Identifying the Effects on Fish of Changes In Water Pressure during Turbine Passage

The Pacific Northwest National Laboratory has conducted experiments to determine how water pressure and dissolved gas levels associated with hydroelectric facilities may affect the survival of fish. What are the results of the experiments, and what do these results mean to turbine designers and hydro project managers?

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The survival of fish passing dams remains one of the most important environmental issues for hydroelectric power production. Fish are exposed to many stresses during dam passage that are not encountered in natural, unimpounded rivers. These include rapid and extreme water pressure changes in turbine systems and excessive levels of dissolved gas due to water being spilled, both of which may cause mortality to fish.

Jim Becker, a research scientist at Pacific Northwest National Laboratory (PNNL), synthesized data from turbine passage experiments with respect to its application to turbine operation and design. Scott Abernethy operates the aquatic laboratory at PNNL. He conducted the turbine passage experiments and analyzed the data. Dennis Dauble, PhD, director of PNNL's Natural Resources Division, oversaw the turbine passage experiments and provided valuable insight into application of the data.

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In unimpounded rivers, fish experience water pressures ranging from near one atmosphere — approximately 100 kilopascals (kPa) (or 14.7 pounds per square inch) — at the surface to about two atmospheres at a depth of 30 feet. Dissolved gases normally are at or below 100 percent saturation.[1] In contrast, fish may be exposed to pressure changes of four atmospheres or more within turbine systems and to dissolved gas levels in excess of 130 percent of saturation below dams and above dams where there are multiple impoundments.

Researchers who reviewed studies of the effects of water pressure changes and dissolved gas supersaturation on fish concluded that additional studies were needed of the direct effects of pressure changes on fish during turbine passage under varying dissolved gas concentrations.[1,2,3]

To address these issues, we designed and conducted laboratory experiments for the U.S. Department of Energy's Advanced Hydropower Turbine Systems Program. Our objective was to determine how changes in water pressure and dissolved gas levels associated with hydroelectric facilities may affect the survival of fish. We simulated fish passage under pressure scenarios representing two types of turbines and total dissolved gas (TDG) levels typical of hydroelectric projects in the Columbia River Basin.

Conditions at Columbia Basin hydropower projects

The vertical Kaplan turbine is an axial, adjustable pitch, propeller-type turbine typically used at low- to medium-head dams. Kaplan turbines account for 31 percent of the total hydroelectric generation capacity and 57 percent of the discharge for the West Coast. (Francis turbines dominate hydro generation in the East and upper Midwest.) The Kaplan turbine is the turbine type typically associated with passage issues for Pacific salmon in California, Oregon, Washington, and Idaho.[4] The Kaplan turbine is used exclusively at dams on the lower Columbia and Snake rivers.

The bulb turbine is a horizontally mounted, Kaplan-type turbine that is much less frequently employed, and is used on lower-head dams. As of 1995, nine dams used bulb turbines in the U.S., three in the Pacific Northwest, including Rock Island Dam on the middle Columbia River, and the rest in the eastern U.S. Because the bulb turbine operates horizontally in low-head situations, flow velocities are reduced, increasing the time required for fish passage. We selected the bulb turbine to compare with the Kaplan to observe the trade-off between the lower pressure gradient and higher exposure time created by the former with the higher pressure gradient and shorter exposure time created by the latter.

The Kaplan turbine is used here to illustrate the most extreme changes in water pressure that could be experienced by fish during the juvenile salmon emigration. For example, at 980-MW McNary Dam on the Columbia River, the most extreme pressure changes would be expected for fish acclimated at an elevation near the intake ceiling of a Kaplan turbine and that subsequently pass along the bottom side of the blade near its tip. In this case, pressure would increase in less than one second from

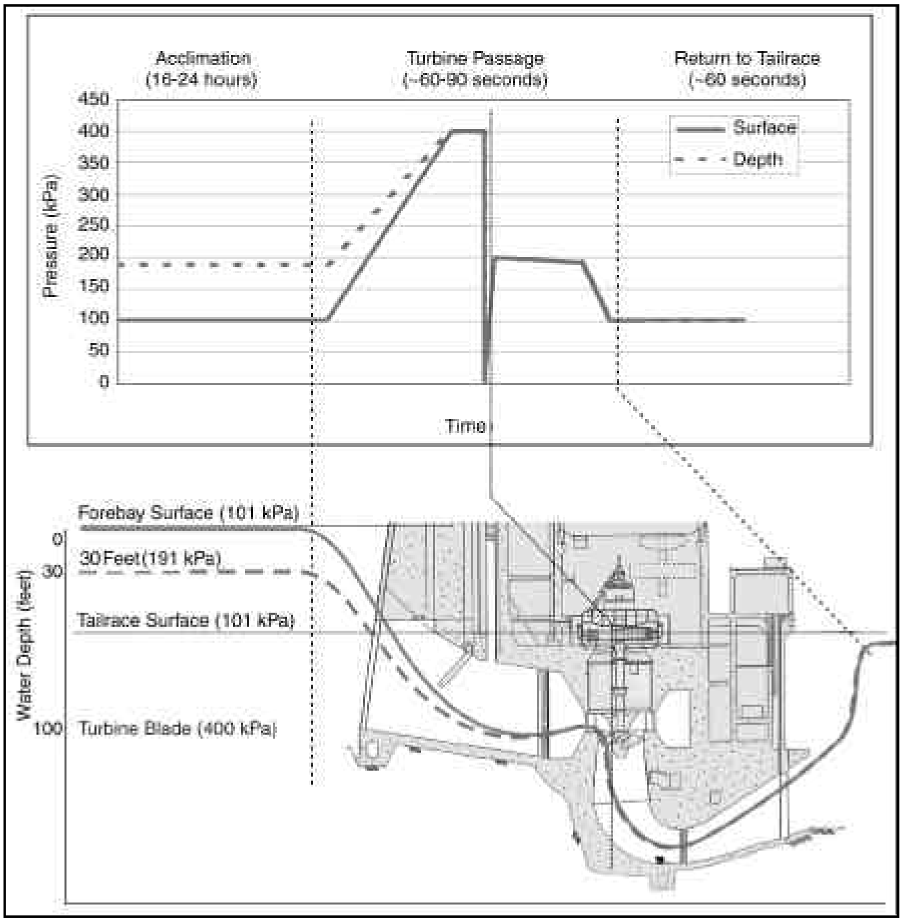

Figure 1: This graph/drawing tracks simulated fish passage through a Kaplan turbine during research conducted by scientists at the Pacific Northwest National Laboratory. Test fish — surface- or depth-acclimated for 16 to 24 hours — move through the turbine in 60 to 90 seconds and into the tailrace in approximately 60 seconds. The upper graph shows the rapid pressure changes the fish undergo.

about 200 kPa (about two atmospheres) at the intake ceiling to about 340 kPa (about 3.4 atmospheres) approaching the runner, and then decrease to 2 kPa (slightly above zero atmosphere) near the blade tip. Although the entire blade generally is subject to the same water pressure due to equal submergence, the lowest pressure (nadir) occurs in the leakage vortex at the bottom of the blade near its tip (representing several percent of the blade cross-sectional area). Exposure to the 2-kPa nadir is estimated to last no more than 0.25 second before pressure rapidly returns to near atmospheric in the draft tube and tailwaters.[5] The rapid decrease in pressure to sub-atmospheric can cause a corresponding increase in the volume of gases entrained in a fish's swim bladder and blood. (Boyle's Law: If the volume of a container is decreased, the pressure increases.) This exposure may result in injury or mortality.

Total dissolved gas levels from 115 to 143 percent have occurred in the Columbia and Snake rivers during periods of high spilling.[6] Dissolved gas supersaturation problems were first identified in the 1960s, but declined in the 1970s and 1980s owing to the installation of turbines, spill deflectors, and generally low levels of precipitation and runoff.[1,6] However, with the increased use of spill in the 1990s to enhance downstream juvenile salmon passage, gas supersaturation has once again become a problem.[1] Water that is supersaturated with dissolved nitrogen is known to cause gas bubble trauma (GBT) in fish.[1,6] Further, dissolved gas supersaturation may exacerbate the trauma that may result from the rapid decreases in water pressure that occur during turbine passage.

Simulating conditions during turbine passage

Our turbine passage system consisted of two acrylic exposure chambers — 27.5 centimeters in diameter, 55 centimeters long, and with a volume of 34 liters. The chambers were pressurized using computer software (Labtech Control Version 4.2.0 for Microsoft Windows, Laboratory Technologies Corporation). The mechanics of the turbine passage and gas supersaturation systems are described in detail in the documents cited in Notes 5 and 12. The water delivery system is described in Note 7.

The pressure scenarios for which we simulated fish passage were considered representative of Kaplan and bulb turbines, as follows.

Kaplan turbine: We simulated passage of juvenile fall chinook salmon, rainbow trout, and bluegill in an experiment that consisted of twelve conditions. In six of these, the nadir of the turbine pressure spike was near zero (2 to 10 kPa).[7] This represented the most extreme nadir that could be experienced by fish passing hydroelectric projects in the Columbia Basin during the juvenile salmon migration. In the other six conditions, a modified, less severe nadir (50 kPa) was simulated.[8] This represented the minimal pressure at which turbines generally are operated to avoid the risk of cavitation (i.e., formation of gas bubbles in a liquid caused by a localized reduction in pressure to a point at or below the vapor pressure), which can damage turbomachinery and injure fish.[4]

Fish exposed to both nadirs were either surface-acclimated (about 101 kPa) or depth-acclimated (about 191 kPa) and exposed to one of three levels of total dissolved gas levels — 100 percent, 120 percent, or 135 percent — for from 16 to 24 hours. Each test condition was replicated three times with 20 fish, except for surface-acclimated fish exposed to 135 percent TDG, in which only two replicates of 20 fish were used due to high levels of gas bubble trauma-induced mortality during acclimation.

During the sequence, water pressure increased from acclimation (either about 101 kPa or about 191 kPa) to about 400 kPa over 30 to 60 seconds to simulate fish entering the turbine intake and approaching the runner. Fish were then subjected to a sudden (0.1 second) decrease in pressure to 2 to 10 kPa (chinook salmon, rainbow trout, and bluegill) or about 50 kPa (chinook salmon and blue-gill) and a corresponding (0.1 second) increase to about 191 kPa before returning to surface pressure. Figure 1 shows the pressure changes and time lapses during this simulated passage.

Bulb turbine: We simulated passage of fall chinook salmon and blue-gill in an experiment that consisted of four conditions. In two of these, the nadir of the turbine pressure spike was about 68 kPa, a value that was estimated for Racine Dam, located on the Ohio River, at 16,000 cubic feet per second (cfs) in a bottom, centerline passage route representative of the majority of the turbine cross-sectional area. The 68 kPa did not represent the most extreme nadir. (The worst-case nadir would likely be similar to that of the Kaplan. It would be experienced in the upper portion of the turbine blades where submergence pressures are least, and would probably occupy only several percent of the blade cross-sectional area.) In the other two conditions, a less severe nadir (95 kPa) was simulated.

Fish exposed to both pressure spike scenarios were either surface- (101 kPa) or depth-acclimated (30 feet depth at 191 kPa), and all fish were held at a total dissolved gas level of 100 percent (i.e., the additional effects of gas supersaturation were not tested) during acclimation. Each test condition was replicated three times with 20 fish each. During the sequence, pressure increased from acclimation pressures (either 101 kPa or 191 kPa) to 220 kPa over 30 to 60 seconds to simulate fish entering the turbine intake and approaching the runner. Fish were then subjected to a sudden (0.8 sec) decrease in pressure to 68 kPa or 95 kPa and a corresponding (0.8 sec) increase to 191 kPa before returning to surface pressure.

Biological effects

We found that fall chinook salmon, rainbow trout, and bluegill experienced a range of survival and types of injuries resulting from specific pressure changes as well as from pressure changes with total dissolved gas levels as an additive factor. Further, such effects may be amplified or diminished by depth acclimation.

Fall chinook salmon

Nadir of 2 to 10 kPa: Five percent of depth-acclimated fish at 120 and 135 percent TDG died from the pressure spike within one hour. Necropsies revealed massive gas bubbles in the heart (TDG 135 percent) and gas bubble blockage in the afferent lamellar arteries of the gills (TDG 120 percent), both blocking blood flow to the gills. No depth-acclimated fish at 100 percent TDG died from the spike. Less than 10 percent of depth-acclimated fish at all TDG levels were injured (ruptured swim bladder) by the spike.

No surface-acclimated fish at 100 or 120 percent TDG died from the spike, and only 2 percent at 120 percent TDG were injured. No spike-related effects in surface-acclimated fish exposed to 135 percent TDG were possible, since all had already died during the acclimation period from gas bubble trauma.

Nadir of 50 kPa: No depth-acclimated fish at any TDG level died or were seriously injured from the spike. No surface-acclimated fish at 100 or 120 percent TDG died from the spike, and only 3 percent at 120 percent TDG were injured. Again, no spike-related effects in surface-acclimated fish exposed to 135 percent TDG were possible, since all had already died during the acclimation period from gas bubble trauma. Although no external signs of injury or trauma were evident after turbine passage simulation, some fish developed a black spot on the tops of their heads, identical to those described below for rainbow trout, except that these were not as pronounced or persistent. Depth-acclimated fish and fish acclimated at elevated TDG levels had more head spots than surface-acclimated fish and fish acclimated at 100 percent TDG.

Nadirs of 68 kPa and 95 kPa: No depth- or surface-acclimated fish exposed to 68 kPa or 95 kPa were injured.

Rainbow trout

Nadir of 2 to10 kPa: Neither depth- nor surface-acclimated fish at any TDG level died from the spike. Although no external signs of injury or trauma were evident one hour after turbine passage simulation, during the first 24 hours in holding troughs, some fish developed a black spot on the tops of their heads. The spot usually persisted throughout the 48-hour holding period. The black spot was more frequent in depth-acclimated than surface-acclimated fish. And among depth-acclimated fish, higher TDG levels were associated with a progressively higher occurrence of the injury (8 percent at 100 percent TDG; 15 percent at 120 percent TDG; and 23 percent at 135 percent TDG).

No ruptured swim bladders were observed in any of the turbine-passed fish. However, a few turbine-passed fish (from surface- and depth-acclimated groups, both at 100 percent TDG) gradually developed over-inflation of the swim bladder during the 48-hour observation period, resulting in floating excessively high in the holding trough.

Bluegill

Nadir of 2 to 10 kPa: Spike-related mortality for depth-acclimated fish increased from 35 percent at 100 percent TDG to 43 percent at 135 percent TDG, and most died within one hour following simulated turbine passage. A relatively high injury rate (48 to 57 percent) also occurred at all TDG levels. Necropsies revealed ruptured swim bladders as the most common injury.

The death rate for surface-acclimated fish ranged from 2 percent (100 percent TDG) to 7 percent (120 and 135 percent TDG). Injuries also occurred at all TDG levels (10 to 23 percent), although at a much lesser rate than in depth-acclimated fish.

Nadir of 50 kPa: Spike-related mortality for depth-acclimated fish (2 to 18 percent) was much lower than at the more severe nadir, and the death rate for surface-acclimated fish was virtually non-existent (0 to 5 percent). However, both depth- and surface-acclimated fish incurred substantial injuries (50 to 63 percent and 43 to 100 percent, respectively).

Nadirs of 68 kPa and 95 kPa: Only one spike-related death occurred in depth-acclimated fish from exposure to 68 kPa. No other deaths occurred for depth- or surface-acclimated fish exposed to 68 or 95 kPa. Injuries (internal hemorrhaging of blood vessels near the

Some rainbow trout developed a black spot on the top of their heads during the 48-hour observation period following simulated passage through a Kaplan turbine. This injury was more frequent in depth-acclimated than surface-acclimated fish.

Table 1: Nadirs[1] at which mortality/injury appears to be negligible during a one-time exposure

	Effect	
Species	*Death*	*Injury*
Bluegill Sunfish	~50 kPa	>50 kPa[2]
Fall Chinook Salmon	2-10 kPa	2-10 kPa
Rainbow Trout	2-10 kPa	2-10 kPa

Notes:
[1]Lowest pressure in kilopascals (kPa)
[2]Since the bluegill injury rate at approximately 50 kPa appeared to be substantial and the injury rate at 68 kPa and 95 kPa could not be evaluated, a higher, currently unknown, nadir is suggested.
Since total dissolved gas level was not an important contributor to spike-related mortality, it is not considered as an additive factor in this table.

swim bladder) in depth- and surface-acclimated fish resulting from exposure to either nadir could not be evaluated because the associated control fish experienced similar injury rates, likely due to difficulty in handling.

What have we learned?

Bluegills were much more susceptible to the effects of abrupt changes in pressure than either of the two salmonids. Bluegill mortality was greatest at the higher-pressure gradients associated with lower nadir or greater acclimation depth. For example, bluegill mortality resulting from the 2 to 10 kPa nadir was significantly greater than under the 50 kPa nadir. The mortality rate for depth-acclimated bluegill was significantly greater than for surface-acclimated bluegills for both the 2 to 10 kPa and 50 kPa nadirs. Total dissolved gas level did not appear to be an important contributor to the number of spike-related bluegill mortalities or injuries.

Chinook salmon mortalities were very low and only observed in depth-acclimated fish exposed to the 2 to 10 kPa nadir at TDG levels at or above 120 percent. However, TDG level did not appear to be an important contributor to chinook salmon mortality. No chinook salmon died or incurred serious injury at 50 kPa nadir. There was no rainbow trout mortality at the 2 to 10 kPa nadir, and injury rates were generally low, so tests were not conducted at the 50 kPa nadir.

Although pressure gradients associated with the 68 and 95 kPa nadirs were smaller than those associated with the 2 to 10 kPa and 50 kPa nadirs, the times that fish were exposed to the pressure spikes were greater. The times were 1.6 seconds for the 68 and 95 kPa nadirs versus 0.2 second for the 2 to 10 kPa and 50 kPa nadirs. Consequently, while the chinook salmon and bluegill swim bladders did not expand as much at the 68 kPa and 95 kPa nadirs as they did under the 2 to 10 kPa and 50 kPa nadirs, they remained expanded for a longer period of time. However, neither the 68 kPa nor the 95 kPa nadirs resulted in mortality or significant injuries in chinook salmon or bluegill. Table 1 provides a summary of the specific nadirs at which mortality/injury appears to be negligible for one-time exposure for the three species tested.

We believe that these species' differences are related to the structure of the swim bladder.[7] In physotomous fish — such as salmon and trout — the swim bladder is connected to the esophagus via the pneumatic duct, enabling gas to be quickly taken into or vented from the swim bladder through the mouth. Thus, adjustment to changes in water pressure can take place rapidly, often on the order of seconds. On the other hand, physoclistous fish — such as bluegill — lack a direct connection between the swim bladder and esophagus, so pressure within the swim bladder is adjusted via gas diffusion into the blood, a process measured on the order of hours.[9]

Consequently, bluegills experienced higher mortality/injury rates than chinook salmon or rainbow trout when exposed to the same pressure changes. Bluegills could not reduce the volume of their swim bladders quickly enough to compensate for the rapid decrease in water pressure. In contract, chinook salmon and rainbow trout were able to vent excess gas quickly enough to largely avoid mortality/injury.

It is important to note that while the mortality/injury rates corresponding to the nadirs in Table 1 appear low, the cumulative rates for fish passing several dams in sequence are currently unknown.

Implications for hydro managers and turbine designers

Water pressures at or greater than approximately 68 kPa appear to provide safe passage for both juvenile salmonids and bluegill.

At TDG concentrations less than 120 percent, depth- and surface-acclimated juvenile salmonids would be expected to incur negligible mortality and injury during a one-time exposure to a nadir of 2 to 10 kPa. This generally represents the most extreme nadir that could be experienced by fish during dam operation within 1 percent of peak efficiency during the juvenile salmon migration. This nadir is less than the value corresponding to 30 percent of acclimation pressure (30 kPa and 57 kPa for surface- and depth-acclimated fish, respectively) recommended to protect salmonids.[3] However, a one-time exposure to 2 to 10 kPa appears to cause substantial mortality and injury in bluegills, particularly if acclimated to 30 feet of depth or greater.

Consequently, modification of turbine operation or design to reduce pressure gradients within the runner does not appear to be warranted, at least for juvenile salmonids. However, modifications to protect bluegill may be warranted for hydroelectric projects where the protection of such fish stocks is an issue.

Based on our studies, increasing a nadir of 2 to 10 kPa to approximately 50 kPa would largely protect depth- and surface-acclimated bluegill from mortality, but would still result in a substantial number of injuries. It is currently unknown to what extent such injuries may contribute to indirect mortality (post-passage lethality due to increased susceptibility to predation or disease) in turbine-passed fish in the field.[10] To be conservative in the absence of such knowledge, a higher nadir may be required, perhaps at or above 60 percent of acclimation pressure.[3] Consequently, further experimentation would be required to establish a nadir considered to be sufficiently protective for centrarchid (e.g., sunfish) or other physoclistous species.

The U.S. Army Corps of Engineers (Corps) operates turbines in the Columbia River Basin within 1 percent of peak operating efficiency during juvenile salmon migration, as mandated by the National Marine Fisheries Service.[11] Further, the Corps generally operates turbines so that the nadir does not fall below approximately 50 kPa, to avoid the risk of cavitation damage to its turbines and generally minimize effects on fish.

This nadir could be increased to further protect fish such as bluegill. For example, a simple means of increasing the nadir is to raise the tailwater elevation or inject air. However, this would result in a corresponding loss of head, which, in turn, could produce a substantial reduction in turbine operating efficiency, depending on the magnitude of the pressure increase. For example, a Corps spokesman said an increase of approximately 3.5 kPa — accomplished by raising the forebay 1 foot — above about 50 kPa would be expected to produce an approximate 2 percent loss in operating efficiency, under otherwise static operating conditions. Consequently, turbine operation or design modifications aimed at accommodating a higher nadir would need to be optimized in order not to reduce operating efficiency below an unacceptable level. ■

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