improve water conditions and minimize losses from the system.

Acknowledgments

The results reported herein are simply the essence of two much larger programs. Portions of these were conceived by my predecessors and I have had substantial assistance along the way in carrying them to their present levels of completion.

Mr. William Heubach, Associate Fishery Biologist, directed the biological phase of the field program for the louver study and is directing the present laboratory studies aimed at developing the fish facility design criteria. He also is responsible for most of the statistical procedures, analysis and evaluation. Messrs. Marcus Sazaki and Phil Hansen, Assistant Fishery Biologists, headed field crews for the louver evaluation program and Marc did the bulk of the data tabulation, processing and analysis after Mr. Hansen left the program.

Mr. Herbert Hyde, Senior Engineer with the Department of Water Resources, guided the engineering aspect of the louver program, including the design and construction of the test facilities. Mr. A. B. De Jarnett served as engineer in charge of the louver testing program in 1970. Mr.

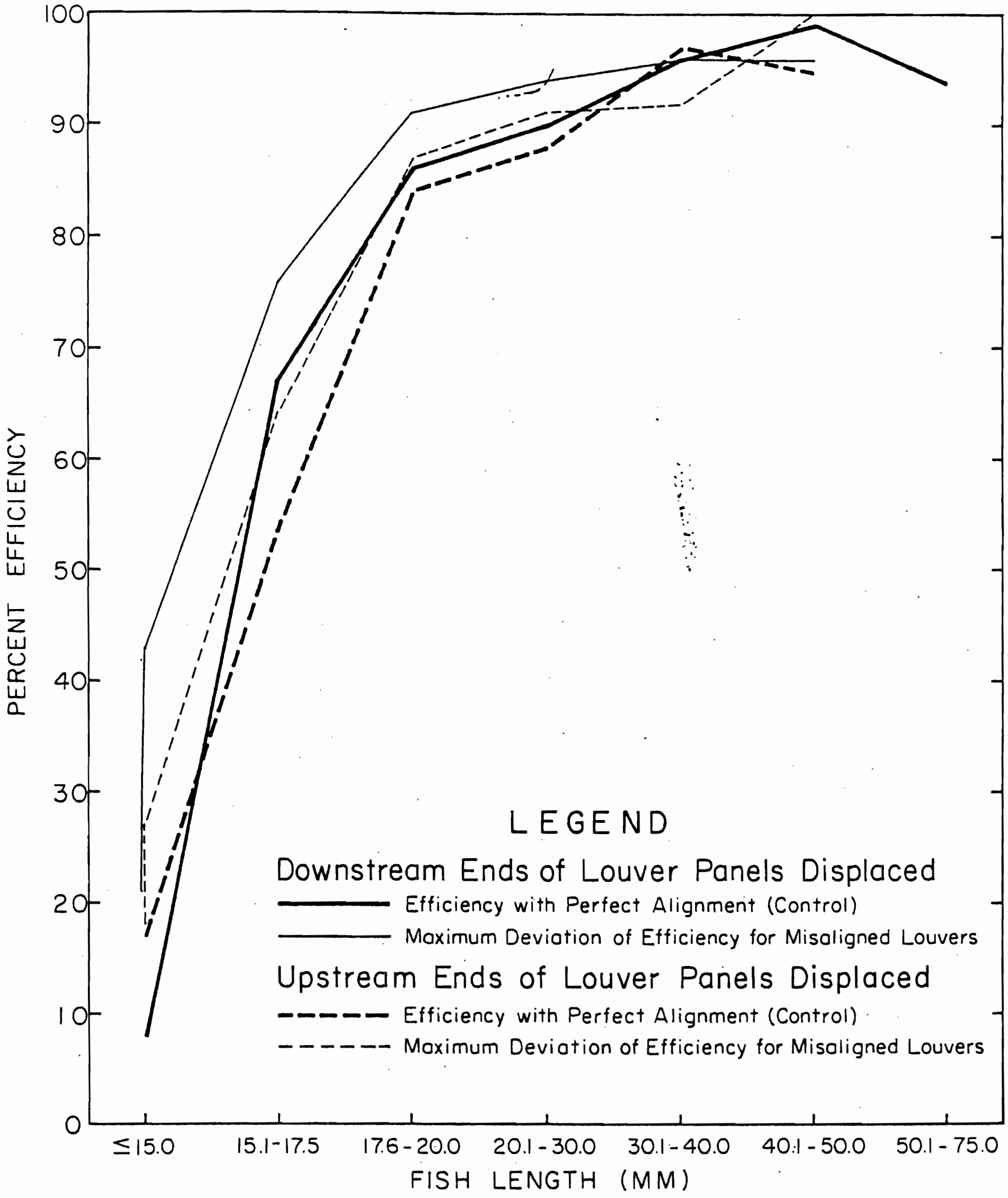


FIG. 26. Effect of louver alignment on striped bass efficiency at 0.53 m/sec (1.75 ft/sec).

William Kritikos, Chief of the Delta Field Division (Department of Water Resources) and his staff, whose facilities have been used for most of the research, have been extremely cooperative and instrumental to the success of the program.

Messrs. Russell Franson, Ron Lunsford and James Gibboney of the Department of Water Resources, form the engineering support for the fish facilities program. They designed and implemented the construction, repair and maintenance of the test facilities.

Mr. Richard Beland, Fisheries Management Supervisor, Fred Groh, Werner Jochimson, Philo Jewett and Frank M. Cochrane, all hatchery managers, deserve particular thanks for their assistance in providing us with fish, equipment and/or the use of their facilities.

Miss Nancy Dong, Mr. Kenneth Gonzalez and Harry Inouye did the illustrations.

Mr. Harold K. Chadwick, Program Manager of the Bay-Delta Fishery Project has, at all times, been a patient and helpful critic of the program.

To these, and the many others I have failed to mention, I wish to extend my sincere appreciation.

BIBLIOGRAPHY

Bates, D. W., R. Vinsonhaler and D. F. Sutherland. 1964. Preliminary tests with louvers in the Troy laboratory on the Grande Ronde River. Fish Passage Research Program, Review of Progress 1964, Vol. III.

Beamish, F. W. H. 1966. Swimming endurance of some northwest Atlantic fishes. J. Fish. Res. Board Can. 23: 341-347.

Ducharme, L. J. A. 1972. An application of louver deflectors for guiding Atlantic salmon smolts from power turbines. J. Fish. Res. Board Can. Vol. 29, No. 10.

Greenland, D. C. and A. E. Thomas. 1972. Swimming speed of fall chinook salmon (*Oncorhynchus tshawytscha*) fry. Amer. Fish. Soc., Trans. 101:696-700.

Kerr, J. E. 1953. Studies of fish preservation at the Contra Costa Steam Plant of the Pacific Gas and Electric Co. Fish. Bull., No. 92, Calif. Dept. Fish and Game.

Author's address:

John E. Skinner
Department of Fish and Game
3900 North Wilson Way
Stockton, California 95205