EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers

Cover image (left to right, top to bottom) (1) sensor fish; (2) Alden turbine; (3) aerating Francis turbine; (4) CFD streamlines on turbine runner; (5) Kaplan minimum gap runner (MGR); and (6) Hi-Z Tag.

EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines: Technical Papers

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Product Description

This report presents the proceedings of a conference held to discuss developments in the field of environmentally friendly hydroturbines. The Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE), in cooperation with the U.S. Army Corps of Engineers (USACE), the U.S. Bureau of Reclamation (USBR), and the National Hydropower Association (NHA), conducted the conference May 19–20, 2011, in Washington, D.C., to disseminate information on the state of the art in environmentally enhanced hydroturbines. This report describes the development and organization of the conference and presents extended abstracts for the conference presentations.

Background

The EPRI-DOE Conference on Environmentally Enhanced Hydropower Turbines was held under the auspices of a larger project in which the fish-friendly Alden turbine underwent final developmental engineering required to advance the commercialization of this technology. Conveying the results of these final engineering efforts thus encompassed a large part of the conference. The conference was also an outgrowth of a federal Memorandum of Understanding among DOE, USBR, and USACE to share technical information on hydropower.

More generally, the conference presented an opportunity for a comprehensive review of the recent research that has spurred the development of useful turbine technologies for the hydropower industry. The results can be used by the industry to reevaluate its strategy for making use of these technologies to increase the generation of renewable hydropower while minimizing potential impacts to the environment.

Objectives

The objective of the conference was to demonstrate that environmentally enhanced hydro technologies are ready for deployment and demonstration. These technologies have undergone more than 15 years of intensive research and development by the hydropower industry's top engineers and biologists. Consequently, turbines (including the Alden turbine) that have fish-friendly, energy-efficient and water-quality-enhancing features are now commercially available and ready for full-scale deployment.

Approach

EPRI formed a conference organizing committee to aid in developing the content of this conference. Committee membership was diverse, with representation from multiple federal agencies and private industry. Having broad-based representation was instrumental in providing the opportunity for interagency collaboration.

Results

The agenda for the one-and-a-half-day conference featured six sessions:

1. Progress in Developing New Technologies
2. Approaches to Addressing Turbine Fish Impacts
3. New Turbines for Downstream Fish Passage
4. New Turbines for Improved Water Quality
5. Tools for Verifying Turbine Performance
6. Planned Demonstration Projects

A total of 26 presentations were delivered, for which extended abstracts are included in this proceedings document. Conference attendance exceeded 100.

Applications, Value, and Use

The target audience included not only technology experts, but also resource agency staff, regulating authorities, legislators, and hydropower owners who may be interested in the benefits that these technologies offer. It was the organizing committee's intent that this conference serve as a referendum on the need for additional deployment and demonstration of these technologies.

Keywords

Hydropower
Environmentally enhanced hydroturbines
Fish-friendly hydroturbines
Downstream fish passage
Conference proceedings

Abstract

The EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines was a component of a larger project. The goal of the overall project was to conduct the final developmental engineering required to advance the commercialization of the Alden turbine. As part of this effort, the conference provided a venue to disseminate information on the status of the Alden turbine technology as well as the status of other advanced turbines and research on environmentally-friendly hydropower turbines. The conference was also a product of a federal Memorandum of Understanding among DOE, USBR, and USACE to share technical information on hydropower.

The conference was held in Washington, DC on May 19 and 20, 2011 and welcomed over 100 attendees. The Conference Organizing Committee included the federal agencies with a vested interest in hydropower in the U.S. The Committee collaboratively assembled this conference, including topics from each facet of the environmentally-friendly conventional hydropower research community.

The conference was successful in illustrating the readiness of environmentally-enhanced hydropower technologies. Furthermore, the topics presented illustrated the need for additional deployment and field testing of these technologies in an effort to promote the growth of environmentally sustainable hydropower in the U.S. and around the world

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Section 1: Introduction

Background

Turbines that are fish-friendly (up to 100% survival of fish passing through the turbine), energy efficient, and able to mitigate water quality issues are now commercially available and ready for full-scale deployment. Significant progress has been made in recent years in the development of environmentally-enhanced conventional hydro turbines, beginning in the early 1990s with the efforts of the U.S. Army Corps of Engineers' (USACE's) Turbine Survival Program and the U.S. Department of Energy's (DOE) Advanced Hydropower Turbine Systems (AHTS) Program. The AHTS program commenced with an initial financial contribution of \$500,000 from EPRI and a coalition of industry supporters. The DOE matched this contribution and subsequently solicited proposals from the industry to develop environmentally-enhanced hydropower turbine technologies that were also efficient for generating hydroelectric power. Research and development (R&D) was envisioned as a three-phase effort focusing on 1) conceptual designs, 2) detailed designs and model testing, and 3) construction and testing of full-sized prototypes. From this solicitation, awards were made for the design of fish-friendly hydro-turbines to two teams: one led by Voith Hydro, Inc. (Voith) and the other by Alden Research Laboratory (Alden). The Voith concept focused on modifying an existing (Kaplan) runner design; the Alden concept focused on a radical new runner design created specifically for safely passing fish.

Along with the development of the two turbine designs mentioned above, there has also been considerable research on the methods and tools required to measure fish passage survival, to quantify potential injury mechanisms associated with fish passage through turbines, to assay the responses of fish to those injury mechanisms, and to verify generation performance. These details feed into an effective and efficient turbine design/modification process in which biological criteria can be taken into account while engineering efficient machines for producing carbon-free electricity. These methods and tools also provide a means to verify the predicted performance of these technologies in a full-scale field setting. Beyond the advancement in turbines designed to safely pass fish downstream, other significant advancements have been made with technologies designed to address common downstream water quality issues (e.g., low dissolved oxygen [DO] in tailraces and the potential release of oil and grease used for lubrication of turbine components). EPRI and DOE identified the need to disseminate information relative to all of the above advancements in the design, evaluation, and testing of environmentally-enhanced hydro-turbines, and

subsequently assembled a Conference Organizing Committee to develop a one and half-day conference on these topics.

In 2010, an ambitious new Memorandum of Understanding (MOU) on hydropower was established among the U.S. Department of Energy, the DOE, the Department of the Interior's U.S. Bureau of Reclamation (USBR), and the USACE. This federal MOU focused specifically on development of reliable, affordable and environmentally sustainable hydropower. It included an action item on technology development and deployment that committed to share research and development information on emerging new technologies. Since these federal agencies are supporting most of the fish-friendly technologies relevant to this conference, the agencies were recruited to help organize the conference.

Conference Objective

As part of the larger project in which the fish-friendly Alden turbine underwent final developmental engineering, this conference was designed to provide a forum to share results of this work. It was also designed to put this work in the context of other advancements in the field by providing a forum in which other research on environmentally-enhanced hydroturbines, such as that taking place at DOE's national labs, could be shared. Tremendous strides have been made in the development of turbine technologies designed to address the modern day environmental concerns associated with hydropower. Deployment and demonstration of these technologies is critical for the advancement of environmentally sustainable hydropower in the U.S. The target audience, therefore, included not only technology experts, but also staff from resource agencies, regulatory authorities, legislators, and hydropower owners that may be interested in the benefits that these technologies offer.

Conference Organizing Committee

A critical component to the success of this conference was the collaborative nature in which it was developed and implemented. EPRI sought input from the major organizations interested in environmentally-friendly hydropower development in the U.S. by inviting them to participate in the development of this conference. The resulting Conference Organizing Committee was comprised of representatives from EPRI, the DOE, the USACE, the USBR, and the National Hydropower Association (NHA). With the diverse representation from each of these groups, the Committee was able to develop an equally robust agenda that covered a broad range of topics related to the subject of environmentally-friendly hydropower.

As noted above, of particular importance was the participation of each of the federal agencies that entered into the federal MOU. This conference, with substantial participation by the MOU agencies in the Conference Organizing Committee, was successful in satisfying a principal goal of the MOU, namely to convene a workshop to discuss federally-funded efforts, initiatives, and technology R&D in the hydropower industry.

Agenda

The agenda was developed over approximately six months through periodic conference calls with the Conference Organizing Committee. The conference was comprised of the six sessions listed in the agenda (Figure 1-1). Brief descriptions of each session are provided below.

SESSION 1: Progress in Developing New Turbine Technologies – This introductory session was designed to highlight the successes in developing new technologies and advancing the role of hydropower in the U.S. It provided both historical context and a status update of advanced turbine development in the U.S. The topics discussed demonstrated that although hydropower is often considered a mature technology, there is still plenty of room for technological innovation in both environmental and energy performance.

SESSION 2: Approaches to Addressing Turbine Fish Passage Issues – This session focused on the recent research that has been conducted on the biology of turbine passage issues. Panelists in this session highlighted the range of approaches needed in assessing the biological performance of turbines, from detailed research on an individual turbine component to a fully systematic approach incorporating everything from numerical modeling to monitoring the responses of fish passing through turbines.

SESSION 3: New Turbines for Downstream Fish Passage – This session presented information about the various new turbine designs available for use as downstream passage routes for fish. The turbines discussed included the Alden turbine, the Voith Minimum Gap Runner (MGR) Kaplan, and advanced adjustable (Kaplan) and fixed-blade units at the Ice Harbor Project. This session emphasized that there are exciting, new, environmentally-enhanced turbine designs available for full-scale deployment that have been put through the rigors of scientific scrutiny and are ready for increased commercial application.

SESSION 4: New Turbines to Improve Water Quality – This session presented information on turbine technologies designed to improve downstream water quality parameters. The technologies discussed included aerating turbines to increase DO concentrations in tailraces as well as more environmentally-friendly turbine lubrication systems.

SESSION 5: Tools for Verifying Turbine Performance – This session presented information on the tools available for verifying the biological performance of environmentally-enhanced turbine technologies. The presentations demonstrated that not only are new turbine technologies now available, but the tools required to verify their performance have been developed and are available as well.

SESSION 6: Next Steps in Deploying and Demonstrating Enhanced Turbines –
This session's goal was to envision the future for these environmentally-enhanced turbine technologies. The presentations demonstrated that tremendous strides have been made in the development of turbine technologies designed to address the modern day environmental concerns associated hydropower. As the panelists indicated, the next step is to deploy and test the turbines in the field.

Thursday, May 19, 2011		
Continental Breakfast: 7:00 AM		
Time	Presentation Title	Presenter
SESSION 1: Progress in developing new turbine technologies		
Moderator: Linda Church-Ciocci, National Hydropower Association		
8:00	Welcome & Keynote	Invited speaker TBD
8:20	Public-private partnerships in advanced turbine development	Mike Sale, DOE Consultant
8:40	EPRI's program to develop, install and test the "new wheel" - the Alden turbine story	Doug Dixon, EPRI
9:00	U.S. Army Corps of Engineers (USACE) Turbine Survival Program	George Medina, USACE
9:20	U.S. Bureau of Reclamation's progress in improving hydropower	Max Spiker, Bureau of Reclamation
9:40	Q&A	
10:00	Break	
SESSION 2: Approaches to addressing turbine fish passage issues		
Moderator: Glenn Cada, Oak Ridge National Laboratory (ORNL)		
10:20	Strategies for assessing the biological performance and design of hydropower turbines	Thomas Carlson, Pacific Northwest National Laboratory (PNNL)
10:40	Injury mechanisms for juvenile Chinook salmon passing through hydropower turbines	Alison Colotelo, PNNL
11:00	Designing leading edges of turbine blades to increase fish survival from blade strike	Steve Amaral, Alden
11:20	Computational fluid dynamics framework for turbine biological performance assessment	Marshall Richmond, PNNL
11:40	Q&A	
12:00	Lunch	
SESSION 3: New turbines for downstream fish passage		
Moderator: Douglas Dixon, Electric Power Research Institute		
1:20	The Alden fish friendly turbine: preliminary design, model performance, and applicability to hydro sites	Brian Murtha, Voith Hydro
1:40	Verification of a numerical model to assess fish survival in the Alden turbine	George Hecker, Alden
2:00	New turbine design criteria and process at the Ice Harbor Project	Shawn Nelson, USACE
2:20	The Wanapum success story: improved salmon passage & increased generation	Steve Brown, HDR
2:40	Q&A	
3:00	Break	
SESSION 4: New turbines to improve water quality		
Moderator: Charles Allen, U.S. Army Corps of Engineers		
3:20	Hydraulic and environmental performance of aerating turbines	Patrick March, HPPI
3:40	The technical challenges of dissolved oxygen enhancement	Michel Sabourin, Alstom
4:00	Using dissolved oxygen prediction methodologies in the selection of turbine aeration equipment	Jason Foust, Voith Hydro
4:20	Turbine lubrication systems - small changes can make a big difference in water quality	Eric Auger, AECOM
4:40	Q&A	
5:00	ADJOURN FOR DAY	
5:30-7:30	Conference Reception: Washington Court Hotel, Cocktails and Hors d'œuvres	

Figure 1-1

Agenda from the EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines

Friday, May 20, 2011		
Continental Breakfast: 7:00 AM		
Time	Presentation Title	Presenter
SESSION 5: Tools for verifying turbine performance		
Moderator: Max Spiker, Bureau of Reclamation		
8:00	Development of external and neutrally buoyant acoustic transmitters for turbine passage evaluation	Daniel Deng, PNNL
8:20	Assessing fish condition after passage through fish-friendly turbines with the HI-Z Tag Recapture Technique	Paul Heisey, Normandeau
8:40	Physical modeling methods and techniques	Robert Davidson, USACE
9:00	Computational analysis of fish survival at the John Day Powerhouse	James Kiel, USACE
9:20	Estimating juvenile salmon survival with implanted transmitters	Richard Brown, PNNL
9:40	Q&A	
10:00	Break	
SESSION 6: Next steps in deploying and demonstrating enhanced turbines		
Moderator: Mike Sale, Department of Energy Hydropower Consultant		
10:30	Developing environmental standards and best practices for hydraulic turbines	Juliusz Kirejczyk, Toshiba
10:45	Expected fish survival for full scale deployment of the Alden turbine	Greg Allen, Alden
11:00	Demonstrating the performance of the Alden turbine in the real world	Norman Perkins, Alden
11:15	Potential markets for new turbines	Brennan Smith, ORNL
11:30	Panel Discussion: Conference Round-up & Summary	Session Moderators
12:30	Adjourn	
12:30	Lunch to go	

Figure 1-1 (continued)
Agenda from the EPRI-DOE Conference on Environmentally-Enhanced Hydropower Turbines

Section 2: Extended Technical Abstracts

EPRI's Program to Develop, Install and Test the "New Wheel": The Alden Turbine Story

Douglas A. Dixon, Electric Power Research Institute

Norman Perkins, Alden Research Laboratory, Inc.

Abstract

In 1996, DOE, EPRI, and industry began a multi-year effort to develop 'fish-friendly' turbines. This arose from concerns over fish mortality caused by existing turbines, high cost and low performance associated with downstream fish screening and bypasses, and lost generation and water quality issues associated with spillage for fish passage. By 2001, the research produced two design concepts. The first or Kaplan minimum gap runner (MGR) turbine, for modernizing large river projects, has been installed and tested at several Columbia River projects. The second, for new units in smaller rivers and fish bypasses, is the Alden turbine which features a helical-shaped runner with only three blades. DOE pilot-scale/laboratory tests with this turbine demonstrated that fish survival, when scaled to a full-size field installation, would be in excess of 98% for many fish species. Following initial proof-of-concept testing, an optimized conceptual design of the Alden turbine with increased power density to be competitive with existing designs was completed. Once the conceptual design was completed, EPRI and DOE funded Alden and Voith Hydro to enhance the turbine's performance through modification of the hydraulic passageways, including the spiral case, distributor, runner and draft tube. Each design modification was also evaluated for fish passage in order to ensure that the original fish friendly characteristics of the machine were maintained. The final stage of the Alden turbine design effort included a model test at Voith Hydro's hydraulic laboratory in York, PA, in addition to the updated mechanical and balance of plant equipment sizing necessary for actual field installation. Model testing indicated a maximum calculated prototype efficiency of almost 94% at conditions corresponding to a prototype net head and flow of 92.0 ft and 1,504 cfs, respectively. The tested performance characteristics were also flat across the anticipated operating range for the design prototype. The scope of supply and pricing information for the commercial design application was determined to be roughly \$1,450/kW with a total supply cycle of 28 months. These costs include turbine, generator, unit controls, limited balance of plant equipment, field installation, and commissioning. The next stage in developing the Alden turbine

is a field demonstration project. Toward that goal, EPRI in 2010 launched an industry solicitation for potential demonstration sites. Twenty-three applications were received and quantitatively evaluated and a preferred alternate site was selected. EPRI is currently working with the owner of the preferred site toward developing the demonstration project.

Background

By the late 1980s, environmental issues were emerging as a growing problem for the hydropower industry. This was a natural outgrowth of the environmental movement as well as a result of growing concerns about the severe population declines in high profile wild stocks of Pacific and Atlantic salmon and American shad and the contribution the extensive public and private hydropower system was contributing to their decline (OTA 1995). A 1991 DOE sponsored survey (Sale et al. 1991) of non-federal projects documented the extent of the environmental concerns and found that fish passage (upstream and downstream) and instream flow protection were two key issues requiring mitigation. As Sale et al (1991) noted, determination of instream flow requirements was the most common issue, and fish passage was the most costly. Beginning in the early 1990s, turbine entrainment and entrainment survival studies were increasingly being required (FERC 1995; EPRI 1997). Turbine entrainment, while highly variable, could be as high as 2,500 fish/hr (FERC 1995) and mortality could range from 0 to 100% (OTA 1995) depending on a number of site-specific factors. Despite controversy over the extent of turbine mortality, it was and is still widely believed to be a significant factor in the reduction of many anadromous (salmon and shad) and catadromous (eel) and riverine fish. The concern is greater when there are multiple dams in a basin because of the cumulative impact (Cada 1990). Fish Passage technology development to preclude turbine passage began in earnest in the 1990s (OTA 1995, EPRI 1998) and continue to this day¹. Overall, however, the effectiveness of many technologies is less than optimal, extremely expensive, and result in lost generation. In many cases, direct spillage for downstream fish passage protection is the preference to technologies and spillage results in significant generation loss (Coutant et al. 2006). Provisions for instream flow further result in foregone power generation. Sale et al. (2006) reviewed the costs of protection (>\$700,000/project average in 1991 dollars) and lost generation (>6,000 MWhr/yr for downstream passage and 2,500 MWhr/yr for instream flow) at non-federal projects, based on the aforementioned 1991 survey, and, as he notes, the frequency and costs of environmental mitigation have undoubtedly gone up since that study period. It is against this background that the idea for developing “fish-friendly” hydropower turbines evolved as subsequently discussed.

¹ For example, a Business Wire News Release of May 19, 2008 noted the initial success of Puget Sound Energy's new \$50 million “floating surface collector” at their Baker Lake Project in Washington. The 1,000-ton apparatus floating above Baker Lake's 280-foot-deep bottom is designed to attract and safely capture young salmon for transport around PSE's two Baker River hydropower dams. The river's 2008 out-migration of sockeye, biologists estimate, is at least 70 percent complete. With more than 200,000 juvenile sockeye already collected, the out-migration is peaking as the second highest total run on record and may be on pace to shatter the existing record.

At a meeting in 1993 in Denver, CO among DOE, EPRI and the R&D Committee of the National Hydropower Association (NHA) the idea for developing “fish-friendly” turbines was born. The principle was straight-forward, downstream fish passage protection was more often than not problematic for performance and financial reasons, why not then improve performance of turbines to reduce the environmental impact thereby maintaining (possibly improving) hydropower generation? NHA formed the non-profit Hydropower Research Foundation (HRF) to support the research and along with an initial financial contribution of \$500,000 from EPRI and a coalition of industry supporters that was matched by DOE, the Advanced Hydropower Turbine System (AHTS) program began. R&D began as a three-phase, multi-year effort: (1) Phase I – conceptual designs; (2) Phase II - detailed design and model testing; and (3) Phase III - construction and testing of full-sized prototypes.

Phase I included competitive DOE solicitations and awards were made to two teams; one led by Voith Hydro, Inc. (now VSH) and the other by Alden. The Voith design (Odeh 1999) focused on how existing designs could be modified to improve efficiency and reduce fish injury and mortality. Voith’s concepts were applicable for rehabilitating or upgrading existing projects or for new turbine designs. Voith’s concepts moved rapidly through Phase II and III including several field projects to test concepts, most notably the new minimum gap runner (MGR) currently installed and undergoing testing at Grant County PUD’s Wanapum Project (Brown 2006; Dresser et al. 2006 a&b). DOE’s support of this project and other related projects essentially came to an end in 2005 when DOE’s Hydropower Program closed.

The Alden project focused on a radical new turbine runner design (Figure 2-1). The Alden runner was limited to three blades, reduced gradients of pressure and velocity, minimized clearance between the runner and housing, and maximized the size of flow passages (Odeh 1999). Because the Alden runner had never been built, DOE decided to build a prototype and test facility where its performance could be evaluated. The test facility was constructed at Alden and testing began in 2001 and ran through 2003 (Cook et al 2003). Based on the prototype test results and compared to field data from traditional turbines, the Alden turbine is predicted to have substantially higher fish survival rates for comparable flows, heads, and fish types. Engineering performance indicated that the turbine efficiency can be expected to be about 90% in full-size runners (Hecker and Cook 2005; Hecker and Allen 2005). The Phase III field deployment and testing effort for this new design, unfortunately, was not accomplished despite a DOE solicitation. Essentially, the timing for field deployment; i.e., a hydropower operator with new development plans did not exist at the time of the DOE solicitation. The close-out of the DOE Hydropower Program in 2005 further ended the possibility of a Phase III effort.

*Figure 2-1
Original Alden Turbine Runner*

In 2006, EPRI, in recognition of the unfulfilled potential with the Alden turbine and the need to continue its development toward a machine that could be manufactured, initiated continued conceptual developmental work. The EPRI developmental work on the Alden turbine focused on re-design of the scroll case (EPRI 2007) to double its flow-handling capability and re-design of the runner and draft tube and overall conceptual optimization of the scroll-runner-draft tube system (EPRI 2009). Funding support comes from EPRI membership and specific-company sponsorship. In parallel to the work on the turbine, EPRI has also sponsored a multi-year program to investigate the relationship between turbine leading edge blade shapes and fish injury and mortality (EPRI 2008). Potential favorable leading edge blade designs were identified for testing using computational fluid dynamics (CFD) techniques (Figure 2-2), a test facility (flume) was constructed, and two-years of testing performed. Key results from this effort were that as the ratio of the diameter of the leading edge of the turbine blade and fish length increased, survival decreased. Essentially, rounded and wide leading edge blade shapes reduce fish injury and increase survival (Amaral et al. 2008; EPRI 2008). Results of this research were incorporated into the conceptual design of the Alden turbine to further insure the environmental performance of the turbine when it is deployed and tested.

Figure 2-2
CFD Image of Alden Turbine Runner

EPRI-DOE Preliminary Engineering and Model Testing

Collaborative research among EPRI, DOE and industry recently improved the performance characteristics of the Alden turbine while maintaining its fish-friendly characteristics. This research resulted in the preliminary engineering required to make the turbine commercially available. The primary goal of the recent engineering study was to provide a cost competitive turbine that produces fish passage survival rates comparable to or better than the survival rates associated with bypassing or spilling flow. Throughout this research study, design modifications to the turbine components were shown to improve the turbine efficiency to almost 94% at the selected design point, while providing the same or slightly improved fish survival characteristics. The predicted survival rate of fish passing through the full scale turbine is greater than 98% for a 200 mm long fish. These turbine modifications were also selected to decrease manufacturing and supply costs, resulting in a design that is significantly more competitive than the earlier version.

After the release of the modified Alden turbine geometry, a physical model of the turbine was designed and constructed for performance testing in Voith Hydro's hydraulic laboratory in York Pennsylvania. During the time period from September to November 2010, efficiency, power, cavitation inception, axial thrust, pressure pulsations, wicket gate torque, runaway speed and steady radial thrust data were collected across a range of head and flows corresponding to an application at Brookfield Renewable Power's School Street Station. The tested peak efficiency level scales to nearly 94% for prototype application, with flat performance characteristics demonstrated across the majority of the anticipated operating range. Visual observations from below the runner verify that the 7.4 psia minimum pressure criteria is met at the design condition. Further data for pressure pulsations, runaway speed and axial thrust fall within values anticipated for conventional application.

Figure 2-3 and Figure 2-4 show the model runner under construction.

Figure 2-3
Model Blade Assembly without Band (prior to testing)

Figure 2-4
Photo of Assembled Turbine Runner with Band (prior to testing)

The final aspect of the developmental engineering phase relates to the design for the supporting mechanical and balance of plant equipment for supply of the complete unit. In this phase, Finite Element Analysis (FEA) has been performed to determine the static stresses for the stay vanes, wicket gates and runner modifications. Mechanical design and analysis of the final spiral case and stay

ring decks has also been completed. Design of the overall power-unit incorporates a generator featuring a combined vertical thrust and radial guide bearing located below the generator rotor and a water lubricated turbine guide bearing. At the completion of the study, the scope of supply and pricing information for commercial application at School Street Station was determined to be roughly \$1,450/kW with a total supply cycle of 28 months. These costs include turbine, generator, unit controls, limited balance of plant equipment, field installation, and commissioning. The final report (EPRI 2011) of this effort is available and free for public download on EPRI's website at: http://my.epri.com/portal/server.pt?Product_id=000000000001019890.

Figure 2-5
Photo of Final Model Turbine Runner with Band

EPRI Demonstration Site Selection

EPRI conducted a study to identify a demonstration project for the installation and testing of the Alden turbine. In mid 2010, a solicitation was distributed to the hydropower industry for potential demonstration sites. A quantitative evaluation process was developed and implemented to objectively evaluate and rank the applications. Site visits to the five highest ranked candidate sites were conducted during the fall of 2010 to verify application information and collect additional project details. The five sites were then again quantitatively evaluated based upon applicant commitment, sizing and general layout of turbine and water conveyance, predictions of fish survival, and project development schedule. A final numeric ranking of the sites led to the selection of one site as the preferred location for development as a demonstration program for the Alden turbine. An alternate site was also identified in the event the preferred site could not be developed. In 2012, pending receipt of commitment from the preferred demonstration site host company, EPRI will assist the owner with activities that will further the design, installation, and funding of the field demonstration project.

EPRI Demonstration Project Development

The next phase of research for the Alden Turbine is implementing a field demonstration project whereby the anticipated performance of the turbine can be verified for ultimate acceptance by resource and regulatory agencies, environmental stakeholders, and, most importantly, the hydropower industry. Both engineering and biological testing is planned with the results to be generally available to all interested organizations.

In 2011, pending receipt of a commitment to proceed from the preferred demonstration site host company, EPRI will assist the owner with activities that will further the design, installation, and funding of the field demonstration project. Key demonstration program development activities include:

1. Turbine Design: the preliminary design which will result from the ongoing EPRI-DOE project will need to be modified for the selected demonstration site. This task includes scaling the current turbine design to the demonstration site conditions. Scaling may include resizing the turbine runner diameter and speed of the unit depending on head and flow conditions. Based upon the scaling results, mechanical equipment sizing may need to be analyzed and adjusted.
2. Demonstration Program Plan: for the selected demonstration site an overall management plan needs to be developed such that implementation activities can effectively proceed. The management plan will include documentation of all activities to be performed for implementing the demonstration project including the funding plan, turbine purchase, site preparation and construction, turbine installation and performance testing.
3. Funding Plan: there is an expectation that the host will provide a significant amount of the funding needed for the demonstration. In addition, the funding plan will have two additional components: (1) preparation of a proposal to DOE for the demonstration project (a DOE funding opportunity is expected in the first half of 2011) and (2) preparation of marketing materials that will be used to solicit collaborative Demo funding in support of the project.
4. Preliminary Site Design Plan: involves preliminary design of all demonstration site components to support the turbine's installation including intake gates and/or penstocks, power house, draft tubes, and tailrace modifications.

It is hoped that by 2012-13 the turbine fabrication and installation can begin and its performance evaluated during 2014-15.

Potential Market

Several types of installations can be considered for the application of the Alden turbine at existing and new hydro projects. These include project expansions, powering non-power dams, and use of the turbine as a means to generate power from minimum flow releases and fish bypasses. The turbine is not planned as a

modernization unit, however, that application is possible particularly at locations where protecting endangered and threatened fish species is an issue. Project expansions and unit replacements can be accomplished without the need for new, modified, or additional downstream fish passage facilities. The suitability of the Alden turbine for any of these purposes will be based on certain biological and engineering criteria. In general, the turbine can be considered for any projects with more than 20 ft of head, available flows greater than about 900 cfs, and for fish less than 200 mm (8 in) in length. Depending on the operational conditions (mainly runner rotational speed), larger fish may pass through the turbine with little or no mortality. Also, results of laboratory testing with a pilot-scale unit and various leading edge blade thicknesses indicate that larger sturgeon and adult American eel may have survival rates as high as 100%. The protection of sturgeon species is an important issue throughout the US due to declining or low population levels. Similarly, American eel have been the target of considerable interest from resource agencies and environmental groups due to population declines in the U.S. and Canada. Reducing turbine mortality of silver eels at hydro projects has been a major goal of state and federal agencies and non-governmental organizations.

Downstream fish passage is an issue that must be addressed at many non-federal and federal projects throughout the U.S. For non-federal projects, the NOAA Fisheries or the U.S. Fish & Wildlife Service typically prescribe upstream and downstream fish passage during the FERC licensing process. These mandatory downstream fish passage prescriptions nearly always involve diverting flow for bypass systems. Federal projects also must address downstream passage and it may involve the use of bypasses and/or spill through dam gates. The Alden turbine provides an opportunity to capture flows diverted through bypasses and spill gates and increase a project's generating capacity.

The potential market for the Alden turbine has not been directly assessed; however, a rough estimate can be made based on estimates of additional generating capacity available for development in the U.S. DOE has estimated that approximately 21,000 MW of generating capacity can be added at existing dams with and without current power developments and that about 19,000 MW could be generated at new small hydro developments (1 – 30 MW) (Conner et al. 1998; EPRI 2007). Conservatively assuming that one half of this additional generation is suitable for units in the 5 to 20 MW capacity range, there is a potential market for 2,000 turbines with an average capacity of 10 MW per turbine. This potential for increased generating capacity at existing and new developments provides for significant opportunity where the Alden turbine can meet future energy needs and, at the same time, address and mitigate downstream fish passage issues, which is one is often the leading environmental concern at many sites. The addition of fish-friendly turbines would allow water being used for minimum flows and downstream passage to be captured for energy production.

References

- Amaral, S., G. E. Hecker, and P. Stacy, and D. A. Dixon. 2008. Effects of Leading Edge Turbine Blade Thickness on Fish Strike Survival and Injury. HydroVision 2008 Technical Paper, HCI Publications, Kansas City, MO.
- Brown, S. R. 2006. Innovations in turbine design and fish protection at Wanapum, USA. Hydropower & Dams Issue 4.
- Brown, S. R., and G. M. Garnant. 2006. Advanced-design turbine at Wanapum Dam improves power output, helps protect fish. HydroReview Special Report. April 2006.
- Cada, G.F., T.J. Carlson, D.D. Dauble, R.T. Hunt, M.J. Sale, and G. L. Sommers. 2004. DOE Hydropower Program Annual Report for FY 2003. DOEIID-11136, U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, DC.
- Cada, G. F. 1990. A review of studies relating to effects of propeller-type turbine passage on fish early life stages. *North American Journal of Fisheries Management* 10:418-426.
- Conner, A. M., J. E. Francfort, B. N. Rinehart. 1998. U.S. Hydropower Assessment Final Report. Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID. December 1998. DOE/ID-10430.2.
- 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. Holden, MA. Prepared for U.S. Department of Energy, Washington, DC. Contract No. DE-AC07-99ID13733.
- Coutant, C. C., R. Mann, and M. J. Sale. 2006. Reduced spill at hydropower dams : opportunities for more generation and increased fish protection. Prepared for U. S. Department of Energy, Office of Energy Efficiency and Renewable Technologies by Oak Ridge National Laboratory, Oak Ridge, TN. Report No. ORNL/TM-2005/179.
- DOI (U.S. Department of the Interior), U.S. Department of the Army, and U.S. Department of Energy. 2007. Potential Hydroelectric Development at Existing Federal Facilities, for Section 1834 of the Energy Policy Act of 2005.
- Dresser, T. J., C. L. Dotson, R. K. Fisher, Jr., P. Heisey, D. Mathur, J. R. Skalski, and R. L. Townsend. 2006a. Wanapum Dam advanced hydro turbine upgrade project: Part 1 – passage survival and condition of yearling Chinook salmon through an existing and advanced hydro turbine at Wanapum Dam, Mid-Columbia River, USA. Paper presented at HYDROVISION 2006, Portland, OR. HCI Publications, Inc., Kansas City, MO.
- Dresser, T. J., C. L. Dotson, R. K. Fisher, Jr., M. J. Graf, M. C. Richmond, C. L. Rakowski, T. J. Carlson, D. Mathur, and P. Heisey. 2006b. Wanapum Dam

advanced hydro turbine upgrade project: Part 2 – evaluation of fish passage test results using computational fluid dynamics. Paper presented at HYDROVISION 2006, Portland, OR. HCI Publications, Inc., Kansas City, MO.

Electric Power Research Institute (EPRI). 2009. “Fish Friendly” Hydropower Turbine Development & Deployment: Alden Turbine Preliminary Engineering and Model Testing. Technical Report 1019890, Palo Alto, CA. September 2011.

Electric Power Research Institute (EPRI). 2009. Redesign of the Alden/Concepts NREC Helical Turbine for Increased Power Density and Fish Survival Evaluation of a Conceptual Prototype Turbine. Technical Report 1015600, Palo Alto, CA, July 2009.

Electric Power Research Institute (EPRI). 2008. Evaluation of the Effects of Turbine Blade Leading Edge Design on Fish Survival. Technical Report 1014937, Palo Alto, CA, May 2008.

Electric Power Research Institute (EPRI). 2007. Assessment of Waterpower Potential and Development Needs. Technical Report 1014762, Palo Alto, CA, March 2007.

Electric Power Research Institute (EPRI). 1998. Review of downstream fish passage and protection technology evaluations and effectiveness. Report TR-111517, Palo Alto, CA.

Electric Power Research Institute (EPRI). 1997. Turbine entrainment and survival data base – field tests. Report TR-108630, Palo Alto, CA.

Federal Energy Regulatory Commission (FERC). 1995. Preliminary assessment of fish entrainment at hydropower projects: a report on studies and protective measures. Office of Hydropower Licensing, Washington, DC. Paper No. DPR-10.

Hecker, G. E., and G. S. Allen. 2005. An approach to predicting fish survival for advanced technology turbines. HydroReview, November 2005. HCI Publications, Inc., Kansas City, MO.

Hecker, G. E. and T. C. Cook. 2005. Development and Evaluation of a New Helical Fish Friendly Hydro-Turbine. *Journal of Hydraulic Engineering* 131(10):1-21

Odeh, M. 1999. A summary of environmentally friendly turbine design concepts. U.S. Department of Energy, Idaho National Laboratory, Idaho Operations Office, Idaho Falls, ID. DOE/ID-13741.

Office of Technology Assessment (OTA). 1995. Fish Passage Technologies: Protection at Hydropower Facilities. Congress of the United States, OTA-ENV-641, Washington, DC: U.S. Government Printing Office.

Sale, M. J., G. F. Cada, and D. D. Dauble. 2006. Historical perspective on the U.S. Department of Energy's Hydropower Program. Paper presented at HYDROVISION 2006, Portland, OR. HCI Publications, Inc., Kansas City, MO.

Sale, M. J. et al. 1991. Environmental mitigation at hydroelectric projects. Vol. I. Current practices for instream flow needs, dissolved oxygen, and fish passage. DOE/ID-10360, U.S. Department of Energy, Idaho Falls, Idaho.

Sommers, G.L., and 7 co-authors. 2005. DOE Hydropower Program Annual Report for FY 2004. U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

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U.S. Army Corps of Engineer's Turbine Survival Program

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Abstract

The Corps of Engineers Turbine Survival Program began in 1997 in an effort to address the Northwest Power & Conservation Council's request to enhance survival of migrating juvenile salmonids passing through the Columbia River hydropower system and the National Marine Fisheries Service 1995 Biological Opinion on the Operation of the Federal Columbia River Power System. The primary TSP objectives are: 1) improved understanding of the turbine passage environment and the impacts that environment has to downstream migrating juvenile salmonids; 2) optimize turbine operations for safer fish passage, and; 3) improve future turbine designs for safer fish passage. The TSP team is a cross-functional, multi-disciplinary team with member representatives from the Corps of Engineers' Hydroelectric Design Center, Walla Walla and Portland District's, Engineer Research and Development Center; Bonneville Power Administration, and; the National Marine Fisheries Service. Over the years, the TSP has developed tools to measure and model the turbine environment and its dynamics, as well as fish survival and injuries through turbines and in the laboratory. We have developed an understanding of operations and design factors and how they relate to turbulence, sheer, strike, and barotrauma, allowing us to develop supportable recommendations for operation of turbines and design criteria for new turbines for safer fish passage. Internal transmitters are used to study and evaluate fish passage and survival. We have identified and will continue to investigate a negative bias in estimated survival rates for fish tagged with internal transmitters passing through turbines. Additional, ongoing challenges include estimating the relative magnitudes of fish injury and mortality among factors, and conducting rigorous evaluations to demonstrate increased survival with modified turbine operations. While it would be ideal to study voluntarily fish passage, under normal project operations, the facts remain that we are challenged, given the aforementioned tag bias, the fact that powerhouses are configured and operated with an emphasis on minimizing voluntary fish passage, in effect; the use of turbine intake screens, surface flow outlets and voluntary spill. New technologies such as external neutrally buoyant transmitters, innovative study design and close collaboration with regional fisheries managers may help facilitate solutions to these challenges.

Introduction

The U.S. Army Corps of Engineers (COE's) Turbine Survival Program (TSP) is part of the COE's multi-faceted Columbia River Fish Mitigation (CRFM) program. The TSP was developed to quantitatively evaluate juvenile fish passage through turbines with an emphasis on identifying turbine structures and operations responsible for injury to fish. The three main objectives are: 1) Explore methods to evaluate and understand fishery impacts caused by turbine

operation; 2) Develop turbine operational changes to improve fish passage through turbines, and; 3) Identify biological criteria for use in turbine re-design.

Much of the electrical power in the Pacific Northwest is generated by hydro turbines installed within the many dams located throughout the Columbia River Basin. With the increase in regional power demands, and the need for improving salmonid fish recovery, these turbines must be more efficiently and effectively operated. In understanding the issues associated with turbine passage of migrating juvenile salmonids, there are three related measures of turbine fish passage that are important. These are: “direct”, “indirect” and “total passage route” survival and injury. Direct turbine passage measures apply to the immediate turbine environment from the intake entrance to the draft-tube exit. Indirect measures apply to the tailrace environment immediately downstream from the draft-tube exit. Total turbine passage measures are the sum of the direct and indirect measures and are the measures used by fish resource managers to compare the safety of turbine passage with other bypass alternatives. Even though the hydrosystem strategy for improving downstream migration has been to minimize turbine passage through turbine bypass systems and voluntary spill, significant numbers of juvenile fish will continue to pass through turbines. Therefore, improving turbine passage for fish remains a desirable goal. The Turbine Survival Program (TSP) was established to achieve this goal.

Assumptions

Future power demands in the Pacific Northwest will increase. The population in the four Northwest states - Washington, Oregon, Idaho and Montana - grew by approximately 12 percent since 2000, and the region’s consumption of electricity increased accordingly (2010 census). It is also likely that the endangered species policy for salmon recovery in the Pacific Northwest will not change anytime soon. As a matter of fact, the 2010 Biological Opinion included an Adaptive Management Implementation Plan that calls for: 1) immediately accelerate and enhance particular RPA actions; 2) enhance research, monitoring and evaluation to increase and improve the data and analytic tools available to gauge salmon and steelhead status and to inform responses, if the fish are declining; 3) establish new biological triggers that, when exceeded, will activate near- and long-term responses to address significant fish declines; 4) identify and establish the process for implementing those near- and long-term responses if a trigger is exceeded, and; 5) include a wide range of specific rapid response and longer-term contingency actions, including the potential for John Day drawdown and lower Snake River dam breaching (FCRPS Adaptive Management Implementation Plan 11 September 2009). Rehab needs will also continue to grow. Almost all of the turbines installed at Federal dams on the Columbia and Snake Rivers are Kaplan turbines, procured and installed approximately over forty years. In recent years several units have failed due to blade linkage related problems and more are anticipated to fail. Regardless of preventative measures (screens, surface bypass systems, etc.) fish will inevitably find their way into turbines and data indicates that survival rates can be relatively high. Therefore, it is logical to maximize survival efforts for those fish that do go through turbines and incorporate that as part of a sustainable solution.

Approach

Applying scientific methods, the TSP integrated the use of hydraulic turbine modeling (CFD, 1:25 physical model and hyper/hypobaric chambers), engineering measurements and field biological studies to better understand the turbine environment and the impacts to fish passing through that environment. Additionally, the understanding of the turbine environment is being used to develop new turbine design criteria and evaluate operational and physical modifications to existing turbines to facilitate safer passage and survival.=

Since the early 1990's during the fish passage season, turbines have been required to operate at their peak efficiency point, plus or minus 1%. Index testing and operational adjustments were performed to establish "on cam" operating tables for both with and without screen conditions. These studies resulted in revised one-percent operating limit tables for McNary, Bonneville First Powerhouse, The Dalles, John Day, Lower Monumental, and Lower Granite. Various performance model tests were conducted in hydraulic laboratories to better define the existing turbines operation and investigate potential physical improvements for improved fish passage and operational efficiencies.

Analytical Tools

Physical hydraulic models have been used to evaluate hydraulic conditions within the turbine passageway, and power performance characteristics. Two types of hydraulic models were used: observational models and performance models.

Performance models, typically conducted by turbine manufacturers are used to estimate the power, efficiency, and cavitation limits. Data from the performance model is needed to set up the observational model. Performance models are tested using Reynolds similitude. The high velocity and pressure vessel hinder observations of flow path and quality of flow.

To evaluate hydraulic characteristics through the turbine, observational models were constructed, tested and utilized at the COE Engineer Research and Development Center (ERDC) at Vicksburg, Mississippi (Figure 2-6). The observational models are made primarily of clear acrylic material, which allows visual access to the entire water and fish passageway. Nearly neutrally buoyant beads (emulating fish) and dye are used in combination with high-speed photography and laser Doppler velocimeter (LDV) measurements, to evaluate conditions likely to cause fish injury. The ERDC hydraulic models are constructed and tested based on Froude similitude.

*Figure 2-6
Bonneville First Power House 1:25-scale observational model.*

Biological studies to estimate direct and indirect mortality rates were conducted using Hi- Z Turb’N Tagged fish (Heisey et al. 1992) and radio tracking (Skalski et. al. 1998) technologies. Balloon tagging techniques permit fish to be recovered immediately following turbine passage. Figure 2-7 shows a tagged fish prior to release. As the fish can be recovered, determining their condition (alive, dead, injured, or uninjured) and the types of injuries they sustained during turbine passage is possible. Radio or acoustic tracking technology permits the detection and tracking of tagged fish as they pass through arrays of receivers at locations downstream following exposure to a test condition. These technologies permit identification of test fish as individuals, which permits higher precision estimates of survival rates with smaller sample sizes than would otherwise be feasible.

Figure 2-7
Hi-Z Turb'n Tag

Because pressure, shear and turbulence in the turbine environment can cause injury and delayed mortality (Abernethy et al. 2001, 2002; Čada et al. 1997; Carlson 2000; Neitzel et al. 2000; Wittinger et al. 1995; Turnpenny 1998), Sensor Fish technology, developed by Pacific Northwest National Laboratories. The Sensor Fish records pressures and accelerations experienced as it passes the turbine, and were used to better understand the relationship between injuries, hydraulic conditions and the respective location where these injuries may be occurring (Figure 2-8).

Figure 2-8
Sensor Fish (PNNL) Carlson, Tom et. al.

CFD Modeling

Computational Fluid Dynamics (CFD) modeling was used to better understand the potential for improving juvenile fish passage through a Kaplan turbine distributor, runner, and draft tube. However, the complex nature of the flow field and limited data from prototype turbines, physical models and sensor fish highlight the difficulties of measuring the flow field throughout the domain. Sensor fish provide for pressure information, pressure rate of change and

acceleration of stream line of passage but are limited by release point, random route, number of samples and anomalies along the sensor fish body. CFD models of the Kaplan turbine runner environment provide a relative prediction of the physical flow field. If the CFD model results adequately represent the turbine runner flow regime, the output data will be used to support a risk analysis for juvenile salmonids passing through large Kaplan turbine units. To develop summary statistics on the pressure regime, TSP, with support from Pacific Northwest National Laboratory utilized the CFD visualization software package Tecplot. Figure 2-9 shows a sample CFD result for the John Day Turbine.

Figure 2-9
Computational Fluid Dynamic modeling; Andritz VA TECH Hydro 2008

Hyper/Hypobaric Pressure

Rapid decompression occurs as fish pass through hydro-turbines, which may be complicated by total dissolved gas super-saturation. These conditions, when combined, result in increased probability of severe barotraumas. PNNL researchers (Rich Brown, PNNL Energy and Environmental Directorate Jan 2011) have been studying the impact of barotrauma on juvenile salmonids passing through simulated turbine passage. Using hyper/hypobaric chambers researchers can expose fish to rapid decompression exposures over a pressure range from ~410 to 3 kPa absolute, and with total dissolved gas super-saturation from 100% to greater than 125%. They are able to replicate complex pressure exposure conditions in a laboratory setting (Figure 2-10).

Figure 2-10
Hyper/hypobaric chambers; Rich Brown PNNL 2010

What Have We Learned?

Observations made using physical models have determined that the turbine environment is notably more turbulent at lower discharge. Sensor fish observations made for passage through operating turbines have confirmed these observations. Additionally, given that fish survival through the spillways is high, sensor fish data suggests that turbulence in the spillways is higher than typically found in turbines.

Other observations, suggest that lower discharge poses higher risk of injury compared to higher turbine discharge. Study data also suggest that a more streamlined introduction of fish into the turbine environment, i.e., the wicket gates, stay vanes and runner, may reduce injury and help minimize fish mortality. Geometry, runner and draft-tube design, along with the elimination of gaps, sharp edges and rough surfaces in the interior of the turbine environment may also enhance fish survival. The hydraulic conditions within the turbine environment, from entrance to the stay vane and wicket gate assemblies to the draft-tube exit, appear to be smoother and less turbulent at discharges near the upper limit of the turbines' operating range. With lower turbine unit discharges, fish may spend as long as one complete turbine revolution within the immediate runner environment, which is less desirable.

Direct mortality and injury of fish passing through turbines due to strike is relatively low (between 2 and 4 percent). We can reduce strike and shear related injuries by changing how we operate and design the turbine units. Study data suggests that operating the units above the one percent operating range improves the quality of flow and thus improves direct survival.

Barotraumas studies using Chinook salmon have attributed the probability of mortal injury to turbine pressure cycling delta, that is; the pressure the fish was acclimated to relative to the nadir (lowest) pressure of the cycle. The pressure nadir experienced will depend on the exact route through the turbine. Fish passing near the suction side of a blade will typically experience lower pressures than a fish passing on the pressure side or midway between blades. Fish experiencing a nadir greater than 12 psia have small probability for mortal injury. However, the presence of an internal transmitter for tagged fish increases the probability of mortal injury. Because existing turbine pressures are not as extreme as previously perceived and are generally greater than 12 psia, it is surmised that indirect mortality can be reduced through design improvements.

Unfortunately, wicket gate and blade angles that improve quality of flow and decrease probability of strike also result in higher discharges and lower pressure nadirs, thereby increasing the probability of mortal injury due to barotrauma. This trade off is not yet well understood. Although we now have a better understanding of mechanisms of injury to fish, we lack a robust risk assessment for a design or operation among the factors. Such a model would require development of response curves for probability of mortality, given exposure of strike, sheer, turbulence, pressures. To know the exposure, we have to know the route of passage from forebay to tailrace.

Improving juvenile survival at the majority of the projects on the Lower Columbia and Lower Snake Rivers should be achievable. Recent improvements at Bonneville 1st Powerhouse have shown good turbine survival with the installation of the Minimum Gap Runner Turbines. Turbine survival is on the order of 92% to 95%. John Day Dam, with higher discharge turbines, higher head, and more eddies and lower velocity in the tailrace has turbine survival ranges from 73% to 86% and improvements are definitely needed and we are confident, are achievable.

Summary

Over the past 15 years we have gained a better understanding of the turbine environment and the effects of that environment on juvenile fish. Reducing gaps and exposure to sharp edges and operating the units with a more open geometry will improve direct survival. Data also suggests that operating within the upper one percent operating range creates a better environment for fish passing through the turbines. Recent and on-going pressure studies also suggest that indirect mortality, attributed to the effects of barotraumas, may be reduced or mitigated with new turbine designs. Further study is needed to develop less intrusive tags that may help reduce tag bias, and certainly, there is the need for better biologic field studies, such as direct capture, to better evaluate the source and cause of both direct and indirect mortality. Other presentations in this conference present the details of most aspects of this program.

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Strategies for Assessing the Biological Performance and Design of Hydropower Turbines

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Abstract

The biological response of fish to turbine passage has been of concern for several decades and emphasized recently by consideration of hydro as a “green” power source. The current state-of-the-art of hydro-turbine biological performance assessment, while still inadequate, has advanced considerably the past 10 years. For example, the importance of assessment of exposure to pressure changes during turbine passage has been emphasized by findings of laboratory studies of rapid decompression. It is now very clear that hydroturbine biological assessment must consider the physiological state and behavior of fish at turbine entry and changes in physiological state that drive aspects of behavior during tailrace passage. Such considerations are in addition to concerns about exposure of fish to mechanical and pressure sources of injury during turbine passage. Experimental designs and assessment tools have evolved for acclimation of test fish, observation of test fish behavior at approach and upon exit from the turbine environment, and precise estimation of turbine passage mortality. Fish condition assessment continues to improve permitting better classification of observed injuries to injury mechanisms. Computational fluid dynamics (CFD) models and other computer models permit detailed investigation of the turbine passage environment and development of hypotheses that can be tested in field studies using live fish. Risk assessment techniques permit synthesis of laboratory and in-field study findings and estimation of population level effects over a wide range of turbine operation scenarios. Risk assessment is also evolving to provide input to turbine runner design. These developments, and others, have resulted in more productive biological performance assessment studies and will continue to evolve and improve the quantity and quality of information obtained from costly live fish hydroturbine passage studies. This paper reviews the history of hydro-turbine biological assessment, presents the current state-of-the-art, and identifies areas needing improvement.

Introduction

Conventional hydropower is being reassessed as a source of “green” renewable energy. Achievable changes in turbine design and operation could provide increases in efficiency of energy production, more power from existing civil structures, and improvements in safety for fish (Cada 2001, Franke et al. 1997). One of the challenges for wider use of conventional hydropower is acceptance of the turbines as sources of “green” energy. A step toward acceptance is validation of new “green” turbines as safer passage routes for fish. Over the past decade experimental strategies have evolved that have improved assessment of the biological performance of hydroturbines.

The safety of fish passing through hydroturbines has been a concern since installation of the first hydroturbines in waterways containing fish. For a number of reasons, it is quite difficult to determine the number of fish that enter a turbine and the number that survive passage. As a result, a number of methods to release a known number of fish into a turbine and to assess their survival, and in some cases condition, following passage have been developed.

The causes of injury to fish during turbine passage are well known and can be broadly categorized into mechanical injury and barotrauma (Cada et al. 2006, Carlson 2001). Mechanical injuries result from exposure to moving or stationary turbine structure and severe turbulence or shear (Neitzel et al. 2004, Deng et al. 2005). Barotrauma injuries result from rapid decompression. The most severe response to injury is immediate mortality. However, the injuries incurred during turbine passage may also result in delayed, or indirect, mortality some time after turbine passage from predation in consequence of reduced fitness or deviation from normal behavior following turbine passage. Only immediate mortality occurs within the confines of the hydroturbines, the region between the turbine intake trash racks and the exit of the turbine draft tube. All other mortality occurs in the powerhouse tailrace or further downstream (Ferguson et al. 2006).

Biological Performance Assessment

Consideration of the definition of “turbine environment” for assessment of the biological performance of installed hydroturbines is warranted. It is typically quite difficult to satisfy the assumptions of experimental designs to assure that fish survival estimates apply only to immediate turbine mortality (Carlson and Skalski 2010). In addition, it can be argued that biological assessment of turbine performance need to include total impact of turbine passage on fish. Such an assessment would need to include at least a portion of the environment downstream of the turbines.

The typical measures for assessment of the biological performance of hydroturbines are relative or absolute survival. Absolute turbine passage survival estimates are much more challenging to obtain and require considerably more rigorous experimental designs and more attention to all sources of potential bias (Carlson and Skalski 2010). Biological assessment for validation of a hydroturbine as “green” will require evaluation of absolute fish passage survival.

An example of a widely used and successful biological performance assessment strategy to estimate the relative survival of turbine passed fish is balloon tagging (Mathur et al. 2000). Specially designed balloons that contain a chemical that produces gas are attached to test fish. Test fish are introduced into a hydroturbine using an injection system that has headworks on the powerhouse intake deck and a terminus in the turbine intake. Test fish brought to the surface by inflated balloons following turbine passage are recovered in the dam’s tailrace. The condition of recovered fish are assessed to estimate the source of any injury observed and to estimate relative turbine passage survival. Using this method the relative biological performance of different turbine designs and operating conditions can be considered. Such comparisons are limited to mechanical injury

only because the method does not permit the release of fish acclimated to neutral buoyancy and therefore cannot evaluate the effect of pressure changes (rapid decompression) during turbine passage on test fish. This limitation is one of the reasons this strategy, in its current form, cannot be used to obtain estimates of absolute turbine passage survival.

Hydroturbine biological assessment strategies for estimation of absolute turbine passage survival have evolved very rapidly over the last few years in the Columbia River basin (Carlson and Skalski 2010). This evolution has been driven by the need for precise and unbiased absolute dam passage survival estimates to determine if dams in the Federal Columbia River Power System (FCRPS) have been configured and are being operated in a manner that will meet requirements of biological opinions for the recovery of listed salmon and steelhead stocks (NMFS 1995, 2000). These assessments consider all routes of passage past dams, spillways, engineered bypass systems, and turbines.

The strategy for assessment of the absolute survival of fish passing dams in the FCRPS is based on experimental designs that control the most significant sources of bias in survival estimates and the use of acoustic telemetry (AT) (Carlson and Skalski 2000). The acoustic telemetry system used for these assessments, JSATS, was developed by the US Army Corps of Engineers specifically for these assessments (Deng et al. 2011a, McMichael et al. 2010, Weiland et al. 2011). An element of development of the system has been extensive evaluation of the effect of the transmitters, which are surgically implanted, on test fish (Carlson et al. 2010). These biological assessments have included determination of the differential response to rapid decompression of fish bearing an AT transmitter and those not (Brown et al. *in press*, Brown et al. 2009). These assessments have found that test fish bearing an acoustic transmitter are more susceptible to barotrauma than those not bearing a transmitter (Carlson et al. 2010).

Data acquired using Sensor Fish devices provide information about the quality of flow through a turbine as well as changes in pressure and interaction with turbine structure (Carlson et al 2008, Carlson et al 2006, Carlson et al. 2004, Deng et al 2010, Deng et al 2007b, Deng et al. 2007c, Deng et al. 2005, Deng et al. 2004, Richmond et al 2009). These field data can be used in conjunction with physical and numerical models of the turbine environment to gain a more complete picture of hydraulic conditions are fish are exposed to during turbine and spillway passage.

The development of strategies to estimate dam passage absolute survival for run-of-river fish have contributed to development of strategies that focus on hydroturbines alone. The approach to hydroturbine biological assessment has parallels in the engineering assessments that identify the turbine designs and operations that will optimize the production of power. Biologically, the focus of assessment is identification of turbine design and operation alternatives that optimize the turbine environment for fish passage, one measure being absolute fish passage survival. The long sought and ultimate goal for the design and

operation of hydroturbines that must pass fish is that the condition of fish at exit of the turbine is the same as that at entry.

The evolving strategy for biological assessment of hydroturbines contains three elements: (1) the use of computational fluid dynamics (CFD) and risk analysis to estimate the probable biological performance of existing and new turbine designs, (2) development of experimental design to perform prototype field tests of hypotheses obtained through CFD and risk analyses, and (3) development of instrumentation and methods to implement the experimental designs.

Computational fluid dynamics is widely used for design of hydroturbines (Keck and Sick 2008). CFD analysis is also used to identify the areas within a turbine of most risk to fish and to identify design alternatives to reduce that risk (Cada et al 2006). In addition to CFD models, other mathematical models can be used to estimate the risk of exposure to strike from turbine runner blades (Deng et al. 2011; Deng et al. 2007a).

Research is currently underway to use CFD, Sensor Fish device data sets, and risk analysis for strike, shear, turbulence, and rapid decompression to develop predictions for the biological performance of new hydroturbine designs (Richmond et al. 2011). These methods utilize laboratory derived data for the response of fish to different injury mechanisms such as rapid decompression to estimate the risk of barotrauma. Beyond their use in engineering design, these analysis tools will lead to field testable hypotheses of hydroturbine biological performance. The strategy of hypothesis driven in-field testing is necessary because of the high cost of prototype field testing over the total operating range of a hydroturbine. The assumption underlying this strategy is that hypothesis acceptance for a subset of hydroturbine operating conditions will provide the level of validation needed to motivate regulatory acceptance of predicted biological performance over the total operating range of a turbine at a specific installation.

References

Brown, RS, TJ Carlson, AJ Gingerich, JR Stephenson, BD Pflugrath, AE Welch, MJ Langeslay, ML Ahmann, RL Johnson, JR Skalski, AG Seaburg, RL Townsend. *In press*. Quantifying mortal injury of juvenile Chinook salmon exposed to simulated hydro-turbine passage. Transactions of the American Fisheries Society.

Brown, RS, TJ Carlson, AE Welch, JR Stephenson, CS Abernathy, BD Ebberts, MJ Langeslay, ML Ahmann, DH Feil, JR Skalski, and RL 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.

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

Čada, G., J. Loar, L. Garrison, R. Fisher Jr, and D. Neitzel. 2006. Efforts to reduce mortality to turbine-passed fish: locating and quantifying damaging shear stresses. *Environmental Management* 37:898–906.

Carlson TJ, Z Deng, RS Brown, AHA Colotelo, JJ Martinez, BD Pflugrath, TK Abel, JM Janak, AP LeBarge, JR Stephenson, RP Mueller, and A Seaburg. 2011. *Design, Production, and Assessment of a Neutrally Buoyant Externally Attached Acoustic Transmitter for Studying Behavior and Survival of Juvenile Salmonids*. PNNL-20330, Pacific Northwest National Laboratory, Richland, WA.

Carlson TJ, RS Brown, JR Stephenson, AJ Gingerich, BD Pflugrath, AHA Colotelo, AE Welch, PL Benjamin, JR Skalski, A Seaburg, and RL Townsend. 2010a. *Assessment of Barotrauma in Untagged and Tagged Juvenile Chinook Salmon Exposed to Simulated Hydro-Turbine Passage*. PNNL-19625, Pacific Northwest National Laboratory, Richland, WA.

Carlson TJ, and JR Skalski. 2010. Compliance Monitoring of Juvenile Yearling Chinook Salmon and Steelhead Survival and Passage at The Dalles Dam, Spring 2010b. PNNL-19819, Pacific Northwest National Laboratory, Richland, WA.

Carlson TJ, RS Brown, JR Stephenson, BD Pflugrath, AHA Colotelo, AJ Gingerich, PL Benjamin, M Langeslay, ML Ahmann, RL Johnson, JR Skalski, A Seaburg, and RL Townsend. 2010c. "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." PNNL-SA-76806, Pacific Northwest National Laboratory, Richland, WA.

Carlson TJ, JP Duncan, and Z Deng. 2008. *Data Overview for Sensor Fish Samples Acquired at Ice Harbor, John Day, and Bonneville II Dams in 2005, 2006, and 2007*. PNNL-17398, Pacific Northwest National Laboratory, Richland, WA.

Carlson TJ, JP Duncan, and Z Deng. 2006. *Use of the Sensor Fish Device to Evaluate the Biological Performance of an Advanced Turbine Design at Wanapum Dam in 2005*. PNWD-3743, Battelle—Pacific Northwest Division, Richland, WA.

Carlson TJ, JP Duncan, TL Gilbride, and G Keilman. 2004. "The Sensor Fish - Making Dams More Salmon-Friendly." *Sensors Magazine* 21(7):31-34.

Carlson TJ, and GR Ploskey. 2004. *Comparison of Blade-Strike Modeling Results with Empirical Data*. PNNL-14603, Pacific Northwest National Laboratory, Richland, WA.

Carlson, T. 2001. Proceedings of the turbine passage survival workshop. June 14-15, 2000. PNNL-SA-33996. U.S. Army Corps of Engineers Portland District, Portland, Oregon.

Dauble DD, Z Deng, MC Richmond, RA Moursund, TJ Carlson, CL Rakowski, and JP Duncan. 2007. *Biological Assessment of the Advanced Turbine Design at Wanapum Dam, 2005*. PNNL-16682, Pacific Northwest National Laboratory, Richland, WA.

Deng Z, MA Weiland, T Fu, TA Seim, BL Lamarche, EY Choi, TJ Carlson, and MB Eppard. 2011a. "A Cabled Acoustic Telemetry System for Detecting and Tracking Juvenile Salmon: Part 2. Three-Dimensional Tracking." PNNL-SA-78690, Pacific Northwest National Laboratory, Richland, WA.

Deng Z, JJ Martinez, AHA Colotelo, TK Abel, AP LeBarge, RS Brown, BD Pflugrath, RP Mueller, TJ Carlson, A Seaburg, RL Johnson, and ML Ahmann. 2011b. "Development of External and Neutrally Buoyant Acoustic Transmitters for Turbine Passage Evaluation." PNNL-SA-79155, Pacific Northwest National Laboratory, Richland, WA.

Deng Z, TJ Carlson, DD Dauble, and GR Ploskey. 2011c. "Fish Passage Assessment of an Advanced Hydropower Turbine and Conventional Turbine Using Blade-strike Modeling." *Energies* 4(1):57-67. doi:10.3390/en4010057

Deng Z, TJ Carlson, JP Duncan, MC Richmond, and DD Dauble. 2010. "Use of an Autonomous Sensor to Evaluate the Biological Performance of the Advanced Turbine at Wanapum Dam." *Journal of Renewable and Sustainable Energy* 2(5):053104. doi:10.1063/1.3501336

Deng Z, TJ Carlson, GR Ploskey, MC Richmond, and DD Dauble. 2007a. "Evaluation of Blade-Strike Models for Estimating the Biological Performance of Kaplan Turbines." *Ecological Modelling* 208(2-4):165-176. doi:10.1016/j.ecolmodel.2007.05.019

Deng Z, TJ Carlson, JP Duncan, and MC Richmond. 2007b. "Applications of the Sensor Fish Technology." *Hydro Review* 26(5):10-14.

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

Deng Z, TJ Carlson, GR Ploskey, and MC Richmond. 2005a. *Evaluation of Blade-Strike Models for Estimating the Biological Performance of Large Kaplan Hydro Turbines*. PNNL-15370, Pacific Northwest National Laboratory, Richland, WA.

Deng Z, GR Guensch, CA McKinsty, RP Mueller, DD Dauble, and MC Richmond. 2005b. "Evaluation of Fish-Injury Mechanisms During Exposure to Turbulent Shear Flow." *Canadian Journal of Fisheries and Aquatic Sciences* 62(7):1513-1522.

Deng Z, MC Richmond, CS Simmons, and TJ Carlson. 2004. *Six-Degree-of-Freedom Sensor Fish Design: Governing Equations and Motion Modeling*. PNNL-14779, Pacific Northwest National Laboratory, Richland, WA.

Ferguson JW, RF Absolon, TJ Carlson, and BP Sanford. 2006. "Evidence of Delayed Mortality on Juvenile Pacific Salmon Passing through Turbines at Columbia River Dams." PNNL-SA-49512, Pacific Northwest National Laboratory, Richland, WA.

Franke, G. F., D. R. Webb, R. K. Fisher, D. Mathur, P. N. Hopping, P. A. March, M. R. Headrick, I. T. Laczo, Y. Ventikos, and F. Sotiropoulos. 1997. Development of environmentally advanced hydropower turbine system design concepts. Voith Hydro, Inc. Report No. 2677-0141. Prepared for the U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

Keck, H, and M. Sick. 2008. Thirty years of numerical flow simulation in hydraulic turbomachines. *Acta Mechanica* 201, 211–229. doi: 10.1007/s00707-008-0060-4

Mathur, D., P. G. Heisey, J. R. Skalski, and D. R. Kenney. 2000. Salmonid smolt survival relative to turbine efficiency and entrainment depth in hydroelectric power generation. *Journal of the American Water Resources Association* 36:737-747.

McMichael GA, MB Eppard, TJ Carlson, JA Carter, BD Ebberts, RS Brown, MA Weiland, GR Ploskey, RA Harnish, and Z Deng. 2010. "The Juvenile Salmon Acoustic Telemetry System; A New Tool." *Fisheries* 35(1):9-22.

Neitzel DA, DD Dauble, GF Cada, MC Richmond, GR Guensch, RP Mueller, CS Abernethy, and BG Amidan. 2004. "Survival Estimates for Juvenile Fish Subjected to a Laboratory-Generated Shear Environment ." *Transactions of the American Fisheries Society* 133:447-454.

Nennemann, B., TC Vu, and M. Farhat. 2005. "CFD prediction of unsteady wicket gate-runner interaction in Francis turbines: A new standard hydraulic design procedure". Proceedings Hydro 2005, Villach, Austria, 17-20 October 2005.

NMFS (National Marine Fisheries Service). 1995. Biological Opinion—Reinitiation of consultation on 1994-1998 operation of the federal Columbia River power system and juvenile transportation program in 1995 and future years. Endangered Species Act Section 7 consultation. Northwest Region, Seattle, Washington.

NMFS (National Marine Fisheries Service). 2000. Biological Opinion—Reinitiation of consultation on operation of the federal Columbia River power system, including the juvenile transportation program, and 19 Bureau of Reclamation projects in the Columbia Basin. Endangered Species Act Section 7 consultation. Northwest Region, Seattle, Washington.

Paik, J, F. Sotiropoulos and M.J. Sale, Numerical simulation of swirling flow in a hydroturbine draft tube using unsteady statistical turbulence models, *ASCE J. Hydraul. Eng.* **131** (6) (2005), pp. 441–456.

Richmond MC, Z Deng, CA McKinstry, RP Mueller, TJ Carlson, and DD Dauble. 2009. "Response Relationship Between Juvenile Salmon and an Autonomous Sensor in Turbulent Flows." *Fisheries Research* 97(1-2):134-139. doi:10.1016/j.fishres.2009.01.011

Richmond MC, JA Serkowski, TJ Carlson, LL Ebner, M Sick, and GF Cada. 2011. "Computational Fluid Dynamics Framework for Turbine Biological Performance Assessment." EPRI-DOE Conference on Environmentally-Enhanced Hydro Turbines . PNNL-SA-79735, Pacific Northwest National Laboratory, Richland, WA.

Richmond MC, CL Rakowski, WA Perkins, JA Serkowski, LL Ebner, and SJ Schlenker. 2009. "Modeling Juvenile Salmon Egress Conditions in The Dalles Dam Tailrace using Computational Fluid Dynamics." In *Waterpower XVI: New Roles for Hydro in a Changing World*, July 27-30, 2009, Spokane, Washington, p. Paper No. 173.

Stephenson JR, AJ Gingerich, RS Brown, BD Pflugrath, Z Deng, TJ Carlson, M Langeslay, ML Ahmann, RL Johnson, and A Seaburg. 2010. "Assessing barotrauma in neutrally and negatively bouyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory." *Fisheries Research* 106(3):271-278. doi:10.1016/j.fishres.2010.08.006

Weiland MA, Z Deng, TA Seim, BL Lamarche, EY Choi, T Fu, TJ Carlson, MB Eppard, and AI Thronas. 2011. "A cabled acoustic telemetry system for detecting and tracking juvenile salmon: Part 1. Engineering design and instrumentation." PNNL-SA-78490, Pacific Northwest National Laboratory, Richland, WA.

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Injury Mechanisms for Juvenile Chinook Salmon Passing through Hydropower Turbines

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Abstract

Passage of fish through hydroturbines occurs globally. This is of particular importance for dams that are located in waters where migratory fish species exist. Within the Snake and Columbia Rivers, thousands of salmonids pass through hydroelectric dams during annual seaward migrations. A proportion of these fish will pass through hydroturbines. A number of misconceptions with this passage exist, including the rate of contact related mortality associated with turbine blades. However, all fish are subjected to varied decompression and may sustain injuries related to barotrauma. We examined this interaction using Chinook salmon (*Oncorhynchus tshawytscha*) in a laboratory setting. Juvenile fish were acclimated to a range of depths and subsequently exposed to simulated turbine passage. These simulations exposed fish to rapid changes in pressure between 6.89 to 413.68 kPa (1 to 60 PSI) using computer controlled hyper/hypobaric chambers. Rates of mortal injury were a function of acclimation depth (pressure equivalent) and exposure pressures. The relationships between barotrauma and pressure exposure can be used to guide turbine operations and turbine design globally.

Introduction

Survival of juvenile salmonids during turbine passage at hydroelectric projects is an important environmental issue (Cada 2001; Brown et al. 2009). Mechanisms of injury can include contact with the blade, shear stresses, and grinding, however, the proportion of fish exposed to these mechanisms is believed to be low (Neitzel et al. 2000). In contrast, all fish that pass through hydro-turbines are exposed to a rapid decrease in pressure as they pass by turbine blades which has been shown to lead to injury and/or mortality for some individuals (Brown et al. 2009).

Barotraumas occurring during rapid decompression are caused by the expansion of gases in the swim bladder and tissues as existing bubbles expand, or as gases are moved out of solution and new bubbles are formed (Feathers and Knable 1983). Fish house gases in their swim bladder to maintain neutral buoyancy and the amount of gas necessary to achieve this is dependent on their depth in the

water column. Fish found deeper in the water column are required to uptake larger quantities of gas to maintain neutral buoyancy, and therefore may be at greater risk of barotrauma during rapid decompression.

In addition to the acclimation depth (and associated pressure), the exposure pressure (nadir) during turbine passage is also an important component involved in determining the likelihood of barotraumas. More specifically, the ratio of acclimation pressure to exposure pressure has been shown to influence the magnitude of barotraumas (Beyer et al. 1976; Čada 1990; Abernathy et al 2001, 2002, 2003; Rummer and Bennett 2005; Brown et al. 2009). The nadir pressure is dependent on turbine design and operating conditions at specific hydroelectric facilities. Carlson et al. (2008) reported nadir values below vapor pressure in Columbia River turbines, with the majority of values between 34 and 200 kPa. Due to the variability in the depth of migration for juvenile Chinook salmon and the nadir pressures experienced, a range of ratios of acclimation to exposure pressures is necessary for testing.

Fish may be at greater risk for barotraumas when their habitats are saturated or supersaturated as is often the case in river systems with hydroelectric facilities. Total dissolved gas saturation in the Columbia River Basin (CRB) is highly variable, typically ranging from 100% to 120% (Columbia River DART 2010). While the concentration of gases in the swim bladder and tissues influences the occurrence of barotraumas, it is unknown how the concentration of gases in the external environment influences this.

The objectives of the current study was to determine what factors (i.e., ratio of acclimation pressure to exposure pressure, rate of pressure change and total dissolved gas saturation) contribute to the incidence of barotraumas and mortal injury in hatchery-reared juvenile Chinook salmon exposed to rapid decompression associated with hydro-turbine passage.

Experimental Methods

Hatchery-reared juvenile Chinook salmon, *Oncorhynchus tshawytscha* (n = 5713) were exposed to simulated turbine passage (STP) treatments in the hypo/hyperbaric chambers of our Mobile Aquatic Barotrauma Laboratory (MABL; as described in Stephenson et al. 2010). Testing was conducted with ambient well water (median = 17.0°C, range = 15.8 to 17.9°C) that was pumped in to the chambers after total dissolved gas (TDG) levels were elevated to 115% (median = 114.8, range = 112.7 to 118.2) and 125% (median = 124.5, range = 122.2 to 127.5).

Seven juvenile Chinook salmon were marked with individual fin clips and loaded into each chamber. Fish were given at least 16 hours to acclimate to pressure equivalents of 1.5 m (116.5 kPa; n = 1193), 4.6 m (146.2 kPa; n = 3786), and 7.6 m (175.8 kPa; n = 734). During the acclimation period, fish were given access to an air bubble to fill their swim bladders in an attempt to achieve neutral buoyancy.

Pressure profiles used in this study were generated from Sensor Fish data collected at hydroelectric facilities containing large Kaplan turbines in the CRB (Deng et al. 2007). Pressures in the chamber were increased to ~400 kPa over 20 s and then fish were subjected to rapid decompression within 0.5-3.5 s (nadir: median = 44.1 kPa, range = 6.4 to 144.8 kPa).

Immediately following exposure any fish that died as a result of the exposure were identified and noted. The remaining fish were euthanized. Necropsies on all fish were conducted within 15 minutes to establish the presence or absence of a number of injuries, 8 of which are included in the mortal injury metric (McKinstry et al. 2007). The mortal injury metric was derived from analysis of a large data set of fish exposed to rapid decompression. The injuries seen most often in fish that died within minutes of exposure (determined using odds ratios, Fisher's exact tests, and stepwise logistic regression modeling using AIC [McKinstry et al. 2007]) were included in the metric and include: exophthalmia (eye-pop), hemorrhaging in the pericardium, liver or kidney; ruptured swim bladder; blood or bile in secretions from the vent; and emboli in the gills or pelvic fins. Therefore, the presence of one of the injuries, or fish that were dead within 10 minutes of exposure was classified as mortally injured.

Mortal injury for each test served as the response variable. The statistical design and analysis used in this study encompassed six explanatory variables.

- Rate of pressure change (ROC)
- Total dissolved gas (TDG) level
- Ratio of acclimation to exposure (nadir) pressures with natural log applied (LRP)
- Fish length
- Fish weight
- Fish condition factor (Winter 1983)

Mortal injury was modeled using general linear models based on a logistic link function and Bernoulli error structure. Analysis of deviance was used in modeling the data and testing hypotheses where (Equation 1).

$$y_{ij} = \begin{cases} 1 & \text{if fish died/injured} \\ 0 & \text{otherwise} \end{cases}$$

All the main treatment factors of LRP ($P < 0.0001$), condition factor ($P < 0.001$), ROC ($P=0.0003$), and the interaction effects of TDG by condition factor ($P < 0.001$), and LRP by TDG ($P = 0.0005$) were significant predictors of mortal injury in juvenile Chinook salmon. The main model plus the two interactions explained 40.2% of the deviance in the data. LRP explained by far the most deviance in the model 39.1%, while all other variables combined explained less than 1% of the deviance in the model. Since LRP explained the most deviance, it was determined to be an adequate predictor of mortal injury for fish exposed to

rapid decompression. The equation for predicting mortal injury given LRP is (Equation 2, Figure 2-11).

$$\text{Probability of mortal injury} = \frac{e^{-5.56+3.85*LRP}}{1 + e^{-5.56+3.85*LRP}} \quad (2)$$

Figure 2-11

Probability of mortal injury along a range of LRP (natural log of the ratio of acclimation to nadir pressures) for juvenile Chinook salmon.

The 95% confidence interval on the prediction is shown on either side of the regression line (center line). Each dot on the graph indicates an individual fish exposed to simulated turbine passage.

Discussion

The natural log of the ratio between acclimation and nadir pressures (LRP) was the main factor associated with mortal injury of juvenile Chinook salmon. As the LRP increased, the probability of mortal injury also increased in a sigmoidal fashion, where the largest changes in mortal injury occurred in the middle range of pressure ratios tested. At a low LRP, very little mortality was observed, while at a high LRP the probability was almost 1.0. The current study expands the understanding of the ratio of pressure change on the rate of barotraumas by examining a range from 1.0 to 20.1 (LRP: 0 to 3.12).

This research highlights the importance of determining the depth of neutral buoyancy of fish prior to, as well as the pressures at which fish are exposed during

turbine passage. The depth at which juvenile salmonids migrate in the water column is directly related to acclimation pressures. Studies have reported juvenile salmonids travelling at water depths less than 6.1 m in the CRB (Dauble et al. 1989; Faber et al. 2001), however, it is unknown if these fish were neutrally buoyant at this depth. Neutral buoyancy is an important component for examining mortal injury of fish exposed to STP since their depth in the water column determines how much air, in terms of mass, is found within a fish.

Total dissolved gas saturation, condition factor, rate of pressure change and a number of interaction factors were all found to be statistically significant in accounting for variability in the model; however, they did not increase the predictive power of the model and were not included in the final equation. Despite the lack of predictive power observed in this study, the importance of TDG saturation and rate of pressure change may still influence the probability of mortal injury under other scenarios. The TDG saturation levels used in the current study are reasonable for the CRB, however, levels have been recorded above 125% (Ebel 1969) and it is unknown how these dramatic levels may influence mortal injury rates. Periods of high TDG saturation in the CRB are typically observed during the spring when there is increased spill at hydroelectric facilities to facilitate downstream migration of juvenile salmonids (Johnson et al. 2007) and this is a concern for dam operators in their attempts to maintain water quality. As with TDG saturation, the rate of pressure change values used in the current study are representative of some facilities in the CRB, but higher rates have been observed at other facilities (Duncan 2010) and it is unclear how these values would influence mortal injury.

Conclusions and Recommendations

Future research is needed to understand how the pressure scenarios use in the current study influence other species of fish. There are many other migratory physostomous species (e.g., sockeye salmon [*O. nerka*], Atlantic salmon [*Salmo salar*], steelhead [*O. mykiss*]) which pass through hydro-turbines and may be influenced differently due to differences in physiology and behavior. Additionally, it is unclear how juvenile migratory Pacific lamprey are affected by rapid decompression, given the anatomical absence of a swim bladder and uncertainties related to migration depth. Physoclistous fish also may present a unique response to STP as their swim bladder is closed and gases cannot be expelled through the pneumatic duct during decompression.

The results of this study provide valuable information to fisheries managers and engineers about the relationships between rapid decompression and barotraumas for juvenile Chinook salmon. This information coupled with pressure data should assist in improvements in design and operating conditions of hydroelectric facilities to minimize mortality of turbine passed fish.

References

Abernethy CS, BG Amidan, and GF Čada. 2003. Fish Passage through a Simulated Horizontal Bulb Turbine Pressure Regime: A Supplement to

Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish. PNNL-13470-B, Pacific Northwest National Laboratory, Richland, Washington.

Abernethy CS, BG Amidan, and GF Čada. 2001. Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish. PNNL-13470, Pacific Northwest National Laboratory, Richland, Washington.

Abernethy CS, BG Amidan, and GF Čada. 2002. Simulated Passage through A Modified Kaplan Turbine Pressure Regime: A Supplement to Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish. PNNL-13470-A, Pacific Northwest National Laboratory, Richland, Washington.

Beyer DL, BG D'Aoust, and LS Smith. 1976. Decompression-induced bubble formation in salmonids: comparison to gas bubble disease. *Undersea Biomedical Research* 3:321–338.

Brown RS, TJ Carlson, AE Welch, JR Stephenson, CS Abernethy, BD Ebberts, MJ Langeslay, ML Ahmann, DH Feil, JR Skalski, and RL 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.

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

Carlson TJ, JP Duncan, and Z Deng. 2008. Data Overview for Sensor Fish Samples Acquired at Ice Harbor, John Day, and Bonneville II Dams in 2005, 2006, and 2007. PNNL-17398, Pacific Northwest National Laboratory, Richland, Washington.

Columbia River DART. 2009. Columbia River DART - Data Access in Real Time. Columbia Basin Research, School of Aquatic & Fishery Sciences, University of Washington, Seattle. Available at <http://www.cbr.washington.edu/dart/> (July 2010).

Dauble DD, TL Page, and RW Hanf Jr. 1989. Spatial distribution of juvenile salmonids in the Hanford Reach, Columbia River. *Fishery Bulletin* 87:771–790.

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

Duncan JP. 2010. Characterization of Fish Passage Conditions Through a Francis Turbine, Spillway, and Regulating Outlet at Detroit Dam, Oregon,

Using Sensor Fish. Draft Report, Pacific Northwest National Laboratory, Richland, Washington.

Ebel WJ. 1969. Supersaturations of nitrogen in the Columbia River and its effect on salmon and steelhead trout. *Fishery Bulletin* 68(1):1–11.

Faber DM, MA Weiland, R Moursund, TJ Carlson, N Adams, and D Rondorf. 2001. Evaluation of the Fish Passage Effectiveness of the Bonneville I Prototype Surface Collector using Three-Dimensional Ultrasonic Fish Tracking. PNNL-13526, Pacific Northwest National Laboratory, Richland, Washington.

Feathers MG and AE Knable. 1983. Effects of depressurization upon largemouth bass. *North American Journal of Fisheries Management* 3:86–90.

Johnson EL, TS Clabough, CA Peery, DH Bennett, TC Bjornn, CC Caudill, and MC Richmond. 2007. Estimating adult Chinook salmon exposure to dissolved gas supersaturation downstream of hydroelectric dams using telemetry and hydrodynamic models. *River Research and Applications* 23(9):963–978.

McKinstry CA, TJ Carlson, and RS Brown. 2007. Derivation of Mortal Injury Metric for Studies of Rapid Decompression of Depth-Acclimated Physostomous Fish. PNNL-17080, Pacific Northwest National Laboratory, Richland, Washington.

Neitzel DA, MC Richmond, DD Dauble, RP Mueller, RA Moursund, CS Abernethy, GR Guensch, and GF Čada. 2000. Laboratory Studies on the Effects of Shear on Fish: Final Report. DOE/ID-10822, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

Rummer JL and WA Bennett. 2005. Physiological effects of swim bladder overexpansion and catastrophic decompression on red snapper. *Transactions of the American Fisheries Society* 134:1457–1470.

Stephenson JR, AJ Gingerich, RS Brown, BD Pflugrath, Z Deng, TJ Carlson, MJ Langeslay, ML Ahmann, RL Johnson and AG Seaburg. 2010. Assessing barotraumas in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory. *Fisheries Research* 160:271–278.

Winter J. 1996. Advances in underwater biotelemetry. In *Fisheries Techniques*, 2nd edition, BR Murphy and DW Willis (eds), pp. 455. American Fisheries Society, Bethesda, Maryland.

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John Stephenson's (PNNL) research primarily includes the evaluation of physiological effects of simulated hydro-turbine passage on juvenile salmonids and other migratory fish. Research is focused on the development of new generation hydro-electric turbines that will optimize turbine efficiency and safely pass fish. Mr. Stephenson has also been associated with the deployment of radio and acoustic telemetry systems. John has also been involved in the deployment of hydroacoustic systems on many hydro-electric projects in the Columbia and Snake River watersheds.

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Designing Leading Edges of Turbine Blades to Increase Fish Survival from Blade Strike

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Introduction

Injury to fish passing through hydro turbines is caused by various mechanical, pressure, and hydraulic mechanisms that vary with turbine design and operation. The relative importance of these mechanisms depends primarily on fish size, turbine type, and certain project design features. Mechanical mechanisms are considered the predominant source of injury and mortality to fish passing through turbines at many projects and include fish impact on stay vanes and wicket gates, leading edge turbine blade strike, abrasion of fish against surfaces and “grinding” within narrow gaps between moving and stationary turbine components. Of these mechanical-related injury sources, leading edge blade strike likely is the primary source of turbine passage mortality at many hydro projects.

To provide information on how turbine blade leading edges can be designed to reduce strike-related injury and mortality, a computational fluid dynamics (CFD) analysis was conducted of several leading edge geometries and a series of biological evaluations using the leading edge geometry considered to have the most potential for minimizing fish injury. The results of the CFD analysis indicated that a semi-circular profile provided the best opportunity to deflect fish as the blade approached and made contact. Using this leading edge geometry, biological testing was conducted to estimate injury and survival rates for various combinations of test conditions (i.e., different species, fish lengths, blade thicknesses, and impact velocities). The data from these tests can be used by hydro project owners and turbine manufacturers to optimize the shape and thickness of turbine blade leading edges for improved survival of fish. This paper provides a summary of the biological testing.

Study Methods

The test facility used for the biological evaluation was designed to reach strike speeds up to about 12 m/s with a maximum leading edge blade thickness of 150 mm. Simulated turbine blades with leading edge thicknesses of 9.5, 25, and 50 mm had parallel surfaces after the leading edge; the 100 and 150-mm thick blades had tapered trailing edges to reduce drag (Figure 2-12). The strike velocities evaluated represented the relative velocity between fish approaching a runner and the runner’s rotating blades, assuming there is little movement of fish against approach flows. It is important to note that the relative velocity of fish and flow to a turbine blade is lower than the blade tip speed relative to a stationary reference.

Figure 2-12

Blades used to simulate leading edge blade strike during the biological evaluation. All of the blades have a semi-circular leading edge and the 100 and 150-mm thick blades have a tapered design to reduce drag.

The test tank was 0.91 m square and about 7.6 m in length for 2006 tests and 16.5 m in length for testing in 2007 and 2010. The longer tank provided more distance for acceleration and braking, allowing a higher blade speed to be obtained. A 1.2 m square opening was located on the top of the tank through which fish were placed in the path of a blade at the location where they were struck (Figure 2-13). A side window was also located at this point along the length of the tank to allow for recording of each blade strike with a high speed video system. The test blades were mounted to a streamlined cart which traveled along rails mounted to the inside of the back wall of the tank (Figure 2-13). To propel the blades and cart along the rails, a chain mechanism was used in 2006 and a cable and spool system was used 2007 and 2010. The cable drive shaft was connected to a clutch, brake, transmission, and main drive motor using v-belts. Blade speed and direction were controlled by changing the speed and direction of the 20 horsepower electric motor using a variable frequency drive controller (VFD). The clutch and brake were electronically controlled to start and stop the cart and blade. Each strike speed selected for testing required a configuration within the clutch/brake controller for accelerating and decelerating the blade. Magnetic sensors provided start and stop locations and timing through the strike area to determine the speed of the blade just prior to striking a fish.

*Figure 2-13
Schematic and photo of linear test tank used for the evaluation of leading edge blade strike.*

Blade strike testing was primarily conducted with rainbow trout (100 to 300 mm fork length), with a limited number of test conditions also evaluated with white sturgeon (100 to 225 mm fork length). Between 25 and 75 fish were tested for each set of conditions evaluated (species, fish length, blade thickness, and strike velocity). Control groups also included similar numbers of fish and were subjected to all of the same handling and testing procedures as treatment fish, with the exception of being struck by a blade. Each individual treatment and control test was initiated by randomly selecting a fish from one of the holding tanks. After removal from the holding facility, fish were placed in an anesthetic bath (clove oil solution) for three to four minutes. Separate pieces of fishing line were then tied around the base of the caudal fin and through the gill and mouth. Fish were positioned at the strike location by placing the free ends of the fishing lines in foam slits located at the bottom (caudal line) and top (head line) of the test apparatus. The lines were tight enough to keep the fish suspended before a test blade was fired (Figure 2-14), but generally loose enough to pull free when fish were struck by a blade. Most fish were positioned to be struck in the midsection (75 to 80%), with smaller percentages hit in either the head or tail regions (10 to 15%). The side of each fish that was struck (i.e., ventral, dorsal, or side) was also recorded but could not be controlled due to fish spinning slightly on the tether lines after being positioned in the tank.

Immediately after each fish strike, or after controls were positioned in the test apparatus for the same time it took for treatment fish to be struck, fish were removed with a dip net, measured for length and examined for external injuries. Following post-test examinations, fish were placed in a recovery tank until the effects of the anesthesia were no longer evident. Immediate mortalities (i.e., those that occurred within 1-hr of testing) were recorded and live fish were

placed in a net pen and held for 96 hours to assess latent mortality. Each treatment and control test took approximately six to eight minutes to complete from the time a fish was removed from the holding facility until it was placed in the recovery tank.

Figure 2-14

Rainbow trout positioned at 90 and 45 degrees to an approaching blade prior to being struck.

The primary parameters of interest for the evaluation of blade strike survival were the ratio of fish length (L) to blade thickness (t) and strike speed. The L/t ratio varied from about 0.75 to 25 for rainbow trout tests and about 1 to 8 for white sturgeon tests. Immediate (1-hr) and total (immediate and 96-hr combined) survival rates were calculated for each combination of L/t and strike speed evaluated. Blade strike survival rates were adjusted with control fish data to account for any mortality associated with testing and handling. However, control survival was typically high (at or near 100%), indicating that the test procedures resulted in little or no mortality. Because the location of a blade strike along the body of a fish likely affects survival, it was important to examine the blade strike survival data based on where fish were struck (i.e., head, midsection, and caudal regions). Also, even though we attempted to strike the same proportion of fish in each of the three regions, there was some variability among the different test conditions evaluated. This variability could lead to differences in survival rates being attributed to differences in fish-to-blade angle, L/t ratio, and/or strike speed when they may actually be due to differences in the proportion of fish that were struck in each location. For example, if more fish were struck in the caudal region for any given set of conditions, the estimated overall survival rate could be higher than less injurious test conditions for which more fish were struck in the midsection or head. Therefore, we calculated survival rates for fish struck in each of the three body regions and applied these estimates to a standardized strike region distribution based on the proportional length of each region to the total

fish length. A mean proportional length for each strike region was estimated from a sub-sample of test fish. The head region accounted for about 0.21 of a fish's fork length, the mid-body about 0.46, and the caudal region about 0.33.

Results

Rainbow trout positioned at 90 degrees to approaching blades were tested with L/t ratios ranging from about 1 to 25 at strike speeds of about 3 to 12 m/s. Tests with L/t ratios greater than 2 were only evaluated at strike velocities of 7.3 m/s and less due to high mortality rates at this upper speed, whereas tests with L/t ratios of 2 and less were evaluated at strike velocities 7 m/s and greater due to high survival at the lower speeds. Blade strike survival of trout decreased with increases in the L/t ratio and strike speed (Figure 2-15). Total survival rates were 97 to 100% at strike speeds of 3 and 5 m/s for the three higher L/t ratios evaluated at these velocities, but decreased considerably for each ratio when the strike speed was increased to about 7.3 m/s. Survival was high (>90%) for trout tested at an L/t ratio of 1 at strike speeds up to about 8.5 m/s, and exceeded 96% for an L/t ratio of 0.75 (i.e., fish length was less than the blade thickness) at strike velocities greater than 10 m/s.

Figure 2-15
Total survival (immediate + 96-hr) by L/t ratio and strike speed for rainbow trout suspended at a 90 degree angle to the approaching blades. Survival rates have been adjusted for control mortality and strike location (head, mid-section, and caudal region).

White sturgeon were evaluated with L/t ratios of about 1 to 8 for a relatively narrow range of strike velocities (10.6 to 12.2 m/s). A regression analysis of the white sturgeon data demonstrated a statistically significant inverse relationship between total survival and L/t ratio, with 93% of the variability in survival attributed to L/t ratio (i.e., $r^2 = 0.93$) (Figure 2-16). White sturgeon survival was about 97% for an L/t ratio of 3.4 at the highest strike speed (12.2 m/s), indicating they are less susceptible to mortality from blade strike than rainbow trout. This observation is supported by the results of pilot-scale biological testing with the Alden turbine, for which white sturgeon survival was significantly higher than rainbow trout and other species tested at similar lengths. Sturgeons have cartilaginous skeletons and they lack scales, which may make them less vulnerable to severe injuries when passing through turbines.

To examine the effects of fish angle relative to a blade and where along the body fish are struck, we compared survival rates by strike location (head, mid-section, and caudal region) and L/t ratio for the two fish angles that were tested (90 and 45 degrees) at a strike speed of about 12 m/s. Blade strike survival rates were lower for rainbow trout struck in the mid-section of the body when fish were suspended 90 degrees to the approaching blades (Figure 2-16). When positioned at 45 degrees to the blades, survival rates were lowest for fish struck in the head (Figure 2-16). Survival rates for fish struck in the caudal (tail) region were at or near 100% for both fish angles and all L/t ratios examined. Total survival rates (adjusted for body region strike location) were higher for fish angled 45 degrees to the blades than they were for the 90 degree orientation at the L/t ratios and two strike speeds for which both angles were evaluated (Figure 2-17 and Figure 2-18).

Figure 2-16
Total survival (immediate + 96-hr) by L/t ratio white sturgeon suspended at a 90 degree angle to the approaching blades. Survival rates have been adjusted for control mortality and strike location (head, mid-section, and caudal region).

Figure 2-17
Total survival by strike location (head, mid-section, and caudal region) for fish positioned 90 and 45 degrees to the approaching blades and struck at a velocity of about 12 m/s.

Figure 2-18
Total survival for fish angled 45 and 90 degrees to the approaching blade and struck at a velocity of about 7.3 m/s.

Figure 2-19
Total survival for fish angled 45 and 90 degrees to the approaching blade and struck at a velocity of about 12.2 m/s.

Conclusion

The following are general conclusions from the EPRI studies investigating the relative importance of the various factors that affect the survival of fish struck by the leading edge of turbine blades:

- Strike survival of rainbow trout and white sturgeon increased with decreases in the ratio of fish length to blade thickness (L/t ratio) and, for rainbow trout, L/t ratios of 1 or less (i.e., fish lengths equal to or less than leading edge blade thickness) will result in relatively high strike survival rates at strike speeds up to about 12 m/s.
- Strike survival of rainbow trout increased with decreasing strike velocity for L/t ratios of 1 and greater, but mortality was high for L/t ratios of 2 and higher at strike speeds greater than 5 m/s. Strike velocities of 5 m/s should result in little or no mortality regardless of fish length and blade thickness (within the ranges evaluated).
- White sturgeon were less susceptible to strike mortality than rainbow trout.
- Strike survival was slightly higher for fish angled 45 degrees to the approaching blades than for fish positioned at 90 degrees. The angle of fish also affected survival rates for fish struck in the head and mid-section, with greater mortality for head strikes and lower mortality for mid-section strikes when fish were angled at 45 degrees.

The results this study provide valuable data that describe the effects of the various parameters that influence blade strike survival (i.e., fish length, fish orientation, leading edge blade thickness, strike speed). This information has been used to redesign the blade leading edges of the Alden turbine to increase strike survival and should be considered in the design of other turbine types. However, additional information on the orientation of fish when they are struck by a blade and the probability of being struck in various body regions would further strengthen the data that have been collected.

Authors

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Computational Fluid Dynamics Framework for Turbine Biological Performance Assessment

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Abstract

In this paper, a method for turbine biological performance assessment is introduced to bridge the gap between field and laboratory studies on fish injury and turbine design. Using this method, a suite of biological performance indicators is computed based on simulated data from a computational fluid dynamics (CFD) model of a proposed turbine design. Each performance indicator is a measure of the probability of exposure to a certain dose of an injury mechanism. If the relationship between the dose of an injury mechanism and frequency of injury (dose–response) is known from laboratory or field studies, the likelihood of fish injury for a turbine design can be computed from the performance indicator. By comparing the values of the indicators from various turbine designs, the engineer can identify the more-promising designs. Discussion here is focused on Kaplan-type turbines, although the method could be extended to other designs. Following the description of the general methodology, we will present sample risk assessment calculations based on CFD data from a model of the John Day Dam on the Columbia River in the USA.

Introduction

Over the past decade, there have been many studies describing injury mechanisms associated with turbine passage, the response of various fish species to these mechanisms, and the probability of survival through specific dams under certain conditions. However, transforming and integrating these data into tools to design turbines that improve survival by minimizing impacts to fish during passage has been difficult and slow. Although identifying the locations and hydraulic conditions where injuries occur is challenging, a more robust quantification of the turbine environment has emerged through integrating balloon tag, sensor fish data, and computational fluid dynamics (CFD) studies. Field-testing new designs is very expensive, so tools that improve the linkage between fish injury data and turbine characteristics are needed to identify the most promising designs.

In this section, a new method, the biological performance assessment (BioPA), is introduced for bridging this gap between laboratory studies on fish and turbine design. Using this method, a suite of biological performance indicators is

computed based on data from a CFD model of a proposed turbine design. Each performance indicator is a measure of the probability of exposure to a certain dose of an injury mechanism. If the relationship between the dose of an injury mechanism and frequency of injury (dose–response) is known from laboratory or field studies, the likelihood of fish injury for a turbine design can be computed from the performance indicator. By comparing the values of the indicators from various turbine designs, the engineer can identify the more-promising designs. Discussion here is limited to Kaplan-type turbines, although the BioPA method could be extended to other designs.

Following the description of the general methodology, a sample risk assessment calculation based on CFD data from a model of the John Day Dam turbine is presented for fish exposure to rapid pressure change.

In this section, a new method, the biological performance assessment (BioPA), is introduced for bridging this gap between laboratory studies on fish and turbine design. Using this method, a suite of biological performance indicators is computed based on data from a CFD model of a proposed turbine design. Each performance indicator is a measure of the probability of exposure to a certain dose of an injury mechanism. If the relationship between the dose of an injury mechanism and frequency of injury (dose–response) is known from laboratory or field studies, the likelihood of fish injury for a turbine design can be computed from the performance indicator. By comparing the values of the indicators from various turbine designs, the engineer can identify the more-promising designs. Discussion here is limited to Kaplan-type turbines, although the BioPA method could be extended to other designs.

Following the description of the general methodology, a sample risk assessment calculation based on CFD data from a model of the John Day Dam turbine is presented for fish exposure to rapid pressure change

Method

Fish passing through turbines are subjected to multiple stressors, including collisions with solid objects, shear, pressures changes, and turbulence (Čada 1997). Because the turbine environment is extremely heterogeneous, the level of exposure to these stressors is dependent on the path the fish takes. Measurement of the exact paths of fish through working turbines has not been possible due to the severe conditions present in the runner area and difficulty of access. For similar reasons, comprehensive field measurements of the turbine flow environment also are lacking. The basis for the BioPA is that CFD models of the turbine can be used to not only compute the flow environment but to also estimate the distribution of probable fish paths through the turbine so that a probability distribution of exposure to the relevant stressors can be estimated. Currently, the BioPA assumes that fish passing through a turbine follow streamtraces that are calculated from the CFD solution. A streamtrace is the path taken by a neutrally buoyant, massless particle when advected through a velocity field. The streamtrace is a surrogate for the trajectory of a fish through the turbine environment.

A key element of the BioPA method is to identify the turbine characteristics (i.e., stressor statistics) that correspond to the known fish-injury mechanisms. Turnpenny (1992), Čada (1997), and others have identified four major categories of injury mechanisms—collision, pressure, shear, and turbulence. A set of stressor statistics is computed from CFD model results that relate to each of these mechanisms. These statistics are computed for each fish passage route—that is, each model streamtrace. The focus in this paper is on only one stressor, pressure nadir, to demonstrate how the calculations are made.

To evaluate the turbine environment, the BioPA employs the technique of sampling by streamtraces. In this scheme, each streamtrace represents an equally likely path through the turbine. The exposure to stressors along this path is summarized by an appropriate stressor statistic. Collecting stressor statistics for each path accumulates a representative data set for the entire domain. With this type of sampling, those regions of the CFD model domain that receive a higher density of streamtrace visits are more heavily represented in the data set.

Once the model domain has been sampled by the streamtraces, the exposure probability density for the stressor statistic data collected along each streamtrace path can be computed. Next, a dose–response relationship is used to describe the response of a fish to various levels, or doses, of a stressor. The dose is defined as the amount of exposure to an injury mechanism that a fish experiences during a turbine passage. The response is defined as the *probability* that a fish subjected to a specific injury-mechanism dose will be injured.

As an example of a well-quantified dose–response relationship, Abernethy (2002), Brown (2009), and others observed that fish subjected to sudden changes in water pressure suffer various injuries. In general, the more severe the pressure change the more likely that a fish will receive a mortal injury. By exposing many fish to various levels of pressure change and counting the number that died at each dose, Brown et al. (2010) were able to define a dose–response relationship between the ratio of acclimation pressure of the fish at the start of the passage and the lowest pressure to which it is exposed (nadir pressure), which usually occurs at the underside of the turbine blade. This relationship is shown in Figure 2-20.

Figure 2-20

Dose-response curves for nadir pressures given a typical range of fish acclimation depths (AccDepth).

If a mortality dose-response relationship (Pm_d) is known, the stressor exposure probability density (Pe_d) computed from streamtrace sampling of the CFD model can be used to estimate a fish mortality probability as follows:

$$P_{mortality} = \frac{\sum_d (Pe_d \cdot Pm_d \cdot N_d)}{\sum_d N_d} \quad \text{Equation 1}$$

where N_d is the number of streamtraces with exposure to dose d .

Case Study – John Day Dam

In this section, application of the BioPA method is illustrated using a CFD model of a turbine unit at John Day Dam. John Day Dam is a hydroelectric facility located on the Columbia River at the border between Washington and Oregon. In 2007, the USACE Portland District requested Andritz Hydro to construct and run a CFD model of one of the turbines in the facility (Andritz 2008). Andritz completed a three-dimensional CFD model of the turbine from the intake to draft tube using the ANSYS CFX solver. To reduce the run time and complexity of the model, only one blade of the six-bladed runner was modeled. This sectional piece was modeled in a rotating frame of reference to simulate movement of the runner assembly. Circumferential averaging of the

velocities obtained at the outlet of the wicket gates was used as input for the runner component.

After constructing and validating the model, Andritz ran several discharge scenarios. For this paper, we have selected three operating conditions listed in Table 2-1.

Table 2-1
Operational Conditions.

Operation	Discharge (cfs)
BP01	16450
BP02	11800
BP05-C	20895

The first task in the BioPA method is to develop a streamtrace seeding plan that adequately samples the model domain. This includes the number of seeds to use and their placement location and pattern. Ideally, streamtraces should be placed across the entire intake boundary in a pattern that mimics the actual fish distribution. However, fish distribution data are often not available, so a uniform distribution is often chosen by default. Here, we have chosen two streamtrace distributions, a uniform and a non-uniform based on hydro-acoustic studies of fish distributions at John Day Dam (Figure 2-21).

*Figure 2-21
Streamtrace seed distribution patterns. Plots to right of the seeds indicate the vertical density profiles. Intake guidance screens are shown in green.*

The streamtraces (Figure 2-22 and Figure 2-23) are generated using the CFD analysis software Tecplot360™ and the model variables are interpolated onto each point of the path. The stressor statistics, in this case just pressure nadir, are then computed for each path. This results in a single nadir value for each of the 5,000 to 10,000, or so, paths. A basic statistical package such as exists in Excel® 2010 is used to divide the range of nadir values into bins and count the number of streamtraces with nadirs in each bin. When the frequency count is divided by the total number of streamtraces used in the sample, a probability density distribution is obtained (Figure 2-24 and Figure 2-25).

Figure 2-22
Sample streamtraces colored by pressure value (Pa).

Figure 2-23
Sample streamtraces colored by pressure value (Pa).

Figure 2-24
Probability density distribution comparing pressure-nadir exposure for uniformly distributed seeds.

Figure 2-25
Probability density distribution comparing pressure-nadir exposure between uniformly and sigmoidally distributed seeds.

The final step in the BioPA process is to link the exposure probability density computed using the CFD model to the appropriate dose–response relationship for the stressor. The pressure mortality relationship developed by Brown et al. (2010), shown in Figure 2-20, yields the red curve shown in Figure 2-24 and Figure 2-25, assuming a fish acclimated at 10 m depth. This curve, for example, indicates that the probability of mortality for a nadir pressure exposure of 100,000 Pa is about 2%. Figure 2-24 and Figure 2-25 also show the computed exposure probability density in blue, cyan and green. The majority of streamtraces have pressure nadirs in the range of 100,000 to 200,000 Pa.

To compute an overall mortality probability, Equation (1), is used to integrate over all the doses. This results in values of mortality due to pressure nadir shown in Table 2-2. These mortality estimates show several interesting features:

- As expected, higher discharges tend to increase mortality because pressure drops are larger under these conditions.
- Sigmoidal seed distribution, which contains a higher density of seeds closer to the roof of the intake (higher elevation) than at the floor, has slightly lower mortality values than the uniformly distributed seeds. This suggests that fish entering the turbine intake at a higher elevation tend to encounter the runner closer to the hub and experience milder pressure changes than those beginning their passage at a lower elevation.
- Depth of fish acclimation is a significant factor in the prediction of passage mortality due to rapid pressure change. However, fish acclimation depth may not necessarily equal actual fish depth at the entry to the turbine intake, so estimates for this value are currently uncertain.

*Table 2-2
Mortality estimates for each operating condition and fish distribution.*

Operation	Discharge (cfs)	Acclimation Depth (m)	Mortality (%)	
			Uniform	Sigmoidal
BP02	11800	0	0.07	0.04
		5	0.2	0.1
		10	0.9	0.8
BP01	16450	0	0.08	0.06
		5	0.3	0.3
		10	0.5	0.4
BP05-C	20895	0	0.6	0.5
		5	1.5	1.4
		10	3.5	3.4

Future Plans and Recommendations

A computational fluid dynamics modeling framework to assign a biological performance for a given fish species has been developed that can be applied in the design process for turbines. This paper outlines this CFD-based modeling approach and summarizes one of its current applications in the Columbia River

basin for the John Day Dam. Efforts are currently underway to add blade strike, shear, and turbulence to the stressors included in the framework and design tool.

Future efforts and recommendations include:

- Include the effects of fish mass in the calculations. PNNL is currently adapting an in-house Lagrangian particle tracking code for this purpose.
- Confirm the model performance using fish passage data from prototype field tests.
- Extend the framework for unstudied fish species. The value of analogous approaches from the ecotoxicity field (e.g., the application of safety factors, environmental quality factors, species sensitivity distributions, and interspecies correlation estimation models) should be examined.

References

Abernethy, C.S. B.G. Amidan, and G.F. Čada. 2002. Simulated passage through a modified Kaplan Turbine pressure regime: A supplement to Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish. PNNL-13470-A. Report to the U.S. Department of Energy Hydropower Program. Idaho Falls, ID.

Andritz Hydro. 2008. *Computational Fluid Dynamics Modeling of the John Day Dam Kaplan Turbine*, Report prepared for US Army Corps of Engineers, Portland District, Portland, OR.

Brown RS, TJ Carlson, AJ Gingerich, JR Stephenson, BD Pflugrath, AE Welch, JR Skalski, AG Seaburg, and RL Townsend. 2010. *Quantifying mortal injury of juvenile Chinook salmon exposed to simulated hydro-turbine passage*. Chapter 2 in *Assessment of Barotrauma in Untagged and Tagged Juvenile Chinook Salmon Exposed to Simulated Hydro-Turbine Passage* in TJ Carlson, RS Brown, JR Stephenson, AJ Gingerich, BD Pflugrath, AH Colotelo, AE Welch, PL Benjamin, JR Skalski, AG Seaburg, and RL Townsend (eds). Pacific Northwest National Laboratory, Richland, Washington.

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The Alden Fish Friendly Turbine: Preliminary Design, Model Performance, and Applicability to Hydro Sites

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Abstract

In order to address the issue of fish passage in hydraulic turbines, Alden Research Laboratory developed a conceptual three bladed turbine to provide fish with reduced strike exposure and more favorable pressure gradients than conventional hydro turbines. This combination is predicted to produce exceptional survival rates for fish passing through the turbine, but results in lower turbine power densities when compared to conventional turbines. As an alternative to more conventional hydro turbines, the Alden turbine is a solution for projects where fish passage is paramount. During the final stages of its development, Alden collaborated with Voith Hydro to refine the hydraulic design, to develop the turbine mechanical design, and to scope the ancillary equipment into a complete hydro package. All project parameters were specific to a pilot site located in the northeastern United States.

This paper will address two main topics. First, the hydraulic and mechanical design results of the pilot site will be discussed. The hydro development of the pilot site with the Alden concept will be compared to conventional turbine types including Francis, Kaplan, and Voith Hydro's minimum gap (MGR) Kaplan. A technical comparison will focus on sizing, performance, and fish survivability. Furthermore, comparative costs for the machine alternatives will be presented.

The second topic of this paper will address the applicability of the Alden turbine concept to other hydro sites. Although the current development work was performed for application at a specific site, the Alden turbine can be sized to provide similar fish passage characteristics for a variety of hydraulic conditions. This topic will review which range of sites may fit the newly developed design and which sites would require design changes.

Introduction

The Alden Fish Friendly hydro turbine concept was developed by Alden Research Laboratory (Alden) as part of the Advanced Hydro Turbine System (AHTS) program which receives funding from the U.S. Department of Energy (DOE). Recent collaboration with Voith Hydro (Voith) focused on refining the hydraulic passages for improved fish survival and commercial characteristics. As a completely new turbine family, the Alden concept provides high survival rates for migrating fish. The Alden turbine serves as an alternative to the more

conventional hydro solutions for projects particularly concerned with fish passage (Coulson et al. 2011).

Although the turbine runner is a novel hydraulic design, the mechanical design and plant layout is a blend of conventional Francis and Kaplan technologies. No additional equipment or maintenance is required for an Alden turbine installation beyond what would be expected for a new conventional unit at a typical site. Since similar mechanical designs have been successfully utilized in numerous sites worldwide, the technology necessary for the mechanical application does not represent a high-risk leap in design.

The application range of the Alden turbine overlaps with conventional turbine application ranges. However, for new sites which have the most strict fish passage requirements, the Alden turbine becomes a very attractive solution. For such sites, the Alden turbine can eliminate the need for costly fish bypass systems. Moreover, the Alden turbine will produce revenue while conventional technologies require spill flow.

In this paper, the hydraulic and mechanical designs of the Alden turbine are discussed and compared with conventional applications. The plant layout and corresponding ancillary equipment are likewise compared to sites with conventional technologies. Finally, the applicability of the Alden turbine to other sites is discussed.

Section I - Comparison with Conventional Turbines

The construction and layout of an Alden turbine is comparable to that of a vertical Francis turbine. Unlike a typical vertical Francis machine, the Alden turbine utilizes an innovative runner design and an optimized distributor to enhance fish passage. To meet the desired design criteria, the Alden turbine is larger than conventional turbines for the same operational application.

Apart from the special hydraulic design, the Alden turbine power unit is similar to conventional turbine technology. The power unit is a vertical shaft arrangement with three bearings: an oil guide bearing above the generator, a combined thrust/guide bearing below the generator, and a water bearing above the turbine.

The turbine spiral case is a rectangular cross section, concrete lined, full spiral case. Fixed stay vanes support the embedded stay ring. The wicket gates are adjustable with pressurized oil moving two, single acting servomotors. As the water discharges from the Alden runner, energy is recovered in the concrete lined, elbow type draft tube.

The generator, automation, and balance of plant equipment which are required for an Alden site are very similar to what would be expected at a corresponding conventional site. No increased installation scope, additional ancillary equipment, or special maintenance is required.

Hydraulic Design

The hydraulic design of the Alden turbine was centered on the turbine rotating elements. The Alden runner is a patented, three bladed, radial flow Francis type runner with very long runner blades and thick entrance edges to minimize both the occurrence of fish strike and the damage that results in the event of strike (Foust et al. 2010, Coulson et al. 2011).

In addition to the runner, the distributor section has been optimized for fish passage. First, the number of stay vanes and wicket gates have been reduced from conventional turbine applications to minimize the opportunity for fish strike. Further, the clearance between stay vanes and wicket gates has been minimized to eliminate the possibility for fish pinching. Finally, a large clearance between the wicket gate trailing edges and the runner blade entrances edges ensures that fish up to twelve inches in length can pass the distributor without being obstructed (Coulson et al. 2011).

Since the Alden turbine operates at a relatively low head, the Alden turbine for the pilot project has been designed with a rectangular cross section, concrete lined, full spiral case thereby reducing the material cost of the turbine (Coulson et al. 2011).

Mechanical Design

During the early mechanical design, three major turbine components were identified for in-depth mechanical analysis. Finite Element Analysis (FEA) was used to confirm (i) structural integrity of the runner blades; (ii) rib design and weld geometry for rigidity of the stay vanes; and (iii) stem design for acceptable wicket gate radial forces, torques, and bearing pressures.

The remainder of the power unit was designed using industry and Voith guidelines and sizing rules. Further analyses were done to (i) determine wicket gate mechanism layout and servomotor sizing, (ii) calculate head cover deflections, and (iii) calculate bottom ring / discharge ring and draft tube cone thicknesses. Since these turbine components were not modified significantly from conventional turbine technology, an in-depth analysis was not conducted at this stage of design.

In summary, the design review indicates that the Alden turbine is readily implementable for the range of application presently foreseen.

Unit Sizing

The sizing philosophy of an Alden turbine is fundamentally different from that of conventional turbine technologies. While conventionally turbines are sized to ensure cavitation free performance at the maximum flow, the Alden turbine is designed to ensure acceptable pressure gradient criteria under fish passage conditions (Hecker et al. 2009, Foust et al. 2010). This results in an Alden

machine that is larger and which rotates more slowly than conventional applications.

Table 2-3 represents a comparative sizing of the Alden turbine, a conventional Francis, and a conventional Kaplan. The below sizing considers only hydraulic site conditions and does not make any adjustment for comparable fish passage. Note that the Alden turbine is larger but can be set higher above tailwater.

*Table 2-3
Sizing Alternatives for an Alden Turbine Pilot Site*

		Alden Turbine	Conventional Francis	Conventional Kaplan
Reference Diameter, [mm]	D_{ref}	3900	2510	2650
Rotational Speed, [rpm]	N_{nom}	120.0	189.5	276.9
Rated Specific Speed	N_q	70	110	160
Intake Type	-	Concrete Lined Modified Full Spiral	Concrete Lined Full Spiral	Concrete Lined Semi Spiral
Outlet Type	-	Elbow Draft Tube	Elbow Draft Tube	Elbow Draft Tube
Number of Runner Blades	Z_2	3	13	5
Number of Wicket Gates	Z_0	10	16	24
Turbine Setting, [m]	h_s	+1.5	+0.5	-5.0

* A negative setting implies that the runner centerline elevation is below rated tailwater

Turbine Performance Characteristics

In 2010, a 1:8.71 fully homologous scale model of the Alden Turbine spanning from the intake pipe through the draft tube exit was designed and manufactured for performance testing at the Voith Hydro *S. Morgan Smith Hydraulic Testing Laboratory* located in York, Pennsylvania, USA.

Testing showed that the Alden turbine efficiency remains high across the anticipated operating range for a pilot site. The shape and peak of the efficiency curve was similar but higher and broader compared to a conventional Francis

machine. By comparison, the efficiency for a conventional Kaplan has a lower peak but a much flatter shape (Coulson et al. 2011). Figure 2-26 shows a comparison of the model tested efficiencies for the machines represented in Table 2-3.

Figure 2-26

A cross plot showing the relative performance of an Alden turbine, a conventional Francis turbine, and a conventional Kaplan turbine. Performance is normalized to the Alden turbine.

Fish Survivability

Blade strike has a significant influence on fish mortality. The probability of strike is proportional to the number of blades, the rotational speed of the runner and the size of the fish (Hecker et al. 2005). Secondary factors influencing fish mortality include pressure change rates, minimum pressure, fluid shear, and gap flows (Fisher and Roth, 1995; Hecker et al. 2009; Foust et al. 2010).

As turbine size decreases and the units are optimized for costs, the smaller, faster machines have a negative influence on fish survival. Some large, minimum gap Kaplan turbines have achieved survival rates in the mid-nineties due to their characteristic few blades, slower rotational speed, and minimization of leakage flow (Fisher et al. 2000).

The Alden turbine has been specifically designed to maximize survival rates even in smaller turbine sizes. A comparison of expected survival rates for the Alden turbine application when compared to the more conventional application of a Minimum Gap Kaplan is provided in Figure 2-27 (Coulson et al. 2011).

Fish Friendly Turbine Application Ranges

Figure 2-27

Expected fish survival rates for Alden turbine application relative to Minimum Gap Kaplan technologies. Note that the survival rates are calculated for an 8" fish and the turbine power outputs reflect the best efficiency point (fish passage condition) for the Alden turbine and the rated point for the Kaplan. (Coulson et al. 2011)

As Figure 2-27 shows, the Alden turbine is the most fish friendly solution for smaller turbine sizes. The Kaplan Minimum Gap Runner (MGR) survivability approaches Alden turbine survivability only at high head/high outputs sites with large turbine runner diameters. For lower output sites, the Alden turbine has expected fish survival rates that are superior even to the best Kaplan MGR. It should be noted that the predictions given in Figure 2-27 are based solely on strike and do not account for differences in predicted shear, pressure change rates, or minimum pressures throughout the turbine.

When compared with conventional turbine technology, the Alden turbine has superior fish survivability. Table 2-4 was constructed for the turbine sizing presented in Table 2-3.

Table 2-4

Comparison of Fish Survivability Between Alden Turbine and Conventional Technologies

	Alden Turbine	Conventional Francis	Conventional Kaplan
Survival Due to Strike for an 8" Fish	98%	< 50%	86%

Relative Pricing

The Alden turbine is, by design, lower in power density than conventional turbines. The larger more slowly rotating equipment which allows for the enhanced fish passage performance also leads to a relatively more expensive turbine/generator solution.

The fully installed equipment price for the Alden turbine, including turbine, generator, unit controls, various BOP equipment, installation, and commissioning is roughly 35% higher than what would be expected for a conventional Francis or Kaplan in a similar application. This scope includes equipment supply and installation, but does not include any civil work. It should be noted that the higher setting of the Alden turbine will help to reduce excavation costs.

Since the Alden turbine is a solution which provides both fish passage and power generation, the additional equipment cost for an Alden turbine should only be compared with conventional turbine solutions which include (i) the cost of fish bypass systems, and (ii) spilling water from the upper reservoir and the resulting lost revenue potential.

The additional civil costs for fish bypass systems and the lost revenue from spilled water are still under evaluation and will be site specific. Once this evaluation is complete, a true comparison between a conventional solution and one with the Alden turbine can be made for a specific site.

Section II - Applicability to Other Hydro Sites

The Alden turbine was hydraulically and mechanically designed for a specific site condition. However, the current Alden turbine design could be used at sites with net heads up to about 100 feet with turbine power outputs up to about 13.6 megawatts. With further development, the application range of the Alden turbine could be expanded to heads above 120 feet, which will translate into higher power outputs.

Summary and Conclusions

The Alden turbine was developed by the Alden Research Laboratory with collaboration on the hydraulic design by Voith Hydro with funding from the U.S. Department of Energy, the Electric Power Research Institute (EPRI) and industry partners. The innovative fixed position three bladed Francis type turbine is predicted to produce exceptional fish survival rates at full scale applications.

Though the hydraulic design has a specialized runner and distributor section, the layout and mechanical design is a blend of conventional turbine technology. For a site with an installed Alden turbine, the supporting equipment is the same as would be expected at another conventional site. Moreover, there is no need for any additional installation scope, additional ancillary equipment, or specialized maintenance.

The Alden turbine eliminates the need to choose between fish passage and energy production. Instead, the innovative Alden turbine design allows for excellent fish passage characteristics while efficiently generating power. In particular for the small hydro market where projects are heavily economics driven, the ability to generate power while meeting fish passage requirements makes the Alden turbine a truly unique solution.

At this point, the Alden turbine has been hydraulically and mechanically designed sufficiently to verify proof of concept. As a consequence of the work done, the Alden unit is now ready to enter the phase of site selection and implementation of a prototype demonstration unit.

Concurrent with the DOE-funded study, the Electrical Power Research Institute (EPRI) is conducting a separate study to identify a demonstration project site for the installation and testing of the Alden turbine. In mid 2010, a solicitation was distributed to the hydropower industry for potential demonstration sites. A quantitative evaluation process was developed and implemented to objectively evaluate and rank the applications. One site was selected as the preferred location for development as a demonstration program for the Alden turbine, with an alternate site identified in the event the preferred site could not be developed. In 2011, pending receipt of commitment from the preferred demonstration site host company, EPRI will assist the owner with activities that will further the design, installation, and funding of the field demonstration project (Coulson et al. 2011).

References

Coulson, S., Foust, J.M., Hecker, G.E., Allen, G.A., S.V. Amaral, and D.A. Dixon (2011), Alden Fish Friendly Turbine: Final Development for Commercial Application, HydroVision 2011, Charlotte, NC.

Fisher, Richard K. and Alan D. Roth (1995), Design considerations for enhancing environmental compatibility of hydraulic turbines, Waterpower 1995, San Francisco, CA.

Fisher, R., D. Mathur, P.G. Heisey, R. Wittinger, R. Peters, B. Rinehart, S. Brown, and J.

R. Skalski (2000) Initial test results of the new Kaplan Minimum Gap Runner design on improving turbine fish passage survival for the Bonneville first powerhouse rehabilitation project, Proceedings of the 20th IAHR Symposium on Hydraulic Machinery and Systems, International Association of Hydraulic Research, Charlotte, North Carolina.

Foust, J.M., Coulson, S., Hecker, G.E., Allen, G.A., and D.A. Dixon (2010), Design considerations for the Alden fish friendly turbine, HydroVision 2010, Charlotte, NC.

Hecker, G. E., and G. S. Allen. 2005. *An Approach to Predicting Fish Survival for Advanced Technology Turbines*. Hydro Review, November 2005, HCI Publications, Inc., St. Louis, Missouri.

Hecker, G.E., M. Frain, S.V. Amaral, G.S. Allen, D.A Dixon, R.K Fisher, and D.J. Cooper (2009). The Alden/Concepts NREC fish-friendly hydro turbine: progress from design concepts to working demonstration project, Waterpower 2009, Spokane, WA.

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Mr. Smith was appointed to the position of Manager, Small Hydro, working at Voith Hydro Inc, in 2006. Mr. Smith is responsible for managing the Offer Project Managers and Lead Engineers to develop and achieve Voith Hydro's Small Hydro order intake plan. In 2000, Mr. Smith began his professional career at Voith Hydro, Inc. as a Mechanical Design Engineer, responsible for turbine rehabilitation design, mechanical design of new and rehabilitation turbine parts, engineering calculations and analysis, 2D/3D CAD and generation of production drawings. Between 2003 and 2005, Mr. Smith was involved in the Voith Hydro Management Training Program and underwent the company's corporate training program. As part of the training program, Mr. Smith spent nine months at Voith Hydro's German headquarters where he was part of the Hydraulic Layout department. Mr. Smith earned a Bachelor of Science degree in Mechanical Engineering in 2000, with a minor in Economics, from Lehigh University.

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Verification of a Numerical Model to Assess Fish Survival in the Alden Turbine

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Abstract

Prior to using computational fluid dynamics (CFD) to evaluate flow conditions in the Alden turbine relative to fish survival criteria, it is important to verify that the CFD simulations provide realistic results. Because it is essentially impossible to measure flow parameters inside the rotating machinery of a turbine for comparison to CFD simulations, the verification presented herein involves a more global check on the overall turbine efficiency as dependent on gate opening and non-dimensional head and flow coefficients. A “hill chart” of turbine efficiency is produced using CFD results and then compared to the hill chart derived from physical model testing of the Alden turbine. This comparison leads to conclusions regarding operating ranges that are reliably simulated by the developed CFD model. Within that range, the CFD model is used to demonstrate specific flow conditions in the Alden turbine related to fish survival.

Fish passing through turbines are subject to abrasion along surfaces and in small gaps, impact on stay vanes and gates, strike by leading blade edges, rapid pressure drops, flow shear and minimum pressures, all of which may cause injury and even death (Čada. et al. 1997). Limiting acceptable values for the flow induced mechanisms concerning pressure and shear have been established (see below) and were used in designing the Alden turbine. To determine how well these criteria have been met in various parts of the turbine, it is customary to use computational fluid dynamics (CFD), which can predict the locations and volumes which meet or exceed these limiting values. Various assumptions and approximations used in CFD simulations, the mesh type and resolution and the choice of turbulence model may have an effect on the validity of the predictions. Therefore, it is useful to verify the efficacy of the CFD method and that is the main subject of this paper. Because it is essentially impossible to measure local flow phenomena in the runner, this verification is performed by comparing the efficiency “hill chart” derived from CFD simulations with that resulting from physical scale model tests of the Alden turbine. Efficiency is an indicator of flow conditions in the runner. Thereafter, the CFD simulations are used to predict flow parameters related to the allowed limits for shear, pressure change rates, and minimum absolute pressures.

Performance testing was conducted in 2010 on the Alden Turbine using a 1:8.7 scale physical model at the Voith Hydro test stand in York, PA. These tests included determining the usual characteristics of efficiency and power versus flow and head at various gate openings. Other operating parameters were also recorded, such as axial and radial thrust, wicket gate torque, run-away speed,

cavitation limits, overload draft tube pressure pulsations and transients. The data on efficiency and power, scaled up to prototype values, were used to compile the usual “hill chart” to visually show the best efficiency point (BEP) and the range of acceptable operating conditions.

CFD Formulation

At about the same time as the physical model tests, the Alden Research Laboratory (Alden) started CFD model development and simulations of the entire turbine from the penstock to the draft tube outlet and tail water. These simulations included the fluid filled spaces between the outer runner shroud and the casing, as well as between the head cover and the runner top, thereby including the same loss sources as in the physical model. The CFD simulations were conducted using FLUENT version 6.3.26 and the model consisted of about 19.5 million computational cells. The governing equations solved are Reynolds-Averaged Navier-Stokes (RANS) equations combined with turbulence modeling equations for three-dimensional (3D), steady-state, Newtonian, incompressible and viscous flows without heat transfer. The shear stress transport (SST) $k-\omega$ two-equation turbulence model was used to calculate the turbulent kinetic energy k and its specific dissipation rate ω , and k and ω were used to obtain the turbulent eddy viscosity ν_t . The mixing-plane approach was used to model the fluid in the stationary reference frame and around the rotating parts in the moving reference frame. Two mixing planes between the rotating and fixed portions of the turbine were used and profiles of each flow property were obtained by performing circumferential averages at specific axial or radial stations and these profiles were then used to update the boundary conditions at the upstream and downstream fluid zones of the mixing-plane interface. Actual field dimensions of the entire turbine were used in the simulations to avoid scale up issues. Figure 2-28 and Figure 2-29 show the CFD model mesh at the stay vanes and wicket gates and at the runner blades and shroud, respectively.

Figure 2-28
Mesh at stay vanes and gates

Figure 2-29
Mesh at runner blades and shroud

Boundary conditions of a uniform velocity distribution (with 10% turbulence intensity and 10 viscosity ratio) and hydrostatic tail water pressure were set at the scroll inlet and draft tube outlet, respectively. The tail water level was set at the outlet of the runner. To run one operating condition, the wicket gate opening and runner rotational speed were fixed and the flow was independently selected, the simulation resulting in a total head across the turbine. The mechanical power out was calculated from multiplication of the runner torque caused by the pressure and viscosity forces and the shaft rotating speed, and the reported turbine efficiency was the ratio of that power to the available hydraulic power.

Plotting the resulting efficiencies from both the CFD simulations and the physical model using non-dimensional head and flow coefficients, which included the turbine diameter and rotational speed (in radians per second), aided a direct comparison between the best efficiency point (BEP) operating conditions and maximum efficiency values.

A dimensional analysis of the functional dependence of water head H , power output (power delivered by the runner), flow rate Q , characteristic turbine size D , and runner rotating speed n (radians/s), leads to the following dimensionless similarity parameters:

Table 2-5
Equations

Flow Coefficient:		(Eq. 1),
Head Coefficient:		(Eq. 2),
Power Coefficient:		(Eq. 3).

The efficiency of the turbine is a function of the discharge, head, and power coefficients, defined as

$$\eta = C_p/C_Q C_H = P_{W_D}/(p g H Q) \quad (\text{Eq.4})$$

The total available water head is

$$H = P_{W_T}/(p g Q) \quad (\text{Eq.5})$$

In the above expressions, g is gravity acceleration, P_{WT} is the total available power from the scroll inlet to the draft tube outlet. The latter is a summation of the energy flux differences across the three components of the turbine: the scroll and distributor, the runner and the draft tube.

Results

Figure 2-30 shows the efficiency hill chart derived from the CFD simulations. The sloping series of dots of different colors are each at a given gate opening, ranging from 18 degrees (bottom four in purple), 20 degrees (4 dots in blue), 21.1 degrees (6 dots in red) and 26 degrees (top three in dark). An interpolation program was used to derive the contour lines of efficiency. As is evident, there is a large predicted area of efficiency at 93.5%, indicating the Alden turbine with a given diameter and rotational speed would operate well over a large head range at similar flows (by changing the gate opening). This flexibility is due mainly to the relatively thick leading edges and few blades, which makes the runner less sensitive to the approach velocity.

Figure 2-30
Efficiency contours derived from the CFD simulations

These results are compared to the similar plot from the physical model in Figure 2-31. The red contours are those shown in Figure 2-30 and the green contours are derived from the physical model. The design point for the turbine is at the (scaled up) maximum efficiency from the model tests; namely 93.64% at a flow coefficient of 0.0575 and a head coefficient of 0.115. The difference between the CFD and physical model test contours of efficiency is shown on Figure 2-32. At the design point, the differences between efficiencies are very small (tenths of percent) and there is a band of such small difference at nearly constant flow for a wide range in head. Higher flows produced smaller differences in efficiency compared to lower flows.

Figure 2-31
 Comparison of efficiency contoured "hill chart" between CFD simulations (red) and physical model test results (green)

Figure 2-32
Differences in efficiency between CFD simulations and physical model test results

The CFD simulations produce more reliable results in the range where differences in efficiency compared to the physical model tests are small. Therefore, the CFD simulations would also be more reliable in this range for evaluation of parameters related to fish survival. In the following examples of flow features related to fish survival, the design point is selected as the point of comparison, being in the range of reliable results.

Evaluation of Fish Survival

Flow shear is produced by velocity gradients over distance. A maximum change in velocity of 30 ft/sec over a distance of 0.083 ft (one inch) was used for development of the Alden turbine, based on tests with alewife at Alden in the 1970s. This corresponds to a value of 360 1/sec. Tests by PNNL (Nietzel et al. 2000) indicated that a higher value, about 500 1/sec, is acceptable for salmonids. Larger values are considered harmful to fish. Regions with greater shear magnitudes determined by CFD for the redesigned Alden turbine are shown in Figure 2-33. Excessive shear values only occur in small bands next to solid surfaces at the bottom of the leading edges and along the trailing edges due to the realistic “no-slip” boundary condition of the CFD simulations. For the vast majority of the flow passage, shear values are well below critical values.

Figure 2-33
Shear regions greater than 360 1/sec in the redesigned Alden turbine

The maximum allowed rate of pressure reduction for the turbine design was established at 500 psi/sec based on tests conducted by PNNL wherein salmon survived a reduction from 4 atm to 0.5 atm in 0.1 sec with no significant injuries (Abernethy 2002). This rate is equal to about 500 psi/sec. Values exceeding this criterion only occur in the redesigned Alden runner as flow turns to the suction side of the leading edge, as shown in Figure 2-34. The affected region is only 0.25% of the runner water volume.

Figure 2-34
Regions of pressure reduction rate greater than 500 psi/sec (3.5 MPa/sec)

A goal of the Alden turbine design was to establish a minimum absolute pressure anywhere in the runner of 0.5 atm or about 7.4 psia (51 kPa). More recent tests by PNNL indicate this value should be closer to 0.6 atm (Stephenson et al. 2010) when fish are exposed to the low pressure for a few seconds. These CFD simulations with the tail water set at the runner exit show that the (time average) pressure is higher than 0.6 atm throughout the runner flow field, as shown in Figure 2-35.

Figure 2-35
Flow regions with absolute pressure less than 0.5 atm (7.4 psia) in the runner

Figure 2-36 shows the absolute pressure variations with time along representative path-lines (of 32 thousands samples) through the turbine runner, not including the draft tube. The location of each representative path-line in Figure 2-36 is shown in Figure 2-37. The high pressure is about 48 psia at the runner entrance and the minimum absolute pressure is about 10 psia when leaving the trailing edges of the blades. This difference in pressure of about 38 psi occurs in a minimum time of about 0.1sec, indicating a maximum pressure change rate of about 380 psi/sec. This is well below the accepted criterion of 500 psi/sec (see Figure 2-34). The spikes at the end of some path-lines are caused by the wake at the trailing edge of the blades.

Physical model tests showed that the local and transient minimum absolute pressure (determined by raising the tail water above that for incipient cavitation) is about 0.5 atm with the vast majority of the turbine flow region above this pressure. This safety margin above cavitation existed at the BEP for a wide range of heads and corresponding flows.

Conclusions

From the above CFD simulations, it may be concluded that

- The efficiencies predicted by the CFD model are in good agreement with data from the physical model tests, especially near the point of maximum efficiency.
- CFD simulation at the best efficiency shows that the fish survival criteria (shear, pressure change rate and minimum absolute pressure) are met for all or the vast majority of the turbine flow field.
- Blade strike is the dominant remaining mechanism of fish injury in the Alden turbine and the use of only three blades with relatively thick, half round leading edges and low runner rpm minimizes blade strike mortality.

Figure 2-36
Absolute pressure variations with time along pathlines through the runner

Figure 2-37
Locations of typical pathlines through the runner

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, DOE/ID-10853, March 2001
- Abernethy C.S., B.G. Amidan, and G.F. Čada. 2002. Simulated Passage through A Modified Kaplan Turbine Pressure Regime: A Supplement to Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-Passed Fish. PNNL-13470-A, Pacific Northwest National Laboratory, Richland, Washington.
- Čada, G. F., C.C. Coutant, and R.R. Whitney. 1997. Development of biological criteria for the design of advanced hydropower turbines. DOE/ID-10578, U. S. DOE, Idaho Operations Office, 1997
- Nietzel, D. A. 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 on the Effects of Shear on Fish: Final Report, DOE/ID-10822.
- Stephenson, J.R., A.J. Gingerich, R.S. Brown, B.D. Pflugrath, Z. Deng, T.J. Carlson, M.J. Langeslay, M.A. Ahmann, R.L. Johnson, and A.G. Seaburg.. 2010. Assessing barotrauma in neutrally and negatively buoyant juvenile

salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotraumas laboratory. Fisheries Research 106(2010) p. 271-278, 2010

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George Hecker is currently Senior Consultant at Alden Research Laboratory, Inc., formerly serving Alden as Director and President from 1975 to 2000. Prior to joining Alden, he worked at Stone and Webster and the TVA. He has published widely on R&D in hydraulic engineering, recently focusing his time on further development of the Alden turbine, of which he is co-inventor. George has degrees from Yale and MIT.

Dr. Jason Foust is employed by Voith Hydro, Inc. in York, Pennsylvania. After completing his graduate studies in Experimental Fluid mechanics at Lehigh University in 2006, he accepted a position as a hydraulic engineer. Since that time, Dr. Foust has been responsible for the hydraulic design and model testing of several turbines. In addition to his design responsibilities, he has also been heavily involved in the development of environmentally friendly hydro turbines in regard to turbine aeration and fish passage.

New Turbine Design Criteria and Process at the Ice Harbor Project

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Abstract

Paper provides an overview of the U.S. Army Corps of Engineers (USACE) selected design criteria and design process for two new replacement turbines at the Ice Harbor Lock and Dam Powerhouse. The criteria and design process were developed through the USACE's Turbine Survival Program (TSP). The new criteria and design process support the design of turbines that will minimize risk of injury to juvenile salmonids passing through them. The design of the new Ice Harbor turbines is a collaborative effort by the USACE's Walla Walla District (NWW), Hydroelectric Design Center (HDC) and the Engineer Research and Development Center (ERDC), and Voith Hydro. Other stakeholders in this effort include the Bonneville Power Administration (BPA) and the National Marine Fisheries Services (NMFS-NOAA).

Most turbines within the hydroelectric power plants of the Federal Columbia River Power System (FCRPS) are nearing the end of their design life. Some are currently being rehabilitated and others are being considered for replacement. While hydroelectric power is an important resource, endangered salmon populations are an equally critical resource to the region. Therefore, to sustain and maintain long term operation of the turbines they must be able to safely pass juvenile salmonids. The alternative to passing fish through the turbines is to divert fish from the intakes with the use of screens, bypassing them around the powerhouse, or passing them through the spillways. Neither alternative is efficient with respect to power generation. With the replacement or rehabilitation of any turbine unit there is an opportunity and a responsibility to improve upon the operation and design of the turbine for fish passage. The 2008 Regional Biological Opinion from the National Marine Fisheries Service (NMFS) requires that fish passage improvements be incorporated into the replacement or rehabilitation of any turbines within the Lower Snake and Columbia River Projects. Recently, Bonneville Power Administration (BPA) determined that Ice Harbor turbine units 2 and 3, located near Pasco Washington on the Snake River, to be most feasible and beneficial to replace with runners designed to improve fish passage survival. With this endeavor comes a new set of design criteria and a design process that differs from the Corps of Engineers (COE) normal contract structure.

Introduction

Ice Harbor Units 2 and 3 are nearly 50 years old, placed into operation in 1961 they have a history of maintenance issues and are two of the lowest rated units in the FCRPS. Ice Harbor Unit 2 was considered for replacement in 2000 due to mechanical problems and persistent oil leakage, but economic analysis

determined that the power benefits did not sufficiently off-set the replacement costs, therefore the unit is currently operated in a fixed bladed configuration. In 2006, the COE Turbine Survival Program (TSP) team proposed a design process, design criteria and the potential to reduce overall risk of injury to turbine passed fish to BPA and FCRPS representatives. Choosing Ice Harbor Unit 2, and later Ice Harbor Unit 3, BPA and FCRPS representatives agreed that improving fish survival through turbines was an important investment opportunity and that the environmental benefits provide sufficient justification to proceed with a turbine replacement in spite of the previous economic analysis.

Ice Harbor Unit 2 and Unit 3 turbine runners provide an excellent opportunity to design and test large turbine runners with emphasis on fish passage for both a fixed (propeller) and adjustable (Kaplan) runner based upon their location on the Snake River. Along with the runner, the entire water passageway can be explored for fish passage improvement. The TSP team has analyzed fish passage through turbines at various operating points and conditions for several Snake River and Columbia River Dams through field study (sensor fish, telemetry tags, and balloon tags) coupled with laboratory study (pressure studies by Pacific Northwest National Laboratories (PNNL) and observational modeling at the Engineer and Research Development Center (ERDC)). These studies by the TSP team have led to the development of design criteria that differs from the typical Corps of Engineers (COE) turbine runner replacement project. These criteria include increasing nadir pressures, improving flow quality, decreasing shear and turbulence, and minimizing the potential for mechanical strike. In order to incorporate these criteria and general fish friendly knowledge base into a design while taking full advantage of industries' turbine runner design expertise - a collaborative and iterative design contract was created. This contract structure, although a Firm Fixed Price Contract, provides significantly more latitude than a typical COE turbine runner replacement contract to explore the full extent of fish survival potential through a turbine.

A Different Type of Contract

A COE turbine runner replacement project is typically authorized based on the value of improved hydraulic performance (efficiency and power output) over the lifetime of the rehabilitated turbine, as well as increased reliability and decreased O&M expense. The Corps request for proposal (RFP) for such a project typically specifies minimum required turbine hydraulic efficiencies and the location (head and power output/flow rate) at which those efficiencies shall occur. It additionally requires power output levels that the turbine must minimally produce and defines a cavitation free operating range. A manufacture's typical proposal guarantees values equal to or exceeding the Corps stated minimums for power, efficiency and cavitation. The proposals received are evaluated based on price and the value of improved hydraulic performance, with an award made to the commercially and technical qualified bidder whose proposal offers the highest net present value.

The Ice Harbor contract is different than other turbine replacement contracts because the goal is to maximize overall turbine fish passage survival. As such, the

Corps RFP did not specify minimum efficiency values, minimally required power output levels and minimal cavitation free operating range, although in some cases non binding guidelines were provided. Instead, the RFP contained fish passage design criteria and described a design process formulated to guide a joint manufacturer/Government team in the design of a turbine maximizing overall fish passage survival. While turbine performance is not necessarily in direct conflict with fish passage survival, turbine performance guarantees were not sought since the runner and wetted passage modifications that might result from the design process could have an unknown influence on turbine performance. Proposals for Ice Harbor were evaluated primarily based on the manufactures' environmental design experience, their understanding of the project goals and RFP stated design methodology, and the manufacturer's proposed technical approach. Other considerations included cost, the manufacturer's commitment to schedule and past performance.

New Design Criteria

Turbine passage can result in fish death or injury through multiple mechanisms. Efforts to manage these mechanisms resulted in the Corps incorporation of the following design criteria as part of the turbine design process:

Mechanical Strike: The number of structures in the turbine wetted passage that that are exposed to flow should be minimized and their edges rounded, including stay vane and runner blade leading edges. Wicket gate leading edges should be positioned in the shadow of the stay vane trailing edges throughout the fish passage region of operation, which may be accomplished by the addition of stay vane trailing edge additions.

Figure 2-38

Stay Vane - Wicket Gate alignment design analysis for mechanical strike and shear

Shear: Gaps within the passageway present potentially high shear zones. Therefore the gaps between stay vane trailing edges and the wicket gate leading

edges should be minimized, as should the gaps at blade tips and for Kaplan designs gaps at the hub. In general, shear rates should be lower than 180 s^{-1} (Cook *et al.* 1997).

Turbulence: Turbulence including vortices, wakes and backflows, which can direct fish into structures or cause a fish to lose equilibrium or become disoriented, should be eliminated or reduced to the extent practicable. Improvements in the flow approaching the stay vanes can be made by the addition of stay vane leading and trailing edge extensions. Improvements in draft tube quality can be made by adjustments to runner shape and wetted passage transitions. Improvements in draft tube quality of flow can be made by the addition of material to the draft tube floor.

Pressure: The COE's interpretation of studies conducted by Pacific Northwest National Laboratory (Carlson *et al.* 2010) is that the lowest nadir pressure to which fish can be exposed in turbine passage without harmful effects is 10 psia (using conservative assumptions on fish acclimation pressures). The same studies have indicated that pressure rate of change is not harmful at rates typically experienced by fish in turbine passage within the FCRP system. Computational fluid dynamics (CFD) is a tool that can be employed to determine the runner passage pressure profile and to rapidly analyze changes that might improve the profile.

Optimum Operating Point: Peak turbine efficiency (peak of the hill curve) should coincide with optimum hydraulic conditions wherein the stay vanes and wicket gates are aligned and flow is streamlined throughout the passage environment, without regions of turbulence, reverse flow and flow separation.

New Design Process

The Ice Harbor turbine design process is a combined Voith Hydro / Government team effort guided by the aforementioned design criteria. The collaborative process allows Voith Hydro and the Government to combine their expertise, strengths and combined resources under an environment of trust, open communication and sharing of information. The process is iterative in that hydraulic modifications are developed, evaluated and refined in a stepwise manner throughout multiple design cycles. A design iteration is one cycle of hydraulic design consisting of three steps; Computational Fluid Dynamic (CFD) analysis, performance model testing and observational model testing. CFD modeling is the first design step Voith uses to evaluate potential runner designs and modifications to existing hydraulic components. Performance model testing is the traditional Reynolds scale model turbine testing performed by the turbine manufacturer at the manufacturer's laboratory. Observational model testing is conducted at the Corps Waterways Experimental Station in Vicksburg, MS using a low head open flume 1:25 scale physical model operating under conditions of Froude similitude. Aside from the runner, distributor, fish screen, and trash racks, the majority of the observational model stationary structures are constructed of transparent acrylic to allow for visual observations and laser Doppler velocity measurements.

The iterative process is conducted for both the fixed and adjustable runners for two iterations each and the contract allows for a third iteration if further refinement to the design is needed. In order to maximize the use of the various design tools the two design paths are dovetailed together in the schedule as shown in Figure 2-39 below. Overlapping design paths and staggered tools allows design feedback from one model to the next.

*Figure 2-39
Iterative design process schedule, dovetailing fixed and adjustable runner designs*

A CFD model of the existing Ice Harbor turbine was initially constructed and analyzed as a baseline for comparison to other designs. The iterative process then began with the design and CFD analysis of a replacement fixed blade runner. Once this design had advanced to the performance model testing phase the design of an adjustable blade replacement runner was begun. CFD analysis is required to evaluate the pressure profile and pressure gradients through the runner region, with emphasis on the minimum pressure (nadir pressure) fish will be exposed to as they pass through the runner. CFD is also used to investigate modifications to water passageway components, in particular the stay vanes. Prior to the award of the contract the Corps' observational model was used to evaluate the hydraulic performance of the existing turbine and to identify and investigate a number of modifications to the water passageways that might improve fish passage conditions. The most promising modifications, namely a stay vane shape modification and draft tube floor fill, were the starting point for Voith's initial CFD investigation of alternatives. Additional CFD derived results for both runners and stationary components included shear rates, velocity profile, and streamline analysis.

The performance model runners are constructed for installation and testing in the performance model and the Corps observational model. The purpose of the performance tests is to further develop and evaluate the runner and other selected modifications with respect to operations and hydraulic performance. It is also necessary to determine the flow, head, wicket gate and runner blade (for adjustable blade designs) angle relationships required for observational model testing.

*Figure 2-40
Observational Model - looking at the draft-tube elbow and draft tube flow conditions*

The transparent observational model is the primary tool used for the evaluation of the turbine for fish passage (Figure 2-40). The injection of dye, and neutrally buoyant beads representing the approximate scale of juvenile salmonids, allow streamlines to be visualized. Analysis of high speed video enables a count of the number of beads striking various structures and the number undergoing sudden accelerations. Laser Doppler velocity (LDV) measurement is used to define flow distributions, directions and turbulence.

The completion of observational model testing of the turbine runner marks the end of an iteration, and subsequent iterations will utilize information from each of the modeling steps (CFD, performance, and observational) to effect a redesign or refinement of hydraulic features to eliminate undesirable conditions that may be harmful to fish. The redesign or refinement direction of each subsequent iteration shall be a cooperative Voith Hydro / Government effort as described above for the first iteration. The second, and third iteration if required, may not include the same level of effort required for the first iteration as the process may be refined based on the successes and "lessons learned" during the previous iteration.

Coupling the use of new and old design tools with designing turbine runners to meet improved fish passage survival criteria and characteristics is the ultimate challenge for this project team. The COE has asked Voith Hydro to step outside their typical turbine runner design mold, highlighted by an iterative and collaborative design process. The team has been successful thus-far, with a fixed runner in observational modeling and an adjustable runner in performance modeling, the project is nearing the end of the first iteration. Installation of the new runner(s) as well as the required modified passage components will be completed by separate contract, and is currently scheduled for fall 2014 and summer of 2015.

References

Carlson, Brown, Stephenson, Gingerich, Pflugrath, Coloteco, Welch, Benjamin, Skalski, Seaburg, Townsend. 2010. Assessment of Barotrauma in Untagged and Tagged Juvenile Chinook Salmon Exposed to Simulated Hydro Turbine Passage. Contract No. PNNL-19625.

Cook, Hecker, Faulkner. 1997. Development of a More Fish Tolerant Turbine Runner. Advanced Hydropower Turbine Project. Contract No. DE-AC07-95ID13383. ARL Report No. 13-97/M63F.

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Hydraulic and Environmental Performance of Aerating Turbine Technologies

Patrick March, Hydro Performance Processes Inc.

Abstract

EPRI's 2002 report, *Maintaining and Monitoring Dissolved Oxygen at Hydroelectric Projects: Status Report* (1005194) provided a comprehensive review of a wide range of techniques and technologies for improving the dissolved oxygen (DO) levels in releases from hydroelectric projects. Aerating turbine technologies have been developed and demonstrated by multiple turbine manufacturers. These technologies can provide higher generation efficiency, higher capacity, and improved environmental performance. However, aerating turbine technologies have not been widely implemented, in part due to insufficient information on, and industry understanding of, the life-cycle costs and benefits from the technologies. This paper is based on a December 2009 EPRI report, *Technology Update on Aerating Turbines* 9 (March, 2009). The 2009 report and this paper supplement the 2002 EPRI report and focus primarily on aerating turbine technologies for new turbine installations and turbine upgrades. Limited information on performance of retrofitted aeration systems is also presented for comparison purposes.

Turbine manufacturers, utilities, and agencies provided information and performance data for aerating turbine technologies. Specific industry examples are examined and presented as case studies, with an emphasis on hydraulic performance (turbine efficiency with and without aeration, turbine capacity increases) and environmental performance (air flows and DO increases). The paper discusses the development of aerating turbine technologies, describes some of the difficulties in assessing the performance of aerating turbines, provides detailed case studies for three aerating turbine technologies (central aeration, peripheral aeration, and distributed aeration), discusses the implications of the case study results for plant operation and optimization, and makes recommendations for additional related research.

Introduction

Overview of Aeration

Impoundments and flow releases from hydropower facilities can adversely impact the aquatic life upstream, downstream, and passing through the sites. In the United States, regional environmental concerns include the improvement of dissolved oxygen (DO) levels to protect aquatic habitat in tailwaters below dams.

Hydropower projects likely to experience problems with low DO include those with a reservoir depth greater than 15 m, power capacity greater than 10 MW, reservoir volume greater than $6.1 \times 10^7 \text{ m}^3$, densimetric Froude number less than 7, and a retention time greater than 10 days (EPRI 1990). In general, these include projects with watersheds yielding moderate to heavy amounts of organic

sediments and located in a climate where thermal stratification isolates bottom water from oxygen-rich surface water. At the same time, organisms and substances in the water and sediments consume and lower the DO in the bottom layer. For projects with bottom intakes, this low DO water may create problems both within and downstream from the reservoir, including possible damage to aquatic habitat.

Before about 1980, detailed studies of the potential impacts of hydropower on water quality, including low DO, generally were not required prior to licensing. In 1986, however, the Electric Consumers Protection Act (ECPA) defined a process by which the development of hydropower must be balanced with concerns for the protection of environmental site characteristics. As a result of ECPA, and based on criteria developed by the U.S. Environmental Protection Agency, requirements for monitoring and maintaining DO levels have become a regular part of license agreements for affected hydro projects. Among the largest owners of affected hydro projects, however, are federal agencies, which are exempt from the licensing protocol of the Federal Energy Regulatory Commission (FERC). These include the U. S. Bureau of Reclamation (USBR), the U. S. Army Corps of Engineers (USACE), and the Tennessee Valley Authority (TVA).

Development of Technologies for DO Enhancement

Under the self-imposed targets and deadlines of a five year, \$50,000,000 Lake Improvement Program funded from power system revenues, TVA developed a variety of new technologies for increasing DO in turbine discharges and successfully resolved minimum flow and dissolved oxygen problems throughout its reservoir system. The minimum flow and water quality enhancements have been responsible for the recovery of 290 km of aquatic habitat lost due to intermittent drying of the riverbed and for DO improvements in more than 480 km of rivers below TVA dams (March and Fisher 1999). The technologies developed and deployed under the Lake Improvement Plan include minimum flow hydropower units, reliable line diffusers for cost-effective oxygenation of reservoirs upstream from hydro plants, effective labyrinth weirs and infuser weirs which provide minimum flows and aerated flows downstream from hydro plants, retrofit turbine aeration systems, and aerating turbines. Aerating turbines, which use the low pressures created by flows through the turbines to induce additional air flows, are typically the most cost-effective DO enhancement technology for the Francis-type turbines typical of hydroplants with DO concerns. This report focuses on aerating turbine technologies for new turbine installations and turbine upgrades.

Historical Perspective on Aerating Turbines

In the 1950s, turbine venting was introduced in Wisconsin to reduce the water quality impact of discharges from the pulp and paper industry and from municipal sewage systems (Lueders 1956). Research was also conducted in Europe to develop turbine designs that would boost dissolved oxygen (DO) levels in water passing through low head turbines (Wagner 1958). By 1961, turbine

aeration systems were operating in the U. S. at eighteen hydroplants on the Flambeau, Lower Fox, and Wisconsin Rivers (Wiley et al. 1962; Wisniewski 1965).

Aeration systems using draft tube deflectors were developed using physical model tests and installed by Alabama Power during the 1970s at ten turbines in hydroplants on the Black Warrior and Coosa Rivers, resulting in DO increases of 0.5 to 1.0 mg/L and efficiency losses up to 2% (Bohac et al. 1983). During the late 1970s and early 1980s, the Tennessee Valley Authority (TVA) developed small, streamlined baffles, called hub baffles, which reduced energy losses while increasing air flows and operating range. The hub baffles installed at TVA's Norris Project provided DO uptakes averaging 2 to 3 mg/L with typical efficiency losses of 1 to 2% (Bohac et al. 1983).

During the mid-1980s, Voith Hydro Inc. and TVA invested in a joint research partnership to develop improved hydro turbine designs for enhancing DO concentrations in releases from Francis-type turbines. Scale models, numerical models, and full-scale field tests were used in an extensive effort to validate aeration concepts and quantify key parameters affecting aeration performance. Specially-shaped geometries for turbine components were developed and refined to enhance low pressures at appropriate locations, allowing air to be drawn into an efficiently absorbed bubble cloud as a natural consequence of the design and minimizing power losses due to the aeration. TVA's Norris Project, which was scheduled for unit upgrades, was selected as the first site to demonstrate these "auto-venting" or "self-aerating" turbine technologies. The two Norris aerating units contain options to aerate the flow through central, distributed, and peripheral air outlets, as shown in Figure 2-41.

In testing the aerating turbines, measurements were required to evaluate both the hydraulic and the environmental performance of the aeration options. The hydraulic performance is based on the performance compared to the original turbines and the amount of aeration-induced efficiency loss. The environmental performance is evaluated primarily by the amount air flow and the amount of the DO uptake. At Norris, each aeration option was then tested in single and combined operation over a wide range of turbine flow conditions.

Compared to the original Norris turbines, the innovative aerating replacement units provide overall efficiency and capacity improvements, weighted over the operating range, of 3.7 percent and 10 percent, respectively, as shown in Figure 2-42 (March and Fisher 1999). This corresponds to an additional annual generation, for the same amount of rainfall, of about 17,000 MWh for the Norris Project. The new turbines have also shown significant reductions in both cavitation and vibration.

For environmental performance, results show that up to 5.5 mg/L of additional DO uptake can be obtained for single unit operation, with all aeration options operating and a zero level of incoming DO. In this case, the amount of air induced into the turbine is more than twice that obtained in the original turbines, which had a retrofitted aeration system utilizing hub baffles. At the Norris

Project, turbine aeration is typically initiated in July, when the DO level monitored upstream from the turbines begins to drop. Throughout the low DO season, various combinations of aeration options are used, based on the head, power, and required DO uptake. Aeration typically ends in November, when cold, dense surface water promotes enough vertical mixing to reduce the thermal stratification. Typical DO improvement through the Norris turbines is 5.5 mg/L, with an additional 0.5 mg/L of DO improvement obtained from air entrainment in the flow over a re-regulating weir that provides minimum flows downstream from the powerhouse to meet the DO target level of 6.0 mg/L. Results from bioenergetics modeling of trout growth, calibrated and confirmed by fishery studies, indicate a 270% increase in the annual growth for a downstream DO of 6 mg/L compared to the base case without environmental improvements and a 160% increase in the annual growth compared to the previous Norris hub-baffle aeration system that maintained a downstream DO of approximately 4 mg/L.

Figure 2-41
Sectional View of Norris Francis Turbine Showing Distributed Aeration (Green), Central Shaft Aeration (Blue), Central Vacuum Breaker Aeration (Red), and Peripheral Aeration (Yellow)

Figure 2-42
Hydraulic Performance Results for Norris Aerating Francis Turbine

As shown in Figure 2-43, typical efficiency losses during aeration at Norris range from -0.2 to +4 percent, depending on the operating conditions and the aeration option or options used. For the Norris aerating turbines, the central aeration option has the highest impact on efficiency, the peripheral aeration option has an intermediate impact on efficiency, and the distributed aeration option has the least impact on efficiency. The average aeration-related turbine efficiency loss during the July to November aeration period has been held to less than 2 percent at the Norris Project.

Figure 2-43
Typical Effects of Aeration on Hydraulic Performance for Norris Francis Turbine

The successful demonstration of multiple technologies for turbine aeration at TVA's Norris Project in 1995 has helped to develop market acceptance for aerating turbines. Major turbine manufacturers who currently offer aerating turbines include ALSTOM, American Hydro, Andritz, and Voith Hydro.

Updated Literature Review

Review of Recent Literature (1998 - 2009)

In the past, several comprehensive reviews, covering a wide range of techniques and technologies for improving the dissolved oxygen (DO) levels in releases from hydroelectric projects, were completed (Bohac et al. 1983; EPRI 1990). Most recently, EPRI (2002) discusses hydrological conditions contributing to low DO levels in reservoirs, describes biological effects of low DO levels, provides a comprehensive summary of techniques and technologies for improving low DO levels, and discusses DO modeling and monitoring. EPRI (2002) also includes case studies for the aerating turbines at TVA's Norris Project and the "second-generation" aerating turbines at Duke's Wateree Project.

The current paper and the related report (March 2009) supplement EPRI (2002) by focusing primarily on aerating turbine technologies for new turbine installations and turbine upgrades. The literature review in the following portions of Section 2 describes aerating turbine technologies reported during the period from 1998 through 2009. This date range provides several years of overlap with EPRI (2002) and updates some of the EPRI (2002) references.

Overview Papers

During the 1998 - 2009 period for this review, several papers provide an overview of DO-related topics.

March and Fisher (1999) discusses technologies for turbine design and control systems to improve dissolved oxygen levels in turbine discharges and survival of fish during turbine passage. The paper describes development, testing, and test results for these technologies, with an emphasis on collaboration of stakeholders and balance between environmental stewardship and economical power production.

Čada et al. (1999a) and Čada et al. (1999b) describe the U. S. Department of Energy's Advanced Hydropower Turbine System Program and its goal of maximizing hydropower resources while minimizing adverse environmental effects. In addition to discussing fish passage issues, these papers provide a summary of DO concerns, low DO mitigation technologies, and aerating turbine progress.

Black et al. (2002) summarizes technological advances achieved between 1990 (EPRI 1990) and 2002 (EPRI 2002). The paper includes results from a review of FERC documents related to low DO levels for approximately 300 projects. Over one-third of the licenses reviewed include requirements for the applicants to maintain a minimum DO level in the tailrace. The paper provides a matrix comparing technologies for mitigation of low DO levels and commenting on their general advantages and disadvantages. For aerating turbines, the listed advantages include a broad operational range, high levels of DO uptake, reduced efficiency losses compared to baffles or other air injection methods, reduced O&M costs, and minimum efficiency impact during non-aerating operations. The listed disadvantage is a high initial cost, which can be reduced by incorporating aeration capabilities into a scheduled turbine rehabilitation.

Retrofitted Turbine Aeration Systems

During the 1998 - 2009 period for this review, a variety of papers describe retrofitted turbine aeration systems. Retrofitted turbine aeration systems, typically using the existing vacuum breaker system, additional air piping through the headcover, and/or draft tube ports below the turbine, are one of the least expensive forms of aeration in terms of initial cost. However, life-cycle costs can be substantial due to efficiency losses and increased O&M costs.

Jarvis et al. (1998) describes early work with turbine venting at AmerenUE's Osage Project in central Missouri.

Harshbarger et al. (1999) provides a summary of results for retrofitted turbine aerations systems at the U. S. Army Corps of Engineers' eight-unit, 340 MW Bull Shoals Project, the two-unit, 80 MW Norfolk Project, and the four-unit, 200 MW Table Rock Project. The retrofitted turbine aerations systems increased air flows and resulted in typical DO uptakes of 1 to 2 mg/L at Bull

Shoals for eight-unit operation, 2 to 2.5 mg/L at Norfolk for two-unit operation, and 2 to 3 mg/L at Table Rock for single unit operation. Little impact on efficiency or capacity was observed for Bull Shoals and Table Rock. At Norfolk, the overall efficiency and capacity were relatively unchanged, but the best efficiency point shifted from 38 MW to 33 MW and the efficiency at maximum capacity dropped by about 2%, both of which have implications for optimized plant operations.

Shultz et al. (2002) reports the successful use of unsteady flow and water quality models to evaluate operating scenarios included DO improvements from the retrofitted draft tube aeration system installed at the PPL Holtwood LLC's 40 MW Lake Wallenpaupack Project.

Ware et al. (2004) discusses American Hydro's Retrofit Aeration System (RAS), which is a design methodology utilizing computational fluid dynamics (CFD) analyses, mechanical redesign of air and water passageways, and procedures for implementing the RAS with minimal outage time. The RAS methodology was applied at AmerenUE's Osage Project to Unit 3, an aerating replacement turbine supplied by American Hydro in 2002, and to Unit 6, an original Osage turbine supplied by Allis-Chalmers in the early 1930s. For Unit 3, DO uptakes ranged from 4 mg/L at low flows to 2.5 mg/L at high flows. The corresponding Unit 3 efficiency losses ranged from -40% (i.e., an efficiency improvement) at low flows to 4% at high flows. For Unit 6, DO uptakes ranged from 3.5 mg/L at low flows to 0.4 mg/L at high flows. The corresponding Unit 3 efficiency losses ranged from -20% (i.e., an efficiency improvement) at low flows to 0% at high flows. The authors conclude that "...a refined turbine upgrade, including re-running, will provide the best environmental enhancement, and yet very significant improvements to water quality can be made by implementing a Retrofit Aeration System to existing turbine hardware." Information on subsequent retrofit modifications to Osage Unit 6, including additional air piping and a draft tube door vent, is provided in Ware and Sullivan (2006).

Désy et al. (2004) describes the collaboration between the U. S. Bureau of Reclamation (USBR) and G. E. Hydro (now Andritz) to evaluate alternative aeration solutions and, ultimately, to choose a retrofitted peripheral aeration system for the USBR's Canyon Ferry Project. Canyon Ferry includes three 18 MW Francis units. DO uptakes ranging from 5.6 mg/L at low loads to 2.1 mg/L at maximum load were predicted.

Moore (2009) provides information on the retrofitted draft tube aeration systems installed on three units at Southern Company's 18 MW Lloyd Shoals Project, located in Georgia on the Ocmulgee River. These systems allowed the project to meet Georgia's DO requirement (i.e., a minimum discharge DO of 4 mg/L and an average of 5 mg/L) without using the downstream aerating weir, which needed costly repairs. During aeration, additional efficiency losses of 2 to 3% are experienced at Lloyd Shoals.

Aerating Turbines

During the 1998 - 2009 period for this review, a variety of papers describe aerating turbines. Aerating turbines are designed to use the low pressures created by flows through the turbines to induce additional air flows.

Jablonski and Kirejczyk (1998) provides some information on the new, centrally aerating ALSTOM turbines installed at Unit 1 of Duke Power Company's two-unit, 36 MW Oxford Project and at Unit 3 of Duke's four-unit, 60 MW Wylie Project. Duke evaluated low DO mitigation technologies, including vacuum breaker venting, forebay oxygen diffusers, retrofitted turbine venting, and forced air venting on the basis of capital costs, maintenance costs, lost capacity due to aeration, and lost efficiency due to aeration. Because Duke was also preparing specifications for replacement turbines for Oxford and Wylie under their Upgrade and Modernization Program, the selection of new aerating turbines was a cost-effective solution. Capital costs for the aeration systems were less than 8% of the total turbine costs, with no additional efficiency losses or capacity losses when the aeration systems are not in operation.

ALSTOM's central aeration system channels air to the runner cone from an air intake located in the head cover. Performance test results for Oxford and Wylie showed that air flow can have a significant impact on loss of capacity and efficiency. For example, efficiency losses up to 2.5% at maximum gate opening and 9.6% in the vicinity of the best efficiency gate opening were experienced. Station operators use guide charts to control air valve settings based on wicket gate opening, tailwater elevation, and DO target levels and to provide the proper balance between power production and DO enhancement. Gaffney et al. (1999) summarizes Jablonski and Kirejczyk (1998) and provides additional information on Duke's Upgrade and Modernization Program.

Papillon et al. (2000a) and Papillon et al. (2000b) describe an ALSTOM central aeration system and provide rules of similitude for interpreting and scaling results from physical model test of the aeration systems. Results from model tests and prototype tests are presented as confirmation. Papillon et al. (2002) provides model test results for three variations of ALSTOM's central aeration system and a peripheral aeration system. The peripheral aeration system had a significantly lower impact on efficiency compared to the central aeration alternatives.

Sigmon et al. (2000) discusses the evaluation of four DO enhancement methods for Duke's Wateree Project, including vacuum breaker aeration, retrofitted central aeration, an aerating replacement turbine, and a forebay oxygen injection system. The alternative selected for Wateree Unit 3 was a Voith Hydro replacement turbine with distributed aeration, due to the long term environmental benefits from increased DO uptake and the operational flexibility for increased generation during the time of year when DO is low and energy values are high. Reported DO uptakes range from a low of 3.9 mg/L to a high of 4.3 mg/L as output power ranges from 9 MW to 19 MW.

Parrott and Fisher (2003) provides preliminary results from the installation of Unit 5, the first upgraded unit at the USACE's seven-unit, 364 MW Thurmond Project with a Voith Hydro distributed aeration system. The distributed aeration system draws air from three air intakes located in the head cover through hollow turbine blades to the trailing edge of each blade. Additional information is provided in Parrott and Fisher (2006) and Hobbs (2008) (see below).

Fraser et al. (2005) describes the use of physical model tests to measure and predict the effects of central and peripheral air injection on the DO levels and operating efficiencies for a GE (now Andritz) Francis turbine. The paper also includes some discussion of similitude requirements for predicting prototype aeration performance from a physical model study.

Kepler and Hager (2005) and Hager (2006) describe the runner upgrade for Unit 5 at Exelon Power's 514 MW Conowingo Hydroelectric Generating Station, located on the Susquehanna River. The upgraded runner was designed for low flow operational capability, increased efficiency, increased capacity, and DO enhancement. Voith Hydro's distributed aeration system channels air from six air intakes located in the head cover through hollow turbine blades to the trailing edge of each blade. Each air intake includes a valve operated by the control system. Performance results were not available at the time of publication.

Parrott and Fisher (2006) updates results for the USACE's Thurmond Project as more units have been upgraded with distributed aeration Voith Hydro turbines. Additional DO uptakes up to 4 mg/L are reported, as well as significant water quality improvements throughout a monitored 16-mile reach of the Savannah River downstream from the Thurmond Project.

Hobbs (2008) describes the USACE Savannah District's experience with three DO enhancement technologies, including a retrofitted turbine aeration system at the five-unit, 432 MW Hartwell Project, a forebay oxygen diffuser system at the eight-unit, 684 MW Russell Project, and distributed turbine aeration at the seven-unit, 364 MW Thurmond Project. The retrofitted turbine aeration system at Hartwell provides DO uptakes up to 3 mg/L with a corresponding efficiency loss of 0.5%. The Voith Hydro distributed aeration systems for all of the Thurmond turbines draw air from three air intakes located in the head cover of each unit through hollow turbine blades to the trailing edge of each blade. The turbine efficiency impact is 0.2% when providing 2 mg/L of DO uptake, and the turbines are capable of providing more than 4 mg/L. This paper also describes several advanced control and monitoring systems for turbine efficiency, water quality, oxygen diffuser control, and turbine aeration control.

Foust et al. (2008) provides some of the most comprehensive results for central, peripheral, and distributed aeration systems. The paper presents data on the relationships among aeration airflows, aeration injection locations, and aeration system head losses and discusses the effects of air induction on local pressures. For flow rates approximately 20% below best efficiency, central aeration provides the largest pressure differentials and air induction capability, followed by distributed aeration and peripheral aeration. For flow rates from 10% below best

efficiency to maximum capacity, distributed aeration provides the largest pressure differentials. The effect of aeration on local pressures is greatest for central aeration, followed by peripheral aeration. Distributed aeration has the least effect on local pressures. Consequently, when local pressures are adjusted for the effects of aeration, distributed aeration shows the potential for inducing the largest air flows into the turbine. The paper also examines the influence of aeration technology on turbine performance. For flow rates approximately 20% below best efficiency, peripheral aeration and distributed aeration provide the lowest impact on turbine efficiency, and central aeration provides the highest impact, up to 13% for air/water flow ratios of 5%. For flow rates at best efficiency, peripheral aeration and distributed aeration provide the lowest impact on turbine efficiency, and central aeration provides the highest impact, up to 17% for air/water flow ratios of 5%. For flow rates at 20% above best efficiency, peripheral aeration and distributed aeration provide the lowest impact on turbine efficiency, and central aeration provides the highest impact, up to 25% for air/water flow ratios of 5%. In addition, for flow rates from best efficiency to 20% above best efficiency, distributed aeration is significantly more efficient than peripheral aeration. Field data is also presented to show that the DO uptake efficiency for distributed aeration is significantly greater than the DO uptake efficiency for central aeration and peripheral aeration. At best efficiency, the DO uptake efficiencies are 42%, 33%, and 23% for distributed aeration, peripheral aeration, and central aeration, respectively. Corresponding results at flows of 20% above best efficiency, typical of maximum load, show DO uptake efficiencies of 54%, 38%, and 36% for distributed aeration, peripheral aeration, and central aeration. The authors conclude that the highest DO uptakes and the lowest impacts on efficiency are achieved with a distributed aeration system, followed by a peripheral system.

Rohland and Sigmon (2008) describe a Voith Hydro aeration system designed for a replacement powerhouse at the Bridgewater Hydroelectric Station near Nebo, North Carolina. While distributed aeration would have been the preferred solution, the small size of the runner required the substitution of a combined system using both central aeration and peripheral aeration. Both central and peripheral aeration will be used during periods of low flow operation, and only the peripheral aeration will be used during periods of high flow operation requiring DO enhancement.

Foust et al. (2009) describes airflows, efficiency effects, and oxygen uptakes associated with new distributed aeration turbines installed at AmerenUE's Osage Hydroelectric Project on the Osage River near Lake Osage, Missouri. This eight-unit, 240 MW plant has recently installed four new Voith Hydro turbines with distributed aeration and has conducted extensive hydraulic and environmental performance tests on the units. Air/water flow ratios ranged from 3.2% to 6.6%, depending on flow rate and tailwater elevation. At best efficiency flows, impacts on turbine efficiency ranged from 1.6% at an air/water flow ratio of 4.8% to 3.5% at an air/water flow ratio of 6.4%. At flows 10% above best efficiency, impacts on turbine efficiency ranged from 2.1% at an air/water flow ratio of 4.5% to 4.1% at an air/water flow ratio of 6.0%. During the performance testing, typical incoming DO levels ranged from 2.1 mg/L to 2.4 mg/L, and

typical outflow DO levels ranged from 5.7 mg/L to 6.3 mg/L, depending on tailwater level and flow. At the lowest tailwater level, DO uptakes ranged from 4.4 mg/L to 5.1 mg/L, and at the highest tailwater level, DO uptakes ranged from 3.4 mg/L to 3.8 mg/L. At all of the tested tailwater levels, the effect of aeration on turbine efficiency was less than 1% for DO uptakes up to 3 mg/L.

Kao (1997), Kao et al. (1998), and Kao et al. (1999) describe an innovative turbine design which includes an updraft flow arrangement, a vertical flow control valve replacing the wicket gates, a divergent flow chamber replacing the draft tube, and exit flow into the tailwater free surface. Laboratory results show that this design may provide effective tailwater aeration.

Related Topics

During the 1998 to 2009 period for this review, several papers describe topics related to aerating turbines.

For example, Almquist et al. (1998) provides a draft test code for evaluating the performance of aerating turbines. This draft test code is also included as an appendix to a final report under the U. S. Department of Energy's Advanced Hydropower Turbine System Program (Franke et al. 1997).

Hopping et al. (1999) reports "lessons learned" from the Norris experience with multiple aeration technologies. The paper provides industry guidelines on economic justification for turbine aeration systems, preparation of appropriate procurement specifications for turbine aeration systems, and verification of the hydraulic and environmental performance of turbine aeration systems.

Faulkner (2000) describes applications for environmental monitoring at hydroplants, including DO and other water quality monitoring. The article provides information on the environmental monitoring and optimization system used by TVA for the aerating turbines at the Norris Project.

Peterson et al. (2001) addresses multiple approaches to DO improvements at hydropower facilities. These include structural approaches (e.g., aerating turbines, aerating weirs, oxygen diffuser systems), operational approaches (e.g., modified timing and duration of flow releases), and regulatory approaches (e.g., site-specific DO standards, standards based on biocriteria, watershed-based trading). The authors conclude, "A combination of mitigation techniques, including structural, operational, and regulatory approaches, may be the most effective way to address DO problems at hydropower projects."

Kühlert and Ware (2004) discusses the development of a computational fluid dynamics (CFD) model to understand and predict performance of retrofitted aeration systems for AmerenUE's Osage Project. The model was used to analyze effects on turbine performance, pressure losses in air flow passageways, air flow rates, and DO uptake for potential design modifications to the retrofitted aeration system.

Bevelheimer and Coutant (2006) describes a modeling study to predict downstream environmental benefits which can be achieved due to low DO mitigation techniques, such as aerating turbines. A suite of models simulated hydrodynamics, water quality, and fish growth as affected by DO, water temperature, and food availability for a 26-mile portion of the Caney Fork River downstream from Center Hill Dam. The study assessed the effects of alternative mitigation techniques and levels of improvement on the water quality and fish growth throughout the modeled portion of the river. The authors note that results from the study demonstrate the value of the modeling techniques for evaluating tradeoffs among hydropower operations, power generation, and environmental quality.

March (2006) discusses modern systems for plant optimization, unit commitment, and control that combine environmental constraints associated with increased dissolved oxygen levels, the effects of the environmental operations on unit performance, and periodic optimization at the system level and the plant level, including real-time plant optimization for the constantly varying loads associated with automatic generation control (AGC). The paper provides several examples, including aerating turbines at the USACE's Thurmond Project and AmerenUE's Osage Project, to show that periodic and real-time environmental optimization can lead to improved environmental performance, improved operating efficiencies, and improved profitability. Smith et al. (2007) extends the discussion of environmental optimization to include the challenges of selecting environmental objectives considering ecosystem complexity and the differing uncertainty, time scales, and hierarchy between conventional hydro system optimization and emerging concepts of environmental optimization.

McGinnis and Ruane (2007) describes the development of a discrete-bubble model (DBM) for two hydropower projects, Duke's Wylie Project and South Carolina Electric & Gas Company's Saluda Project. The DBM predicts the rate of oxygen transfer from a single bubble traveling through a draft tube and tailrace as a function of flow rate, air/water ratio, and bubble size. The model was used successfully to predict the discharge DO for the Saluda Project and the Wylie Project to within 10% of the observed values. Ruane and McGinnis (2007) details the application of the discrete-bubble model at the Saluda Project for a variety of operating policy scenarios, resulting in a cost-effective, site-specific DO standard for the Lower Saluda River.

Hydraulic and Environmental Performance

Introductory Remarks

Performance testing is typically conducted to verify conformance with environmental and hydraulic goals or guarantees for aerating turbines (Hopping et al. 1999). As shown in Figure 2-44, testing of aerating turbines can be broadly divided into two categories, aeration and non-aeration performance testing. Non-aeration testing is conducted with all aeration systems off, and essentially identical to the performance testing of conventional hydroturbines. Typical

parameters include turbine efficiency, maximum power, cavitation level, vibration, shaft runout, and thrust load. Testing of an aerating turbine encompasses additional evaluations for both environmental performance and hydraulic performance. Environmental performance is typically measured by the DO uptake and sometimes the level of total dissolved gases (TDG). Air flow is needed to verify gas transfer characteristics of individual aeration options. The hydraulic performance is measured by the aeration-induced efficiency change, $\Delta\eta$. In computing $\Delta\eta$, both η_a (with aeration) and η_0 (without aeration) are found using the procedures of PTC-18 or IEC 41. Airflow and pressures at the aeration outlets are desirable to verify hydraulic characteristics of individual aeration options. Aeration can affect other mechanical aspects of turbine operation, so measurements for cavitation and vibration can also be a part of aeration performance testing.

To help the hydro industry standardize the proper procedures by which ΔDO , $\Delta\eta$, and other parameters should be measured and evaluated, TVA engineers used the Norris aerating turbine testing as the bases for developing a draft test code for aerating turbines (Almquist et al. 1998). The draft test code gives guiding principles for determining the environmental and hydraulic performance of aerating turbines. Included are recommendations for methods of measurement, instrumentation, test procedures, and analysis of data. The draft test code is also included in a final USDOE Advanced Hydro Turbine Project report (Franke et al., 1997).

Hydraulic Performance

For this paper, the terminology in Figure 2-44 is simplified. Environmental performance is unchanged, but hydraulic performance combines mechanical performance and hydraulic performance from Figure 2-44. Test codes, such as PTC-18 (ASME 2002) and IEC 41-1991 (IEC 1991), apply and include procedures to measure flow rate, head, and power output to calculate the turbine efficiency. Because changes in performance, rather than absolute performance, are of primary interest, index testing is often utilized for aeration performance tests.

Figure 2-44
Flowchart for Testing Aerating Hydroturbines, from Hopping et al. (1999)

Environmental Performance

Difficulties in evaluating environmental performance are graphically illustrated in Figure 2-45. Errors in the measurement of dissolved oxygen contribute significantly to the uncertainty associated with determining the environmental performance (i.e., DO uptake) (Hopping et al. 1999). This is primarily due to spatial variations of DO in the turbine penstock and in the tailwater. Variations in the penstock result from DO stratification in the reservoir and withdrawal flow patterns, while variations in the tailwater are due to incomplete mixing of air in the turbine discharge and an uneven distribution of flow in the tailrace.

Figure 2-45
Sectional Diagram Illustrating Difficulties in Testing Aerating Hydroturbines

Due to these variations, the estimated confidence interval for measured values of DO can easily vary between 0.5 mg/L and 1.0 mg/L, which can create large uncertainty in the computed DO uptake. The effect of large uncertainty in DO uptake can be costly, not only in determining conformance to environmental performance guarantees, but also in terms of supplying and operating DO

enhancement systems. With a large uncertainty, a conservative approach must be taken in selecting and operating these environmental systems.

To increase accuracy in the measurement of turbine environmental performance, the draft test code for aerating turbines recommends multiple DO readings in the turbine penstock and tailwater. Uncertainty in the incoming DO can be reduced by obtaining independent, continuous DO measurements from multiple taps upstream from the turbine. In the tailwater, multiple, continuous DO measurements at several points across the turbine discharge are recommended. The optimum number of tailwater sensors depends on the magnitude of DO spatial variations and the size of the tailrace. Due to the high cost of deploying multiple sensors, it is beneficial to perform a pre-test evaluation of velocity and DO patterns in the tailrace. This will allow DO sensors to be strategically located to avoid redundant measurements in areas of flow stagnation or recirculation. Pre-test, mid-test, and post-test calibrations of DO sensors in a common bath to a common standard also should be performed to reduce uncertainty.

Case studies

Overview

The three case studies in this section describe examples where utilities have, to varying degrees, assessed the hydraulic and environmental performance of aerating turbine technologies and provided results for incorporation into this paper. The case studies describe the available hydraulic and environmental performance information for aerating turbines using peripheral, central, and distributed aeration.

Case Study, Aerating Turbine with Peripheral Aeration

Description of Plant

This four-unit, 119 MW hydroplant is owned and operated by an industrial utility. In 2001, Unit 4 was upgraded with a Voith Hydro Inc. aerating turbine using peripheral aeration supplied through two air inlets. This case study is based on results for Unit 4. Subsequently, two additional units at this plant have been upgraded with similar aerating turbines using peripheral aeration.

In preparation for turbine upgrades and modernization, index tests were conducted on Unit 4 in 1999. After the Unit 4 runner upgrade in 2001, additional index tests were conducted to evaluate the new unit. Air flows into the peripheral aeration system were also measured, using differential pressures measured at the throats of the bellmouth intakes for the air supply piping. For the Unit 4 upgrade, a complete physical model study, including the draft tube, was conducted. The best efficiency results from the model study were used as the index reference for the test results reported in this case study.

Hydraulic Performance

Physical model test results and index test results for Unit 4 are shown in Figure 2-46. The peak efficiency from the physical model results has been used to “index” and normalize both the upgraded turbine results and the original turbine results. The shape of the efficiency curve for the prototype turbine agrees closely with the model results. Without aeration, the upgraded turbine achieves a best efficiency increase of about 2% and a capacity increase of 4 MW, about 14%, compared to the original turbine. With maximum aeration, the upgraded turbine achieves a best efficiency increase of about 1% and a capacity increase of 2.7 MW, about 9.5%, compared to the original turbine. With maximum aeration, the best efficiency point remains at 24 MW, similar to the original unit. With no aeration, the best efficiency point is at 27 MW. Actual efficiency losses during operation are lower than these values when DO and TDG targets can be met with reduced air flows.

Figure 2-46
Hydraulic Performance for Aerating Turbine with Peripheral Aeration (Net Head 174.5 ft)

Environmental Performance

Only limited environmental performance data is available for this unit.

Figure 2-48 shows air flow results as the percentage ratio of volumetric air flow to volumetric water flow, Q_a/Q_w , also called ϕ , versus turbine output expressed in megawatts (MW). Q_a/Q_w values between 8% and 9% are achieved in the

range of 10 MW to 17 MW. When the vacuum breaker closes above 17 MW, the Q_a/Q_w value drops to 7%. At 22 MW, the Q_a/Q_w values begin to drop gradually throughout the remaining power range, with a low of 5% at the maximum load of 31 MW. Based on previous experience with other installations, these values of Q_a/Q_w should be able to provide DO uptakes of about 4 mg/L to 6 mg/L.

Additional Information

Additional, more comprehensive information on environmental performance could be obtained from this site through detailed analyses of plant operational data and environmental monitoring data.

Figure 2-47

Qa/Qw Versus Turbine Output for Aerating Turbine with Peripheral Aeration (Net Head 174.5 ft)

Case Study, Aerating Turbine with Central Aeration

Description of Plant

This eight-unit, 240 MW hydroplant is owned and operated by an investor-owned utility. In 2002, Units 3 and 5 were upgraded with aerating turbines using central aeration, supplied by American Hydro Company. The original units, supplied by Allis-Chalmers, were also retrofitted with central aeration. This case study is based on test results for Unit 3.

In preparation for additional turbine upgrades and modernization, efficiency tests were conducted on Unit 3 and Unit 6 in 2005. Efficiency test procedures followed ASME Performance Test Code 18-2002 (ASME 2002). The pressure-time method was used for water flow measurements. Air flows into the central aeration systems were also measured, using differential pressures measured at the throats of the bellmouth intakes for the air supply piping.

The plant's original design also included two small station service units, manufactured by Allis-Chalmers. Each of the station service units was designed to operate at 170 cfs and approximately 60% efficiency. The station service units were replaced in 2010 with American Hydro units including peripheral aeration, rated for 3.6 MW and 450 cfs at 90 ft of head and operating at approximately 90% efficiency.

Hydraulic Performance

Numerical model predictions for Unit 3 performance and results from the 2005 efficiency tests for Unit 3 and Unit 6 are shown in Figure 2-48. The peak efficiency from the numerical model results has been used to normalize both the upgraded Unit 3 turbine results and the original Unit 6 turbine results. Without aeration, the upgraded Unit 3 turbine achieves approximately equal efficiency and a capacity increase of 6.3 MW, about 21%, compared to the Unit 6 original turbine. With maximum aeration, the upgraded turbine achieves approximately equal efficiency at maximum capacity and a capacity increase of 3.2 MW, about 11%, compared to the Unit 6 original turbine. Actual efficiency losses during operation are lower than these values when DO and TDG targets can be met with reduced air flows.

Figure 2-48
Hydraulic Performance for Aerating Turbine with Central Aeration
(Net Head 95 ft)

Environmental Performance

Figure 2-49 shows air flow results as Q_a/Q_w versus turbine output expressed in megawatts (MW). Q_a/Q_w values between 4.4% and 2.7% are achieved in the range of 10 MW to 33 MW, with Q_a/Q_w gradually dropping with increased turbine output. The upgraded Unit 3 turbine provides significantly higher Q_a/Q_w values across the operating range.

Limited DO uptake information, provided for this unit in Ware and Sullivan (2006), is shown for multiple tailwater elevations in Figure 2-50. Incoming DO was measured with instrumentation installed in the penstock, and tailrace DO was measured from a boat in the tailrace. The data for a tailwater elevation of 560 ft corresponds to the performance data reported in this case study. The reported DO uptakes ranged from 4.4 mg/L at a turbine flow of 1,700 cfs to 4.3 mg/L at a turbine flow of 3,900 cfs.

Figure 2-49
Qa/Qw versus Turbine Output for Aerating Turbine with Central Aeration (Net Head 95 ft)

Figure 2-50
DO Uptake Versus Turbine Flow for Aerating Turbine with Central Aeration, from Ware and Sullivan (2006)

Additional Information

Additional, more comprehensive information on environmental performance could be obtained from this site through detailed analyses of plant operational data and environmental monitoring data.

The project's new FERC license, issued in 2007, raises the minimum flow from 450 cfs to 900 cfs. The two station service units were upgraded in 2010 to supply the increased minimum flow as well as 7.2 MW of combined power production. In addition, the new station service units have aeration capabilities, which can provide increased environmental benefits compared to flow alone (March and Fisher 1999). The additional annual generation benefit from the upgrade to the station service units, certified by FERC for a production tax credit, is 10,575 MWh (FERC 2011).

Case Study, Aerating Turbine with Distributed Aeration

Description of Plant

This eight-unit, 240 MW hydroplant is owned and operated by an investor-owned utility. In 2008, Units 1 and 7 were upgraded with aerating turbines using distributed aeration, supplied by Voith Hydro Inc. This case study is based on test results for Unit 1.

For the Unit 1 and Unit 7 upgrades, a complete physical model study, including the draft tube, was conducted. After the Unit 1 and Unit 7 upgrades, efficiency tests were conducted on Unit 3 and Unit 6 in 2008. Efficiency test procedures followed ASME Performance Test Code 18-2002 (ASME 2002). The pressure-time method was used for water flow measurements. Air flows into the central aeration systems were also measured, using differential pressures measured at the throats of the bellmouth intakes for the air supply piping.

Hydraulic Performance

Model test results and efficiency test results for Unit 1 are shown in Figure 2-54. The peak efficiency from the physical model results has been used to normalize both the upgraded Unit 1 turbine results and the original Unit 6 turbine results. Within the test uncertainty, the peak efficiency from the model tests corresponds to the measured efficiency. The shape of the efficiency curve for the prototype turbine agrees closely with the model results. Without aeration, the upgraded turbine achieves the best efficiency at turbine output of 32.6 MW, which is an efficiency increase of about 3.4% compared to the original turbine, and a maximum capacity of 36.9 MW, which is an increase of 7.4 MW, about 14%, compared to the original turbine. With maximum aeration, the upgraded turbine achieves the best efficiency at a turbine output of 31 MW, which is an efficiency increase of about 1% compared to the original turbine, and a maximum capacity of 35.8 MW, which is an increase of 6.3 MW, about 21%, compared to the original turbine. With maximum aeration, the efficiency at maximum capacity is 3.8% higher than the efficiency at maximum capacity for the original turbine.

Maximum aeration at best efficiency for Unit 1 reduces the efficiency by 2.4% and reduces the best efficiency turbine output from 32.6 MW to 31 MW. Actual efficiency losses during operation are lower than these values when DO and TDG targets can be met with reduced air flows.

Figure 2-51
Hydraulic Performance for Aerating Turbine with Distributed Aeration (Net Head 95 ft)

Environmental Performance

Figure 2-52 shows air flow results as Q_a/Q_w versus turbine output expressed in megawatts (MW). Q_a/Q_w values between 7.4% and 5.0% are achieved in the range of 10 MW to 36 MW, with Q_a/Q_w gradually dropping with increased turbine output between 10 MW and 15 MW, leveling off between 15 MW and 26 MW, then rising gradually between 15 MW and 26 MW. The upgraded Unit 1 turbine provides significantly higher Q_a/Q_w values across the operating range compared to the Unit 6 original turbine.

Limited DO uptake information, provided for this unit in Foust et al. (2009), is shown for multiple tailwater elevations in Figure 2-53. Incoming DO was measured with instrumentation installed in the penstock, and tailrace DO was measured from a boat in the tailrace. The data for a tailwater elevation of 562 ft corresponds to the performance data reported in this case study. The reported DO uptakes ranged from 3.4 mg/L to 3.8 mg/L for turbine flows from 3,100 cfs to 4,850 cfs.

Additional Information

Additional information on hydraulic and environmental performance at other heads is provided in Foust et al. (2009). More comprehensive information on environmental performance could be obtained from this site through detailed analyses of plant operational data and environmental monitoring data.

Figure 2-52

Qa/Qw Versus Turbine Output for Aerating Turbine with Distributed Aeration (Net Head 95 ft)

Figure 2-53
DO Uptake Versus Turbine Flow for Aerating Turbine with Distributed Aeration,
from Foust et al. (2009)

Discussion of Results from Case Studies

Aeration Effects on Turbine Efficiency

Typical effects of air flows on turbine efficiency for peripheral, central, and distributed aeration are provided in Foust et al. (2008). Figures from Foust et al. (2008) are re-plotted and extended to higher values of Q_a/Q_w (i.e., the volumetric air flow rate divided by the volumetric water flow rate, expressed as a percentage) in Figure 2-54, Figure 2-55, and Figure 2-56. The original guidelines from Foust et al. (2008) are shown as solid lines, and linear extrapolations are shown as dotted lines. Data points corresponding to test results for the three case studies are provided in these three figures.

Figure 2-54 shows typical decreases in turbine efficiency with peripheral aeration (red line), central aeration (blue line), and distributed aeration (green line) for a Q_w/Q_{wopt} of 0.8 (i.e., a water flow rate which is 80% of the water flow rate at the maximum turbine efficiency without aeration). A Q_w/Q_{wopt} of 0.8 corresponds to a flow range that is typical of the lower limit for a normal operational range. In this flow range, the decrease in efficiency from the peripheral aeration case study is lower than expected, the decrease in efficiency from the central aeration case study is higher than expected, and the decrease in efficiency from the distributed aeration case study is close to the expected value.

Figure 2-54

Decreases in Turbine Efficiency for Peripheral (Red), Central (Blue), and Distributed (Green) Aeration at Q_w/Q_{wopt} of 0.8, adapted from Foust et al. (2008)

Figure 2-55 shows typical decreases in turbine efficiency with peripheral aeration (red line), central aeration (blue line), and distributed aeration (green line) for a Q_w/Q_{wopt} of 1.0 (i.e., a water flow rate which equal to the water flow rate at the maximum turbine efficiency without aeration). A Q_w/Q_{wopt} of 1.0 corresponds to the flow range for the most efficient turbine operation. In this flow range, the decrease in efficiency from the peripheral aeration case study is lower than expected, the decrease in efficiency from the central aeration case study is somewhat higher than expected, and the decrease in efficiency from the distributed aeration case study is somewhat higher than expected.

Figure 2-55

Decreases in Turbine Efficiency for Peripheral (Red), Central (Blue), and Distributed (Green) Aeration at Q_w/Q_{wopt} of 1.0, adapted from Foust et al. (2008)

Figure 2-56 shows typical decreases in turbine efficiency with peripheral aeration (red line), central aeration (blue line), and distributed aeration (green line) for a Q_w/Q_{wopt} of 1.2 (i.e., a water flow rate which is 20% higher than the water flow rate at the maximum turbine efficiency without aeration).

A Q_w/Q_{wopt} of 1.2 corresponds to a flow range that is typical of the upper limit for a normal operational range. In this flow range, the decrease in efficiency from the peripheral aeration case study is lower than expected, and the decrease in efficiency from the distributed aeration case study is close to the expected value. No results are available from the central aeration case study for a Q_w/Q_{wopt} of 1.2.

Figure 2-56

Decreases in Turbine Efficiency for Peripheral (Red), Central (Blue), and Distributed (Green) Aeration at Q_w/Q_{wopt} of 1.2, adapted from Foust et al. (2008)

This comparison of the effects of aeration on turbine efficiency from the case study results with the typical expected values from Foust et al. (2008) underscores the scatter inherent in the data behind the three lines in each graph. Presumably, site-specific details such as draft tube design contribute significantly to the observed variation.

Efficient Operation and Environmental Optimization

The central aeration case study and the distributed aeration case study describe units located at the same hydroplant. Figure 2-57 shows turbine efficiencies versus turbine outputs for the three unit types at this plant, operating at a net head of 95 ft. The turbine efficiencies have been normalized to the maximum measured efficiency of the most efficient unit. The plant has two original units with retrofitted central aeration, two 2002 upgraded units with central aeration, and four 2008 upgraded units with distributed aeration. The challenges for efficient operation of the plant's eight units under non-aerating and aerating conditions, over a range of heads, and with rapid load swings are apparent.

To improve the overall efficiency at this plant, a SCADA (Supervisory Control and Data Acquisition) system upgrade called the "Advanced Features Control System" (AFCS) was implemented at Osage. The goal of the AFCS was to optimize overall plant efficiency while ensuring that overriding constraints, such as license compliance and environmental compliance, were also met. The AFCS includes unit (i.e., turbine and generator) performance information for non-aerating and aerating operation over the anticipated head range of the plant. The

control algorithm receives a plant load setting from the Independent Transmission System Operator (ISO), calculates the optimum method to dispatch each of the eight main units, then every few seconds automatically adjusts the power on each unit to meet the time-varying load setting. As the head changes, the AFCS maintains each operating unit within a narrow band of its most efficient operating point and automatically brings units from condensing operation or reduced load to generating operation or from generating operation to condensing operation or reduced load as required to meet the total plant load demand.

Figure 2-57
Normalized Turbine Efficiencies versus Turbine Output for Three Unit Types

For operations under aerating conditions, an Air Order Model (AOM) has been implemented to control and optimize the airflows supplied to the eight units. A Discrete Bubble Model (DBM) is incorporated into the AOM. The DBM predicts the rate of oxygen transfer from a single bubble traveling through the draft tube and tailrace as a function of flow rate, air/water ratio, and other factors. The DBM, which was calibrated based on DO uptake tests at the plant, uses real-time data to determine the amount of air that is needed to attain DO targets in the tailrace. The input data includes inflow DO, unit flow rates, tailrace elevation, temperature, and total dissolved gases (TDG). Using the DBM results, the AOM balances airflows among unit, utilizing the most efficient units first, and controls valves on the air intake piping for each unit to ensure that DO and TDG targets are attained and that excess aeration does not occur. The AOM and DBM self-adjust based on feedback data from the tailrace DO and

TDG monitor , which is located about 1 mile downstream, and the travel time between the powerhouse discharge and the downstream water quality monitor.

This combination of the Advanced Features Control System and the Air Order Model provides an advanced form of environmental optimization that has not been achieved elsewhere. Additional evaluations and improvements to the AFCS and the AOM are ongoing.

Summary and Recommendations

Summary

This paper uses a review of the technical literature from 1998 through 2009 and contacts with personnel from turbine manufacturers, utilities, and agencies to provide information and performance data on aerating turbine technologies. Hydraulic and environmental performance results are analyzed and presented as case studies for three aerating turbine technologies (central aeration, peripheral aeration, and distributed aeration). The paper describes some of the difficulties in assessing the performance of aerating turbines, discusses the implications of the case study results for plant operation and optimization, and provides recommendations for additional related research.

Recommendations

To further assist turbine manufacturers, agencies, and utilities in their efforts to evaluate and improve the hydraulic and environmental performance of aerating turbines, the following recommendations are provided:

- Turbine manufacturers, agencies, and utilities should be encouraged to assist the hydropower industry by providing access to existing hydraulic and environmental performance information for aerating turbines.
- The hydropower industry should establish a national database of hydraulic and environmental performance data for aerating turbines. The national database could be funded by EPRI, DOE, USACE, or another appropriate sponsor and maintained by a national laboratory with related experience, such as Oak Ridge National Laboratory.
- Additional performance information should be solicited for the smaller “minimum flow” turbine installations which include DO enhancement.
- Additional performance information should be solicited from European and Asian utilities and agencies as aerating turbine solutions are applied in those areas.
- ASME PTC-18’s continuing efforts for the development and standardization of a comprehensive test code for aerating turbines should be encouraged and financially supported by the hydropower industry.
- Long term monitoring and data analyses for various aerating turbine technologies should be conducted to provide hydraulic and environmental performance results over a much wider range of conditions.

- As a collaborative R&D study and a contribution to the hydropower industry, EPRI should survey turbine manufacturers and utilities and compile incremental cost information for various aerating turbine technologies.
- A wide variety of related research activities should be encouraged and supported. Some of these research topics include:
 - Improving the aeration-related scaling relationships between physical models and prototypes;
 - Improving numerical models for predicting draft tube effects on decreases in turbine efficiency under non-aerating and aerating conditions;
 - Improving numerical models for predicting gas transfer and resulting DO and TDG levels;
 - Developing cost-effective DO enhancement options for Kaplan and bulb turbine units;
 - Developing and improving environmental optimization tools; and
 - Developing new, more cost-effective methods to measure DO in reservoir releases.

References

Almquist, C. W., P. N. Hopping, and P. J. Wolff. 1998. Draft Test Code for Aerating Hydroturbines. TVA Report No. WR98-1-600-125, Norris, Tennessee: Tennessee Valley Authority (TVA), August 1998.

American Society of Mechanical Engineers (ASME). 2002. Performance Test Code 18: Hydraulic Turbines and Pump-Turbines. ASME PTC 18-2002, New York, New York: .

Bevelhimer, M. S., and C. C. Coutant. 2006. Assessment of Dissolved Oxygen Mitigation at Hydropower Dams Using an Integrated Hydrodynamic/Water Quality/Fish Growth Model. Report No. ORNL/TM-2005/188, Oak Ridge, Tennessee: Oak Ridge National Laboratory, March 2006.

Black, J. L., E. P. Taft, D. A. Davis, and D. A. Dixon. 2002. Methods for Meeting and Monitoring Dissolved Oxygen Standards for Hydroelectric Projects. *Proceedings of HydroVision 2002*, Kansas City, Missouri: HCI Publications, July 2002.

Bohac, C. E., J. W. Boyd, E. D. Harshbarger, A. R. Lewis. 1983. *Techniques for Reaeration of Hydropower Releases*, USACE Technical Report No. E-83-5, Vicksburg, Mississippi: U. S. Army Corps of Engineers (USACE), February 1983.

Čada, G. F., P. A. Brookshier, J. V. Flynn, B. N. Rinehart, G. L. Sommers, and M. J. Sale. 1999. Advanced, Environmentally Friendly Hydroelectric Turbines for the Restoration of Fish and Water Quality. Paper IGWM-39, *Proceedings of*

EPRI Conference on Integrated Global Water Management, September 1999a (cancelled).

Čada, G. F., P. A. Brookshier, J. V. Flynn, B. N. Rinehart, G. L. Sommers, and M. J. Sale. 2004. The use of advanced hydroelectric turbines to improve water quality and fish populations. *Proceedings of the 4th International Congress on Energy, Environment, and Technological Innovation*, September 1999b, pp. 545-549.

Désy, N., É. Demers, R. Grenier, and D. O. Hulse. 2004. The Dissolved Oxygen Experience at Canyon Ferry. *Proceedings of HydroVision 2004*, Kansas City, Missouri: HCI Publications, July 2004.

Electric Power Research Institute (EPRI). 1990. *Assessment and Guide for Meeting Dissolved Oxygen Water Quality Standards for Hydroelectric Plant Discharges*, Report No. GS-7001, Palo Alto, California: Electric Power Research Institute (EPRI), November 1990.

EPRI. 2002. *Maintaining and Monitoring Dissolved Oxygen at Hydroelectric Projects: Status Report*, Report No. 1005194, Palo Alto, California: Electric Power Research Institute (EPRI), May 2002.

Faulkner, E. 2000. Tools for Environmental Monitoring and Response at Hydro Projects. *Hydro Review*, April 2000, pp. 38-42.

FERC. 2011. *Order Certifying Incremental Hydropower Generation for Production Tax Credit*, Ameren Missouri, Project No. 459-301, January 19, 2011.

Foust, J. M., J. Etter, and R. K. Fisher. 2008. Predicting Dissolved Oxygen and Nitrogen Uptake during Turbine Aeration. *Proceedings of HydroVision 2008*, Kansas City, Missouri: HCI Publications, July 2008.

Foust, J. M., R. K. Fisher, P. M. Thompson, M. M. Ratliff, and P. A. March. 2009. Integrating Turbine Rehabilitation and Environmental Technologies: Aerating Runners for Water Quality Enhancement at Osage Plant. *Proceedings of Waterpower XVI*, Kansas City, Missouri: PennWell Publications, July 2009.

Franke, G. F., D. R. Webb, R. K. Fisher, Jr., D. Mathur, P. N. Hopping, P. A. March, M. R. Headrick, I. T. Laczó, Y. Ventikos, and F. Sotiropoulos. 1997. Development of Environmentally Advanced Hydropower Turbine System Design Concepts. Report No. 2677-0141, York, Pennsylvania: Voith Hydro Inc., 1997.

Fraser, R., N. Désy, É. Demers, C. Deschênes, J. Fau, and S. Hamel. 2005. Improvements to Self-Venting Francis Turbines. *Proceedings of Waterpower XIV*, Kansas City, Missouri: HCI Publications, July 2005.

Gaffney, S. R., T. A. Jablonski, and J. Kirejczyk. 1999. Using Hydro Turbines to Enhance Dissolved Oxygen Levels. *Hydro Review*, August 1999, pp. 10-14.

Hager, G. 2006. Conowingo Unit 5 Rehabilitation: What Went Well and What Didn't. *Proceedings of HydroVision 2006*, Kansas City, Missouri: HCI Publications, July 2006.

Harshbarger, E. D., B. Herrold, G. Robbins, and J. C. Carter. 1990 Turbine Venting for Dissolved Oxygen Improvements at Bull Shoals, Norfork, and Table Rock Dams, *Proceedings of Waterpower 99*, Reston, Virginia: American Society of Civil Engineers, August 1999.

Hobbs, V. 2008. Addressing environmental challenges at US hydro dams. *International Journal on Hydropower & Dams*, Vol. 15, No. 3, 2008, pp. 41-43.

Hopping, P. N., P. A. March, and P. J. Wolff. 1999. Justifying, Specifying, and Verifying Performance of Aerating Turbines. *Proceedings of Waterpower 99*, Reston, Virginia: American Society of Civil Engineers, August 1999.

International Electrochemical Commission (IEC). 1991. Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps, and pump-turbines. International Electrotechnical Commission (IEC) Publication 41-1991, Geneva, Switzerland: Bureau Central de la Commission Electrotechnique Internationale, November 1991.

Jablonski, T. A., and J. Kirejczyk. 1998. A Case Study: DO Enhancement Utilizing Hydraulic Turbines at Oxford and Wylie Hydro Stations. *Proceedings of HydroVision 1998*, Kansas City, Missouri: HCI Publications, July 1998.

Jarvis, D. E., C. Kempf, F. L. Putz, and G. A. Stover. 1998. Using Vents, Low Flows to Enhance Tailwater Dissolved Oxygen. *Hydro Review*, August 1998, pp. 72-73.

Kao, D. T. 2007. Industrial Application of an Innovative Eco-Environmental Friendly Hydropower Turbine. *Proceedings of Waterpower XV*, Kansas City, Missouri: HCI Publications, July 2007.

Kao, D. T., G. Yuan, X. Chen, and S. Liu. 2008. New Frontiers and Opportunities for Hydropower: A Broad Vision of Sustainable Energy to Better Serve Future Global Needs. *Proceedings of HydroVision 2008*, Kansas City, Missouri: HCI Publications, July 2008.

Kao, D. T., T. Zhong, and J. R. Mahar. 2009. A Cost Effective and Environmentally Sustainable Approach to Retrofitting Existing Dams for Hydroelectric Power Generation. *Proceedings of Waterpower XVI*, Kansas City, Missouri: PennWell Publications, July 2009.

Kepler, J. L., and G. Hager. 2005. Upgrade, Rehabilitation, and Aeration of Exelon's Conowingo Hydro Turbines. *Proceedings of Waterpower XIV*, Kansas City, Missouri: HCI Publications, July 2005.

- Kühlert, K. H., and A. D. Ware. 2004. A CFD System to Predict Dissolved oxygen Uptake in Hydraulic Turbines. *Proceedings of HydroVision 2004*, Kansas City, Missouri: HCI Publications, July 2004.
- Lueders, B. C. 1956. Turbine Venting for Stream Reaeration. Presentation to Paper Company Officials, Mead Hotel, Wisconsin Rapids, Wisconsin, August 15, 1956.
- March, P. A. 2006. Real-Time Environmental Optimization: A New Frontier for Performance and Profitability. POWER-GEN Renewable Energy & Fuels 2006, Las Vegas, Nevada, April 12, 2006.
- March, P. A. 2009. *Hydropower Technology Roundup Report: Technology Update on Aerating Turbines*, 1017966, Palo Alto, California: Electric Power Research Institute, 2009.
- March, P. A., and R. K. Fisher. 1999. It's Not Easy Being Green: Environmental Technologies Enhance Conventional Hydropower's Role in Sustainable Development. *Annual Review of Energy and the Environment*, Volume 24, November 1999, pp. 173-188.
- McGinnis, D. F., and R. J. Ruane. 2007. Development of the Discrete-Bubble Model for Turbine Aeration Systems. *Proceedings of Waterpower XV*, Kansas City, Missouri: HCI Publications, July 2007.
- Moore, L. B. 2009. Increasing Dissolved Oxygen with a Draft Tube Aeration System. *Hydro Review*, March 2009, pp. 32-38.
- Papillon, B., J. Kirejczyk, and M. Sabourin. 2000a. Determination of Similitude Rules for Hydroturbine Aeration. *Proceedings of the XXth LAHR Symposium on Hydraulic Machinery and Systems*, Charlotte, August 2000a.
- Papillon, B., J. Kirejczyk, and M. Sabourin. 2000b. Atmospheric air admission in hydroturbines. *Proceedings of HydroVision 2000*, Kansas City, Missouri: HCI Publications, August 2000b.
- Papillon, B., M. Sabourin, M. Couston, and C. Deschênes. 2002. Methods for Air Admission in Hydroturbines. *Proceedings of the XXIst LAHR Symposium on Hydraulic Machinery and Systems*, Lausanne, 2002.
- Parrott, D. L., and R. K. Fisher. 2003. New Turbine Technology: Improving Plant Performance and Water Quality. *Hydro Review*, October 2003, pp. 10-14.
- Parrott, D. L., R. K. Fisher, G. A. Snyder, and J. Sykes. 2006. J. Strom Thurmond Major Rehabilitation Project: The Effects of Operation and Multiple Units on Aerating Performance of the J. Strom Thurmond Francis Turbines. *Proceedings of HydroVision 2006*, Kansas City, Missouri: HCI Publications, July 2006.

- Peterson, M. J., G. F. Čada, and M. J. Sale. 2001. "Non-Structural Approaches for Addressing Dissolved Oxygen Concerns at Hydropower Facilities," *Proceedings of Waterpower XII*, Kansas City, Missouri: HCI Publications, July 2001.
- Rohland, K. M., and J. C. Sigmon. 2008. Aeration Solutions for New Hydro - The Bridgewater Project. *Proceedings of HydroVision 2008*, Kansas City, Missouri: HCI Publications, July 2008.
- Ruane, R. J., and D. F. McGinnis. 2007. Applications of the Discrete-Bubble Model for Turbine Aeration Systems. *Proceedings of Waterpower XV*, Kansas City, Missouri: HCI Publications, July 2007.
- Shultz, B. R., R. J. Ruane, T. J. Oakes. 2002. Water Quality Enhancements of the PPL Wallenpaupack Project Hydroelectric Discharge into the Lackawaxen River. *Proceedings of HydroVision 2002*, Kansas City, Missouri: HCI Publications, July 2002.
- Sigmon, J. C., G. D. Lewis, G. A. Snyder, and J. R. Beyer. 2000. Using Hydro Turbine Aerating Runner Technology to Enhance Dissolved Oxygen Levels. *Proceedings of HydroVision 2000*, Kansas City, Missouri: HCI Publications, July 2000.
- Smith, B. T., H. I. Jager, and P. A. March. 2007. Prospects for Combining Energy and Environmental Objectives in Hydropower Optimization. *Proceedings of Waterpower XV*, Kansas City, Missouri: HCI Publications, July 2007.
- Thompson, E. J., J. S. Gulliver. 1997. Oxygen Transfer Similitude for Vented Hydroturbine. *Journal of Hydraulic Engineering*, ASCE, Vol. 123, No. 6, 1997.
- Voith Siemens Hydropower Generation (VSH). 2008. Narrows Unit 4 Aeration Study. Internal report. January 2008.
- Wagner, H. 1958. Experiments with Artificial River Water Aeration. *Voith Forschung und Konstruktion*, Heft 4, November 1958.
- Ware, A. D., W. Colwill, and A. Sullivan. 2004. The Retrofit Aeration System - A Comprehensive Design Approach to Enhance Dissolved Oxygen Uptake in Existing Hydroturbines. *Proceedings of HydroVision 2004*, Kansas City, Missouri: HCI Publications, July 2004.
- Ware, A. D., and A. Sullivan. 2006. Additional Dissolved Oxygen Enhancement at Bagnell Dam: Field Test Results from a Retrofit Aeration System for an Existing Osage Hydroturbine. *Proceedings of HydroVision 2006*, Kansas City, Missouri: HCI Publications, July 2006.
- Wiley, A. J., B. F. Lueck, R. H. Scott, and T. F. Wisniewski. 1962. Commercial Scale Stream Reaeration. *Journal of the Water Pollution Control Federation*, Volume 34, April 1962.

Wisniewski, T. F. 1965. Improvement of the Quality of Reservoir Discharges through Turbine or Tailrace Aeration. Proceedings of the Symposium on Streamflow Regulation for Quality Control, Cincinnati, Ohio: U. S. Public Health Service, 1965.

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The Technical Challenges of Dissolved Oxygen Enhancement

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Abstract

This paper makes first a review of different turbine aeration methods to increase dissolved oxygen (DO) concentration in water downstream hydroelectric power plants and describes the impact of aeration on turbine performances. Aeration model test, model to prototype transposition, prediction of aeration performances and parameters influencing oxygen dissolution in water are all discussed. Increasing water DO content by turbine aeration involves many complex physical processes which make the design of dissolved oxygen enhancement systems a real technical challenge. Past successes clearly show the relevance of this technology. However, further research and development in this field, in particular regarding numerical modeling, would allow better performance predictions and device optimizations. Finally, addressing turbine aeration and DO enhancement in performance Codes would help progress of this technology.

Introduction

Even though hydropower already provides a very clean source of energy, the hydroelectric power generation industry is greatly concerned by environmental issues. One of them is the dissolved oxygen (DO) downstream power plants. This issue is particularly important in warm climate regions, generally at the end of summer. In these regions, low DO level, often less than 1 mg/L while fish need minimum of 5 mg/L, can occur in reservoir near turbine intake because of thermal stratification, as described for instance by Ruane and Hauser (Ref. 7). In these conditions, water released to the river with a very low DO content may damage the aquatic habitat downstream the power plant. In the past, this problem has been mainly a concern in the southern part of USA. However, it seems it is now arising in other regions of the world.

Several methods exist to increase the amount of dissolved oxygen (DO) downstream power plants such as aeration weirs, bubble diffusers or surface water flow pumps. However, it is well established that air admission in low pressure zones of a hydraulic turbine is often the most economical method to achieve this goal. In this paper, different turbine aeration methods are briefly presented and their effects on turbine performances are described. Difficulty to perform aeration model tests as well as to transpose them to prototype is discussed. Finally, methods for predicting aeration performances, parameters influencing oxygen dissolution and the importance of pursuing research and development in this field are discussed.

Aeration Methods

Turbine aeration is used since a long time by turbine manufacturers to reduce part load or high loads pressure pulsations. Air flow required to reduce pressure pulsations corresponds usually to about one percent of the turbine discharge. To increase DO levels downstream power plant, required air flow is generally greater (up to four percent of the turbine discharge and more), depending of the DO content of incoming water, water temperature, aerating device performance, turbine design and required DO level downstream power plant.

Figure 2-58 shows typical locations where air is usually injected in turbines to take advantage of low pressure zones under the runner. Location 1 corresponds to central aeration. At this location, air can be introduced through the runner cone center, runner cone baffles or a tube crossing the draft tube cone (this latest configuration being seen mainly in small and medium size hydro). Location 2 corresponds to peripheral aeration. At this location, air can be introduced by the discharge ring or by the draft tube cone. Finally, location 3 corresponds to the runner outlet. Typically, location 1 is very efficient at low load while locations 2 and 3 are more efficient at medium to high loads. This is one reason why aerating at many locations can be required when a certain DO level has to be maintained over the full operating range.

Locations 1, 2 and 3 take advantage of the low static pressure in these zones. Atmospheric air can often be admitted through these locations naturally, ie without any need of a compressor or a fan, thus minimizing cost and complexity of the aeration systems. In some cases however, use of a compressor or a fan can be needed due, for instance, to too high tailwater levels or a too large air discharge requirement.

Figure 2-58

Typical air injection locations and contour plot of static pressure in a turbine water passage near the optimal efficiency point.

Figure 2-59 shows a typical aeration system piping bringing here atmospheric air from the turbine pit over the runner crown in order to introduce air in the water flow through the runner cone. Typically, the aeration system includes a manual butterfly valve, a check valve, an electrically controlled proportional valve (that can be operated from the control room) and a muffler. During the design phase, duct sizing and prediction of the air flow in the aeration system is performed using a detailed model of the aeration system. This model takes account of every components of the system with the appropriate loss coefficients. The piping model solves the one dimensional equations for a steady state compressible flow with friction. Static pressure at the outlet of the aeration system in the water flow is estimated from computational fluid dynamics (CFD) calculations, experience and test results on model and prototype with similar systems.

*Figure 2-59
Typical aeration system bringing air to the runner*

Effects of Aeration

Aeration, of course, increases dissolved oxygen in water (and other gas composing air). This is the objective. Figure 2-60 shows the effect turbine aeration can have on dissolved oxygen content. However, turbine aeration does not only affect DO. It affects turbine performances as well, in term of flow rate, power output and turbine efficiency. Air bubbles replace water, modify the density of the fluid and perturb water velocities. In addition, massive air admission modifies local pressure, generally resulting in a reduction of the “internal” head seen by the runner, inducing both a shift of the runner operating point and, as the internal head decreases, an efficiency and output drop. Thus, air admission modifies the complete hill chart. Furthermore, aeration system can impact turbine performances even without air admission when these systems modify the optimal water passages that would be designed if no DO

enhancement was needed. These last losses are generally quite low but must be taken into account during the design process. Figure 2-61 and Figure 2-62 show what can be the impact of turbine aeration on turbine performances.

Figure 2-60
Contour plot of the tailwater dissolved oxygen in mg/L as function of water temperature and ratio Q_a/Q_w between air flow and water flow for a particular project. The scroll case DO content is 1.2 mg/L in this case.

Figure 2-61
Efficiency change with air admission as a function of the ratio of the air flow on the turbine discharge for different aeration devices. Data from a model test of a Francis runner near peak efficiency at a test net head of 12 m.

(a)

(b)

Figure 2-62

(a) Water aerated by central aeration exiting from draft tube. b) Normalized performance curves without and with central aeration measured on this prototype (system fully opened).

Aeration on Model and Transposition to Prototype

Aeration model tests are performed to determine the effect of aeration on performances (flow rate, power output and efficiency), on pressure pulsations and on dissolved oxygen content. They are also used to measure pressure at air injection locations as a function of the air flow for different operating points. During model testing, many devices can be tested and compared. Figure 2-63 shows photos of some aeration tests on model.

Figure 2-63

Cross section of a turbine model used to perform aeration tests (a). Flow under the runner near peak efficiency without aeration (b), with central aeration (c) and with peripheral aeration (d).

DO is the most difficult parameter to measure during an aeration test on model. Most model test rigs are of a closed-circuit type. In such closed circuits, air

injected through the model turbine increases rapidly. Degassing is thus needed periodically to be able to measure DO enhancement. The second issue relates to the similarity of the entire DO transfer system. Field tests have indicated that a significant part of oxygen is transferred to the dissolved state in the tailrace. The DO level can still increase as much as 300m downstream of the powerhouse. That effect is of course not modeled on the test rig. Thus a significant part of the oxygen transfer process is not represented on the model.

Transposition from model to prototype is also difficult to calculate with today's knowledge. The similarity law addressing air flow and performances in ref. 1 and 2 is based on an empirical coefficient which still contains some uncertainties. Regarding DO, similarity laws that can be applied to relate results of the model test with the prototype (see ref. 6 and 7) also bring significant uncertainties. Indeed, here also, empirical constants based on model and prototype test are used and are function of the test conditions of a particular project.

For the time being, the best method of assessing the dissolved oxygen increase is to rely on field test, measuring the amount of air admitted and the resulting difference in DO. This way a reliable relation of oxygen transfer efficiency and air flow / turbine discharge ratio can be established. In summary, the amount of dissolved oxygen increase can be related to the required air admission and corresponding performance alteration. For that, however, model tests need to be complemented by results of field testing.

Prediction of Aeration Performances

Prediction of aeration performances relies on analytical model, CFD, model test and past experience. Figure 2-64 shows examples of CFD calculations and model test. Complex models like two phase flow models can be used but, again, many parameters have to be tuned from experiments, mainly prototype testing. All these tools are used to estimate DO uptake, impact on performances and pressure at the air injection location as a function of air flow for different aerating devices.

(a)

(b)

(c)

Figure 2-64

a) CFD calculation of the turbine from the stay vanes to the outlet of the draft tube. b) Two phase flow CFD calculation to estimate pressure at the air injection location as a function of the air flow. c) Model of a Francis turbine used for aeration and DO tests.

Parameters Influencing Oxygen Dissolution and Possible Areas of Development and Research

The design of an aeration system in order to achieve a certain DO level downstream power plant while estimating required air flow and the impact of

aeration on turbine performances is a challenge. Many parameters influence the oxygen dissolution: water temperature, incoming DO concentration, local pressures in the water passageways, bubbles size, turbulence, velocity and residence time. When air is introduced in the turbine, it modifies the local velocity of water and increases the pressure. Moreover, it modifies the global density of the fluid. It creates bubbles that are entrained by the flow. The flow by its turbulence and shear forces breaks the bubbles that can also coalesce. Size of bubbles can vary in time due to local pressure and dissolution of gas in water. The phenomenon is very complex and involves various sciences like bi-phases, turbulence and unsteady flow.

Today, one of the most advanced numerical tool in this field is a Lagrangian model (or “discrete bubble”) that track bubbles without considering the effect of other bubbles. Therefore, collisions between bubbles are neglected. This model needs DO data from prototype measurements in order to estimate initial bubble size. ALSTOM believes that development of numerical models of aerated turbine flows should be pursued to consider breakup and coalescence of bubbles and to predict bubble size distribution. Detailed experimental studies with measurements of bubble size would be required to validate these models. This quite fundamental research, which could be performed in partnership with Universities, would be useful to design optimal DO enhancement systems.

Finally, another improvement in the turbine aeration and dissolved oxygen enhancement field would be to define standards or guidelines. Indeed, existing Codes (ASME or IEC) do not presently really address turbine aeration, either on model or prototype. Guidelines defining how aeration and DO enhancement tests have to be made and interpreted could help this science to progress.

Conclusion

In this paper, turbine aeration methods as well as their effects on hydraulic and environmental performances are summarized. Challenges related to model test, model to prototype transposition and design of aerating devices are discussed.

Turbine aeration is an efficient method to increase dissolved oxygen content in water. However, oxygen dissolution is influenced by many parameters. This makes the design of dissolved oxygen enhancement devices a real technical challenge. More research and development, in particular regarding a better modeling of all physical processes involved, as well a better standardization would bring significant advancements.

References

Ref. 1 Papillon, B., Kirejczyk, J., Sabourin, M. 2000. Atmospheric air admission in hydroturbines, Hydrovision 2000, Charlotte, North Carolina, USA, August 2000.

Ref. 2 Papillon, B., Kirejczyk, J., Sabourin, M. 2000. Determination of similitude rules for hydroturbine aeration, 20th IAHR Symposium, Charlotte, August 2000.

Ref. 3 Papillon, B., Sabourin, M., Couston, M., Deschênes, C. 2002. Methods for air admission in Hydroturbines, 21st IAHR Symposium, Lausanne, Switzerland, 2002.

Ref. 4 Gaffney, S. R., Jablonski, T. A., Kirejczyk, J. 1999. Using Hydro Turbines to Enhance Dissolved Oxygen Levels, Hydro Review, August 1999.

Ref. 5 Thompson, E.J., Gulliver, J.S. 1993. Oxygen Transfer Similitude for the Auto-venting Turbine, Waterpower 1993, Proceedings of the International Conference on Hydropower, ASCE, Nashville, TN, August 1993.

Ref. 6 Thompson, E.J., Gulliver, J.S. 1997. Oxygen Transfer Similitude for Vented Hydroturbine J. of Hydraulic Engineering ASCE, June 1997.

Ref. 7 Ruane, R.J., Hauser, G.E. 1991. Factors Affecting Dissolved Oxygen in Hydropower Reservoir, Waterpower 1991, Proceedings of the International Conference on Hydropower, ASCE, Denver, Colorado, July 1991.

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Using Dissolved Oxygen Prediction Methodologies in the Selection of Turbine Aeration Equipment

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Abstract

During hydropower production, stratification of the upper reservoir can result in exceedingly low levels of dissolved oxygen (DO) below the water surface. At many sites, this water can enter the turbine intakes and continue downstream of the plant where low DO levels can have an adverse effect on aquatic life and water quality in the tailrace. In an effort to further reduce the environmental impact of hydropower generation, governmental regulations are being established which require minimum tailwater DO concentrations.

One of the most effective methods for improving DO levels in the discharges of hydro plants is to implement turbine venting, where low pressures below the runner are utilized to draw air into the water passing through the turbine. As the air-water mixture develops within the draft tube, oxygen transfers into the surrounding water resulting in higher DO levels in the tailrace.

Several turbine venting methodologies exist, including central, peripheral and distributed aeration. Each method has unique aeration performance characteristics and can be customized according to site specific aeration needs. Over the years, Voith Hydro has developed extensive aeration experience for each technique. Dissolved oxygen uptake values are predicted with the use of the Discrete Bubble Model (DBM) to ensure that aeration goals are met while minimizing the costs associated with aeration. The current paper illustrates the use of the DBM to predict uptakes associated with central, peripheral, and distributed aeration for a hydro plant located in the southern United States. These predictions are then utilized to size an aeration system that will meet water quality requirements.

As design technologies improve, aeration applications are becoming more widespread. Voith recently designed and installed a peripheral aeration system for Kaplan turbine operation. The dissolved oxygen uptakes observed during aeration testing are presented.

Study Overview

Hydro power production is extremely reliable, featuring robust equipment that operates over the span of several decades with little maintenance. As these units age, several factors are evaluated when determining whether turbine rehabilitation is necessary and feasible, including changes to site hydrology, advances to design technology, lifecycle extension, as well as economic considerations. Often times, higher turbine performance levels and larger power outputs alone justify the cost for the upgrades. Turbine rehabilitation also

provides the opportunity for hydro power owners to integrate environmental solutions into the replacement equipment. The following paper presents an assessment of aerating turbines for a representative hydro power site located in the southern United States. Dissolved oxygen uptake predictions are documented for three varieties of auto-venting turbine aeration techniques, including central, peripheral and distributed (aerating runner). For each aeration methodology, expected air flow values, dissolved oxygen uptakes and efficiency impacts are provided. Results from the investigation were utilized to help the plant owner select the aerating solution that optimizes dissolved oxygen needs at the plant.

Introduction

Despite the numerous environmental benefits of hydro power production, storage of water in the upper reservoir for prolonged periods of time can result in thermal stratification during the warmer months of late summer. Reservoir stratification prevents natural water column circulation from transporting oxygen rich water near the surface to the turbine intakes located adjacent to the reservoir bottom. Under these conditions, dissolved oxygen levels within the lower portion of the reservoir can drop below 1 mg/l before passing through the turbines and into the tailrace downstream of the plant (Figure 2-65).

Figure 2-65

Typical reservoir stratification, producing low dissolved oxygen levels adjacent to the turbine intakes.

Low dissolved oxygen levels within the tailrace can have an adverse effect on water quality and aquatic life. While the aforementioned issues are more pronounced closer to the turbine discharges, these effects have been shown to extend as far as ten river miles downstream of the hydropower facilities (Thompson and Gulliver, 1997). In an effort to reduce the environmental impacts of hydropower generation, new regulations are being established which require minimum tailrace DO concentrations of 5 mg/l or higher in turbine discharges (Foust et al. 2008).

Aeration Techniques

For many hydro facilities, economic studies have led to the implementation of aeration methods that occur within the turbine, where sub-atmospheric pressure

can develop under the runner during power production. If available, these low pressure regions are vented to the atmosphere, creating a natural flow of air to the water passage. The incorporation of atmospheric air into the turbine is referred to as auto-venting turbine (AVT) aeration and is a particularly cost-effective method for injecting large quantities of air into the discharge.

Auto-venting turbine aeration generally consists of three different aeration options, including distributed, central and peripheral aeration. Each method has a unique piping system that transports air from outside the turbine to the air inlet location located within the water passage. These piping systems, and the corresponding inlet locations under the runner, are outlined in Figure 2-66.

Figure 2-66
Representative distributor section of a Francis turbine showing distributed (green), central shaft (blue), central vacuum breaker (red) and peripheral (yellow) (Foust et al. 2008).

Distributed aeration (green) draws air from several pipes positioned above the headcover (typically within the wheelpit), where it is collected in a continuous chamber above the runner crown. The air then passes into the hollow runner blades before entering the water passage through a series of slots positioned along the discharge edges of the blades. Two primary forms of central aeration exist, and both methods transport air from the region above the headcover. Vacuum breaker aeration (red) typically distributes the air flow to several locations around the side of the deflector, while central aeration via the turbine shaft (blue) has one larger opening at the tip of the deflector. Peripheral aeration (yellow) occurs further downstream, near the entrance to the draft tube. Typically, the draft tube access corridor provides a convenient location for the placement of the inlet piping when retrofit into an existing plant. Peripheral air is collected in a manifold system that distributes the flow around the outside of the water passage. Air exits the manifold through a configuration of slots positioned along the

inside of the draft tube. While various air injection configurations are possible, a continuous ring is preferred due to the larger exit area, and smaller disturbances to the flow in the draft tube which may occur when a series of eductors is positioned along the draft tube wall. The continuous ring configuration also provides better mixing of air within the draft tube flow compared to eductors.

Voith holds a number of patents on aerating runner technologies, including distributed aeration through the hollow blades, in addition to the continuous slot methodology for peripheral aeration below the runner².

Each aeration method utilizes the pressure difference across the piping system to draw air into the turbine, but because of the different injection locations, each method has distinct characteristics induced by the local flow patterns under the runner. These unique features influence aeration performance, including the quantity of air drawn into the turbine; the associated impact of aeration on turbine performance; and dissolved oxygen uptake efficiencies (Foust et al. 2008). During the current investigation, aeration performance was evaluated for the three primary auto-venting turbine techniques across a typical discharge range for Francis turbine operation. These operating conditions are summarized below in Table 2-6.

*Table 2-6
Flow range corresponding to typical operation of a Francis turbine.*

H/H_{opt} [-]	Q/Q_{opt} [-]
1.0	0.8
1.0	1.0
1.0	1.2

Note that Q refers to the local discharge for a specific operating condition, while Q_{opt} refers to the discharge rate that produces the optimum efficiency for the turbine.

Turbine setting relative to tailwater elevation can have a large impact on the ability of the turbine to draw air into the unit during aeration. Turbines that are set higher relative to tailwater have the potential to draw larger amounts of air due to the lower static pressures within the water passage. For the current Francis turbine investigation, air injection from the tip of the deflector occurs 1.3 ft above the tailwater of interest. Distributed aeration from the blade trailing edges occurs at a lower elevation, with the representative slot located 1 ft below tailwater. Peripheral aeration from the upper portion of the draft tube cone is located the deepest with respect to tailwater elevation, occurring 2.4 ft below tailwater elevation.

² Patents Related to Aeration: 4780051, 5823740, 5879130, 5896657, 5924842, 5924844, 5941682, 5953227 and 6095749.

Although each of the three aeration methodologies are evaluated, distributed aeration provides the largest potential for improving tailrace dissolved oxygen levels across the operating range. One of the key features of the aerating runner is the air injection slots located along the blade discharge edges, as illustrated in Figure 2-67.

Figure 2-67
Distributor section of an aerating runner showing air passageway (green).

These slot locations along blade trailing edges take advantage of the low pressures that develop during operation. The rotation of the runner also helps to distribute the air evenly throughout the draft tube, producing a fine bubble cloud that mixes uniformly below the runner. An illustration of the mixing that is expected to occur during Francis turbine aeration at overload ($Q/Q_{opt} > 1$) is given in Figure 2-68.

Figure 2-68
Draft tube bubble distribution for an aerating Francis runner.

Air Flow Calculations

To predict the dissolved oxygen uptake for a specific operating condition, the air flow into the turbine must first be calculated. As previously described, these air flows depend on the pressure differential across the piping system and the piping losses associated with the predicted air flow. Ultimately, the amount of air flow that passes through the system will increase until the head losses inherent to the

piping geometry match the pressure difference between the outside (atmospheric) and inside of the water passage.

To calculate the pressures at the air inlet locations during aeration, the pressures are first determined under non-aerating conditions and then adjusted to account for the air presence. These adjustments are based on empirical relations developed during previous aeration experience.

For the purposes of the current aeration investigation, preliminary piping systems for each aeration method were incorporated into the air flow predictions. These piping configurations were selected from representative aeration projects and scaled according to the turbine geometry. An overview of the predicted air flows is given in Table 2-7 (central),

Table 2-8(peripheral) and Table 2-9 (distributed) for the settings outlined in the previous section.

Table 2-7

Air flow predictions corresponding to central aeration

H/H_{opt} [-]	Q/Q_{opt} [-]	ϕ [%]
1.0	0.8	2.4
1.0	1.0	1.6
1.0	1.2	1.6

Table 2-8

Air flow predictions corresponding to peripheral aeration

H/H_{opt} [-]	Q/Q_{opt} [-]	ϕ [%]
1.0	0.8	3.5
1.0	1.0	2.6
1.0	1.2	2.8

Table 2-9

Air flow predictions corresponding to distributed aeration

H/H_{opt} [-]	Q/Q_{opt} [-]	ϕ [%]
1.0	0.8	7.5
1.0	1.0	6.5
1.0	1.2	6.4

It is clear from Table 2-7, Table 2-8 and Table 2-9 that, under the assumed site conditions, the air flows created by the aerating runner (distributed aeration) are significantly larger than those of both central and peripheral across the investigated flow range. Further comparison of the predicted void fractions for the three aeration methods are given in Table 2-10.

Table 2-10

Air flow prediction summary for natural aspiration.

H/H_{opt} [-]	Q/Q_{opt} [-]	Central ϕ [%]	Peripheral ϕ [%]	<i>Distributed</i> ϕ [%]
1.0	0.8	2.4	3.5	7.5
1.0	1.0	1.6	2.6	6.5
1.0	1.2	1.6	2.8	6.4

Dissolved Oxygen Uptake Values

Once the air flows are determined for each operating point, these quantities are utilized to predict the amount of dissolved oxygen uptake that will result using the discrete bubble model (DBM) for mass transfer within a two phase mixture.

As bubbles travel through the solution domain, the mass flux equations for oxygen and nitrogen are solved to obtain the dissolved oxygen and total dissolved gas uptakes along the bubble paths (see McGinnis and Ruane, 2007). During auto-venting turbine aeration, the calculation begins at the air inlet location within the water passage and continues through the draft tube and finishes when the bubbles reach the tailwater surface. A representation of the calculation domain is given in Figure 2-69.

Figure 2-69

Bubble transit during turbine aeration.

The primary model input parameters include air quantity, turbine discharge, barometric pressure, initial dissolved oxygen and nitrogen concentrations, initial bubble radius, bubble distribution, discharge temperature, turbine geometry, and tailwater elevation. At each evaluation point in the domain, local changes in pressure, bubble radius, transfer coefficients and dissolved gas are reflected in the mass transfer calculations. Once the bubbles reach the tailwater surface, final dissolved oxygen and total dissolved gas concentrations are determined.

Dissolved oxygen transfer depends on the DO concentration already present within the turbine intakes. Although dissolved oxygen levels within the reservoir can fall below 1.0 mg/l at various elevations, the water entering the intakes is a mixture from various layers where DO levels are typically higher. For the calculations included herein, a scroll case water temperature and dissolved oxygen level of 73.4°F and 1.0 mg/l, respectively, were included in aeration modeling.

Once the turbine geometry and site conditions were incorporated into the discrete bubble model, the dissolved oxygen uptakes were determined for the air flows calculated in Table 2-7, Table 2-8 and Table 2-9 above. An overview of the predicted dissolved oxygen uptakes are given in Table 2-11 (central), Table 2-12 (peripheral), and Table 2-13 (distributed).

Table 2-11

Dissolved oxygen predictions corresponding to central aeration.

H/H_{opt} [-]	Q/Q_{opt} [-]	Dissolved Oxygen Uptake [mg/l]	Tailrace Dissolved Oxygen [mg/l]
1.0	0.8	2.0	3.0
1.0	1.0	1.5	2.5
1.0	1.2	1.5	2.5

Table 2-12

Dissolved oxygen predictions corresponding to peripheral aeration.

H/H_{opt} [-]	Q/Q_{opt} [-]	Dissolved Oxygen Uptake [mg/l]	Tailrace Dissolved Oxygen [mg/l]
1.0	0.8	2.5	3.5
1.0	1.0	2.4	3.4
1.0	1.2	2.8	3.8

Table 2-13

Dissolved oxygen predictions corresponding to distributed aeration.

H/H_{opt} [-]	Q/Q_{opt} [-]	Dissolved Oxygen Uptake [mg/l]	Tailrace Dissolved Oxygen [mg/l]
1.0	0.8	5.3	6.3
1.0	1.0	5.1	6.1
1.0	1.2	5.1	6.1

Central aeration provides the smallest DO uptake and therefore lowest tailrace dissolved oxygen levels, ranging between 2.5 and 3.0 mg/l across the operating range. This type of aeration methodology performs better at lower discharges ($Q/Q_{opt} < 0.8$). Peripheral aeration provides slightly higher tailrace dissolved oxygen levels, approaching 4 mg/l at higher flows ($Q/Q_{opt} = 1.2$). The tailrace dissolved oxygen levels associated with distributed aeration are significantly larger than those produced by central and peripheral, surpassing 6 mg/l across the range of flows investigated ($0.8 \leq Q/Q_{opt} \leq 1.2$).

Table 2-14

Predicted tailrace dissolved oxygen levels.

H/H_{opt} [-]	Q/Q_{opt} [-]	Central Tailrace Dissolved Oxygen [mg/l]	Peripheral Tailrace Dissolved Oxygen [mg/l]	Distributed Tailrace Dissolved Oxygen [mg/l]
1.0	0.8	3.0	3.5	6.3
1.0	1.0	2.5	3.4	6.1
1.0	1.2	2.5	3.8	6.1

Influences on Performance During Aeration

One cost associated with aeration relates to the impact that the air flows have on draft tube performance. As the draft tube flow characteristics become altered during aeration, turbine efficiency levels generally decline. These aeration impacts are dependent on several parameters, including draft tube design, air flow quantities, bubble size, aeration method, and point of turbine operation. Although efficiency impacts during aeration are difficult to accurately predict, distributed aeration from an aerating runner has shown to provide the smallest influence on draft tube flow characteristics as high fluid shear at the blade discharge edge creates a well distributed cloud of small bubbles downstream of the runner (Foust et al. 2008). These small, well-dispersed bubbles lead to better draft tube performance during aeration. The larger surface areas created by the

smaller bubbles also facilitates efficient transfer of oxygen to the surrounding water.

Throughout the current aeration investigation, it has been documented that the central and peripheral methodologies are not expected to produce dissolved oxygen uptakes under conditions of natural aspiration that match those generated through distributed aeration with an aerating runner. The use of compressors or blowers can however be utilized to improve the dissolved oxygen uptakes associated with these two aeration techniques. To compare the central and peripheral aeration impacts on efficiency with those resulting from distributed aeration, the air flows necessary to reach 6.0 mg/l tailrace dissolved oxygen levels are given in Table 2-15.

Table 2-15

Predicted central and peripheral void fractions required to meet tailrace dissolved oxygen levels of 6.0 mg/l.

H/H_{opt} [-]	Q/Q_{opt} [-]	Central Φ [%]	Peripheral Φ [%]
1.0	0.8	7.8	9.0
1.0	1.0	7.2	6.9
1.0	1.2	6.9	6.1

Efficiency impacts ($\eta_{\text{non aerating}} - \eta_{\text{aerating}}$) associated with the void fractions outlined in Table 2-15 are summarized below in Table 2-16.

Table 2-16

Summary of efficiency losses associated with tailrace dissolved oxygen levels.

H/H_{opt} [-]	Q/Q_{opt} [-]	Central		Peripheral		Distributed	
		Φ [%]	Δη [%]	Φ [%]	Δη [%]	Φ [%]	Δη [%]
1.0	0.8	7.8	>10	9.0	>10	7.5	8.3
1.0	1.0	7.2	>10	6.9	7.4	6.5	3.4
1.0	1.2	6.9	>10	6.1	6.2	6.4	4.6

The losses associated with central aeration are very large due to the disruption of the runner-draft tube interaction caused by the sub-optimal mixing that occurs below the runner. This method will also require a compressor since the natural aspiration will not draw enough air to facilitate comparable dissolved oxygen levels in the tailrace. The power consumed by the compressor will effectively increase the efficiency losses associated with aeration. Note that the compressor

impacts for central and peripheral aeration are not accounted for in Table 5. Peripheral aeration shows better performance than central at higher outputs ($Q/Q_{opt} > 1.0$), with predicted efficiency impacts decreasing below 10%. At these higher turbine outputs, the influence of distributed aeration on turbine performance drops below 5%, while providing enough air flow to meet the most challenging dissolved oxygen uptake goals (> 5 mg/l) without the use of a compressor.

Conclusions

The current paper investigates the aeration needs for a representative hydro plant located in the southern United States according to three different aeration methodologies, including central, peripheral and distributed (aerating runner). Geometry and site condition assumptions were incorporated into a mass transfer model which determines the amount of oxygen that passes between the air-water mixture as it continues through the turbine and into the tailrace during operation. Of the three aeration techniques, distributed aeration is the only method that produces enough dissolved oxygen uptake to meet and exceed typical water quality requirements of 5 mg/l of dissolved oxygen in the tailrace.

In addition to dissolved oxygen predictions, aeration influence on turbine performance was also investigated. The fine bubble cloud and uniform mixing created by the aerating runner is expected to have the smallest influence on turbine performance during aeration.

Throughout the current study, Voith Hydro has demonstrated that runner rehabilitation can also address water quality enhancements. Each of the three aeration techniques discussed is characterized by unique aeration characteristics and these features are utilized to meet site specific water quality requirements. As these aeration technologies develop, their implementation is becoming more diverse. Recently, Voith Hydro designed and installed a peripheral aeration system for a Kaplan turbine discharge ring replacement. Despite the deeper turbine setting necessary to meet Kaplan cavitation requirements (discharge ring bottom located up to 6 ft below tailwater), aeration testing showed that the unit was able to draw enough air to produce 1 to 3 mg/l dissolved oxygen uptakes across the range of flows tested. The achieved uptakes push tailrace dissolved oxygen levels well above water quality requirements at the plant.

References

Foust, J. M., J. Etter, and R.K. Fisher. 2008. Predicting Dissolved Oxygen and Nitrogen Uptake During Turbine Aeration, Hydro Vision 2008 - Copyright HCI Publications, 2008.

Foust, J.M., R. K. Fisher, P. M. Thompson, M. M. Ratliff, and P. A. March. 2009. Integrating Turbine Rehabilitation and Environmental Technologies: Aerating Runners for Water Quality Enhancement at Osage Plant, WaterPower 2009 - Copyright PennWell Publishing, 2009.

McGinnis, D. F. and J. C. Little. 2002. Predicting diffused-bubble oxygen transfer rate using the discrete-bubble model, *Water Research* 36 (18), 4627-4635.

McGinnis, D. F. and R.J. Ruane. 2007. Development of the discrete-bubble model for turbine aeration systems. *Waterpower XV* - Copyright HCI Publications, 2007.

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Turbine lubrication Systems - Small Changes Can Make a Big Difference in Water Quality

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Abstract

When addressing the topic of “Environmental turbines” the first things that come to mind are efficient runners, fish friendly hydraulic profiles, water filled Kaplan runners, dissolved oxygen enhancement, hydrostatic water turbine guide bearings, etc. While these aspects clearly have a major impact on the environmentally friendliness of the turbines, for the owners of hydroelectric facilities, replacing current major equipment, such as runners, by new equipment may causes major downtime, works and costs, which are often difficult to justify from an economical stand point. For this reason, smaller changes at lower costs, which can have a significant impact on the environment, can be envisioned. For example, small changes can be the modernization of the grease distribution system used for lubricating the wicket gate bronze bushings, servomotors and other components of wicket gate mechanism. The lubrication systems themselves are often outdated and usually have several leaks. It can be possible to replace the existing lubrication systems to a system which uses organic grease with improved biodegradable properties. It is also possible to limit and reduce the use of grease by replacing several traditional bronze bearings by self lubricating bearings. Often, only partial disassembly of certain parts inside the turbine pit, without the need for the removal of the generator, allows the replacement of several bushings, such as the ones used for the wicket gate mechanism. It is even possible to replace the wicket gate bushings if the turbine design has them mounted in removable pots. These interventions can be planned well in advance, parts can be pre-sourced and the teams needed to perform the disassembly and reassembly do not require the special expertise required for a full disassembly and reassembly of the turbine and generator unit.

Introduction

Hydro-electric turbines have many moving parts that require lubrication systems to ensure proper working order. Theses lubricated joints operate automatically by pumping grease between moving parts and letting it ooze out. As effective as these application points are at making sure that the moving parts don't jam, they have the unfortunate downside of letting grease seep into unwanted areas of the powerhouse and even in some cases into the waterways. Cleanup of this grease is done regularly, however it can never be completely be eliminated by cleaning.

Figure 2-70
Grease and water accumulation in a head cover

Turbine lubrication systems can have up to 140 application points that can operate up to 4 times a day. These application points apply grease mainly to the following systems:

Figure 2-71

Locations of lubricated bearings, pins and segments. The pins for the servomotor links (1 & 2), the horizontal and vertical pads on which the operating ring slides (3 & 4), the pins for the wicket gate links and levers (5), the upper guide and thrust bearing of the wicket gate (6), the intermediate guide bearing of the wicket gate (7), the lower guide bearing of the wicket gate (8)

Greaseless self lubricating bearings offer the cleanest approach to lubrication; however, less invasive techniques such as biodegradable greases, intelligent grease management systems and a rethink of the distribution circuits, can also improve the environmental impact of such systems.

Biodegradable Grease

By far, the simplest modification available to a hydroelectric powerhouse owner is to use biodegradable grease. These greases are designed to dissolve rapidly in water, and are produced using synthetic oils specifically designed for this cause. Modification basically consists in changing the barrel of grease and adjusting the distribution system to the new specifications. Biodegradable greases are generally more expensive than mineral based greases; they do however result in a far less consequential loss in case of accidental seepage into the waterways. Compared to the complete overhaul of a unit to install self-lubricating bearings, or the overhaul of the grease management system to better distribute and manage the grease; biodegradable grease is a low cost way of improving the environmental footprint of a unit. Tribospec-Biospec GRL is an example of these types of greases. This

grease, which is non toxic, has a biodegradability index superior to 97%. Traditional greases have indices in the 20% to 30% range.

Grease Management and Distribution

Another simple yet effective modification is the review of the grease management and distribution systems.

Grease based lubricating systems use a series of pipes and distributors to automatically distribute grease to multiple application points. The grease management system generally controls consumption by using elapsed time and unit start/stop cycles to determine when to apply grease. Therefore after every “X” amount of time and at every “X” start/stop cycle, grease is applied to the system. Older systems tend to be mechanically timed and therefore can’t detect long periods of inactivity or multiple start/stop cycles within a short time period. In the case of long periods of inactivity grease is continually added to a non functioning machine due to the elapsed time and in the case of multiple start/stop cycles in a short time period, the system can’t detect when the last grease was applied and therefore new grease is added needlessly.

Due to a growing environmental consciousness, distributors have adapted older technologies to better control grease distribution. New technologies and growing knowledge of the grease requirements of hydro turbines have paved the way for newer systems that can better manage grease distribution. Newer grease management systems can now detect and prevent overuse situations. These systems permit the use of conditional criteria for grease application. For example, a rule may require grease application for every start/stop cycle and “at least” every 7 days. Therefore, if a start/stop cycle occurs within the 7 day time period, the elapsed time counter will reset to 7 days. Conditional criteria can also limit the amount of grease applied for a certain time period; in this case the rule could be, “if” grease has been applied in the last X hours, no more grease is required, “unless” X amount of start/stop cycles have occurred.

These are but a few examples of the possibilities offered by newer grease management systems that are capable of understanding conditional rules. These systems are generally compatible with the already installed piping and distribution network and usually only require the replacement of the control portion of the grease management system.

Grease is distributed to the appropriate lubrication points via a network of pipes and distributors which control the amount of grease sent to each application point. Some application points require considerably more grease than others, such as the wicket gate intermediate and lower bearings that are constantly degreased by the water flow.

Units can have anywhere from a single circuit to 3 or even 4 independent grease distribution circuits. Multiple circuits let the powerhouse owner set different grease management patterns for different areas of the unit. Older units may

already have multiple circuits, however the distribution of which application point is in which circuit isn't always optimal from an environmental stand point.

Many units have 2 grease distribution circuits. The first is for application points that are constantly in contact with running water, which is called the external circuit, and the second, called internal circuit, is for application points which are dry. By separating the application points into these categories, it is possible to have the grease management system operate more frequently for the external circuit since its grease is constantly being flushed away. Grease is therefore not wasted on the internal circuit, which can operate much longer with a single application.

Combined with an effective grease management system, multiple grease distribution circuits can provide just the right amount of grease to the right systems at the right time. The relocation of a single distribution point (upper wicket gate bearing) from the external circuit to the internal circuit has in some cases provided a 75 % reduction of grease accumulation in the units' headcover.

Modern grease management systems combined with multiple distribution circuits and biodegradable greases can greatly improve the environmental footprint of a unit without the time and cost constraints of a major refurbishment or even of a complete disassembly of the unit.

Replacement of Grease Lubrication by Self Lubrication

The previous sections of this article presented the improvements that are possible to the grease systems if and when they are kept in place. The following sections outline possible interventions on the turbines which partially or completely eliminate grease based lubrication systems.

When a major unit overhaul is already planned, it is a good opportunity to replace the grease based system by a self lubricated one since it has little impact on cost and schedule. A major overhaul of the turbine, complete with the disassembly of the rotating parts is however, not accessible to all Powerhouse owners and operators. Major unit refurbishment is difficult to justify based solely on the desire of replacing the lubrication system, due to the high cost of the work and the production losses caused by a prolonged shutdown of one or more units. The following alternatives can therefore be used to partially eliminate the turbine lubrication system and reduce the use of grease and oil that can be harmful for environment.

*Figure 2-72
Wicket gate mechanism with its lubrication system in operation*

The lubrication circuit which provides grease to the wicket gate mechanism is where the intervention is generally easiest to achieve.

Wicket gate and servomotor links are generally easily accessible. These parts can be disassembled in the turbine pit, removed through pit access and sent for refurbishment, cleaning, inspection, machining, painting and the installation of new greaseless self lubricating bearings. The dismantling of the wicket gate levers within the turbine pit is more complex, but still technically feasible with the appropriate tools. In some designs, the wicket gate bearing bushings are mounted in a cylinder which is bolted on to the headcover for the upper and intermediate bearings and on the bottom ring for the lower bearing. These tubes are made of steel pipe or cast iron. Intermediate and upper bushings become accessible from the turbine pit once these cylinders are removed from the headcover. Without this configuration, the only way to access the wicket gate bearings is with a complete unit disassembly.

The replacement of the operating rings wear and sliding pads requires lifting the ring until the pads are accessible. In some cases this is hindered by the configuration of the major components in the turbine pit, rendering the operation impossible without disassembly of the unit. However, when the lifting is possible, replacing the pads is a relatively simple task.

Self lubricating bearings started being installed in hydro-electric units in the mid 1980's. However, widespread acceptance of their ability to replace greased

bearings wasn't until mid 1990's. Many companies now produce a wide range of bearings.

Figure 2-73
Example of self lubricating bearings (Orkot TXMM)

The thickness of the self lubricating bearings is generally similar to the thickness of the bronze bearings they replace and the specific load capacity of the self lubricating bearings is generally equal to or greater than that of bronze bearings. In addition to reducing the amount of grease used, self-lubricating bearings generally reduce the friction forces acting on the wicket gate mechanism and therefore have a beneficial effect on the amount of oil pressure required from the servomotors and the pumping units.

Before replacing greased bearings by self lubricating ones, it is important to ensure that the mating surface, on which the bearing will slide, is made of stainless steel and has the recommended surface finish. In all cases, before undertaking such work, a feasibility study is required to ensure that the replacement is possible.

Execution of Work

The replacement or adaptation work can be performed by turbine manufacturers, by general contractors or by the power plant maintenance teams. Turbine manufacturers tend to have their own engineering teams; however general contractors and power plant operators generally use internal project engineering teams or external consulting engineer firms. Six months of engineering effort is required and ten to twelve weeks are generally required to complete the work on site. This schedule can be optimized by purchasing new parts before beginning the work. The new parts are installed in the first unit and the dismantled parts can be refurbished for the next unit.

It is also important to ensure that all special devices required for the handling of the servomotors and guide bearings are available and in proper working order. If these devices are absent or defective, the schedule and budget must allow for new ones to be design and purchased.

Typical steps to carrying out such work are:

- review and modify the grease management system;
- remove/replace/reconfigure the distribution circuits of the turbine and turbine inlet valve (if applicable);
- dismantle the pipes and fittings for now unused application points, and plug all the holes;
- remove the turbine pit components which would hinder the lifting of the operating ring or the removal of other parts;
- remove the entire operating mechanism, including the connecting rods of the servomotors;
- clean the headcover in order to remove accumulated grease and water;
- replace the carbon steel pins with new stainless steel pins;
- replacing the bronze bushings with self lubricating bearings
- replace the bronze wear pads with stainless steel plates or pads often screwed into the same holes than the bronze pads;
- install low friction pads on the operating ring. The choice of self lubricating pads is often limited due to the available working clearance at this location;
- replace all accessories;
- adjust the closing and the pre-stress of the wicket gates;
- commission the unit.

Figure 2-74

Self lubricating wicket gate mechanism after 2 years of operation

- Other opportunities for improvement of the environmental footprint of a unit
- Other parts or components where self-lubricating bearings can be installed:

- the spiral case door hinges;
- the draft tube door hinges;
- the servomotors and main bearings of the spherical or butterfly turbine inlet valve.

A green technology offered by some turbine manufacturers is a water based (hydrostatic) turbine guide bearing (1). Several replacements of traditional oil based turbine guide bearings by hydrostatic ones have been done in recent years. The pressurized water from the penstock is used to maintain the water film required for the lubrication and cooling of the bearing. This kind of bearing also has the advantage of eliminating the requirement for a shaft seal and can therefore be installed closer to the runner, offering an easier maintenance and better performance of the turbine.

Another technology developed and implemented in the last 5 to 10 years replaces the oil in the Kaplan runners with water (2). Self lubricated bearings are then installed to support the blades of the runner. This greatly reduces the oil volumes and therefore the risk of leakage into the river.

New units are generally designed to operate with self lubricated bearings, unless the customer specifically requires the installation of a grease based systems.

Other possible sources of water contamination in units on which interventions can be made include:

- oil leaks from the hydraulic cylinders;
- oil leaks from guide bearings;
- oil leaks from the generator breaks;
- oil leaks from all the oil pipes. (These can easily be handled by replacing ANSI flanges by SAE o-ring flanges.)

These interventions can greatly reduce the accumulation of hydrocarbon fluid in the turbine pits and therefore reduce or eliminate leakage into the environment as well as all the costs associated with treatment and safe disposal of oily water.

References

Gilson, P., Roy, S., Doyon, J. and Godec, E. 2009. Hydrostatic Water Guide Bearings “Making Environmental Technology Profitable!”. Waterpower XVI, 2009

Falkenheim, R., Nakawaga, N. and Havard, D. 2011 Technologies for Eliminating Oil in Kaplan Turbines. Hydro world, Volume 18, Issue 6, 2011

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Development of External and Neutrally Buoyant Acoustic Transmitters for Turbine Passage Evaluation

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Abstract

Recent studies show transmitters surgically implanted into juvenile salmonids, for the purposes of estimating survival of fish passing through turbines, increases the risk of injury and mortality due to the presence of the tag and exposure to rapid turbine pressure changes. Neutrally buoyant external tags may instead be used to eliminate this bias. However, the externally tagged fish could be affected by other factors such as shear and turbulence which may also bias survival estimates. Studies have been conducted to examine the influence of shear and turbulence on non-tagged juvenile salmonids, however, tests have never been conducted in the laboratory or field to determine the influence of shear and turbulence on retention and injury related to attachment of external transmitters. We designed and manufactured two different configurations of neutrally buoyant (nearly zero g weight in water) external transmitters, termed Type A and Type B, respectively. The Type A transmitters weigh approximately 0.60 g in air and are attached to fish using two sutures anterior to the dorsal fin. The Type B transmitters weigh approximately 0.83 g in air and consist of battery part and transducer part with both parts neutrally buoyant. They are attached to both sides of the dorsal fin using two enamel coated 25 gauge magnet wires. This study provides a broad approach using evaluation measures such as holding, swimming performance, shear, turbulence, rapid decompression exposures, and predation to determine the efficacy of using neutrally buoyant external transmitters to estimate survival of juvenile salmonids passing through turbines. Preliminary results show the Type A design is a viable design for turbine passage evaluation and is being planned for field deployment in the near future.

Introduction

The Juvenile Salmon Acoustic Telemetry System (JSATS) is a nonproprietary technology developed by the U. S. Army Corps of Engineers (USACE), Portland District, for evaluating behavior and survival of juvenile salmonids migrating through the Columbia River Federal Power System (McMichael et al. 2010, 2011). The JSATS consists of acoustic microtransmitters; autonomous, cabled, or portable receivers with hydrophones; and data management and processing applications. Each microtransmitter, surgically implanted in study fish, transmits a unique 31-bit binary code encoded using Binary Phase Shift Keying at 416.7 kHz. Self-contained autonomous receivers that detect, decode, and store decoded messages are typically deployed in areas within the Columbia

River basin where a power source is not readily available and cable runs are not feasible. Cabled systems are deployed at hydroelectric facilities and are used to determine passage route and near-dam behavior for tagged fish (Weiland et al. in review). Each cabled system is synchronized to a universal GPS clock and the acquired waveforms are saved to the computer before being decoded. Valid detections are separated from spurious detections using a filtering process requiring a minimum of six messages with a pulse repetition interval matching that expected from a properly functioning tag within a fixed period. Time of arrival information for valid detections on four hydrophones is used to solve for the 3D position of tagged fish (Deng et al. in review).

Several approaches have been taken to determine if tagging juvenile salmonids or carrying a transmitter causes a negative influence. Research typically includes an examination of swimming behavior (for examples see Brown et al. 1999, Anglea et al. 2004, or Brown et al. 2006), response to predation (Anglea et al. 2004), tag expulsion, growth and mortality (for examples see Anglea et al. 2004, Brown et al. 2006, and Brown et al. 2010). However, only recently has the aspect of a tagging bias during turbine passage been considered. For example, Carlson et al. (2010) demonstrated that the presence of a telemetry tag inside the body of a juvenile salmon increased the likelihood of these injuries occurring. The increased excess mass (weight in water) of the tag requires fish to uptake more molecules of gas in their swim bladder to maintain neutral buoyancy, resulting in increased trauma during rapid decompression. The presence of the transmitter in the coelom during rapid decompression could also increase the likelihood of compression-related injuries. Carlson et al. (2010) outlined the need for improvements in telemetry technology that would minimize bias for fish carrying a tag, improving the accuracy of telemetry studies. Use of an external transmitter to eliminate the bias due to barotrauma when carrying an internal transmitter may lead to other forces influencing the tagged fish. Having a transmitter attached externally may lead to issues with shear and turbulence. Several studies have been conducted examining the influence of shear and turbulence effects on juvenile salmon (See examples by Johnson et al. 2003, Neitzel et al. 2004, Deng et al. 2005, 2010). However, tests have never been conducted in the laboratory or field to determine the influence of shear and turbulence on retention and injury related to carrying external transmitters. This study provides a broad approach using swimming performance, shear, turbulence and rapid decompression exposures, and predation to determine the efficacy of using neutrally buoyant external transmitters for estimating survival of juvenile salmonids through turbines

Methods

Study fish

Juvenile fall Chinook salmon were originally obtained as eyed eggs from the Washington Department of Fish and Wildlife Priest Rapids Hatchery in December 2009. Fish were reared at the Aquatic Research Laboratory (ARL) at the Pacific Northwest National Laboratory in Richland, Washington. During the study period, the test population was held inside the ARL in a 650-L circular

tank. The holding tank was supplied with 16.8–17.8°C well water. Fish within the rearing and test population were fed Bio Vita Starter (Bio-Oregon, Longview, Washington) ad libitum. Test fish (subyearling Chinook salmon) had a mean fork length ($\pm$ SD) of 122 mm $\pm$ 7 (range 95–139 mm) and mean weight ($\pm$ SD) of 20.0 g $\pm$ 4.0 (range 8.4–29.9 g).

Tag designs and attachment

The Type A tag is designed to be attached anterior to the dorsal fin using two sutures (Figure 2-75, top). Each suture rests in a notch that is 0.9 mm deep and 1.3 mm wide. The portion of the tag that contacts the juvenile salmonid's back has an interior angle of 90 degrees with a 2.1-mm-radius fillet. The maximum width of the tag is 9.3 mm, the maximum length is 18.5 mm, and the volume is 0.60 cm³. The Type B tag is a two-part design; each half of the transmitter is attached beneath the dorsal fin (Figure 2-75, bottom). One part of the tag contains a Size 337 silver oxide button cell battery with two electrical leads consisting of 25-gauge enamel-coated magnet wire protruding from the flat side (toward the fish). The other part of the tag contains electronics needed to drive the piezoelectric transducer. The volume of the half containing the battery is 0.41 cm³, and the half with the transducer is 0.43 cm³.

Type A tags were externally attached anterior to the dorsal fin with two sutures (Figure 2-76), each secured by a $2 \times 2 \times 2 \times 2$ knot as described by Deters et al. (in press). Type B tags (Figure 2-77) were attached using two 25-7/8-gauge needles (Becton, Dickinson and Company, Franklin Lakes, NJ) mounted on 3-mL syringes (Becton, Dickinson Medical). The needles were used to pass the 25-gauge enamel coated magnet wires (attached to the battery side) through the dorsal musculature. On the opposite side, the needles were removed, and the wires were threaded through the transducer side and the excess wire trimmed. Internally implanted fish were surgically implanted with a JSATS acoustic transmitter (with an expired battery) and a passive integrated transponder (PIT) tag (Destron Technologies, St. Paul, MN). The PIT tags were 12.5 mm (length) by 2.1 mm (width) and weighed 0.10 g in air (0.06 g in water, 0.04 cm³ volume). Acoustic transmitters were 12.0 $\times$ 5.2 $\times$ 3.8 mm; they weighed 0.43 g in air (0.30 g in water; 0.14 cm³ volume). Tags (acoustic and PIT) were surgically implanted using methods similar to Panther et al. (in press).

Figure 2-75
 Prototype external transmitters. Top: Type A tag; Bottom: Type B tag.

Figure 2-76
 Type A tag attached to a fish.

Figure 2-77 Type B tag attached to a fish.

Evaluation criteria

To determine the efficacy of these tags under non-turbine passage related conditions, fish had one of the tags attached and were held for 14 days to determine any effects that the presence of the tag may have on growth, survival and tissue damage. We also evaluated the attachment method by monitoring tag retention. These two neutrally buoyant tag designs were compared to nontagged individuals and those surgically implanted with current JSATS transmitters and passive integrated responder (PIT) tags. In addition, two suture materials (Monocryl and Vicryl Rapide) were tested for attachment of Type A tags.

The efficacy of Type A and Type B tag designs was compared to nontagged individuals under shear exposure calculated using methods outlined in Deng et al. (2005, 2010). Fish were exposed to one of three nozzle velocities (3.0 m/s, 9.1 m/s and 12.2 m/s) in a fiberglass flume to simulate turbine conditions within the Columbia River basin. Immediate mortality rates, tag retention, and the occurrence of shear injuries all were observed for test fish. Fish were then held for 4 days post-exposure to monitor delayed mortality and tissue damage associated with the shear exposure.

The evaluation of the effects on swimming performance and predator avoidance due to the presence of a neutrally buoyant externally attached transmitter were also evaluated. The critical swimming speed (U_{crit}) for juvenile Chinook salmon tagged with two different neutrally buoyant external transmitters was measured and compared to nontagged individuals and those surgically implanted with the current JSATS acoustic transmitter. Further testing was then conducted to determine if predator avoidance ability was affected due to the presence of Type A tags when compared to nontagged fish. Tagged and nontagged individuals were simultaneously released into a tank containing predatory rainbow trout. The tank was monitored until 50% of the prey had been consumed; all prey then were removed and the ratio of tagged to nontagged was assessed.

Based on the results of other evaluation factors, it was determined that Type A tag design should be the focus of further studies. Therefore, fish tagged with

Type A design and nontagged fish acclimated to a pressure of 21.2 psia 15-ft water depth equivalent) were exposed to a nadir pressure of 1.6 to 11.6 psia in the Mobile Aquatic Barotrauma Laboratory hypo/hyperbaric chambers (Stephenson et al. 2010). Rates of mortal injury were then assessed for all individuals.

Results and Discussion

No mortality occurred in any of the tagged fish over the 14-d holding period. Overall, the attachment and bearing of Type A transmitters led to a less negative influence on growth and tissue response than Type B transmitters. It did not appear that either Type A transmitters attached using Monocryl sutures or surgically implanted internal transmitters negatively influenced fish growth over the 14-d holding period. Tag retention was high (no transmitter loss until Day 13) over the 14-d holding period but did vary by tag type and tagging technique. Tags were designed for use on short-term studies (3 d to 1 week) of survival of fish through hydroelectric turbines. There were no losses of Type B transmitters or internally implanted transmitters during the 14-d holding period. Vicryl Rapide sutures are designed to dissolve faster in humans than other types of sutures (Deters et al. 2010). However, there was no difference in tag loss over the 14-d period between the tags attached with either Monocryl or Vicryl Rapide sutures. Although retention of Type B transmitters was slightly higher than that of Type A transmitters, their use resulted in lower growth and more negative tissue response.

A total of 151 fish were exposed to shear forces at three nozzle velocities: 3.0 m/s, 9.1 m/s, and 12.2 m/s. Overall, no mortalities were observed throughout the study. Of the 151 test fish, 6.0% (n = 9) had injuries that were observed immediately after shear exposure, all of which were classified as minor. Fish externally implanted with Type A tags sustained slightly lower injuries than fish externally implanted with Type B tags. In addition Tissue damage rates observed at necropsy were higher for fish tagged with Type B tags when compared to those tagged with Type A tags (Table 2-17). However, there was no significant difference in shear injury rates between externally implanted and untagged fish.

Table 2-17

Analysis of variance comparing tail velocity and tag type for tissue damage occurrence within nozzle velocity groups.

Groups	Source	df	Sum square	Mean square	F	Pr(>F)
3.0 m/s	Tag Type	1	11.571	11.571	59.961	<0.0001
	Residuals	19	3.667	0.193		
9.1 m/s	Tag Type	1	0.744	0.744	4.54	0.0396
	Residuals	38	6.231	0.164		
12.2 m/s	Tag Type	1	7.225	7.225	15.644	0.0003
	Residuals	38	17.55	0.462		

Fish tagged with the Type A and B designs had lower swimming performance when compared to nontagged individuals. However, there was no difference in swimming performance among fish tagged with Type A or B designs or those with surgically implanted tags (Figure 2-78). In addition, there was no significant difference in the number of tagged and nontagged fish consumed throughout the predation trials. These results supported the efficacy of the neutrally buoyant externally attached Type A tag design.

Figure 2-78

Box plots of critical swimming speed $FL\ s^{-1}$ for each treatment. The top and bottom edges of the boxes indicate the 25th and 75th percentile of data.

The rates of mortal injury were not significantly different ($P = 0.3804$) for tagged and nontagged juvenile Chinook salmon, indicating that juvenile Chinook salmon tagged with Type A tags are not at a greater risk for mortal injury than nontagged fish (Table 2-18). This contrasts with previous research that has shown the negatively buoyant surgically implanted tags or injected PIT tags increase the rates of mortal injury for juvenile Chinook salmon experiencing rapid decompression. Our results further support the efficacy of this novel tag design for use in turbine passage survival studies in the Columbia River basin.

Table 2-18

Analysis of deviance of the factors associated with the mortal injury of juvenile Chinook salmon with respect to simulated turbine passage.

Source	df	Deviance	Mean deviance	F	P
NULL	61	115.36			
Nadir	1	47.988	47.988	42.581	<0.0001
Tag type	1	0.88	0.88	0.781	0.3804
Error	59	66.492	1.127		

Future Plans and Recommendations

Our team of design engineers and fisheries biologists has designed, manufactured, and tested the efficacy of a neutrally buoyant externally attached tag that may be an effective design for future turbine passage survival studies throughout the Columbia River basin. Based on the results in this study, our conclusions and recommendations for future research are as follows:

Future research should be conducted to test the efficacy of this tag design in field conditions. Despite the positive results seen in these laboratory tests, field conditions present a range of conditions and exposure to stressors simultaneously, all of which influence the efficacy of the tag design. Comparison of current tagging strategies (surgical implantation) to our proposed method is therefore warranted.

In comparison to current tagging methods (surgical implantation of negatively buoyant transmitters), our novel tag design has eliminated the excess mass of the transmitter and the volume of the body cavity occupied by the tag. This neutrally buoyant externally attached tag did not result in increased rates of mortal injury associated with rapid decompression, as was seen for the current JSATS tag design and PIT tags. The next evolution of tag design should include investigation into the mechanisms behind this lack of bias.

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References

- Anglea SM, DR Geist, RS Brown, KA Deters, and RD McDonald. 2004. Effects of acoustic transmitters on swimming performance and predator avoidance of juvenile Chinook salmon. *North American Journal of Fisheries Management* 24:162–170.
- Brown RS, DR Geist, KA Deters, and A Grassell. 2006. Effects of surgically implanted acoustic transmitters >2% of body mass on the swimming performance, survival and growth of juvenile sockeye and Chinook salmon. *Journal of Fish Biology* 69:1626–1638.
- Brown RS, SJ Cooke, WG Anderson, and RS McKinley. 1999. Evidence to challenge the “2% rule” for biotelemetry. *North American Journal of Fisheries Management* 19:867–871.
- Brown RS, RA Harnish, KM Carter, JW Boyd, and KA Deters. 2010. An evaluation of the maximum tag burden for implantation of acoustic transmitters in juvenile Chinook salmon. *North American Journal of Fisheries Management* 30:499–505.
- Carlson TJ, RS Brown, JR Stephenson, BD Pflugrath, AH Colotelo, AJ Gingerich, PL Benjamin, JR Skalski, AG Seaburg, and RL Townsend. 2010. Assessment of factors influencing mortal injury of tagged juvenile Chinook salmon exposed to rapid decompression. Chapter 3 in *Assessment of Barotrauma in Untagged and Tagged Juvenile Chinook Salmon Exposed to Simulated Hydro Turbine Passage*, TJ Carlson, RS Brown, JR Stephenson, AJ Gingerich, BD Pflugrath, AH Colotelo, AE Welch, PL Benjamin, JR Skalski, AG Seaburg, and RL Townsend. PNNL-19625, Pacific Northwest National Laboratory, Richland, Washington.
- Deng Z, GR Guensch, CA McKinstry, RP Mueller, DD Dauble, and MC Richmond. 2005. Evaluation of fish-injury mechanisms during exposure to turbulent shear flow. *Canadian Journal of Fisheries and Aquatic Sciences* 62:1513–1522.
- Deng Z, RP Mueller, MC Richmond, and GE Johnson. 2010. Injury and mortality of juvenile salmon entrained in a submerged jet entering still water. *North American Journal of Fisheries Management* 30(3):623–628.
- Deng Z, MA Weiland, T Fu, TA Seim, BL LaMarche, EY Choi, TJ Carlson and MB Eppard. In review. A Cabled Acoustic Telemetry System for Detecting and Tracking Juvenile Salmon: Part 2. Three-Dimensional Tracking. Sensors.
- Deters KA, RS Brown, KM Carter, JW Boyd, MB Eppard, and AG Seaburg. 2010. Performance assessment of suture type, water temperature, and surgeon skill in juvenile Chinook salmon surgically implanted with acoustic transmitters. *Transactions of the American Fisheries Society* 139:888–899.

Deters KA, RS Brown, JW Boyd, and AG Seaburg. In Press. Optimal suturing technique and number of sutures for surgical implantation of acoustic transmitters in juvenile salmonids. Transaction of the American Fisheries Society 00:000–000.

McMichael, GA, RA Harnish, MA Weiland, Z Deng, and MB Eppard. 2011. Fish Passage: A new tool to investigate fish movement: JSATS. Hydro Review 30 (3):34–42.

Johnson, GE, BD Ebberts, DD Dauble, AE Giorgi, PG Heisey, RP Mueller, and DA Neitzel. 2003 . Effects of jet entry at high-flow outfalls on juvenile Pacific salmon. North American Journal of Fisheries Management 23:441–449.

McMichael GA, MB Eppard, TJ Carlson, JA Carter, BD Ebberts, RS Brown, M Weiland, GR Ploskey, RA Harnish, and ZD Deng. 2010. The Juvenile Salmon Acoustic Telemetry System: A new tool. Fisheries 35(1):9–22.

Neitzel, DA, DD. Dauble, GF. Cada, MC. Richmond, GR. Guensch, RP Mueller, CS Abernethy, and BG Amidan. 2004. Survival estimates for juvenile fish subjected to a laboratory-generated shear environment. Transactions of the American Fisheries Society 133:447–454.

Panther JP, RS Brown, GL Gaulke, CM Woodley, and KA Deters. In Press. Influence of Incision Location on Transmitter Loss, Healing, Incision Lengths, Suture Retention, and Growth of Juvenile Chinook Salmon. Transaction of the American Fisheries Society. 00:000–000.

Stephenson JR, AJ Gingerich, RS Brown, BD Pflugrath, Z Deng, TJ Carlson, MJ Langeslay, ML Ahmann, and RL Johnson. 2010. Assessing decompression in fishes using a mobile aquatic barotrauma laboratory: Case study examining the incidence of barotrauma in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage. Fisheries Research. 106:271–278.

Weiland, MA, Z Deng, TA Seim, BL LaMarche, EY Choi, T Fu, TJ Carlson, AI Thronas, and MB Eppard. In review. A Cabled Acoustic Telemetry System for Detecting and Tracking Juvenile Salmon: Part 1. Engine.

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Assessing Fish Condition after Passage through Fish-Friendly Turbines Using a Release-Recapture Method

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The ability to examine fish after turbine passage provides valuable information on how fish friendly turbine designs, passage locations, and operating conditions are on captured fish. Prior to the development of the HI-Z Tag, fish recapture technique netting the turbine discharge was the primary method to assess the post passage condition of turbine passed fish. However, net deployment is often feasible only at low discharge units and has the following significant shortcomings: captured non turbine passed fish; selective capture of turbine passed fish (i.e. injured fish captured at higher rate); and net induced injuries. The principal objective of this presentation is to show how the HI-Z Tag recapture technique has been used to assess the direct effects (mortality and injury) of conventional and environmentally advanced turbines on entrained fish during the last 20 years. Assessing the rate, type, severity, and cause of injuries and mortality rates has proven to be beneficial in developing fish friendlier units.

The ability to examine turbine passed fish within minutes of turbine passage has assisted the development of fish friendly turbine designs and operating conditions in the following ways: the closing of gaps at the turbine hub and blade tip; reduction in the number of blades, rounder and thicker leading blade edge, larger and slower rotating units, and operating beyond peak efficiency. Concurrent tests at conventional and advanced turbines have proven to be the best protocol for assessing fish friendly features. Some recent tests indicate that shape and thickness of the blade leading edge may have a considerable effect on the severity of injuries to fish that contact a blade during passage; however more field tests are needed.

Introduction

There are two primary components of total mortality of fish entrained in hydro turbines: direct and indirect effects. The direct effects (e.g., mechanically-induced, pressure, cavitation, or shear related) are manifested immediately after turbine passage as instantaneous fish mortality, injury, and loss of equilibrium; the indirect effects (e.g., predation, disease, physiological stress, etc.) may occur over an extended period or distance downstream after passage. Tailrace netting and the HI-Z Turb'N Tag (Heisey *et al.* 1992) are the two principal methods that have been utilized to assess direct effects of turbine passage. Utilizing the HI-Z Tag capture method, studies can be conducted to determine causes of fish injury or mortality by direct capture. This method insures that the retrieved fish are indeed the test fish and not non-turbine passed fish.

The HI-Z Tag recapture technique has been used to assess different turbine types, spillways, sluiceways, fish bypass structures, and the characteristics and operations of these structures on the condition of passed fish (Heisey *et al.* 1992,

2008 a, b; Johnson *et al.* 2003; Mathur *et al.* 1994, 1996, 1999, 2000). The ability to examine the fish shortly after passing these structures provides information on the cause, rate, type and the severity of injuries. The HI-Z tagged fish are not acclimated to different depths prior to passage thus primarily injuries associated with mechanical and shear forces are assessed. Examinations of injury data from multiple sites have been beneficial in ascertaining what passage conditions are beneficial to passed fish. The emphasis of this paper is on how the condition of recaptured turbine passed fish at both conventional and recently installed fish friendly units can assist in further developing fish friendlier turbines. We provide four specific examples where different turbine designs were tested for fish survival and injury mechanisms.

HI-Z Tag Recapture Methodology

A brief description of the HI-Z tag application follows: uninflated balloons tags are attached with a small cable tie through the musculature along the fish's back via a curved cannula needle or a modified ear piercing gun. Typically, two HI-Z balloon tags are attached to fish less than 9.8 in or 250 mm and three to six tags on larger fish (approximately 11.8 in or 300 mm to 39.4 in or 1000 mm). A radio tag is usually attached in combination with one of the HI-Z tags to aid in tracking released test fish. Just prior to release, the HI-Z tags are activated by injecting a small amount of water into the HI-Z tag, which causes the tag to inflate in approximately 2 to 4 minutes. Once the HI-Z tags are activated, test fish are released via an induction system which directs the fish to the desired release point.

Released fish are tracked and retrieved when buoyed to the surface downstream of the passage route by recapture boats crews. Recaptured fish are immediately examined for mortality (1 h), visible injuries and loss of equilibrium. Recaptured fish are then transported to holding pools to monitor delayed (48 h) effects of tagging and turbine passage. Injuries are categorized by type, severity, area of body, and probably cause. Photographs are taken of injured fish.

Factors Affecting Fish Condition

Many physical and operational features of turbines have been shown to affect the condition of passed fish. The principal features associated with fish injuries include; number of blades, shape and blade thickness, particularly the leading edge; gaps between turbine blade and hub and blade tip and discharge ring; revolution rate of blades (rpm), size of turbine, runner diameter, operating efficiency, number of stay veins and wicket gates and gaps along upper and lower edges of wicket gates. In one of the earlier studies conducted at a large Kaplan turbine, the importance of gaps near the hub was identified (Normandeau and Skalski 1996). A conventional six blade Kaplan turbine was replaced with a newer turbine that was similar except the gap near the leading edge of the blade was minimized by providing a recessed pocket in the hub to allow the blade to move; however the gap between the trailing edge of the blade and the hub was not minimized. Injury rate was 5% for juvenile Chinook salmon (average length 7.2 in or 184 mm) that were directed towards the hub. When the gap near the

trailing edge of the blade was minimized with a steel wedge welded onto the hub, the juvenile salmon injury rate decreased to 2.8% (Figure 2-79). The results of this study indicated the benefits of minimizing gap to decrease fish injuries.

Figure 2-79
Temporary gap closure at trailing edge of blade at the hub/blade interface.
(Source: Normandeau Associates Inc. and Skalski 1996)

Results

The following four studies are presented to demonstrate the effects of different turbine features and the incorporation of fish friendlier features on the condition of passed fish.

Bonneville

An extensive direct survival/injury study was conducted at the Bonneville Dam Fish Powerhouse on the Lower Columbia River to compare performance of a conventional and minimum gap runner (Normandeau *et al.* 2000). More than 7,000 juvenile Chinook salmon (average length 6.5 in or 166 mm) were released through a conventional Kaplan unit and a new minimum gap runner (MGR) at four power levels. The MGR was designed to minimize gaps between the blade and hub as well as between the blade tip and the discharge ring. Both turbines types had a runner diameter of 23.3 ft or 7.1 m, rotational speed of 75 rpm and 5 runner blades. The fish were directed towards the hub, mid blade, and tip by release pipes mounted on the stay vanes (Figure 2-80).

Figure 2-80
Fish release pipe deployment to direct fish towards the hub, mid blade, and blade tip of a turbine. (Source: Supplied by Voith Siemens in Normandeau Associates Inc. et. al. 2000)

Fish that passed near the blade tip of the MGR unit had higher survival and lower injury rates than those passing the conventional unit. Depending on the power level, absolute survival of blade tip released fish was up to 3% higher for the MGR unit than the conventional unit; injury rate was 1.9% for the MGR versus 3.9% for the existing unit. However, the benefits of closing the gaps near the hub for the MGR were not obvious from the study. Survival rates were higher and injury rates were low for fish that were directed towards the hub for both units, and these rates were similar for both units. The overall survival for fish passing towards the hub was 99.4% for the existing unit and 98.0% for the MGR; injury rate was 0.7% for the existing unit and 1.0% for the MGR.

The benefit of closing the gaps between the blade and the hub for the MGR unit was not evident from the tests; however, subsequent examination of the release pipe deployment indicated that most of the fish may have actually passed some distance away from the hub and did not encounter the gaps. Because the termini of the release pipes were mounted on the stay veins in close proximity to the turbine blades, the fish had little chance to disperse prior to interacting with the rotating blades and their trajectory likely transported most of them beyond the hub gaps.

Overall, this study revealed that passage towards the hub area just beyond the hub/blade interface was quite benign for juvenile Chinook salmon at both a conventional and MGR unit and the hydraulic characteristics and turbine features encountered by these fish should be evaluated for future turbine designs. Additionally, if direct injury/survival data are desired from a specific region of a turbine blade to assess modifications Computational Fluid Dynamics (CFD) modeling should be considered to aid in the fish release pipe location.

Wanapum

Another extensive direct survival/injury study was conducted at Wanapum Dam (Dresser *et al.* 2006 and Normandeau *et al.* 2006). Again, more than 7,000 juvenile Chinook salmon (average length 6.7 in or 169 mm) were released through a conventional Kaplan turbine and a new Advanced Hydro Turbine System (AHTS) at four generation levels as part of U.S. Department of Energy Program. The AHTS was designed to minimize gaps between the blade and hub and the tip of blade and discharge ring. Additionally, the geometries of the blades, stay vanes, wicket gates and draft tube of the AHTS unit were modified to make them fish friendlier. Both units rotated at 85.7 rpm, and operated near a 77 ft or 23.5 m head. The runner diameter was 23.6 ft or 7.2 m and 25.3 ft or 7.7 m for the conventional and AHTS units, respectively. The AHTS unit had one more blade (6) than the conventional unit (5).

The juvenile salmon were released from pipes positioned in a head gate slot so they were introduced approximately 10 ft or 3.0 m and 30 ft or 9.1 m below the ceiling of the intake. However, after the study was completed CFD modeling results indicated fish released at 10 ft or 3.0 m may not have been exposed the hub gaps and may have actually passed about 15% of the blade distance from the hub (Figure 2-81 and Figure 2-82) while the fish released at the 30 ft or 9.1 m depth may have passed near mid blade. However, since the fish were released a considerable distance (approximately 70 ft or 21.3 m) upstream of the turbine blades and into an area of relatively low water velocity (<10 ft or 3.0 m/sec) a portion of the shallower released fish could have passed near the hub while some of the deeper passed fish could have passed near the blade tips.

Figure 2-81
Projected flow path past the turbine blade for fish released 10 ft. below intake ceiling. (Source: Supplied by Voith Siemens in Normandeau Associates et. al. 2006)

*Figure 2-82
Projected flow path past the turbine blade for fish released 30 ft below intake ceiling. (Source: Supplied by Voith Siemens in Normandeau Associates et. al. 2006)*

The survival estimates (48 h) for the conventional and AHTS fish released 10 ft or 3 m below the intake ceiling were 97.9 and 98.5% respectively. The respective survival estimates for the fish released at the 30 ft or 9.1 m depth were 97.1 and 95.4%. Although not significantly different, the survival estimates trended higher for the shallow and lower for the deeper released fish at the AHTS unit. This trend was also present for the injury estimates with an injury rates 0.8% at the AHTS Unit versus 1.8% for the conventional for the shallow released fish. The corresponding rates for the deeper released fish were 3.3 and 2.5% for the AHTS and conventional units, respectively.

Although the exact path the fish took through the two turbines types are unknown, the results of this study indicated that the juvenile salmon did fare better when they entered near the ceiling of the intake and likely passed close to the hub and the AHTS Unit provided better conditions near the hub than the conventional unit. However, fish that entered 30 ft below the intake ceiling had lower survival and higher injury rates at both units with slightly worse values for the AHTS unit. The inclusion of a sixth blade in the AHTS unit may have

contributed for the slightly lower survival and higher injury values for the deeper passed fish even though other turbine features were modified to make the unit fish friendlier.

Kelsey Station

The effect of blade number and design was assessed for large fish passed through two turbines at Manitoba Hydro's Kelsey Generation Station (North/South Consultants Inc. and Normandeau Associates, Inc. 2007, 2009). The two units were essentially the same except the unit tested in 2008 was new; had one less blade and both units were fixed propeller. Turbines operating head was approximately 56 ft or 17 m, runner diameter of 26 ft or 7.9 m, and rotation rate of 125 rpm. The older unit had 6 blades and the new unit had 5 blades and leading edge of the blades was narrower (Figure 2-83).

Figure 2-83

Shape and leading edge thickness of blades from two different turbines tested at the Kelsey Generating Station. (Source: Study photographs courtesy of Normandeau Associates)

A total of 190 adult walleye (average length approximately 17.7 in or 450 mm) and 183 adult northern pike (average length 24 in or 600 mm) were introduced at the three locations into the intake at both units. The fish were released through hoses positioned in a head gate slot with the ends of the hose 4.9 ft or 1.5 m, 16.4 ft or 5.0 m and 28.8 ft or 8.8 m below the intake ceiling.

The survival estimates (48 h) for both the walleye and northern pike increased with a decrease in the number of turbine blades. Walleye survival for the 6 bladed and 5 bladed units was 80.4 and 87.8 %, respectively. The corresponding survival rates for the northern pike were 65.8 and 75.5%. Although the survival rates improved the incidence of fish with injuries did not. Injury rates of the

walleye were similar for the two units (32.6 and 31.8% for 6 and 5 blades, respectively) but injury rates of northern pike increased for the 5 bladed unit (62.4%) versus the 6 bladed unit (54.8%).

Some fish passed through the 5 bladed unit displayed an injury type not observed at the 6 bladed unit. A swath of scales and tissue was scraped from the fish's flank with the inception of the injury displaying a defined line (Figure 2-84). This injury was likely associated with the sharper narrower leading edge of the 5 bladed unit. Laboratory studies reported by Amaral *et al.* 2008 showed the importance of the shape and thickness of the leading edge of blades on fish condition. Their test results indicated that fish survival was strongly dependent on both the impact velocity and the thickness of the leading edge of the blades relative to the fish length. Maintaining a ratio of 1 and 0.75 of the thickness of the blade leading edge to the length of the fish has dramatically enhanced fish survival.

Figure 2-84
Injury type noted on several adult fish passed through a turbine at the Kelsey Generating Station. (Source: Study photographs courtesy of Normandeau Associates)

French Hydro Stations

The effect of the blade number was assessed on 581 adult eels (23.6 in or 599 mm – 39.4 in or 1001 mm) in length with a mean near 27.6 in or 701 mm passed through two Kaplan turbines on the Rhine River in France. The two turbines were similar except for blade number. The one unit had 4 blades, rotated at 88 rpm, and had a runner diameter of 21.9 ft or 6.7 m. The other unit had 5 blades, rpm of 94.0 and runner diameter of 20.3 ft or 6.2 m. Both units operated at a head near 49.2ft or 15 m. Eel at both units were released near ceiling, middle and

bottom of the turbine intake. The direct 48 h survival was substantially higher for the 4 bladed unit (92.4%) than the 5 bladed unit (78.6%). The corresponding injury rates of the recaptured eels were 7.4 and 27.5%. The one additional blade and slightly smaller unit markedly decreased survival and increased the incidence of injuries.

Summary

Our studies have indicated that minimizing gaps between turbine blade and hub and between blade tip and discharge ring can make turbine's fish friendlier. Decreasing the number of blades and increasing distance between blades generally provides the greatest benefits to turbine entrained fish by reduction the probability of encountering a turbine blade. Recent laboratory and field studies indicate that blade shape and thickness, particularly the leading edge can also markedly affect survival and injury. Additionally field tests should be conducted with a range of blade shapes to ascertain what design best minimizes injury to fish while still providing efficient turbine operations. If practical, it would be beneficial to develop a full size turbine where different interchangeable blade shapes that could be tested.

References

- Amaral, S.V.; G. Hecker, and P. Stacy. 2008. Effects of leading edge blade thickness in fish strike survival and injury. Proceedings of Waterpower'08. HCI Publications, St. Louis, Missouri.
- Dresser, T.J. Jr., C.L. Dotson, R.K. Fisher Jr., P.G. Heisey, D. Mathur, J.R. Skalski, and R.L. Townsend. 2006. Wanapum Dam Advanced Hydro Turbine Upgrade project: Part 1- Passage survival and Condition of Yearling Chinook Salmon through an existing and Advanced Hydro Turbine at Wanapum Dam, Mid Columbia River, USA. HydroVision 2006 Proceedings, HCI Publications, St. Louis, Missouri.
- Heisey, P.G., D. Mathur, and T. Rineer. 1992. A reliable tag-recapture technique for estimating turbine passage survival: application to young-of-the-year American shad (*Alosa sapidissima*). Can. Jour. Aquat. Sci. 49:1826-1834.
- Heisey, P.G., D. Mathur, J. L. Fulmaer, and E. Kotkas. 2008. Turbine passage survival of late running adult American shad and its potential effect on population restoration. American Fisheries Society Symposium 61:165-178, Amer. Fish. Soc., Bethesda, MD.
- Heisey, P.G., D. Mathur, J. R. Skalski, R. D. McDonald, and G. Velazquez. 2008. Effects of spillway structural modifications on fish condition and survival. American Fisheries Society Symposium 61:165-178, Amer. Fish. Soc., Bethesda, MD.

Johnson, Gary E., B. D. Ebberts, D. D. Dauble, A. E. Giorgi, P. G. Heisey, R. P. Mueller, and D. A. Neitzel. 2003. Effects of jet entry at high flow outfalls on juvenile Pacific salmon. *Jour. Fish. Mang.* 23: 441-449.

Mathur, D., P.G. Heisey, and D. A. Robinson. 1994. Turbine-passage mortality of juvenile American shad in passage through a low-head hydroelectric dam. *Trans. Am. Fish. Soc.* 123:108-111.

Mathur, D., P.G. Heisey, K. J. McGrath, and T. R. Tatham. 1996. Juvenile blueback herring (*Alosa aestivalis*) survival via turbine and spillway. *Water Res. Bull.* 32:155-161.

Mathur, D., P.G. Heisey, E. T. Euston, J. R. Skalski, and D. R. Kenney. 1999. Survival of Chinook salmon smolts through the surface bypass collector at Lower Granite Dam, Snake River. Pages 119-127 in M. Odeh, editor. *Innovations in fish passage technology*. American Fisheries Society, Bethesda, MD.

Mathur, D., P.G. Heisey, E. T. Euston, J. R. Skalski, and D. R. Kenney. 2000. Salmonid smolt survival relative to turbine efficiency and entrainment depth in hydroelectric power generation. *Jour. Amer. Water Resour. Assoc.* 36:737-747.

Normandeau Associates, Inc., and J. R. Skalski. 1996. Relative survival of juvenile chinook salmon (*Oncorhynchus tshawytscha*) in passage through a modified Kaplan turbine at Rocky Reach Dam, Columbia River, Washington. Report prepared for Public Utility District No. 1 of Chelan County, Wenatchee, WA.

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. Report prepared for Grant County Public Utility District No. 2, Ephrata, WA.

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 Dam First Powerhouse, Columbia River. Report prepared for Department of the Army, Portland District, Corps. Of Engineers, Portland, OR.

North/South Consultants, Inc., and Normandeau associates, Inc. 2007. Fish movements and turbine passage at selected Manitoba hydro generating stations. 2005-2006 interim report prepared for Manitoba Hydro, Winnipeg, Manitoba.

North/South Consultants, Inc., and Normandeau associates, Inc. 2009. Survival and movement of fish experimentally passed through a re-runner turbine at the Kelsey Generating Station, 2008. Report prepared for Manitoba Hydro, Winnipeg, Manitoba.

Physical Modeling Methods and Techniques

Robert Davidson, Vicksburg District, U.S. Army Corps of Engineers

Abstract

The US Army Corps of Engineers (USACE) own and operate eight hydroelectric projects located within the lower Columbia River drainage basin in the Pacific Northwest region of the United States. Downstream migration of juvenile salmon is a major concern. At each of the USACE projects juvenile salmon are bypassed around the turbines by passing fish over the project spillways or through juvenile bypass systems located in the intake structure of the powerhouse. However, a significant number of fish still pass through turbines at these projects. The turbine type at these projects is Kaplan.

USACE has constructed 1:25-scale section turbine models of several of its projects at the Engineer Research Development Center (ERDC) in Vicksburg, MS, USA. The passageways of these models are fabricated of acrylic to allow for observation of flow conditions approaching the turbine, through the turbine, in the draft tube and the area downstream of the draft tube exit. These models, which have operational turbines and wicket gates are used to investigate areas of the water passageway for potential to injure fish and to investigate turbine operations and designs that may increase survival of juvenile fish passing through them. In particular potential injury due to blade strike or high velocity shear can be accessed. These models have also been used to design and evaluate modifications to the turbine environment to improve fish survival while increasing the efficiency of the turbine.

Introduction

The USACE owns and operates eight hydropower plants on the lower Snake and Columbia Rivers within the Pacific Northwest region of the United States (Figure 2-85). These hydropower projects form a part of the Federal Columbia River Power System (FCRPS) from which the electrical power is managed by the Bonneville Power Administration (BPA). The Ice Harbor Lock and Dam is the last dam on the lower Snake River approximately 9 miles upstream Snake and Columbia River confluence. This Project includes six Kaplan turbine units. Units 1-3 are rated at 143,000 hp and units 4-6 are rated at 174,000 hp.

The safe passage of juvenile salmonids migrating downstream through the hydropower system is a major Regional issue. The turbines are considered an unacceptable passage route for the juvenile fish. During the migration periods (the months of April through August) large volumes of river flow are spilled and the majority of the turbine intakes are screened to prevent fish from passing through them. This effort to increase the survival of fish through the system results in lost power generation and reduced turbine efficiency.

Most turbines within the FCRPS are nearing the end of their design life and will eventually require rehabilitation or replacement. To assure the long term

operation and efficient use of the turbines, they must be able to safely pass the juvenile fish migrating downstream. Realizing this, the 2004 National Oceanic and Atmospheric Administration (NOAA) Biological Opinion requires fish passage improvements be considered for implementation during the replacement or rehabilitation of any turbines within the Lower Snake and Columbia River Projects. The Corps of Engineers established the Turbine Survival Program (TSP) to develop a better understanding of the turbine environment with the ultimate goal of developing operational and design improvements for safer fish passage. The TSP team consists of biologists and engineers from the COE Portland and Walla Walla Districts, as well as engineers from the Corps' Hydroelectric Design Center (HDC) and the Engineer Research and Development Center (ERDC).

Figure 2-85
USACE Project Location Map

ERDC has constructed numerous hydraulic turbine models and developed new investigation techniques to support the TSP in investigating the turbine environment as well as to design waterway passage modifications to improve fish passage. The ERDC models have been used to determine potential best operating points for better fish passage, define potential hazards in the hydraulic

passageway, design numerous water passageway modifications and compare different turbine runners.

Types of Models Utilized by TSP

Computational Fluid Dynamics Model

Computational fluid dynamic (CFD) is used to develop the initial design of replacement runner(s) and to refine the design of hydraulic passageway improvement alternatives. A critical output of the CFD is the determination of the pressure distribution and pressure profile of flow thru the turbine runner(s). This output is evaluated and compared to the threshold values identified for safe fish passage. In runner development, the design of the runner is adjusted until low pressures are raised above the threshold limits. In existing runners, CFD may be used to determine operating points that may need to be avoided due to low pressures.

Performance Model Testing

Performance models are an important element of the runner design process. Performance models are normally operated at high head and constructed of metal with a plexiglass discharge ring allowing for flow observation of the only the runner region. The performance models are used to evaluate the performance of the runner(s) with respect to power and cavitation. The performance models may also be used to further refine or develop other modifications to the hydraulic passageway including the runner. In addition performance models supply cam information for operation of the ERDC hydraulic turbine models.

Figure 2-86
Voist Alpine MCE Lower Granite 1:25 Scale Turbine Model

ERDC Physical Hydraulic Turbine Models

ERDC has constructed five 1:25 scaled observational hydraulic turbine models to investigate and define regions or conditions within the turbine environment with potential to harm fish. These models represent Ice Harbor (Figure 2-87 and Figure 2-88), Bonneville First, Bonneville 2nd, John Day, McNary and the Lower Granite USACE projects. Each model structure is manufactured from acrylic; they geometrically replicate the upstream approach, the intake, the distributor with stay-vanes and operating wicket gates, a fully adjustable Kaplan runner, the draft-tube and the draft-tube exit with a representative section of the downstream channel. These models are operated according to Froude which means they are operated at a model head of 1/25 that of the prototype head. The cam information to operate the models (the relationship between blade angle, wicket gate angle and discharge for a given head) is obtained either from performance models or from the prototype.

Figure 2-87
Ice Harbor Hydraulic Turbine Model Structure

Figure 2-88
General view of Ice Harbor Hydraulic Turbine Model

ERDC Model Test Methods

The hydraulic conditions within the turbine environment are evaluated using dye traces for general observations, flow velocity measured with a laser doppler velocimeter and neutrally buoyant bead tracked using high speed digital imaging. Through these evaluations, the leading edges of stay-vanes, the gap between the stay-vane and wicket gates, runner gaps at the hub and blade periphery, shear at the trailing edge of the runner blades, and flow in the draft-tube and areas immediately downstream of the draft-tube exit have all been identified as areas of concern. Additional model investigations have shown that these conditions can be improved through operational changes and/or physical modifications to the prototype unit.

The observational models are also used to determine appropriate locations to release test fish into the turbine intake for biological testing of turbines. Neutrally buoyant beads are released at multiple locations within the intakes, and are tracked using high-speed digital cameras. The release points are adjusted until a point is identified that will pass beads through desired locations of the runner and draft-tube. A similar approach is also used to identify test fish release points that allow test fish to pass within zones the in-river population of fish would most likely go. Systems were then designed to release test fish at the appropriate locations.

Bead experiments are also used to evaluate potential benefits of alternate runner designs and other turbine modifications such as alterations to the stay vane and wicket gate assemblies and the draft-tubes. The high-speed digital cameras, with a capture rate of 1000 frames per second, are used to study the bead path and assess the potential for bead strike and exposure to shear forces by observing bead strike and sudden changes direction.

Data Acquisition and Analysis with Neutrally Buoyant Beads

A high-speed digital camera system is used to film neutrally buoyant beads as they pass through the stay-vane and wicket gate cascade, runner region and in the tailrace. This system consists of four monochrome cameras set up to capture images of bead passage at a frame rate of up to 1000 frames per second with a resolution of 1024 pixels. Because of file size, the maximum film duration is limited to 6 seconds. Each 6 second segment will capture the passage of 25 to 50 beads depending on passage route, visible access and the analysis to be conducted. The film segments are stored in an AVI format.

The passage of beads through the stay-vane, wicket gates and runner are captured using the high-speed digital cameras. The beads are individually evaluated in order to identify rate and severity of contacts with surfaces in the stay-vane and wicket cascade and runner region (Figure 2-89). A surface contact grading system was established as follows:

- 1 = Very Severe (Direct, hard contact causing a severe change in direction)
- 2 = Severe (Direct contact with change in direction)
- 3 = Moderate Strike (light contact with change in direction)
- 4 = Glancing Strike (makes contact with surface with little change in direction)
- 5 = Touching (Bead travels with slight bump of surface or sliding along surface)
- 6 = No contact with any surface

The beads are also individually evaluated for abrupt changes in direction, which might indicate areas of high shear. The grading system for bead change in direction was as follows:

- 1 = Severe sudden change in direction
- 2 = Moderate sudden change in direction
- 3 = Small change in direction
- 4 = No significant change in direction

Pre-test determination of bead sample size is determined with the same method as by for direct survival tests. Direct survival tests sample size are determined for a precision level (ϵ) of $\leq \pm 0.03\%$, 95% of the time. Based on the results of the post biological bead experiments (report under preparation), 600 beads per runner release (based on 14% expected probability) and 350 beads per stay vane release (based on 4% expected probability) would attain a precision level (ϵ) of $\leq \pm 0.03\%$, 95% of the time for determination of severe contacts or severe changes in direction.

Between 300 and 700 beads are evaluated for each release location for each targeted test condition. After grading each bead, the contact scores and change

in direction scores were averaged to obtain an overall score for the stay vane and wicket cascade, and an overall score for the three zones of the runner (blade tip, mid-runner and hub). The percentage of severe contacts (those with a score of 1 and 2) and severe direction changes (those with a score of 1) were also calculated. The grading of the beads was performed manually by the same technician.

Figure 2-89
John Day model runner bead results.

Beads are not fish and do not behave as fish react to a stimulus in the flow field. However, fish passing through the stay vane cascade entrance and through the runner would experience velocities where they have little control and then pass into the runner region where velocities are so high that fish would have no choice but to go with the flow. Beads are excellent tools to indicate and predict contact and/or shear impacts fish might experience passing through these areas. Also, beads are excellent tools to compare one turbine operation to another (relative comparison). Correlation of beads experiments to direct biological survival tests are presently being explored for several Corps of Engineers projects.

Data Acquisition with Laser Doppler Velocity (LDV) Meter

A four-beam, two-color LDV is used to measure draft tube velocities (enclosure 13). This system consisted of a 4-watt Argon laser, optics to split and color separate the laser beam according to precise frequencies of light, fiber optics to carry the light to the model, a fiber probe with a 23.6-inch focal length, and signal processors for analyzing the signal from the fiber probe. A computer-controlled traversing system precisely controlled the position of the fiber probe for each velocity measurement. This system measured two components of the flow field within a plane perpendicular to the light beam. The LDV system is a

critical tool for defining flow distributions, velocity magnitudes and direction, turbulence, and for investigations of hydraulic shear under the runner and in the draft tube.

The velocity data is used to document the flow split between the two draft tube barrels as well as provided an overall turbulence intensity value for each barrel (Figure 2-90). Overall barrel turbulence intensity is defined as:

Average Section Standard Deviation of Velocities/Average Section Mean Velocity*100

This information is used to indicate where to operate the turbine to provide better quality of flow within the draft tube.

Figure 2-90
Draft Tube flow splits for Ice Harbor Turbine (with and with out modifications).

Use of ERDC Hydraulic Turbine Models

- Some of the projects ERDC hydraulic turbine models have been used for:
- Support prototype direct survival tests for Bonneville First Powerhouse, John Day, McNary and Lower Granite projects.
- Design and compare different modifications to the Lower Granite Stay ring to improve fish passage
- Design and test different modifications to the Lower Granite Draft tube to improve draft tube quality of flow to potentially improve egress

- Investigate numerous operating points for John Day, McNary, Ice harbor and Bonneville First powerhouse turbines
- Evaluate multiple runners for the McNary powerhouse
- Design and evaluate numerous water passageway designs for Ice Harbor turbine
- Presently being used for Ice Harbor turbine replacement

Conclusion

Models are valuable tools. All three models types are used and needed by TSP to investigate the turbine environment and hydraulic passageway to improve survival of juvenile salmon through turbines for both existing turbines and new replacement turbine runners.

Author

Robert (Bob) A. Davidson. Graduated from Mississippi State University in 1982 with a BS in Civil Engineering. Obtained a master's degree in Hydraulics from Mississippi State in 1989. Davidson is a research hydraulic engineer at the Engineer Research and Development (31 years) and is a registered professional engineer. Davidson has been involved in studies to improve fish bypass on the Colombia and Snake Rivers for 26 years. He has been a working team member of the Corps of Engineers Turbine Survival Program since 1995. In addition Davidson has been involved in research to improve Kaplan turbines for fish since 1990 and is presently the project research engineer on McNary, Ice Harbor, Lower Granite, John Day, Bonneville First and Second powerhouse turbine models.

Computational Analysis of Fish Survival at the John Day Powerhouse

James Kiel, Portland District, U.S. Army Corps of Engineers

Laurie Ebner, Portland District, U.S. Army Corps of Engineers

Abstract

This document will summarize:

- Some key findings and learnings documented in the CFD report
- The steps used to develop the pressure statistics
- Recommend pressure statistics to be used in the risk assessment

Introduction

A task order was awarded to ENSR/VATECH to develop a CFD model of the John Day Kaplan Turbine. The CFD model was necessary to provide a measure of the pressure domain throughout the turbine runner. There is the potential to improve juvenile fish passage through a Kaplan turbine distributor, runner, and draft tube cone but the flow field needs to be defined. The complex nature of the flow field and limited data from prototype turbines, physical models and sensor fish highlight the difficulties of measuring the flow field throughout the domain. Sensor fish provide for pressure, pressure rate of change and acceleration of stream line of passage but are limited by release point, random route and number of samples. Computational Fluid Dynamics (CFD) models of the Kaplan turbine runner environment provide a prediction of the physical flow field. If the CFD model results adequately represent the turbine runner flow regime, the output data will be used to support a risk analysis for juvenile salmonids passing through large Kaplan turbine units. The CFD model is documented in “Computational Fluid Dynamics Modeling of the John Day Kaplan Turbine, Final Report”, Contract No. W9127N-06-D-004, Task Order No. 013, dated September 2008. To develop summary statistics on the pressure regime CENWP-EC-HD with support from Pacific Northwest National Laboratory (PNNL) utilized a CFD visualization software Package Tecplot. This analysis allowed for a method of determining areas where fish might pass through regions of nadir pressure deemed harmful to fish survival. In addition, there was a comparison performed between sensor fish results and those found through the CFD post-processing.

CFD Model

There are several commercially available CFD codes that could have been used to perform this work, but it was important at this time to select a CFD code typically used by turbine manufacturers. VATECH utilizes the commercial code CFX and the John Day Kaplan Turbine was modeled using CFX. In reviewing turbine modeling the most commonly used commercially available code for turbine design appears to be CFX.

The components to be modeled are shown in Figure 2-91. (Figures describing the CFD model come from the final report or the various presentations that were presented by VATECH.) The CFD model was built in two pieces – the intake and the runner/draft tube. The first model is shown in Figure 2-92 and includes the intake which includes a section of the forebay, the trashrack, fish screens, scroll case and stators. Figure 2-93 is the second model and consists of a stator, a runner and draft tube. Only one stator is modeled and CFX automatically accounts for the hydraulic flow conditions between the single stator to one blade. Only a single blade is modeled and the results for the turbine can be achieved by replicating the results with the appropriate rotation.

Figure 2-91
Components of the CFD Turbine Model

Figure 2-92
Intake Model

*Figure 2-93
Runner and Draft Tube*

Although the method of breaking the domain into two domains and using a single stator and single runner have been shown to be adequate for turbine design some limitations of this approach exist when trying to track streamlines from the forebay through the runner and out the draft tube. These limitations will be discussed further but the John Day CFD model is consistent with turbine manufacturing practices.

The CFX code has been tested in several benchmark test and when applied properly provides excellent results. With time and utilization of the code CFD modelers become knowledgeable about how to develop CFD models. The John Day Kaplan Turbine CFD model was developed by experts in the field and the report documents various validation steps that they have participated. Results were presented in the CFD report which highlights the impact of the following simplifications:

- Steady state vs time domain (minor differences but for computational time required to perform time domain not warranted)
- Circumferentially averaging at the stator (optimistic prediction of torque – less than 1% PSI error in small localized areas)
- Stage interface with a single stator and single runner interact (velocity comparisons are provided for a single runner to a 360° simulation – approximation is valid)
- Draft Tube – literature shows that significant uncertainty exist in being able to accurately model the draft tube. But knowing that there is potential error in the draft tube what would be the impact on the pressure in and around the runner. The CFD model was ran with different draft tube assumption and the pressure field in the runner compared. Results showed very little sensitivity of the extent of low pressures zones with respect to the uncertainty of predications of pressure recovery in the draft tube.

- Prototype scale and boundary layer – turbine manufacturers typically carry out CFD simulations at model scale to directly compare results to physical models. In this case the CFD simulations are carried out in prototype scale. The prototype has higher Reynolds numbers and the boundary layer thickness is relatively smaller than in a model, leading to reduced friction loss. The computational grid for the prototype simulation must be more refined near the wall boundaries. Using the industry standard tools this is difficult to implement without significantly changing the mesh and significantly increasing the run times.
- OP3 and OP5-C. Both conditions are the same physical geometry but different discharge. OP3 is the original HDC computed discharge but refinement in the procedure provided an increase in the discharge. If you look at the actual head – 102.9 feet and the two computed heads 83 feet and 100.1 feet. Obviously the higher discharge appears to be much closer to a valid solution since the head and power computed from the model are closer to the actual values.
- OP1 appears to have reasonable prediction of the head and power. If the model was reran with the corrected discharge it is anticipated that the head and power would be closer to the actual values.
- OP2 is off but if the model were to be reran with the corrected discharge it is anticipated that the computed head and power would be closer to the actual values. For comparisons OP3 (upper 1%) was ran with a 4.76% increase in discharge and the head prediction was off by 19%. OP2 discharge is 3.67% different and the head difference is 16.6%.
- OP4, OP5-A and OP5-B are just small tweaks off of a operating point (OP4). The results suggest that the discharge for OP4 was reasonable, OP5-A slightly low in the discharge estimate and OP5-B slightly high in the discharge estimate. But even though the discharges and operating points are slightly different the volumes of zones below a threshold pressure are not significantly different.
- If model runs were being ran locally would recommend that the model discharge be tweaked until the computed head and power numbers are $\pm 5\%$ of the prototype.
- If the computed head and computed power numbers are close to the prototype data the general pressure regime in the CFD model must approximate that of the prototype.

Probabilities: The model report documents the volume within the runner that is equal to or below a certain absolute pressure threshold (7.25 PSIA, 10 PSIA and 14 PSIA). Additional analysis has been done to quantify the pressure within the runner. A CFD visualization package, Tecplot was used to create nadir pressure probability plots. A horizontal plan was placed above the top of the runner. Streamline seeds were uniformly distributed over the horizontal plan and allowed to move through the fluid domain. The minimum pressure along the streamline was captured and probability curves developed. The probabilities are for a uniform distribution through the runner and typically include at least

40,000 streamlines. Figure 2-94 shows the results for OP1, OP2, OP3, OP5-C along with the sensor fish results. The plots go from left to right: Upper 1% (OP5-C and OP3), Peak (OP1), and Lower 1% (OP2) rather it is CFD results or sensor fish. The sensor fish data are released at two locations mid blade and tip and are comprised of approximately 100 data points. So is the difference due to release location or is the pressure data in the CFD model is too high?

To take a closer look at the sensor fish data bead results from the physical model have been used. The xy location of the bead data at the downstream end of the runner have been captured for beads release at mid blade and at the blade tip. Bead data has been provided for Upper 1%. Streamline seeds were placed at the xy bead location and moved back through the fluid domain. The xy data was rotated 0°, 15°, 30°, 45°, and 60° because the single runner results are duplicated to represent the full 360° and any initial orientation would be valid. Figure 2-95 shows the results for the mid blade beads. The CFD results and the sensor fish results match up well until you get to nadir pressures of 20 PSIA and then they appear to diverge. But the area of interest concern is the low pressures and the probabilities in this region are very similar. Figure 2-96 shows the results for the tip release. There appears to be a 5 PSIA offset with the sensor fish showing lower pressures, but the shapes are similar.

The offset was puzzling especially since the mid blade results were so favorable. The tip bead location was further dissected by the distance from the scroll case. Figure 2-97 shows results for the tip release, inside tip release, and the outside tip release. All of the data was created in the 30° rotation of the runner. An offset of -5 PSIA was added to the outside tip release. The results then appear to match up better with the sensor fish results, as shown in Figure 2-98.

Several ideas of been bounced around as to why the CFD and sensor fish results are not matching at the tip. But there are two simplifications in the development of the CFD model that might make getting accurate readings in this zone problematic: stage interface and boundary layer. The stage interface simplification means that the vortices/wakes that would normally be created at the edge do not get created. The boundary layer is not ideal for a prototype scale model and the boundary layer may extend too far into the fluid.

What is the distribution of fish through the runner? Is the distribution of fish similar to the two release points used for sensor fish? Is the distribution of fish more uniform throughout the runner? The one stator to one runner limits the ability to do streamlines from the intake through the runner and exiting out the draft tube. Thus assumptions on the distribution of fish will have to be assumed to developed probabilities.

Appendix A is the probability distributions for OP1, OP2 and OP3 given different distribution at the top of the runner. The different distributions do not significantly change the probability distributions. There are some minor changes in the 0 to 1% probability.

Conclusions: When the CFD model results predict the head and power that are computed correspond to the prototype values the pressures in the CFD model represent the prototype pressures. Results for Peak (OP1), Upper 1% (OP5-C) and the point between Peak and Upper 1% and off cam point (OP4 and OP5-A) provided good predictions of head. Although it should be noted that OP4, OP5-A and OP5-B do not show significant difference in the pressure probabilities. The bead data does suggest that pressures at the tip of the runner is too high. There are limitations in being able to evaluate different intake distributions because of the one stator to one runner simplification in the development of the model.

Recommendations: Probability distributions of nadir pressures should be developed two different ways. In both cases assume a uniform distribution at the top of the runner. Case 1 would use the data has computed in the model. Case 2 will radially reduce the pressure by 5 PSIA at the tip of the runner and 0 PSIA at the center of the runner. Probability distributions will be created for all operating points but it should be noted that lower 1% (OP2) and the first upper 1% (OP3) will most likely under-predict the nadir pressures. The one off cam point (OP5-B) may over-predict the nadir pressures.

In addition, the overall concept of whether CFD is a good tool to determine the pressure regimes within the turbine runner environment is certainly viable. As long as its limitations are taken into account, such as a suitable offset to the sensor fish data, it can be a source to draw from when working on turbines with a focus on environmentally improving them for fish passage.

Table 2-19
Operating Conditions and Results

Variable	OP1 (Peak)	OP2 (Lower 1%)	OP3 (Upper 1%)	OP4 (Between Peak and Upper 1%)	OP5-A (OP4 + 1%)	OP5-B (OP4 - 1%)	OP5-C (OP3 - corrected Q)
GV Angle (Absolute)	35	28.7	40.8	37.5	41	35.7	40.8
Blade Angle (Absolute)	26.2	19.6	31.6	29	29	29	31.6
Discharge (cfs) given	16450	11800	19900	18660	19240	18520	20895
Recomputed Discharge (cfs)	16950	12250	20895	18660	19240	18520	20895
% in Discharge	2.95%	3.67%	4.76%	0.00%	0.00%	0.00%	0.00%
Head (ft) given	102.9	103.3	102.9	100	100	100	102.9
Output (MW) HDC	128.28	92.38	154.97				154.97
Head (ft) computed	96.6	86.1	83.0	100.9	96.0	107.4	100.1
Runner Output (MW) computed	121.86	76.78	125.65	144.18	141.14	152.33	159.16
Efficiency (%) computed	90.83	89.48	88.65	90.74	90.47	90.72	90.13
Difference in Head	6.13%	16.63%	19.33%	-0.85%	3.97%	-7.38%	2.69%
Difference in Output	5.00%	16.89%	18.92%				-2.70%
Volume of Zone Below Threshold							
7.25 PSIA	0.000124	0.0000106	0.000316	0.000308	0.000406	0.000309	0.00066
10 PSIA	0.000268	0.000015	0.000565	0.000684	0.000815	0.000707	0.0028
14 PSIA	0.00101	0.0000489	0.00727	0.00215	0.00415	0.00232	0.0286

Figure 2-94
CFD and Sensor Fish Nadir Pressures

Figure 2-95
Probability Curve for Mid Blade Bead Releases

Figure 2-96
Probability Curve for Tip Blade Bead Releases – No Corrections

Figure 2-97
Probability Curve for Tip Blade Bead Releases – With Corrections

Figure 2-98
Sensor Fish and CFD Data for John Day, OP1 – Peak approximate blade angle of 26.20 Degrees, OP5-C – Upper 1% approximate blade angle of 31.4 Degrees and OP2 – Lower 1% approximate blade angle of 19.6 Degrees.

Authors

Laurie Ebner is a hydraulic engineer for the US Army Corps of Engineers, Portland District. She introduced and incorporated Computational Fluid Dynamics (CFD) modeling into the District. Since starting we have developed over a hundred models that range from simple models that involved 100,000 cells to several million. They have become a staple part of our analysis tools. We utilize CFD results with physical model results, prototype data sets and analytical tools to understand the hydraulic nature of the projects and design more effective structures.

James D. Kiel graduated in mechanical engineering from Oregon State University in 2006. He joined the Army Corps of Engineers in June 2006 and works in the Turbine Section of the Hydroelectric Design Center as a senior mechanical engineer.

Estimating Juvenile Salmon Survival with Implanted Transmitters

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Abstract

Passage through hydropower turbines exposes fish to rapid decompression and the risk of barotrauma. The lowest pressures experienced can range from near vapor pressure to well above atmospheric pressure. Pressure related mortality and injury to fish depend upon the differential between the pressure (depth) to which fish are acclimated prior to turbine passage and the lowest pressure experienced during passage. In addition, the presence of surgically implanted transmitters may increase the likelihood of injury during turbine passage. Following acclimation, juvenile Chinook salmon surgically implanted with one of several different transmitters in combination with a PIT tag were exposed to simulated turbine pressure time histories using computer controlled hyper / hypobaric chambers. The nadir of the simulated turbine pressure profiles ranged between 1 and 15 PSI absolute. Rates of mortal injury for test fish were a function of the ratio between acclimation pressure and nadir pressure, and the size of the transmitter. Understanding the relationship between barotrauma and the presence of an implanted transmitter is critical when evaluating survival study results of juvenile salmonids passing through hydroelectric dams. Illustrations are provided of how the presence of transmitters can bias (higher mortality with bigger transmitters) survival estimates of fish passing through hydroturbines.

Introduction

Each year, millions of juvenile salmonids migrate downstream through hydropower-influenced rivers on their seaward migration. As a way of monitoring routes of passage and survival past hydropower facilities, fish are outfitted with telemetry tags. One of the main assumptions associated with all tagging studies is that tagged individuals behave in the same manner as untagged fish. Previous research, however, has suggested that the presence of a tag may influence the survival, growth, and behavior of fish, possibly limiting the inferences that can be made about the general population (Winter 1996; Brown et al. 2010).

One of the passage routes through hydropower facilities of particular concern for managers and researchers is through hydro turbines (Mathur et al. 1996; Coutant and Whitney 2000; Čada et al. 2006). Passage through hydro turbines may expose individual fish to a variety of sources of injury and mortality, including mechanical strike, cavitation, shear forces, and rapid and extreme pressure changes (Čada 2001). Although the areas in which fish may be exposed to mechanical strike, cavitation, and shear forces in a hydro turbine are limited (Coutant and Whitney 2000; Neitzel et al. 2000), rapid decompression, and possibly associated barotraumas, is a risk for all fish that pass through turbines. Barotrauma is characterized by the presence of emboli in the gills, damage to the vasculature and the swim bladder, as well as other injuries (Feathers and Knable 1983; Rummer and Bennett 2005; Brown et al. 2009).

The change in pressure from acclimation to exposure, expressed as a ratio, is a large factor in predicting the likelihood of barotraumas for fish exposed to rapid decompression (Brown et al. 2009; Brown et al. in press). To fully understand the influence of hydro turbine passage on fish, it is necessary to investigate the likelihood of barotraumas across a wide range of changes in pressure, representative of the occurrence at hydropower facilities.

Another factor that influences the occurrence of barotrauma in hydro turbine-passed fish is the burden associated with carrying a telemetry tag. Brown et al. (2009) showed that fish carrying a transmitter had higher rates of mortality compared to non-tagged individuals exposed to simulated turbine passage (STP). Fish implanted with telemetry tags can compensate for the additional mass of the tag by increasing their displacement via increased swim bladder volume (Gallepp and Magnuson 1972; Perry et al. 2001). This increased mass of gas in the swim bladder may put tagged fish at increased risk of barotrauma and mortality when exposed to STP.

The objective of this research was to identify the factors that influence the injuries and mortality of juvenile Chinook salmon carrying a range of tag burdens and exposed to a range of pressure changes. Factors taken into account included LRP (natural log of the ratio between acclimation and nadir pressure), tag burden, tag type, fish length, fish weight, and condition factor.

Methods

Subyearling and yearling Chinook salmon were exposed to STP treatments between March 7, 2007, and March 6, 2010 at the PNNL Aquatic Research Laboratory (ARL, in Richland, Washington; Table 1). Fish had one of four transmitter types surgically implanted into the intraperitoneal cavity: 1) double-battery acoustic transmitter and passive integrated transponder (PIT) tag, 2) single-battery acoustic transmitter and PIT tag, 3) single-battery acoustic transmitter only, or 4) PIT tag only. There was also one treatment in which fish were not implanted with a transmitter but were only anesthetized and handled as described above. The double-battery acoustic transmitter and PIT tag and PIT-tag only treatments are currently used in the Columbia and Snake rivers to monitor the passage and survival of fish through hydroelectric facilities.

After fish recovered from surgery, denoted by regaining equilibrium and actively swimming, they were loaded in the hyper/hypobaric chambers of the Mobile Aquatic Barotrauma Laboratory for acclimation to 4.6m depth (146.1 kPa). Fish were held for a 16–24 h period, according to the methods outlined in Stephenson et al. (2010), to allow for ample time to attain neutral buoyancy and equilibration of gas tensions in bodily fluids and tissues. Treated water was supplied to all chambers at a continuous rate of 7.6 L/min with a flow control accuracy of ± 0.95 L/min, similar to the conditions described in Stephenson et al. (2010). Ambient well water was supplied to the chambers (median temperature = 17.0°C; range = 15.4°C to 17.9°C) and total dissolved gas (TDG) levels were about 115% saturation (median = 115.0%; range 112.7% to 127.5%).

Exposure pressures (nadir pressures) ranged from 9.0 to 200.5 kPa (median = 46.9 kPa), and the rate of change during STP ranged from 103.4 to 3824.6 kPa/s (median = 1495.4 kPa). After STP exposure, fish were euthanized with an overdose of MS-222 (250 mg/L of water). Necropsies were performed as detailed in Stephenson et al. (2010). Mortal injury (described in Brown et al. in press) served as the endpoint of all analysis and is defined as fish when a fish died within a few minutes or received pressure related injuries (barotrauma) sufficient to cause eventual mortality.

The experimental factors examined in this study were 1) natural log of the ratio between acclimation and nadir pressure (LRP; as detailed in Brown et al. in press), 2) tag burden, 3) transmitter treatment, 4) condition factor (measure of energy storage; Winter 1983), 5) fish length, and 6) fish weight. In total, 10,742 fish were surgically implanted with one of five transmitter combinations (double-battery acoustic tag and PIT tag, single-battery acoustic tag and PIT tag, single-battery acoustic tag only, PIT tag only, or no tag) and then either exposed or not to STP in a replicated experimental design.

Mortal injury was modeled using general linear models based on a logistic link function and Bernoulli error structure. Analysis of deviance was used in modeling the data and testing hypotheses where a fish received a score of 1 if it died or was mortally injured and 0 otherwise. Logistic model performance was evaluated using a measure called area under the curve (AUC; Hosmer and Lemeshow 1999). We compared AUC values between alternative logistic models to identify their relative levels of performance.

Results

Factors Associated with Mortal Injury

The main treatment factors of LRP ($P < 0.0001$), tag burden ($P < 0.0001$), fish length ($P < 0.0001$), tag type ($P = 0.0006$) and condition factor ($P = 0.0007$) and several interaction effects were significant predictors of mortal injury for tagged juvenile Chinook salmon. Fish weight was not significant ($P = 0.2367$). The main model plus the seven interactions explained 44.4% of the variability in the data. The LRP explained the most variability in the model (35.6%), and tag burden explained 6.3% of the variability in the model. The other variables and

interaction factors combined explained less than 1% of the variability in the model (fish length = 0.3%, tag type = 0.1%, condition factor = 0.06%, fish length × tag type = 0.2%, fish length × condition factor = 0.07%, LRP × tag burden = 0.006%, LRP × fish length = 0.006%, LRP × tag type = 0.1%, tag burden × tag type = 0.05%, and LRP × condition factor = 0.03%).

Similar to the analysis of deviance results, the area under the curve (AUC) analysis also indicated the LRP and tag burden were the most influential factors in determining the likelihood of mortal injury. The model containing all significant effects and interactions had an AUC score of 0.9055. The model containing only LRP explained a large portion of the variability in the model with an AUC score of 0.8783. However, the model containing LRP and tag burden had an AUC score of 0.9034, thus explaining all significant variability in the model. This simplified model using LRP and tag burden appears to be an adequate predictor of mortal injury.

An analysis of deviance of this simplified model indicates that LRP and tag burden are significant predictors of mortal injury ($P < 0.0001$ and $P < 0.0001$, respectively, explaining 41.9% of the variability in the model. Equation (1) for predicting mortal injury given LRP and tag burden (%) is:

$$\text{Probability of mortal injury} = \frac{e^{-5.997 + 4.201 \cdot \text{LRP} + 0.603 \cdot \text{Tag burden}}}{1 + e^{-5.997 + 4.201 \cdot \text{LRP} + 0.603 \cdot \text{Tag burden}}} \quad (1)$$

Using the data collected in this study, three-dimensional plots were constructed to display the relationship among LRP, tag burden, and mortal injury (Figure 2-99). These plots demonstrate that as LRP and tag burden increase, mortal injury also increases.

Discussion

Factors Associated with Mortal Injury

This research demonstrates that the derived variables—natural log of the ratio between acclimation and nadir pressures (LRP) and tag burden—are the most important factors in determining the likelihood of mortal injury for juvenile Chinook salmon exposed to rapid decompression associated with turbine passage. Because millions of juvenile salmon are tagged with telemetry tags (acoustic, radio, inductive) each year to assess passage and survival through hydropower facilities, the implications of these results are important for understanding the effect of these facilities on their downstream migration. Bias in survival estimates of fish passing through hydropower facilities can lead to inaccurate information being used for their management, and it is likely, based on these findings, that results from many previous studies may have been biased.

Changes in pressure have previously been shown to be an important factor in predicting the likelihood of injury and mortality for juvenile Chinook salmon

undergoing rapid decompression as a result of STP (Brown et al. 2009; Brown et al. in press). However, Brown et al. (2009) examined the occurrence of injury and mortality for a range of LRP from only 1.7 to 3.3 (ratios of pressure change from 5.3 to 27.0), while this current study examines the likelihood of mortal injury from no pressure change to an LRP of 3.12 (ratios of pressure change from 0.0 to 22.6). Only the current study and the work done by Brown et al. (2009) have addressed the additional influence of a telemetry tag on barotrauma due to rapid decompression.

This research has indicated that, as tag burden increased, the rate of mortal injury also increased. The presence of a telemetry tag has also been shown to influence injury and mortality rates by other researchers (Brown et al. 2009). Brown et al. (2009) examined the effects of rapid decompression associated with the presence of a telemetry tag (with tag burdens ranging from 1.3% to 4.7%) for juvenile Chinook salmon. Smaller fish (subyearlings) acquired higher rates of injury and mortality associated with STP when compared to larger individuals (yearlings). However this could not be clearly linked to the tag burden carried by smaller fish, as tag burden was similar for both subyearling and yearling fish (subyearling: mean = 2.9%, range = 1.4% to 4.2%; yearling: mean = 3.1%, range = 1.3% to 4.7%; Brown et al. 2009). The current work examined a broader range of tag burdens (0.0% to 6.6%) and looked specifically at the relationship between tag burden and the likelihood of mortal injury. The current study also expanded the relationship between tag burden and mortal injury over a range of LRPs. The highest rates of mortal injury were seen for fish exposed to high changes in pressure and carrying high tag burdens. By comparison, fish exposed to low changes in pressure and carrying low tag burdens exhibited lower rates of mortal injury. The understanding of this relationship is important for application to field studies examining turbine survival through hydropower facilities.

Tag burden has varied considerably among field studies conducted within the Columbia and Snake rivers examining route-specific survival, including passage through hydro turbines. Fish have been tagged with a variety of tag types, including radio, acoustic and PIT tags, which have varied in mass from 0.1 g (for an implanted PIT tag; e.g., Achord et al. 2009) to 1.4 g or higher (combined weight of implanted radio and PIT tags; e.g., Hockersmith et al. 2003). The size of fish being used to examine hydro turbine passage survival at U. S. Army Corps of Engineers projects in the Snake and Columbia rivers also varies. Based on information available in reports, it can be estimated that tag burdens of juvenile Chinook salmon used in these studies generally ranged from 1.0% to 6.4%, depending on size of fish and tag type used. Increased rates of injury and mortality resulting from these tag burdens used in these studies may have created bias in survival estimates.

Figure 2-99

Overlays of fitted logistic curves of mortal injury along a range of LRP (ratio of pressure with natural log applied) and tag burden for juvenile Chinook salmon. Plots were rotated on the z-axis of mortal injury to provide alternative perspectives of the surrounding plane. In the current study, tag burdens of 0.0% to 6.6% were tested.

Conclusions and Discussion

This research demonstrates that the derived variables—natural log of the ratio between acclimation and nadir pressures (LRP) and tag burden—are the most important factors in determining the likelihood of mortal injury for juvenile Chinook salmon exposed to rapid decompression associated with turbine passage. This research has indicated that, as tag burden increased, the rate of mortal injury also increased. Based on the results of the current study, the tag burden of implanted fish used in survival studies may have influenced the reported survival estimates of turbine passed juvenile Chinook salmon. This in turn can influence overall dam passage survival estimates.

The results of this study have large implications for the management of hydroelectric facilities. Findings indicate that the presence of a telemetry tag likely creates a bias in the estimates of survival for juvenile Chinook salmon undergoing rapid decompression associated with hydro-turbine passage. This is especially true for those fish undergoing large changes from acclimation to nadir pressures and fish with large tag burdens. This knowledge has a direct impact on

the interpretation of survival estimates for fish passing through hydropower facilities because past estimates may be biased toward higher rates of mortality than would have occurred for untagged fish. In the future, the smallest telemetry tag possible should be used for turbine survival studies. In addition, research should be conducted to identify technology that can be used to determine accurate estimates of hydro-turbine passage survival.

References

- Achord, S., B. P. Sandford, E. E. Hockersmith, M. G. Nesbit, N. D. Dumdei, J. L. Lamb, K. W. McIntyre, N. N. Paasch, and J. G. Williams. 2009. Monitoring the migrations of wild Snake River spring/summer Chinook salmon juveniles, 2007–2008. Report by NOAA for Bonneville Power Administration, Portland, Oregon.
- 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, R. L. Townsend. *In press*. Quantifying mortal injury of juvenile Chinook salmon exposed to simulated hydro-turbine passage. Transactions of the American Fisheries Society.
- 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., D. R. Geist, K. A. Deters, and M. A. Grassel. 2006. Effects of surgically implanted acoustic transmitters >2% of body mass on the swimming performance, survival, and growth of juvenile sockeye and Chinook salmon. Journal of Fish Biology 69(6):1626–1638.
- Brown, R. S., R. A. Harnish, K. M. Carter, J. W. Boyd, K. A. Deters, and M. B. Eppard. 2010. An evaluation of the maximum tag burden for implantation of acoustic transmitters in juvenile Chinook salmon. North American Journal of Fisheries Management 30:499–505.
- Čada, G. F. 2001. The development of advanced hydroelectric turbines to improve fish passage survival. Fisheries 26:14–23.
- Čada, G., J. Loar, L. Garrison, R. Fisher Jr, and D. Neitzel. 2006. Efforts to reduce mortality to turbine-passed fish: locating and quantifying damaging shear stresses. Environmental Management 37:898–906.
- Coutant, C. C. and R. R. Whitney. 2000. Fish behavior in relation to passage through a hydropower turbine: a review. Transactions of the American Fisheries Society 129:351–380.

Feathers, M. G. and A. E. Knable. 1983. Effects of depressurization upon largemouth bass. *North American Journal of Fisheries Management* 3:86–90.

Gallepp, G. W. and J. J. Magnuson. 1972. Effects of negative buoyancy on the behavior of the bluegill, *Lepomis macrochirus* Rafinesque. *Transactions of the American Fisheries Society* 101:507–512.

Hockersmith, E. E., W. D. Muir, S. G. Smith, B. P. Sandford, R. W. Perry, N. S. Adams, and D. W. Rondorf. 2003. Comparison of migration rate and survival between radio-tagged and PIT-tagged migrant yearling Chinook salmon in the Snake and Columbia rivers. *North American Journal of Fisheries Management* 23:404–413.

Hosmer, D. W. Jr. and S. Lemeshow. 1999. *Applied Survival Analysis: Regression Modeling of Time to Event Data*. John S. Wiley & Sons, Inc., New York.

Mathur, D., P. G. Heisey, E. T. Euston, J. R. Skalski, and S. Hays. 1996. Turbine passage survival estimation for Chinook salmon smolts at a large dam on the Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 53:542–549.

Neitzel, D. A., M. C. Richmond, D. D. Dauble, R. P. Mueller, R. A. Moursund, C. S. Abernethy, and G. R. Guensch. 2000. Laboratory studies on the effects of shear on fish. Pacific Northwest National Laboratory, PNNL-13323, Richland, Washington.

Perry, R. W., N. S. Adams, and D. W. Rondorf. 2001. Buoyancy compensation of juvenile Chinook salmon implanted with two different size dummy transmitters. *Transactions of the American Fisheries Society* 130:46–52.

Rummer, J. L. and W. A. Bennett. 2005. Physiological effects of swim bladder over expansion and catastrophic decompression on red snapper. *Transactions of the American Fisheries Society* 134:1457–1470.

Stephenson, J. R., A. J. Gingerich, R. S. Brown, B. D. Pflugrath, Z. Deng, T. J. Carlson, M. J. Langesley, M. L. Ahmann, R. L. Johnson, A. G. Seaburg. 2010. Assessing barotraumas in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotraumas laboratory. *Fisheries Research* doi:10.1016/j.fishres.2010.08.006.

Winter, J. D. 1996. Advances in underwater biotelemetry. Pages 555–590 in B. R. Murphy and D. W. Willis, editors. *Fisheries Techniques*, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Biographical Sketches

Dr. Richard Brown (PNNL) is a senior research scientist and his research focuses on fish ecology and physiology, bioengineering and biophysics. He studies the effects of turbine passage on the physiology of salmonids. This research is aimed

at determining more accurate estimates of survival through turbines, identifying optimal turbine operations for fish and aiding in the design of more fish friendly turbines.

Dr. Thomas Carlson (PNNL) is a program manager at PNNL's Marine Sciences Laboratory. Dr. Carlson leads projects addressing various topics in the design, operation, and biological and physical performance assessment of conventional hydropower turbines. Dr. Carlson is also a technical lead in the application of acoustic measurement technologies for measurement of underwater noise and the application of active and passive acoustic systems for assessment of fish populations, observation of fish behavior, and the detection, classification, and localization of vocalizing and other marine mammals.

John Stephenson's (PNNL) research primarily includes the evaluation of physiological effects of simulated hydro-turbine passage on juvenile salmonids and other migratory fish. Research is focused on the development of new generation hydro-electric turbines that will optimize turbine efficiency and safely pass fish. Mr. Stephenson has also been associated with the deployment of radio and acoustic telemetry systems. John has also been involved in the deployment of hydroacoustic systems on many hydro-electric projects in the Columbia and Snake River watersheds.

Alison Colotelo is a research associate at Pacific Northwest National Laboratory (PNNL). Her research includes investigating how the surgery process and the presence of a telemetry tag influence fish responses to hydro-turbine passage.

Brett Pflugrath (PNNL) recently completed his M.Sc. degree investigating the maximum depth that juvenile Chinook salmon can become neutrally buoyant, and how that influences hydro-turbine design and operation.

Andrew Gingerich is currently employed by Douglas County Public Utility District (DCPUD) in East Wenatchee, WA. As a senior aquatic resource biologist, he is involved in the FERC relicensing of Wells Dam on the Columbia River, contributes to research surrounding juvenile and adult anadromous fish migration and habitat conservation, and management of white sturgeon, bull trout, and resident fish species in the Mid-Columbia River. Wells Dam is the farthest upstream dam on the Columbia River that provides upstream passage of adult salmonids and located at river mile 515.6.

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Developing Environmental Standards and Best Practices for Hydraulic Turbines

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Abstract

The need to comply with increasing environmental standards of water quality and fish survival becomes a part of today's reality of hydropower. Consequently, requirements of this nature find their way into specifications for supplying generating equipment.

As of now, there are no guidelines how to define related guarantees and how to verify that environment-enhancing systems will work as intended. In response to that, PTC-18 Committee has been working on development of recommendations related to the environmental performance of hydraulic turbines. As a first assignment, performance of aerating turbines is being addressed.

The goal of the Committee is to develop a set of "best practice" environmental recommendations that would help in establishing a fair distribution of duties between plant owners and equipment suppliers, while satisfying environmental needs. The aim of this work is to reduce risks of involved parties by helping them to define and verify performance of such systems.

The need to comply with increasing environmental standards becomes part of today's reality. This is an understandable consequence of ever increasing environmental consciousness of the society. It is quite evident that the future will bring more of those requirements.

In hydropower, the main environmental factors considered are water quality and fish survival. To cope with related requirements, plant owners need to implement new strategies. Consequently, environmentally related stipulations often find their way into specifications for supply of generating equipment. This, in turn, requires setting guarantees and finding methods of their verification.

Traditionally understood performances of hydraulic turbines relate to energy, i.e. power, efficiency, rate of flow. In the new situation, that definition needs to be broadened, to include environmental performance.

Main Environmental Concerns

Water Quality

Water pollution and dissolved gases are two main issues related to water quality.

Water pollution, although not intended, is still an issue. Even modern turbines with self-lubricating bushings have eliminated constant releases of mineral

lubricants, there is still a possibility of accidental spills as large quantities of oil, often pressurized, are stored in proximity of water.

Another class of water quality related issues is related to dissolved gases. There are two extremes of the problem:

- Depletion of Dissolve Oxygen (DO)
- Supersaturation with Total Dissolved Gases (TDG)

Oxygen depletion is mainly associated with reservoir management during hot periods of the year in warm climates. Due to high water temperature, saturation concentration decreases. This is aggravated by the fact that older power plants often draw water from reservoirs at a substantial depth, where concentration of DO is low.

Among methods of dealing with the problem is aerating water passing through hydraulic turbines. Turbines naturally contain areas of low pressure, where air under atmospheric pressure could be channeled and mixed with water. This is a relatively inexpensive method of increasing the DO contents.

Excessive aeration, often associated with spilling or the use of air to attenuate pressure pulsation in turbines, can cause supersaturation with TDG. This problem occurs mostly in regions with cold, well-aerated water.

Fish Survival

Despite decades of studies, only recent years saw systematic investigation of factors affecting fish survival in turbines. This is followed by design measures to address this problem. The design process has been slow and as of now, only few turbine designs to improve fish survival have been built and tested.

Need for Guidelines

One of the ways to comply with the environmental standards is to require hydraulic turbines to be designed in ways that address those needs. This is complicated by the fact that turbine designers have relatively limited experience in addressing these issues. This implies a need for several related steps:

- More basic research, helping in better understanding turbine environment
- Guidelines how to guarantee and verify environmentally related performances
- Gradual introduction of environmental requirements, so turbine designers could learn during the process
- Information sharing

To demonstrate that environmental guarantees are satisfied there is a need for special test methods. The guarantees relate to certain operating conditions, typically the most desirable from the point of view of environmental compliance

or energy production. Verification is carried out in conditions existing during the test, rarely the same as of the guarantees.

As an example, in a DO enhancement using aerating turbines, requirements typically stipulate what DO increase is to be achieved and with what efficiency or power loss due to the aeration.

The reality of field verification there are many factors influencing that enhancement, such as:

Water quality:

- water temperature and DO saturation conditions,
- oxygen content of the incoming water,

Operating parameters of the turbine:

- plant head and tailwater elevation in relation to the aerating turbine,
- rate of flow, especially in relation to the design flow,

Conditions of verifying measurements:

- type of DO sensors,
- location of the sensors in the tailrace,
- time necessary for oxygen to transfer to the dissolved state,

Particular design of the aerating turbine.

Each of these items could substantially affect results of the measurements. There is a clear need for criteria to take account for such variations.

The Role of ASME PTC-18 Goals

Understanding difficulties involved, members of the American Society of Mechanical Engineers Performance Test Code Committee on Hydraulic Turbines and Pump-Turbines (PTC-18), started work on development of recommendations related to the environmental performance of hydraulic turbines.

The goal of the Committee is to develop a set of "best practice" environmental recommendations that would help in establishing a fair distribution of duties between plant operators and equipment suppliers. The aim of this work is to reduce risks of the involved parties by helping them to define and verify performance of such systems. Specifically, the work focuses on the following issues:

- Developing guidelines for environmentally related guarantees
- Recommendations how to verify these guarantees

Step One – Aerating Turbines

As the first step in this direction, PTC-18 focuses on performance of aerating turbines, designed to increase the amount of DO. Flow aeration is relatively well understood and besides traditional turbine engineering, involves only elements of physics.

The steps necessary to accomplish the task of codifying include:

- gathering information on related affinity laws,
- recommendation how to set environmental performance guarantees,
- fundamentals of field verification of those guarantees,
- limits of applicability of verifying tests to prove that guarantees have been fulfilled,
- guidelines for measurement of performance change due to the aeration.

The process of setting the guidelines will be gradual and will begin with providing examples of successful solutions, perhaps not from the point of view of the designs themselves (often proprietary), but rather from the perspective of setting the guarantees and their verification.

Next Steps

Further steps considered include work on fish survival and any other environmental requirements that might emerge.

Need for Help

ASME PTC-18 is composed of representatives of various interest groups in hydropower, with different exposure to environmental issues. Even we understand the need for environmental standards, our expertise in this respect is limited. The Committee needs support of experienced industry professionals. In particular, we look for input in:

- setting environmental requirements related to hydraulic turbines
- description of verifying tests, test setups, equipment, results

How this help could be accomplished:

- providing us with results of completed tests
- reviewing documents prepared by the Committee
- writing parts of the standards
- any other help that might be offered

Any interested persons or organizations are encouraged to contact the author at juliusz.kirejczyk@toshibatic.com, tel. 413-320-5286

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Juliusz Kirejczyk is a Turbine Engineer at Toshiba International Crop. For most part of his over 35 years in hydropower industry, he has been working with suppliers of turbines and pump-turbines. He joined PTC-18 in 2003.

Expected Fish Survival for Full Scale Deployment of the Alden Turbine

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Abstract

The fish friendly Alden turbine is designed to safely pass fish downstream while generating power. Applications for the new technology include using the turbine as a downstream fish bypass, passing minimum flows, adding new capacity, and new developments at non-powered dams. A theoretical method for estimating fish passage survival has been developed from an extensive pilot study and subsequent blade strike studies. This method allows predictions to be developed for sites with varying turbine design conditions. This paper presents survival predictions for full scale application of the Alden turbine at three potential sites. Predicted survival estimates range from 98% to 100% for fish less than 8 inches in length. Field testing is an important next step in verifying predicted performance and in garnering industry and resource agency acceptance of the turbine as a viable method of passing fish downstream at hydroelectric projects.

Introduction

The fish friendly Alden turbine is being considered as a method for safely passing fish downstream at several hydro projects. This turbine design was developed and pilot-scale tested as part of the U.S. Department of Energy's Advanced Hydro Turbine Systems program. The design of the Alden turbine was based on minimizing damage to fish by ensuring hydraulic, pressure, and mechanical sources of injury were either eliminated or sufficiently reduced. The results of the pilot-scale tests demonstrated that turbine passage survival was high when scaled to full prototype (about 98% or greater) for six species of fish (rainbow trout, coho salmon, smallmouth bass, alewife, American eel, and white sturgeon). Of particular interest, immediate survival rates scaled to full prototype for American eel and white sturgeon were approximately 100%.

The development of the Alden turbine design has continued since the pilot tests with: (1) a redesign of the scroll case and runner to double the power and improve efficiency; and (2) an evaluation of the effects of turbine blade leading edge design and thickness on fish strike survival. Both of these efforts were funded by the Electric Power Research Institute (EPRI). The blade strike studies have demonstrated that thicker leading edges will be less damaging to fish and likely will improve the fish-friendliness of most turbines designs, including the Alden turbine.

Data from the pilot-scale biological evaluation and leading edge blade testing indicate that species and life stages of interest, including adult shortnose sturgeon and silver American eels, passing through a full-scale Alden turbine designed for a specific site will experience very high survival rates (greater than 98%). This

paper presents survival predictions for several potential full-scale applications of the Alden turbine.

Probability of Fish Mortality from Turbine Blade Strike

Probability of Blade Strike

The probability of blade strike can be derived from the distance the leading edges move relative to the total distance between leading edges during the time it takes the fish to move through the arc of leading edge blade motion. For example, if turbine blades move relatively little in that time (say 10% of the total distance), then relatively few fish will be struck (10%) and most fish (90%) will pass without being hit by a leading edge. Conversely, if turbine blades move most of the distance between blades (say 90%) in the time that fish pass through the arc of blade motion, then most of the fish (90%) will be struck by a leading edge. Other parameters, such as the length of the fish compared to the length of a flow streamline that passes between blades or the time it takes for fish to pass through the blade arc versus the time for one blade pass, all lead to the same blade strike probability model presented below (Ploskey and Carlson 2004).

$$P_s = n [L \sin \alpha] N / 60 V_r \quad (\text{dimensionless}) \quad (1)$$

where:

N = number of blades

n = rpm of runner

L = fish length

α = angle of absolute inflow (see Figure 2-100)

V_r = radial (or axial) component of inflow velocity

This is a logical expression, indicating that the probability of strike increases with runner rpm, fish length, and number of blades, but decreases with increasing velocity carrying the fish past the arc of blade movement. This strike probability model has appeared in the literature for many years (Von Raben 1957) and has become the accepted method for calculating probability of blade strike (Ploskey and Carlson 2004).

Figure 2-100

Plan view of absolute and relative velocities at leading edge of turbine blade.

Probability of Mortality from Blade Strike

In addition to the probability of blade strike, researchers have also determined that only a fraction of the fish struck by turbine blades are likely to be killed (Turnpenny et al. 2000; EPRI 2008). To account for this, Equation 1 is multiplied by a “mortality” coefficient (K) as follows:

$$P_{sm} = K n [L \sin \alpha] N / 60 V_r \quad (2)$$

Where:

P_{sm} = blade strike mortality rate

K = fraction of fish that are killed after being struck by a leading edge

The probability of mortality from blade strike (K) is derived from experiments conducted in a linear flume with simulated turbine blades accelerated to pre-determined velocities before striking anesthetized fish (EPRI 2008). The results of these studies demonstrate that the ratio of fish length (L) to leading edge thickness (t) is an important factor influencing fish mortality from blade strike. To maximize fish deflection away from the leading edge, a semi-circular leading edge shape was proposed and used during this study. It was determined that blade strike survival is considerably greater if the leading edge blade thickness is close to the fish length. That is, L/t ratios of approximately one or less produced high strike survival rates (> 90%) even at the higher strike velocities tested (up to 40 ft/s). It was also apparent from the results of this study that the maximum strike velocity at which the survival is 100% varies with the L/t ratio, and that the slope (m) of the decrease in survival (increase in mortality) with corresponding increases in strike velocity changes with the L/t ratio.

Estimates of Turbine Passage Survival for Field Installations of an Alden Turbine

The above information allows estimates of turbine passage survival for an Alden turbine to be calculated for any given site. By using well established “homologous” machinery equations to scale from the tested pilot-scale turbine characteristics to a field site (i.e., to the same or different head and flow in the field application), the runner diameter, rotational speed (rpm), V_{rel} , and V_r will be known for any site of interest. By selecting a leading edge blade thickness (such as 150 mm), the L/t ratio can be calculated for selected ranges of fish lengths to determine corresponding K values (i.e., mortality of fish struck by a blade). Since the same turbine is involved in the scale-up (i.e., the Alden turbine), all other features such as the number of blades and the inflow angle remain the same. Thus, all parameters required are known and the strike mortality (or survival) can be calculated for each selected fish length. The data that were examined previously were for rainbow trout, but the method of predicting turbine passage survival is the same using data specific to any other species.

Turbine passage survival rates were developed for three potential applications of the Alden turbine. The following hydroelectric projects were evaluated:

Project A, New England, United States

Project B, Northeast, United States

Project C, France

The characteristics of each project are provided in Table 2-20.

Based on the site characteristics and methodology described above, survival predictions were developed for each site. Greater than 90% of fish entrained at hydropower projects are less than 8 inches in length (Winchell et al 2000). Survival predictions for fish 8 inches in length are presented below for each site:

Project A	99.8 %
Project B	98.4%
Project C	98.1%

In addition, using the parameters of each site, turbine survival predictions were developed as a function of fish length and are presented in Figure 2-101 through Figure 2-103 for each field installation evaluated.

Table 2-20

Characteristics of projects that were evaluated for application of the Alden Turbine

Site details	Project A	Project B	Project C
Head (ft)	35	92	66
Flow (cfs)	1200	1500	1267
Turbine diameter (ft)	13	12.7	10.6
Turbine speed (rpm)	72	120	101
Leading edge blade thickness (inches)	6	6	5
Strike velocity (ft/sec)	25	38.3	32.4

Figure 2-101

Turbine passage survival prediction for Project A Alden turbine application (head 35 ft, flow 1200 cfs, turbine diameter 13 ft).

Figure 2-102

Turbine passage survival prediction for Project B Alden turbine application (head 92 ft, flow 1500 cfs, turbine diameter 12.7 ft).

Figure 2-103

Turbine passage survival prediction for Project C Alden turbine application (head 67 ft, flow 1267 cfs, turbine diameter 10.6 ft).

The turbine passage survival prediction for Project A (Figure 2-101) indicates very high survival (99.8%) for Atlantic salmon less than 8 inches in length. This prediction assumes similar survival for salmon as we observed with rainbow trout. Rainbow trout data is applicable to predict survival for all bony fish. Test data from the pilot scale tests and blade strike tests indicate sturgeon and eel survival is greater than other bony fish tested. Survival predictions of sturgeon were developed for Project A and indicate 100% survival for fish up to 300 mm in length. This high survival is due to the low strike speed (25 ft/sec, 7.7 m/s), which is below the velocity threshold that causes injury for sturgeon with an L/t ratio of 2.

The turbine passage survival prediction for Project B indicates high survival (98.4%) for fish less than 8 inches in length (Figure 2-102). The species of concern for Project B are blueback herring and American eel. American eel is expected to have high survival, (100% survival for pilot scale tests). Blueback herring, a bony fish, is expected to have survival similar to rainbow trout. A conventional Kaplan turbine has been considered for Project B for comparison to the Alden turbine. Predicted fish survival for a Kaplan unit is 84% using the same methodology described above, but applied to the characteristics of the proposed Kaplan unit.

The turbine passage survival for Project C also indicates high survival (98.1%) for salmon less 8 inches in length (Figure 2-103).

Summary and Conclusion

The high survival estimates indicate that the Alden turbine has potential to generate power, while passing fish downstream without the need for costly fish exclusion, collection, or bypass systems. The next important step in the development and acceptance of the Alden turbine is a field demonstration project. A demonstration test would verify the fish passage performance of the turbine and provide valuable information to the industry and resource agencies for application and acceptance of this new turbine technology.

References

EPRI (Electric Power Research Institute). 2008. Evaluation of the Effects of Turbine Blade Strike Leading Edge Design on Fish Survival. Prepared by Alden Research Laboratory, Inc., EPRI Report No. 1014937.

Hecker, G. E. and G. S. Allen. 2005. An Approach to Predicting Fish Survival for Advanced Technology Turbines. Hydro Review, Vol. XXIV, No.7.

Ploskey, G. R., and T. J. Carlson, T.J.. 2004. Comparison of Blade Strike Modeling Results with empirical Data. Pacific Northwest National Laboratory, PNNL 14603.

Turnpenny, A. W. H., S. Clough, K. P. Hanson, R. Ramsay, and D. McEwan. 1992. Risk Assessment for Fish Passage through Small, Low Head Turbines. Marine and Freshwater Biology Unit, National Power, Fawley, Southampton, England, Report No. ETSU H/06/00054/REP.

Von Raben, K.. 1957. Regarding the Problem of Mutilations of Fishes by Hydraulic Turbines. Originally published in Die Wasserwirtschaft (100) 4:97; Translation in Fisheries Research Board of Canada Translation Series, No. 448, 1964.

Winchell, F., S. Amaral, and D. Dixon. 2000. Hydroelectric Turbine Entrainment and Survival Database: An Alternative to Field Studies. Proceedings of Hydrovision 2000. HCI Publications, Inc., St. Louis, Missouri.

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Demonstrating the Performance of the Alden Turbine in the Real World

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Douglas A. Dixon, Electric Power Research Institute

Abstract

With an increasing demand for renewable energy throughout the world, the ability to produce power while minimizing environmental impacts has become a driving force in the continued development of hydropower. A new hydropower turbine that has potential to contribute to power demands while minimally impacting fish populations is the Alden turbine, which was developed through the U.S. Department of Energy's (DOE) former Advanced Hydro Turbine Systems Program and, more recently, Electric Power Research Institute (EPRI)-sponsored research. This turbine has been designed and model tested by Voith Hydro and is ready for commercial application. EPRI has conducted a study to identify a demonstration project for the installation and testing of the Alden turbine. In mid 2010, a solicitation was distributed to the hydropower industry for potential demonstration sites. A final numeric ranking of the sites led to the selection of one site as the preferred location for development as a demonstration program for the Alden turbine. In 2011 and beyond, EPRI will assist the owner with activities that will further the design, installation, and funding of the field demonstration project.

Introduction

EPRI's next objective in the continued development and deployment of the Alden turbine was to identify a site where it can be installed and tested. While there was a preliminary plan by Brookfield Renewable Power Company to install and test the turbine at its School Street Hydroelectric Project near Albany, NY, as of 2009 some uncertainty developed whether that will come to fruition. To insure that a demonstration project occurs, EPRI committed to finding an additional or alternate test site where development and deployment of the Alden turbine could be supported. Toward that end, in late 2009 a proposal to find a test site was submitted to the EPRI 3% Demonstration Program for funding consideration. The proposal effort was successful and this paper summarizes the result of the work proposed.

EPRI developed a list of preferred site criteria for evaluating the performance of the turbine. These criteria were included in an application solicitation distributed to the U.S. and international hydropower industry. Applications received were reviewed, quantitatively prioritized and a preferred site selected.

In 2011 and beyond, EPRI will assist the owner with activities that will further the final design, installation, and funding of the field demonstration project. Details of this process and the results to date are provided herein.

Demonstration Project Background (2010)

In mid 2010, a solicitation was distributed to the hydropower industry for potential demonstration sites (Figure 2-104). Twenty three applications were submitted to EPRI via a web-based platform. A quantitative evaluation process was developed and implemented to objectively evaluate and rank the applications. Site visits to the five highest ranked candidate sites were conducted during the fall of 2010 to verify application information and collect additional project details. The five sites were then again quantitatively evaluated based upon applicant commitment, sizing and general layout of turbine and water conveyance, fish species of concern and predictions of fish survival, and project development schedule (EPRI 2011a).

Seeking Additional Turbine Demonstration Site

EPRI is seeking additional potential demonstration sites at existing and new hydropower developments to install and evaluate the fish-friendly Alden turbine.

Benefits:

- Lead the industry in a strategic environmental R&D initiative
- Obtain potential cost share to minimize investment risk

Ideal Site Features:

- Head from 40 to 80 ft
- Flow from 1,000 to 2,000 cfs

To submit an application for consideration as a potential demonstration site, go to www.aldenlab.com/EPRIDemoapplication.
For more information, contact Douglas Dixon (ddixon@epri.com)

See opposite side for additional information.

EPRI Seeks Additional Site to Install and Test the Fish-Friendly Alden Turbine.

EPRI is seeking an additional demonstration site at an existing or new hydropower development to install and evaluate the fish-friendly Alden turbine. With a grant from the U.S. Department of Energy (DOE), EPRI is currently working on the engineering design of this innovative hydropower turbine with features that have been shown to significantly reduce injury and mortality of fish.

The industry solicitation for an additional demonstration site will be launched in April 2010 and respondents can apply using a web-based application form. From the applications received, two or three projects will be selected for a detailed feasibility assessment. Based on the results of the detailed assessments, a final recommendation will be made at the end of 2010 for the site that is best suited for installation and demonstration of the Alden turbine.

Future work for the additional demonstration project will focus on site design engineering and installation planning, site construction and turbine installation, and biological and operational turbine testing. EPRI will seek funding from industry and government sources to support these efforts.

In addition to maximizing fish passage survival while increasing generating capacity, a successful demonstration of the Alden turbine may enhance corporate and industry opportunities to further expand hydropower generation. Submitting an application involves no commitments at this time. A commitment will be established for the selected site following the completion of the detailed feasibility assessment. For additional information on this initiative, please contact Douglas Dixon at ddixon@epri.com or 804-642-1025.

The EPRI Demo Project Application is available on the Alden Research Laboratory Inc. web site: www.aldenlab.com/EPRIDemoapp/ica100

Figure 2-104
Project Announcement

The final numeric ranking of the sites led to the selection of one site as the preferred location for development as a demonstration program for the Alden turbine. An alternate site was also identified in the event the preferred site could not be developed. Applicant names and the identity of the preferred and alternate site remain confidential at this time until requisite licenses and/or permit actions are formally filed with the involved licensing/permitting authorities.

The preferred demonstration site would be located at an existing facility which is composed of two Kaplan units commissioned in 1950 (Figure 2-105). The conceptual plan would be to construct a stand-alone powerhouse adjacent to the existing powerhouse to accommodate the Alden turbine. This way, the existing units could continue to generate during most of the construction. One of the last

construction tasks would be to tie into one of the existing penstocks to divert flow to the Alden unit. One of the existing units would then be abandoned.

Figure 2-105

Preferred Demonstration Site - View of the proposed powerhouse location, existing powerhouse seen at the left (looking downstream from the headworks).

The alternate demonstration site would be a new hydropower facility installation at an existing non-powered dam (Figure 2-106). The greatest attribute of this site would be that a new powerhouse could be built specifically for the Alden turbine with minimal interruption to current site irrigation operations. The powerhouse would be located adjacent to an existing valve control structure and similar to the preferred demonstration site, one of the last construction tasks would be to tie into one of the existing valve penstocks to divert flow to the Alden unit.

Figure 2-106

Alternate Demonstration Site - View of the proposed powerhouse location, existing valve house seen at the right (looking downstream from the dam crest).

Demonstration Project Work in 2011

To continue the demonstration project development work begun in 2010, a request for additional EPRI 3% Fund Expenditures for Industry Technology Demonstration Projects was submitted and approved for 2011. The work to be completed in 2011 will further the final design, installation, and funding of the field demonstration project and further the Front End Engineering and Design (FEED) to deploy the turbine.

The preliminary turbine design that was recently completed by Voith during the EPRI-DOE supported project (EPRI 2011b) will need to be modified somewhat for the selected demonstration site. This task includes scaling the current turbine design to the demonstration site conditions. Scaling may include resizing the turbine runner diameter and speed of the unit depending on the selected head and flow conditions. Based upon the scaling results, mechanical equipment sizing may need to be analyzed and adjusted.

Once the parameters of the demonstration site operating conditions and geometry have been established, Voith and the site owner would begin the formal turbine proposal process. Voith has an exclusive license to supply the turbine. The proposal typically requires three months to complete and would be followed by approximately six weeks of negotiations between Voith and the site owner. The next six weeks would consist of contract preparation culminating in a signed agreement on or about Jan. 2012.

An overall management plan will be developed for the selected demonstration site such that implementation activities can effectively proceed. The management plan will include documentation of all activities to be performed for implementing the demonstration project including the turbine purchase, site preparation and construction, turbine installation, and performance testing.

The deployment and demonstration of the Alden turbine is an investment risk beyond the usual financial resources of any single power company or public utility. A national and even international collaborative is required. One objective of the proposed program is to minimize the cost impact on the selected demonstration site host. EPRI will develop a funding plan and will research potential sources of revenue to design, construct, install, and test the Alden turbine. Assuming an appropriate DOE funding opportunity becomes available, EPRI will prepare a proposal, on behalf of the selected utility, for the demonstration project. An EPRI Supplemental Project Opportunity will also be created and EPRI will acquire industry funding to support the demonstration project.

An important task to ensure the successful installation and acceptance of the Alden turbine is to educate the turbine end user and the regulatory agencies that monitor and dictate environmental criteria for the demonstration site. Education would be provided via face to face meetings and prepared presentations.

The FEED involves the preliminary design of all demonstration site components to support the turbine's installation including intake gates and/or penstocks, power house, draft tubes, and tailrace modifications. The preliminary design will expand upon the conceptual design work completed in 2010. EPRI has assumed that the preliminary design will be conducted in unison with the site owner's chosen Architectural/Engineering (A/E) firm.

Demonstration Project Work in 2012-2014

Assuming the preferred site owner commits to the demonstration project, a contract is reached with Voith, and the EPRI board of directors accepts the project as a worthy EPRI demonstration program, the current demonstration project would then become a typical design, permit, and construction project. The following are tasks that EPRI intends to be supporting during this time:

- Permitting
- Preliminary engineering
- Oversight of A/E design
- Site investigations
- Preliminary engineering
- Final engineering design
- Development of commissioning program
- Initiation of project construction

- Inspection of turbine components
- Inspections, equipment QA/QC
- Turbine delivery and installation
- Project commissioning
- Development of an operation and maintenance program

Since the goal of the Alden turbine demonstration project is to show the high survival of downstream migrating fish while providing efficient electrical generation, the performance of both parameters must be independently verified post commissioning. Turbine survival testing and turbine performance study plans will be created prior to the completion of construction. The key to industry and agency acceptance for widespread use of the turbine is to develop testing plans beyond what may be required at the site specific level. The actual physical testing and results will be peer reviewed to confirm testing procedures, data collection, and data analysis.

The final steps to ascertain project success will be to complete the evaluation of predicted versus field performance (engineering and survival) and summarize the results in public forums and a peer reviewed journal. Equally important will be the evaluation of predicted costs versus as-built costs to allow an accurate economic analysis when considering the Alden turbine as a fish by-pass.

References

Electric Power Research Institute (EPRI). 2011a. Demonstration Development Project: Solicitation and Selection of a Site to Test a Fish-Friendly Hydropower Turbine. Prepared by Alden Research Laboratory, Inc. EPRI Technical Update #1022538.

Electric Power Research Institute (EPRI). 2011a. "Fish Friendly" Hydropower Turbine Development & Deployment: Alden Turbine Preliminary Engineering and Model Testing. EPRI Technical Report 1019890, Palo Alto, CA. September 2011.

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Section 3: Conference Survey

A survey form was supplied to all attendees at the conclusion of the conference. A total of 36 surveys were returned. The results of the survey are presented in Table 3-1.

In general, the response was very positive. Comments from attendees included:

- Would like to have see more involvement from resource agencies, regulators, and non-governmental organizations (NGOs)
- Would like to have heard something on the topic of hydrokinetic turbines
- Session 3 (New turbines for downstream fish passage) was the most informative to attendees
- The presentations by Brian Murtha (“The Alden fish-friendly turbine: preliminary design, model performance, and applicability to hydro sites”) and Brennan Smith (“Potential markets for new turbines”) were the most informative
- Alternative locations suggested for future conferences of this type included the American Fisheries Society annual meeting, annual Hydro Vision hydropower industry trade conference, and the NHA annual and regional meetings.

Table 3-1
Results of Conference Survey

Question	Number of Responses	% Responding	Yes	No	N/A	No Response	Comments
Did the content of the workshop live up to your expectations?	36	100%	34	0	1	1	Hoped for more NGO and agency participation; fantastic collection of leaders in the industry; broad but not enough details, US-specific; gave overview of current state-of-the-art; didn't have specific expectations
Was there any topic that you would have liked to hear discussed? If yes, what would it have been?	36	100%	18	16	0	2	Retrofit equipment/procedures; instream flows, TDG (including field test data for aerating turbines), more on DO; application of technos to high head projects; fish passage for non-salmonids; CFD particle tracking analysis; business models for utility buy-in; enviro impact comparison of hydro and other renewables (and non-renewables); politics of hydro; pumped storage; debate on tools; runner design features for fish survival; hydrokinetics; regulatory turbine biological performance expectations; more on barriers and uncertainties of techno development; other water quality issues; more on resources/regulatory views; practical applications of technologies (cost, benefits, etc.); more laymen's terminology for Hill audience
Which session was the most informative	31	86%	NA	NA	NA	5	* Session 3 (28%), Session 2 (22%), Session 5 (17%), Session 6 (14%), all sessions (11%), Session 4 (8%), Session 1 (0%)
Which session was the least informative	27	75%	NA	NA	NA	9	* None of the sessions (28%), Session 4 (24%), Session 1 (24%), Session 6 (14%), Session 5 (10%), Session 2 (0%), Session 3 (0%)
Which presentation was the most informative?	24	67%	NA	NA	NA	12	** Murtha (6), Smith (6), all (4), March (4), R. Brown (3), Amaral (2), Colotelo (2), Hecker (2), Perkins (2), Allen (1), Carlson (1), Dixon (1), Foust (1), Kirejczyk (1), Papillion (1)

Question	Number of Responses	% Responding	Yes	No	N/A	No Response	Comments
Which presentation was the least informative?	18	50%	NA	NA	NA	18	** NA/none (6), Murillo (2), Papillon (2), Allen (1), Amaral (1), Auger (1), Keynote (1), Medina Shuttles (1), Sale (1)
Are there other topics you would like to have presented?"	21	58%	14	6	1	15	** NA/No (6); hydrokinetics (3); CFD particle tracking; more info on turbine types, performance, and applications; post-trauma impacts past 3 days after passage; agency and politics; pumped storage; overall impact of hydropower on enviro; more discussion of specific runner design features; regulatory perspective; business perspective vs. engineering/science perspective
Did you have adequate time to network with others at the workshop?	36	100%	36	0	0	0	
Were there other speakers you would have liked to have heard? If yes, who would you have invited?	27	75%	10	14	3	9	** Resource agencies/regulators (10), economic analysis of all costs, NGO perspective (5), politicians, great job bringing the experts in, more industry representations (owners/operators) (2), international speakers

Question	Number of Responses	% Responding	Yes	No	N/A	No Response	Comments
Was the location a valuable experience? Can you suggest other venues where we can present this information?	31	86%	29	1	1	5	** Alternative venues: American Fisheries Society (4), Hydrovision (4), National Hydropower Association (3), Canadian Hydropower Association, Ecological Society of America, West Coast, publications (Fisheries, Hydro Review, international magazines), regional meetings in Northeast, Southeast, and Pacific Northwest
Did you enjoy the food provided?	33	92%	33	0	0	3	
Do you have any constructive criticisms or comments that would help with the organization of future workshops of this nature?	23	64%	10	12	1	13	** One of the best workshops I've been to; extend invite to NGOs, NMFS, FWS, and regional offices (2); sequence of talks not optimal - could have built on each other; well-organized and executed (2), hotel nice but pricier than used to; excellent organization, support, people, etc.; just do it; would have reorganized papers with historical perspectives in separate session and given more thought to synthesizing the content for Hill target audience; room layout odd with back section on different level; set a date/year for next workshop; was the right length; when sun was out it was difficult to see the screen; schedule conference outside of peak field season for resource agencies.

Question	Number of Responses	% Responding	Yes	No	N/A	No Response	Comments
What is your role in the industry?	30	83%	NA	NA	NA	6	** Regulator (8), consultant (7), fish biologist (2), grad student (2), hydraulic engineer (2), researcher (2), energy consultant, power marketing agency, senior scientist for Onatario Power Generation, small hydro producer, turbine component manufacturer, trade association, CFD engineer
General Comments	Great job, please have more like this in the future. I had a great time interacting with technicians, people from industry, and veterans in the turbine field. Just loved it!						
	Needed more presence from regulator and resource agency staff.						
	Excellent presenters; very interesting; I look forward to other conferences of this type.						
	Would be interesting to get a global perspective on environmentally-friendly turbines.						
	Can't wait to see field trial data of Alden turbine.						
	Need to integrate Canadian and U.S. research; both are related and we have similar issues/concerns.						
	One day would be enough. Lots of politics. I would emphasize more on the technical and technology. Very good first throw.						
	I think more thought could have been given to sequence of talks; but I think all speakers managed this well.						
	We need to take new presentations like Greg Allen's on Alden turbine to agencies and Hill to explain what we are doing and benefit. Add cost savings to that and get to operations within industry. This last panel does was exceptionally good in telling the story to policymakers, resource community, and other stakeholders - even the states and state agencies. Great job!						
	Extend invitation to widen range of countries (Canada, Europe, etc.) and to more industry (energy suppliers, academic, NGOs, policymakers, etc.). Presentations almost only U.S.A.-related: extend international. More emphasis on technical aspects compared to general, politics, partnerships, etc.						
	Must be familiar with the bigger picture of why all these studies around new designs of turbines. Answer - the concern for all this expenditure of funds for studies on new turbine designs is a result of the loss of threatened salmon on the west coast where back to back dams each add to the losses of salmon moving past them to and from the ocean. These are endangered species and the last of their kind - thus the concern about how we can save these species.						
	Very informative. Thanks!						

Question	Number of Responses	% Responding	Yes	No	N/A	No Response	Comments
							Alden tells me they will be participating near-term in a wider range conference on fish, dam removal, etc. where they plan to discuss options i.e., broader outreach, which I think is very helpful. Is there any opportunity to do a feature on this subject on Discovery/History Channel, etc.? Public opinion is probably even more important than NGO's, etc. How do we get more non-Federal owners engaged?
							Excellently organized. Excellent presentation subjects, well delivered. Excellent discussion opportunities.
							Great presentations. Well organized.
							Early focus on relative "attractiveness" of hydropower and how to increase its profile within OMB was not really appropriate for this technical conference.
* Percentages represent the percent of the total number of votes received.							
** Numbers in parentheses represent the total number of votes received.							

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