U.S. Army Corps of Engineers
Portland District

Effects of John Day Dam Bypass Screens and Project Operations on the Behavior and Survival of Juvenile Pacific Lamprey (*Lampetra tridentata*)

FINAL REPORT

14 January 2000

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Effects of John Day Dam Bypass Screens and Project Operations on the Behavior and Survival of Juvenile Pacific Lamprey (*Lampetra tridentata*)

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Prepared for:
U.S. Army Corps of Engineers
Portland District
Portland, Oregon

By:
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Executive Summary

Pacific lamprey (*Lampetra tridentata*) is the largest and most abundant lamprey species in the Snake and Columbia River system. As an endemic and anadromous species, the U.S. Army Corps of Engineers has an interest in facilitating their protection at federally operated hydroelectric projects. The goal of this study was to begin to determine the effects of the John Day Dam bypass facilities, specifically the turbine intake screens, and project operations on the behavior and survival of juvenile Pacific lamprey. Laboratory studies were conducted to determine swim speed capability and response to a fixed bar screen in an experimental flume.

We found that juvenile Pacific lamprey were highly nocturnal with >90% of their swimming activity restricted to hours of darkness. They also had a strong preference for substrate and remained near the bottom of test aquaria during daylight hours. This behavior is consistent with lack of buoyancy compensation (i.e., they have no swim bladder and slightly negative specific gravity). That lamprey are mainly demersal and nocturnal would be advantageous for predator avoidance, but this same behavior increases the possibility that they will pass dams via turbines and underneath the screen or surface bypass systems designed to guide juvenile salmonids.

Our studies also demonstrated that juvenile Pacific lamprey are fairly weak swimmers. They had an average maximum burst speed of 2.3 ft/sec, or less than the average perpendicular velocity at the face of extended length submersible bar screens at John Day Dam. We also found that 70% and 97% of test fish became impinged on bar screens at velocities of 1.5 ft/sec for 1-min and 12-hr exposures, respectively. The tendency of juvenile lamprey to use their tails for locomotion resulted in some individuals becoming permanently wedged between the bar spacings.

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Table of Contents

List of Figures

List of Tables

Introduction

Pacific lamprey (*Lampetra tridentata*) is the largest and most abundant lamprey species in the Snake and Columbia river systems (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 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 or 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).

Operations at mainstem hydroelectric projects may impact juvenile lamprey during downstream passage. One concern is that juvenile lamprey 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. Another key concern is how juvenile lamprey respond to barrier screens designed to bypass fish into collection facilities. For example, some investigators have reported large numbers of juvenile lamprey were 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 during passage of mainstem hydroelectric dams was the focus of our research.

The goal of this study was to begin to determine the effects of the John Day Dam bypass facilities, specifically the turbine intake screens, and project operations on the behavior and survival of juvenile Pacific lamprey. John Day Dam is the third most downstream hydroelectric facility in the Columbia River system located at river mile 216 (Figure 1). It has a generating capacity of 2,160 MW from 16 turbine units. Prototype extended-length submersible bar screens (ESBS) are undergoing field testing for use in the turbine intakes.

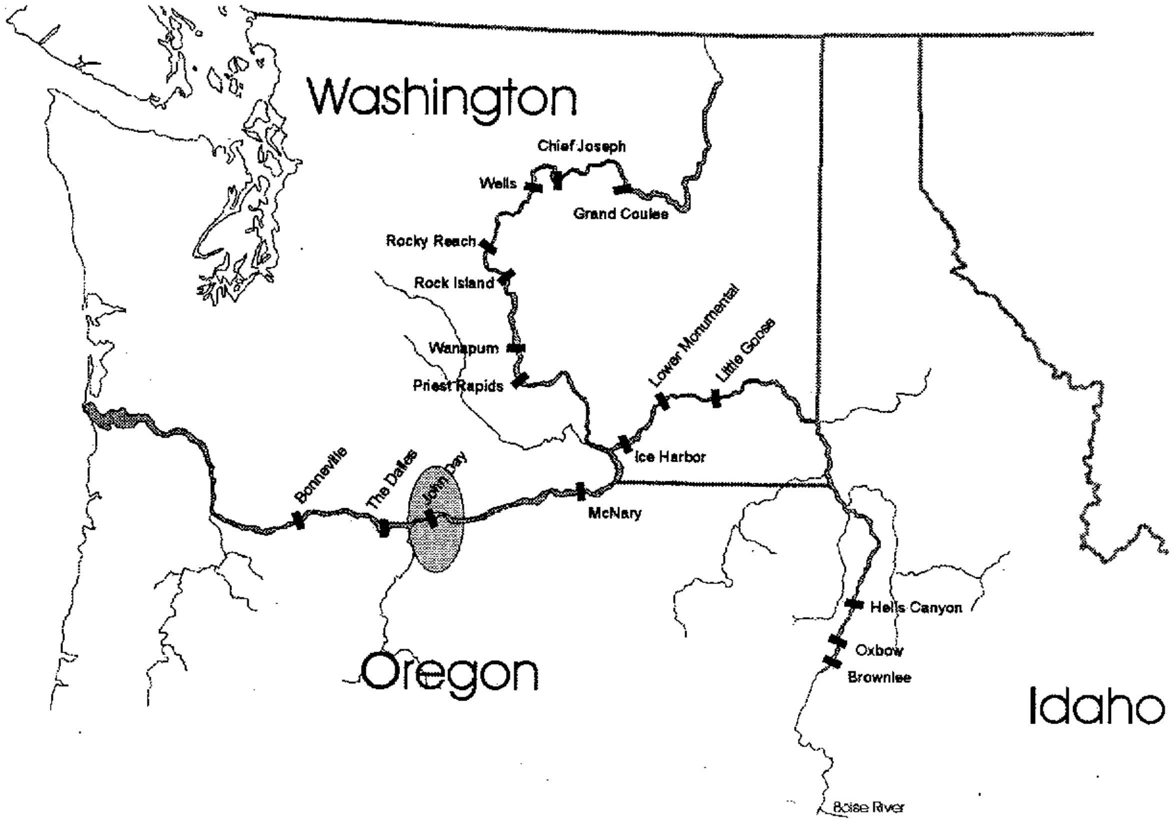

Figure 1. Location of John Day Dam in relation to the mainstem Columbia and Snake rivers.

Laboratory studies were designed to determine potential injury mechanisms and turbine passage conditions that affect the survival of juvenile lamprey. Specifically, the swimming performance of the juvenile lamprey was evaluated in our laboratory to document their behavior and threshold impingement velocities. Shear stress affecting survival during turbine passage was also documented using a simulated turbine passage system (Neitzel et al. 1998). Collectively, the studies will provide the U.S. Army Corps of Engineers (Corps) with information to mitigate any adverse effects of ESBS on juvenile Pacific lamprey. This information will also be generally applicable to other hydroelectric projects with submersible bar screens.

Methods

Juvenile Pacific lamprey (*Lampetra tridentata*) were collected from the juvenile bypass fish facilities at John Day and McNary (river mile 292) dams. All the juvenile lamprey had, therefore, been intercepted by the intake bypass screen and traveled through the juvenile bypass system before their transport to the Pacific Northwest National Laboratory (PNNL). All these fish were actively migrating downstream and were in the seventh and final stage of metamorphosis according to the criteria described in Youson and Potter (1979; Figure 2). All tests were conducted at PNNL in Richland, Washington, during or immediately following the peak juvenile outmigration period of May and June (Figure 3).

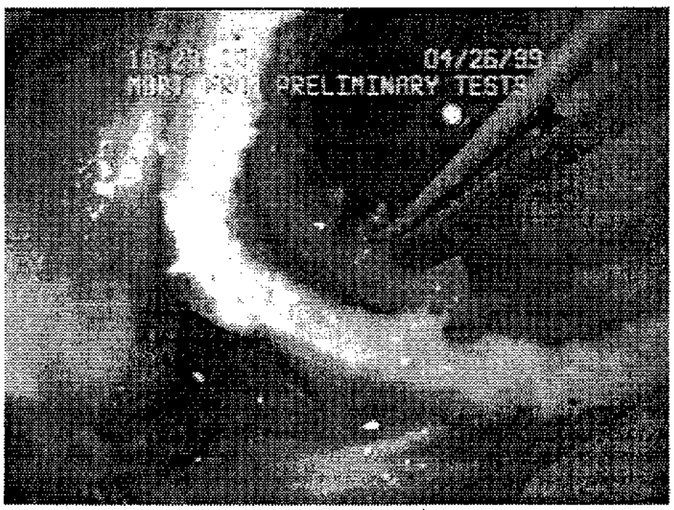

Figure 2. Oral cavity of juvenile Pacific lamprey. Note tooth development and lack of oral fimbrae pigmentation.

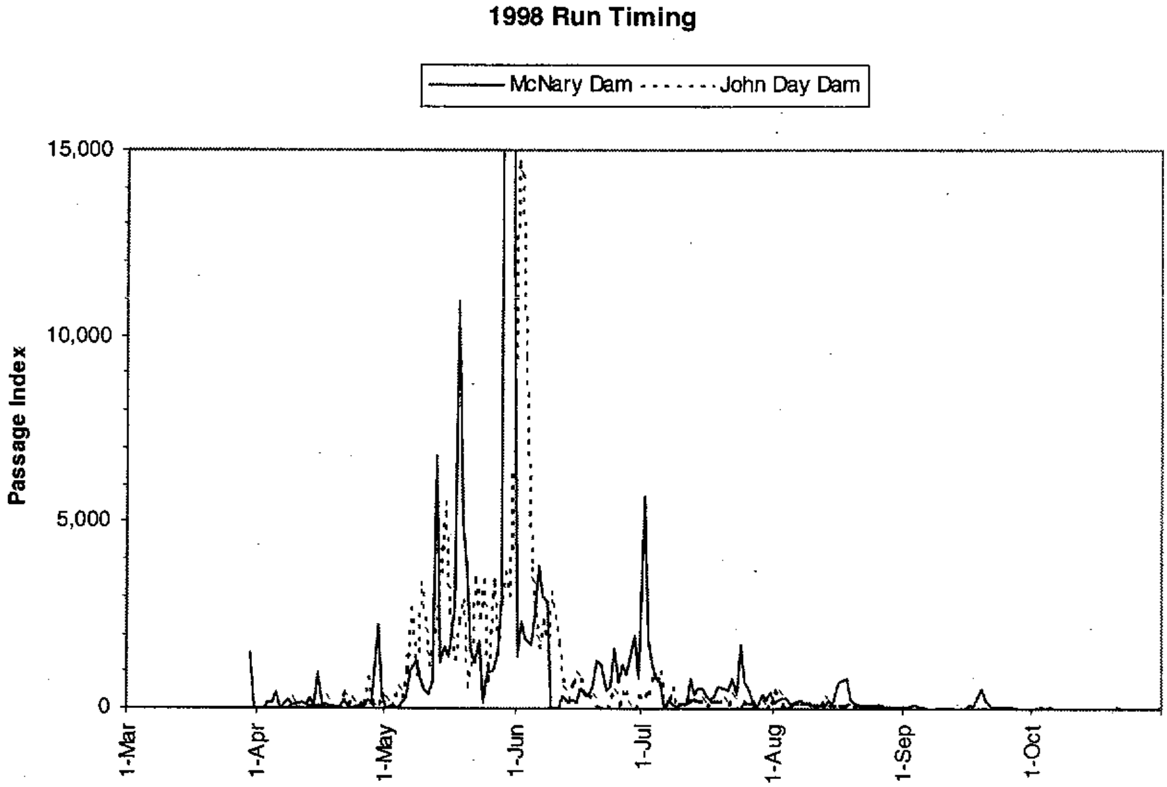

Figure 3. Juvenile Pacific lamprey run timing from the Smolt Monitoring Program. The single value off the vertical scale is the passage of 60,000 lamprey through McNary Dam on May 29.

Diel Behavior

A preliminary search of the literature suggested the outmigrating individuals were more active at night (Hardisty and Potter 1971). Therefore, we designed a series of tests to better understand juvenile lamprey responses to the diel cycle. Initial results indicated that laboratory experiments needed to be conducted during periods of darkness because lamprey exhibited little volitional activity during daylight hours. Infrared illuminators were used to record events on video without altering behavior. The 880-nm wavelength output of the illuminators is beyond the visible spectrum, but certain cameras are sensitive to that range.

We designed two tests under static flow conditions, with and without a cobble substrate. The primary objective was to characterize diel activity and general behavior; a secondary objective was to evaluate substrate choice. Substrate choice in this case was for cobble or bare tank similar to the photo below (Figure 4).

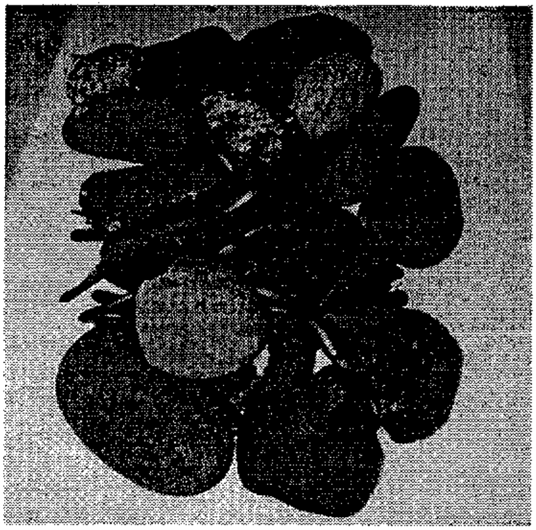

Figure 4. Selection of cobble substrate for cover by juvenile lamprey.

A 50-L observation tank (94 cm wide × 63.5 cm deep × 47 cm height) was used with a full side observation window. This was supplied with flow-through 10°C raw river water. A white backdrop included four depth reference strata. The tank was top-lit with infrared illuminators, and the camera had a full field of view (Figure 5). The laboratory was on a 12-hr light cycle with approximately a 20-min transition period. For the test, 20 lamprey were placed in the tank. Videotaping occurred continuously over 3 days with a time-lapsed video tape recorder in 72-hr mode (0.6-s frame interval). Position and activity of all lamprey were recorded at 15-min intervals.

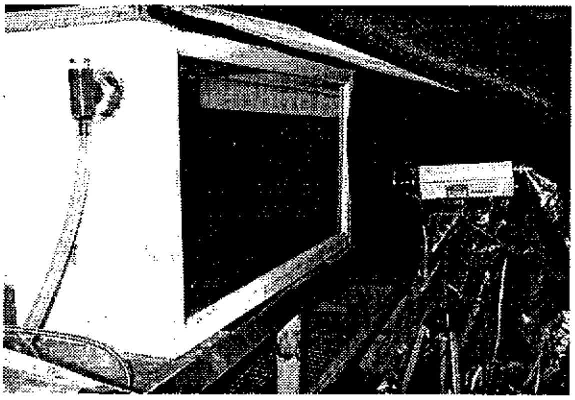

Figure 5. Group diel tank shown with observation window and camera.

An additional set of tests was conducted to evaluate the diel behavior of individual lamprey. Four 10-gallon tanks with cobble substrate were set up with flow-through chilled 8.5°C well water. These tests were conducted after the ambient river water temperature had increased and the lamprey were being held in chilled river water (see the

Other Observations in the Results section for more details). In each test, a single juvenile lamprey was placed into a tank 12 hours before testing began. Taping occurred continuously over 24 hours with a time-lapsed video tape recorder in 72-hr mode (0.6-s frame interval). Position and activity were recorded at 15-min intervals.

Swim Speed

Two holding troughs were designed to examine maximum burst speed. A plastic grid was placed on the bottom with markings at 10-cm intervals, and a camera was suspended over the troughs to record lamprey movement. Each lamprey was placed into one of the troughs and allowed to acclimate for 3 minutes. Once the fish was in view of the camera, it was induced to swim by squirting water through a pipette. The fish was then allowed to rest for 3 minutes before being stimulated again. This process was repeated a total of five times per fish and was conducted on 30 lamprey. Video was collected in 2-hr mode (1/30-s frame interval). The maximum speed attained was the fastest run as measured within a 10-frame (1/3-s) interval. An average maximum burst speed was attained for all 30 individuals (Figure 6).

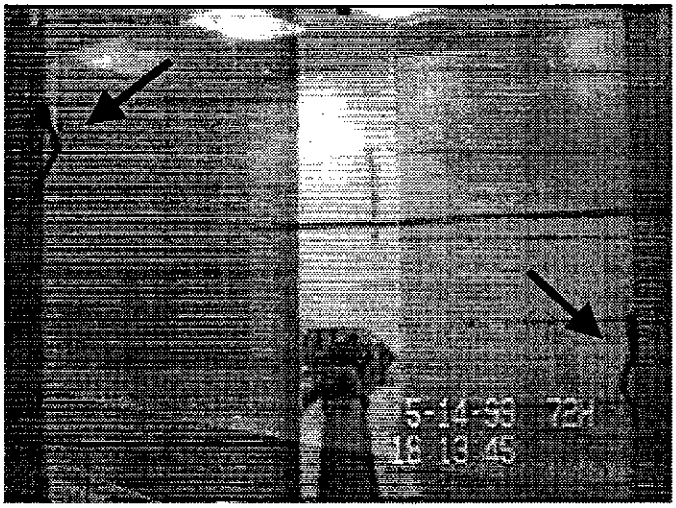

Figure 6. Juvenile lamprey exhibiting anguilliform motion in paired trough during burst speed trials.

A second set of experiments was designed to measure sustained swim speed. This required that we deal with the general unwillingness of juvenile lamprey to swim. A 40-cm diameter × 115-cm length mesh tube was constructed and placed inside a 2,200-L Brett-type respirometer (Figure 7). The 1/8-in nylon mesh was from a John Day Dam submersible traveling screen. The tube was sealed at both ends, had a small entry port at the upstream end, and a downstream end that was electrified with wire woven into the mesh (Figure 8). This design succeeded in accomplishing three things necessary to conduct the experiment. First, juvenile lamprey were forced to continuously swim because they could not attach to the mesh screen. Second, the electrification prevented them from resting at the back of the tube. Third, fish could be observed through the light-colored mesh (Figure 9). A control panel was used to regulate the voltage and current of the electrified portion to 5V and 0.6A DC. Initially, water velocity was increased at 0.5 ft/s intervals every 15-min until the lamprey became fatigued. The time interval between velocities was later decreased to 5-min because of observations that fish were becoming fatigued in the second half of the longer interval.

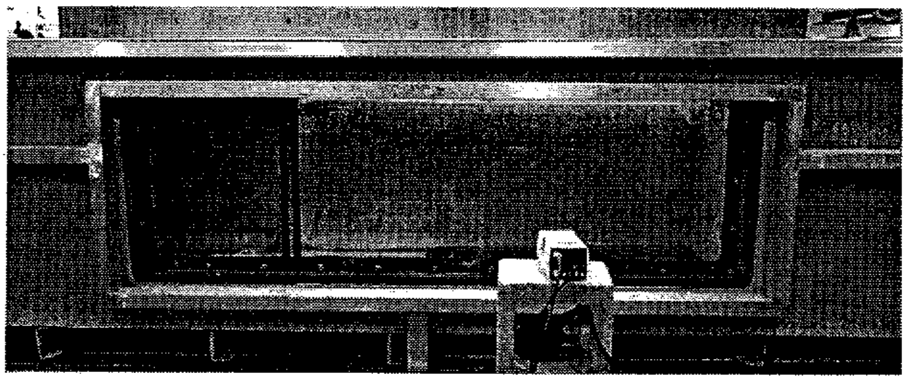

Figure 7. Electrified mesh tube inside the respirometer flume. A juvenile lamprey is shown to the right swimming upstream.

Figure 8. Electrified downstream portion of mesh tube. The wires extended some distance along the bottom as well.

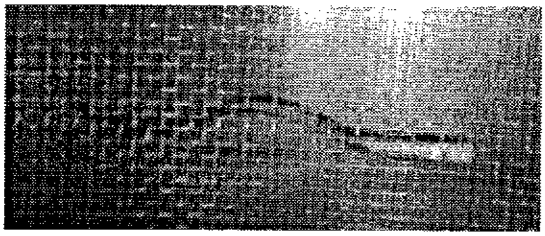

Figure 9. Lamprey were unable to grasp the nylon mesh, though it wasn't for lack of trying.

Response to Bar Screens

All bar screen exposures were conducted in the 2,200-L Brett-type respirometer (Brett 1965). A 25-hp variable speed alternating-current motor drove an impeller to provide velocities from 0 to 2 ft/s. A 50 cm × 50 cm section of bar screen (1/8" spaced wedge wire or Johnson bar) was used. This was set perpendicular to flow and all subsequent tests were conducted with the bar screen perpendicular to flow (Figure 10). Cameras were set to look through the observation window to evaluate behavior during tests. Infrared illuminators were used to capture lamprey activity on video at night (Figure 11). The velocity of the water within the test apparatus was measured using an acoustic doppler velocimeter. Appendix B describes the details of the flume velocity calibration in greater detail.

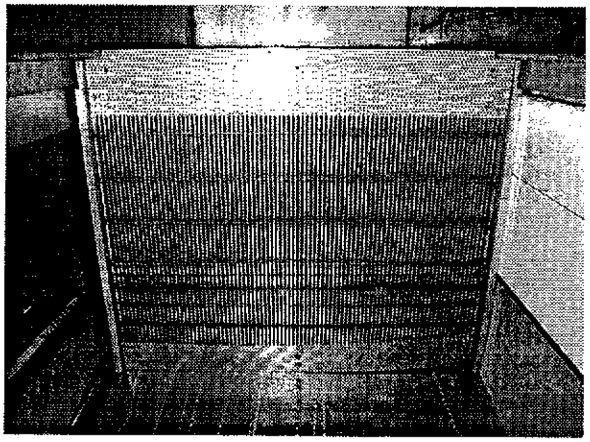

Figure 10. The bar screen insert placed in the flume. All tests were conducted as shown with the bar screen perpendicular to flow.

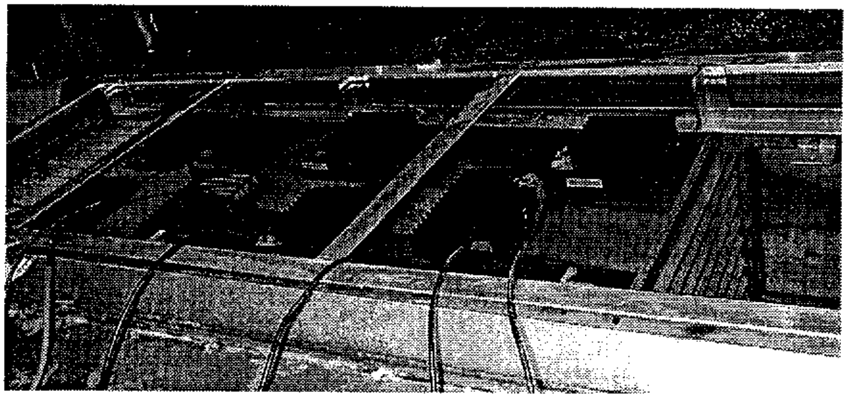

Figure 11. Infrared lighting shown here above the flume illuminated the observation area and bar screen during night-time tests.

We conducted a series of tests to determine the velocity at which juvenile lamprey became impinged on the bar screen while under continuous flow. (We define the critical impingement velocity for lamprey as the water velocity at which individuals are unable to remove themselves from the screen face.) All bar screen exposures were done at night to ensure that movement was volitional. Two groups of 20 randomly selected lamprey each were tested over an 8-day period (4 days for each group). Four treatment velocities were tested: control (no flow), 0.5 ft/s, 1.0 ft/s, and 1.5 ft/s. This range was based on previous testing which showed that a 12-hr exposure to greater than 2 ft/s flume velocity was lethal. That is, all juvenile Pacific lamprey in Stage 7 of metamorphosis exposed to 2.5 ft/s flows for 12 hours became impinged on the bar screen and died. Each of the four experimental treatments was applied overnight (1800h to 0600h) with no treatment (i.e. static conditions) applied during the day. Velocity regimes were randomized over each of two replicate test series (Table 1). Time-lapse video recorded events in 72-hr mode (0.6-s frame interval).

Table 1. Experimental design for 12-hr screen exposure.

WEEK 1 (Group 1)

Day 1	Day 2	Day 3	Day 4
Control	1.5 ft/sec	1 ft/sec	2 ft/sec

WEEK 2 (Group 2)

Day 1	Day 2	Day 3	Day 4
Control	2 ft/sec	1 ft/sec	1.5 ft/sec

A final test was designed to determine initial reactions of juvenile lamprey to the bar screen. Four groups of 10 lamprey each were introduced into the swim chamber of the respirometer via a Plexiglas tube. They were placed into 0 to 1.5 ft/s velocity flows. Observations of their behavior (i.e., interaction with the bar screen, swimming patterns) were made from the video record. All video was recorded in normal 2-hr mode. This entire test was conducted in the dark using infrared illuminators.

Shear Stress

Juvenile lamprey were subjected to a range of shear forces, such as those encountered as a fish passes through a turbine. Individual lamprey were placed directly into the shear zone and their location in the water column recorded using high-speed video photography. Three replicates with 10 fish per treatment were exposed to jet velocities (0, 20, 30, 40, 50, 60).

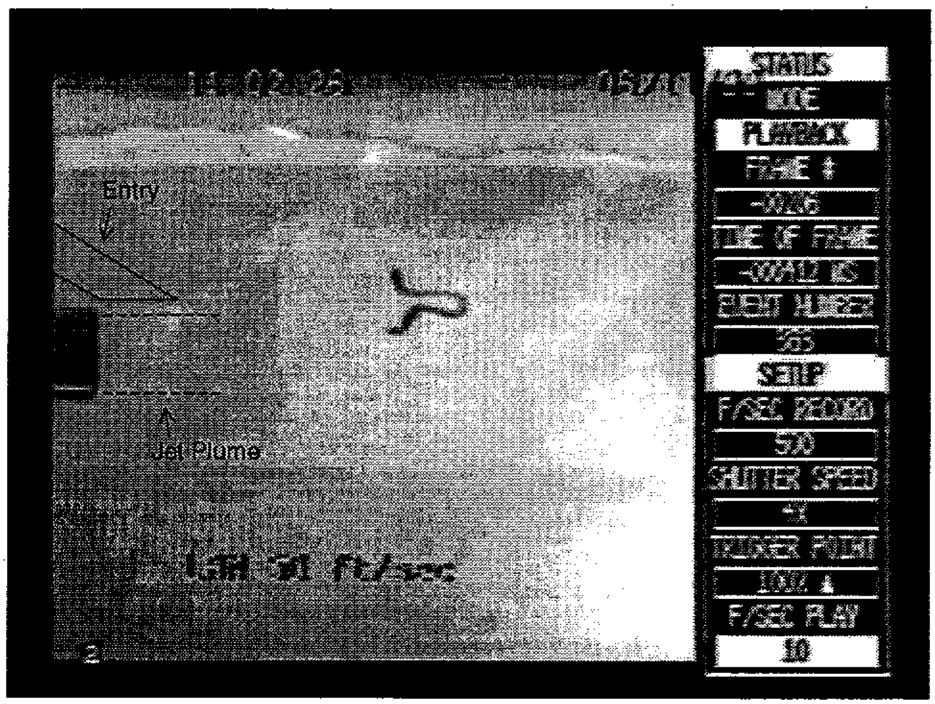

Figure 12. Example of lamprey shear test at 50 ft/s jet velocity, recorded at 500 frames/s.

Each group was observed five times after the shear exposure (0 hr, 24 hr, 48 hr, 72 hr, 96 hr), and their health was categorized into grades. Proportional tests were performed to compare biological endpoints of control fish to those of the test population.

The reported jet velocities correspond to a rate of strain shown in Table 2. It should be noted that the scale at which the strain calculations are made is critical. The rate of strain calculations are based on an assumed $\Delta y = 1$ cm (Equation 1) and are consistent with the calculations currently used by Neitzel et al. (pers comm). The 1-cm unit was chosen to represent the order of magnitude of a smolt width.

Table 2. Jet velocity and rate of strain relationship.

Jet Velocity (ft/s)	Rate of Strain (cm/s/cm)
0	0
10	305
20	610
30	915
40	1220
50	1525
60	1830

$$e = \frac{\partial \overline{u}}{\partial y}$$

Equation 1. Laminar form of the rate of strain.

Results and Discussion

Juvenile lamprey ranged from 110 to 165 mm in total length; the mean length was 136 for the test population (Figure 13). Lamprey lack a swim bladder for buoyancy regulation. They also lack paired fins, e.g., pectorals that produce upward lift forces for some other non-teleosts (Alexander 1990). Negative buoyancy may be deduced from the observation that the bodies of all lamprey hang down when attached to a tank surface, and all inactive lamprey were either attached or on the bottom. Lamprey must rely on their tail to move off the bottom and to propel forward. The lack of pectoral fins and proportionately higher number of body segments involved in movement likely has higher energetic costs (Webb 1975).

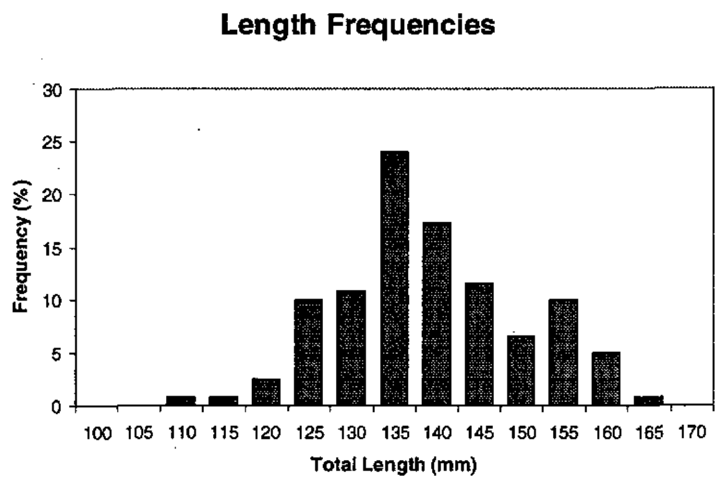

Figure 13. Total length frequencies of tested juvenile lamprey; n = 121.

Diel Behavior

Initial experiments showed that volitional movement of juvenile lamprey was restricted to night only. We also noted the availability of cobble substrate affected the resting or attached position of juvenile lamprey (Figure 14). When given a choice, lamprey always chose a cobble substrate over the bare tank. Without a choice, lamprey attached to the side of the observation tank near the surface or top strata, often by the water inlet. There was no apparent influence of substrate on swimming activity or depth distribution (Figure 15).

The presence of other lamprey did not appear to affect the vertical distribution of actively swimming individuals, based on their depth in the water column (Figure 16). In general, the activity of individual lamprey appeared greater than that noted for group tests (Figure 17). That is, individual lamprey spent a higher proportion of the time actively swimming than lamprey that were tested in groups of 20.

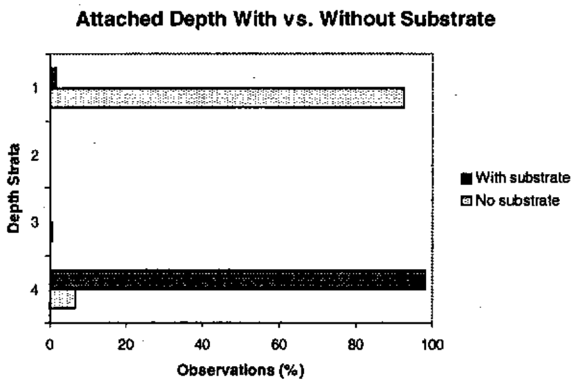

Figure 14. Relative distribution of attached juvenile Pacific lamprey with and without cobble substrate (group test, both day and night combined), n = 7680. Depth strata 4 is the bottom of the observation tank.

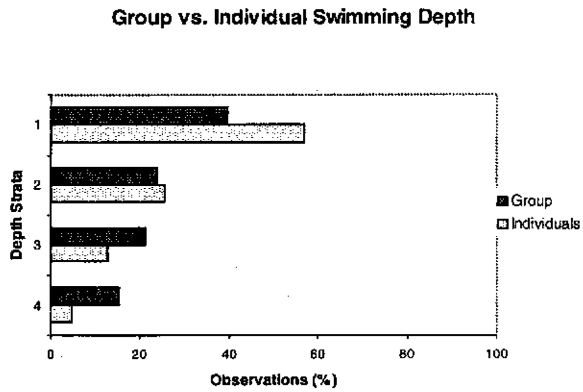

Figure 16. Depth distribution for actively swimming individuals and groups of juvenile Pacific lamprey (both day and night combined). Depth strata 4 is the bottom of the observation tank.

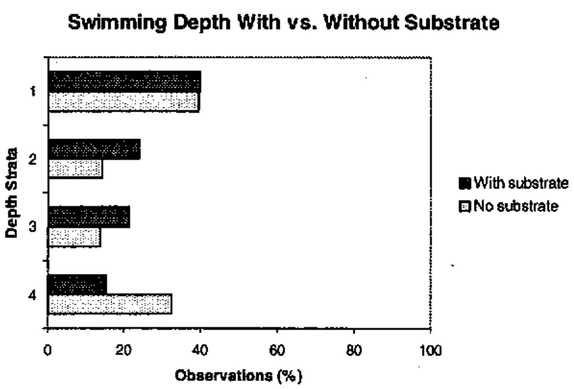

Figure 15. Relative distribution of actively swimming juvenile Pacific lamprey with and without substrate (group test, both day and night combined), n = 7680. Depth strata 4 is the bottom of the observation tank.

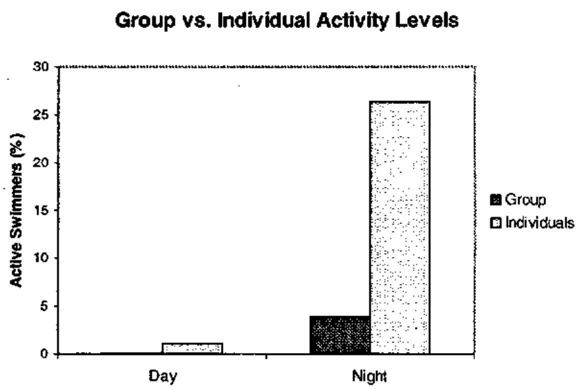

Figure 17. Diel activity levels (active swimmers) of grouped and individual juvenile Pacific lamprey, both with cobble substrate.

For all the tests, swimming activity was greatest in the early evening and gradually declined through the night. This pattern was the same for all tests regardless of substrate or group status (Figure 18). Nearly all (94%) of the swimming activity was observed during the dark period. Increased movement at night is consistent with diel movement observed for downstream migrant juvenile Pacific lamprey at mainstem dams. For example, Long (1968) reported 62% of lamprey ammocoetes were collected during the night at The Dalles Dam powerhouse.

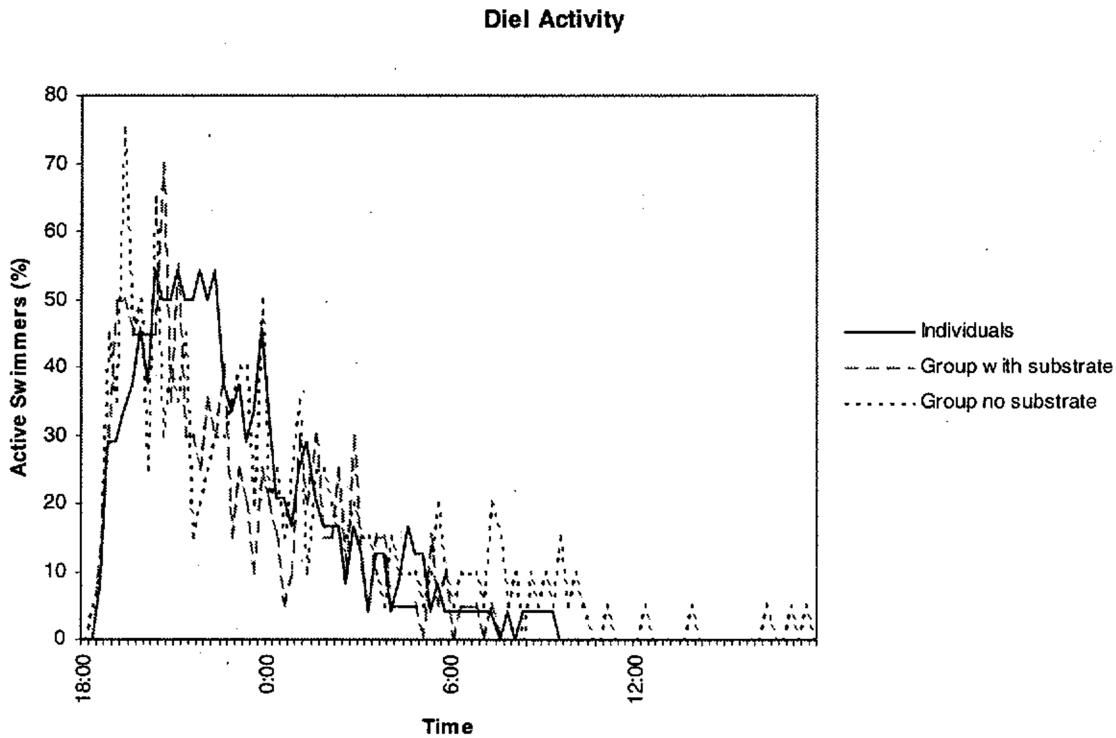

Figure 18. Diel activity patterns for all diel tests. The dark period began at 1800h and ended at 0600h.

Swim Speed

Fish swimming performance metrics and nomenclature are not standardized. Burst speed is typically defined as the maximum speed attained on the order of seconds. Sustained speed is usually described on longer exposures, on the order of minutes. A cruising speed may be defined as a speed that can be maintained for hours (Bell 1986, Webb 1975). Subcategories may also be defined. For instance, Webb notes that the burst definition includes speeds for less than 1 second, but that these may be considered in a separate category for unsteady peak speeds.

Burst speed of juvenile Pacific lamprey during our paired trough tests ranged from 1.8 to 3.1 with a mean of 2.3 ft/s for n = 30 (Figure 19). This equates to a specific swim speed (normalized to body length) of approximately 5.2 L/s. The specific swim speed measure has been shown to be length dependent and varies for different species; however, it is still a useful metric to make comparisons between otherwise disparate experiments. The elver stage of *Anguilla*, for example, was shown to have a specific swim speed of 7.5 L/s for a 0.27-min interval. Juvenile salmonids have been shown to be generally capable of burst speeds on the order of 9-12 L/s. (McCleave 1980, Webb 1975).

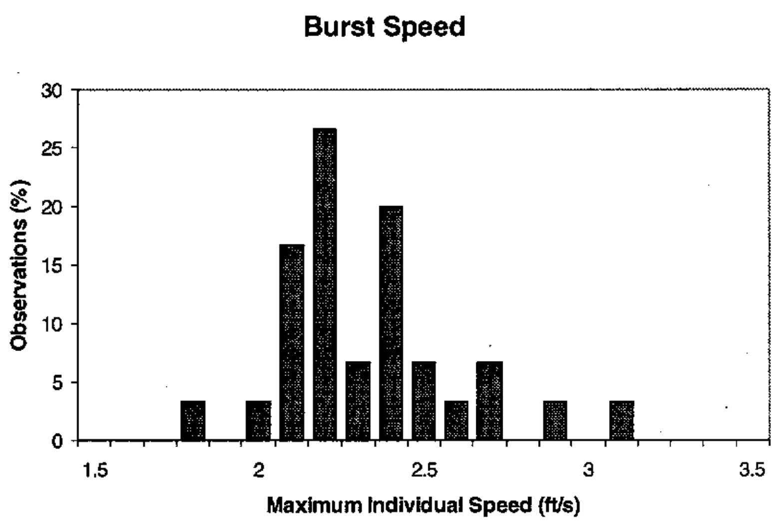

Figure 19. Distribution of burst speed values for individual lamprey. Average maximum burst speed was 2.3 ft/s (n = 30).

Sustained swim speed at 5-minute intervals in the mesh tube ranged from 0 to 1.5 ft/s with a median of 0.75 ft/s (n = 30). Sustained swim speed at 15-minute intervals was slower and ranged from 0 to 1.0 ft/s with a median of 0.5 ft/s (n = 10). Collectively, these values show that swimming endurance decreased slightly from 0.5 to 1.0 ft/s, then rapidly at velocities ≥ 1.5 ft/s (Figure 20). The shape of this curve also concurs with the following swim speed relationship equation (Equation 2).

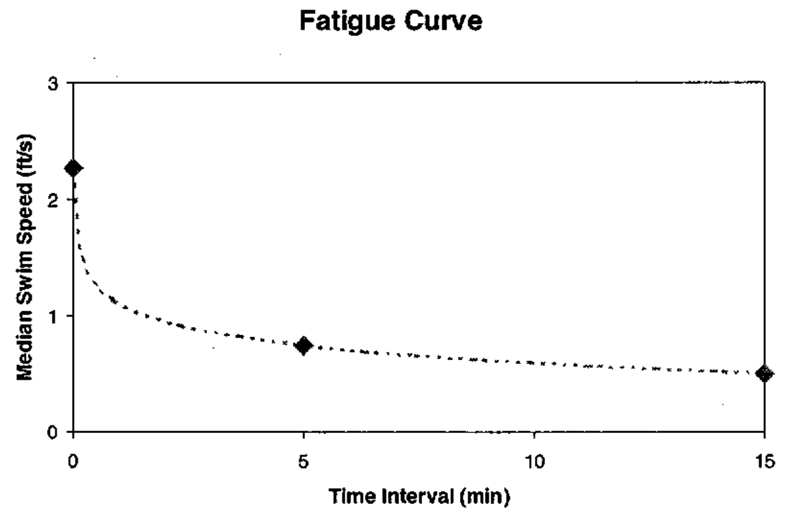

Figure 20. Fatigue curve based on a hypothetical logarithmic fit to median sustained swim speed.

$$\text{Dart Speed} = \text{Sustained Speed} \times 2 = \text{Cruise Speed} \times 6$$

Equation 2. Swim speed relationships based on Bell (1986).

Based on these data, we find that juvenile Pacific lamprey are relatively poor swimmers. This fact becomes critical when the turbine intake environment is considered where the average perpendicular velocity at an ESBS is 2.4 ft/s (Figure 26). We will also see in the next section that their behavioral response to bar screens is markedly different from the salmonids for which the screens were designed.

Response to Bar Screens

Juvenile Pacific lamprey spent an increasingly higher proportion of time in the downstream portion of the tank, including on the screen face, as velocities were increased in the test flume. Approximately 55% and 98% of all lamprey occurred on the screen face at velocities of 1.0 and 1.5 ft/s, respectively, during 12-hour exposures (Figure 21). This distribution indicated that approximately 98% of juvenile lamprey were unable to free themselves from the screen face at velocities of ≥ 1.5 ft/s when exposed to flows over extended periods of time. Additionally, more than half of the test fish were on the screen at velocities ≥ 1.0 ft/s. The typical response to these screen exposure scenarios is shown for a control and a 1.5-ft/s flume velocity (Figure 22 and Figure 23).

At all velocities greater than 0 ft/s, juvenile lamprey made contact with the bar screen within 1 minute of their entry into the water column upstream of the bar screen. They dispersed throughout the test flume and generally avoided continuous contact with the screens at velocities ≤ 1.0 ft/s. All lamprey moved toward the bar screen and made immediate contact with the screens at 1.5 ft/s velocity; 70% of the lamprey never moved off the screen face (Figure 24). Therefore, we have defined the impingement velocity for lamprey as the water velocity at which individuals are unable to remove themselves from the screen face. Collectively, these tests indicate that juvenile lamprey have difficulty extracting themselves from screens at velocities ≥ 1.5 ft/s for intervals as short as 1 minute. Furthermore, impingement occurred for velocities ≥ 1.0 ft/s over 12-hour exposure periods.

Some lamprey appeared to use their tails to "push off" and extract themselves from the bar screen when they became fatigued and unable to swim away at higher velocities. Because the tip of their tail is narrower than the rest of their body, this resulted in a few individuals becoming wedged between the bar screen slots (Figure 25). We noted lamprey were able to push their tail in and back around consecutive bars. This behavior was also observed in the field and resulted in the death of the entwined lamprey.

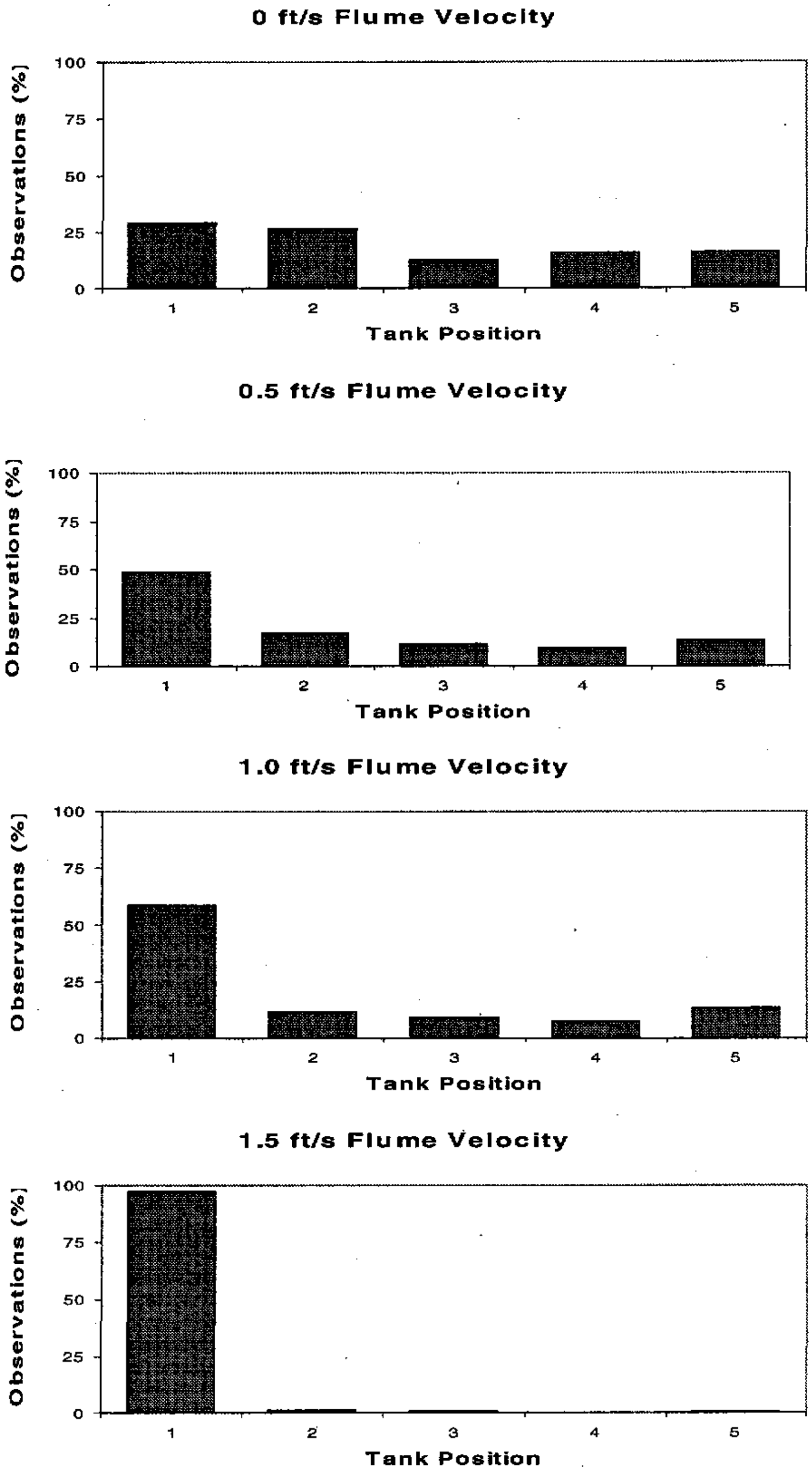

Figure 21. Relative position of juvenile lamprey during 12-hour screen exposures, n = 1960 per velocity (7840 total observations). Position 1 is the most downstream location, i.e., next to or on the bar screen.

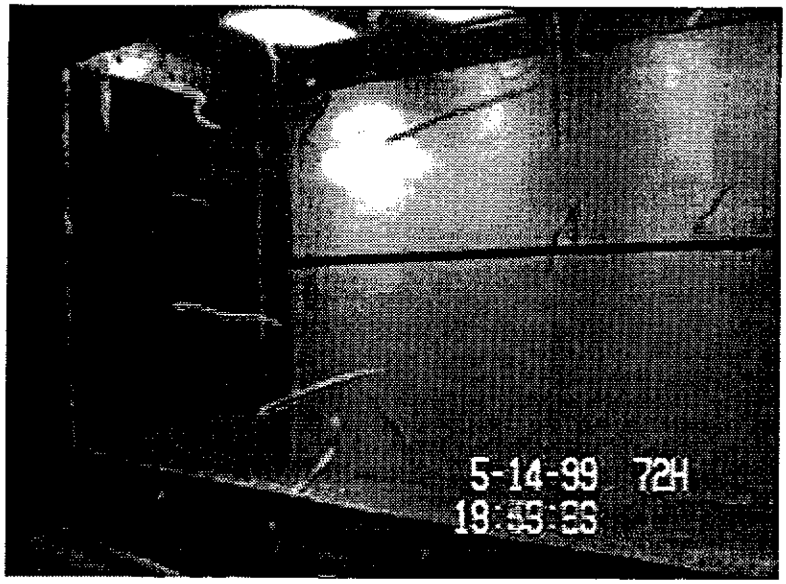

Figure 22. Example of 12-hour bar screen exposure at 0 ft/s flume velocity (control). Note that lamprey are swimming freely throughout the water column.

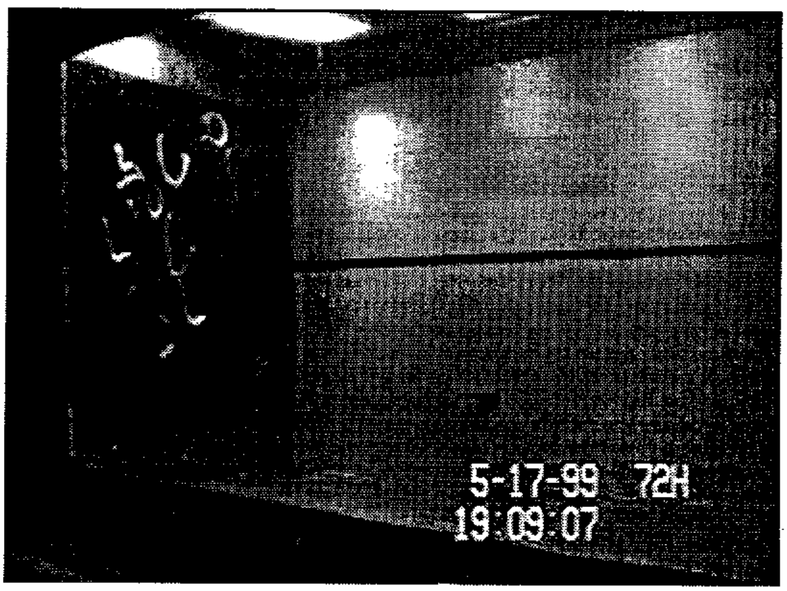

Figure 23. Example of 12-hour bar screen exposure at 1.5 ft/s flume velocity. The bar screen is at the left (downstream) portion of the picture. Most lamprey are impinged on the bar screen, others are attached to the tank wall or floor.

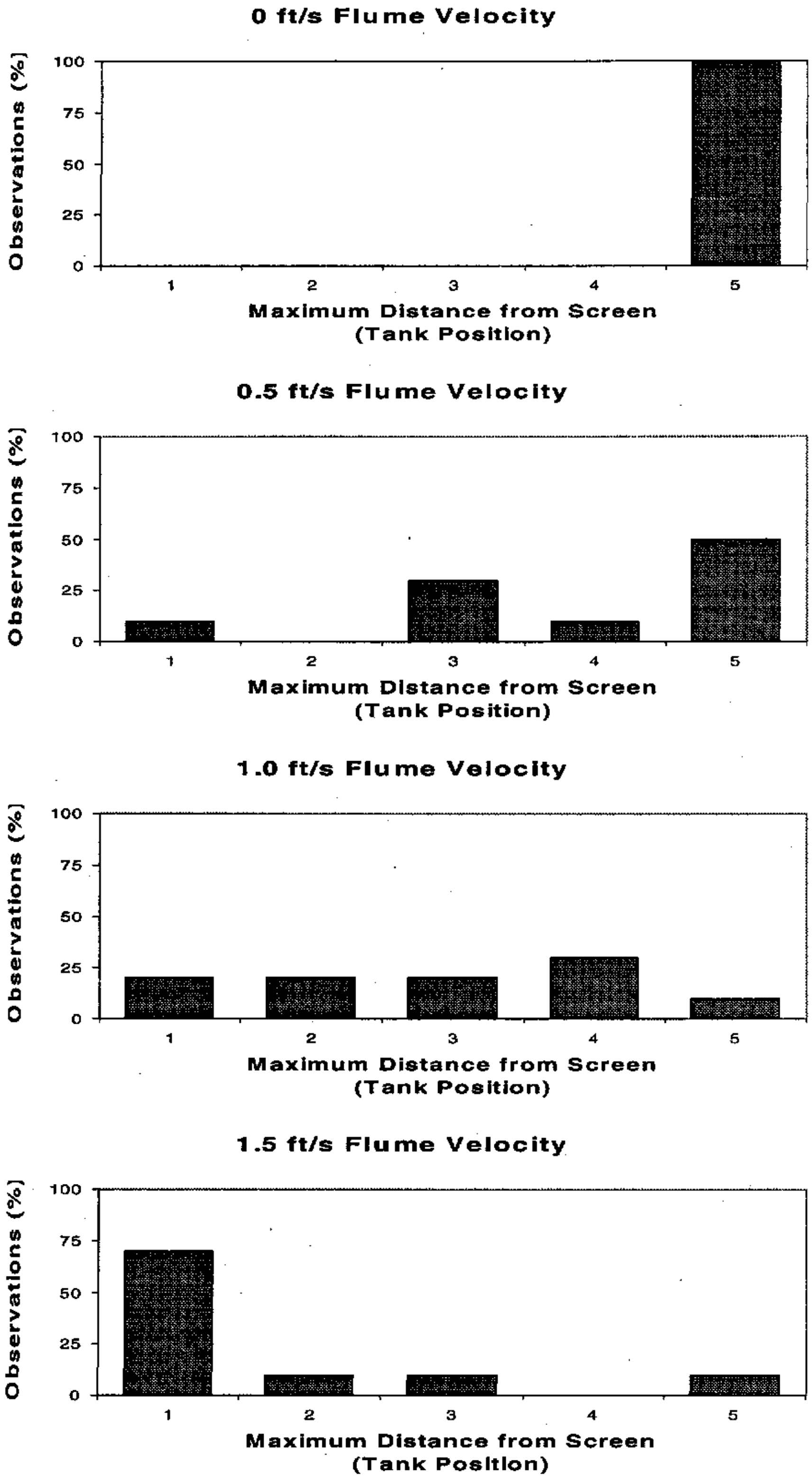

Figure 24. Relative position of juvenile lamprey during 1-minute exposures, n = 10 per velocity (40 total observations). Position 1 is the most downstream location, i.e. next to or on the bar screen.

Figure 25. Back view (left) and front view (right) of impinged lamprey on bar screen. Note the tail-first orientation

The average velocity of flow perpendicular to the ESBS's at John Day Dam is estimated to be 2.4 ft/s (Figure 26). This velocity exceeds the levels resulting in impingement of juvenile lamprey during all our laboratory tests. This value is also slightly higher than the average burst speed of our test population. Highest velocities occurred at the upper portion of the ESBS and sweeping velocities exceeded 10 ft/s near the gatewell slot entrance.

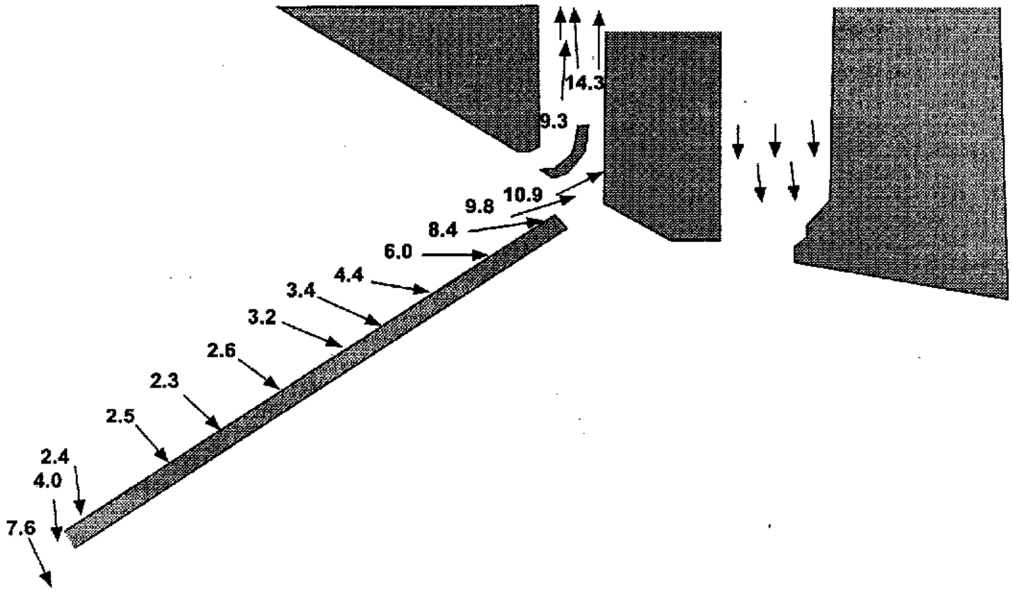

Figure 26. Cross-section diagram of the velocity vectors at a deployed ESBS based on physical model data from the Corps.

Shear Stress

Currently no data exist pertaining to the effects of shear on juvenile Pacific lamprey. The results from our study provide baseline species information for quantifying the biological criteria of the turbine passage environment. In addition, they provide a comparative data set for salmonid research.

Lamprey did not suffer any ill effects at exposure to the jet velocities (equivalent to rates of strain 1220 to 1830 cm/s/cm) that injured and/or killed salmonids (Neitzel et al 1998). There were no immediate deaths and no immediate gross injuries. Gross injuries to teleosts (bony fish) included missing eyes, hemorrhaging from the eyes and/or gills, inverted gills, torn isthmus, severe bruising, and greater than 80% scale removal. Possible reasons for the hardiness of juvenile lamprey may include their flexibility (Figure 12) and the reduced size of vulnerable structures. For example, injuries to salmonids often involved the operculum or jaw—structures absent in lamprey.

Other Observations

Increased water temperatures resulted in greatly increased incidence of fungal infection for lamprey held at the Aquatic Laboratory. Ambient river water temperature exceeded 15° C in June, 1999, when lamprey were held in raw river water tanks. Other researchers holding juvenile lamprey at that time noted problems with infections (Jen Bayer, USGS, pers comm, and Carl Shreck, OSU, pers comm). It was assumed this was a fungal infection, but the exact nature of the disease has not been determined.

We used salt as a treatment in order to avoid water discharge regulations with prophylactic chemicals (e.g. formalin). We tested survivability of juvenile lamprey in both 50% (17 ppt) and full (35 ppt) seawater concentrations. Transfer from freshwater to full seawater was lethal. In contrast, survival rates were high in the 50% seawater solution, and the fungal infection ceased. Lamprey held in seawater were returned to chilled well water to hold for the sustained swim speed tests. Due to limited availability of test fish, formal bioassays regarding a seawater prophylaxis protocol were not conducted. A suggested procedure is to hold juvenile lamprey in 50% seawater for 1 week, then place in cold sterile freshwater (e.g., ≤10° C well water). We currently have juvenile lamprey that have been held in chilled 50% seawater for 4 months that are still healthy.

We observed juvenile lamprey feeding on dead rainbow trout while held in freshwater (Figure 27). Richards and Beamish (1981) exposed live Pacific herring to juvenile lamprey at Stage 7 of metamorphosis in freshwater, but observed no feeding until they were transferred to saltwater. We also observed attachment and feeding on live rainbow trout regularly for juvenile lamprey held in the 50% seawater tanks.

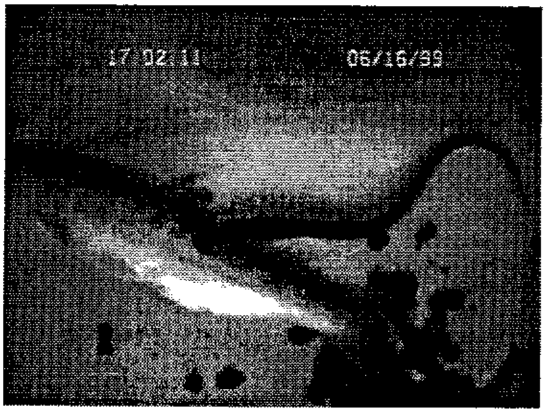

Figure 27. Juvenile lamprey feeding on dead rainbow trout in freshwater.

Conclusions

We found that juvenile Pacific lamprey were highly nocturnal during our laboratory studies, with >90% of their swimming activity restricted to hours of darkness. They also had a strong preference for substrate and remained near the bottom of test aquaria during daylight hours. This behavior is consistent with lack of buoyancy compensation (i.e., they have no swim bladder and slightly negative specific gravity). That lamprey are mainly demersal and nocturnal would be advantageous for predator avoidance, but this same behavior increases the possibility that they will pass dams via turbines and underneath the screen or surface bypass systems designed to guide juvenile salmonids.

Our studies also demonstrated that juvenile Pacific lamprey are fairly weak swimmers. They had an average maximum burst speed of 2.3 ft/s, or less than the average perpendicular velocity at the face of extended length submersible bar screens at John Day Dam. We also found that 70% and 97% of test fish became impinged on bar screens at velocities of 1.5 ft/sec for 1-minute and 12-hour exposures, respectively. The tendency of juvenile lamprey to use their tails for locomotion resulted in some individuals becoming permanently wedged between the bar spacings.

Additional tests are planned in FY 2000 to evaluate lamprey behavior with different screen materials (e.g., STS-type 1/8-in nylon mesh, narrower bar screen with 3/32-in spacing; or ESBS-type bar screen in a lateral configuration). The stamina or ability of lamprey to survive impingement over a range of velocities that occur in the turbine intake will also be tested. This information, along with in-turbine observations of juvenile lamprey on bypass screens, could be used to provide insight toward optimum brush cleaning cycles.

References

Alexander RM. 1990. Size, speed, and buoyance adaptations in aquatic animals. Amer. Zool. 30:189-196.

Bell, MC. 1986. Fisheries handbook of engineering requirements and biological criteria. Fish Passage Development and Evaluation Program, U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Brett JR. 1965. The respiratory metabolism and swimming performance of young sockeye salmon. J. Fish. Res. Bd. Can. 21:1183-1226.

Close DA, M Fitzpatrick, H Li, B Parker, D Hatch, and G James. 1995. Status report of the Pacific lamprey (*Lampetra tridentata*) in the Columbia River basin. Prepared for the U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Hardisty MW and IC Potter (eds.). 1971. The biology of lampreys. London: Academic Press.

Hatch D, and B Parker. 1998. Lamprey research and restoration project. 1996 Annual Report. Part (B) Abundance monitoring for Columbia and Snake Rivers. Prepared for U.S. Department of Energy, Bonneville Power Administration, Portland, Oregon.

Kan TT. 1975. Systematics, variation, distribution and biology of lampreys of the genus Lampetra in Oregon. PhD Thesis. Oregon State University, Corvallis, Oregon.

Long CW. 1968. Diurnal movement and vertical distribution of juvenile anadromous fish in turbine intakes. Fishery Bulletin 66(3):599-609.

McCleave JD. 1980. Swimming performance of European eel (*Anguilla anguilla* (L.)) elvers. J. Fish. Biol. 16:445-452.

Neitzel DA, CS Abernethy, MC Richmond. 1998. Laboratory studies of the effects of turbulence and shear stresses on turbine-passed fish: 1997-98 program report. Prepared for the Idaho National Engineering and Environmental Laboratory.

Richards JE, and FWH Beamish. 1981. Initiation of feeding and salinity tolerance in the Pacific lamprey *Lampetra tridentata*. Mar. Biol. 63:73-77.

Youson JH, and IC Potter. 1979. A description of the stages in the metamorphosis of the anadromous sea lamprey, *Petromyzon marinus* L. Can. J. Zool. 57:1808-1817.

Webb PW. 1975. Hydrodynamics and energetics of fish propulsion. Bull. Fish. Res. Bd. Canada 190:1-158.

Wydoski RS, and RR Whitney. 1979. Inland fishes of Washington. University of Washington Press. Seattle, Washington.

Appendix A: Equipment Specifications

A custom-built 2,200-L Brett-type respirometer (Brett 1965) was constructed of stainless steel and contained a working section with removable cover, impeller, flow straightener, and view window. The observation section measured 1.8 m long, 0.53 m wide, and 0.53 m high. A 25-hp variable speed alternating-current (AC) motor drove the impeller that provided velocities that ranged from 0 to 150 cm/s. The respirometer unit was immersed in a fiberglass cooling tank that measured 4.5 X 1.7 m. Water temperature could be regulated between 10 and 23°C. The respirometer operated with the follow motor and controller:
25 hp Reliance Electric AC motor P32G0431K, s/n 05MN320431
Powermaster AC motor speed controller CIMR-G304018, s/n E131457

Flow measurements were taken with an acoustic doppler velocimeter, Sontek ADV Field s/n A205.

The following infrared illuminators, 880 nm λ output, and associated power supplies were used:
Infrared illuminators, 30W American Dynamics AD1020/3050
Infrared illuminators, 60W American Dynamics AD1020/6050
Power supplies, Trip Lite PR-15 (13.8V DC 15A)

The low-light, black and white, CCD cameras, with peak sensitivity in the infrared band were:
Video camera, Ikegami ICD-4224 with 6mm lens, s/n F07807
Video camera, Ikegami ICD-4224 with 6mm lens, s/n F07857

The following video tape recorders were used:
Time-lapse SVHS video recorder, Panasonic AG-6730P s/n C4TA00357
Time-lapse SVHS video recorder, Panasonic AG-6730P s/n C4TA00339
Video Hi8 recorder, Sony EV-C200
Video Hi8 recorder, EV-S5000
Video overlay, Video Typewriter 5100 serial number 3113

A research stereo microscope was used for identifying the morphological features used in determining the developmental stage:
Research stereo microscope, Olympus SZH10
Video camera (attached to scope), Sony DXC-970MD

Appendix B: Flume Velocity Calibration

The following relationship was determined with an acoustic doppler velocimeter (Figure B.1). For the screen exposure tests, these measurements were taken at the screen face in the center of the flume. For the swimming performance test, measurements were taken immediately downstream of the tube in the center of the flume. Variation of velocity within the tank ranged approximately ± 0.1 ft/s. Turbulence was not measured for these tests. The turbulence intensity that lamprey or other fish may encounter in the turbine intake environment is not yet known.

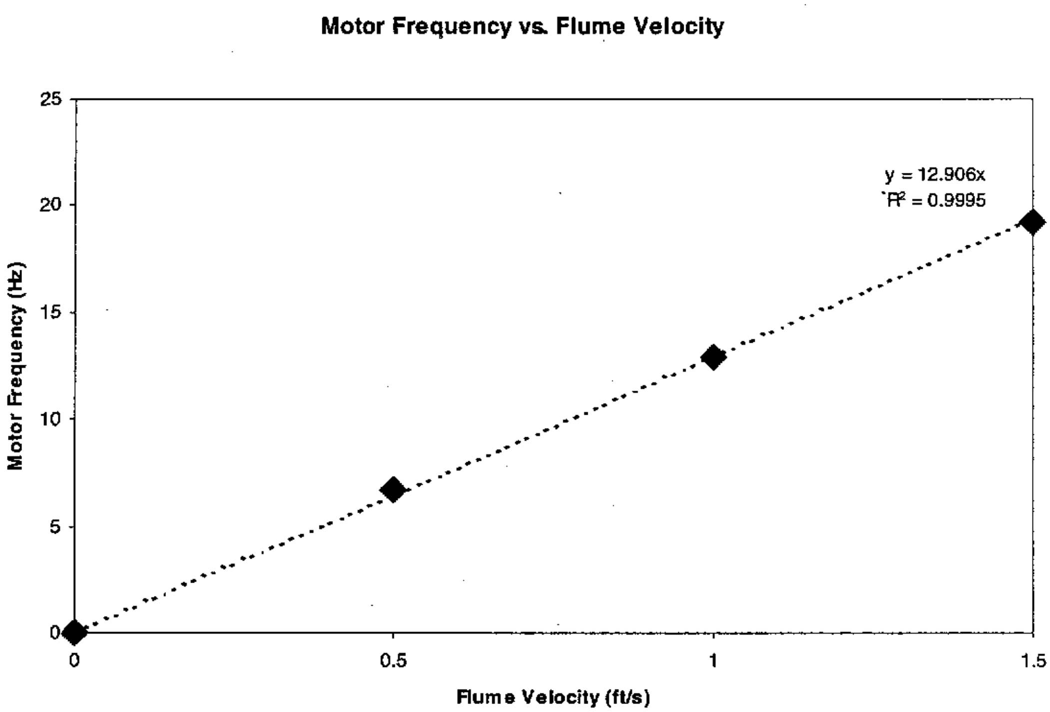

Figure B.1. Relationship between motor frequency and flume velocity.