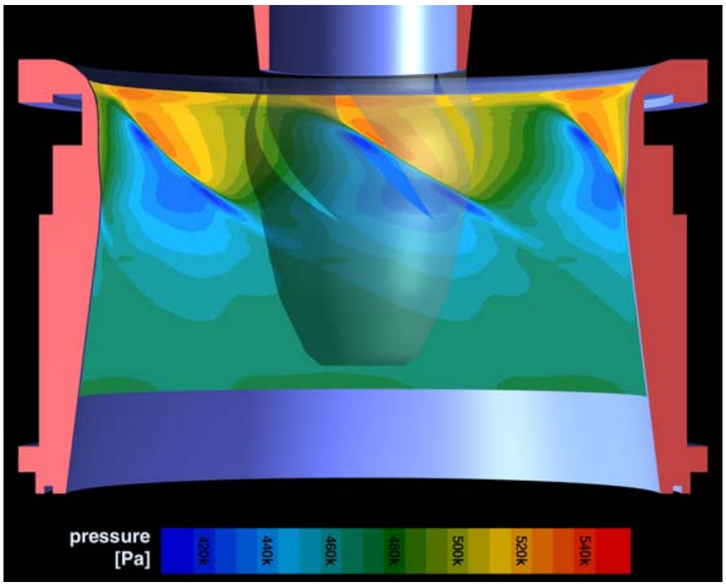
PNNL-15011

Pilot Study of the Effects of Simulated Turbine Passage Pressure on Juvenile Chinook Salmon Acclimated with Access to Air at Absolute Pressures Greater than Atmospheric



T.J. Carlson
C.S. Abernethy

May 2005

Prepared for the U.S. Army Corps of Engineers
Portland District, Portland, Oregon
Under a Related Services Agreement
with the U.S. Department of Energy
Contract DE-AC05-76RL01830

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

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UNITED STATES DEPARTMENT OF ENERGY
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FINAL REPORT
May 2005

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Under a Related Services Agreement
with the U.S. Department of Energy
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Pacific Northwest National Laboratory
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Richland, Washington 99352

Executive Summary

The impacts of pressure on juvenile salmon who pass through the turbines of hydroelectric dams while migrating downstream on the Columbia and Snake rivers has been assumed to be negligible for physostomous juvenile salmonids. The laboratory study described here was conducted in 2004 by Pacific Northwest National Laboratory for the US Army Corps of Engineers Portland District at PNNL's fisheries research laboratories to investigate the impacts of simulated turbine passage pressure on fish permitted access to air while held for acclimation at absolute pressures greater than atmospheric. The objective of the study was to take an abbreviated first look at the effect of pressure on juvenile salmonids that were neutrally buoyant at depths where absolute pressure would be greater than atmospheric.

Samples of two size groups of juvenile Chinook salmon, 80-100mm and 125-140mm, were held for 22 to 24 hours in hyperbaric chambers at pressures approximately equivalent to 15 ft, 30 ft, and 60 ft depth with access to an air bubble within an acclimation chamber. At the end of the acclimation period, test fish were exposed to a pressure time history simulating passage through a mainstem Columbia River Kaplan turbine. Control fish were handled, acclimated, and held in the same manner as the "treatment" fish, however the control fish were not exposed to the turbine passage pressure time history. Fish killed during the exposure were necropsied upon recovery from the hyperbaric chamber. Fish that survived the exposure were held for 48 hours then sacrificed for necropsy. Fish that died during the holding period were necropsied at the time of death.

The results of these tests are not definitive but indicate that juvenile salmonids that are acclimated to depths greater than atmospheric, with access to air so that neutral buoyancy can be achieved, may be at greater risk of injury and death than fish that are acclimated to pressures very near atmospheric. The results also cause concern for potentially higher injury and mortality rates for turbine-passed fish with implanted telemetry devices. Additional laboratory and field experiments will be required to investigate whether or not and to what extent juvenile salmonids may seek neutral buoyancy at depths significantly greater than atmospheric and the consequences, during and following turbine passage, of this behavior.

Acknowledgments

The work described here was supported by the US Army Corps of Engineers' Turbine Survival Program. We acknowledge the oversight provided by the Corps' Turbine Survival Program technical team. We thank Dennis Dauble of PNNL for technical review of this report.

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1.0 Introduction

The impacts of pressure on juvenile salmon who pass through the turbines of hydroelectric dams while migrating downstream on the Columbia and Snake rivers has been assumed to be negligible for physostomous juvenile salmonids. The laboratory study described here was conducted by Pacific Northwest National Laboratory for the US Army Corps of Engineers Portland District at PNNL's fisheries research laboratories in 2004 to investigate the impacts of simulated turbine passage pressure on fish permitted to achieve neutral buoyancy at pressures corresponding to the depths at which they are observed during downstream migration.

1.1 Background

Barotrauma in humans is defined as injury of a part or organ as a result of changes in barometric pressure. For fish this definition may be extended to all changes in pressure, which includes the rapid change in pressure during passage through a hydroturbine runner. The consequences of barotrauma in fish include a variety of injuries and immediate or delayed death. In general, barotrauma injuries result from changes in the volume of air cavities in the body of a fish. These air cavities can include bubbles or bubble nuclei in tissue or blood. However, injuries to swimbladders and surrounding organs are those most commonly associated with barotrauma. Death can result from bubbles inhibiting blood flow or the correct function of organs. Death and serious injury may result from the effects of swimbladder expansion and contraction on surrounding tissue and organs, swimbladder rupture, and various other traumas. There is evidence that exposure to supersaturated dissolved gas can exacerbate barotrauma (Abernethy et al. 2001).

Fish that have swimbladders are thought to use them to achieve neutral buoyancy as a means of reducing the energy demands of maintaining a preferred depth in water in addition to other potential benefits. In the case of physoclistous species, the relationship between swimbladder volume and neutral buoyancy appears quite straightforward because these fish do not require access to air to add gas to their swimbladders. For physostomous fish, the relationship between position in the water column and buoyancy is not as clear, particularly for species that rely on gulping air at the surface to fill their swimbladder and that have a means to rapidly reduce swimbladder volume. In particular, while juvenile Chinook salmon moving through the hydropower system are often observed at depths where ambient static pressures are significantly above atmospheric pressure, there are no data for their swimbladder volume at these depths; nor are there data on whether or not they are neutrally buoyant at these depths. There is considerable laboratory evidence, however, suggesting that essentially all juvenile salmon that pass through turbines are negatively buoyant when they enter the powerhouse tailrace (Abernethy et al. 2001, 2002).

In a further complication of the issue of swimbladder volume management by juvenile salmonids, laboratory studies have shown that juvenile salmonids implanted with telemetry devices, such as radio or acoustic micro-transmitters, can and do increase swim bladder volume to achieve neutral buoyancy when permitted access to air (Anglea et al. 2003). These observations imply that juvenile salmonids have some feedback mechanism about their buoyancy, that the swimbladder and abdominal wall is extensible, and that juvenile salmonids have the ability to willfully inflate their swimbladders in excess of that required for neutral buoyancy at near atmospheric pressure when unencumbered by additional excess mass. As is the case with juvenile salmonids in general, there are no observations of the state of the swimbladder of juvenile salmonids bearing telemetry devices during movement through the hydropower system. A common assumption is that these fish manage their swimbladder volume as do those observed in the laboratory.

Telemetry studies conducted to assess the survival of juvenile salmonids passing through mainstem turbines are of two types. In one type of study, fish acclimated to near-surface pressure are injected into the turbine intake or other location. The status of the swimbladder of these fish is unknown and may even be modified from the assumed condition of swimbladder volume consistent with neutral buoyancy at the pressure in holding tanks by handling prior to injection. In the second type of study, fish are implanted with a telemetry device and are released upstream of a project with the objective of permitting the test fish to realize a condition more similar to that of the population of migrants of interest. The condition of the swimbladder of these fish is also unknown but it is assumed that if these fish have access to air they will behave like fish implanted with telemetry transmitters under laboratory conditions and will attempt to achieve neutral buoyancy at near-surface depths. Laboratory studies show that the swimbladder of these fish is most likely not in the same state as that of the population at large.

Another commonly used study method is balloon tag testing. In these studies, as in the case of telemetry fish injected directly into a turbine intake, test fish are outfitted with location and recovery aids and injected directly into a turbine intake. The status of the swimbladders of the test fish is unknown at the time of injection.

Almost all laboratory studies of the effect of pressure changes during simulated turbine passage on fish are conducted with fish that have swimbladder volumes consistent with neutral buoyancy at near-surface depths. In those cases where fish are held (acclimated) at higher pressure prior to exposure to simulate turbine passage pressure time histories, they have not been permitted access to air and therefore have not been able to increase swimbladder volume to achieve neutral buoyancy at acclimation pressures. In these types of tests, the rates of injury and mortality of test fish are very low (Abernethy et al. 2001, 2002, Cada et al. 1997). Review of gray and peer reviewed literature indicates that studies have not been conducted for juvenile physostomous fish where test fish were exposed to turbine passage pressure time histories after being allowed to fill their swim bladders to the volume necessary to achieve neutral buoyancy during acclimation at pressures greater than atmospheric.

1.2 Objectives

The question of interest that led to the pilot study reported here was: “Is the effect of simulated turbine passage different for fish permitted to achieve neutral buoyancy at pressures corresponding to depths at which they are typically observed during downstream migration compared to the acclimation scenarios typically used for these types of studies?”

In this pilot study we did not seek to answer this question but to perform limited-range testing to assess the validity of the question. Because the study was very restricted in scope and was not designed with a hypothesis in mind there is no statistical treatment of data other than that needed to summarize observations.

1.3 Overview of this Report

Section 2 describes our testing methodology. Results of the pressure cycling tests are provided in Chapter 3. Chapter 4 discusses potential implications of the results. Chapter 5 is conclusions and recommendations. Chapter 6 is references.

2.0 Methods

The basic methods used for this pilot study were the same as those used for previous studies of the response of fish to simulated turbine passage pressure time history exposures. These methods are described in detail in Abernethy et al. 2001 and 2002.

Two sizes of juvenile Chinook salmon were tested, 80-100mm and 125-145mm total length. All fish were from the same group. The smaller fish were tested in July 2004. Fish that were not used in this first test were used for tests conducted in September after they had grown to a larger size.

Test fish were acclimated for 22 to 24 hours in hyperbaric chambers (Figure 2.1) at pressures simulating depths of 15, 30, or 60 ft, with access to an air bubble. After acclimation, the bubble was removed without changing the acclimation pressure. One hyperbaric chamber was then pressure-cycled (Figure 2.2) and the second was not cycled (control). Instead, the pressure in the control chamber was gradually lowered to surface (atmospheric) pressure (0 ft). Fish were then removed from the hyperbaric chambers and placed in holding tanks. Mortalities were recorded over the next 24 hours and were necropsied at the time of their deaths. After 24 hours, surviving fish were euthanized with MS-222 and necropsied. Necropsy consisted of making an incision along the fish's side about midway between the lateral line and the ventral midline from just anterior of the anus to the pectoral girdle. The tissue was gently lifted with a forceps to determine if the swim bladder was inflated or empty. Internal hemorrhaging and other internal injuries were noted.

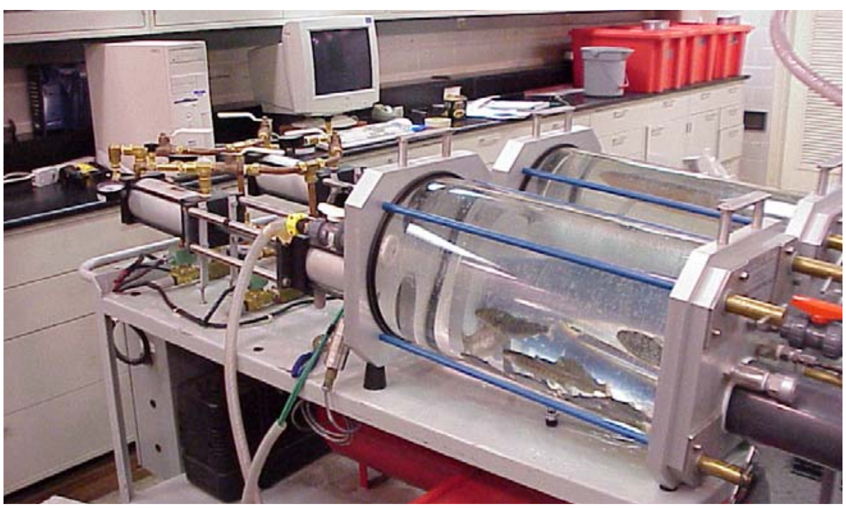

Figure 2.1. Hyperbaric Chamber for Pressure Cycling Test Fish

The smaller Chinook salmon juveniles were tested at three acclimation pressures equivalent to depths of 15, 30, and 60 feet (~50K, 101K, and 202K Pa). Larger Chinook salmon juveniles were only tested at two acclimation pressures, which were equivalent to 15- and 30-foot depths (~50K and 101K Pa).

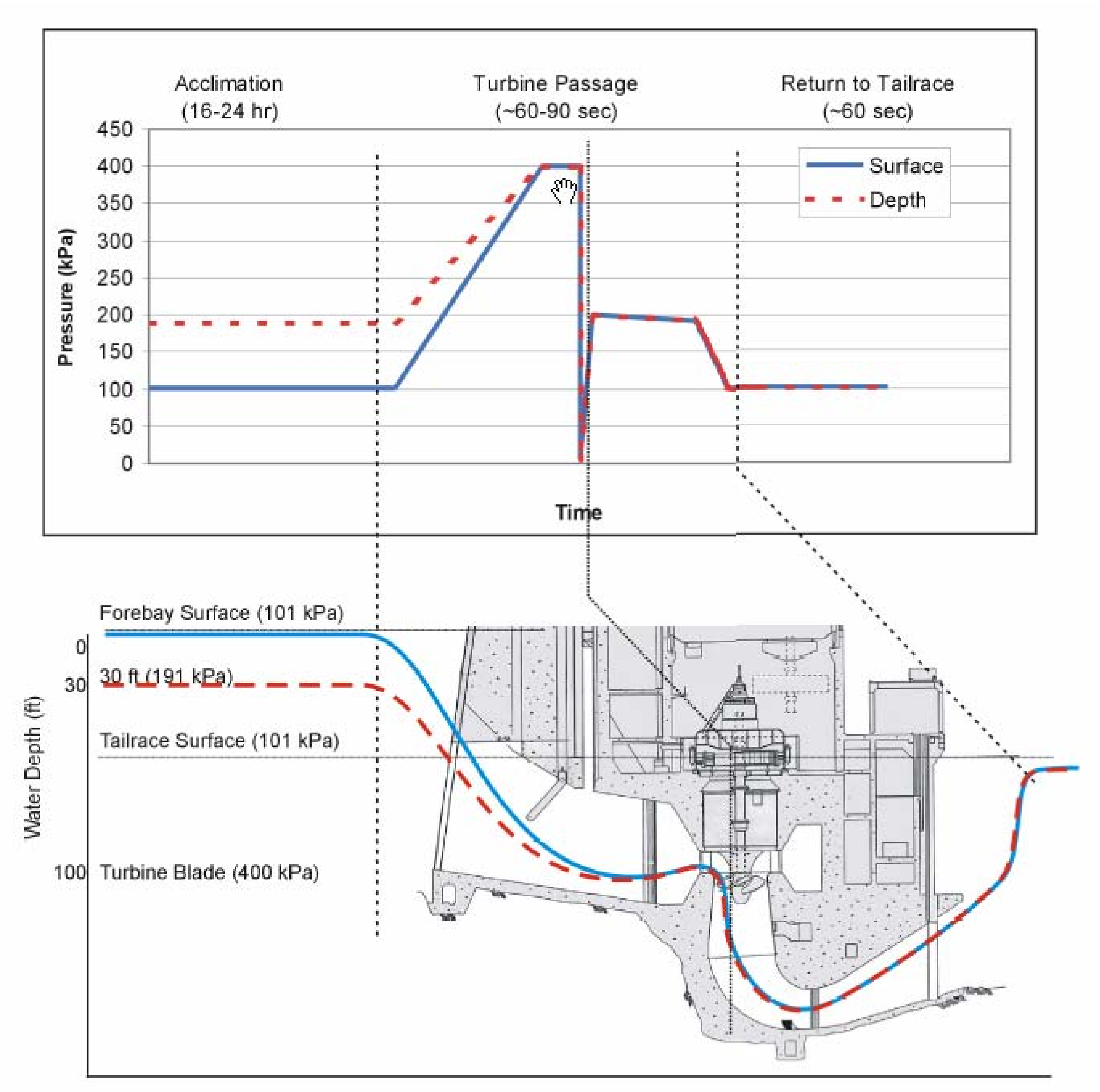

Figure 2.2. Pressure Cycling of Hyperbaric Test Chamber to Match Pressure Experienced by Fish during Actual Turbine Passage

3.0 Results

The results of the tests conducted with small and larger Chinook salmon juveniles are shown in Tables 3.1 and 3.2. No control fish died during the study and, with the exception of one trial, none were injured.

Table 3.1. Results of Pressure Cycling Tests, Small Chinook

Small Chinook Smolts (80-100 mm)				
Acclimation Depth (ft)	Group	Number Tested	% Injured	% Killed
15	Pressure-Cycled	30	23.3	3.3
15	Control	28	0.0	0
30	Pressure-Cycled	30	23.3	10.0
30	Control	30	0	0
60	Pressure-Cycled	30	0	0
60	Control	28	0	0

Table 3.2. Results of Pressure Cycling Tests, Large Chinook

Large Chinook Smolts (125-145 mm)				
Acclimation Depth (ft)	Group	Number Tested	% Injured	% Killed
15	Pressure-Cycled	30	36.7	10.0
15	Control	30	0.00	0
30	Pressure-Cycled	30	10.0	3.3
30	Control	30	3.3	0

Uninjured fish were characterized by inflated swim bladders and the absence of internal hemorrhaging or other internal injuries. All but one control fish had fully inflated swim bladders.

Many pressure-cycled fish had un-inflated swim bladders but lacked any signs of internal hemorrhaging. Small holes or tears in the swim bladders were sometimes, but not always observed.

Several fish died following pressure cycling. There were no signs of embolism in the gills or heart. On two occasions, pressure cycling resulted in the fish's stomach being extruded into the mouth. Figures 3.1, 3.2, and 3.3 below show the appearance of one of these fish.

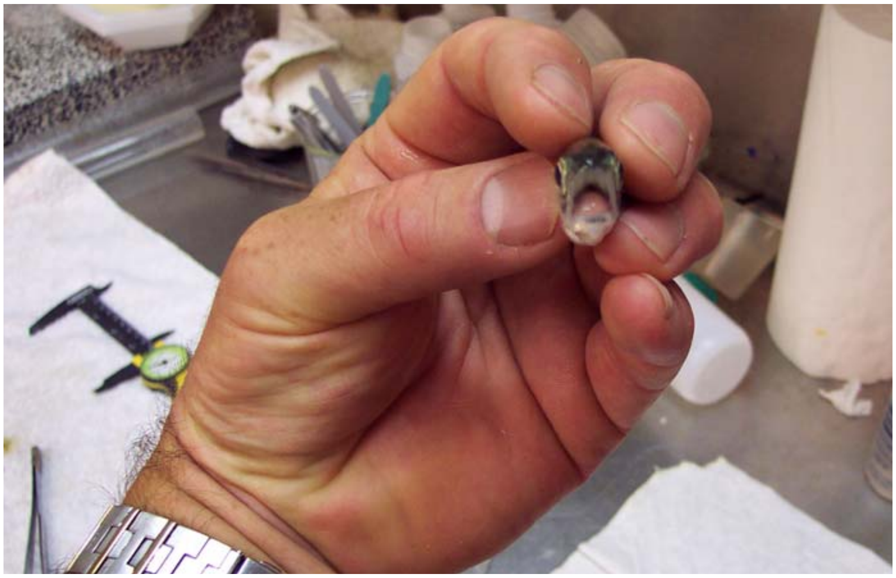

Figure 3.1. Fish with stomach extruded into mouth as a result of pressure cycling, external front view

Figure 3.2. Fish with stomach extruded into mouth as a result of pressure cycling, external side view

Figure 3.3. Fish with stomach extruded into mouth as a result of pressure cycling, internal side view

4.0 Discussion

The results of this pilot study are not definitive in any way. However, they do indicate that juvenile salmonids that achieve neutral buoyancy at depths greater than near surface may show a different physical response to pressure changes during simulated turbine passage. The pattern of injuries and mortalities are not particularly meaningful because of the small number of fish tested. What is important is the much higher injury and mortality rates seen in this study for juvenile Chinook salmon compared to those conducted previously (Abernethy et al. 2001). In these studies, juvenile Chinook salmon were acclimated at various pressures without access to air in water at 100% gas saturation levels then subjected to simulated turbine passage pressure exposures. None of the 60 test fish exposed to the conditions in the preceding sentence in the Abernethy studies died and only one was found to have a ruptured swimbladder.

Other interesting observations were made in previous PNNL studies (Abernethy et al. 2001). Following simulated turbine passage, most test fish were negatively buoyant when placed in holding troughs and some had trouble maintaining equilibrium. When necropsied, test fish having trouble maintaining equilibrium were found to have ruptured swimbladders. In addition, some of the test fish remained negatively buoyant throughout a 48-hour holding period. All test fish in the Abernethy study were observed to be capable of achieving neutral buoyancy at atmospheric pressure prior to testing.

It is interesting to consider the potential impact of the additional swimbladder volume juvenile fish must acquire to compensate for telemetry device excess mass. For example, the excess mass of a fish is typically considered to be on the order of 5% of total fish mass. Thus, a fish with a mass of 30 grams would have an excess mass in water of 1.5 grams. (Here excess mass is the mass of the fish minus the mass of water displaced by the fish.) Fish swimbladder volume would have to be approximately 1.5 cm^3 at atmospheric pressure to displace a sufficient volume of water to compensate for this excess mass (assuming changes in swimbladder volume are mirrored by changes in fish displacement volume). If a telemetry device with an excess mass of 0.5 grams were implanted in this fish it would have to inflate its swimbladder with an additional 0.5 cm^3 at atmospheric pressure to compensate for this excess mass. This amount of air is also equal to that the fish would have to take in to be neutrally buoyant at a depth of approximately 10 feet. The data from the pilot study indicate a high rate of injury and a significant rate of mortality for both large and small Chinook salmon at these relatively shallow depth equivalents.

While it is useful to consider requirements for neutral buoyancy in terms of swimbladder volume, it is actually the volume of water displaced by the body of the fish that determines the buoyant force acting on the fish. Apparently, increases (or decreases) in swimbladder volume increase (or decrease) the total volume of a fish, thereby changing the volume of water displaced and the buoyant force acting on the fish. What is not clear is the relationship between changes in swimbladder volume and changes in fish volume. It is likely that the relationship is relatively linear for small changes in swimbladder and fish total volumes, becoming less so as the fish's body expands, approaching a limit determined by abdominal tissue elasticity. The limit of tissue elasticity, if approached as a fish bearing a telemetry device sought neutral buoyancy, would leave little room in the fish's body for other life-sustaining activities such as feeding that also require space in the gut.

An interesting observation made during this study of small Chinook salmon was their inability to achieve neutral buoyancy at pressures equivalent to a depth of 60 feet, even when a pocket of air was available. This was true for all test fish exposed at this pressure. The reason for this was not determined. A hypothesis is collapse of the duct leading from the swimbladder to the esophagus.

Interpretation of the significance of the results of this pilot study for run-of-the-river juvenile Chinook salmon depends upon interpretation of available information about swimbladder management by fish. One school of thought is that salmonids fill their swimbladders at the surface at atmospheric pressure and that the pressure in the bladder does not exceed atmospheric pressure. On the other hand, since little is known about how salmonids draw air into their bladder, it is not clear that they cannot create internal bladder pressure in excess of atmospheric when taking in air at the surface. Laboratory studies of compensation by juvenile salmonids for the excess mass of telemetry devices indicate that these fish do have mechanisms for drawing a volume of air into their swim bladders in excess of what they would otherwise need for neutral buoyancy.

Regardless of interpretation of available evidence about swimbladder inflation by juvenile Chinook salmon, it has been demonstrated that juvenile Chinook salmon and other juvenile salmonids are capable of drawing additional air into their swimbladder to compensate for the excess mass of implanted telemetry devices. The results of this study indicate that juvenile fish may pay a price in terms of increased susceptibility to injury and death for this additional air. If verified by additional study, the consequence of increased susceptibility to injury and mortality suggests mortality estimates from fish passage studies for hydroturbines conducted to date using telemetry devices may be biased.

These results, again if substantiated, would cast serious doubt on any assessment of the consequences to fish health of exposure to pressure changes during turbine passage or assessments of direct or total turbine passage mortality using test fish injected directly into the turbine intake following acclimation to near-surface pressures and extensive handling. This would be true of studies conducted using telemetry devices, balloon tags, or PIT tags. These results might not preclude the use of these methods for relative comparisons of turbine biological performance for injuries and mortality caused by mechanisms other than pressure.

Finally, observations of the behavior of test fish following simulated turbine passage indicate that recovery from negative buoyancy and the effects of swimbladder rupture, while not necessarily fatal, might result in many turbine-passed fish being more susceptible to predation. These observations place importance on consideration of the tailrace conditions awaiting turbine-passed fish. Conditions that would provide some protection from predators for a period of time to permit recovery of buoyancy could be beneficial.

5.0 Conclusions and Recommendations

Laboratory studies are needed to clarify the risk of injury and mortality from pressure changes experienced during turbine passage for physostomous juvenile fish that are acclimated to depths greater than the surface or to the presence of a telemetry device. Here acclimated means swimbladder management to achieve neutral buoyancy. These studies should consider the following factors:

1. the depth distribution of juvenile fish approaching and entering turbine intakes,
2. actual (observed) pressure time histories for turbine passage at the discharges of typical operation,
3. estimated pressure time histories for turbine passage through new design runners intended for rehabilitation of existing turbines,
4. the range of excess mass (wet weight in fresh water) of telemetry devices currently in use as well as those used recently to obtain turbine passage survival estimates,
5. potential for injury during turbine passage to test fish implanted with telemetry devices and additional devices to compensate for telemetry device excess mass,
6. the full size range and species of fish used or planned for use in telemetry studies to obtain turbine passage survival estimates, and
7. assessment of methods available to estimate the conditions of the swimbladders of juvenile fish approaching turbine intakes.

The need for studying the susceptibility of fish neutrally buoyant at pressures greater than atmospheric to injury or death has been questioned because of the lack of information about “depth acclimation” of run-of-the-river fish. The state of the swim bladders of run-of-the-river fish is unknown but it is generally assumed that salmonids do not attempt to achieve neutral buoyancy at any but very near-surface depths. Because of this assumption any study of the effects of pressure exposure during turbine passage has been restricted. It is unlikely that information about the state of the swim bladder in run-of-the-rive juvenile salmonids will be forthcoming anytime soon to address this uncertainty. However, even in the event that it is eventually shown that juvenile salmonids do not achieve neutral buoyancy except nearer surface, it makes some sense to consider a sensitivity study to explore the potential for injury and mortality for fish neutrally buoyant at depths less than 10 feet. We know from studies of buoyancy compensation by fish bearing telemetry devices that juvenile salmonids can gulp sufficient air into their swimbladders to compensate for excess mass in addition to that of their bodies. It is possible that fish do not accurately control the air they take into their swimbladder and that a portion of the population may fill their swimbladders inadvertently to provide for neutral buoyancy at shallow depths.

Studies of the potential for injury and mortality from pressure changes during turbine passage for juvenile salmon neutrally buoyant at depth less than or equal to 10 feet should consider the following factors:

1. actual pressure time histories for turbine passage at the discharges of typical operation,

2. estimated pressure time histories for turbine passage through new design runners intended for rehabilitation of existing turbines,
3. the full size range and species of fish exposed to turbine passage, and
4. pressure acclimation equivalents up to a depth of 10 feet.

It may also be possible to conduct field studies that would help resolve ambiguities about the susceptibility of run-of-the-river fish to pressure exposure during turbine passage. Such studies would need to collect turbine-passed fish and assess the condition of their swimbladders and internal organs to estimate the probability of injury from turbine passage then segregate injuries resulting from pressure exposure from injuries resulting from other mechanisms. In addition, some acoustic measurement technologies that utilize the resonant properties of fish swimbladders might also be used to obtain information about the state of the swimbladders of migrating juvenile salmonids.

6.0 References

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