# *Improving hydroturbine pressures to enhance salmon passage survival and recovery*

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RESEARCH PAPER

# Improving hydroturbine pressures to enhance salmon passage survival and recovery

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**Abstract** Barotrauma caused by rapid decompression during hydroturbine (turbine) passage may occur as fish move through the low pressure region below the turbine runner. This scenario is of particular concern in North American rivers with populations of ESA-listed salmon. The US Army Corps of Engineers (USACE) and the Pacific Northwest National Laboratory released Sensor Fish into lower Snake and Columbia River turbines to determine the magnitude and rate of pressure change fish might experience. Recorded pressures were applied to simulated turbine passage (STP) in laboratory studies to determine the effect of rapid decompression on juvenile Chinook salmon. These STP studies have increased our understanding of how pressure effects fish passing through turbines and suggest that the ratio of pressure change [acclimation pressure (the depth upstream of the dam where fish are neutrally buoyant) divided by nadir pressure (lowest pressure)] is highly predictive in determining the effect on smolt survival. However, uncertainty remains in smolt acclimation depth prior to entering turbine intakes at hydroelectric facilities. The USACE continues to make progress on salmon survival and recovery efforts through continued research and by applying pressure study results to turbine design. Designing new turbines with higher nadir pressure criteria is likely to provide safer fish passage for all salmonid species experiencing turbine passage.

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## Introduction

Hydropower dams constructed on major rivers in the Atlantic Northeast (New England) and Pacific Northwest of the United States (US) provide obstruction to both upstream and downstream passage of anadromous salmonids (Brownell et al. 2012). While most species of salmon and steelhead have evolved to traverse extreme obstacles such as waterfalls, dams provide a different series of challenges. These challenges may include water temperature gradients, increased predation, as well as unnatural sounds, vibrations and hydraulic conditions associated with hydroturbine (turbine) passage. The impacts of hydropower dams on fish passage has been researched for many years with significant improvements made over time; however, research continues at many hydropower facilities, particularly in the Pacific Northwest to improve survival of out migrating smolts as well as the success of upstream migrating adult salmon and steelhead. While improvements in upstream passage for adult salmonids has provided benefits to returning adults, downstream passage for all salmonids, particularly turbine passage, at Pacific Northwest dams is of concern for fisheries managers and researchers.

Among the different downstream passage routes available to anadromous fishes at hydropower dams (i. e. spillways, turbines, and bypass systems), estimates of survival through turbines are typically the lowest. In the mid-1950s the US Army Corps of Engineers (USACE) Walla Walla District began field studies of juvenile salmonid passage and survival (Schoeneman et al. 1955). The first physical turbine model testing efforts to improve juvenile fish passage were documented by Schoeneman et al. (1961) and Cramer and Oligher (1964). This included research to develop design criteria for high-head Francis turbines and to establish operations for Francis and Kaplan turbines that would reduce risk of injury to juvenile Chinook salmon (*Oncorhyncus tshawytscha*) and steelhead (*Oncorhyncus mykiss*; Cramer and Oligher 1964).

By the late 1990s, research provided an increased amount of information on turbine passage in the Columbia River Basin (CRB), largely in response to the need to protect declining salmon and steelhead stocks (Čada 2001). In 1997, the USACE formed the Turbine Survival Program (TSP) that was comprised of a team of mechanical and hydraulic engineers and fisheries biologists from USACE, Bonneville Power Administration, and the National Marine Fisheries Service (TSP 2004). The TSP was tasked with developing operational guidelines for the existing turbines and identifying and implementing biological criteria for the design of new turbines to improve fish passage survival (TSP 2004).

Advancements in technology have provided the USACE TSP and other researchers with the ability to characterize the turbine environment in terms of pressure, probability of physical strike, and hydraulic forces such as turbulence and shear. The magnitude of these forces may vary with different turbine designs and operations, but all have the potential to injure passing fish. These mechanisms of injury have been studied over the years, and reducing direct force injuries, such as blade strike, has been a primary goal in turbine design efforts (Čada and Rinehart 2000); however, pressure changes have been more difficult to address.

Negative effects of rapid pressure changes on turbine passed fish were identified as an issue by the USACE as early as 1960 (Cramer and Oligher 1960), but turbine pressure data were not readily available for correlating pressure changes to barotrauma (damage to fish due to changes in barometric pressures). In the late 1990s the development of the Sensor Fish made it possible for turbine pressures to be quantified and subsequently linked to barotrauma (Deng et al. 2007). The Sensor Fish (Fig. 1) is an autonomous device developed by the Pacific Northwest National Laboratory (PNNL) for the US Department of Energy and the USACE to better understand the physical conditions fish experience during passage through turbines, spillways, and alternative bypass routes (Deng et al. 2007). This device measures pressure and six angular accelerations capable of characterizing the turbine passage environment to provide evidence of shear forces, potential blade strike and pressure spikes. Pressure data collected by Sensor Fish has helped to quantify the pressure changes juvenile fish may experience when passing through turbines. This allows researchers to expose fish to realistic pressure scenarios and provide laboratory derived relationships between barotrauma injuries and pressure changes that are needed to guide turbine design and operation (Brown et al. 2012a, b).

This paper provides a detailed overview of turbine pressure data collection and barotrauma studies relative to fish passage through large Kaplan turbines (approximately $\geq$6.3 m dm) and how this information may be applied to achieve safer fish passage through turbines. Kaplan turbines are of propeller design with variable pitch blades to allow for a wider operating range (i. e. a greater range of flow through the turbine). Kaplan turbines are common in Pacific Northwest hydropower dams and have been installed within the eight lower Columbia and Snake River federal hydropower facilities, as well as facilities in New England such as Holyoke Dam on the Connecticut River. The majority of turbine pressure and barotrauma data available to date are for large Kaplan turbines. This data may not be applicable to smaller Kaplan, Francis, Pelton, or cross-flow turbine designs. The specific objectives of this paper are to (1) discuss Kaplan turbine pressures defined by Sensor Fish releases; (2) discuss what has been learned about pressure effects on salmonids and the factors influencing barotrauma associated with simulated turbine passage; (3)

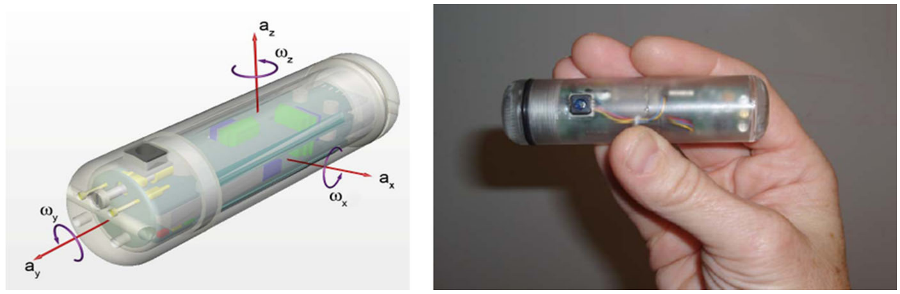


**Fig. 1** Sensor Fish device for characterizing fish passage environments at hydroelectric dams (Deng et al. 2007)

elucidate data gaps associated with fish behavior and passage that influence barotrauma during turbine passage; (4) discuss how the results of these studies have led to turbine design criteria for safer fish passage; and (5) relate this information to salmon recovery efforts and safer fish passage for both Pacific and Atlantic salmonids.

## Sensor Fish studies

The current Sensor Fish model's dimensions and weight are similar to a yearling salmon smolt (Fig. 1). It is 24.5 mm (mm) in diameter, 90 mm long, has a dry weight of 43 g, and is nearly neutrally buoyant in fresh water (slightly negatively buoyant). It provides in situ measurements of 3-dimensional (3D) accelerations, 3D rotational velocities, and pressure at a sample frequency of 2,000 Hz. The pressure–time profiles recorded by these autonomous devices (Fig. 2) provide evidence of pressures throughout the turbine environment.

Sensor Fish are typically released directly into turbine unit intakes and record pressure (Fig. 2) and acceleration data. These data are indicative of the forces fish may encounter as they pass specific regions within the turbine environment. Data collection begins as the Sensor Fish enters the turbine intake from the release pipe. Sensor Fish data indicates that pressure steadily increases as water flow transitions through the scroll case and enters the stay vane and wicket gate assembly (also known as the distributor which directs and controls flow through the turbine; Fig. 3), then drops rapidly as the flow passes through the runner region (turbine blade and hub assembly; Fig. 3). The bottom side of the turbine runner blade is termed the "suction side" where pressure drops to the lowest point referred to as the pressure "nadir". Pressure then

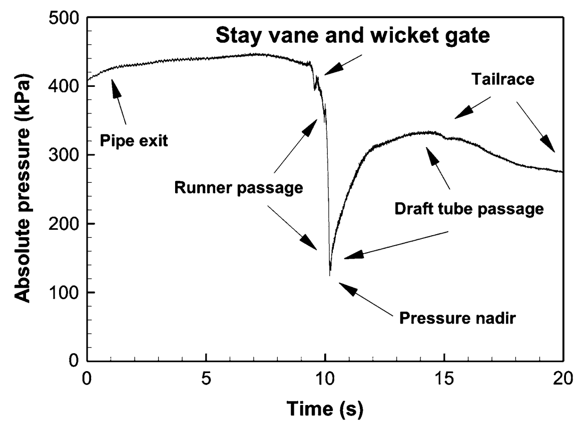


**Fig. 2** An example of the turbine pressure–time profile acquired using a Sensor Fish at Ice Harbor Dam (data from Carlson et al. 2008)

begins to increase as water flows into the draft tube elbow and may climb back up to near atmospheric pressure as water flows through and exits the draft tube.

Over the past 10 years, the Sensor Fish has been used widely in the CRB to evaluate turbine design and operating alternatives. Recent investigations have been conducted at the Bonneville Dam powerhouse II (BON II), and at John Day (JDA) and Ice Harbor dams (IHR; Carlson et al. 2008). Sensor Fish are released at controlled elevations which influence turbine passage routes and thus pressure conditions. Targeted passage routes include the runner hub region, mid-blade region, and blade-tip region. Defined passage routes are of interest as the pressure magnitude and rate of change will vary across and between the runner blades. Pressure distribution, magnitude and rate of change will also vary by turbine operation where higher turbine discharges typically provide lower nadir pressures (lowest recorded pressure) that are more widely distributed compared to lower discharge operations. Finally, pressure distribution,

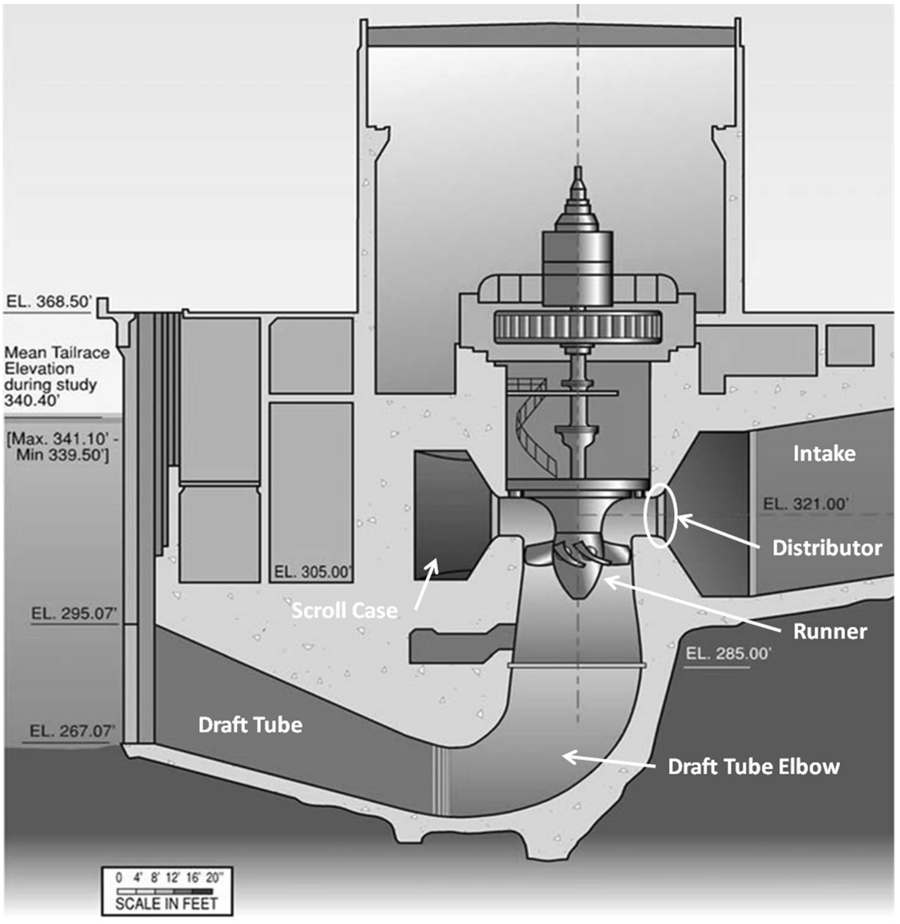


**Fig. 3** Cross section of Ice Harbor turbine unit 2 (Carlson et al. 2008). Elevations provided in feet above mean sea level

magnitude and rate of change are design dependent and will vary with changes in total project head (forebay-tailrace water surface elevation differential) and turbine runner submergence (depth the turbine runner is set below the tailrace water surface elevation). As discharge through the turbine runner increases, the nadir pressure observed for a single Sensor Fish passage decreases, thus increasing the rate of pressure change (Carlson et al. 2008; Deng et al. 2010; Fig. 2).

A wide range of operations have been tested using Sensor Fish at BON II, JDA and IHR because different hydraulic conditions exist for different operations, turbine designs, and dams (Carlson et al. 2008). The TSP has tested and defined operations for fish passage within ±1 % of peak turbine power generating efficiency, at peak efficiency, at best stay vane-wicket gate-Kaplan blade geometry, and at the maximum power generating limit for lower Columbia and Snake River dams (Wittinger et al. 2010). Maximum power generating limit typically occurs beyond the upper 1 % of peak efficiency and may differ among hydropower facilities dependent upon facility configuration, head, and turbine design. Different operating points equate to different wicket gate and turbine blade angles that influence the amount of flow through the turbine runner. Manipulating operations and subsequent geometries of these parts within the turbine environment can influence fish passage injury and survival (Wittinger et al. 2010).

A total of 719 Sensor Fish datasets were collected at BON II, JDA and IHR. While the sample sizes for any one set of conditions were too few to properly describe the full distribution of nadir pressures, the lowest nadir pressures were observed under the upper 1 % operation, and the highest nadirs were observed under the lower 1 % operation. Nadir pressures of 0 kPa (vapor pressure) were reported for JDA and IHR at the upper

1 %; however, these low nadirs were outliers relative to the full dataset which indicated that the vast majority of nadirs were greater than 50 kPa. Sensor Fish data indicate that the highest rates of pressure change (approximately 4,8260 kPa/s) were observed at IHR upper 1 % operation and the lowest (approximately 345 kPa/s) were observed at BON II lower 1 % operation.

Low pressures, such as those observed by Sensor Fish during turbine passage, have been identified as harmful to juvenile salmonids; however, the rate of pressure change is also important for understanding the effects of pressure on these fish. Research using data collected by Sensor Fish has made it possible to evaluate the pressure effects of turbine passage on smolt injury and survival in a controlled environment. Applying Sensor Fish pressure–time profiles in a laboratory setting allows researchers to simulate turbine pressure and evaluate smolt responses to a range of nadir pressures and rates of pressure change.

## Simulated turbine passage

Studies exposing fish in a laboratory setting to realistic pressure–time profiles associated with turbine passage are referred to as simulated turbine passage (STP). The goal of STP studies is to evaluate barotrauma experienced by fish passing turbines under a wide range of pressure scenarios. Over the past decade, the TSP has presided over a majority of the STP research that has been completed. This research has been conducted using a series of pressure testing devices that have evolved from the original chambers described by Abernethy et al. (2001, 2002, 2003) and Brown et al. (2009) to the much more complex system described by Stephenson et al. (2010). The results of these studies have provided information on the types of barotraumas that occur during turbine passage as well as the mechanisms that drive them.

In STP research projects, fish are typically acclimated for a period of 16–24 h in pressure chambers before exposure to the pressure profiles (Abernethy et al. 2001, 2002, 2003; Becker et al. 2003; Brown et al. 2009, 2012a, b). Appropriate acclimation provides depth equivalent pressure allowing fish to attain neutral buoyancy, as well as allowing the levels of dissolved gas in the blood and tissues to reach that of the surrounding water; hence, fish that are not neutrally buoyant are not considered to be acclimated. Salmonids are physostomous (having an opening between the throat and the swim bladder via the pneumatic duct) and most require access to air at the surface to fill their swim bladders to attain neutral buoyancy (Hogan 1941; Brown et al. 2009, 2012a, b). The buoyancy of test fish and the mass of air within the fish bladder is important and will affect the results of STP studies. Stephenson et al. (2010) noted that among juvenile Chinook salmon exposed to a given STP scenario, fish that were neutrally buoyant had much higher injury and mortality rates than those that were negatively buoyant. This was due to the higher amount of gas in the swim bladder of neutrally buoyant fish, which in turn led to a higher level of mortality due to swim bladder expansion and rupture and other associated barotrauma injuries (Brown et al. 2012e).

Brown et al. (2012e) recently determined the major factor influencing barotrauma in turbine passed fish is the expansion and rupture of the swim bladder. This was determined by slowly (over the course of 2.2–2.4 min) decompressing juvenile Chinook salmon to very low pressures (13.8 kPa). Since juvenile salmon are physostomous they are able to expel the gas from their swim bladder as it expands upon decompression. In these tests, all juvenile Chinook salmon expelled gases via the pneumatic duct and no mortalities or injuries were observed following slow decompression and recompression to surface pressures. However, research suggests that when juvenile Chinook salmon are rapidly decompressed to the same low pressures, mortality may be ≥80 % (Brown et al. 2012b, c; Fig. 4).

The ratio of pressure change (the acclimation pressure divided by the pressure nadir during turbine passage) is a critical metric for understanding barotrauma. Studies have found that higher ratios of pressure change lead to an increased probability of mortal injury (Brown et al. 2012b, e; Fig. 4). This ratio pressure change also makes it simple to understand injury due to swim bladder expansion and rupture. According to Boyle's Law (Van Heuvelen 1982) a decrease in pressure by ½ is equal to a ratio pressure change of 2 and also an expansion of the swim bladder by a factor of 2. For example, if a fish passing through a turbine goes from surface pressure (101 kPa) prior to turbine passage to a nadir pressure that is half of surface pressure (50.5 kPa) the volume of the

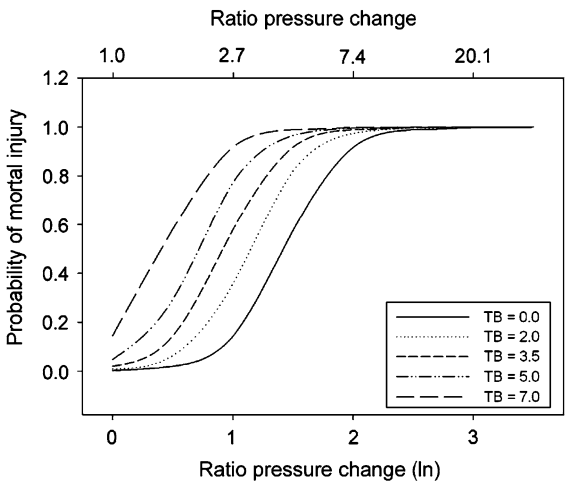


**Fig. 4** Probability of mortal injury and associated tag burden for juvenile Chinook salmon defined by the natural log or the ratio of pressure change (Carlson et al. 2012)

pre-existing gas in the body doubles. Under rapid decompression scenarios such as turbine passage, larger increases in the volume of the swim bladder lead to a much greater risk of barotrauma.

Further exacerbating the complexity of barotrauma is tag burden. Research funded by the TSP has made it clear that turbine passage survival studies that use fish internally implanted with radio or acoustic transmitters may overestimate turbine passage mortality. Carlson et al. (2012) found that fish internally implanted with transmitters had higher rates of injury and mortality when exposed to STP compared to their untagged conspecifics. Tagged fish may increase gas bladder volume to account for added tag mass to maintain neutral buoyancy, thus increasing the associated risk of swim bladder rupture. As the tag burden (tag mass proportional to fish mass) increased, the likelihood of bias in survival estimates also increased (Fig. 4).

## Discussion

Pressure profiles, including nadir pressures, provided by Sensor Fish have been a critical component of the research relating pressure changes to injury and mortality associated with turbine passage. Understanding the magnitude of pressure changes that occur during turbine passage has provided a basis for laboratory research. Although it was known that pressure changes contribute to mortality prior to the invention of the Sensor Fish (Cramer and Oligher 1960), the ability to precisely record the turbine pressure profile for research was likely not possible.

Although Sensor Fish have provided researchers with the ability to understand and recreate turbine pressures, Sensor Fish only sample a proportion of pressure–time profiles that may occur within the turbine environment. To appropriately assess the risk of barotrauma to fish, the probability of exposures to nadir pressure must be defined. Adequate data representative of the entire turbine passage region and associated pressure distribution, and the probability of exposure to adverse nadir pressures and high rates of change are required. Further research to correlate Sensor Fish data with computational fluid dynamics (CFD) models is recommended and may lead to a more comprehensive model to evaluate the probability of barotrauma that a given fish may experience during any given turbine passage event.

Studies of STP have provided a very detailed look into the factors and mechanisms associated with barotrauma and the probability of mortality and injury during turbine passage; however, the accuracy and usefulness of study results are dependent on appropriate acclimation of study fish (Tsvetkov et al. 1972; Brown et al. 2009, 2012b) as well as the ability to determine the probability of exposure to various turbine pressures. Unfortunately, a large amount of work investigating the effects of rapid pressure changes on fish has been conducted without consideration of neutrally buoyant acclimation (Abernethy et al. 2001, 2002, 2003).This research was conducted by holding fish under pressure in an effort to allow acclimation; however, study fish did not have access to air and could not inflate the swim bladder to acquire neutral buoyancy during the acclimation period. Thus, care should be taken when interpreting a wide variety of both laboratory and field based research to ensure fish were properly acclimated to a depth range that is representative of fish approaching the turbines and were neutrally buoyant prior to testing (Tsvetkov et al. 1972; Pflugrath et al. 2012).

Reducing bias in turbine survival estimates resulting from field studies is important for understanding accurate and realistic turbine passage survival. Accurate survival estimates are required to understand baseline conditions and identify the goals for improvement in new turbine designs, and also to accurately evaluate new turbine designs. One factor which could lead to inaccuracies in turbine survival estimates, such as tag burden, may be mitigated through research and development of smaller and/or external neutrally buoyant transmitters. The effects of tag burden on survival as suggested by Carlson et al. (2012) led to the development of a new externally attached, neutrally buoyant acoustic transmitter which had a tag burden of 0 % (no added mass; Brown et al. 2012d; Deng et al. 2012; Janak et al. 2012). Recently completed field tests indicate that this type of transmitter has promise for single dam survival estimates (Brown et al. 2013).

Run timing may also play a role in the risk of barotrauma for turbine passed fish, particularly for subyearling Chinook salmon which migrate somewhat deeper in the water column than yearling Chinook salmon or steelhead smolts (Adams et al. 2011). Warmer water temperatures during the summer run may cause subyearlings to migrate deeper in the water column. Smolts acclimated to deeper depths may need to carry a greater quantity of gas molecules in the swim bladder to maintain the appropriate gas volume to achieve neutral buoyancy under higher pressure. Thus, these smolts are likely more susceptible to barotrauma (Brown et al. 2009, 2012a, b; Pflugrath et al. 2012) and typically survive at a lower rate than their larger spring run cohorts (Ham et al. 2008, 2009a, b, c, d).

As described above, the depth that fish are acclimated to as they approach turbines can influence their survival. Due to this importance, Pflugrath et al. (2012) examined the maximum depth that a juvenile Chinook salmon can attain neutral buoyancy. Their estimate of a median maximum acclimation depth of 6.7 m for juvenile Chinook salmon (Pflugrath et al. 2012) has been accepted as the best available data for maximum acclimation depth by the TSP for this species and is used for modeling the probability of mortal injury due to barotrauma for new turbine designs. A review of vertical distribution studies also suggests that 6.7 m is within the typical migration depth range for juvenile Chinook salmon; however, vertical distribution studies have provided limited information for sub yearling Chinook salmon (Smith et al. 2010). Furthermore, vertical distribution studies do not provide adequate behavior information on smolts prior to their entry into turbine intakes.

Smolt behavior as they approach the dam and enter the turbine intakes may influence pressure effects experienced when passing through the turbine runner region. As smolts enter a turbine intake and approach the turbine runner it is possible that a portion of these fish will evacuate the swim bladder prior to entering the turbine runner, and potentially during rapid decompression as observed by Brown et al. (2012e). A smolt that is neutrally buoyant at a given depth that retains the swim bladder gas volume during turbine passage is much more likely to experience barotrauma due to swim bladder expansion compared to a smolt that may have evacuated a portion or all of the swim bladder gas volume (Brown et al. 2012e). To date, no data known to the authors exists that may characterize smolt behavior in the turbine intake prior to entering the turbine runner. This data would prove to be useful in understanding and evaluating the risk of barotrauma to the run-of-river populations exposed to turbine passage.

Currently, it is possible to 3-D track smolts at the face of dams with Juvenile Salmonid Acoustic Telemetry System (JSATS) technology (McMichael et al. 2010; Deng et al. 2011a; Weiland et al. 2011a, b). These techniques can provide information about fish behavior prior to entering the turbine units. Although these types of data have not been thoroughly analyzed for this purpose to date in the CRB, efforts are currently being planned to conduct such analyses. Preliminary data analysis indicates that large depth changes can occur at the dam face and there may be some difficulty determining when fish are neutrally buoyant versus positively or negatively buoyant as they approach the turbine intakes. However, coupling behavior at the dam face with migration and acclimation depth (estimated with active hydroacoustics prior to fish entering the turbine) may provide insight into the depth distributions at which fish populations are neutral buoyant. This neutral buoyancy depth distribution is important for consideration in turbine passage risk assessments.

## Implications for turbine design

Sensor Fish data coupled with STP studies have provided a progressive way to approach turbine design and currently the USACE is designing new turbines for IHR to be safer for fish passage (Brown et al. 2012a). Considering pertinent information on turbine passage survival provided by research, the TSP has defined biological design criteria for new turbine runner development. The TSP has evaluated turbine passage using CFD models and 1:25 scale physical hydraulic turbine models to evaluate nadir pressures, water flow quality through the turbine runners (turbulence), and mechanical injury potential for juvenile salmonids (Davidson 2011). Although it is not possible to evaluate a physical turbine model with a 1:25 scale smolt, polyurethane beads of appropriate smolt scale are passed through the physical model and evaluated with high speed video for interactions with the flow field or physical boundary such as the turbine runner. The beads are neutrally buoyant (but do have mass allowing them to cross flow lines) and observations of the beads can provide evidence of direct blade strike, shear and turbulence. The combination of evaluation methods provide relative results that can be appropriately applied to the turbine design process.

While mitigating for mechanical injuries, such as shear and blade strike, has been the goal of more recent turbine designs (Dauble et al. 2005; Deng et al. 2011b), IHR replacement turbines are being designed using minimum nadir pressure criteria of approximately atmospheric pressure (101 kPa; Brown et al. 2012a). These turbine runners will be the first propeller and Kaplan runners to be installed in a federal CRB dam that have been designed to meet safe pressure criteria for fish passage. In addition to mortality and severe injury, nonlethal barotrauma may also provide a significant risk of indirect injury associated with turbine passage. Fish that are disoriented from exposure to low pressures during turbine passage may experience a greater risk of predation in the tailrace once they have exited the draft tubes. Therefore, minimizing nonlethal barotrauma is also a benefit for including pressure criteria in the design of new turbine runners to reduce the risk of predation on smolts and further improve turbine passage survival. Furthermore, preliminary turbine design evaluations suggest that biological design criteria may be met without significant impact to power generation and efficiency.

Maintaining nadir pressures to approximately atmospheric pressure in newly designed turbine runners will minimize the ratio of pressure change and greatly reduce the risk of barotrauma to outmigrating salmonid smolts (Brown et al. 2009, Brown et al. 2012a, b, d); however, it should be noted that one size does not fit all, so to speak. A particular turbine design that provides a pressure benefit at one facility may not be suitable for another. The specific configuration of a dam should be considered to design a turbine that will provide the greatest passage and survival benefit. Factors that influence turbine designs and must be addressed on a case-by-case basis include, but are not limited to turbine type, turbine runner speed (revolutions per minute), facility head, submergence, turbine orientation, flow quality and discharge and velocity through the runner. Each of these factors may be different at every facility and may greatly influence turbine design to provide safer fish passage.

## Implications for salmon recovery

Chinook salmon have been the most studied species for evaluating the effects of turbine pressure changes on salmonid smolts; however, improving turbine designs will provide a fish passage benefit to all salmonids. At the same time, further barotrauma research is encouraged for other salmonid and non-salmonid species and life stages.

Although little information is available on Atlantic salmon survival relative to turbine pressures, it may be possible for nadir pressures capable of injuring Atlantic salmon to occur at low head dams in the northeast US. Therefore, improved turbine designs will likely prove beneficial. Survival benefits from improved turbine design may be increased particularly when multiple turbine passages are common (Ham et al. 2005; Wertheimer and Evans 2005).

Downstream migration and survival studies have been conducted on Atlantic salmon smolts that are comparable in size (~170–210 mm) and run timing (April–May) to Pacific juvenile steelhead (Stier and Kynard 1986; Kosteki et al. 1987; Scruton et al. 2005; Holbrook et a. 2011). Survival estimates for turbine passed Atlantic salmon smolts range from approximately 70–100 % in northeast US rivers (Stier and Kynard 1986; Franke et al. 1997; Normandeau 1999; Normandeau and FPL 2002) which encompasses the range of survival of Pacific yearling Chinook salmon and steelhead in the CRB (Ham et al. 2008, 2009a, b, c, d; Normandeau and Skalski 2007). It should be noted that tag burden may bias these turbine survival estimates low (Carlson et al. 2012). Further, when interpreting results from field studies estimating survival of turbine passed salmonid smolts, it should be noted that some of these studies did not depth acclimate fish used for their research. While these studies may only provide a best case scenario for barotrauma, they still provide valuable information on injuries sustained from mechanisms such as shear and strike.

A large proportion of turbine passage barotrauma information is available for juvenile Chinook salmon only. While this information may be extrapolated to steelhead and Atlantic salmon smolts, further research on the effects of turbine pressure changes on these species is needed and is recommended to encompass facilities with lower head and river discharge relative to the federal CRB dams. Turbines designed for safer fish passage that minimize shear, turbulence, and strike in concert with optimal nadir pressure criteria may prove to be important to both Pacific and Atlantic salmon recovery efforts by improving overall smolt survival and subsequent adult returns. Holbrook et al. (2011) estimated reach survival for Atlantic salmon smolts to be as much as 43 % lower for river reaches containing dams. It may be possible that sub-lethal pressures occur at these dams leading to increased loss to predators such as striped bass (Blackwell and Juanes 1998). Although bypass systems at dams in the Pacific Northwest and New England have been designed to route the majority of migrating smolts away from turbines, increasing survival of the small proportion of salmon smolts passing turbines is important to the overall goals of recovery of ESA listed salmonids.

## Conclusion

Improving turbine passage survival may not recover endangered salmonids on its own merit; however, when coupled with other fish passage improvements, the added benefits are important for salmon recovery. Turbines designed for safer fish passage that reduce barotrauma will provide a fish passage and survival benefit for a variety of salmonid and non-salmonid species and hydropower installations. Providing a safer turbine passage route will lead to increased overall smolt survival and further progress toward the recovery of ESA-listed salmonids.

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## References

Abernethy CS, Amidan BG, Čada GF (2001) Laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish. Report of the Pacific Northwest National Laboratory, PNNL-1347, Richland, Washington

Abernethy CS, Amidan BG, Čada GF (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". Report of the Pacific Northwest National Laboratory, PNNL-13470-A, Richland, Washington

Abernethy CS, Amidan BG, Čada GF (2003) 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". Report of the Pacific Northwest National Laboratory, PNNL-13470-B, Richland, Washington

Adams NS, Evans SD, Eds (2011) Summary of juvenile salmonid passage and survival at McNary Dam-acoustic survival studies, 2006–2009. US Geological Survey Open-File Report 2011–1179

Becker JM, Abernethy CS, Dauble DD (2003) Identifying the effects on fish of changes in water pressure during turbine passage. Hydro Rev. September, 2003

Blackwell BF, Juanes F (1998) Predation on Atlantic salmon smolts by striped bass after dam passage. N Am J Fish Manag 18:936–939

Brown RS, Carlson TJ, Welch AE, Stephenson JR, Abernethy CS, Ebberts BD, Langeslay MJ, Ahmann ML, Feil DH, Skalski JR, Townsend RL (2009) Assessment of barotrauma from rapid decompression of depth-acclimated juvenile Chinook salmon bearing radio telemetry transmitters. Trans Am Fish Soc 138(6):1285–1301

Brown RS, Ahmann ML, Trumbo BA, Foust J (2012a) Cooperative research advances fish-friendly turbine design. Hydro Rev 31(8):48–53

Brown RS, Carlson TJ, Gingerich AJ, Stephenson JR, Pflugrath BD, Welch AE, Langeslay MJ, Ahmann ML, Johnson RL, Skalski JR, Seaburg AG, Townsend RL (2012b) Quantifying mortal injury of juvenile Chinook salmon exposed to simulated hydro-turbine passage. Trans Am Fish Soc 141(1):147–157

Brown RS, Carlson TJ, Gingerich AJ, Stephenson JR, Pflugrath BD, Welch AE, Langeslay ML, Ahmann ML, Johnson RL, Skalski JR, Seaburg AG, Townsend RL (2012c) Erratum: Quantifying mortal injury of juvenile Chinook salmon exposed to simulated hydro-turbine passage. Trans Am Fish Soc 141(1):147–157 Equation 5 on Page 152 should read as present in the Erratum. Equation 5 should read as updated in 141:570

Brown RS, Pflugrath BD, Carlson TJ, Deng ZD (2012d) The effect of an externally attached neutrally buoyant transmitter on mortal injury during simulated turbine passage. J Renew Sustain Energy 4:013107. doi:10.1063/1.3682062

Brown RS, Pflugrath BD, Colotelo AH, Brauner CJ, Carlson TJ, Deng ZD, Seaburg AG (2012e) Pathways of barotrauma in juvenile salmonids exposed to simulated hydroturbine passage: Boyle's Law vs Henry's Law. Fish Res 121–122:43–50

Brown RS, Deng ZD, Cook KV, Pflugrath BD, Li X, Fu T, Martinez JJ, Li H, Trumbo BA, Ahmann ML, Seaburg AG (2013) A field evaluation of an external and neutrally buoyant acoustic transmitter for juvenile salmon: implications for estimating hydroturbine passage survival. Plos One 8(10):e77744. doi:10.1371/journal.pone.0077744

Brownell P, Haro A, McDermott S, Blott A, Rohde F (2012) Diadromous fish passage: a primer on technology, planning, and design for the Atlantic and Gulf coasts. Report of the National Marine Fisheries Service and the US Geological Survey Conte Anadromous Fish Research Center

Čada GF (2001) The development of advanced hydroelectric turbines to improve fish passage survival. Fisheries 26(9):14–23

Čada GF, Rinehart BN (2000) Hydropower R&D: recent advances in turbine passage technology. Report of the Oak Ridge National Laboratory and the Idaho National Engineering and Environmental Laboratory to the US Department of Energy, Idaho Operations Office

Carlson TJ, Duncan JP, Deng Z (2008) Data overview for sensor fish samples acquired at Ice Harbor, John Day, and Bonneville II Dams in 2005, 2006, and 2007. Report of the Pacific Northwest National Laboratory to the US Army Corps of Engineers, Portland, Oregon, under Contract DE-AC05-76RL01830

Carlson TJ, Brown RS, Stephenson JR, Pflugrath BD, Colotelo AH, Gingerich AJ, Benjamin PL (2012) The influence of tag presence on the mortal injury of juvenile chinook salmon exposed to simulated hydroturbine passage: implications for survival estimates and management of hydroelectric facilities. N Am J Fish Manag 32:249–261

Cramer FK, Oligher RC (1960) Progress report no. 2, fish passage through turbines: test at Cushman No. 2 hydro-electric plant. Report of the US Army Corps of Engineers, Walla Walla, Washington

Cramer FK, Oligher RC (1964) Passing fish through hydraulic turbines. Trans Am Fish Soc 93(3):243–259

Dauble DD, Deng ZD, Richmond MC, Moursund RA, Carlson TJ, Rakowski CL, Duncan JP (2005) Biological assessment of the advanced turbine design at Wanapum Dam, 2005. Report of the Pacific Northwest National Laboratory for the US Department of Energy, under Contract DE-AC05-76RL01830

Davidson R (2011) Physical modeling methods and techniques. Pages 179–185 in Proceedings of EPRI-DOE Conference on Environmentally-Enhanced Hydro Turbines. Washington, DC, 19–20 May, 2011 (Electric Power Research Institute, Palo Alto, CA 2011)

Deng Z, Carlson TJ, Duncan JP, Richmond MC (2007) Six-degree-of-freedom Sensor Fish design and instrumentation. Sensors 7(12):3399–3415

Deng Z, Carlson TJ, Duncan JP, Richmond MC, Dauble DD (2010) Use of an autonomous sensor to evaluate the biological performance of the advanced turbine at Wanapum Dam. J Renew Sustain Energy 2:053104

Deng Z, Weiland MA, Fu T, Seim TA, Lamarche BL, Choi EY, Carlson TJ, Eppard MB (2011a) A cabled acoustic telemetry system for detecting and tracking juvenile salmon: part 2. Three-dimensional tracking and passage outcomes. Sensors 11(6):5661–5676

Deng ZD, Carlson TJ, Dauble DD, Ploskey GR (2011b) Fish passage assessment of advanced hydropower turbine and conventional turbine using blade-strike modeling. Energies 4:57–67

Deng ZD, Martinez JJ, Colotelo AH, Abel TK, LeBarge AP, Brown RS, Pflugrath BD, Mueller RP, Carlson TJ, Seaburg AG, Johnson RL, Ahmann ML (2012) Development of external and neutrally buoyant acoustic transmitters for juvenile salmon turbine passage evaluation. Fish Res 113(1):94–105

Franke GF, Webb DR, Fisher RK, Mathur D, Hopping PN, March PA, Hedrick MR, Laczo IT, Ventikos Y, Sotiropoulious F (1997) Development of environmentally advanced hydroturbine system concepts. Report prepared for the Department of Energy under Contract DE-AC07-96ID13382

Ham KD, Anderson JJ, Vucelick JA (2005) Effect of multiple turbine passage on juvenile Snake River salmonid survival. Report of the Pacific Northwest National Laboratory to the US Department of Energy under Contract DE-AC05-76RL01830

Ham KD, Arimescu CII, Simmons MA, Duncan JP, Chamness MA (2008) Synthesis of biological research on juvenile fish passage and survival 1990–2006: Lower Granite Dam. Report of the Pacific Northwest National Laboratory to the US Army Corps of Engineers, Walla Walla, Washington, under Contract W9127 N-06-D-005, delivery Order 0002

Ham KD, Arimescu CII, Simmons MA, Duncan JP, Chamness MA, Solcz A (2009a) Synthesis of biological research on juvenile fish passage and survival 1990–2006: Ice Harbor Dam. Report of the Pacific Northwest National Laboratory to the US Army Corps of Engineers, Walla Walla, Washington, under Contract W9127 N-06-D-005, delivery Order 0002

Ham KD, Arimescu CII, Simmons MA, Duncan JP, Chamness MA, Solcz A (2009b) Synthesis of biological research on juvenile fish passage and survival 1990–2006: Little Goose Dam. Report of the Pacific Northwest National Laboratory to the US Army Corps of Engineers, Walla Walla, Washington, under Contract W9127 N-06-D-005, delivery Order 0002

Ham KD, Arimescu CII, Simmons MA, Duncan JP, Chamness MA, Solcz A (2009c) Synthesis of biological research on juvenile fish passage and survival 1990–2006: Lower Monumental Dam. Report of the Pacific Northwest National Laboratory to the US Army Corps of Engineers, Walla Walla, Washington, under Contract W9127 N-06-D-005, delivery Order 0002

Ham KD, Arimescu CII, Simmons MA, Duncan JP, Chamness MA, Solcz A (2009d) Synthesis of biological research on juvenile fish passage and survival 1990–2006: McNary Dam. Report of the Pacific Northwest National Laboratory to the US Army Corps of Engineers, Walla Walla, Washington, under Contract W9127 N-06-D-005, delivery Order 0002

Hogan J (1941) The effects of high vacuum on fish. Trans Am Fish Soc 70(1):469–474

Holbrook CM, Kinnison MT, Zydlewski Z (2011) Survival of Atlantic salmon smolts through the Penobscot River, Maine: a prerestoration assessment. Trans Am Fish Soc 140:1255–1268

Janak JM, Brown RS, Colotelo AH, Pflugrath BD, Stephenson JR, Deng ZD, Carlson TJ, Seaburg AG (2012) The effects of neutrally buoyant, externally attached transmitters on swimming performance and predator avoidance of juvenile Chinook salmon. Trans Am Fish Soc 141(5):1424–1432

Kosteki PT, Clifford P, Gloss SP, Carlisle JC (1987) Scale loss in smolts of Atlantic salmon (*Salmo salar*) after turbine passage. Can J Aquat Sci 44:210–214

McMichael GA, Eppard MB, Carlson TJ, Carter JA, Ebberts BD, Brown RS, Weiland M, Ploskey GR, Harnish RA, Deng ZD (2010) The juvenile salmon acoustic telemetry system: a new tool. Fisheries 35(1):9–22

(Normandeau) Normandeau Associates (1999) Atlantic salmon passage route and survival at the West Buxton Project, Saco River, Maine. Report prepared for FPL Energy Maine Hydro, LLC. Portland, Maine

(Normandeau and FPL) Normandeau Associates, FPL Energy Maine Hydro, LLC (2002) Atlantic salmon passage route and survival at the Bar Mills Project; Saco River, Maine. Report prepared for FPL Energy Maine Hydro, LLC. Portland, Maine

(Normandeau) Normandeau Associates, Skalski JR (2007) Survival/Condition of Chinook salmon smolts under different turbine operations at John Day Dam, Columbia River. Report of Normandeau Associates to the US Army Corps of Engineers, Walla Walla, Washington, under Contract DACW68-02-D-0002, Task Order 24

Pflugrath BD, Brown RS, Carlson TJ (2012) Maximum neutral buoyancy depth of juvenile Chinook salmon: implications for survival during hydroturbine passage. Trans Am Fish Soc 141:520–525

Schoeneman DE, Junge CO, Bostick WE, Meekin TK (1955) Research relating to mortality of downstream migrant salmon passing McNary Dam. Report of the State of Washington Department of Fisheries to the US Army Corps of Engineers under Contract DA.30526-ENG-20893

Schoeneman DE, Pressey RT, Junge CO Jr (1961) Mortalities of downstream migrant salmon at McNary Dam. Trans Am Fish Soc 90(1):58–72

Scruton DA, Penell CJ, Robertson MJ, Clarke KD, Eddy W, McKinley RS (2005) Telemetry studies of the passage route and entrainment of downstream migrating wild Atlantic salmon (*Salmo salar*) smolts at two hydroelectric installations on the Exploits River, Newfoundland, Canada. Proceedings of the Fifth Conference on Fish Telemetry, Ustica, Italy

Smith DL, Nestler JM, Johnson GE, Goodwin RA (2010) Species-specific spatial and temporal distribution patterns of emigrating juvenile salmonids in the Pacific Northwest. Rev Fish Sci 18(1):40–64

Stephenson JR, Gingerich AJ, Brown RS, Pflugrath BD, Deng Z, Carlson TJ, Langeslay MJ, Ahmann ML, Johnson RL, Seaburg AJ (2010) Assessing barotrauma in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory. Fish Res 106:271–278

Stier DJ, Kynard B (1986) Use of radio telemetry to determine the mortality of Atlantic salmon smolts passing through a 17-MW Kaplan turbine at a low-head hydroelectric dam. Trans Am Fish Soc 115(5):771–775

(TSP) Turbine Survival Program (2004) Phase I report 1997–2003. Report of Turbine Survival Program and Hydroelectric Design Center, US Army Corps of Engineers, Portland and Walla Walla Districts

Tsvetkov VI, Pavlov DS, Nezdoliy VK (1972) Changes of hydrostatic pressure lethal to young of some freshwater fish. J Ichthyol 12:307–318

Van Heuvelen A (1982) Physics: a general introduction. Little, Brown and Co., Boston, MA

Weiland MA, Deng Z, Seim TA, Lamarche BL, Choi EY, Fu T, Carlson TJ, Thronas AI, Eppard MB (2011a) A cabled acoustic telemetry system for detecting and tracking juvenile salmon: part 1. Engineering design and instrumentation. Sensors 11(6):5645–5660

Weiland MA, Deng Z, Seim TA, Lamarche BL, Choi EY, Fu T, Carlson TJ, Thronas AI, Eppard MB (2011b) A cabled acoustic telemetry system for detecting and tracking juvenile salmon: part 1. Engineering design and instrumentation. Sensors 11(6):5645–5660

Wertheimer RH, Evans AF (2005) Downstream passage of steelhead kelts through hydroelectric dams on the lower Snake and Columbia Rivers. Trans Am Fish Soc 134:853–865

Wittinger RJ, Sollars R, Hsieh C (2010) Columbia and Snake River turbines stay vane and wicket gate geometry study. Report of the US Army Corps of Engineers Hydroelectric Design Center, Portland