PNNL-13470-B

Pacific Northwest
National Laboratory
Operated by Battelle for the
U.S. Department of Energy

Fish Passage Through a Simulated Horizontal Bulb Turbine Pressure Regime: A Supplement to "Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish"

C. S. Abernethy
B. G. Amidan
G. F. Čada

July 2003

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062;
ph: (865) 576-8401
fax: (865) 576-5728
email: reports@adonis.osti.gov

Available to the public from the National Technical Information Service,
U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161
ph: (800) 553-6847
fax: (703) 605-6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

PNNL-13470-B

Fish Passage Through a Simulated Horizontal Bulb Turbine Pressure Regime: A Supplement to "Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish"

C. S. Abernethy
B. G. Amidan
Pacific Northwest National Laboratory
Richland, Washington

G. F. Čada
Oak Ridge National Laboratory
Oak Ridge, Tennessee

July 2003

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

Migratory and resident fish in the Columbia River Basin are exposed to stresses associated with hydroelectric power production, including pressure changes during turbine passage. The responses of fall chinook salmon and bluegill sunfish to rapid pressure change was investigated at the Pacific Northwest National Laboratory. Previous test series evaluated the effects of passage through a vertical Kaplan turbine under the "worst case" pressure conditions (Abernethy et al. 2001) and under less severe conditions where pressure changes were minimized (Abernethy et al. 2002). For this series of tests, pressure changes were modified to simulate passage through a horizontal bulb turbine, commonly installed at low-head dams. The results were compared to results from previous test series.

Both fish species were acclimated for 16-22 hours at either surface (101 kPa; 1 atm) or 30 ft (191 kPa; 1.9 atm) of pressure in a hyperbaric chamber before exposure to a pressure scenario simulating passage through a horizontal bulb turbine. The simulation was as follows: gradual pressure increase to about 2 atm of pressure, followed by a sudden (0.4 sec) decrease in pressure to either 0.7 or 0.95 atm, followed by gradual return to 1 atm (surface water pressure). Following the exposure, fish were held at surface pressure for a 48-hour post-exposure observation period.

No fall chinook salmon died during or after exposure to the horizontal bulb turbine-passage pressures, and no injuries were observed during the 48-hour post-exposure observation period. As with the previous test series, it cannot be determined whether fall chinook salmon acclimated to the greater water pressure during the pretest holding period. For bluegill sunfish exposed to the horizontal bulb turbine turbine-passage pressures, only one fish died and injuries were less severe and less common than for bluegills subjected to either the "worst case" pressure or modified Kaplan turbine pressure conditions in previous tests. Injury rates for bluegills were higher at 0.7 atm nadir than for the 0.95 atm nadir. However, injuries were limited to minor internal hemorrhaging. Bluegills did not suffer swim bladder rupture in any tested scenarios.

Tests indicated that for most of the cross-sectional area of a horizontal bulb turbine, pressure changes occurring during turbine passage are not harmful to fall chinook salmon and only minimally harmful to bluegill. However, some areas within a horizontal bulb turbine may have extreme pressure conditions that would be harmful to fish. These scenarios were not tested because they represent a small cross-sectional area of the turbine compared to the centerline pressures scenarios used in these tests.

Acknowledgments

We thank Peggy Brookshier and John Flynn of the U.S. Department of Energy for their guidance and support. Joanne Duncan of Pacific Northwest National Laboratory (PNNL) provided technical assistance, and Dennis Dauble and Duane Neitzel of PNNL provided comments and advice during the development of the methods and protocols used to accomplish this work and reviewed draft reports. We thank the Technical Committee of the U.S. Department of Energy's Advanced Hydropower Turbine Program for their valuable comments.

The work was conducted at PNNL in Richland, Washington. PNNL is managed by Battelle for the U.S. Department of Energy. The work was conducted under a Related Services Agreement with the U.S. Department of Energy, Contract DE-AC06-76RLO 1830. This report is a product of the Wind and Hydropower Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

Contents

Tables

Figures

Glossary

bulb turbine	A configuration where water flows around a bulb casing containing the generator. Horizontally mounted bulb turbines may have adjustable Kaplan-style blades and are used at low-head dams.
Kaplan turbine	An axial-flow (propeller-type) turbine with adjustable runner blades and adjustable guide vanes.
kPa	Kilopascals; a measure of pressure (101 kPa = 1 atm = 14.73 psi).
nadir	Lowest pressure in the time versus pressure regime experienced by fish in these experiments.
physoclistous	Fish that lack a direct connection (pneumatic duct) between the swim bladder and the esophagus. These species must adjust the pressures within the swim bladder by the relatively slow process of diffusion of gases from the blood.
physostomous	Fish that have a duct (pneumatic duct) that connects the swim bladder with the esophagus. In these species, gas can be quickly taken into or vented from the swim bladder through the duct, so that adjustment to changing water pressures can take place rapidly.
pneumatic duct	The duct that connects the swim (gas) bladder and the gut in physostomous fish.
pressure spike	In these experiments, the rapid water pressure decrease from several times atmospheric pressure to a low point (nadir) of less than 1 atm.
psi	Pounds per square inch, a measure of pressure.
psia	Pounds per square inch absolute (absolute means that the indicated pressure is referenced to a vacuum).
swim bladder	An internal gas bladder that has a weight-regulating (hydrostatic) function in higher fishes.
vapor pressure	Pressure exerted by a vapor when the vapor is in equilibrium with the liquid form of the same substance; i.e., when conditions are such that the substance can exist in both phases

1.0 Introduction

Migratory and resident fish in the Columbia River Basin are exposed to a variety of stresses associated with hydroelectric power production, including pressure changes and dissolved gas supersaturation during turbine passage. The responses of rainbow trout (*Oncorhynchus mykiss*), chinook salmon *(O. tshawytscha)*, and bluegill sunfish (*Lepomis macrochirus*) to these two stresses, both singly and in combination, were investigated at the Pacific Northwest National Laboratory (PNNL) and reported in Abernethy et al. (2001). A supplemental series of tests using a modified Kaplan turbine passage pressure scenario (less severe) evaluated the response of chinook salmon and bluegill sunfish (Abernethy et al. 2002).

In the initial test series (Abernethy et al. 2001), three fish species were exposed to a pressure regime simulating passage through a Kaplan turbine on the Columbia River. The pressure regime was as follows: pressure was gradually increased to 4 atm, or 3 atm of hydrostatic pressure, followed by a rapid (0.1 sec) decrease to sub-atmospheric pressure (less than 0.1 atm), followed by gradual return to surface pressure (1 atm). When acclimated to surface water pressures, neither rainbow trout nor chinook salmon died after exposure to turbine-passage pressures, although some injuries were observed. More pressure-related injuries were noted among rainbow trout that had been held in greater pretest water pressures. Fall chinook salmon and rainbow trout did not appear to have a substantially greater "turbine-passage" mortality rate if they were held at greater water pressures before exposure. However, the authors are not certain whether these salmonids were able to acclimate to the greater water pressure during the pretest holding period; if not, their experience would have been similar to that of surface-pressure-acclimated fish. Bluegill exposed to turbine-passage pressures had higher injury and mortality rates than salmonids, especially if they had first been acclimated to water pressures equivalent to 30 ft of depth. For all three species, the combination of gas supersaturation and turbine-passage pressure regime was more damaging than either stress separately. The highest injuries and mortalities were experienced by bluegills acclimated to a combination of water pressures characteristic of 30-ft depths, dissolved gas supersaturation, and turbine-passage pressures.

In the second test series (Abernethy et al. 2002), two fish species were exposed to a modified (less severe nadir) pressure regime simulating passage through a Kaplan turbine on the Columbia River. The pressure regime was as follows: pressure was gradually increased to 4 atm, or 3 atm of hydrostatic pressure, followed by a rapid (0.1 sec) decrease to sub-atmospheric pressure of 0.5 atm, followed by gradual return to surface pressure (1 atm). No chinook salmon died as a result of the exposures, and injuries were less frequent and less severe. Mortalities and major injuries still occurred for bluegills exposed to the modified pressure regime. However, mortality rates were much lower, and the occurrence and severity of nonlethal injuries was less than in the first series.

These data indicate that fish in the Columbia River Basin could be killed by pressure changes associated with turbine passage, especially if they are entrained from greater depths. Bluegills were more sensitive to pressure effects than the two salmonid species. Chinook salmon traveling at the surface experienced low injury and mortality rates from turbine-passage pressure changes. Advanced turbine designs, or altered operating conditions, that raise the nadir (low point) of the turbine-passage pressure regime could reduce the injury and mortality of fish caused by pressure changes.

Adjustable-blade turbines can be mounted vertically or horizontally. Vertical turbines are used at most mainstem dams on the Columbia River. With the exception of a few small areas, fish drawn through a vertically mounted turbine experience a similar pressure regime as they pass from the forebay through the wicket gates, runner, and draft tube. However, in a horizontally mounted turbine, the pressure regime experienced by a fish during passage is dependent on where the fish enters and exits the turbine draft tube. Rapid pressure decreases (spikes) downstream from the runner are believed to be the source of most pressure-related damage to fish. These low-pressure spikes are the greatest near the draft tube ceiling and smallest near the draft tube floor, where greater water depths mitigate the pressure drops associated with passage through the runner. To complicate matters, unlike in a vertical turbine, swirl immediately downstream from a horizontally mounted runner will move the fish to a different depth. For example, instead of moving through the turbine in a straight, horizontal line, a fish passing the wicket gates near the ceiling will be carried to greater depths in the draft tube by post-runner swirl. Conversely, fish passing the horizontally mounted runner near the floor will be rotated upwards by swirl.

Bulb turbines (a type of horizontally mounted turbine) are used at the Rock Island Dam near Wenatchee, Washington, and at other low-head dams elsewhere. Because horizontal turbines are often installed at low-head sites, the magnitudes of pressure changes experienced by turbine-passed fish are smaller than at high-head sites. Compared to vertical turbines, horizontally mounted turbines have a slower water velocity through the turbine, which results in fish experiencing a more prolonged, albeit less severe, pressure change. Nonetheless, the bulb turbine at Rock Island Dam has experienced cavitation at high loads,(a) so extreme low pressures that are damaging to fish may occur in at least some areas of the turbine.

Previous tests simulating passage through vertical Kaplan turbines evaluated the effects of the severity of the pressure change (spike), not the rate of change or duration of the pressure spike. To assess the latter two parameters, another test series was developed using time/pressure sequences based on passage through a typical horizontal bulb turbine. There are an infinite number of pathways (or fish trajectories) possible for a horizontal bulb turbine. The authors selected the centerline passage route as the representative time/pressure regime for most fish, recognizing that more and less severe conditions could occur in some areas of the draft tube cross-sectional area. The objective in these tests was to compare mortality and injury rates for fall chinook salmon and bluegills under the more prolonged, but less severe pressure nadir to results from previous tests that simulated passage through the vertical Kaplan and "modified Kaplan" passage scenarios.

The pressure regimes used to develop the time/pressure scenarios were developed from data for the Racine Lock & Dam on the Ohio River near Racine, Ohio. The authors selected two water flows, which represent the most severe pressure conditions but produced slightly different time/pressure regimes and nadirs. The effect of exposure to excess total dissolved gas levels was not evaluated in this test series.

Pretest acclimation, test fish, and handling methods were the same as in previous Kaplan test series reported in Abernethy et al. (2001, 2002) and are described below. The time/pressure sequences for all phases of the turbine passage scenarios (entry into the intake, rate of pressure change, exit in the draft

---

(a) E-mail from J. Kirejczyk, Alstom Power to C. S. Abernethy, Pacific Northwest National Laboratory, December 4, 2001, Richland, WA, personal communication.

tube and tailrace) were altered to simulate passage through a horizontal bulb turbine. Results were evaluated independently and also compared to test results for the same species under the modified Kaplan turbine pressure regimes reported in Abernethy et al. (2002).

2.0 Methods

2.1 Turbine Passage System

The Turbine Passage System (Figure 2.1) was designed and built by Reimers Engineering in 1994 and is described in Montgomery Watson (1995). The system can create a variety of pressure regimes and for this study was used to simulate the pressure history that fish would experience in passing through a hydroelectric turbine. The exposure chambers for the turbine passage system consisted of two 11-in.- (27.5-cm-) diameter acrylic tubes, 22-in.- (55-cm-) long. The volume of each cylinder was about 34 L.

The chambers were connected to hydraulic cylinders, which in turn were connected to pneumatic cylinders. Through a computer-controlled gas pressurization system attached to the pneumatic cylinders, the positions of the hydraulic cylinders were moved to either pressurize or depressurize the chambers. The maximum pressure of the chamber was 100 ft of head (3 atm, or ~400 kPa). The system can drop the pressure from 100 ft (~400 kPa) of head to close to the vapor pressure of water (~1 psi or 2-10 kPa) in 0.1 sec.

The Labtech® software sub-program controlling the sequence simulating the turbine spike was altered to produce a nadir of either 70 kPa or 100 kPa (37 and 52% of acclimation of depth-acclimated groups, respectively). The time/pressure sequence for a bulb turbine also required that needle valves affecting air flow controlling the pneumatic pistons be adjusted to reduce the rate of pressure change during the simulation. The sensitivity and response time of pressure sensors controlling piston movement in the hyperbaric chambers affected precision, making it difficult to achieve an exact nadir. Some tests were aborted and repeated due to mechanical malfunctions resulting in erroneous pressure spike results.

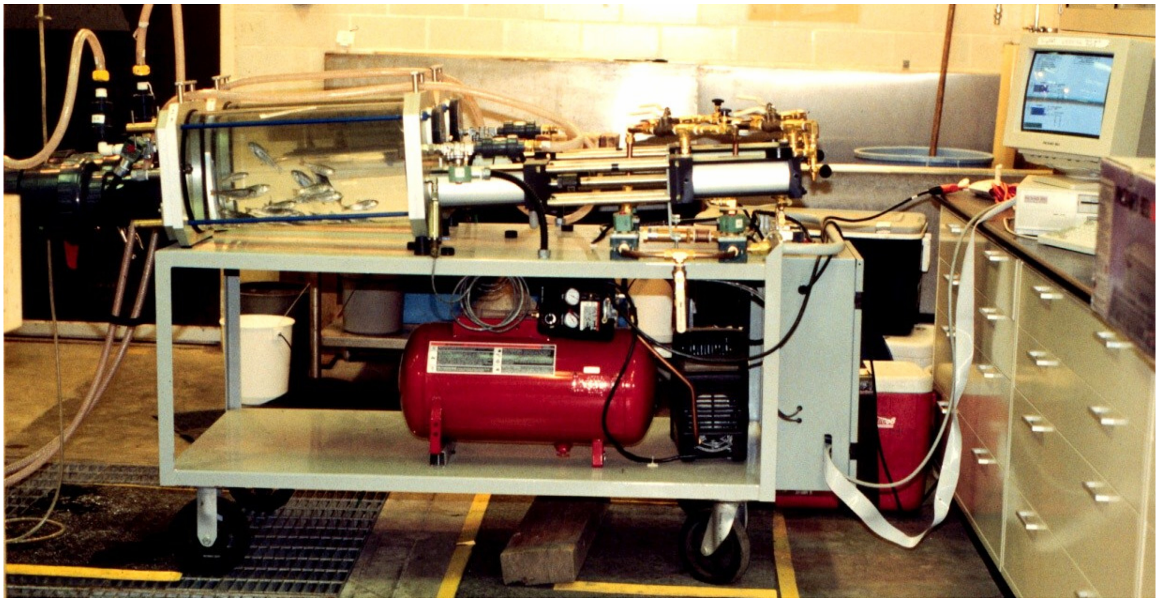

Figure 2.1. Turbine passage system used to create time/pressure sequences simulating turbine passage.

For the 70-kPa simulations, a nadir of 60 to 75 kPa was accepted, and for the 100 kPa nadir simulations, a nadir of 90 to 105 kPa was acceptable. Pretest holding and acclimation conditions were the same as in previous tests. However, both the approach and exit pressures were modified to simulate passage through a horizontal turbine intake, draft tube, and tailrace.

2.2 Selection of Fish Passage Scenarios

Horizontally mounted bulb turbines are generally used in low-head hydropower facilities whereas vertically mounted Kaplan turbines are commonly used at moderately high-head dams such as those found on the mainstem Columbia River. The exception is at Rock Island Dam, near Wenatchee, Washington, where one of the two powerhouses utilizes horizontal bulb turbines. However, Rock Island Dam is a "low-head" dam compared to the rest of the dams on the Columbia River. The lower head associated with bulb turbines results in a smaller pressure increase as fish sound to enter the turbine intake. Lower-head dams also have reduced water velocity through the turbine, resulting in a more prolonged exposure to altered pressures. However, the biggest difference between horizontal and vertical applications is that the pressure scenario in a vertical turbine is relatively uniform throughout the entire cross-section when passing through the turbine runners, whereas the pressure scenario for a horizontal turbine is dependent on whether a fish passes through the turbine near the top, bottom, or at mid-depth. Because it represents the largest cross-sectional area in a bulb turbine, the authors selected centerline passage scenarios for laboratory tests. Figure 2.2 shows two passage "trajectories" for fish approaching a

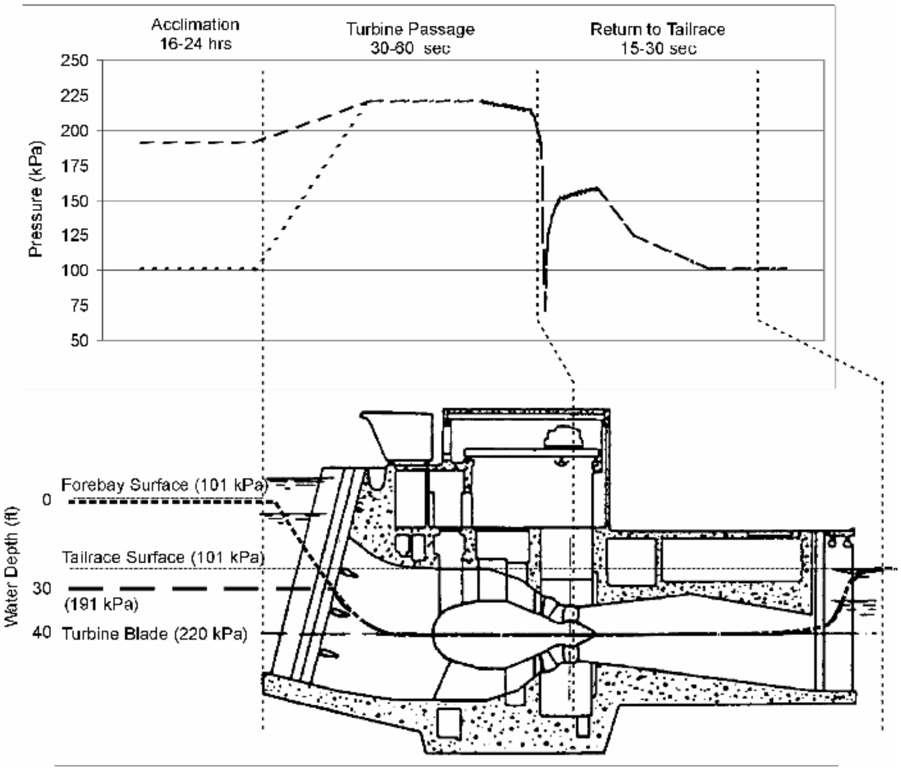

Figure 2.2. Pressure and trajectory for a fish passing through the centerline of a bulb turbine after approaching the turbine intake near the surface (101 kPa) or at a depth of 30 ft (191 kPa).

bulb turbine near the surface (101 kPa) at a depth of 30 ft (191 kPa) and the associated pressure scenario for the surface-approaching fish. In Figure 2.3, two nadirs simulated in bulb turbine tests are compared to turbine passage pressure nadirs simulated in previous tests evaluating a typical vertical-mounted turbine. Mechanical adjustments needed to produce different nadirs in the hyperbaric chamber system resulted in slight pressure differences following the nadirs. However, all simulations converged at surface pressure (101 kPa) less than 15 sec after the nadir.

2.3 Fish Stocks

Eyed fall chinook salmon eggs acquired from the Washington State Department of Fisheries' Priest Rapids Hatchery were raised at PNNL until they reached the subyearling stage and were 10-12 cm fork length (FL). Young-of-the-year bluegill (4-7 cm FL) were acquired from Osage Catfisheries in Osage Beach, Missouri. Test stocks were acclimated and held in flow-through tanks supplied with well water at 17°C.

2.4 Injury Assessment

The condition of fish (alive, dead, any external abnormalities or symptoms) was checked immediately before and after the pressure sequence. Fish were removed from the hyperbaric chambers and placed in partitioned troughs for observation. Fish were checked 1, 24, and 48 hours after the pressure sequence was completed. Observations included the numbers dead, experiencing loss of equilibrium, abnormal swimming behavior or buoyancy, and external signs of trauma. Dead fish were examined immediately to determine the cause of death. Fish surviving 48 hours were euthanized in MS-222 and examined under a dissecting scope (5-50 power) with the aid of optical fiber lighting and a base light. Examples of injuries

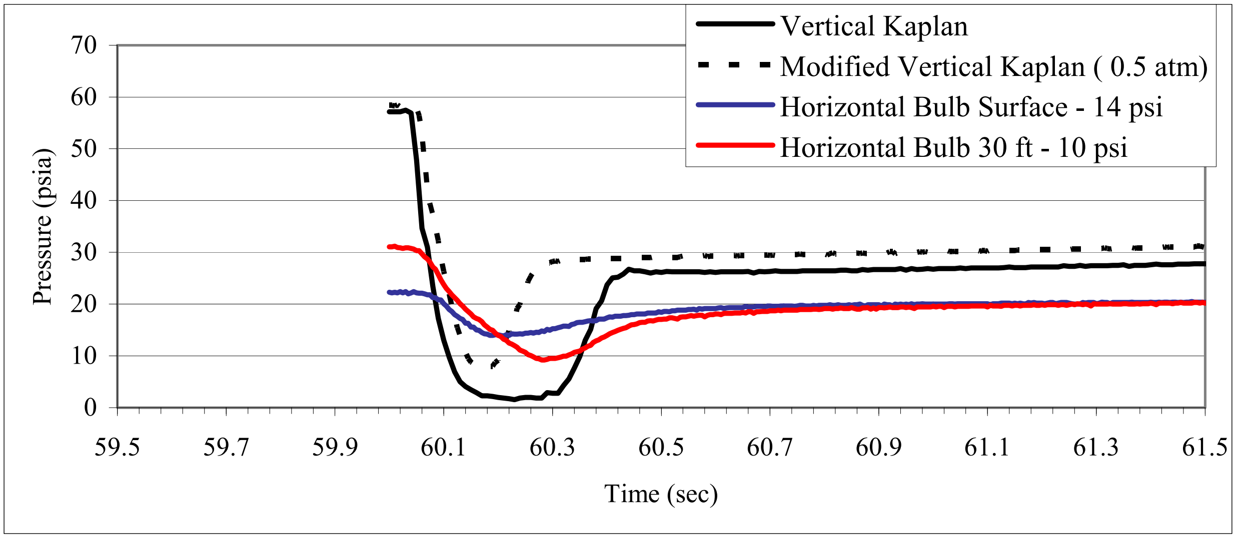

Figure 2.3. Comparison of the expected pressure nadirs during passage through a typical vertical Kaplan turbine, a modified vertical Kaplan turbine, and two horizontal bulb turbine passage scenarios.

were captured as digital images. Examinations included both external and internal examination. External examination consisted of looking for hemorrhaging, exophthalmia, or obvious injuries or abnormalities. Some fall chinook salmon were also examined internally to look for swim bladder rupture or internal bleeding. For bluegills, swim bladder rupture and internal bleeding could be determined without incising the fish by using backlighting.

2.5 Statistical Analyses

Analysis of variance was used to evaluate the effects of simulated passage through a bulb turbine. P-values less than 0.05 indicate a significant difference between the levels, or a significant interaction. The following factors with the accompanying levels were investigated:

1. "**Test**" compared fish that were subjected to simulated turbine passage to control fish (same treatment but no turbine passage simulation)

2. "**Nadir Pressure**" compared injury rates for fish exposed to nadirs of either 10 or 14 psia

3. "**Depth**" determined if depth acclimation depth (0 or 30 ft) prior to simulated turbine passage affected injury rates.

Interactions between the factors were also evaluated. Two responses were analyzed: (1) mortality due to spike, and (2) injury.

3.0 Results

3.1 Fall Chinook Salmon

A series of 12 tests simulating passage through a horizontal bulb turbine pressure sequence was completed during mid-August to mid-September 2001. Yearling fall chinook salmon were acclimated to either surface pressure (101 kPa) or 30 ft of depth (191 kPa) for up to 24 hours prior to exposure to the turbine passage simulations with either a 10 psia (70 kPa) or 14 psia (100 kPa) nadir. No mortalities, injuries, or abnormal swimming behavior were noted following exposure or during the subsequent 48 hours in any test (Table 3.1). Test fish appearance and behavior were indistinguishable from control fish.

Table 3.1. Mortality and injury rates for fall chinook salmon subjected to pressures simulating passage through a bulb turbine, based on acclimation depth and pressure nadir

	Surface Acclimation (101 kPa)						**30 ft Acclimation (191 kPa)**					
Test Group	**10 psia Nadir**			**14 psia Nadir**			**10 psia Nadir**			**14 psia Nadir**		
Replicate	1	2	3	1	2	3	1	2	3	1	2	3
Dead from Spike	0	0	0	0	0	0	0	0	0	0	0	0
Injured	0	0	0	0	0	0	0	0	0	0	0	0
OK - no injuries	20	20	20	20	20	20	20	20	20	20	20	20
	Surface Acclimation (101 kPa)						**30 Ft Acclimation (191 kPa)**					
Control Group	**10 psia Nadir**			**14 psia Nadir**			**10 psia Nadir**			**14 psia Nadir**		
Replicate	1	2	3	1	2	3	1	2	3	1	2	3
Dead from Spike	0	0	0	0	0	0	0	0	0	0	0	0
Injured	0	0	0	0	0	0	0	0	0	0	0	0
OK - no injuries	20	20	20	20	20	20	20	19	20	20	20	20

3.2 Bluegills

A series of 12 tests simulating passage through a horizontal bulb turbine pressure sequence was completed from late September through October 2001. The results of these tests were analyzed to evaluate the overall effect of passage through a horizontal bulb turbine and how depth acclimation and nadir pressure affected the results. Comparison of these results to previous results with vertical Kaplan turbine pressure spike simulations are made in the Discussion section.

The summary of injury and mortalities is shown in Table 3.2. Only 1 of the 240 bluegills subjected to pressure changes simulating bulb turbine passage died. Necropsy revealed that death resulted from gas bubble blockage in the heart. However, immediately after the pressure spike (while fish were still in the hyperbaric chambers), a “rosy” patch appeared on the sides of many “exposed” bluegills (Figure 3.1), indicating that the pressure spike ruptured capillaries near the swim bladder. The “rosy” patch was not observed on control (non-spiked) fish. When bluegills were removed from the hyperbaric chambers, those acclimated to 191 kPa (30 ft) of depth, both controls and exposed, were positively buoyant and struggled to maintain a normal position in the holding trough. Bluegills acclimated to 101 kPa (surface)

Table 3.2. Mortality and injury rates for bluegills subjected to pressures simulating passage through a bulb turbine, based on acclimation depth and pressure nadir

Test Group	**Surface Acclimation (101 kPa)**						**30 ft Acclimation (191 kPa)**					
	10 psia Nadir			**14 psia Nadir**			**10 psia Nadir**			**14 psia Nadir**		
Replicate	1	2	3	1	2	3	1	2	3	1	2	3
Dead from Spike	0	0	0	0	0	0	1	0	0	0	0	0
Injured	13	13	18	14	0	0	10	8	10	8	8	5
OK - no injuries	7	6	2	6	20	20	9	12	10	12	12	15
Control Group	**Surface Acclimation (101 kPa)**						**30 ft Acclimation (191 kPa)**					
	10 psia Nadir			**14 psia Nadir**			**10 psia Nadir**			**14 psia Nadir**		
Replicate	1	2	3	1	2	3	1	2	3	1	2	3
Dead from Spike	0	0	0	0	0	0	0	0	0	0	0	0
Injured	7	4	6	7	2	5	14	5	9	8	9	7
OK - no injuries	13	16	14	13	18	15	6	14	11	12	11	13

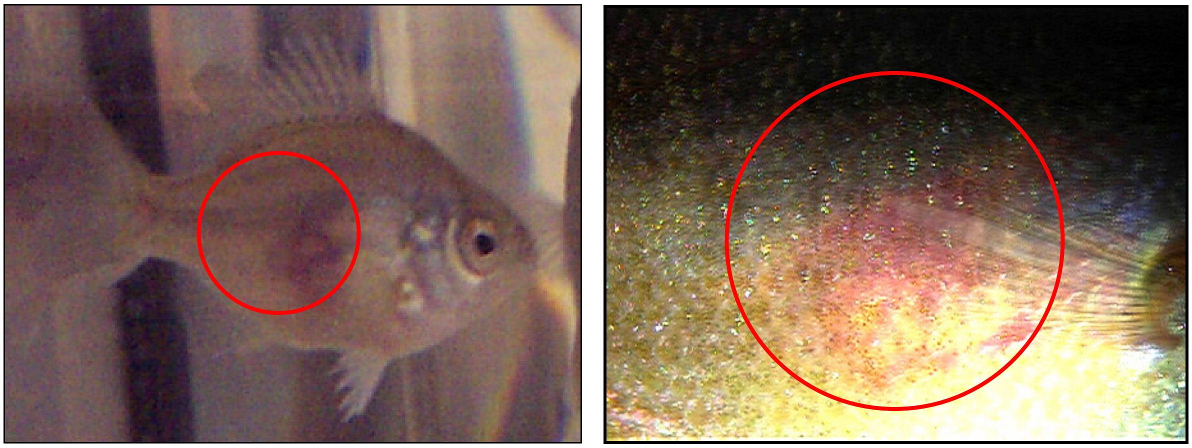

Figure 3.1. External view of hemorrhaging observed in bluegills immediately after pressure spike (left photo) and after 48 hours (right photo).

were not positively buoyant. Within 2 hours, all bluegills were able to equilibrate and achieve neutral buoyancy. No bluegills were observed to be negatively buoyant, suggesting that swim bladders were not ruptured during the simulated turbine passage tests. When bluegills were examined after the 48-hour post-exposure holding period, many of both the control and exposed fish showed signs of internal hemorrhaging (Figure 3.2), but none showed signs of ruptured swim bladders. Handling (loading and unloading fish to and from the hyperbaric chambers) likely contributed to the incidence of internal hemorrhaging injuries in both control and exposed bluegills.

The frequency and severity of internal hemorrhaging was highly variable among replicates and treatments in both the control and exposed groups. Statistical analyses (Tables 3.3 and 3.4) indicated that exposed fish had higher injury rates than control fish (P=0.022). Bluegills exposed to the 10 psia nadir had a higher injury rate than fish exposed to a 14 psia nadir (P=0.043). Figure 3.3 shows that bluegills

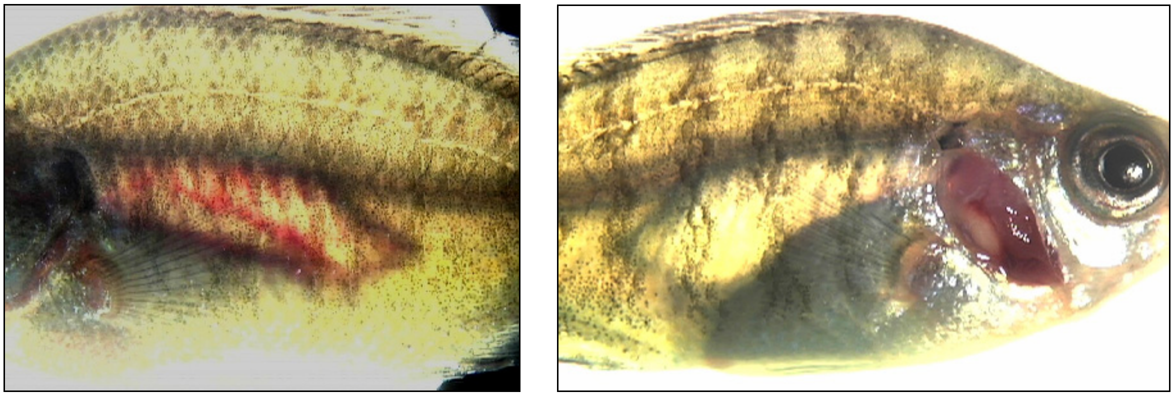

Figure 3.2. External view of internal hemorrhages and non-hemorrhaged juvenile bluegill as viewed with backlighting.

Table 3.3. Analysis of variance of the three response variables for bluegill bulb turbine pressure tests

Factor or Interaction	Injured p-value	Mortality p-value
Test x Control	**0.022**	1.000
Test x Nadir Pressure	**0.043**	1.000
Surface x Depth	0.247	0.267
Test x Depth	0.115	0.267
Nadir Pressure x Depth	0.226	0.332
Test x Nadir Pressure x Depth	0.181	0.332

Table 3.4. Overall proportions of bluegill that were killed or injured under the various test conditions (significant differences bolded)

Factor	Spike Mortality	Injured
Test		
Spike	0.004	**0.449**
Non-spike	0	**0.347**
Nadir Pressure		
10 psia (70 kPa)	0.004	**0.491**
14 psia (100 kPa)	0	**0.304**
Depth		
0 ft (101 kPa)	0	0.374
30 ft (191 kPa)	0.004	0.422

exposed to the 10 psia nadir had a significantly higher injury rate (P=0.044) than bluegills exposed to the 14 psia nadir and both control groups. Other treatment condition interactions did not significantly affect the numbers of injuries.

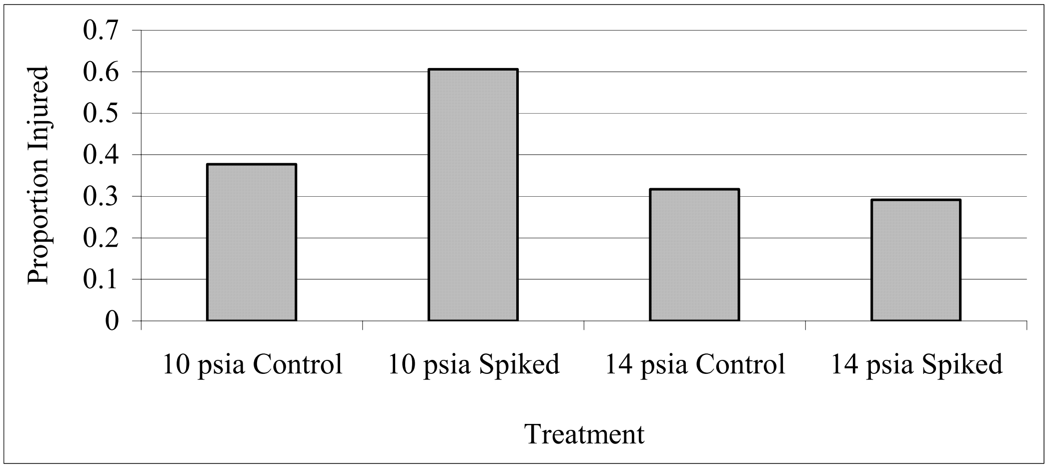

Figure 3.3. Interaction plot of nadir pressure and test for bluegill.

4.0 Discussion

The turbine passage system was designed and built to simulate time/pressure sequences expected during passage through a vertical Kaplan style turbine. The time/pressure sequences used in this test series approximated the pressure regime experienced by fish passing through a horizontal bulb turbine. In a vertically mounted turbine, pressures are relatively constant throughout the cross-section just downstream of the turbine runner, except for some small, specific areas (i.e., near the blade tips) where pressure changes are more extreme. However, in a horizontally mounted turbine, pressure varies significantly depending on whether a fish passes through the turbine near the ceiling, centerline, or bottom. Fish passing near the ceiling of the turbine would experience the lowest-pressure nadir, predicted to be near vapor pressure in some instances. Fish were exposed to "worst-case" pressure scenarios in previous tests evaluating passage through vertical Kaplan turbines. However, for the horizontal bulb turbine passage simulations, pressure scenarios predicted for "centerline" passage were used because those pressures are most representative of the largest cross-sectional area of a horizontal turbine. The flows used to calculate velocity through the turbine and develop the time/pressure passage scenarios include the maximum flow or "worst case" for the turbine.

Pretest acclimation to either 101 kPa or 191 kPa was used so that results could be compared to previous pressure test results. Injury/mortality comparisons were limited to fish exposed to "normal" gas levels (100% total dissolved gas) in previous pressure tests.

The hyperbaric chamber system was originally designed and built to generate pressure spikes approaching vapor pressure. Under ideal conditions, pressures as low as 3 kPa (0.03 atm) were possible. However, achieving an exact nadir between 3 kPa and 100 kPa was difficult because precision was affected by the sensitivity and response time of pressure sensors controlling piston movement in the hyperbaric chambers. The rate of change was also difficult to simulate but changes to needle valve settings made is possible to stretch out the pressure spike to more closely simulate passage through a horizontal bulb turbine. Several tests were aborted and repeated due to mechanical malfunctions resulting in poor pressure spike results.

Injury and mortality rates for fall chinook salmon and bluegills subjected to pressure conditions simulating passage through a horizontal bulb turbine were compared to rates for the same species subjected to the modified Kaplan turbine pressure scenarios. Comparisons for each species are described below.

4.1 Fall Chinook Salmon

No pressure-related mortalities were observed in either bulb turbine test series with fall chinook salmon. In addition, no injuries were observed for fall chinook salmon subjected to the horizontal bulb turbine pressure sequence, regardless of acclimation depth or pressure nadir. All salmon had normal swimming behavior and buoyancy during the 48-hour post-exposure observation period. No salmon developed black head spots as was observed in fall chinook salmon and rainbow trout in earlier tests simulating Kaplan turbine time/pressure scenarios (Abernethy et al. 2001, 2002).

Previous reports have stated that for salmonids, when the minimum pressure is 30% of the acclimation pressure (i.e., exposure pressure/acclimation pressure ratio is 0.3) or higher, no mortality is expected (USACE 1991). For fall chinook salmon acclimated to 101 and 191 kPa (surface and 30 ft of depth), the recommended minimum pressure limit would be 30 and 57 kPa, respectively. None of the bulb turbine pressure scenarios dropped below these minimum pressures, so no mortality was expected.

Although the bulb turbine pressure regime that was tested appeared to be harmless to chinook salmon, it is representative of only a single condition, passage near the centerline of the turbine. Other passage routes would have different pressure regimes. Some, presumably small, areas of a bulb turbine are known to exhibit pressure spikes that are low enough to cause cavitation, which would be damaging to fish. For example, a turbine-passage study of the bulb turbine at Rock Island Dam attributed some of the injuries observed among chinook salmon to pressure effects (Normandeau and Skalski 1997).

4.2 Bluegills

Bluegills used in these tests were the same size and those used in the modified Kaplan turbine pressure tests were smaller than those used in the original Kaplan turbine passage simulations. Table 4.1 shows that the injury rates for bluegills subjected to horizontal bulb turbine passage were significantly lower (P=0.003) than for bluegills exposed to the modified Kaplan turbine (50 kPa nadir) when using the same criteria to assess injuries (backlighting technique). The only observed injury for bluegills in bulb turbine passage simulations was internal hemorrhaging, presumably rupturing of the capillaries surrounding the swim bladder. In addition, the extent (severity) of internal hemorrhaging appeared to be much less than in previous modified Kaplan tests with a 50 kPa nadir.

The cause of the elevated rate of internal hemorrhaging in control bluegills is unknown. Efforts to eliminate or reduce the injury rate by altering handling techniques during loading and unloading had inconsistent results. Bluegills removed from the general population and examined immediately (baseline condition) appeared normal (no internal hemorrhaging).

Injury rates for control and test fish acclimated to 191 kPa (30 ft of depth) and subsequently exposed to the 100 kPa (14 psia) pressure spike were identical. This result indicates that the sudden decrease in pressure from 191 kPa to 101 kPa was no more harmful to bluegills than the gradual decrease in pressure from 191 kPa to 101 kPa experienced by the controls. However, bluegills exposed to the 70 kPa (10 psia) had a significantly higher injury rate than controls that experienced a gradual decrease.

Table 4.1. Comparison of injury and mortality rates for bluegills subjected to pressures simulating passage through a horizontal bulb turbine (70 or 100 kPa nadir) or modified Kaplan turbine (50 kPa nadir)

	Modified Kaplan (50 kPa Nadir)	**Horizontal Bulb Turbine (>70 kPa Nadir)**	**P-value**
Percentage OK	29.4%	60.0%	**0.002**
Percentage Injured	63.5%	39.8%	**0.003**
Percentage Spike Mortality	6.4%	0.2%	0.185

Swim bladders in 10-cm yellow perch burst when pressure was reduced to 40% of acclimation values (Jones 1951, cited in Čada 1990). Because yellow perch and bluegills are both physoclistous fish, a similar outcome could be expected for bluegills. For bluegills acclimated to 101 kPa (surface) and 191 kPa (30 ft of depth), the 40% level would be 40 and 76 kPa, respectively. Nadirs in the bulb turbine simulations were 70 kPa (10 psia) or 100 kPa (14 psia). Therefore, swim bladder rupture might have been expected for bluegills acclimated to 191 kPa and subjected to a 70 kPa pressure nadir. Although the authors did not observe swim bladder rupture, bluegills exposed to this combination of conditions had significantly more injuries (internal hemorrhaging in the region of the swim bladder) than bluegills exposed to less severe pressure reductions.

The use of backlighting to detect internal hemorrhaging in small bluegills is useful for observing extremely minor capillary damage that may or may not significantly affect fish health or behavior. Using this technique, the authors observed that the injury rate for surface acclimated controls (26%) was significantly lower (P=0.004) than for depth-acclimated controls (44%). In addition, injury rates for depth-acclimated test fish exposed to the 14 psi spike were the same as for depth-acclimated controls. Control fish acclimated to 191 kPa of depth were returned to surface pressure over a period of 10-20 sec, whereas test fish (spiked) were subjected to a 14 psi (100 kPa) pressure spike over a period of <0.5 sec, followed by a draft tube pressure simulation before returning to surface pressure. Therefore, observed injuries appeared to be unrelated to the rate of change, but to the magnitude of the pressure change. The injury rate for surface acclimated controls may be indicative of “background” handling variability (noise). Bluegills removed directly from the general population and observed with backlighting did not show signs of internal hemorrhaging.

5.0 Conclusions

Test series results are consistent with previous tests that evaluated the effect of rapid pressure change on fish. Mortality rates, injury rates, post-exposure behavioral observations, and necropsies have shown that effects of pressure change vary among fish species and diminish as the magnitude of pressure change decreases. Conclusions based on the outcome of this test series and comparisons to other studies are summarized below.

- Over a 24-hour acclimation period, fall chinook salmon were unable to reach equilibrium and attain neutral buoyancy to pressures simulating 30 ft of depth (salmon had no access to air while in the sealed test chambers). If salmonids are capable of equilibrating to 10 ft of depth (~130 kPa) by gulping air at the surface and sounding, a rapid pressure reduction to 30% of acclimation pressure (40 kPa) or higher should not cause mortality. The pressure nadirs tested in this series (70 and 100 kPa) are both well above this level and no injuries were observed.

- In worst-case Kaplan turbine time/pressure scenarios with pressure nadirs of <10 kPa, a small percentage of fall chinook salmon had ruptured swim bladders. In modified Kaplan turbine time/pressure scenarios with pressure nadirs of 50 kPa, swim bladder rupture did not occur, but some minor injuries were observed. In the horizontal bulb turbine time/pressure scenarios, no injuries were observed for fall chinook salmon.

- For bluegills, the incidence of swim bladder rupture and other serious injuries decreased as the magnitude of pressure changes decreased. No swim bladder ruptures were observed for either surface or depth-acclimated bluegills when subjected to either a 100 kPa (52% of acclimation pressure) or 70 kPa (37% of acclimation pressure) nadir.

- Injury rate, as measured by the frequency of internal hemorrhaging near the swim bladder, was significantly higher for bluegills acclimated to 30 ft of depth (191 kPa) than for surface-acclimated bluegills. Bluegills (and presumably other physoclistous fish) can equilibrate to 30 ft of depth in a matter of hours. Previous studies state that swim bladder rupture could be expected with a rapid pressure reduction to 40% of acclimation pressure (~75 kPa). Although the authors did not observe swim bladder rupture, elevated injury rates were observed when bluegills acclimated to 191 kPa were subsequently exposed to a rapid pressure decrease to ~70 kPa (37% of acclimation pressure).

- The primary criterion for quantifying injury for bluegills was internal hemorrhaging that occurred near the swim bladder. The magnitude of internal hemorrhaging varied widely. Although the injury was not lethal, the effects of the injury on the bluegills' overall health and ability to perform gas exchange to fill or deflate the swim bladder were not evaluated.

6.0 References

Abernethy, C. S., B. G. Amidan, and G. F. Čada. 2001. *Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish*. PNNL-13470, Pacific Northwest National Laboratory, Richland, WA.

Abernethy, C. S., B. G. Amidan, and G. F. Čada. 2002. *Simulated Passage Through a Modified Kaplan Turbine Pressure Regime: A Supplement to "Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish*." PNNL-13470-A, Pacific Northwest National Laboratory, Richland, WA.

Čada, G. F. 1990. "A Review of Studies Relating to the Effects of Propeller-Type Turbine Passage on Fish Early Life Stages." *North American Journal of Fisheries Management* 10:418-426.

Montgomery Watson. 1995. *Allowable Gas Supersaturation for Fish Passing Hydroelectric Dams*. Project No. 93-8. Final report prepared for Bonneville Power Administration, U.S. Department of Energy, Portland, OR.

Normandeau Associates Inc., and J. R. Skalski. 1997. *Turbine Passage Survival of Chinook Salmon Smolts at the Rock Island Dam Powerhouse I and II, Columbia River, Washington*. Prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

U.S. Army Corps of Engineers (USACE). 1991. *Revised Compendium on the Success of Passage of Small Fish Through Turbines.* North Pacific Division, Portland, OR.