Laboratory Studies of the Effects of Turbulence and Shear Stresses on Turbine-Passed Fish

1997-98 Progress Report

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Executive Summary

The U.S. Department of Energy's Advanced Hydropower Turbine System (AHTS) program supports research and development of "environmentally friendly" turbines (i.e., turbine systems that emphasize environmental attributes such as entrainment survival, particularly for fish). Advanced turbines would be suitable for installation at new hydropower facilities and potentially suitable for replacing aging turbines at existing plants. It is expected that these turbines could permit the efficient generation of electricity while minimizing damage to fish and their habitats.

Further refinement of advanced turbine designs depends on developing reliable biological specifications such as the quantitative description of maximum allowable levels of turbulence and shear that a fish can sustain without receiving irreparable damage or loss of life.

Pacific Northwest National Laboratory (PNNL) completed four tasks in 1997 aimed at developing biological specifications for environmentally friendly turbines. Our objectives were to build a prototype facility and obtain preliminary biological and hydraulic modeling data to support the design and construction of a permanent test facility where fish can be exposed to shear and turbulence levels found in existing and advanced turbines. Progress toward meeting these objectives is briefly described below.

Design Prototype Facility - We set up an interim facility to conduct range finding tests with Pacific salmon to determine shear stresses that must be designed into a permanent experimental facility. The shear test facility must be designed to generate shear stresses of from 0 to 4,000 N/m^2. This can be accomplished using a water jet. The facility also must be designed to introduce test fish to the shear stress environment head-first or tail-first into the water jet and to the inside and outside of the water jet.

Conduct Biological Response Range-Finding Tests - We subjected smolt size (10- to 18-cm long) fall chinook salmon (*Oncorhynchus tshawytscha*) to shear stresses of 3,000 to 4,000 N/m^2, the maximum shear force a fish might encounter when passing through a typical turbine intake. A computer fluid dynamics (CFD) model was used to compute the size of the pump needed to generate shear stresses greater than 3,000 N/m^2. Other fish species that should be tested are rainbow trout (*O. mykiss*), spring chinook salmon (*O. tshawytscha*), American shad (*Alosa sapidissima*), and sockeye salmon/kokanee (*O. nerka*). Test fish should be smolt size.

Measure Velocity Field – We exposed fish to the shear layer of the water jet nozzle then measured velocities in the jet and map using a Pitot tube and a laser Doppler velocimeter (LDV). A CFD code was used to simulate jet flow fields and resulting shear magnitudes.

Design Full-Scale Facility - PNNL engineers and biologists used baseline data from the biological and hydraulic tests to develop a design memorandum to construct and commission a shear and turbulence test facility. We defined design criteria, designed a permanent test facility, selected the facility location, and prepared a 30% design for construction/fabrication of the facility.

Acknowledgments

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Introduction

Background

The U.S. Department of Energy's Advanced Hydropower Turbine System (AHTS) Program supports the research and development of "environmentally friendly" turbines, i.e., turbine systems in which environmental attributes such as entrainment survival are emphasized. Advanced turbines would be suitable for installation at new hydropower facilities and potentially suitable for replacing aging turbines at existing plants. It is expected that these turbines could permit the efficient generation of electricity while minimizing the damage to fish and their habitats.

Development of advanced, environmentally friendly hydroelectric turbines requires knowledge of both the physical stresses (injury mechanisms) that affect entrained fish and the fish's tolerance to these stresses. Instrumentation of turbines and the increasing use of Computational Fluid Dynamics (CFD) modeling can provide considerable information about the levels of each of these potential injury mechanisms that can be expected within the turbine. Frequently missing, however, are data on the biological responses of fish to known levels of stress. A recent review of literature (Cada et al. 1997) concluded that among the injury mechanisms associated with turbine passage (water pressure changes, cavitation, shear, turbulence, strike and grinding), the effects of shear and turbulence were least understood. The contribution of the other injury mechanisms to fish passage mortality are more predictable, based on past studies and knowledge of the turbine design and fish characteristics. In addition, effects of pressure changes within the turbine passages are presently being studied by other organizations, in coordination with the DOE AHTS Program. Thus, collection of experimental data on shear and turbulence effects have been judged a high priority for the continued development of advanced turbine designs.

Uncertainties about fish sensitivities to shear stresses and turbulence intensities predicted to occur in a turbine make it difficult to determine what levels of shear should tested and how shear can be applied and measured in a representative, quantified, reproducible, and biologically meaningful manner. The few studies of the effects of shear on fish (Groves 1972), Turnpenny et al. (1992), Johnson (1970, 1972) have used a "Groves-type" experimental design, in which a high-velocity jet of water is discharged into a static tank. Test fish were introduced into the jet near the nozzle, struck by the jet, swept downstream, and recovered for evaluation. While this experimental apparatus created damaging shear, resulting information was difficult to relate to turbine design criteria for the following reasons:

- The levels of shear to which fish were exposed was not quantified (the independent variable was expressed as the velocity of the jet).
- Shear changes dramatically with distance from the nozzle and the experimental system was relatively uncontrolled, so each fish was exposed to a different shear regime.
- Exposure of one part of the fish body to a jet (initial contact) did not reproduce the compressional, torsional, and deformational forces that impinge on the fish's entire body within a turbine system.

It has been suggested that previously tested exposures do not adequately represent the effects of shear on a fish within the turbine's water passage (Turnpenny et al. 1992). For example, the rotational and deformational forces experienced by the entire fish as it passes through highly turbulent areas of the turbine, draft tube, and tailrace may be more important to turbine passage mortality. These effects have been shown to be damaging to fish eggs and larvae, but have not been adequately studied in larger fish. Even if these aspects of shear and turbulence cause little direct mortality, they are known to disorient the fish (Groves 1972), and may result in increased susceptibility to predators in the tailrace (Long et al. 1968).

The key to a successful design program for the AHTS will require up-front, pre-design specifications for the environmental and biological conditions that occur within the turbine system. Further refinement of advanced turbine designs depends on the development of reliable biological criteria, i.e., the quantitative description of maximum allowable levels of injury mechanisms that a fish can sustain without receiving irreparable damage or loss of life. One method of determining "what will kill a fish?" is to replicate a turbine environment in a laboratory and to then subject fish to a range of these conditions. Quantifying conditions known to injure or kill fish will provide the "biological specifications" that engineers must deal with in the design of a "fish friendly" turbine system.

On April 28, 1997, staff from Pacific Northwest National Laboratory (PNNL), Idaho National Environmental Engineering Laboratory (INEEL), Oak Ridge National Laboratory (ORNL), and various agency and utility biologists and engineers met to discuss shear and turbulence research needs and priorities. Quantification of design criteria needed to construct a test facility were also discussed. A value of 4000 Newtons per meter squared (N/m^2) was selected as the maximum shear to be evaluated in range finding tests, and as the upper limit of force required in a permanent test facility.

Objective and Scope

Our long-term research goal is to quantify the response of fish to levels of turbulence and shear in a complex three-dimensional velocity fields representative of the inside of a hydroelectric turbine, draft tube, and tailrace. Our research objective was to build a prototype facility and obtain preliminary biological and hydraulic modeling data to support the design and construction of a permanent test facility where fish can be exposed to shear and turbulence levels found in existing and advanced turbines.

During FY1998, PNNL engineers and biologists developed a design memorandum to construct and commission a shear and turbulence test facility. We :

- defined the design criteria,
- designed a permanent test facility,
- selected the location for the facility, and
- prepared a 30% design for construction/fabrication of the test facility.

The final design criteria were enhanced by information generated during the FY1998 fluid dynamic modeling, laser Doppler velocimetry (LDV) measurements, and baseline fish exposure studies.

This report summarizes progress made toward research goals in FY1998 and describes a prototype shear test facility used to conduct baseline fish exposures. We present results of

preliminary fish tests and describe the type and frequency of injuries to fish for different orientations and shear force levels. Plots of velocity fields in front of a rectangular jet nozzle are presented and compared. The results of CFD simulations needed by engineers to design a permanent test facility are also presented. These baseline biological and hydraulic data were used to develop the engineer's conceptual design drawings of a shear and turbulence test facility. Alternative design and fabrication options for this facility are also discussed.

Methods

To define the functional design criteria, we designed and built a prototype facility to expose fish to shear stress forces of up to 4000 N/m^2, the maximum shear forces a fish might encounter when passing through a typical turbine intake. Our biological tests were intended to build upon previous research efforts by Groves (1972) and Turnpenny et al. (1992) where fish were exposed to high-velocity jets, but shear stresses were not measured. In our tests, fish were exposed to the shear layer of the water jet nozzle, then the velocities in the jet were measured and mapped using a Pitot tube and an LDV. Shear stresses were calculated from the velocity profiles to estimate the ambient shear stresses that were present when the test fish was introduced into the shear layer of the jet. Fish were subjected to the varying levels of ambient shear stress in different orientations (static, head-first, tail-first) to compare the type and frequency of observed injuries.

Design Prototype Facility

A prototype test facility was designed to perform preliminary tests exposing fish to shear stresses estimated to be as high as ~4000 N/m^2. The prototype system included a 1-hp pump, 2-in. PVC piping, and a rectangular jet with a 3.175-mm (1/8 in.) by 51-mm (2 in.) opening. The jet was designed to produce the desired shear stresses when the water velocity was ~18 m/sec (60 ft/s). A pressure gage and flow meter were built into the supply line to establish a repeatable jet velocity and monitor pump performance. The prototype system was installed in PNNL's aquatic research laboratory, located in the Life Sciences I Building in Richland, Washington. The performance of the pump, piping system, and jet were monitored by observing the readings of the inline flow meter and pressure gage. The flow meter readings were used for reference and comparison only, since actual velocities were measured in later tests at Washington State University's (WSU) hydraulics laboratory.

The design of the prototype facility was based on the need to expose fish to shear forces in a variety of ways to simulate conditions that might occur during turbine passage. Primary factors considered during design were:

- orientation of fish (head-first, tail-first, sideways)
- confinement (free-swimming, anesthetized, harnessed)
- introduction ("slow" fish into "fast" water, "fast" fish into "slow" water)
- biological response (death, descaling, eye injuries, gill/operculum damage, etc.)
- secondary effects (delayed mortality, predation, etc.).

It was not possible to measure all these variables with any statistical precision in the prototype system since scaling the system down made it impossible to evaluate many of the parameters (i.e., "fast" fish into "slow" water). The main purpose of building a prototype and conducting preliminary tests with fish was to ensure that the shear stress levels being targeted in the design of the full-scale testing facility produced a measurable biological effect. Tests with the prototype would also provide insight to what hurdles might be encountered when conducting tests in the permanent test facility.

The prototype system (Figure 2) was designed and installed in the laboratory using an oval swim chamber/respirometer as the reservoir for exposure and water recirculation. The

Figure 1. Smolt size fall chinook salmon (*O. tshawytscha*) used in range-finding tests.

respirometer had a volume of 2.2 m^3. The working area was 0.5 m wide, 2 m long, and 0.5 m deep. Water was withdrawn from the tank with a 1-hp centrifugal pump capable of delivering ≥0.19 m^3/min (50 gal/min [gpm]) of water at 1.76 kg/cm^2 (25 lb/in^2 [psi]) through a jet with a 3.175-mm by 51-mm (1/8-in. x 2-in.) rectangular orifice. Flow and line pressure were monitored with an inline flow meter and a pressure gage. Flow through the nozzle was adjusted by partially opening or closing a valve in the bypass line, reducing line pressure to the jet nozzle. However, most fish tests were made at full flow conditions with the bypass valve completely closed.

Biological Response Range-Finding Tests

Test Fish

Several species of juvenile salmonids may pass through turbines at hydroelectric projects on the Snake and Columbia rivers as they migrate to the ocean. The list includes sockeye (*Oncorhynchus nerka*), coho (*O. kisutch*), spring and fall chinook salmon (*O. tshawytscha*), and steelhead (*O. mykiss*). American shad (*Alosa sapidissima*), an introduced species now common in the Columbia River, are a species of concern on the East Coast and were also considered as a test species. Steelhead and the salmon species listed above, with the exception of the fall chinook race, spend at least one full year in freshwater before outmigrating as smolts. Salmon smolts range from 10 to 18 cm in length. Steelhead, an anadromous rainbow trout, are somewhat larger and may be as large as 25-30 cm during outmigration. The length of time that fish are in the physiological "smolt phase" is limited-lasting for only a few weeks in the spring or summer. Fall chinook salmon parr migrate to the ocean during the summer of their first year, physiologically developing into smolts along the way. They may pass through dams as fingerling-sized parr or as smolts (e.g., 6-16 cm).

Due to the extremely depressed escapement in recent years, most of the fish species listed above are not readily available for research, especially those stocks listed as threatened or endangered. Fall chinook salmon are the only salmon species that are readily available. Although the life history of fall chinook salmon differs slightly from the other salmonid species, we selected them as our first choice for testing because of their availability and because their

physiological condition resembled “smolts” more closely than rainbow trout. For increased flexibility for scheduling and conducting tests, we opted to use smolt-size fall chinook salmon for preliminary biological testing. Fish were about 9 months old and 10.8-14.5 cm fork length (FL) when we conducted our tests (Figure 1). Other species and life stages will be considered for future testing.

Exposure Procedures

Fish were euthanized in a 100-mg/L solution of MS-222 (as approved in our animal use permit for preliminary testing) prior to exposure. Fish were then subjected to the upper edge of the jet shear layer as close to the jet exit as possible (within 2-3 cm) where the highest shear forces occurred. In one series of tests, fish were held at the edge of the shear layer for ~0.5 sec with a hemostat clamped across the body near the posterior insertion of the dorsal fin. In subsequent tests, fish were introduced either head-first or tail-first through a 2.5-cm (1-in.) diameter PVC pipe (Figure 3). The fish either dropped from the pipe due to gravity or were “sucked” from the pipe by the water velocity from the jet across the end of the pipe. After exposure, each fish was examined externally for signs of injury.

Fish were exposed to the most severe conditions possible with our test system in the first round of tests. In “static” tests, euthanized fish were held at the upper boundary layer of the effluent of the nozzle with a hemostat clamped between the adipose and dorsal fins. The fish were lowered down to the edge of the high-velocity water and held there for ~0.5 seconds. In other tests, euthanized fish were introduced either head-first or tail-first through a 2.5-mm PVC pipe held perpendicular to the boundary layer of the jet. The end of the pipe was about 1-2 cm above the upper boundary of the jet exit. The fish dropped from the pipe by gravity or from suction caused by the jet flow across the end of the pipe. In another test series, fish were

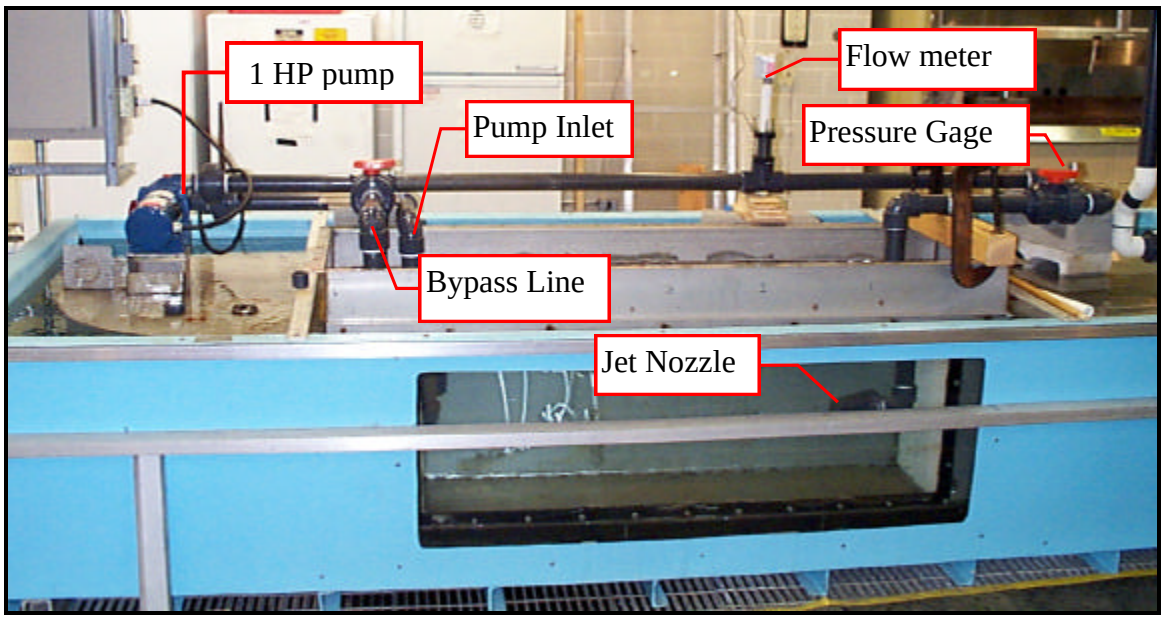

Figure 2. Prototype test system used to expose fish to shear force.

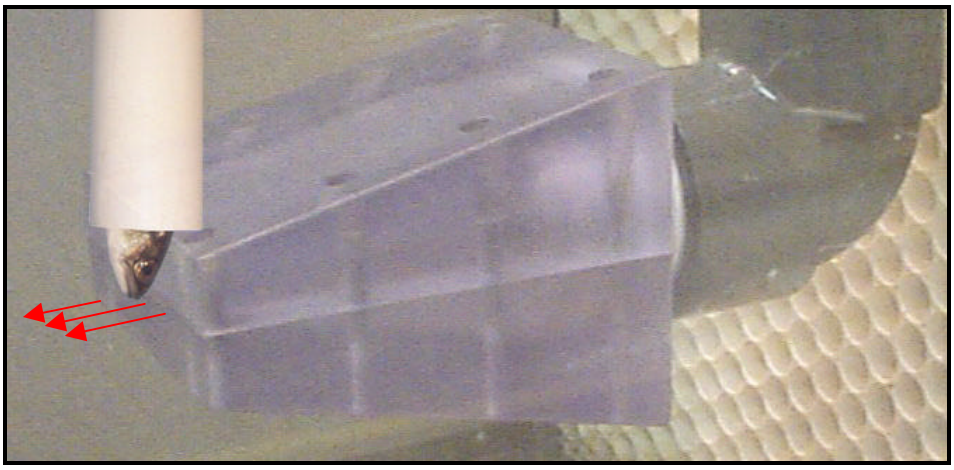

Figure 3. Simulated view of head-first fish introduction through PVC pipe at the upper boundary layer of the PNNL nozzle.

introduced at reduced flows (velocities) to determine if we could detect a "dose response." Flow and pressures were noted for each exposure and used as reference points for subsequent mapping of the velocity field.

Measurement of Velocity Field

After a round of preliminary fish tests were completed, the prototype system was disassembled and moved to the WSU's Mechanical Engineering lab for mapping of velocity fields. The piping system was modified slightly to fit an existing tank (Figures 4 and 5). The tank was approximately 1 m wide, 2.5 m long, and 0.6 m deep. The nozzle was located about 0.4 m below the water surface. Velocity profiles in the jet were measured using a Pitot tube (Figure 6) and a two-component LDV with a fiber-optic probe. Both the jet built by PNNL and a second jet built by WSU were used for flow characterization. The WSU jet was milled from an aluminum block and had flow-straightening screens inside the housing to maximize flow uniformity. When the WSU jet was tested, the exit of the jet was flush with the end of tank (Figure 5). The PNNL nozzle was mounted on a pipe that extended over the top edge of the tank and out into the tank about 25 cm. Velocity fields were measured at the centerline of the jet exit and halfway between the centerline and the edge of the orifice at three flows, which bracketed the flows used in the preliminary fish tests. Shear was then calculated from these measurements.

Design Full-Scale Facility

The CFD simulations were performed to estimate velocity and shear stress fields for a range of rectangular jets and pump configurations. The TEMPEST computer code was used to perform simulations of a rectangular jet to predict flow field and shear stress distributions for source velocities of 25, 20, 15, and 10 m/sec in water. This work was done to support the design of a permanent experimental facility to test the effect of shear and turbulence on fish. The simulations were based on using a rectangular jet and a tank approximately 1.2 m wide, 1.2 m deep, and 9.1 m long.

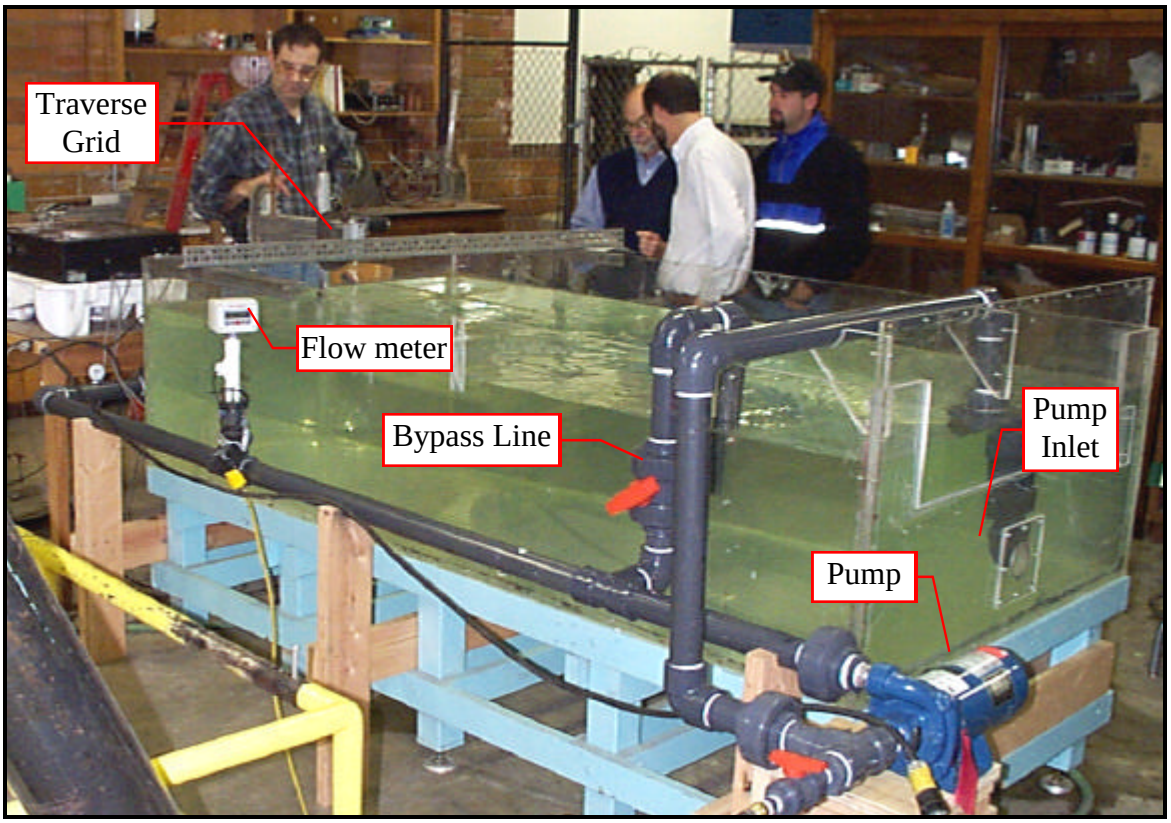

Figure 4. Modified prototype system assembled at WSU's mechanical engineering lab for mapping of velocity fields with LDV equipment.

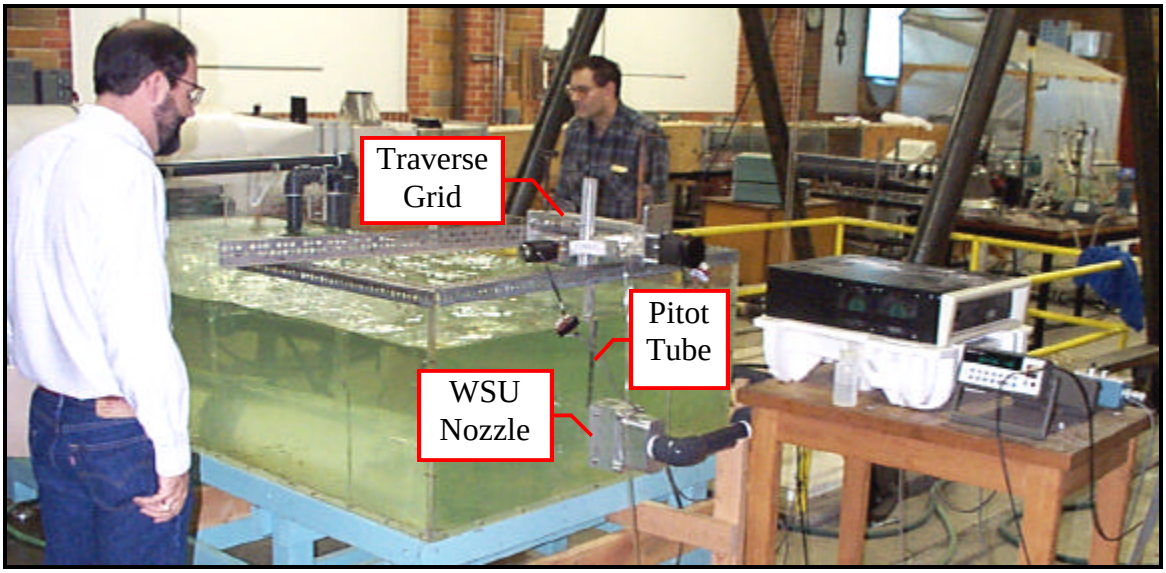

Figure 5. Pitot tube positioned in front of flush-mounted WSU jet nozzle.

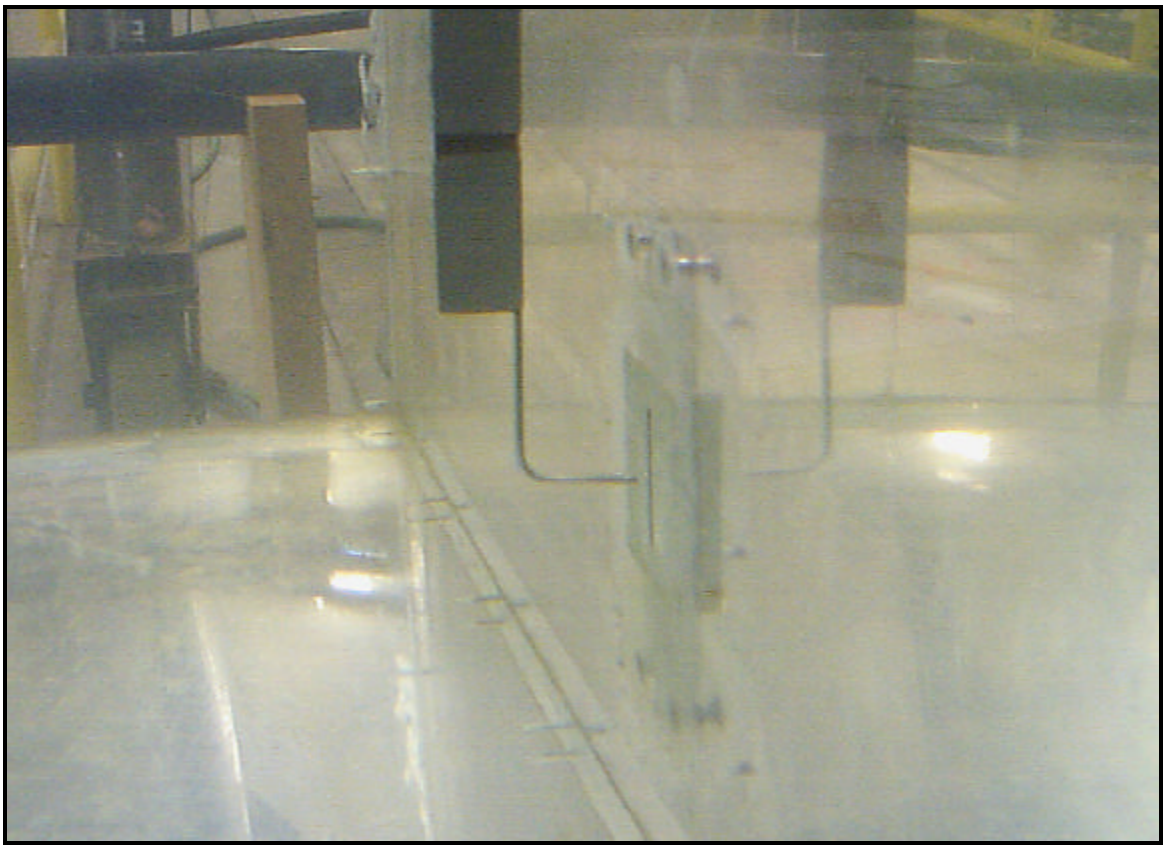

Figure 6. Close-up of Pitot tube mounted in front of the WSU jet nozzle at the centerline of the orifice.

A 7400 cell, three-dimensional TEMPEST model was used to simulate the 1.2-m by 1.2-m by 9.1-m tank of the experimental apparatus. The model used symmetry and simulated one-quarter of the jet and surrounding tank with the Cartesian origin located at the jet centerline. A full-slip boundary condition was used at the free surface, and a no-slip condition was imposed at the walls. In the model, the jet issued from a location 1 m from the end of the tank to allow for entrainment and recirculation of the flow.

Earlier work with TEMPEST (Trent et al. 1993) showed that the features of a momentum jet can be simulated successfully using six axial cells and three radial cells in the potential core region. This grid resolution was chosen and tested for these simulations. Since a rectangular jet of increasing aspect ratio decays differently than a round (or square) jet, a square (5-cm by 5-cm) jet was chosen to test the grid. The resulting centerline velocity is compared to the empirical (Abraham 1963) centerline velocity in Figure 7. The computed velocity compares well with the empirical velocity within 70 nozzle diameters (3.56 m) downstream of the jet. Farther than 70 diameters downstream the end effects of the model geometry are seen as the deviation from the empirical solution. This grid was then modified for the simulations by increasing the cell widths to model the rectangular jet, and the simulations were run. The model coordinate system was established as shown in Figure 8, with the horizontal jet axis along X, the vertical coordinate along Z, and the transverse coordinate along Y.

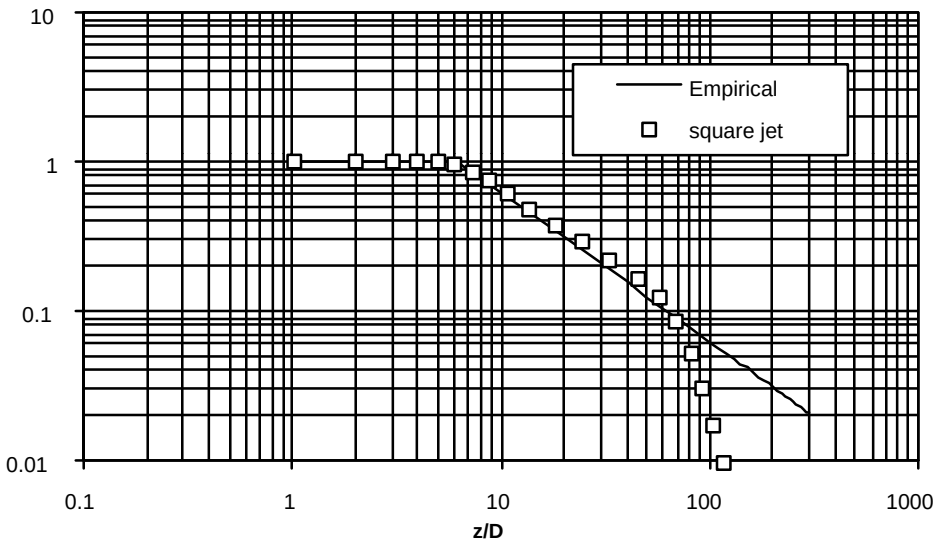

Figure 7. Computed centerline velocity versus axial distance, normalized by the nozzle diameter (D), compared to empirical velocity decay of a round or square momentum jet.

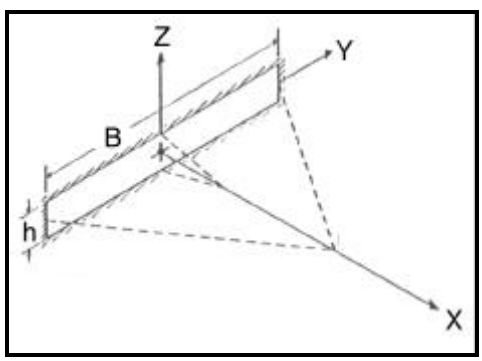

Figure 8. Definition sketch for the rectangular free jet coordinate system and labeling.

Results

Biological Response Range-Finding Tests

With flow to the jet in the full open position and bypass flow closed, the flow meter read ~56 gpm (0.2 m^3/min), with a line pressure of ~25 psi (1.75 kg/cm^2). Based on the cross-sectional area of the jet orifice, velocity at the exit of the nozzle was calculated to be 22 m/sec, and this generated the levels of shear stress needed for our tests.

Static Fish Tests

A total of 10 fish were exposed in this manner. All observed damage was on the side of the fish facing the jet (right side). All 10 fish were descaled, generally in the region between the dorsal fin and the gill aperture. Other observed injuries were eye loss and/or damage (4), opercular flaps turned in or out (3), torn and/or inverted gill arches (3), and damaged tissue at the isthmus (1). Fish had either opercular damage/inverted gills or eye damage, but only 1 fish had both injuries.

Head-First Fish Tests

Of the 10 fish introduced head-first, all fish lost one eye (one fish lost both eyes), and 8 of 10 had moderate to heavy descaling on the same side as where the eye damage occurred (Figure 9). On one fish, bruises were observed on the opposite side as where eye damage occurred.

Tail-First Fish Tests

None of the 10 fish introduced tail-first suffered eye loss, but one fish had an eye bulge and another had a bruise at the shoulder. Descaling was observed on 9 of 10 fish. Whereas most descaling in fish introduced head-first tests was anterior to the dorsal fin, descaling with fish introduced tail-first fish occurred primarily in regions posterior to the dorsal fin.

Figure 9. Eye loss and descaling typical of fish introduced "head-first" from a pipe into the upper boundary layer of the jet nozzle effluent.

Dose-Response Tests

Fish were subjected to lower jet velocities to determine if observed injuries were the result of our fish introduction methods or from the shear forces at the boundary layer of the jet. Table 1 shows the relationship between flow (as measured by the in-line flow meter) and line pressure. Fish were exposed head-first to one of two intermediate flow/pressure scenarios. In previous head-first exposures, all 10 fish exposed to a line pressure of 25 psi (1.75 kg/cm^2), flow = ~0.212m^3/min) had eye loss. Of five fish exposed to a line pressure of 20 psi (1.41 kg/cm^2) (flow = ~0.198 m^3/min), four fish had eye loss. Of the eight fish exposed to a line pressure of 15 psi (1.05 kg/cm^2) (flow = ~0.167 m^3/min), only one fish had eye loss, but all eight fish had scale loss.

Measurement of Velocity Field

Pitot Tube Measurements

Velocity measurements were made at three flows: full flow (61 gpm for WSU jet or 56 gpm for PNNL jet), 45 gpm, and 30 gpm (as measured with the flow meter). Only the full flow data are presented in this report. Velocity fields of the PNNL and WSU jets were very similar (Figures 10 and 11). Peak velocity was ~17.7 m/sec and 16.5 m/sec for the WSU and PNNL jets, respectively, measured at a transect through the centerline of the orifice at a distance of 2 mm. Velocities at 42 mm were for the WSU and PNNL jets were 13.9 and 11.9 m/sec, respectively. Resistance in the additional piping required for the PNNL jet may have resulted in decreased velocity (and discharge). With both jets, abrupt increases in velocity occurred about 3 mm from the centerline of the jet, or about 1 mm from the edge of the 1/8-inch (3.175 mm) thick plume. Profiles measured at distances of 12, 30, and 60 mm from the two jets were also very similar, with the WSU jet velocities always slightly higher than the PNNL jet. The slight differences in velocity profiles at a distance of 2 mm were the result of the WSU jet being mounted flush to the tank wall as opposed to the PNNL jet, which was mounted inside the tank about 25 cm away from the wall during measurements. Another factor that caused some minor differences was that the WSU jet was constructed with internal screens mounted ahead of the exit to increase the uniformity of the jet velocity distribution at the exit.

Table 1. Relationship between flow, line pressure, and estimated velocity at exit of the jet in the prototype test facility.

Flow Meter Reading (gpm)	Pressure Gage Reading (psi)	Estimated Velocity (m/sec)
56	25.5	21.9
52	20	20.3
45	15	17.6
37	10	14.5
23	5	9.0

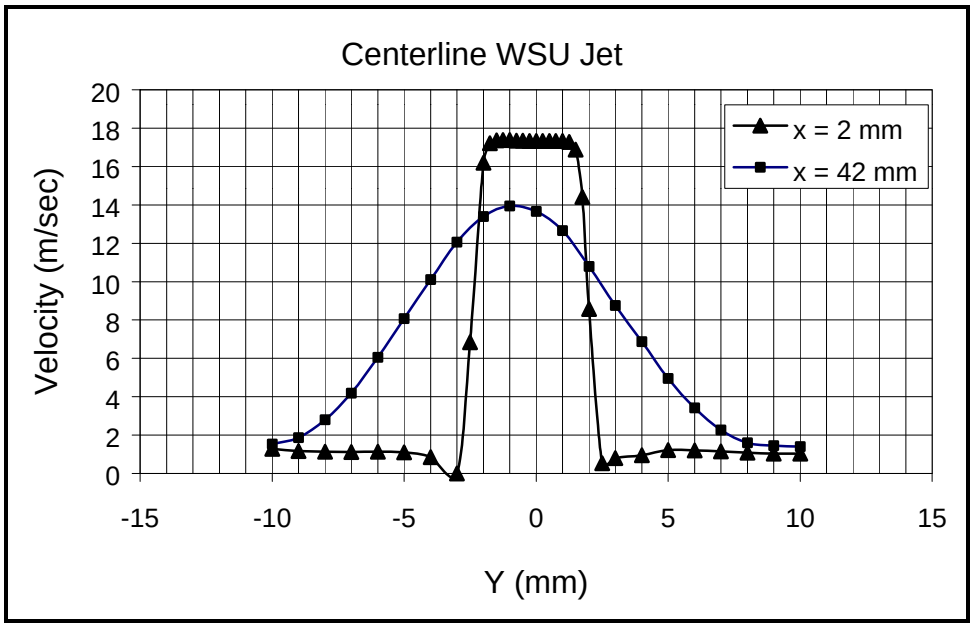

Figure 10. Velocity profile at the centerline of the WSU jet at full flow (61 gpm) using Pitot tube.

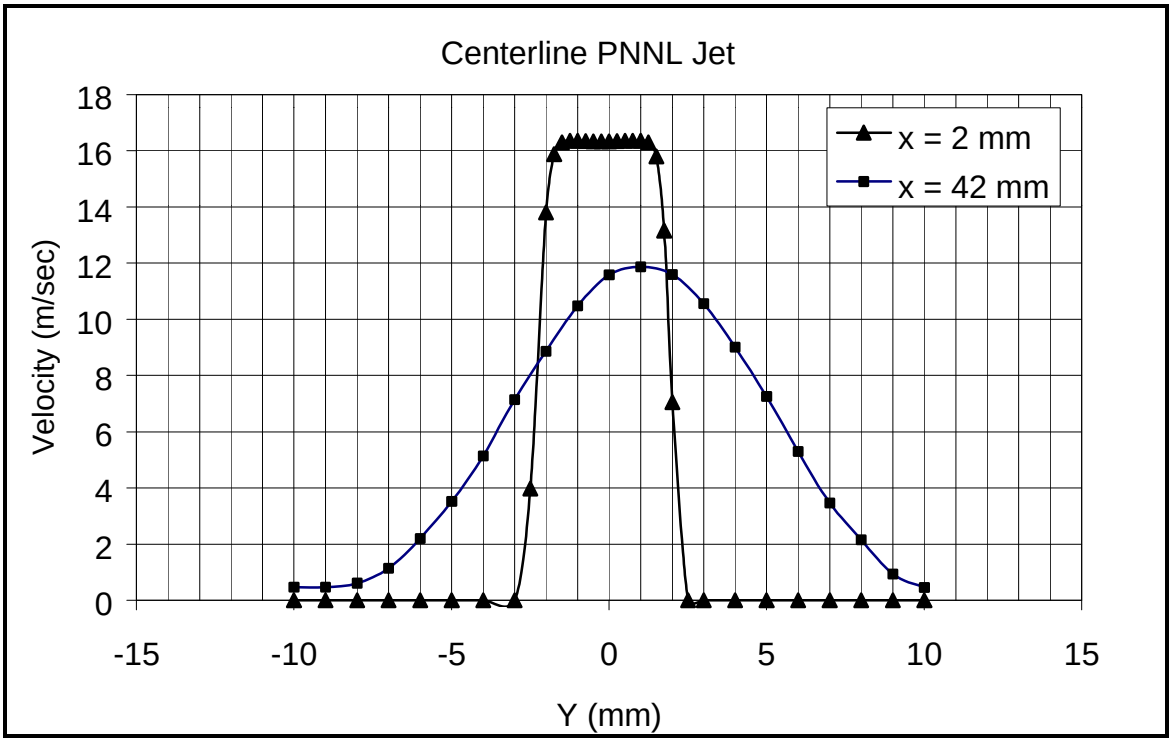

Figure 11. Velocity profile at the centerline of the PNNL jet at full flow (56 gpm) using Pitot tube.

LDV Measurements

The PNNL jet was better suited for making the LDV measurements because it was not mounted flush with the wall of the tank. It was not physically possible to conduct transects close to the exit of the jet unless the jet was away from the tank wall. Since the performance of the two jets using the Pitot tube measurements were similar, LDV measurements were made with the PNNL jet only (Figure 12). Measurements were taken at three flows (56, 45, and 30 gpm readings on the flow meter) but only reported for 56 gpm in this report. Use of the PNNL jet mounted away from the wall also more closely matched the configuration in the CFD simulations described in the next section, which were based on using a nozzle mounted about 1 m from the end wall.

Design of Full-Scale Facility

CFD Simulations

Figure 13 shows the predicted shear stress distribution, in a vertical plane through the jet centerline (X-Z plane in Figure 8), for the 25 m/sec case. The plot gives the vertical stress distribution at several downstream distances. These axial (X) distances are given in jet nozzle heights (h). Figure 14 summarizes the calculated shear stresses in the same vertical plane, for all the jet velocity cases; the shear stress is scaled by the jet exit velocity squared. The results from these same runs are also summarized in Table 2. Table 2 shows that shear stresses at (or above) 3000 Pascals were achieved by all but the 10 m/sec jet. The 25 m/sec jet had 3000 Pascal stresses 81 cm downstream of the jet, and the 20 m/sec jet had the desired shear at about 36 cm.

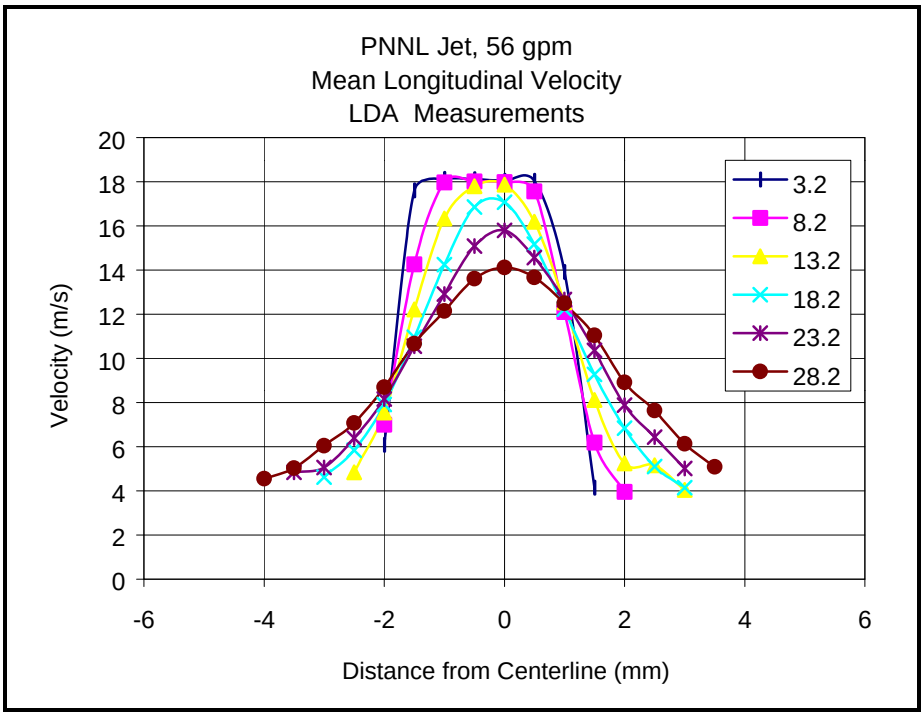

Figure 12. LDA velocity profile of PNNL jet.

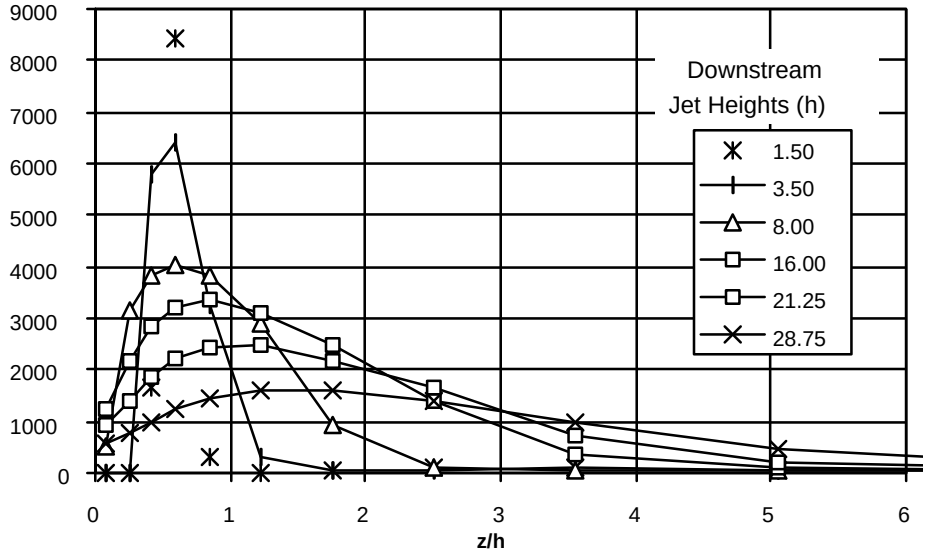

Figure 13. Shear stress distribution in a vertical plane through the jet centerline for several downstream stations.

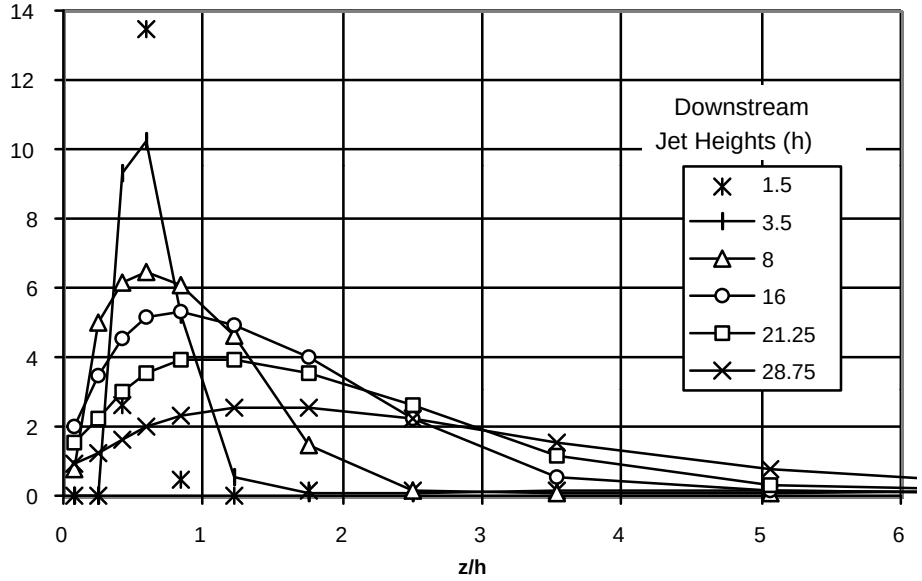

Figure 14. Normalized shear stress distribution in a vertical plane through the rectangular jet centerline for several downstream stations.

Table 2. Summary of shear stress at top edge of rectangular jets.

Jet Source Velocity	Shear Stress (Pascals) at top edge of jet at several distances downstream of the jet (cm)					
(m/sec)	7.6 cm	18cm	41 cm	81 cm	109 cm	147 cm
25	8400	6400	4000	3300	2500	1600
20	5400	4100	2600	2100	1600	1000
15	3000	2300	1500	1200	890	580
10	1400	1000	640	530	390	260

Either of these jets should allow a reasonable working area for experiments with fish. The 15 m/sec jet achieved 3000 Pascals within 7.6 cm downstream of the jet. This distance of 7.6 cm was probably too short for practical experimentation at the desired shear levels. Figure 15 shows the velocity distribution, in a vertical plane through the jet centerline (X-Z plane in Figure 8), for all velocity cases; the local velocity is scaled by the jet source velocity. The plot gives the vertical velocity distribution at several downstream distances. These axial (X) distances are given in jet nozzle heights (h).

Engineer's Conceptual Design

Engineers used data from CFD simulations to make a preliminary design for the permanent test facility (Figures 16 and 17). The tank may be located in the outside aquatic facility south of the Life Sciences I Building. The working section of the tank is 1.2 m wide by 1.2 m deep by 9.1 m long. According to modeling data, a tank with these dimensions would not restrict the expansion of the jet shear layer in the test section of the flume. Plexiglas windows in the bottom and sides of the tank allow the use of high-speed video cameras to document and map fish position during an exposure test. The recirculation pump and associated piping are sized large enough to generate the desired shear forces at the jet nozzle. According to the CFD modeling data, an exit velocity of 20 m/sec would produce shear forces exceeding 4000 N/m^2. Therefore, engineers should select a pump capable of delivering ~0.15 m^3/sec (5.5 cubic feet per second [cfs] or ~2450 gpm) at 1.75 kg/cm^2 (25 psi). Other components of the facility are fish acclimation and introduction systems, a covered work area for computers and electronic equipment, lighting, electrical and water supplies.

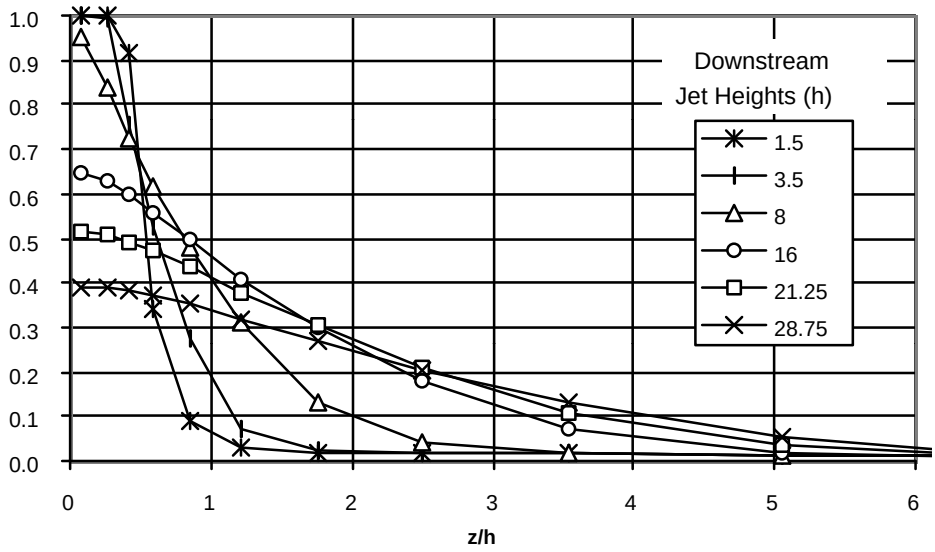

Figure 15. Computed velocity distribution in a vertical plane through the rectangular jet centerline for several downstream stations.

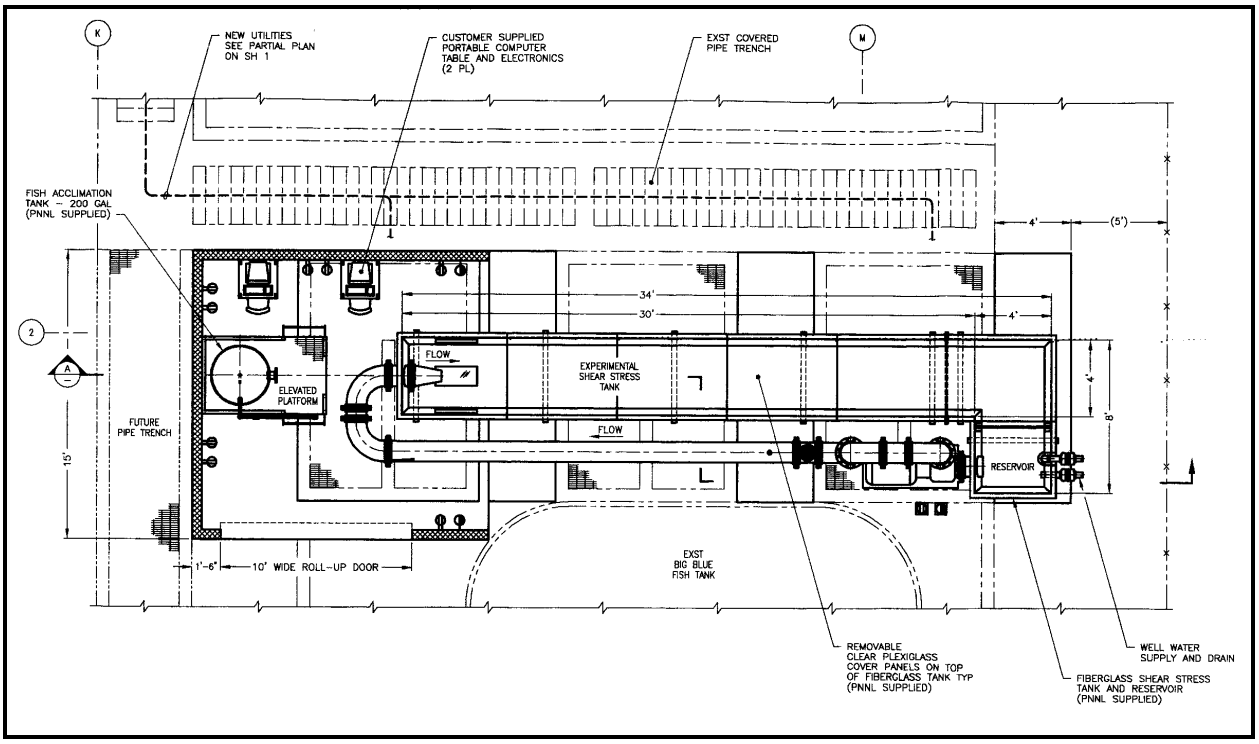

Figure 16. Plan view engineer's drawing showing position of the proposed test facility relative to existing structures at PNNL's aquatic research complex.

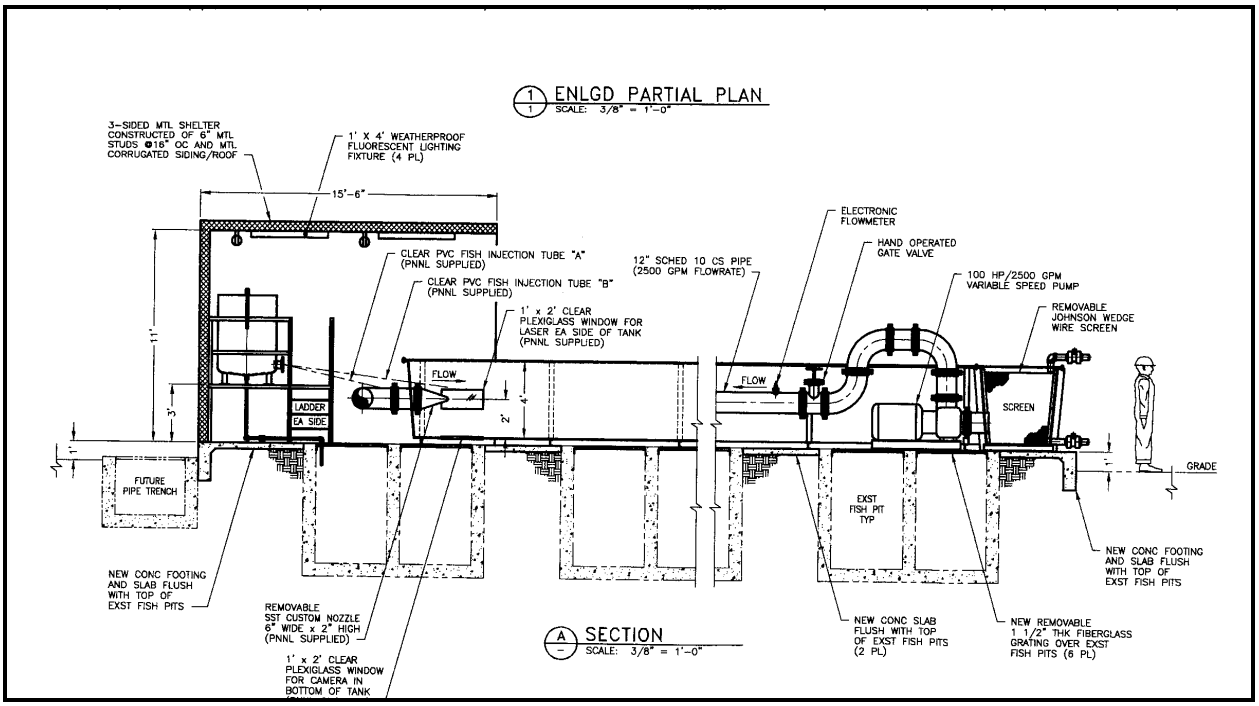

Figure 17. Side view engineer's drawing showing position of the proposed test facility relative to existing structures at PNNL's aquatic research complex.

Discussion

Preliminary biological tests with smolt size fall chinook salmon confirm that damage (eye loss, descaling, opercular damage, gill damage, bruising) occurs when fish are exposed to the shear layer of a jet with exit velocities approaching 20 m/sec. The injuries we observed were virtually identical to those reported by Groves (1972) and Turnpenny et al. (1992) for fish exposed under similar test conditions. The actual force (shear, strike, and turbulence) responsible for the injuries we observed is unknown, and we did not attempt to isolate the effects of different sources of force in the prototype facility.

The orientation and method of introduction of a fish to the shear layer affects the type and extent of injuries to fish. Fish held statically in the shear layer of the jet were subject to gill inversion and opercular injury and less prone to eye injury. Open or bent opercular flaps probably provided protection to the eye socket. Fish released through a pipe head-first were prone to eye injury, but fish introduced tail-first were not. The wall of the introduction pipe may have held the opercular flap shut during introduction to the boundary layer, thereby subjecting the eye socket to the strongest force. With fish introduced tail-first, sides of the body took the brunt of the initial force. By the time the head-end of the fish exited the pipe, the fish may have been washed out of the high-force boundary layer or accelerated to the point where the shear force was diminished. Descaling was evident at all exposure levels, but appeared to be less severe with tail-first introduction into jet shear layer. Our observations on the type and frequency of injuries relative to orientation of fish to the jet were consistent with those reported by Groves (1972).

Estimated velocities at the exit of the PNNL jet (based on the flow meter readings and the cross-sectional area of the jet nozzle) appear to be about 25% lower than velocities measured 2 mm from the jet nozzle with the Pitot tube and the LDV systems. Velocities were lowest using the Pitot tube method. Since flow meter readings are dependent on the position of its impeller and are a function of pipe diameter, the differences we observed may be due to the original setup of the flow meter, which remained the same for all biological and hydraulic testing. Actual flow from the jet nozzle at various flow meter readings was not confirmed. The flow meter was only used as an indicator for monitoring pump output and stability in the prototype system. Shear forces were calculated from velocities measured in the hydraulic studies. The intent of obtaining preliminary biological data was to confirm that observable injuries occurred at the shear force levels being used to design the permanent test facility. We had no intention of trying to establish precise relationships between shear force and fish injuries.

Velocities and shear stresses produced in a jet were evaluated in three ways: measurements using a Pitot tube, measurements with LDV equipment, and through CFD simulations (on full-scale facility only). All three methods showed that shear stresses near and within a jet can be accurately measured, mapped, and modeled. The methods show where fish need to be introduced so the fish are exposed to known shear stresses. Thus, if the path of a test fish is recorded (e.g., using video), the “dose” a fish receives can be estimated. The resulting injuries from each exposure can be correlated to the ambient shear stresses associated with passage scenario. Therefore, it is possible to develop a dose-response relationship for fish encountering shear stresses.

Although high, predictable, and reproducible shear stresses can be generated with a jet, not all conditions that exist during turbine passage may be accurately simulated with a jet plume. Fish are exposed to shear stresses, as well as to other forces in many different ways during passage through a turbine. For example, shear stresses begin to increase in the turbine intake when water begins to accelerate. Shear stresses increase as water velocity increases as it passes through the wicket gates and is turned downward. Another dramatic change in velocity occurs at the turbine blades. Turbulence builds as water passes through the draft tube toward the tailrace. In the tailrace, very turbulent, unstable conditions exist, and fish can become disoriented, and possibly more vulnerable to predation. For these reasons, other methods for generating shear forces were explored (Recknagle and Richmond 1998). Only the water jet provides the shear stresses in a fish test facility needed to simulate the range of conditions expected in a turbine.

Velocity mapping with a Pitot tube was quicker and easier than using the LDV system. Due to the high velocities at the entrance to the jet, which caused vibration of the Pitot tube, the WSU staff working on the project felt that data collected with the LDV system were more precise and accurate, although the data generated by the two methods were very similar. The WSU staff encountered several difficulties during collection of the data with the LDV system that delayed completion of their reporting at this time.

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