U.S. Army Corps of Engineers
Portland District

Effects of Dam Passage on Juvenile Pacific Lamprey (*Lampetra tridentata*)

FINAL REPORT

January 2001

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy
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Effects of Dam Passage on Juvenile Pacific Lamprey (*Lampetra tridentata*)

FINAL REPORT

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January 2001

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Executive Summary

Pacific Northwest National Laboratory (PNNL) initiated studies to evaluate the swimming performance and behavior of juvenile Pacific lamprey (*Lampetra tridentata*). Studies were conducted both in the laboratory under controlled conditions and in the field. This information was needed to provide for future guidelines regarding juvenile lamprey downstream passage survivorship at hydroelectric dams located within the Columbia River basin. Our initial objectives (initiated in 1999) involved conducing studies to determine impingement rates using 1/8-in. bar screens, swimming performance, and effects of shear forces on juvenile lamprey. In 2000, we expanded our evaluation to include impingement rates using different screen materials, effects of angled screens, effects of light and pressure, and a field study to determine lamprey/screen interactions.

A series of trials were conducted at PNNL's Aquatic Laboratory to evaluate the relationship between velocity and duration of exposure resulting in juvenile lamprey impingement at time scales representative of a typical extended length submerged bar screen (ESBS) cleaning brush cycle period. These experiments showed that the longer lamprey stay on the screen and the higher the velocity, the more likely they were to become permanently wedged into 1/8-in. bar screen. This generalization appears consistent for both experimental laboratory results and direct field observations. The 1/8-in. bar screen material currently used in ESBS is more likely to result juvenile lamprey becoming permanently wedged into the bar spacing than in 3/32-in. bar screen or 1/8-in. submerged traveling screen (STS) mesh. A vertical orientation of the bars aligned with the direction of sweeping velocities, resulted in lower impingement rates than a horizontal orientation.

Studies to determine avoidance responses to light were favorable. Juvenile lamprey tested in static and flowing water showed a marked avoidance response and increased activity when subjected to high-intensity halogen or strobe lights. Lamprey were subjected to an abrupt pressure spike simulating turbine passage exhibited no immediate or latent injuries.

A field study conducted at McNary Dam using underwater video cameras documented lamprey partially impinged (unable to lift themselves away from the screen face), because of the water velocity inside an operating intake. Lamprey observed beginning the tail-first penetration process were able to free themselves by volitionally extracting their tail from between the bar spacing. Sweeping velocities along the screen appeared to push the lamprey up the screen toward the gatewell.

Studies to date show that juvenile lamprey are not likely to be harmed by changes in pressure and shear conditions present during turbine passage. However, they are vulnerable to impingement on 1/8-in. ESBS bypass screens because of their weak swimming ability and tendency to use their tail to move on the structure. Tail protrusion was rarely observed when lamprey were tested with 1/8-in. STS and 3/32-in. bar screen.

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We sincerely acknowledge the cooperation, assistance, and hard work of the following:

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1.0 Introduction

1.1 Goals and Objectives

The goal of this study was to determine the effects of turbine intake passage on the behavior and survival of juvenile Pacific lamprey (*Lampetra tridentata*). The results of this study will provide the Corps with information to mitigate any adverse effects of extended length submerged bar screens and project operations on juvenile Pacific lamprey. This information is designed to be generally applicable for all hydroelectric projects in the Columbia River system.

Specific objectives for CY 2000 were to:

1. evaluate potential injury mechanisms and the effects of juvenile bypass screens on juvenile behavior and survival

2. document impingement and mechanisms of injury in the field

3. evaluate effects of pressure changes expected to occur during turbine passage

4. recommend potential structural and operational means to improve passage survival of juveniles

1.2 Background

Pacific lamprey is the largest and most abundant lamprey species in the Snake and Columbia river system (Wydoski and Whitney 1979). It is parasitic as an adult in the ocean, migrates into freshwater to spawn, and larvae develop in the gravel-mud substrate for several years before migrating downstream as young adults. The current distribution of the Pacific lamprey extends from the mouth of the Columbia river to Chief Joseph and Hells Canyon dams, in the mainstem Columbia and Snake rivers, respectively. Principal spawning and rearing habitats occur in tributary streams (Kan 1975), with limited use of mainstem corridors except during adult and juvenile migration periods.

A widespread decline in numbers of Pacific lamprey has occurred since the 1960s, the period when most dam construction occurred in the lower Snake and Columbia rivers. This decline has been attributed to several causes, including habitat loss, water pollution, ocean conditions, and dam passage (Close et al. 1995). Although studies have been initiated to investigate potential causes of population decline, the emphasis has been on abundance monitoring, adult migration, and habitat restoration. No studies have specifically addressed effects of dam operations on juvenile passage and survival.

Operations at mainstem hydroelectric projects may impact juvenile lamprey during downstream passage. Juvenile lamprey also have a higher potential for entrainment through turbines because they swim lower in the water column than anadromous salmonids (Long 1968). Their ability to survive turbine passage, including response to changes in pressure, turbulent flow, and shear stress are unknown.

A critical uncertainty is how juvenile lamprey interact with barrier screens installed at projects to bypass fish into collection facilities. For example, some investigators have reported large numbers of juvenile lamprey impinged between individual bars of fixed bar screens at The Dalles and McNary dams (Hatch and Parker 1998). Addressing the uncertainties associated with these potential mortality factors is the focus of this research.

1.3 Summary of Previous Studies

Laboratory studies completed in 1999 characterized diel swimming behavior, burst swim speed, and effects of velocity on impingement at bar screens. The effects of shear on survival and injury were also evaluated. Our studies demonstrated that juvenile lamprey have a distinct activity period limited almost entirely to periods of darkness. Individual lamprey spent most of their time attached to substrate during the daylight period and actively swam during darkness. Average burst speed for juvenile lamprey during swim trials was 2.3 ft/s or 5.2 body lengths/s. Juvenile lamprey became impinged on bar screens at velocities of 1.5 ft/s or higher during exposures in the swim chamber. Physical model data suggests the average perpendicular velocity at a typical turbine bypass screen is 2.4 ft/s. Tail-first penetration behavior was documented with video cameras in our laboratory test screen system. This behavior resulted in fish being stuck between the bars, a response similar to that observed at John Day and McNary dams. Juvenile lamprey were not injured at shear exposures known to kill and injure juvenile salmonids and juvenile shad.

2.0 Methods

Laboratory evaluations for 2000 focused on characterizing the behavior and performance of juvenile lamprey encountering ESBS. Swimming behavior and threshold impingement velocities were characterized during or following the juvenile outmigration period. Replicate tests were conducted over a series of conditions (e.g., velocity and light regimes) that lamprey may encounter during passage. We also evaluated the response of juvenile lamprey to light and pressure. Test animals were acquired from the fish bypass facility at John Day Dam in April. Field studies were initiated at McNary Dam to determine the feasibility of documenting lamprey when they encounter an ESBS.

2.1 Laboratory Tests

2.1.1 Time-Velocity Screen Exposure

The tests represent an expansion of 1999 methods and results, where a series of trials were conducted to evaluate the relationship between velocity and lamprey impingement. The objective of these tests was to evaluate the swimming endurance of impinged lamprey. The time period for these tests was selected to mimic the duration that lamprey might spend on the screen face before being removed by the cleaning brush. The normal brush cycle on an operating unit occurs every 20-min at most projects with ESBS.

A 17 in. × 17 in. section of 1/8-in. spaced, wedge-wire bar screen was deployed in a 600-gal Brett-type flow respirometer (Brett 1964); the screen was placed perpendicular to the flow within the swim chamber (Figure 1). In three replicate trials, separate groups of 10 lamprey were exposed to velocities of 2.0, 2.5, 3.0, or 3.5 ft/s, for a duration of 20-min followed by a 10-min period at zero flow to observe whether impinged lamprey would be able to free themselves from the screen material. Two additional trials were conducted for a 10-min duration, and one for a 5-min duration, at velocities of 2.0, 3.0, and 4.0 ft/s, again followed by a 10-min observation period. Initially, replicates were conducted in the order 2.5, 3.0, and 3.5 ft/s. After an initial analysis of the data additional trials were then conducted at 2.0 and 4.0 ft/s. These and all subsequent laboratory tests were conducted from 2000-2400 hr, in the dark, using infrared illuminators. Appendix A describes the testing schedule and replicate order used for screen impingement laboratory tests.

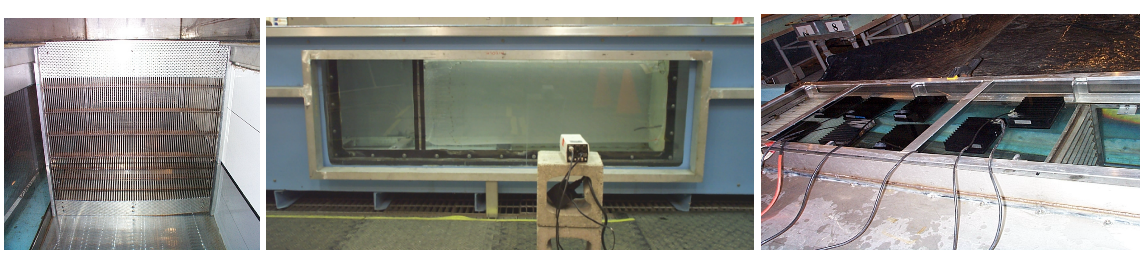

Figure 1. Bar Screen in Position, Side View of the Swim Chamber, and Infrared Illuminators Positioned Above the Viewing Window

2.1.2 Screen Orientation

To investigate whether changing the directional alignment of the bars that make up the bar screen material would reduce the incidence of lamprey impingement, two orientation angles were compared, one with the bars oriented vertically and the other with the bars oriented horizontally. The screens were deployed at an angle of 10° from vertical in the swim chamber and provided upward sweeping velocities not present in our standard perpendicular deployment (Figure 2). Two replicate sets of trials at velocities of 2.0, 3.0, and 4.0 ft/s, and one set at 5.0 ft/s at 48°F were conducted with 10 lamprey in each trial. The tests were run for 10-min, followed by a 10-min observation period at 0 ft/s flow, unless all the lamprey were swept over the screen, in which case the test was stopped after the last individual left the screen face.

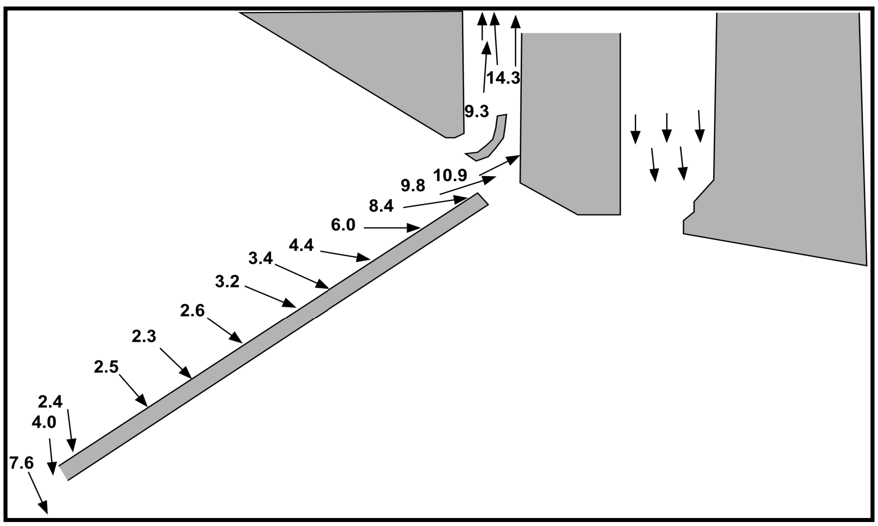

Figure 2. Cross-Section Diagram of the Velocity Vectors at a Deployed ESBS (John Day Dam) Based on Physical Model Data from the Corps

2.1.3 Screen-Type Comparison

To compare the impingement potential of different screen types, comparative tests were conducted with 1/8-in. bar screen (ESBS material), 3/32-in. bar screen, and 1/8-in. nylon STS material. The screens were deployed perpendicular to the flow in the swim chamber. For each of three replicate tests, 10 lamprey were exposed to the screens at velocities of 2.0, 3.0, and 4.0 ft/s. The test duration was 10-min, followed by a 10-min observation period at 0 ft/s flow.

2.1.4 Phototactic Response

Laboratory tests in 1999 showed that juvenile lamprey have a marked negative phototactic response and led us to examine the potential use of light as a deterrent for juvenile lamprey. A series of tests was conducted in the laboratory with both high-intensity strobe and white light. The strobe light tests were conducted with a single flashhead that operated at 300 flashes per minute (fpm). The white light tests were conducted with a 250 W underwater halogen light. All tests were conducted in the dark, during the late evening and nighttime periods (2000-2400 hr), from June through August 2000.

Static Test

Tests were conducted in a reinforced-steel oval fiberglass tank measuring 10-ft wide × 24 ft long × 6 ft deep. A total of 10 lamprey were acclimated to 62°F well water and placed in a net pen constructed of 1/8-in. square plastic netting with overall dimensions of 4 ft × 4 ft × 7.5 ft. The net pen was divided in half to quantify lamprey movements. The strobe light was initially posited at one end of the net pen and the light directed horizontally into the pen. When test trials were conducted, the majority of the lamprey swam to bottom portion of the net pen. All subsequent tests were conducted with the strobe mounted approximately 10-in. from the floor of the net pen pointed upward (Figure 3). Lamprey movements were quantified by visually determining location before and after test and control periods.

For each test replicate, 10 lamprey were placed in the net pen and allowed to acclimate for 3 to 4 hr. Each test was 2-hr in duration, broken into 10-min intervals for a total of 12 events. Six treatment events were chosen randomly for the light tests with the remaining six events being control responses. The treatment or control event started at the beginning of the 10-min interval. A treatment event included activating the light for a total of 40-s and recording the number of lamprey in the lighted and non-lighted half of the pen before and immediately after the light was turned off. Control responses were measured over the same duration with no stimulus applied. In addition, the strobe light was moved to either the right or left half of the net pen halfway through the six test periods. A total of eight 2-hr test replicates were conducted.

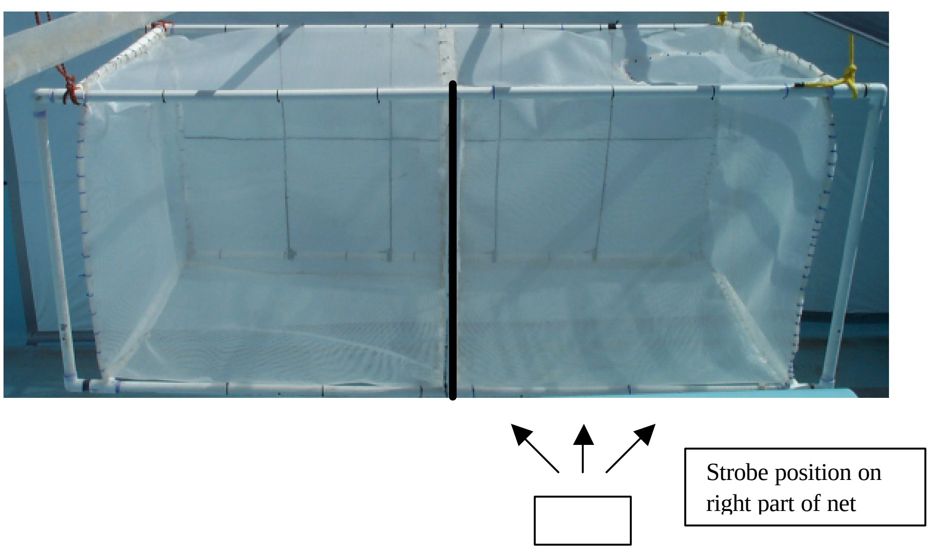

Figure 3. Static Strobe Test Net Pen with Light Position at Right Half of Pen

Light Test with Flow

Both white (halogen) and strobe light tests were conducted in the swim chamber. The lights were fastened to an aluminum pole and positioned 10-in. away from the downstream end of the net pen. A total of 10 lamprey (4.6 to 5.8 in.) were placed inside a 16-in. diameter × 4-in. length mesh tube located inside the swim chamber (Figure 4). The cage was submerged in the swim chamber with a clear lid placed over the cage. The purpose of this mesh tube was to prevent lamprey from adhering to the sides, lid, or floor of the swim chamber. The lamprey were allowed a 1-hr acclimation at 48°F before testing began. The test duration was 2-hr, which was broken up into 5-min intervals for a total of 24 test event periods. The 24 events were split into 12 randomly selected treatment events and 12 control events (Table 1). A total of 3 strobe and 5 white light tests each lasting 2-hr were conducted. The strobe light operated at 300 fpm.

All test events were conducted in the following sequence 1) turning the flow to 0.5 ft/s one minute before activating the light 2) activating the light source for 1-min with continuous water flow 3) turning off light source and, 4) leaving flow on for an additional 1-min. The control period was identical with the exception of the light stimulus. A video camera with the aid of IR lighting was used to record and document lamprey response and location. Two response categories were used 1) flight response (number of lamprey that swam away from the source within the first 15-s), and 2) avoidance response (number and location of lamprey prior to and immediately after the 1–min test period).

Light intensity measurements made within the cage were averaged over three depth ranges. The measured intensity of white halogen light was far greater than the strobe light. The true intensity of the strobe is assumed to be greater as the meter measured the average intensity at 300 fpm. The intensity measured ranged from 177-942 $\mu E/m^2/s$ for the white light and 51-115 $\mu E/m^2/s$ for the strobe light (300 fpm) depending on distance from the source (Figure 5).

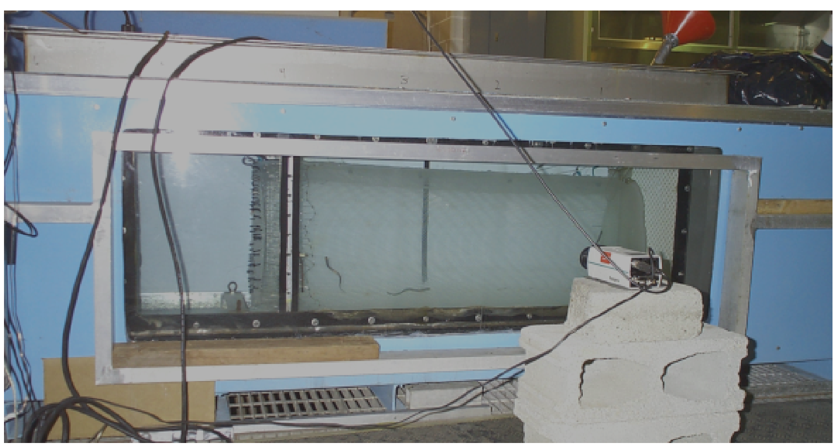

Figure 4. Position of Camera and Mesh Cage Located Inside Swim Chamber

Table 1. Randomization Periods for the Eight Tests Involving White and Strobe Light Stimuli

Time	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
5 min	test	control	control	test	test	test	test	control
10 min	test	test	test	test	control	test	test	test
15 min	control	control	test	control	control	control	control	test
20 min	control	test	control	control	test	test	control	test
25 min	control	test	test	control	test	test	control	control
30 min	test	test	control	test	test	control	control	test
35 min	test	test	test	test	control	test	test	control
40 min	control	control	control	control	test	test	test	control
45 min	control	control	control	test	test	control	test	control
50 min	test	test	test	control	control	control	test	test
55 min	control	control	control	test	control	control	test	test
60 min	control	test	control	control	control	control	control	control
65 min	control	control	control	control	control	test	test	control
70 min	test	control	test	control	control	control	control	control
75 min	test	control	test	test	test	control	control	control
80 min	control	test	test	test	control	control	control	control
85 min	test	control	control	control	test	control	test	test
90 min	control	test	control	test	test	control	test	control
95 min	test	control	test	test	test	test	control	test
100 min	test	test	control	control	test	test	control	test
105 min	control	control	control	test	control	test	control	test
110 min	test	control	test	test	control	control	test	test
115 min	test	test	test	control	control	test	test	control
120 min	control	test	test	control	test	test	control	test

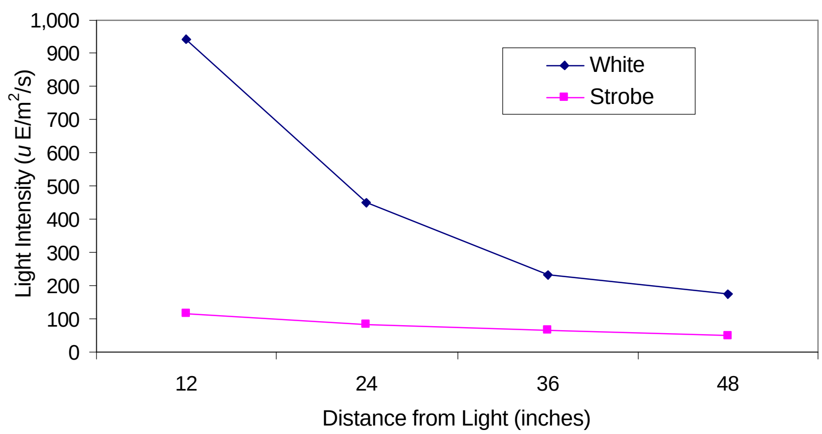

Figure 5. Strobe and White Light Intensities Measured at 12-in. Intervals Within the Swim Chamber

2.1.5 Pressure

The response of juvenile lamprey to changes in hydrostatic pressure using a turbine passage simulation apparatus (i.e., hyperbaric chamber) was documented. The absolute changes in pressure were designed to be similar to those that fish would experience during passage through a turbine environment. We tested what we considered to be a single worst-case scenario for lamprey; or bottom-acclimated with a surface return. The lamprey were acclimated to an equivalent pressure of 60 ft depth for 24-hr prior to passage. Two tests were conducted consisting of paired treatment and control groups (20 lamprey in each group). The exposure system consisted of paired swim chambers, a gas exchange sub-system, and a water supply sub-system (Figure 6). The paired system allowed for the control group to be exposed simultaneously with the pressure treatment group. The control lamprey were loaded into one chamber, but maintained at surface pressure for the duration of the experiment. The entire pressure sequence for the treatment lamprey lasted about 90-s. At the end of the sequence, the chambers were taken to "surface" pressure, and water flow was restored to the chambers (Figure 7). Two minutes after completion of the pressure spike, the lamprey were removed from the chambers and placed in holding troughs. Following the exposure to pressure changes, lamprey were examined for injury (e.g., hemorrhaging) and held for 48-hr post-exposure to determine latent mortality.

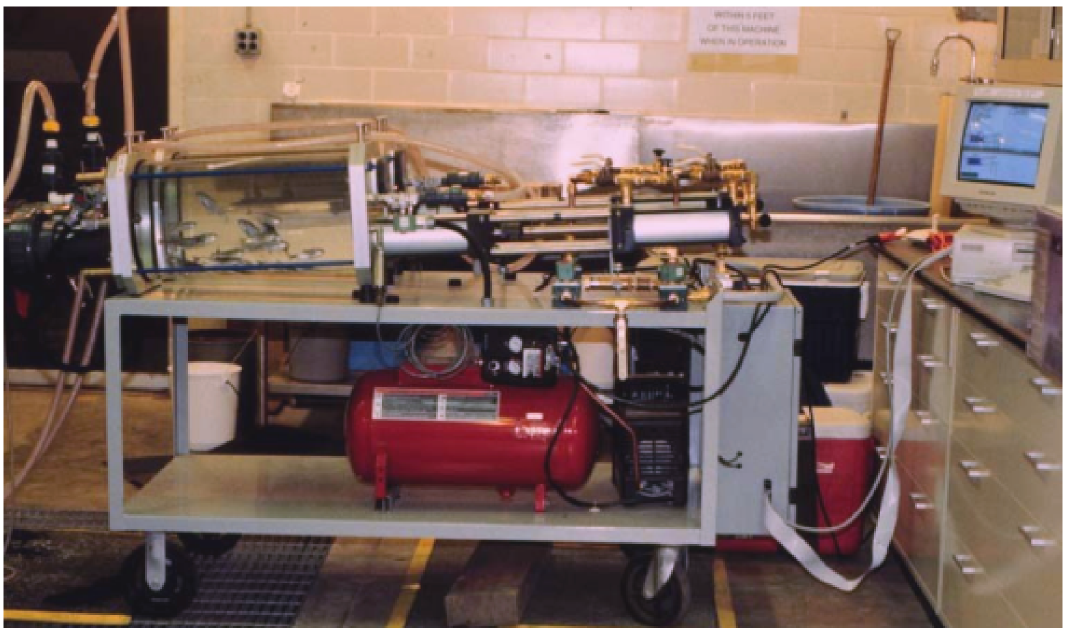

Figure 6. Turbine Passage System with Rainbow Trout in Hyperbaric Chambers (Abernethy et al. 2000)

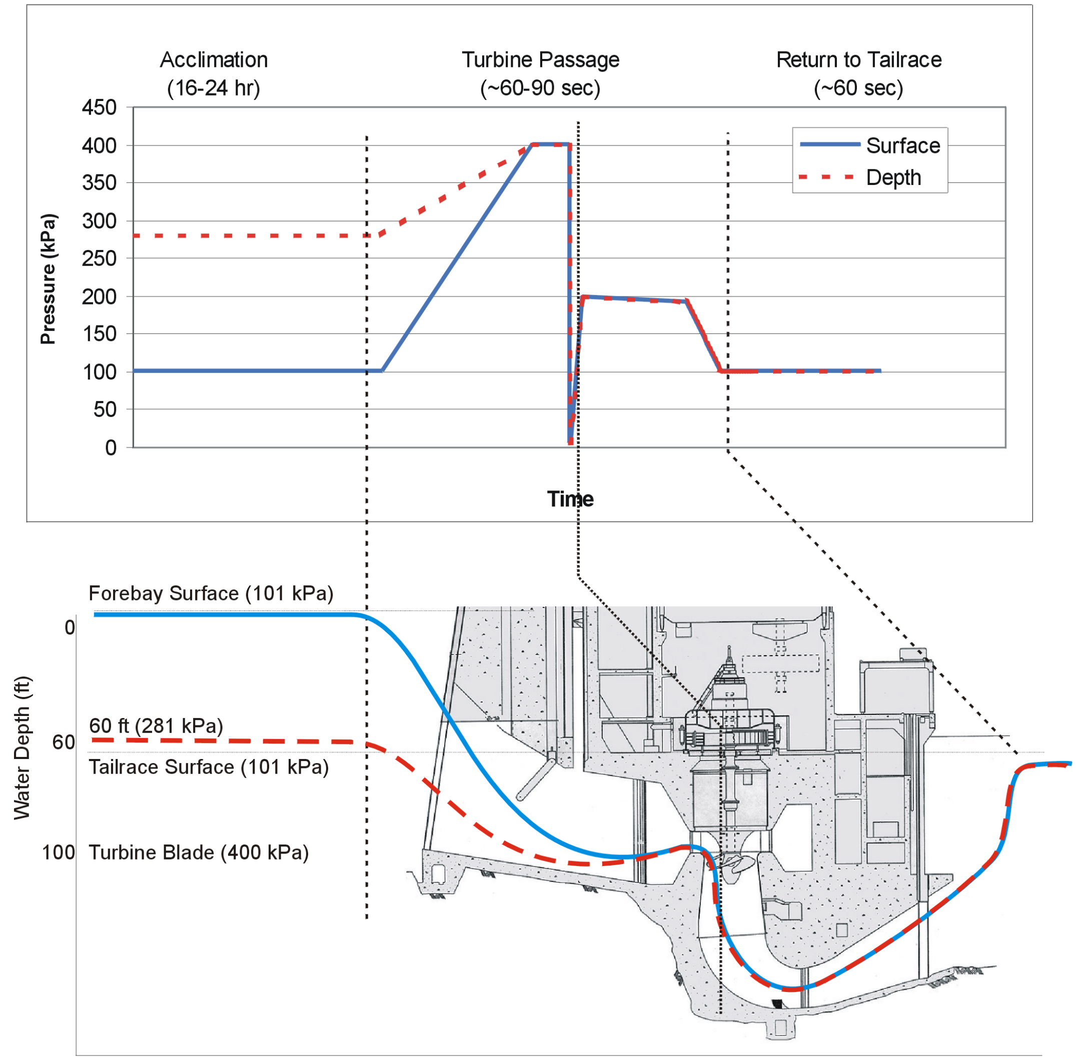

Figure 7. Diagram of Surface and 60-ft Depth Acclimation and Hyperbaric Chamber Pressure Exposure Simulation of Turbine Passage are Shown. Lamprey were acclimated at the 60-ft depth level.

2.2 Field Observations

2.2.1 Historical Run Timing and Abundance

Historical run timing information was obtained from lower Snake and Columbia river dams associated with the Smolt Monitoring Program. These data were based on counts of downstream migrating lamprey from juvenile bypass fish facilities at Lower Granite, Little Goose, McNary, John Day, and Bonneville dams. We have reported only the active migrant, or “silver,” counts. Note that the values reported are a passage index, and not absolute measure of abundance.

2.2.2 McNary Dam Observations

Field studies were initiated at McNary Dam to determine the feasibility of documenting lamprey behavior when they interact with ESBS and the cleaning brush. Critical uncertainties include effectiveness of brushing and sweep flows for removing impinged or mobile lamprey. The monitoring period was based on past passage records and corresponded to the projected peak of the lamprey outmigration. The initial study period was scheduled for May 23 to 26. However, a cable failure resulted in the study being postponed from May 31 to June 2, 2000.

Two low-light monochrome cameras were fastened to a steel bracket welded to the top of the ESBS brush bar. One camera was positioned to look downward, and the other was positioned to look upward. In association with each camera four IR light bar arrays were mounted to the bracket on either side of the cameras to provide illumination (Figure 8).

The bracket was mounted in turbine unit 4 on screen 4B near the center portion of the screen. A single cable with a 5/8-in. wire rope support was used to supply power to the light arrays and cameras. The cable was routed up the face of the screen, around the flow vane, and up to the forebay deck. The cable was manually deployed during brush operation using a large pulley fastened to the hand railing. The brush bar was operated with a portable manual controller and operated at 20-min cycles during the study period. Video was recorded on digital camcorders using 8-mm tape. Recordings were made continuously starting at 1440 hr on May 31 and ending at 0644 hr on June 2, 2000.

Figure 8. Underwater Cameras and Infrared Lighting Mounted on Brush Bar

3.0 Results and Discussion

3.1 Laboratory Tests

3.1.1 Time-Velocity Screen Exposure

Time-velocity tests showed there was a "dose-dependent" relationship between impingement rate of juvenile lamprey and the amount of time they spent in contact with the 1/8-in. ESBS. We found that juvenile lamprey were more likely to become stuck[1] on the test screens as velocities increased from 2 to 4 ft/s and as their exposure duration increased from 5 to 20 min (Figure 9). The stuck behavior occurred when a fish wedged its tail between the 1/8-in. bar spacing. Depending on velocity, the percent of stuck lamprey ranged from 20 to 30%, 15 to 60%, and 30 to 75% for exposure durations of 5, 10, and 20 min, respectively.

All time-velocity tests were conducted with screens in the vertical position. Thus, impinged lampreys did not have the benefit of sweeping flows present at in-turbine bypass screens. Nonetheless, our laboratory studies indicated that extended exposures on the screen can result in behavior harmful to juvenile lamprey. Any action taken to reduce the amount of time that juvenile lamprey spend on the screen surface, would be expected to provide survival benefits.

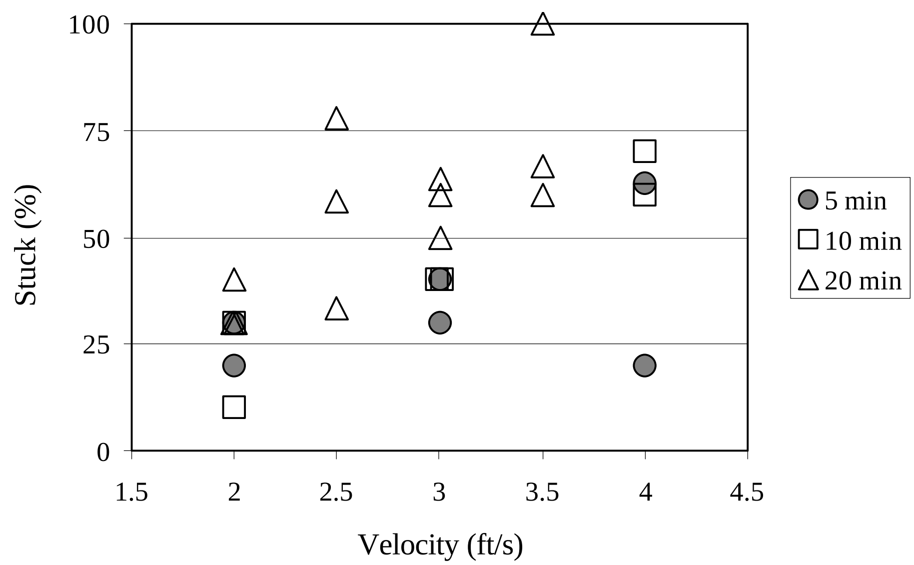

Figure 9. Percent of Lamprey Stuck Versus Exposure Duration for Velocities Ranging from 2 to 4 ft/s (screen perpendicular to flow, n=10)

[1] We defined "stuck" to be when a fish could not free itself during a 10-min rest period when flows in test chamber were reduced to zero ft/s.

3.1.2 Screen Orientation

Additional tests were conducted to evaluate whether changing the orientation of the 1/8-in. ESBS from vertical to horizontal might result in decreased impingement of juvenile lamprey. Our tests showed that 1/8-in. ESBS bar screen material oriented in a vertical position impinged fewer juvenile lamprey than ESBS bar screen material oriented horizontally (Figure 10). Both impingement and stuck values were lower than values reported for tests where the screen frames were perpendicular to the flow. The difference is primarily because some lamprey swam under or over the short section of angled (10° from vertical) test screen after they contacted it. These data do show, however, that changing the orientation of the 1/8-in. ESBS bar screen material to a horizontal position results in a higher proportion of "stuck" lamprey than do vertical slot screens at velocities >3 ft/s.

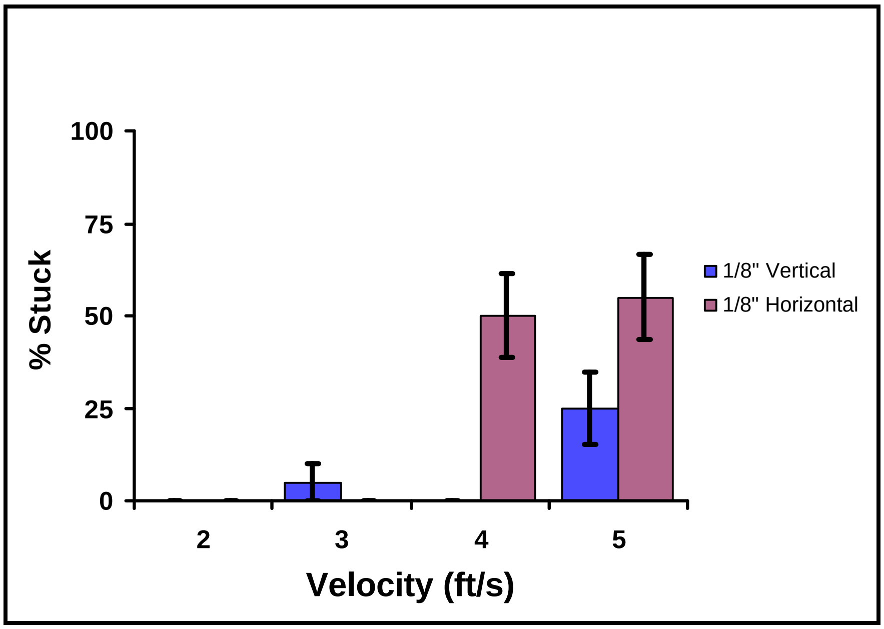

Figure 10. ESBS Screen Material Orientation Effects, Vertical and Horizontal, with a 10° Degree Tilt to Simulate Sweeping Flows (bars = ± SE, n=10)

3.1.3 Screen-Type Comparison

In 1999, tests focused on lamprey response to 1/8-in. ESBS screen material. Additional studies were conducted in 2000 to compare among screen types, including ESBS with smaller slot openings and with the standard STS mesh. Impingement rates were dramatically different among the three types of screen material tested. At velocities ranging from 2 to 4 ft/s, most lamprey remained on the surface of both the 3/32-in. ESBS and 1/8-in. STS mesh screens and did not become "stuck" (Figure 11). No juvenile lamprey remained stuck on the narrower spaced 3/32-in. ESBS after 10-min exposure at velocities up to 4 ft/s. In contrast, the mean percentage of lamprey stuck on the 1/8-in. ESBS increased from approximately 10% of the total at 2 ft/s to approximately 70% of the total at velocities of 4 ft/s.

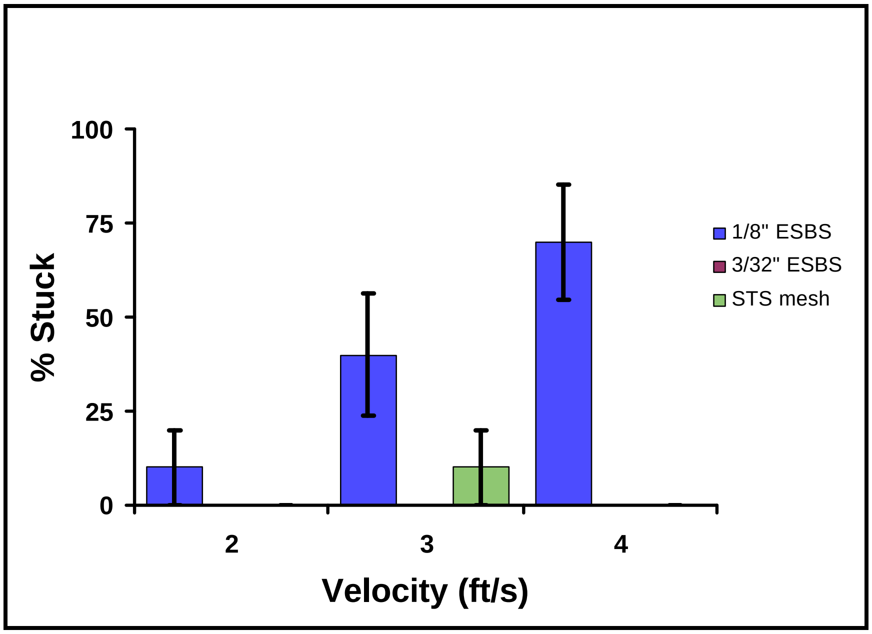

Figure 11. Lamprey Response to Three Types of Screens Material. Tests were conducted with screens perpendicular to the flow for 10-min durations (n=20 for each 1/8-in. ESBS and n=10 for 3/32-in. ESBS and STS tests). Note that no lamprey became permanently stuck on the 3/32-in. bar screen (bars = ± SE).

Overall, these results suggest that the currently used 1/8-in. ESBS pose a higher risk to juvenile lamprey becoming "stuck" than both the 3/32-in. ESBS and 1/8-in. ESBS. The 3/32-in. ESBS material had openings sufficiently small that juvenile lamprey could not wedge their tails in far enough to get "stuck." In contrast, the 1/8-in. ESBS has a larger amount of open space than the 1/8-in. STS material, i.e., the opening is continuous rather than square. Although the width of both the 1/8-in. ESBS and 1/8-in. STS screens is large enough that juvenile lamprey can insert their tail into the open space, the continuous opening in the 1/8-in. ESBS provides more surface area for them to "work" their tail and facilitates further penetration of their tail and posterior body into the opening. Collectively, these characteristics increase the likelihood of juvenile lamprey becoming permanently wedged or "stuck" in the screen material.

3.1.4 Phototactic Response

Static Test

The initial setup for determining a light response was a large net pen under static conditions. Because of the large area of the net pen and the limitations of the IR illuminators it was difficult to observe lamprey behavior during the testing/control events. We therefore discontinued use of the cameras and IR lights and visually determined the location of lamprey before and after the control/test events using white light.

Test replicates were pooled to obtain responses for test and controls. Analysis of variance was used to test the differences in response to the light between test fish and control fish. Factors included in the analysis were: *test* (six test events vs. six control events), *strobe position* (left vs. right), *groups* (four different groups of fish were tested), *runs* (two runs were made for each group), and *time* (12 total events at 10-min intervals). Overall, there was no significant difference between the test and control responses for the duration of a 2-hr test (P=0.579); however, there was a significant time effect (P=0.028). Analysis of the data from the first 80-min of the test showed there was a significant difference between the test and control (P=0.041). This trend suggests that juvenile lamprey became habituated to the stimulus (Figure 12). Lamprey that stayed near the strobe did not vacate the illuminated half of the net pen during the 40-s "strobe on" period.

Because the majority of the lamprey (30-60%) were stationary during the 2-hr testing period, we decided to scale down the testing apparatus, and move the tests to the swim chamber. The following section presents these results.

Flow Test

Two categories of responses were used to determine the behavior of juvenile lamprey when exposed to halogen and strobe white light: 1) immediate flight response, and 2) avoidance during exposure.

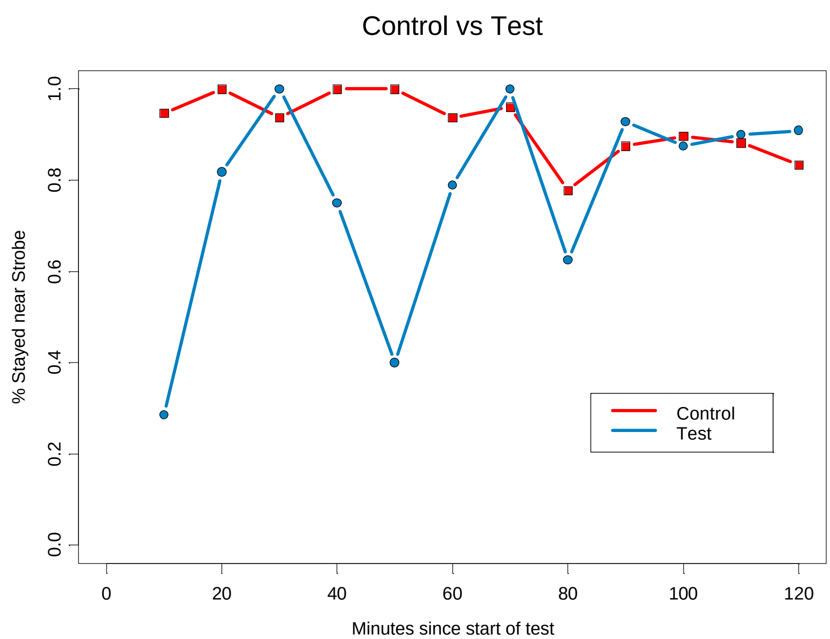

Figure 12. Movement Patterns of Lamprey when Subjected to Strobe Light Under a Static Environment (mean response for 8 test replicates, n=10)

Flight Response

Before activating the light source, the majority (60-80%) of lamprey were located on the downstream portion of the cage at a constant velocity of 0.5 ft/s. Upon activation of either the strobe or white light, the initial response by the majority of the lamprey was to immediately swim down and away from the stimulus and become more active (Figure 13).

Analysis of variance was used to compare the effect of the tests (lights) versus the control periods. The response variable analyzed was the proportion of fish out of 10 that displayed a flight response. Factors included in the analysis were *test* (test vs. control), *type* (halogen vs. strobe light), and *time*. The interaction between *test* and *type* was also analyzed. The test runs saw significantly more lamprey swimming away from the source than was seen during the control periods (P=<0.001). The factor type was also significant (P<0.001), showing a significant difference in the flight response between the strobe and halogen lights.

Habituation to light over time was also examined using regression to see if there was a decline in the number of lamprey swimming away from the light during the 2-hr testing period. The strobe tests showed a significant decrease in the number of fish swimming away from the light during the 2-hr testing period (P=0.0427). A similar decrease was also evident in the white light tests over the 2-hr period (P=0.044).

Avoidance Response

An analysis of variance was performed using the same factors used with the flight response analysis. The response variable analyzed was the proportion of fish that displayed an avoidance response. The test periods had significantly more movement from the left side of the pen to the right (avoidance of the stimulus) than the controls (P<0.001). The analysis showed no significant differences in avoidance responses between the strobe tests and the white light tests (P=0.496).

Regression analyses were performed to examine the effect of lamprey moving from the left side (source end) during the 2-hr testing period. There was no significant change over time during the strobe tests during this testing period (P=0.085). But, there was a trend in decreasing avoidance (P=0.0016) over time based on the number of lamprey moving from the left side of the cage during the white light tests (Figure 14).

Both the strobe and halogen light resulted in a greater number of responses away from the light sources than occurred from random movements (control periods). There was no overall statistical difference in lamprey flight or avoidance responses between the strobe tests and the halogen light tests (Figure 15). Although the measured intensity of the halogen light was significantly greater that than that measured from the strobe, avoidance responses to both types of light was similar, suggesting that the actual intensity produced by the halogen and strobe was also similar. Lamprey were likely responding to the peak light levels produced by the strobe, which the light meter was unable to accurately measure.

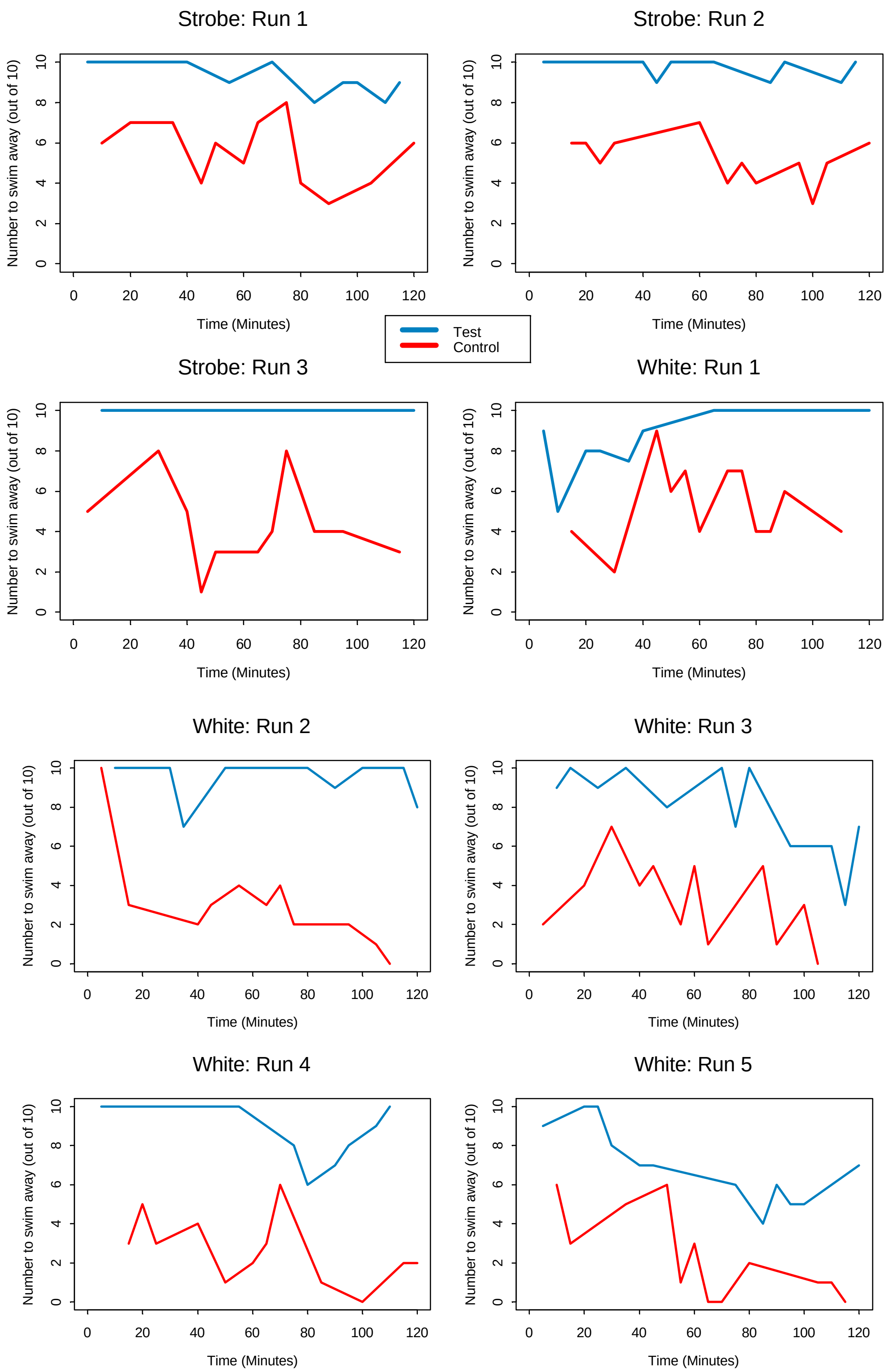

Figure 13. Plots of Lamprey Flight Responses During Strobe and White Light Tests Conducted in Swim Chamber (n=10 for each run)

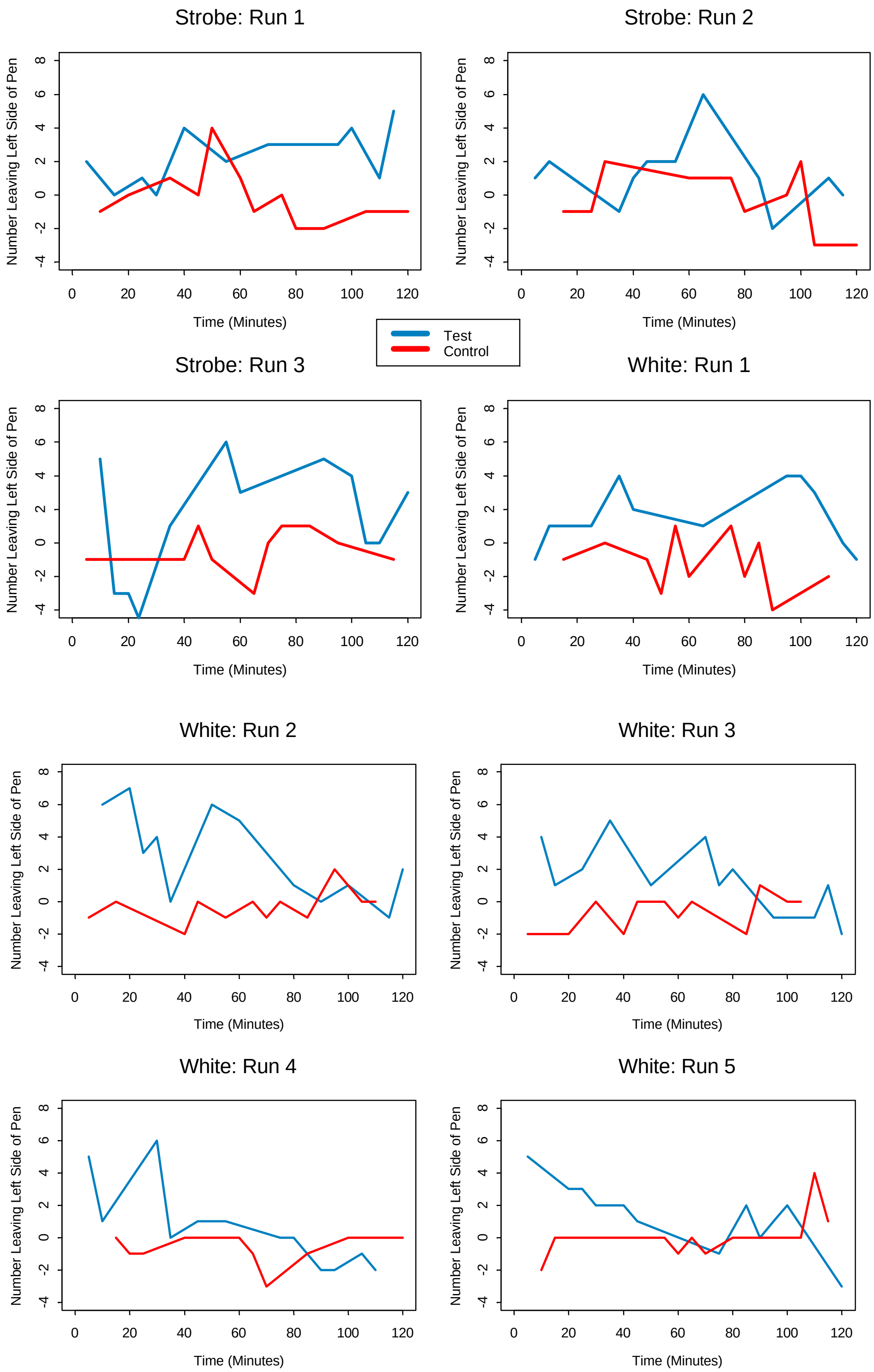

Figure 14. Plots of Lamprey Avoidance Responses During Strobe and White Light Tests Conducted in Swim Chamber (n=10 for each run)

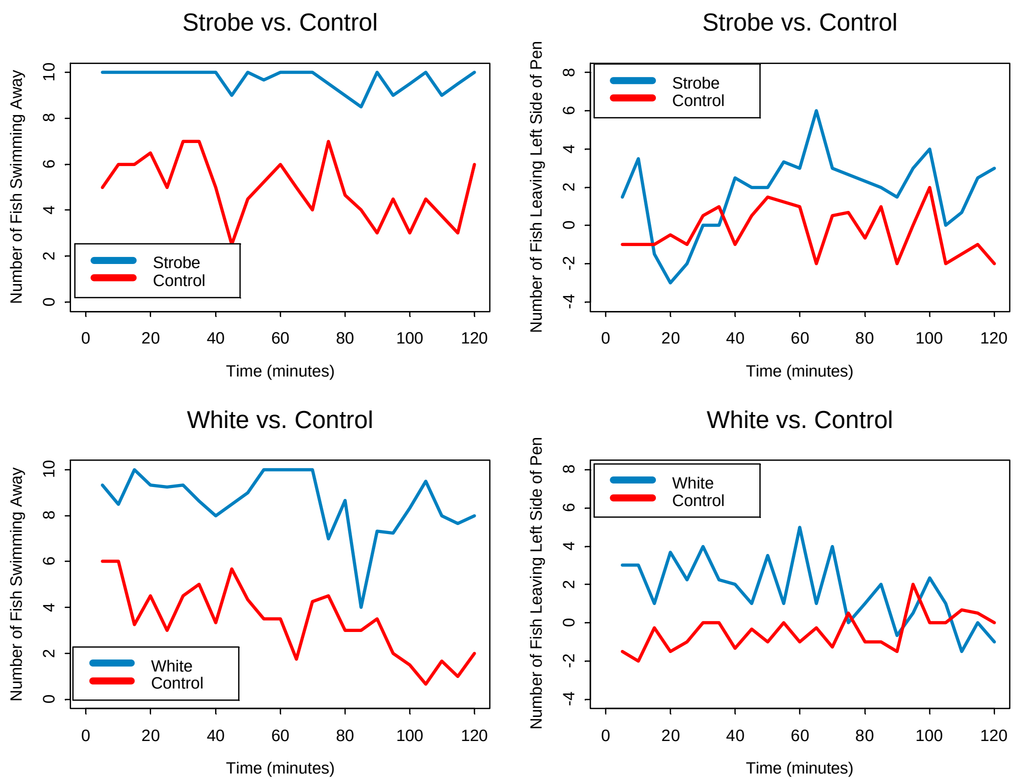

Figure 15. Relative Number of Lamprey Moving from Light Sources (combined test results) During a 2-hr Test

Based on laboratory tests under both static and flowing water we documented that juvenile lamprey exhibit avoidance responses when exposed to both pulsing and constant white light. We are not aware of any other studies conducted on response of light on juvenile Pacific lamprey. Previous studies with adult river lamprey (*Lampetra fluviatilis*) and the land-locked sea lamprey (*Petromyzon marinus*) showed a strong negative phototaxis to incandescent light (Ullen 1996). Numerous studies have shown that strobe lights illicit avoidance behavior in juvenile salmonids. Based on our findings, lights may be useful as a behavior or guidance mechanism to reduce contact with the screening structures at hydroelectric dams.

3.1.5 Pressure

Results from the simulated turbine passage tests showed no immediate external injuries or mortalities for both control and test lamprey exposed to rapid changes in pressure, i.e., 400 kPa to 5 kPa in 0.1-s. A pressure change of this magnitude occurs in the instant of passage through the turbine blade area. In addition, no mortalities were documented for control and test lamprey held up to 48-hr.

Recent studies by Abernethy et al. (2000) have shown that juvenile fall chinook salmon and rainbow trout exhibited no loss of equilibrium or injury under similar exposure scenarios (e.g., surface and 30 ft acclimation). In contrast, turbine passage simulation was harmful to bluegill, sometimes resulting in ruptured swim bladders and internal hemorrhaging. Unlike bluegill and salmonids, lamprey have no swim bladder. Thus, it is not surprising that rapid changes in pressure had little effect on them.

3.2 Field Observations

3.2.1 Historical Run Timing and Abundance

The estimated number of juvenile lamprey passing McNary Dam during the study period ranged from 1,400-4,800. Additional data for passage at other dams is presented in Appendix B.

3.2.2 McNary Dam Observations

Over 40 lamprey were documented during the video evaluation at McNary Dam in 2000. Project flows averaged 233 kcfs with a 40% spill during the evaluation. The average river temperature was 57°F. Video quality was quite good as the screen material provided contrast for observing lamprey on the screen (Figure 16). The majority of the lamprey were observed on the screen during the first few hours of darkness (2000-2400 hr). A short video clip in MPEG-1 format is available with this report.

Lamprey were seen in early stages of becoming stuck, i.e., they were in contact with and unable to swim away from the screen face. We observed no lamprey stuck as we have defined it for our laboratory experiments. However, some lamprey exhibited signs of tail-first penetration behavior. The observed lamprey were still able to free themselves by volitionally extracting their tail from between and the bar spacing. We also noted that sweeping velocities along the screen and appeared to push the lamprey up the screen toward the gatewell. It is speculated that this sliding activity would be interrupted by a horizontal bar configuration.

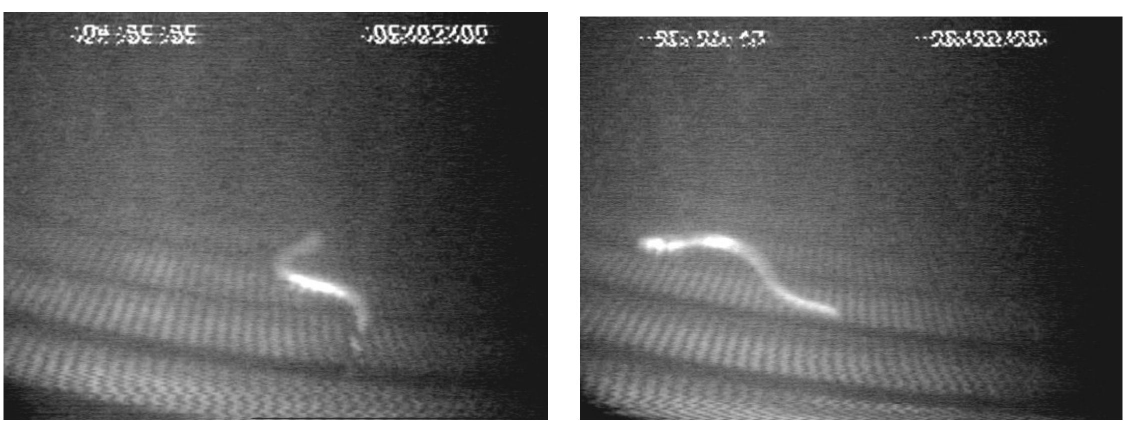

Figure 16. Still Images From Digital Video Footage Taken at McNary Dam on June 2, 2000, at 4:55 AM. The image on the left shows the tail of a lamprey through the bar spacing; the image on the right is the same lamprey a moment later after the tail was extracted volitionally.

Too few lamprey were observed to make inferences about the population at large regarding brush-lamprey interactions, however, we documented dead lamprey that were impinged on screens or caught in the brush material when the screens were pulled during the field study. We documented three dead lamprey on screen 4B and one wedged on screen 6B (Figure 17).

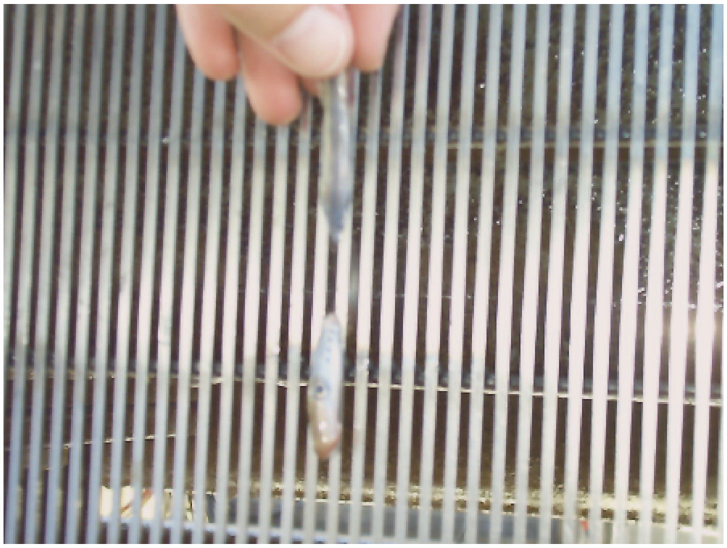

Figure 17. Lamprey Impinged on Screen 6B McNary Dam

4.0 Conclusions

Lamprey were not injured during laboratory tests simulating turbine conditions (i.e., pressure and shear) known to cause mortality in other fish species. We previously showed that juvenile lamprey were less susceptible to shear forces that may occur during turbine passage than juvenile salmonids and shad (Moursund et al. 2000, Neitzel et al. 2000). The study showed lamprey were not injured by rapid changes in pressure known to occur during turbine passage. The pressure results were not surprising because the physiology of lamprey (i.e., lack of swim bladder) make them less susceptible to pressure spikes.

Both white and strobe forms of light elicited an avoidance response for juvenile Pacific lamprey. The static water tests suggested that a diving or sounding response occurred unless the stimulus was from below. When subjected to flows that would otherwise allow them to rest on the screen face, the light stimuli caused a reaction away from the screen. Field tests would need to be conducted to verify avoidance responses at higher water velocities and turbidities found during the spring/summer migration period.

Results of the field test showed that deploying underwater cameras with IR lighting on an ESBS brush inside an operating intake is technically feasible. These deployments provided documentation of lamprey behavior similar to that previously observed in the laboratory. Lamprey became impinged to the face of the bar screen material at intake velocities and slid along the screen in the direction of the sweeping velocities toward the gatewell. Tail-first penetration does occur on the screen face, though not immediately. Because of the high average velocities near the bypass screens and juvenile lamprey weak swimming ability, they will likely become stuck to the bar screen unless efficient methods are designed to reduce their exposure time.

Based on laboratory and field experiments during 2000 we have made the following conclusions:

- Impingement and stuck rates are positively correlated with velocity and duration of exposure.

- Vertical orientation of 1/8-in. ESBS results in lower stuck rates than bars that are oriented horizontally to the direction of flow.

- 1/8-in. ESBS pose a greater risk to juvenile lamprey being stuck than do 3/32-in. ESBS and 1/8-in. STS mesh material.

- Laboratory exposures to shear and pressure changes show turbine passage may be less harmful than juvenile bypass system passage for juvenile lamprey. We have no current means to evaluate the potential for lamprey to become injured from blade strike.

- The current 1/8-in. bar spacing of the ESBS allows some lamprey to become permanently wedged between the bars. Juvenile lamprey are less likely to become stuck in the 1/8-in. nylon mesh of the STS and 3/32-in. bar screen material. Replacement of the 1/8-in. bar screen with 3/32-in. screen would decrease impingement of juvenile lamprey.

- Although debris may be handled better with the bar screen material oriented horizontally, this configuration has higher impingement rates than the current vertical configuration.

- Decreasing the cycle time for debris brushing could lower lamprey impingement rates. However, further research is needed because the effectiveness of brushing on lamprey removal and survival is unknown.

- Field observations can be used to investigate whether the brush may be modified to be hydraulically beneficial to lamprey. The brush mount itself, for instance, might alter localized pressure gradients and produce lift passively because of its location in the flow field.

A conceptual explanation of lamprey behavior on the 1/8-in. bar screen is shown below (Figure 18). This is a generalization of both laboratory experiment and field observation results.

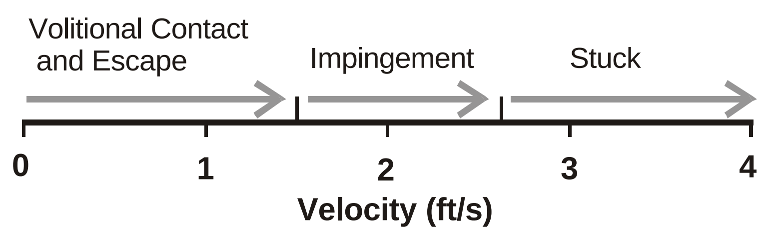

Figure 18. Conceptual Lamprey Behavior on 1/8-in. ESBS

Collectively, the results of our studies provide the Corps with information that could be used to mitigate any potential adverse effects of extended length bar screens and operations on juvenile Pacific lamprey. This information is generally applicable for all hydroelectric projects in the Columbia River system.

5.0 References

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Appendix A

Test Schedule for Screen Impingement Laboratory Tests

Date	Velocity (ft/s)	Duration (min)	Number	Screen Type	Bar Orientation	Screen Angle From Vertical (degrees)
4/28/00	2.5	20	12	1/8" bar	vertical	0
4/28/00	3.0	20	10	1/8" bar	vertical	0
4/28/00	3.5	20	10	1/8" bar	vertical	0
5/1/00	2.5	20	9	1/8" bar	vertical	0
5/1/00	3.0	20	11	1/8" bar	vertical	0
5/1/00	3.5	20	10	1/8" bar	vertical	0
5/3/00	2.5	20	9	1/8" bar	vertical	0
5/3/00	3.0	20	10	1/8" bar	vertical	0
5/3/00	3.5	20	9	1/8" bar	vertical	0
5/10/00	2.0	20	10	1/8" bar	vertical	0
5/10/00	2.0	20	10	1/8" bar	vertical	0
5/10/00	2.0	20	10	1/8" bar	vertical	0
5/10/00	2.0	10	10	1/8" bar	vertical	0
5/10/00	3.0	10	10	1/8" bar	vertical	0
5/10/00	4.0	10	10	1/8" bar	vertical	0
6/5/00	2.0	10	10	3/32" bar	vertical	0
6/5/00	3.0	10	10	3/32" bar	vertical	0
6/5/00	4.0	10	10	3/32" bar	vertical	0
6/6/00	2.0	10	10	1/8" mesh	N/A	0
6/6/00	3.0	10	10	1/8" mesh	N/A	0
6/6/00	4.0	10	10	1/8" mesh	N/A	0
6/6/00	2.0	10	12	3/32" bar	vertical	15
6/6/00	3.0	10	10	3/32" bar	vertical	15
6/6/00	4.0	10	9	3/32" bar	vertical	15
6/6/00	2.0	10	10	1/8" mesh	N/A	15

Date	Velocity (ft/s)	Duration (min)	Number	Screen Type	Bar Orientation	Screen Angle From Vertical (degrees)
6/6/00	3.0	10	10	1/8" mesh	N/A	15
6/6/00	4.0	10	10	1/8" mesh	N/A	15
6/6/00	2.0	10	10	1/8" bar	vertical	15
6/6/00	3.0	10	11	1/8" bar	vertical	15
6/6/00	4.0	10	11	1/8" bar	vertical	15
6/7/00	2.0	5	10	1/8" bar	vertical	0
6/7/00	3.0	5	10	1/8" bar	vertical	0
6/7/00	4.0	5	8	1/8" bar	vertical	0
7/17/00	2.0	10	10	1/8" bar	horizontal	15
7/17/00	3.0	10	10	1/8" bar	horizontal	15
7/17/00	4.0	10	10	1/8" bar	horizontal	15
7/17/00	2.0	10	10	1/8" bar	horizontal	10
7/17/00	3.0	10	10	1/8" bar	horizontal	10
7/17/00	4.0	10	10	1/8" bar	horizontal	10
7/17/00	2.0	10	10	1/8" bar	vertical	10
7/17/00	3.0	10	10	1/8" bar	vertical	10
7/17/00	4.0	10	10	1/8" bar	vertical	10
7/18/00	5.0	10	10	1/8" bar	vertical	10
7/18/00	5.0	10	10	1/8" bar	horizontal	10
7/21/00	2.0	5	10	1/8" bar	vertical	0
7/21/00	2.0	10	10	1/8" bar	vertical	0
7/21/00	4.0	5	10	1/8" bar	vertical	0
7/21/00	4.0	10	10	1/8" bar	vertical	0
7/21/00	3.0	5	10	1/8" bar	vertical	0
7/21/00	3.0	10	10	1/8" bar	vertical	0
7/21/00	3.0	10	10	1/8" bar	vertical	10
7/21/00	4.0	10	10	1/8" bar	vertical	10
7/21/00	5.0	10	10	1/8" bar	vertical	10
7/21-22/00	3.0	10	10	1/8" bar	horizontal	10
7/21-22/00	4.0	10	10	1/8" bar	horizontal	10
7/21-22/00	5.0	10	10	1/8" bar	horizontal	10

Appendix B

Historical Run Timing

The following figures represent collection estimates based on a daily average sample rate; the same sampling procedures are followed at each of the dams listed.

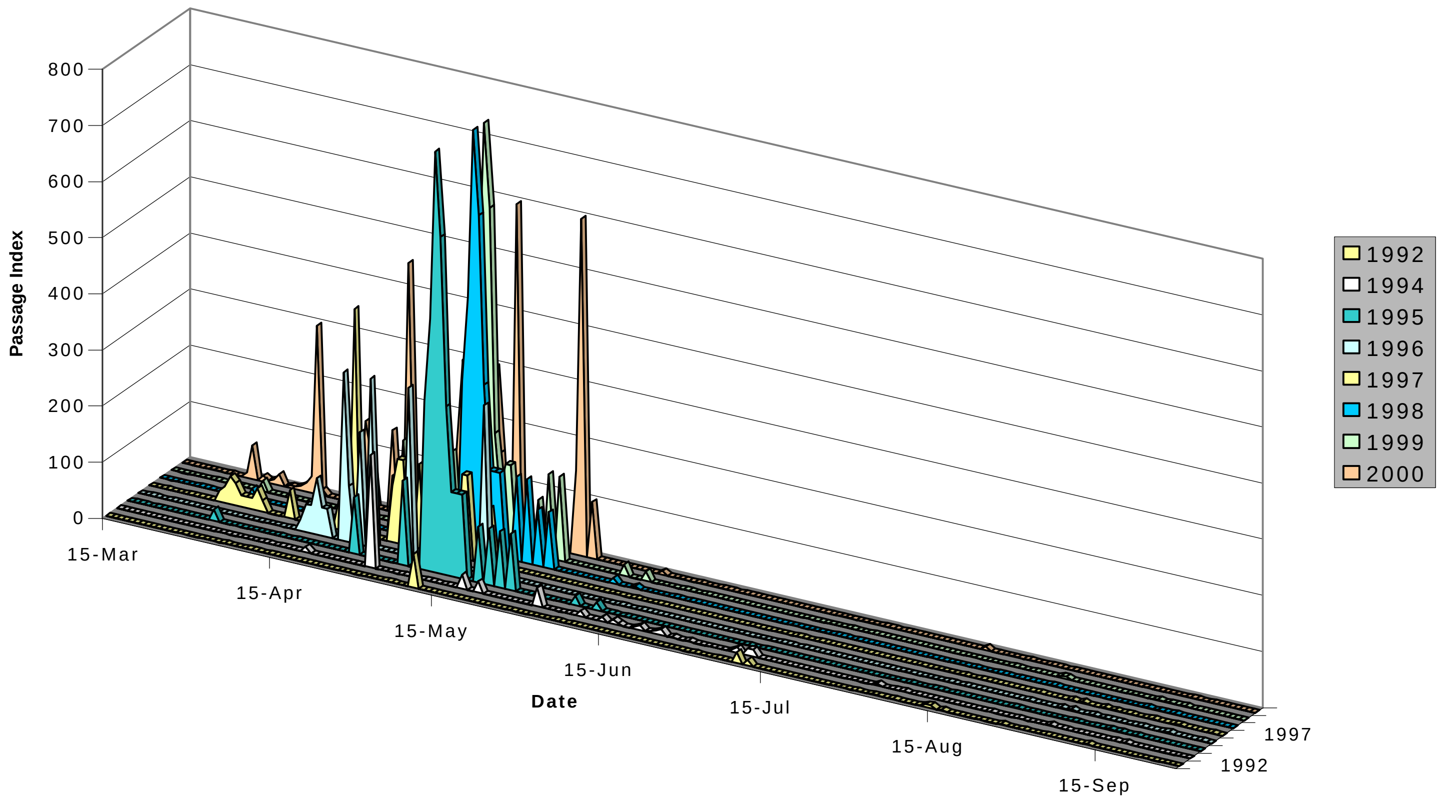

Figure B.1. Historical Run Timing of Juvenile Lamprey at Lower Granite Dam

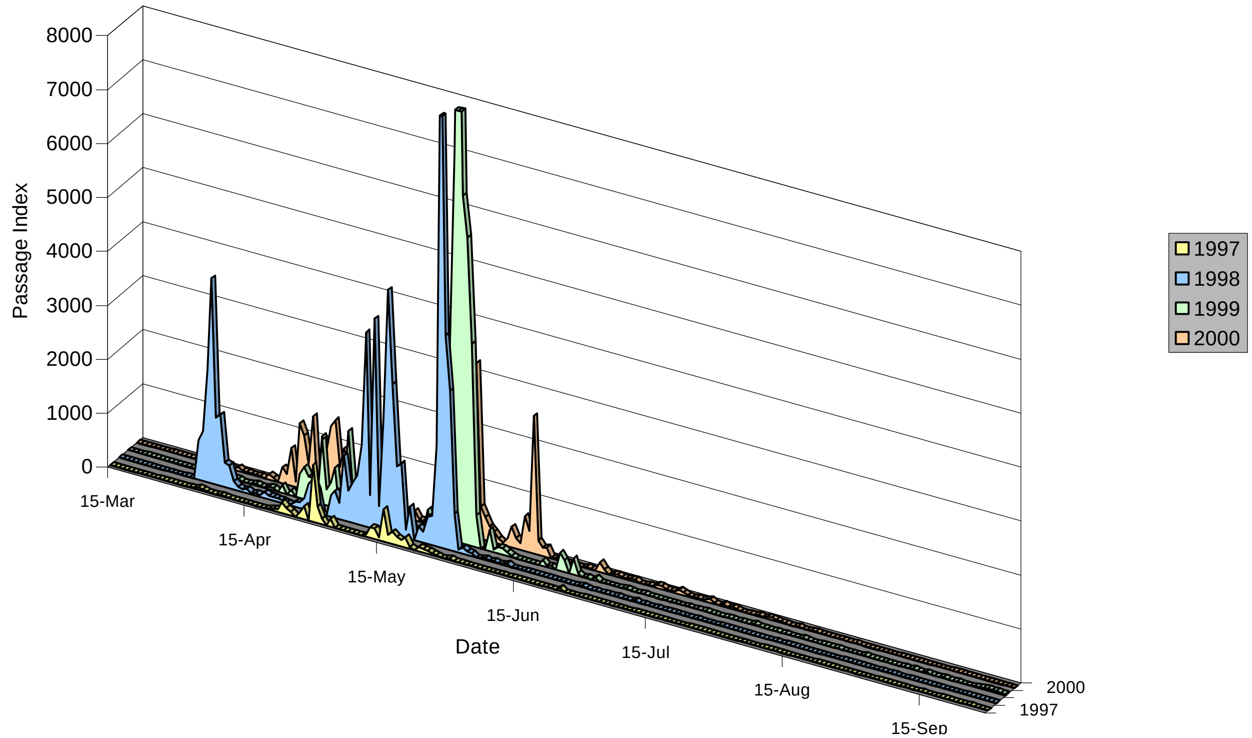

Figure B.2. Historical Run Timing of Juvenile Lamprey at Little Goose Dam

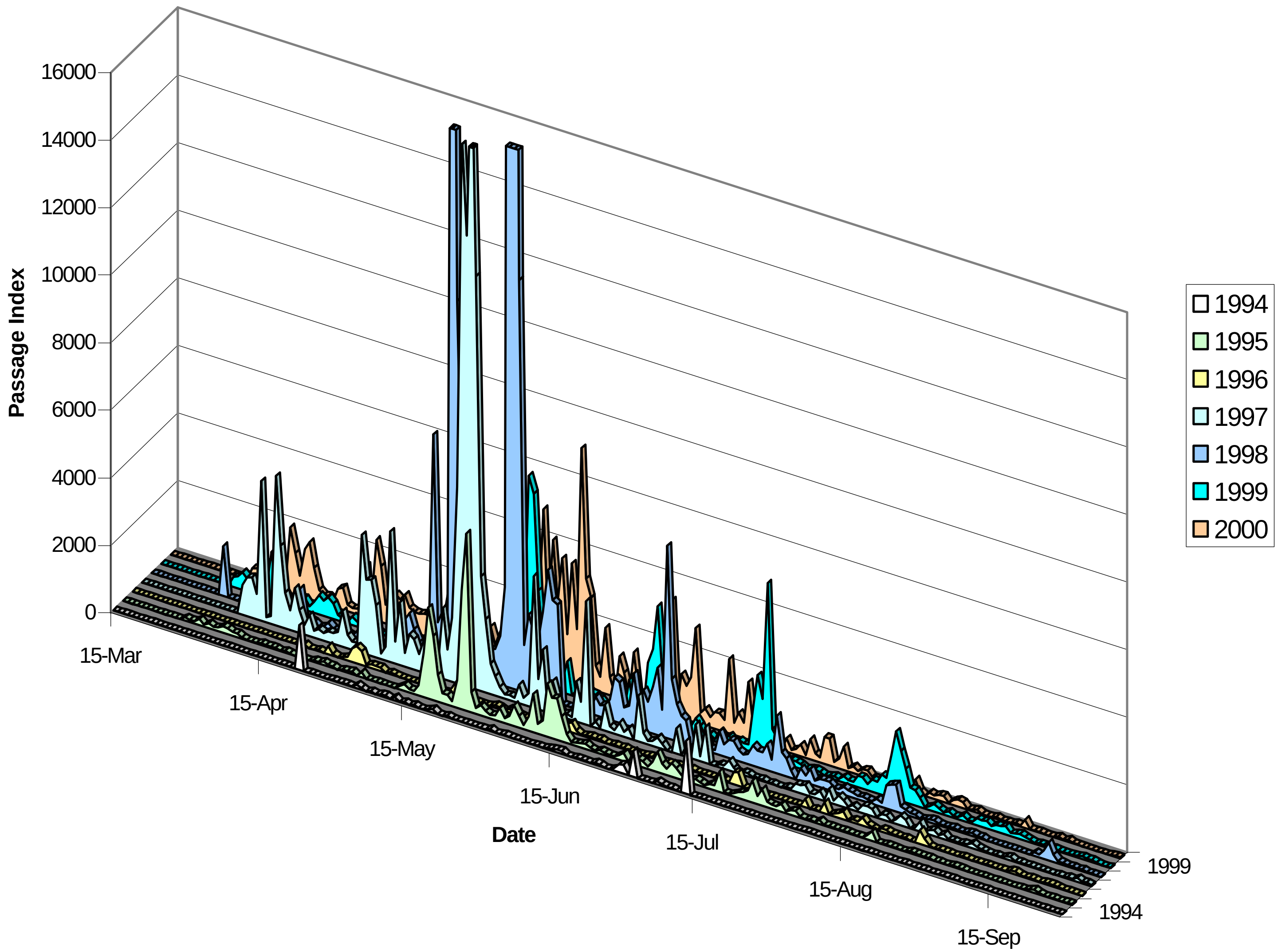

Figure B.3. Historical Run Timing of Juvenile Lamprey at McNary Dam

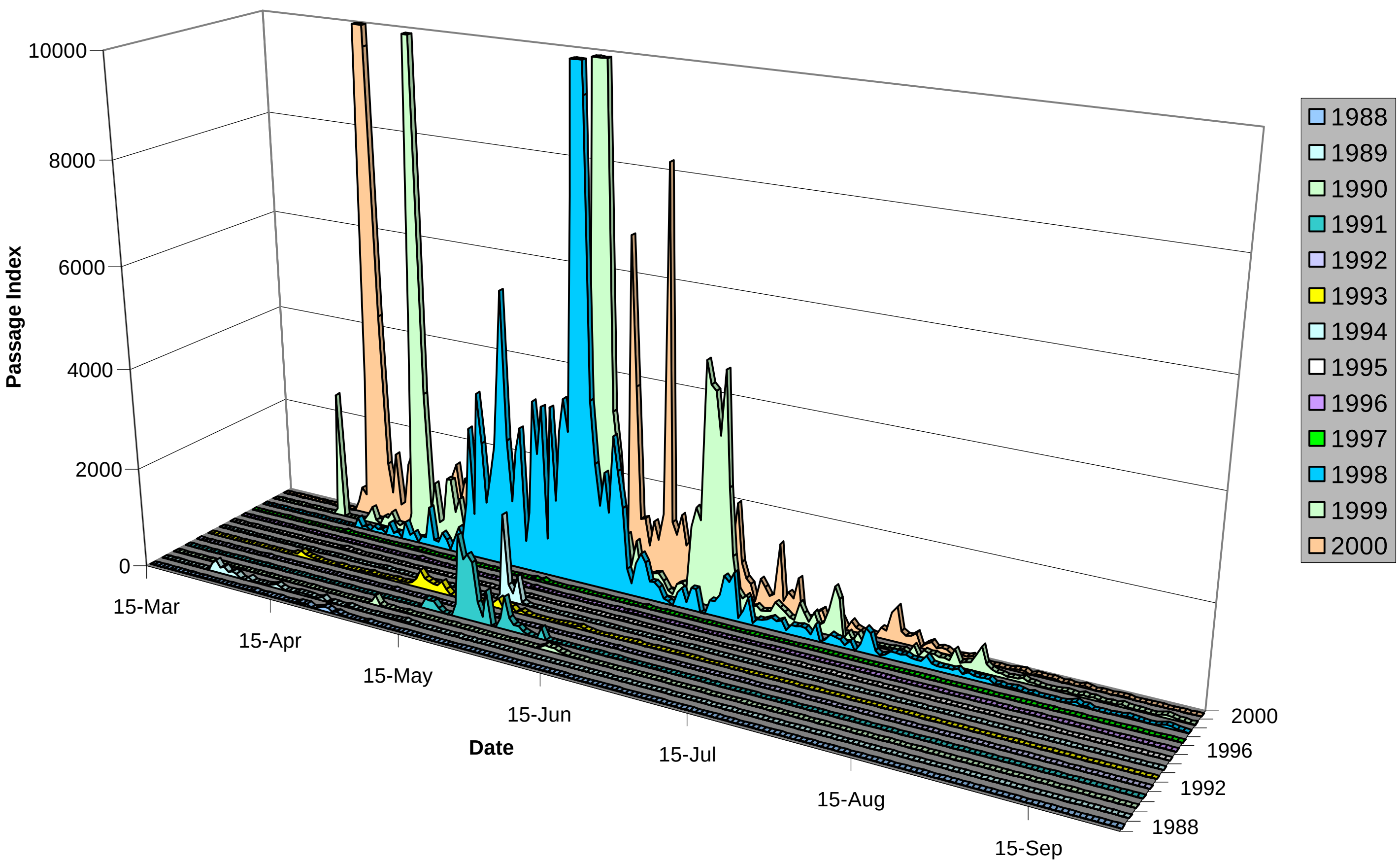

Figure B.4. Historical Run Timing of Juvenile Lamprey at John Day Dam

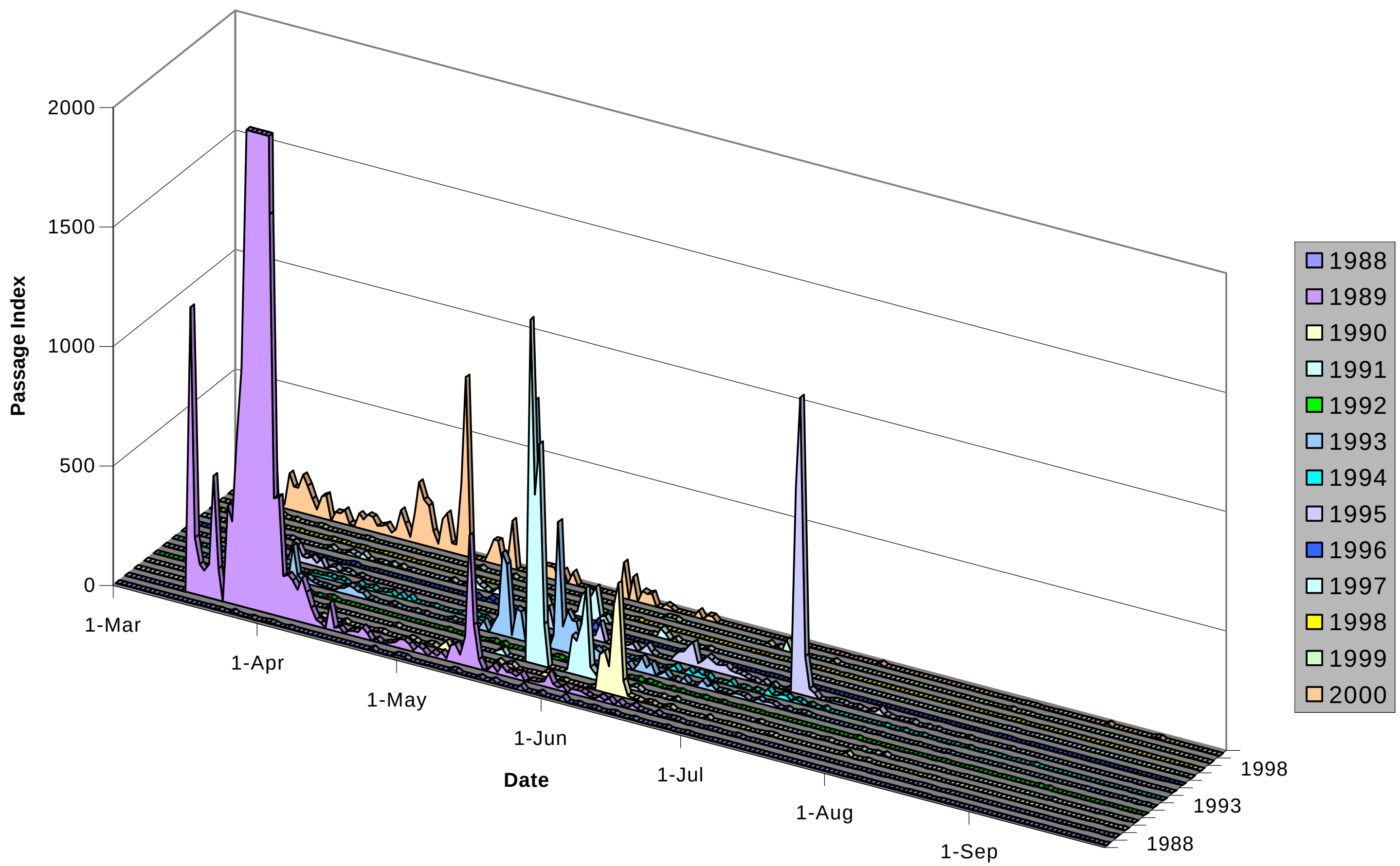

Figure B.5. Historical Run Timing of Juvenile Lamprey at Bonneville Dam

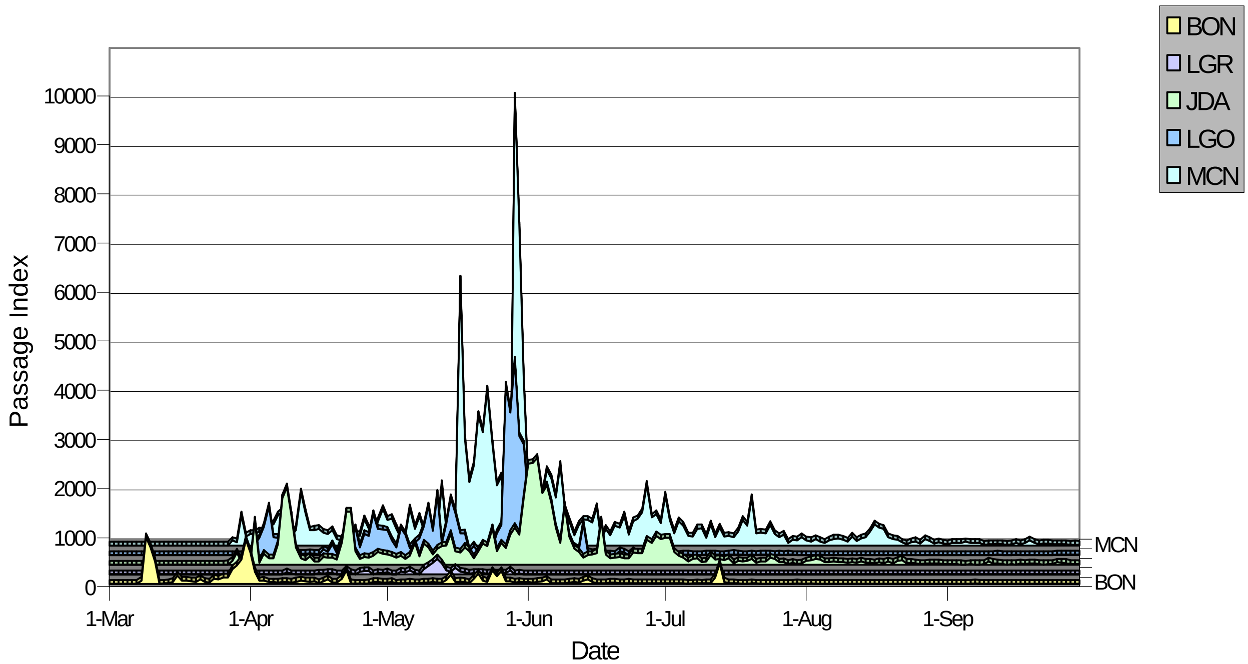

Figure B.6. Historical Run Timing of Five Dams on the Lower Columbia and Snake Rivers

Appendix C

Equipment Specifications

Low-light monochrome cameras:
Deep Sea, model 1060
Ikegami, model ICD-4224

Strobe light:
Flash Technology, AGL 901 Aquatic Guidance Light

Halogen light:
Deep Sea, model MC 120/250 rated at 4,750 lumens

Photometer:
LI COR, LI-188B photometer with an underwater Quantum Sensor model LI-192S.

Respirometer:
A custom-built 600-gal Brett-type respirometer was constructed of stainless steel and contained a working section with removable cover, impeller, flow straightener, and viewing window. The observation section measured 5.9-ft long, 1.7-ft wide, and 1.7-ft high. A 25-hp variable speed alternating-current (AC) motor drove the impeller that provided velocities that ranged from 0 to 5 ft/s. The respirometer was immersed in a fiberglass cooling tank that measured 14.7-ft x 5.5-ft.

Velocity meter:
SonTek, ADVField

Infrared illuminators and associated power supplies:
American Dynamics, AD1020/6050 (880 nm)
TripLite, PR-20 (13.8V DC 20A)

Recorders, and misc. equipment:
Sony, Handycam DCR TR7000
High 8MM Sony video tape
Outland Technology, video typewriter mod. 5100