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FEATURE

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ABSTRACT: *Environmentally enhanced hydroelectric turbines have been developed to reduce injury and mortality of downstream-migrating fishes and to improve downstream water quality. Significant progress has been made in the past decade in the development of such turbines and in the methods to evaluate their biological and power generating performance. Full-scale demonstrations have verified the performance of Voith Hydro's minimum gap runner turbine, which maintains high survival rates for fish while producing more power than conventional designs. Despite a promising pilot study and subsequent design enhancements, similar full-scale demonstrations of the fish-friendly Alden turbine have yet to be conducted. Furthermore, the tools with which to predict and evaluate the performance of new turbine designs are available and are continually being improved. This article provides a status update of advances in this field over the past decade.*

El estado de las turbinas hidroeléctricas ambientalmente mejoradas

RESUMEN: *las turbinas hidroeléctricas ambientalmente mejoradas se desarrollaron para reducir los daños y mortalidad en los peces migratorios en los ríos y para mejorar la calidad del agua en éstos. Se ha logrado un progreso significativo en la última década en el desarrollo de las turbinas y de los métodos de evaluación de su desempeño en cuanto a generación de poder e impacto biológico. Demostraciones a escala real han servido para verificar el desempeño de una hidroturbina Voith de mínimo distanciamiento, la cual mantiene altas tasas de supervivencia en los peces al mismo tiempo que produce mayor cantidad de poder en comparación a los diseños tradicionales. Pese al prometedor estudio piloto y a las subsecuentes mejorías en el diseño, aún están por realizarse demostraciones similares en escala real de la turbina Alden "ictiológicamente-amigable". De hecho, las herramientas con las que se predice y evalúa el desempeño de nuevos diseños de turbinas, ya están disponibles y se encuentran en un continuo proceso de mejoramiento. Este artículo muestra una actualización del estado y avances en este campo durante la última década.*

INTRODUCTION

The advancement of hydroelectric power as a means to generate environmentally friendly, renewable energy depends in part on the success of newly developed technologies for addressing the principal environmental concerns. These concerns include the survival and condition of fish passing through turbines as well as the water quality downstream of hydro projects. In recent years, significant progress has been made in the development of environmentally enhanced conventional hydro turbines. Research and development (R&D) completed to date has considerably increased the hydropower industry's understanding of how fish are affected when passing through turbines. The R&D in this area has contributed to improvements in turbine design and operation that are expected to result in reduced fish injury and mortality; in addition, the employment of new aerating turbine designs has improved downstream water quality by increasing dissolved oxygen concentrations (Electric Power Research Institute [EPRI] and U.S. Department of Energy [DOE] 2011a).

Cada (2001) provided a comprehensive summary of the development of advanced hydroelectric turbines and research on fish injury mechanisms at the time. We present herein a status update of recent advances in the design and evaluation of so-called fish-friendly hydroelectric turbines. In addition to a summary of advancements in turbine design, we include a review of the biological, physical, and numerical investigations that have been conducted to better define the fish injury and mortality mechanisms associated with turbine passage.

ADVANCED TURBINE RESEARCH AND DEVELOPMENT

U.S. Department of Energy

The U.S. DOE, the EPRI, and the Hydropower Research Foundation, Inc., established the Advanced Hydropower Turbine Systems (AHTS) Program in 1994 to support the development of environmentally friendly turbine technologies. Specifically, the AHTS Program aimed to advance the development of turbines that minimize injury and mortality of fish, maintain satisfactory downstream water quality, and produce energy efficiently (Odeh 1999). During the program's life, it funded various R&D efforts that met the DOE's objectives and, most notably, initiated the development of two advanced turbine designs: the Alden turbine and the Voith Minimum Gap Runner (MGR). The DOE Hydropower Program was closed in 2005 due to lack of funding (Sale et al. 2006) but was reinstituted 4 years later as the DOE Water Power Program.

Despite the end of the DOE's original Hydropower Program in 2005, development and testing of advanced turbines continued in various arenas. The DOE's Pacific Northwest National Laboratory (PNNL) continued to conduct research on injury and mortality mechanisms associated with turbine passage. The U.S. Army Corps of Engineers (USACE), through its Turbine Survival Program (TSP), conducts research to improve the knowledge of the turbine passage environment and its impact on fish. The TSP provides the framework to optimize turbine operations for safer fish passage and improve future turbine designs for fish passage (Medina and Shutters 2011). The EPRI has supported further R&D of the fish-friendly Alden turbine through both numeric modeling and biological evaluations to improve the power generation and biological performance of the unit. Since its return in 2009, the DOE Water Power Program has begun to revitalize hydropower through resource assessments, demonstration projects, and engineering and environmental R&D (U.S. DOE 2014).

Pacific Northwest National Laboratory

A clear understanding of the stresses acting on fish passing through turbines and their responses to those stresses is critical to designing turbines that are fish-friendly. To that end, the PNNL has been conducting controlled laboratory research on the effects of known injury and mortality mechanisms in the turbine passage environment. PNNL biologists and engineers have focused on the effects of shear, pressure, and gas supersaturation on salmonids passing through turbines. The responses of fish exposed to these injury mechanisms in the laboratory can be combined with computational fluid dynamics (CFD) simulations that can predict the levels of these stresses in the turbine environment. By coupling biological response data from the laboratory with predicted stress levels generated from CFD simulations, scientists are able to predict injury and survival of turbine-passed fish under various conditions (Richmond 2011).

Most recently, the PNNL has focused its laboratory research on determining the effects of barotrauma on fish passing through turbines (Brown et al. 2009, 2012a, 2012b; Colotelo et al. 2012). Using computer-controlled hyper/hypobaric chambers researchers expose fish to simulated turbine passage pressure changes and assess injury and survival. Results indicated that the injuries sustained during rapid decompression mainly result from swim bladder rupture rather than from gas dissolution from the blood (Brown et al. 2012b). In addition, Brown et al. (2012a) concluded that the principal factor affecting mortal injury of juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) during simulated turbine passage was the ratio between a fish's acclimation pressure and the lowest pressure to which it was exposed (nadir). The PNNL has also demonstrated that the presence of surgically implanted telemetry transmitters (used to track movements of downstream migrating smolts) negatively affects turbine passage survival of juvenile Chinook Salmon (Brown et al. 2009; Carlson et al. 2010, 2012). In response to these results, the PNNL has been developing neutrally buoyant, externally attached transmitters for use in turbine passage studies (Deng et al. 2011) in order to minimize the risk of bias resulting from this artificial source of mortality.

Releases of "sensor fish" through turbines at hydro projects have also provided a means to characterize the hydraulic signature of the turbine passage environment (Deng et al. 2010). The sensor fish is a PNNL-developed tool that has shed light on the hydraulic characteristics of flow passing through turbines. It is a cylindrical, polycarbonate instrument roughly the size of a juvenile salmon and can be used to sense changes in pressure, angular rate of change in position, and linear accelerations during turbine passage. The PNNL is comparing hydraulic field data (such as those provided by the sensor fish) with results of CFD simulations and predictions of injury risk in order to develop a comprehensive method for predicting the biological performance of turbines—the PNNL's Biological Performance Assessment (Richmond 2011). Because field-based biological evaluations of newly installed turbines can be expensive, the Biological Performance Assessment method represents a cost-effective means to bridge the gap between fish evaluations in the laboratory and post-installation field evaluations.

U.S. ARMY CORPS OF ENGINEERS TURBINE SURVIVAL PROGRAM

The USACE established the TSP in 1997 in response to the request of the Northwest Power Planning and Conservation Council and the National Marine Fisheries Service (NMFS) to increase the survival of out-migrating salmonids in the Columbia River (Medina and Shutters 2011). The goals of the TSP are to (1) improve the understanding of the turbine passage environment and its impact on downstream migrating juvenile salmonids, (2) optimize operations of existing turbines for safer fish passage, and (3) improve future turbine designs for safer fish passage. The TSP is a collaborative effort between the USACE Walla Walla and Portland Districts, the Hydroeletric Design Center (HDC), the Engineering Research and Development Center (ERDC) and the NMFS.

The USACE is currently in the process of redesigning replacement turbines for the 603-MW Ice Harbor project on the lower Snake River in Washington State. This work is being conducted collaboratively with Voith Hydro and was formulated as a unique iterative design process with an overall goal of providing safer fish passage for salmon smolts (Nelson and Freeman 2011). The design process progresses from CFD simulations to performance (physical) model testing to the testing of an observational (physical) model at a 1:25 scale. The observational models are constructed at the ERDC of acrylic to allow visualization of streamlines created by the passage of dye and small, neutrally buoyant beads (Figure 1, left). Laser Doppler velocimetry is used to quantify flow characteristics in the models. The objective of the new turbine design is to minimize risks posed by mechanical strike, shear, turbulence, and pres-

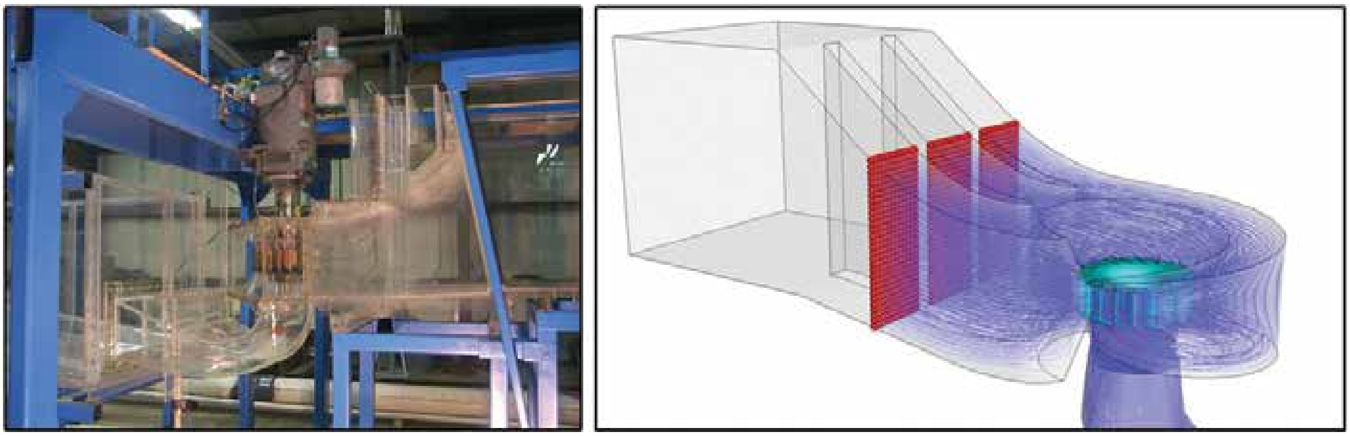

Figure 1. Left: U.S. Army Corps of Engineers Engineering Research and Development Center (ERDC) hydraulic observational turbine model (1:25 scale) for the Ice Harbor runner replacement project. Photo credit: USACE. Right: Computational fluid dynamics (CFD) model used to predict the probability of fish passage through various regions of the turbine. Photo credit: USACE.

sure change (Nelson and Freeman 2011). Installation of the new runner for Unit 2 is projected to be completed by the summer of 2016 with biological testing to occur the following year.

The USACE is also using CFD to predict the characteristics of the flow field in the turbine runner environment (Figure 1, right). This numerical simulation approach has been used to support a pressure risk analysis for salmon smolts passing through the Kaplan units at the John Day Powerhouse on the Columbia River. Comparison of the pressure regimes predicted by the CFD model to the pressures documented with sensor fish passage indicates that CFD is a viable tool for assessing the risk of exposure to nadir (lowest) pressures (Kiel and Ebner 2011). This information can be combined with acclimation distribution and pressure mortality relationships to predict a mortality risk due to pressure (Trumbo et al. 2013).

Industry

The hydropower industry has also made significant strides in advancing the science of environmentally enhanced turbines. Fisheries biologists continue to rely on release–recapture methods to assess turbine passage injury and survival in the field with balloon tags (aka Hi-Z Turb'N tags). Balloon tag studies are considered the industry standard and have been used for evaluating injury and survival of fish passed through environmentally enhanced turbines at various projects, including Bonneville Dam First Powerhouse on the lower Columbia River (Normandeau Associates et al. 2000), Wanapum Dam on the mid-Columbia River (Normandeau Associates et al. 2006), the Box Canyon Hydroelectric Project on the Pend Oreille River (EES Consulting 2011), Kelsey Station on the Nelson River in Manitoba, and at a French hydro project on the Rhine River (Heisey and Avalos 2011). Carlson and Richmond (2011) noted that balloon-tagged fish may not be neutrally buoyant before release, making it difficult to parse the effects of rapid decompression from other injury mechanisms on overall turbine passage survival. In addition to the field-based evaluations, private industry contributes heavily to the advancement of environmentally friendly hydropower through laboratory and CFD evaluations of critical turbine aspects that influence injury and mortality of entrained fish, such as leading-edge blade geometry (EPRI 2007a, 2008, 2011).

NEW TURBINE TECHNOLOGIES

Fish-Friendly Turbines

Alden Turbine

The Alden turbine is a relatively new hydro turbine runner design with fish-friendly characteristics. It was conceptualized and tested at a pilot scale in the laboratory under the former DOE AHTS Program for fish survivability (Cook et al. 2003). More recently, the EPRI (2007a, 2007b, 2008, 2009; EPRI and DOE 2011b) has overseen the laboratory and numerical modeling R&D of the Alden turbine with a goal of optimizing its biological and power generating performance.

The Alden turbine was initially developed using two- and three-dimensional CFD models (Cook et al. 1997, 2003; Lin et al. 2004; Hecker and Cook 2005), later being refined with additional three-dimensional CFD simulations (EPRI 2007a, 2009; EPRI and DOE 2011b).

As part of the development of the Alden turbine, the EPRI (2007a, 2008, 2011) conducted laboratory evaluations of the parameters that affect fish survival due to blade strike. Trials were conducted with a representative bony fish (Rainbow Trout, *Oncorhynchus mykiss*) and a representative cartilaginous fish (White Sturgeon, *Acipenser transmontanus*). Results generally indicated that the ratio of fish length to blade thickness is an important factor, with survival increasing as the ratio decreases. Survival also increased with decreasing strike velocity for trout, with velocities of about 5 m/s or less causing no mortality for any of the fish length–to–blade thickness ratios that were tested (up to a ratio of 25). Notably, survival of sturgeon was greater than that of trout, indicating that physical characteristics of sturgeon (e.g., cartilaginous skeleton, tough integument, and more robust scales, which are also referred to as "scutes") result in less injury from blade strike. This observation was also consistent with the results of the pilot-scale biological evaluation of the Alden turbine (Cook et al. 2003), which demonstrated that White Sturgeon had statistically higher passage survival than the bony fish that were tested (Rainbow Trout, Alewife [*Alosa pseudoharengus*], Coho Salmon [*Oncorhynchus kisutch*], and Smallmouth Bass [*Micropterus dolomieu*]). Results of the blade strike experiments were incorporated into the redesign of the Alden turbine (i.e., incorporation of a thicker blade leading edge) and also hold potential for improving the design of other turbine types (Amaral and Hecker 2011).

Most recently, the Alden turbine underwent mechanical engineering and physical model testing by Voith Hydro (Figure 2), resulting in a commercially available unit predicted to yield fish passage survival rates of 98% or greater for fish less than 20 cm (8 in.) in length and a maximum best efficiency point efficiency of about 94% (EPRI and DOE 2011b). Hecker et al. (2011) have also verified that the CFD model developed for evaluation of the Alden turbine agrees well with the physical model testing done by Voith Hydro. This indicates that the internal runner hydraulics, which were designed to specific biological criteria for safe fish passage, are predicted accurately by the CFD model.

However, the fish survival predictions of the Alden turbine remain to be validated at a full scale in the field. To that end, the EPRI and Alden are actively seeking a demonstration site for a full-scale Alden turbine (Perkins and Dixon 2011). In 2011, the DOE Water Power Program offered its support of this effort, and although the initially selected demonstration site project has since been withdrawn by the power company, the DOE has continued to express its support in identifying an alternate demonstration site for the Alden turbine.

Minimum Gap Runner

The MGR is a modification of a Kaplan turbine in which the gaps between the adjustable runner blade and the hub, and

Figure 2. Alden turbine physical model (1:8.7 scale) used for performance testing by Voith Hydro. Photo credit: Alden Research Laboratory.

Figure 3. Voith Hydro Minimum Gap Runner (MGR) during installation at Wanapum Dam on the Columbia River in Washington State in 2005. Photo credit: Grant County Public Utility District.

between the blade tip and the discharge ring, are minimized at all blade positions (Cada 2001; Figure 3). In addition, there is no overhang of the trailing part of the wicket gate. It has been suggested that these modifications would decrease the fish injury and mortality caused by grinding (fish are injured passing through the narrow, sharp-edged gaps) and the locally high shear stresses, turbulence, and cavitation in the fluid flow created by the gaps. These modifications were also expected to result in efficiency improvements (Odeh 1999). A team of organizations led by Voith Hydro is credited with having developed the MGR under the former DOE AHTS Program, and other manufacturers (e.g., Alstom, Andritz Hydro) have since developed turbines with similar features. MGRs are a product of numerous studies supported by the DOE and USACE TSP. They have been installed and tested at three projects in the Pacific Northwest.

The first installation of an MGR was at the Bonneville Dam First Powerhouse on the lower Columbia River. The MGR turbine was put into commercial operation on 27 July 1999. Survival of juvenile Chinook Salmon through the MGR turbine was subsequently tested between November 1999 and January 2000 (Normandeau Associates et al. 2000). Direct survivals through the new MGR Unit 6 were estimated for three release locations (designed to direct fish toward the hub, mid-blade, and blade tip of the runner) and various power levels (operating efficiencies) and compared to those for the standard Kaplan Unit 5. Turbine passage survivals for the MGR were highest for fish directed toward the hub, intermediate for fish directed toward mid-blade, and lowest for fish directed toward the blade tips. No statistically significant correlations were found between fish passage survival and turbine operating efficiency for either turbine type. Fish passage survival through the MGR was equal to or better than survival through the standard Kaplan, especially for fish directed toward the blade tip; near the hub, survival probabilities were generally greater than 98% for both types of turbines. Overall, significant differences in passage survival were observed between release locations (fish directed toward the tip versus fish directed toward the other two blade locations) but not between turbines (Normandeau Associates et al. 2000). Ploskey et al. (2007) concluded that the Unit 6 MGR did not provide substantive improvement in fish survival over the relatively high survivals already occurring with the existing, standard Kaplan turbine installed in Unit 5.

In addition to good fish passage survival, the new MGR turbines are more efficient and the Bonneville First Powerhouse is expected to produce 15% more electricity with the new turbines. Because of the combined benefits of good fish passage survival and increased power production, replacement of all 10 of the old Kaplan turbines with MGRs continued at the Bonneville First Powerhouse (USACE 2008). Commissioning of the last turbine replacement occurred in January 2011.

The MGR has also been evaluated at the Wanapum Dam in Washington State. Wanapum Dam is one of two dams that comprise the Priest Rapids Project on the mid-Columbia River, Washington. The Wanapum dam had 10 conventional Kaplan turbines that had been operating for over 40 years and were reaching the end of their useful life. In 2005, Public Utility District No. 2 of Grant County began replacing all 10 Kaplan turbines at Wanapum Dam with advanced MGR turbines that were developed with support from the DOE AHTS Program. Compared to the existing Kaplan turbine, the MGR turbine was predicted to have lower values for several potential fish injury mechanisms: shear stress, turbulence, cavitation, and grinding. On the other hand, the MGR has more blades (six vs. five) and more wicket gates (32 vs. 20) than the existing Kaplan turbines at Wanapum, which might increase the potential for strike injuries.

Installation and preliminary engineering performance testing of the MGR at Wanapum Unit 8 were completed by mid-February 2005. Fish survival tests using balloon-tagged and passive integrated transponder–tagged fish were carried out in February, March, and April 2005 (Skalski et al. 2005). Tagged fish were passed through two turbines (the new MGR in Unit 8 and the conventional Kaplan turbine in Unit 9), all three intake bays in each turbine, two intake release depths (3 m [10 ft] and 9 m [30 ft]), and five turbine flows (255, 311, 425, 481, and 524 m^3/s [9,000, 11,000 15,000, 17,000, and 18,500 ft^3/s]). Releases of a total of 8,960 balloon-tagged fish were used to quantify direct mortality associated with turbine passage. Further, 1,000 releases of the sensor fish (Carlson and Duncan 2003) provided information on passage conditions (velocities, accelerations, and water pressures) within the turbines and draft tubes. Over the range of turbine discharges and release depths, 48-h survivals ranged from 94.04% to 99.56% for the MGR and from 95.23% to 99.23% for the existing Kaplan (Skalski et al. 2005). The overall weighted mean survival for the MGR of 97.8% was not significantly different from that of the existing Kaplan of 97.7%.

Because of good fish passage survival and increased power production, Public Utility District No. 2 of Grant County had replaced eight of the Kaplans with MGRs by 2011 and plans to have all 10 turbines replaced by 2014. Other than the initial tests carried out on the first MGR in 2005, no other fish studies have been conducted to date. Under the terms of the new project license (Federal Energy Regulatory Commission 2008), additional fish testing is planned upon completion of the Wanapum turbine replacement project.

The Pend Oreille PUD is in the process of replacing the four existing turbines at the Box Canyon Hydroelectric project on the Pend Oreille River in northeast Washington State with more fish-friendly units manufactured by Andritz Hydro. The new units are expected to improve turbine passage survival while increasing power production. Compared to the existing Kaplan turbines at Box Canyon, the new turbines have fewer blades (four vs. five) and minimum gaps at the blade tips and runner hubs (EES Consulting 2011). A balloon-tag study was carried out in late 2011 to compare the direct injuries and mortalities among juvenile and adult Rainbow Trout that passed through a new MGR turbine and an existing Kaplan turbine (Normandeau Associates 2012). Rainbow Trout were released at three locations to direct them toward the hub, mid-blade, and tip regions of the runners. The most common injuries (decapitation or severed bodies) were indicative of mechanical strike and were more frequent among adults than juveniles. The 48-h survival probabilities for juvenile Rainbow Trout were 96.5% for both the original Kaplan turbine and the new MGR. The 48-h survival probabilities for adult rainbow trout were 83.8% for the original Kaplan and 84.9% for the MGR. For both juvenile and adult Rainbow Trout, there were no statistically significant differences between the MGR and the Kaplan in terms of 1-h and 48-h survival estimates. The nameplate electrical output of the new MGR unit is 30% greater than the Kaplan at the Box Canyon Project (22.5 MW vs. 17.25 MW, respectively). Replacement of all four units is estimated to be complete by 2014 (Atyeo 2010).

Low Head Turbines

With resurgence of interest in the development of renewable hydropower resources, several low-head turbine designs have been recently developed for use at non-powered dams or small dams with decommissioned or abandoned power facilities. Some of these designs have also been described as being fish-friendly and some developers have indicated that turbine passage survival rates will be high due to design and operational parameters that will result in low injury rates. A hydraulic head of 20 m (66 ft) or less is considered low head; very low head is considered 3 m (10 ft) or less.

Very Low Head Turbine

The very low head (VLH) turbine design, which incorporates a Kaplan runner with eight blades, has been developed by MJ2 Technologies (Leclerc 2008). The VLH turbine is designed for heads between 1.4 and 4.5 m (5 and 15 ft) and flows between 10 and 30 m^3/s (353 and 1,059 ft^3/s). The VLH design is described as having an integrated generating set that prevents the need for sophisticated intake and discharge civil structures.

This allows the turbine to be installed in sluiceway-type passages from which it can be easily removed with a crane (Leclerc 2008). The VLH turbine design is considered fish-friendly by the developer; Lagarrigue and Frey (2011) cited the following fish-friendly design characteristics: a large diameter runner (4.5 m [14.8 ft]) with large spaces between blades, low runner speed (approximately 40 cpm [40 rpm]), water velocity inside the runner less than 2 m/s (6.6 ft/sec), small pressure variations, and minimization of gaps.

Turbine passage survival tests were completed by the manufacturer's consultant, Etudes et Conseils en Gestion de l'Environnement Aquatique (ECOGEA), and the results have been made available via the company's periodic newsletters and the consultant's reports. Initial turbine passage survival tests were conducted in 2008 at a site in Millau, France, with a prototype VLH turbine using Atlantic Salmon (*Salmo salar*) smolts (Lagarrigue et al. 2008). Tested smolts measured 147 to 240 mm (5.8 to 9.4 in.) long and weighed between 34 and 150 g (1.2 to 5.3 oz.). Fish were injected at the runner periphery, mid-blade, and at the hub. Overall immediate turbine passage survival was 96.9% for smolts (Lagarrigue et al. 2008) with fish released at the periphery, mid-blade, and hub having survivals of 94.5%, 98.6%, and 99.0%, respectively. Extended survival for all release groups combined (72 to 96 h) averaged 98.6%. However, extended survival for control groups averaged 97.9%; therefore, latent effects of passage were dismissed as negligible.

Additional fish passage tests were completed with the VLH turbine in 2008 with 150 European eels (*Anguilla anguilla*; Leclerc 2008). When the data were averaged, the overall survival rate for passage of adult eels (0.7 to 1.2 m [28 to 47 in.] long and 0.8 to 2 kg [1.8 to 4.4 lb.]) through the VLH turbine was 95%, though there is no documentation of whether this was immediate or extended survival. Survival varied based on injection location, with the highest survival rates documented for fish injected near the hub (100%) and the lowest for fish injected near the blade tips (84%). No information was provided about the statistical significance of these differences (Leclerc 2008).

Additional turbine passage evaluations were conducted with a modified VLH turbine design in 2010 on the Moselle River in France with 200 yellow and silver phase eels (0.6 to 1.0 m [23.6 to 39.4 in.] long and 0.6 to 2.0 kg [1.3 to 4.4 lb.]; Lagarrigue and Frey 2011). More recent tests were conducted in May and June of 2013 with hatchery-reared Rainbow Trout, Common Carp (*Cyprinus carpio*), and Tench (*Tinca tinca*) at the La Glaciere plant on the Tarn River. Results indicate that overall survival was between 95.6% and 100% for all species and sizes tested (Lagarrigue 2013).Though these data are encouraging, data on passage survival of other species would be valuable.

Archimedes Screw Turbine

Archimedes screw turbines are considered to be fish-friendly due to their very low rotational and tip speeds (about 30 rpm and 3.8 m/s [12.5 ft/s], respectively), lack of significant pressure changes or damaging shear forces, and minimal number of blades (typically three or fewer). Archimedes screw turbines typically have diameters between 1.5 and 3.5 m (4.9 to 11.5 ft) and are appropriate for sites with a head of 10 m (33 ft) or less (Figure 4). Evaluations of injury and mortality of fish passed through Archimedes screw turbines have been conducted with a variety of species and size classes (Spah 2001; Fishtek Consulting 2007, 2008, 2009a, 2009b) and indicate that adult European eels, sea-run Brown Trout (*Salmo trutta*), and Atlantic Salmon kelts experience minimal or no injury and no mortality.

More recently, Bracken and Lucas (2013) assessed the potential impact of an Archimedes screw turbine on downstream migrating larval and juvenile River Lamprey (*Lampetra fluviatilis*) in northeast England (River Derwent). Drift netting in the turbine discharge documented no mortality and low injury rates (1.5%); however, the authors noted that the full turbine discharge was not completely sampled.

SUMMARY

The R&D of environmentally enhanced turbines continues to evolve in response to increased demand for renewable energy generation with minimal environmental impacts. Since Cada (2001) first reported on the development of advanced hydroelectric turbines designed to protect fish in 2001, the science of safely passing fish through turbines has expanded considerably. The use of CFD, for instance, has become much more prevalent and more widely accepted for identifying areas of concern in the turbine passage environment. Similarly, the use of three-dimensional acoustic telemetry tags and sensor fish has provided much greater resolution on the behavior of fish approaching turbines and the stresses they experience during passage. These advanced tools give researchers the ability to fine-tune the engineering design and flow characteristics of hydropower projects, particularly within the complex turbine environment, to improve passage survival. Table 1 provides a summary of the characteristics of the fish-friendly turbines discussed above.

The application of advanced turbine designs such as the MGR has resulted in increased power production (up to 30% at the Box Canyon Project) without concurrent increases in fish

Figure 4. Archimedes screw turbine installed on the River Dart in the UK. Photo credit: Fishtek Consulting.

injury or mortality—more power with no greater impact to fish. With passage survival estimated at 98% and greater, the Alden turbine may represent an alternative to other conventional approaches for safely passing fish downstream, with the added benefit of generating power from flows that would otherwise be spilled or bypassed around turbines.

A host of groups (federal, nonprofit, and private) are actively applying the latest tools to design and redesign turbines to make them more environmentally friendly. For example, the USACE is currently working with Voith Hydro on the redesign of the replacement runners for the Ice Harbor Project. The contract mechanism is vastly different from typical federal hydropower contracts in that the goal is to work collaboratively using all available tools to develop a turbine with improved fish passage survival, rather than simply emphasizing power performance.

With an aging fleet of hydropower turbines and undeveloped hydropower resources at existing non-powered dams in the United States (estimated to have the potential to increase hydropower capacity by 15%; Hadjerioua et al. 2012; Figure 5), there is an opportunity to reap environmental benefits of new turbine designs while concurrently increasing the contribution of hydropower to the domestic renewable energy portfolio.

REFERENCES

Amaral, S. V., and G. E. Hecker. 2011. Designing leading edges of turbine blades to increase fish survival from blade strike. Pages 2-39–2-48 *in* T. Hogan, editor. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.

Atyeo, J. 2010. Turbine work nearly a year behind schedule. Newport Miner (September 1). Available: http://news.fwee.org/?p=1818#more-1818. (February 2012).

Bracken, F. S. A., and M. Lucas. 2013. Potential impacts of small-scale hydroelectric generation on downstream moving Lampreys. River Research and Applications 29:1073–1081.

Brown, R. S., T. J. Carlson, A. J. Gingerich, J. R. Stephenson, B. D. Pflugrath, A. E. Welch, M. J. Langeslay, M. L. Ahmann, R. L. Johnson, J. R. Skalski, A. G. Seaburg, and R. L. Townsend. 2012a. Quantifying mortal injury of juvenile Chinook Salmon exposed to simulated hydro-turbine passage. Transactions of the American Fisheries Society 141(1):147–157.

Brown, R. S., T. J. Carlson, A. E. Welch, J. R. Stephenson, C. S. Abernathy, B. D. Ebberts, M. J. Langeslay, M. L. Ahmann, D. H. Feil, J. R. Skalski, and R. L. Townsend. 2009. Assessment of barotrauma from rapid decompression of depth-acclimated juvenile Chinook Salmon bearing radiotelemetry transmitters. Transactions of the American Fisheries Society 138:1285–1301.

Brown, R. S., B. D. Pflugrath, A. H. Colotelo, C. J. Brauner, T. J. Carlson, Z. D. Deng, and A. G. Seaburg. 2012b. Pathways of barotrauma in juvenile salmonids exposed to simulated hydroturbine passage: Boyle's law vs. Henry's law. Fisheries Research 129–130:43–50.

Cada, G. F. 2001. The development of advanced hydroelectric turbines to improve fish passage survival. Fisheries 26(9):14–23.

Carlson T. J., R. S. Brown, J. R. Stephenson, A. J. Gingerich, B. D. Pflugrath, A. H. A. Colotelo, A. E. Welch, P. L. Benjamin, J. R. Skalski, A. Seaburg, and R. L. Townsend. 2010. Assessment of barotrauma in untagged and tagged juvenile Chinook Salmon exposed to simulated hydro-turbine passage. Pacific Northwest National Laboratory, PNNL-19625, Richland, Washington.

Carlson, T. J., R. S. Brown, J. R. Stephenson, B. D. Pflugrath, A. H. Colotelo, A. J. Gingerich, P. L. Benjamin, M. J. Langeslay, M. L. Ahmann, R. L. Johnson, J. R. Skalski, A. G. Seaburg, and R. L. Townsend. 2012. The influence of tag presence on the mortality of juvenile Chinook Salmon exposed to simulated hydroturbine passage: implications for survival estimates and management of hydroelectric facilities. North American Journal of Fisheries Management 32(2):249–261.

Carlson, T. J., and J. P. Duncan. 2003. Evolution of the sensor fish device for measuring physical conditions in severe hydraulic environments. U.S. Department of Energy, DOE/ID-11079, Idaho Falls, Idaho.

Carlson, T. J., and M. Richmond. 2011. Strategies for assessing the biological performance and design of hydropower turbines. Pages 2-22–2-29 *in* T. Hogan, editor. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.

Colotelo, A. H., B. D. Pflugrath, R. S. Brown, C. J. Brauner, R. P. Mueller, T. J. Carlson, Z. D. Deng, M. L. Ahmann, and B. A. Trumbo. 2012. The effect of rapid and sustained decompression on barotrauma in juvenile Brook Lamprey and Pacific Lamprey: implications for passage at hydroelectric facilities. Fisheries Research 129–130:17–20.

Cook, T. C., G. E. Hecker, S. V. Amaral, P. S. Stacy, F. Lin, and E. P. Taft. 2003. Final report—pilot-scale tests Alden/concepts NREC Turbine. Prepared for U.S. Department of Energy, Washington, D.C.

Cook, T. C., G. E. Hecker, H. B. Faulkner, and W. Jansen. 1997. Development of a more

Table 1. Summary of fish-friendly turbine characteristics: premise of development, application ranges, operational details, and fish passage survival.

		Application range						
Fish-friendly turbine type	Premise of development	Flow range (ft³/s)	Head range (ft)	Number of blades	Speed (rpm)	Passage survival	Notes	Reference
MGR	Reduce gaps in a conventional Kaplan unit to minimize potential for injury and increase power output	6,200 to 18,500[1]	41 to 77[1]	4 to 6[1]	75 to 100[1]	Bonneville: 93.9 to 98.2%; Wanapum: 97.8% (overall weighted mean); Box Canyon: 96.5% (extended) for juveniles and 84.9% (extended) for adults	In each case, passage survival was not significantly different from conventional Kaplan units, though MGRs produced more power comparatively	for Bonneville: Normandeau et al. (2000); for Wanapum: Skalski et al. (2005); for Box Canyon: Normandeau (2012)
Alden	Design new turbine runner using known fish injury mechanism thresholds as design criteria	600 to 11,500	30 to 120	3	≤ 120	98% (predicted)	Survival is predicted; not yet field validated	EPRI and DOE (2011b)
VLH	Modify a Kaplan unit to target very low head; minimize civil engineering costs	353 to 1,059	5 to 15	8	≤ 40	Millau 2008: 98.6% for Atlantic aalmon smolts (overall extended); Frouard 2010: 100% for eels (extended); Millau 2013: 95.6 to 100% for Rainbow Trout and Carp	2008 testing was with a prototype unit; later tests were with modified units	for Millau 2008: Lagarrigue et al. (2008); for Frouard 2010: Lagarrigue and Frey (2011); for Millau 2013: Lagarrigue (2013)
Archimedes	Adapt ancient pumping technology for power generation at very low head	4 to 353	3 to 33	3 to 5 (typically 3)	≤ 40	River Dart: 100% for eels and salmon kelts; River Derwent: 100% for all species	Small sample sizes were used for most species	for River Dart: Fishtek Consulting (2008); for River Derwent: Fishtek Consulting (2009a)

[1] Operational ranges based on installations at Bonneville, Wanapum, and Box Canyon.

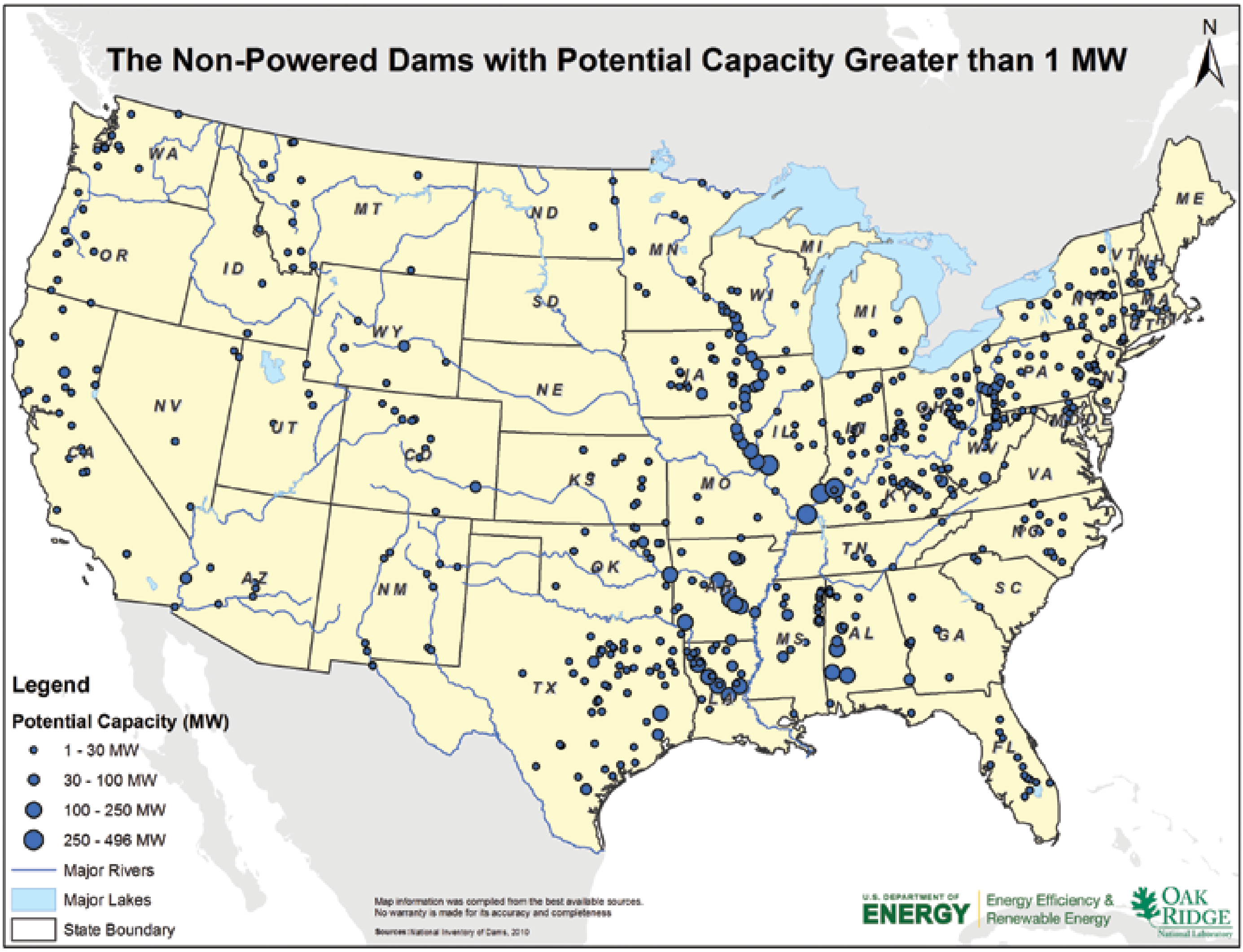

Figure 5. Location of the top non-powered dams in the United States with potential capacities greater than 1 MW.

fish tolerant turbine runner, advanced hydropower turbine system. Prepared for the U.S. Department of Energy, Idaho Falls, Idaho.

Deng, Z., T. J. Carlson, J. P. Dnucan, M. C. Richmond, and D. D. Dauble. 2010. Use of an autonomous sensor to evaluate the biological performance of the advanced turbine at Wanapum Dam. Journal of Renewable Sustainable Energy 2:053104-1–053104-11.

Deng, Z., J. J. Martinez, A. H. Colotelo, T. K. Abel, A. P. LeBarge, R. S. Brown, B. D. Pflugrath, R. P. Mueller, T. J. Carlson, A. G. Seaburg, R. L. Johnson, and M. L. Ahmann. 2011. Development of external and neutrally buoyant acoustic transmitters for juvenile salmon turbine passage evaluation. Fisheries Research 113(1):94–105.

EES Consulting. 2011. Box Canyon Hydroelectric Project. FERC No. 2042. Downstream fishways, fish behavior, survival and design investigations plan. Submitted by Pend Oreille County Public Utility District, Newport, Washington.

EPRI (Electric Power Research Institute). 2007a. Investigation of hydro-turbine leading-edge shapes favorable to fish survival. Prepared by Alden Research Laboratory, Inc., Holden, MA, EPRI Report No. 1012561.

———. 2007b. Program on technology innovation: redesign of the Alden/Concepts NREC helical turbine for increased power density and fish survival: scroll case redesign. Prepared by Alden Research Laboratory, Inc., Holden, MA, EPRI Report No. 1014810.

———. 2008. Evaluation of the effects of turbine blade leading edge design on fish survival. Prepared by Alden Research Laboratory, Inc., Holden, MA, EPRI Report No. 1014937.

———. 2009. Redesign of the Alden/concepts NREC helical turbine for increased power density and fish survival: evaluation of conceptual prototype turbine. Prepared by Alden Research Laboratory, Inc., Holden, MA, EPRI Report No. 1015600.

———. 2011. 2010 Tests examining survival of fish struck by turbine blades. Prepared by Alden Research Laboratory, Inc., Holden, MA, EPRI Report No. 1024684.

EPRI and DOE (U.S. Department of Energy). 2011a. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, CA. Prepared for the U.S. Department of Energy, Washington, D.C.

———. 2011b. Fish friendly hydropower turbine development and deployment: Alden turbine preliminary engineering and model testing. EPRI, Palo Alto, California, and the U.S. Department of Energy, Washington, D.C.

Federal Energy Regulatory Commission. 2008. Order issuing new license for Project No. 2114-116 to Public Utility District No. 2 of Grant County, Washington.

Fishtek Consulting. 2007. Fish monitoring and live fish trials. Ritz Atro Archimedes Screw Turbine, River Dart. Phase 1 report: live fish trials, smolts, leading edge assessment, disorientation study, outflow monitoring. Prepared for Mann Power Consulting Ltd., York, U.K.

———. 2008. Archimedes screw turbine fisheries assessment. Phase II: eels and kelts. Prepared for Mann Power Consulting, York, U.K.

———. 2009a. Howsham fish monitoring: assessment of fish passage through the Archimedes turbine and associated by-wash. Prepared for Mann Power Consulting, York, U.K.

———. 2009b. The Archimedes screw turbine: assessment of three leading edge profiles—8 mm steel edge, hard rubber and compressible bumper. Prepared for Mann Power Consulting, York, U.K.

Hadjerioua, B., Y. Wei, and S. Kao. 2012. An assessment of energy potential at non-powered dams in the United States. Prepared for the U.S. Department of Energy, Wind and Water Power Program by Oak Ridge National Laboratory, Oak Ridge, TN.

Hecker, G. E., and T. C. Cook. 2005. Development and evaluation of a new helical fish friendly hydro-turbine. Journal of Hydraulic Engineering 131:835–844.

Hecker, G. E., S. Li., and J. Foust. 2011. Verification of a numerical model to assess fish survival in the Alden turbine. Pages 2-69–2-79 *in* T. Hogan, editor. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.

Heisey, P. G., and C. Avalos. 2011. Assessing fish condition after passage through fish-friendly turbines using a release–recapture method. Pages 2-165–2-176 *in* T. Hogan, editor. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.

Kiel, J., and L. Ebner. 2011. Computational analysis of fish survival at the John Day powerhouse. Pages 2-186–2-195 *in* T. Hogan, editor. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.

Lagarrigue, T., and A. Frey. 2011. Test for evaluating the injuries suffered by downstream-migrating eels in their transiting through the new spherical discharge ring VLH

turbogenerator unit installed on the Moselle River in Frouard (54)—tests of October 2010 on yellow and silver eels. Prepared by Etudes et Conseils en Gestion de l'Environnement Aquatique (ECOGEA), Pins-Justaret, France.
Lagarrigue, T. 2013. Tests for evaluating damage to fish species migrating downstream during their transit through the VLH hydraulic turbine installed on the Tarn River in Millau - report on tests run in May and June 2013. Prepared by Etudes et Conseils en Gestion de l'Environnement Aquatique (ECOGEA), Pins-Justaret, France.
Lagarrigue, T., B. Voegtle, and J. M. Lascaux. 2008. Tests for evaluating the injuries suffered by downstream migrating salmonid juveniles and silver eels in their transiting through the VLH turbogenerator unit installed on the Tarn River in Millau—tests of February 2008 on Atlantic Salmon smolts. Prepared by Etudes et Conseils en Gestion de l'Environnement Aquatique (ECOGEA), Pins-Justaret, France.
Leclerc, M. 2008. Turbine de tres basses chutes [Very low head turbine]. MJ2 Technologies SARL, Newsletter No. 7, Millau, France.
———. 2010. Turbine de tres basses chutes [Very low head turbine]. MJ2 Technologies SARL, Newsletter No. 10, Millau, France.
Lin, F., G. E. Hecker, and T. C. Cook. 2004. Understanding turbine passage survival using CFD. HCI Publications, Inc., Proceedings of Hydrovision 2004, St. Louis, Missouri.
Medina, G. J., and M. K. Shutters. 2011. U.S. Army Corps of Engineer's Turbine Survival Program. Pages 2-13–2-21 *in* T. Hogan, editor. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.
Nelson, S., and T. Freeman. 2011. New turbine design criteria and process at the Ice Harbor Project. Pages 2-80–2-86 *in* T. Hogan, editor. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.
Normandeau Associates, Inc. 2012. Direct survival/condition of juvenile and adult Rainbow Trout passed through spillbay 2, and existing turbine (Unit 2), and a newly installed turbine (Unit 4) at Box Canyon Hydroelectric Project (FERC No. 2042), Pend Oreille River, Washington. Prepared for Public Utility District No. 1 of Pend Oreille County, Newport, Washington.
Normandeau Associates, Inc., J. R. Skalski, and Mid Columbia Consulting, Inc. 2000. Direct survival and condition of juvenile Chinook Salmon passed through an existing and new minimum gap runner turbines at Bonneville Powerhouse, Columbia River. Prepared for Portland District, U.S. Army Corps of Engineers, Portland, Oregon.
Normandeau Associates, Inc., J. R. Skalski, and R. L. Townsend. 2006. Performance evaluation of the new advanced hydro turbine (AHT) at Wanapum Dam, Columbia River, Washington. Prepared for Grant County Public Utility District No. 2, Ephrata, Washington.
Odeh, M. 1999. A summary of environmentally friendly turbine design concepts. U.S. Department of Energy, DOE/ID-13741, Idaho Falls, Idaho.
Perkins, N. F., and D. A. Dixon. 2011. Demonstrating the performance of the Alden turbine in the real world. Pages 2-219–2-225 *in* T. Hogan, editor. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.
Ploskey, G. R., G. E. Johnson, A. E. Giorgi, R. I. Johnson, J. R. Stevenson, C. R. Schilt, P. N. Johnson, and D. S. Patterson. 2007. Synthesis of biological research on juvenile fish passage and survival at Bonneville Dam through 2005. Pacific Northwest National Laboratory, PNNL-15041, Richland, Washington.
Richmond, M., J. S. Serkowski, T. J. Carlson, L. L. Ebner, M. Sick, and G. F. Cada. 2011. Computational fluid dynamics framework for turbine biological performance assessment. Pages 2-49–2-58 *in* T. Hogan, editor. EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers. EPRI, Palo Alto, California, and U.S. Department of Energy, Washington, D.C.
Sale, M. J., G. F. Cada, and D. D. Dauble. 2006. Historical perspective on the U.S. Department of Energy's hydropower program. HCI Publications, Proceedings of Hydrovision 2006, Portland, Oregon.
Skalski, J. R., R. L. Townsend, and Normandeau Associates, Inc. 2005. Quantitative evaluation of the performance of the new Advanced Hydro Turbine System (AHTS) at Wanapum Dam, Columbia River, Washington. Prepared for Public Utility District No. 2 of Grant County, Ephrata, Washington.
Spah, H. 2001. Fishery biological opinion of the fish compatibility of the patented hydraulic screw from Ritz Atro. Bielfield, Germany.
Trumbo, B. A., M. L. Ahmann, J. F. Renholds, R. S. Brown, A. H. Colotelo, and Z. D. Deng. 2013. Improving hydroturbine pressures to enhance salmon passage survival and recovery. Reviews in Fish Biology and Fisheries. DOI 10.1007/s11160-013-9340-8.
USACE (U.S. Army Corps of Engineers). 2008. Bonneville configuration and operation plan. Amendment #1. Juvenile fish passage recommendations. U.S. Army Corps of Engineers, Portland, Oregon.
U.S. Department of Energy (U.S. DOE). 2014. Water Power Program. Available: http://www1.eere.energy.gov/water/index.html. (March 2014).

90 YEARS AGO - FROM THE ARCHIVES

On May 16th of this year a Conference was called of representatives from every out-of-door section of the country, including everything from Child Welfare to the Conservation of the Forests Fish and Game. This was the first message, so to speak, from the President of the United States to all the people of the United States that out-of-door recreation was of prime importance. The Conference was an exceedingly comprehensive one. It was attended by five or six hundred delegates, and President Coolidge in his opening address, which did not take more than twelve or fifteen minutes, made a clarion call that rang all over the world—it was a wonderful thing.

F. C. Walcott (1924): Report of committee to attend the President's Conference on Outdoor Recreation, *Transactions of the American Fisheries Society*, 54:1, 17.