What's Going On in There? Efforts to Describe the Experiences of Turbine-Passed Fish

By Glenn F. Čada, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA, Garold L. Sommers, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho, USA, and Michael J. Sale, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

ABSTRACT

The U.S. Department of Energy's Advanced Hydropower Turbine System (AHTS) Program is developing advanced, fish-friendly turbines using a variety of integrated research efforts. The AHTS Program supports field studies, including the development of sensor fish - portable, fish-shaped instrument packages that measure pressure, acceleration, and other physical parameters experienced during passage through the turbine. Advanced computational analyses extend the data collected by sensor fish and other instruments in order to estimate the levels of physical stresses throughout the water passage. Laboratory bioassays of individual stresses (e.g., rate of strain, pressure, dissolved gas supersaturation) are used to suggest biological criteria for new, fish-friendly turbine designs. These three complementary efforts, (1) measuring physical conditions in a portion of the turbine, (2) using advanced computational techniques to describe the environment in unmeasured parts of the turbine (or under other configurations or operating conditions), and (3) applying these physical conditions to fish in a controlled laboratory setting to measure the response, will shed light on the causes of mortality among turbine-passed fish. By integrating the results of these studies, this program is characterizing the effects of turbine passage, determining which stresses are most damaging, and developing a better understanding of how turbine operation or design can be modified to reduce the damage.

Background

Since 1995 the U.S. Department of Energy's (DOE) Advanced Hydropower Turbine System (AHTS) Program has focused on the development of environmentally friendly turbines. One of the objectives of the AHTS Program is to reduce mortality of turbine-passed fish to 2 % or less while maintaining efficient production of electricity. The systematic development of advanced, fish-friendly turbines is based on acquiring an understanding of the stresses that kill or injure fish, and then altering the turbine design or operation to reduce those stresses. This has been challenging because such potential injury mechanisms as rate of strain, turbulence, pressure changes, and the likelihood and severity of impact with structures are extremely difficult to measure inside of a turbine. Further, the stresses are not uniformly distributed; estimation of average values for the turbine may not be meaningful if much higher, damaging values are present in localized portions of the water passage. Finally, the significance of average or maximum values for these stresses to fish injury and mortality is often

unknown because the needed bioassays have not been performed. Consequently, DOE is supporting not only the development of conceptual designs for advanced turbines (Brookshier et al. 1995) and the proof-of-concept testing of those designs (Hecker et al. 2000), but also the collection of basic physical and biological data needed to further develop these concepts. This latter effort is the subject of this paper, in which we describe three complementary efforts aimed at understanding the experiences of turbine-passed fish: (1) measuring physical conditions in a portion of the turbine, (2) applying these physical conditions to fish in a controlled laboratory setting to measure the response, and (3) using advanced computational techniques to describe the environment in unmeasured parts of the turbine (or under other configurations or operating conditions). This multi-disciplinary research effort is managed through DOE's Idaho Field Office, with the support of the Idaho National Engineering and Environmental Laboratory (INEEL) and the Oak Ridge National Laboratory (ORNL) and under the advice of the AHTS Technical Committee (Brookshier and Flynn 2001).

Field Measurements

The U.S. Army Corps of Engineers (COE) plans to install advanced, minimum gap runners (MGR) on all ten turbine units at the Bonneville I powerhouse on the Columbia River. As the name implies, compared to a conventional Kaplan runner, the MGR reduces the gaps between the adjustable blade and the hub, and between the blade tip and the discharge ring. It has been suggested that these modifications would reduce the fish injury caused by pinching, cavitation, shear stress and turbulence associated with the gaps found on conventional Kaplan runners. The first units to be replaced were Unit 6 and Unit 4. The COE, Grant County Public Utility District No. 2, U.S. Department of Energy's AHTS Program, and the Bonneville Power Administration jointly funded field tests at Bonneville I between November 15, 1999, and January 31, 2000. The aim of these studies was to compare the survival of fish through Unit 6 (with MGR) to the survival of fish passed through Unit 5, an adjacent, conventional Kaplan turbine.

Preliminary analyses indicate that fish passed through the MGR had better survival overall than through the conventional Kaplan unit (Schwartz 2000). Overall injury rates among turbine-passed fish were low for both units: 1.5% and 2.5% for the MGR and Kaplan unit, respectively. Survival of fish passed near the hub was high (97% or greater) for both units. Survival among fish passed through the mid-blade region ranged from 95 to 97% and did not differ between units. At all four power levels the MGR showed better survival than the conventional Kaplan for fish that passed near the blade tip. Survivals for blade tip-released fish ranged from 90.8 to 95.6% for the conventional Kaplan and from 93.8 to 97.5% for the MGR.

Many of the physical stresses that fish experience during turbine passage are difficult to measure with conventional instruments because localized regions deep within the turbine are inaccessible. The AHTS Program contributed to the development of the

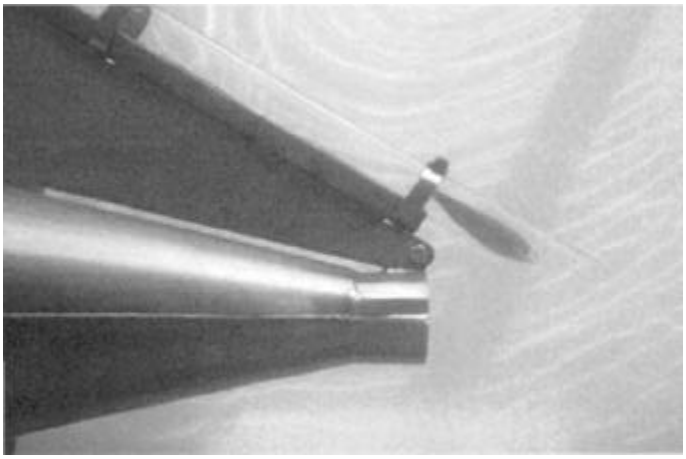
sensor fish (Figure 1), a fish-shaped, smolt-sized package of instruments that, like a real fish, can be sent through a turbine and recovered downstream. Sensor fish were used during the Bonneville I study to record pressure and acceleration experienced as the fish passed through the turbine (Carlson and Duncan 2000). The data recorded during the tests provided information about passage times, pressure cycling, turbulence intensity, and even strike events. When fully developed, these portable instrument packages can be sent through the turbine, spillway, or other dam passage route to collect data needed to better characterize the physical environment to which fish are exposed.

Figure 1. Sensor fish designed to record environmental conditions that fish may encounter while passing through hydroelectric turbines. Courtesy: Pacific Northwest National Laboratory.

Laboratory Bioassays

Although the potential injury mechanisms affecting turbine-passed fish began to be catalogued in the 1990s (Čada 1990; COE 1995), the biological effects are often poorly understood (Čada 1998). In order to address this lack of information, the AHTS Program is supporting laboratory studies of the effects on fish of the kinds of turbulence, rate of strain, pressure changes, and dissolved gas supersaturation that may occur in association with hydroelectric power production.

It is believed that hydraulic forces (e.g., rate of strain, shear stress, and turbulence) experienced during passage through turbines, spillways, and fish bypass systems may injure fish. A test facility where juvenile fish could be subjected to a range of shear environments was conceived through a joint effort of the National Laboratories and the AHTS Technical Advisory Committee and built at the Pacific Northwest National Laboratory (PNNL). Test fish (rainbow trout, steelhead, spring and fall chinook salmon, and American shad) were exposed to fluid stresses generated by a submerged jet (Figure 2) with a range of exit velocities from 0 to 21.3 m/s (0 to 70 ft/s), resulting in a rate of strain of up to 1185 cm/s/cm (based on a spatial resolution of 1.8 cm). Fish were introduced to the edge of the submerged jet plume in either a headfirst or tailfirst orientation, recaptured, and observed for injuries and short- and long-term mortalities.



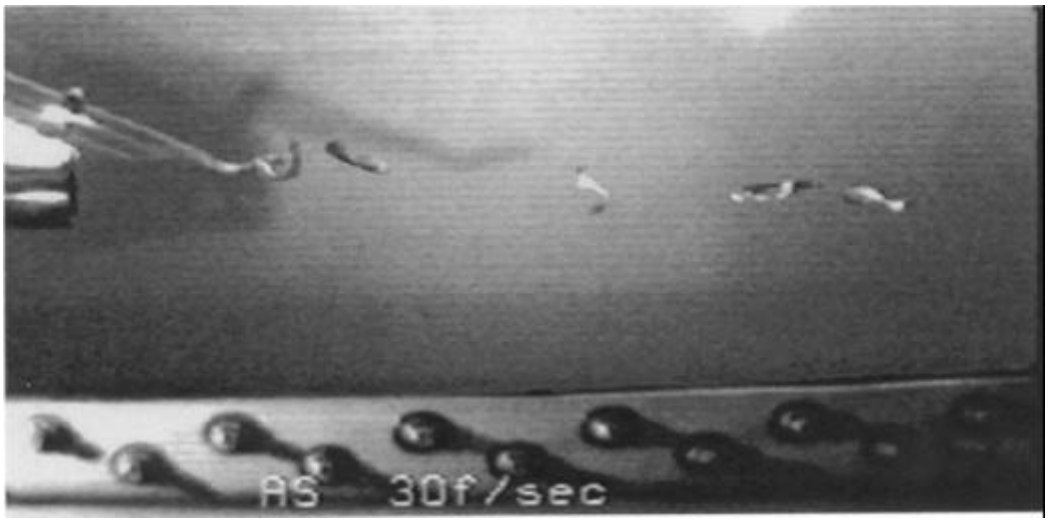


Figure 2. Exposure of fish to shear created by a submerged jet. From Neitzel et al. (2000).

Neitzel et al. (2000) found that fish entering an environment with a high rate of strain may be killed, injured, or, if uninjured, still have increased susceptibility to predation. There were no significant injuries to any fish subjected to rates of strain of less than 517 cm/s/cm (Table 1). Of the species tested, American shad were the most susceptible to injury, while steelhead and rainbow trout were least susceptible. Predation tests were conducted on rainbow trout; whereas strain rates of 688 cm/s/cm had caused no apparent injury, the test fish exposed to even lower values (517 cm/s/cm) were more susceptible to predation than control fish.

Table 1: Summary of strain rate exposures below which fish were not injured or killed in the PNNL shear test facility. From Neitzel et al. 2000

		Rate of Strain (cm/s/cm at Δy=1.8 cm)		
Test Fish	*Test Orientation*	*No Statistically Significant Injury*	*No Statistically Significant Major Injury*	*No Statistically Significant Deaths*
Fall Chinook (age 0)	Headfirst	517	852	1008
Fall Chinook (age 1)	Headfirst	517	517	852
Spring Chinook	Headfirst	517	688	1008
Rainbow Trout	Headfirst	688	1008	1008
Steelhead	Headfirst	517	1008	1008
American Shad	Headfirst	517	517	517
Fall Chinook (age 1)	Tailfirst	688	1008	1008
Spring Chinook	Tailfirst	688	1008	1008
Steelhead	Tailfirst	852	1008	1008
Rainbow Trout	Headfirst with predators	517	-	-

Studies of the effects of pressure changes during turbine passage have also been initiated at PNNL, using a hyperbaric pressure chamber (Figure 3). In these experiments, test fish (juvenile rainbow trout, fall chinook salmon, and bluegill sunfish) were exposed to a pressure regime typical of passage through a Kaplan turbine, i.e., a gradual pressure increase to 3 times atmospheric pressure, followed by a rapid (0.1 second) decrease to sub-atmospheric pressure, followed by a gradual return to 1 atmosphere (Figure 4). When acclimated to surface water pressure, neither rainbow trout nor chinook salmon were killed by exposure to these turbine-passage pressures, although some injuries were observed (Abernethy et al. 2001). Bluegill exposed to the

turbine-passage pressure regime had more injuries and mortalities than salmonids, especially if they had first been acclimated to water pressures equivalent to residence at 30 feet of depth. Gas supersaturated water, as commonly occurs in the Columbia River system, had adverse effects both separately and by increasing the injury and mortality due to turbine passage pressure changes.

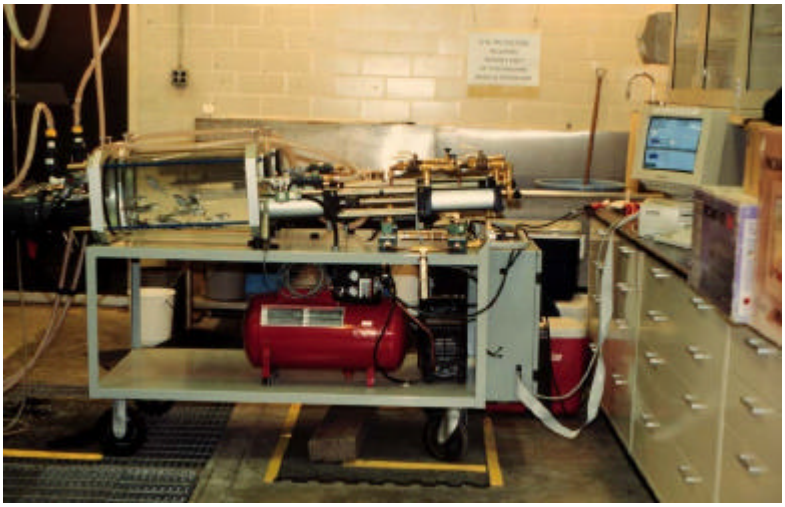


Figure 3. Pressure chambers used to test the effects of turbine-passage pressure regimes on fish. From Abernethy et al. (2001).

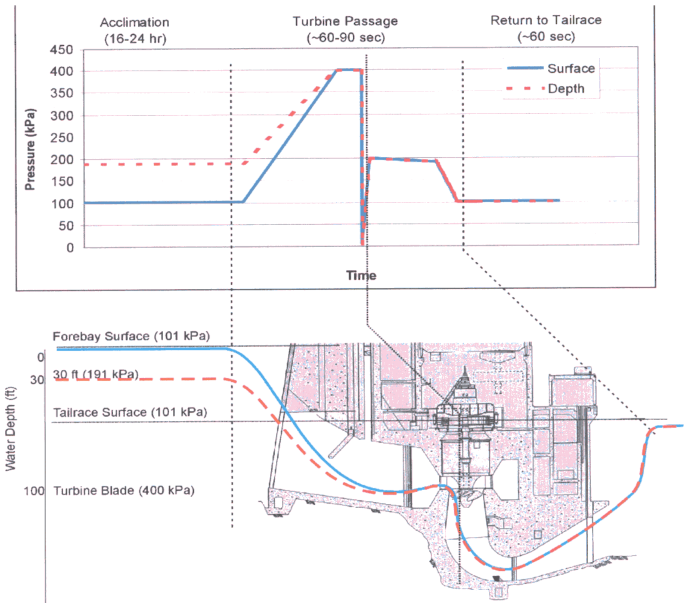


Figure 4. Typical time vs. pressure sequence associated with passage through a Kaplan turbine. From Abernethy et al. (2001).

Laboratory studies of the effects of turbine-passage injury mechanisms are continuing. The data will be used to develop biocriteria (biologically based design specifications) for the turbine manufacturers. When integrated with other components of the AHTS Program, the bioassays will give meaning to *in situ* measurements (from the field tests) and projected future conditions (from computational analyses).

Advanced Computational Studies

Bioassays are generating valuable information on the effects of particular injury mechanisms associated with turbine passage that can be used to develop biocriteria for the design of advanced turbines. For example, if it is found that pressure effects are less damaging to salmonids than fluid effects (strain rates and turbulence), the turbine manufacturer has a better basis for making design tradeoffs to protect fish. However, an additional consideration for putting these fish injury and mortality data into context is the distribution and magnitude of the injury mechanisms. That is, although a given value for rate of strain may be damaging, it is of little consequence if such values only occur in a small portion of the turbine water passage, such that few entrained fish are likely to encounter these values. The parallel development of advanced computational analyses, such as Computational Fluid Dynamics (CFD), is helping us to translate the laboratory data to the actual and projected turbine environments.

Similarly, advanced instruments, such as the sensor fish, can enable us to make actual field measurements of fluid stresses deep within the turbine passage (e.g., pressure, velocity changes, and potentially other parameters such as bending moments). Because we do not know the path followed by the sensor fish as it moves through the turbine passage, we do not know exactly where a particular value for the stress occurred. Hence, we are not sure how representative are the values measured by an instrument whose movements are uncontrolled. We cannot be sure that the highest value for a fluid stress measured by the sensor fish is the highest value that is found within the turbine, or only some intermediate value. CFD analyses can help put these field measurements into perspective.

For example, the locations and extent within a turbine of damaging rate of strain values are being investigated by Voith (2000). By means of CFD analysis of a conventional Kaplan turbine scroll case and runner, Voith found that regions of turbine water passages having high rate of strain values ($\geq$500 cm/s/cm) were found in relatively small areas adjacent to wetted surfaces (i.e., boundary layers) and near sharp-edged structures such as blade gaps. Initial estimates are that these potentially damaging areas constitute less than 1 percent of the water passage area in the scroll case and runner. Although high rate of strain values are unavoidable at boundary layers, efforts to reduce gaps could lower even further the risk of fluid-related fish injuries. This is an example of the value of integrating different components of the AHTS research program; field measurements are used to calibrate the CFD model, which in turn provides estimates of the magnitude and distribution of these potential fish injury mechanisms within a real turbine.

Jones and Sotiropoulos (2000) demonstrated that the actual flow environment experienced by fish in a high rate of strain zone is vastly more complicated than that described by the mean flow. Their simulation of instantaneous, unsteady flow fields in the PNNL flume indicated that fluctuations in the values of vorticity, shear stresses, and pressure gradients were all considerably higher than the mean values. For example, Figure 5 shows that regions of very high vorticity appear and disappear throughout the flow field; the damaging effects of such instantaneous flow-induced loads would not be obvious from consideration of only time-averaged values. They recommended that refined guidelines (i.e., biocriteria) for improving the fish-friendliness of advanced turbines should reflect an understanding and quantification of the structure of turbulence at the size scale of a fish.

(a)

(b)

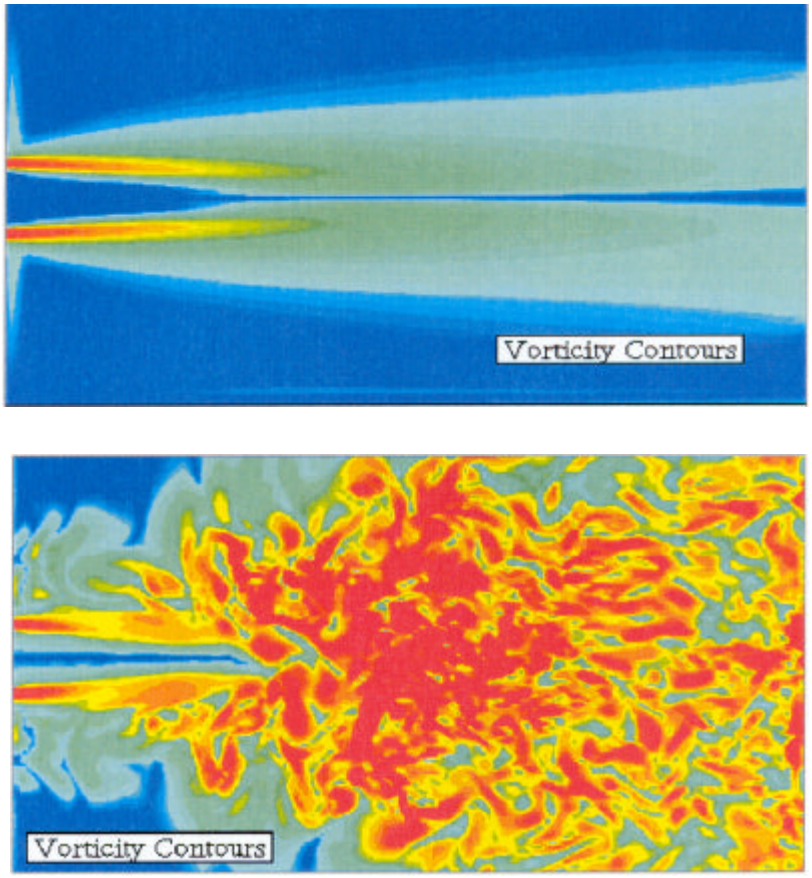


Figure 5. Examples of time-averaged (a) and instantaneous (b) vorticity associated with a submerged jet. From Jones and Sotiropoulos (2000).

The kind of unsteady, numerical models (so-called large-eddy simulations) used to analyze turbulence in the relatively small PNNL flume cannot be applied to modeling flows in hydroelectric turbines because they would require excessive computer resources. However, there may be considerable value to employing other, very-large-eddy simulation approaches to rigorously compare the fluid forces found in turbines (as

studied by Voith) and in laboratory fish-testing apparatuses (as studied by Jones and Sotiropoulos).

Conclusions

All three components of the AHTS Program (field, laboratory, and computational studies) are needed to develop a better understanding of both the adverse effects of turbine-passage injury mechanisms and the modifications needed to reduce those effects. The DOE 's AHTS Program aims to continue these efforts (Brookshier and Flynn 2001).

Measurements of the locations and magnitudes of suspected fish injury mechanisms within a turbine can only come from field studies at hydroelectric power plants. These measurements are done with conventional instruments where possible, but a more intensive look at the complex hydraulic conditions within a turbine often requires the development of advanced measuring techniques such as the sensor fish. Then, the significance of these measurements to fish injury and mortality must be established under controlled conditions in the laboratory. Bioassays will determine whether some injury mechanisms are more harmful than others, information that will be used by the turbine manufacturer to make design tradeoffs. Advanced computational analyses serve a variety of purposes, including estimating conditions within unmeasured areas of the turbine, elucidating the causes for observed fish injuries in the laboratory, and predicting the effects of turbine design changes on fish survival. Coming full circle, field studies of turbine passage survival are again needed to verify the projected biological benefits of changes in turbine design and operation that were suggested by the earlier studies. By systematically exploring the turbine-passage issue and integrating the findings of different approaches, turbine manufacturers will be able to move beyond a trial-and-error approach to advanced turbine development.

References

Abernethy, C.S., B.G. Amidan, and G.F. Čada. 2001. Laboratory studies of the effects of pressure and dissolved gas supersaturation on turbine-passed fish. Report to the U.S. Department of Energy Hydropower Program. Idaho Falls, ID. 61 p.

Brookshier, P.A., J.V. Flynn, and R.R. Loose. 1995. 21st century advanced hydropower turbine system. In J.J. Cassidy (Ed.), Waterpower '95 - Proceedings of the International Conference on Hydropower. American Society of Civil Engineers, New York, NY. pp. 2003-2008.

Brookshier, P.A., and J.V. Flynn. 2001. What's Up DOE? In Proceedings of the Waterpower XII Conference. HCI Publications, Inc. Kansas City, MO.

Čada, G. 1990. A review of studies relating to the effects of propeller-type turbine passage on fish early life stages. North American Journal of Fisheries Management 10(4):418-426.

Čada, G. 1998. Better science supports fish-friendly turbine designs. Hydro Review XVII (6):52-61.

Carlson, T., and J. Duncan. 2000. Turbine environment characterization. Proceedings of the Turbine Passage Survival Workshop. June 14-15, 2000. U.S. Army Corps of Engineers Portland District, Portland, OR.

COE (U.S. Army Corps of Engineers). 1995. Proceedings: 1995 Turbine Passage Survival Workshop. U.S. Army Corps of Engineers Portland District, Portland, OR.

Hecker, G.E., T. Cook, S. Thirumalaisamy, and P. Feffatsidis. 2000. New developments of ALDEN/NREC fish friendly turbine. Proceedings of Hydrovision 2000. HCI Publications, Inc. Kansas City, MO.

Jones, S.C., and F. Sotiropoulos. 2000. Large-eddy simulation of turbulent circular jet flows. Draft Report to the U.S. Department of Energy Hydropower Program. Idaho Falls, ID. 88 p. + appendix.

Neitzel, D.S., M.C. Richmond, D.D. Dauble, R.P. Mueller, R.A. Moursund, C.S. Abernethy, G.R. Guensch, and G.F. Čada. 2000. Laboratory studies of the effects of shear on fish. Report to the U.S. Dept. of Energy Idaho Operations Office, Idaho Falls, ID. 66 p. + appendices.

Schwartz, D. 2000. CRFMP - System Study Turbine Survival Program. Proceedings of the Turbine Passage Survival Workshop. June 14-15, 2000. U.S. Army Corps of Engineers Portland District, Portland, OR.

Voith (Voith Siemens Hydro Power Generation, Inc.). 2000. Overview of CFD analysis of PNNL shear facility and application of results to turbine environment. December, 2000 Draft Report to U.S. Department of Energy Hydropower Program. Idaho Falls, ID. 16 p.

Acknowledgments

We thank the Technical Committee of the U.S. DOE's Advanced Hydropower Turbine Systems Program for their advice, and Mark Bevelhimer and Chuck Coutant for their reviews of this paper. The research was sponsored by the Office of Biopower and Hydropower Technologies, U.S. Department of Energy, under contract number DE-AC05-00OR22725 with UT-Battelle LLC and contract DE-AC07-99ID13727 with Bechtel BWXT Idaho, LLC. This is Publication No. 5065, Environmental Sciences Division, ORNL.

Authors

Glenn Čada, PhD, is a Research Staff Member at the Oak Ridge National Laboratory (ORNL). He has authored over 100 scientific publications in the fields of aquatic biology and the environmental effects of energy development. He advises the DOE Hydropower Program on environmental issues.

Garold Sommers is an Advisory Engineer/Scientist at the Idaho National Engineering and Environmental Laboratory. He has been involved in the DOE Hydropower Program for over 20 years. Garold has served as chairperson on several national committees dealing with hydropower issues and has also participated in the Technical Program Committee for six Waterpower Conferences.

Michael Sale, Ph.D., is a Senior Staff Member and Science Leader for Ecological Management Science and Technology at ORNL. He manages ORNL's hydrosystems R&D, including support to the DOE Hydropower Program, The Federal Energy Regulatory Commission's Office of Energy Projects, and other federal and nonfederal sponsors.