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Hydropower R&D

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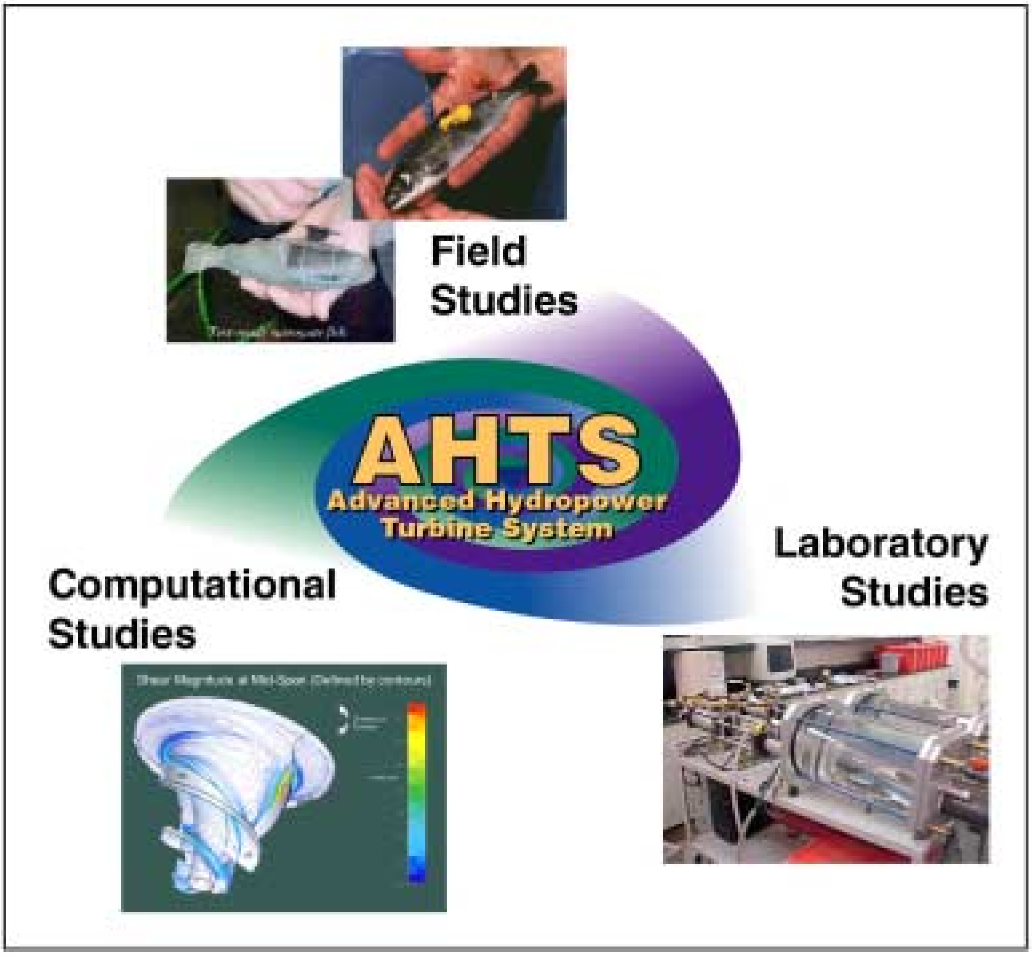

United States
Department of Energy

DOE/ID-10753

Hydropower R&D: Recent Advances in Turbine Passage Technology

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Published April 2000

Prepared for the
U.S. Department of Energy
Idaho Operations Office

ABSTRACT

The purpose of this report is to describe the recent and planned R&D activities across the U.S. related to survival of fish entrained in hydroelectric turbines. In this report, we have considered studies that are intended to develop new information that can be used to mitigate turbine-passage mortality. This review focuses on the effects on fish of physical or operational modifications to turbines, comparisons to survival in other downstream passage routes (e.g., bypass systems and spillways), and applications of new modeling, experimental, and technological approaches to develop a greater understanding of the stresses associated with turbine passage. In addition, the emphasis is on biological studies, as opposed to the engineering studies (e.g., turbine index testing) that are often carried out in support of fish passage mitigation efforts.

SUMMARY

One of the major environmental issues for hydroelectric power production is turbine-passage fish mortality. Downstream-moving fish may be drawn into the intake and suffer injury or mortality when passing through the turbine. Because this damage is caused by physical or fluid forces, turbine passage losses may be lessened by improving passage conditions within the turbine, for example by increasing the size of passages and/or decreasing pressure changes, cavitation, shear stresses, or probability of strike.

Research to improve the survival of turbine-passed fish is being conducted by a variety of organizations, especially power producers in the Pacific Northwest (the U.S. Army Corps of Engineers and Public Utility Districts) and the U.S. Department of Energy's (DOE's) Hydropower Program. The U.S. Army Corps of Engineers (COE) operates eight multipurpose dams on the lower Columbia and Snake Rivers. As part of the Columbia River Fish Mitigation Program, COE has studied engineering and biological aspects of juvenile fish passage through turbines, developed biologically based turbine design criteria, and evaluated prototype advanced turbines that are designed to improve survival of juvenile salmon and steelhead. Turbine passage studies have been carried out by the COE at the Bonneville, McNary, and Lower Granite Dams. Similarly, Public Utility District No. 2 of Grant County and Public Utility District No.1 of Chelan County have studied the effects of turbine structural and operational modifications on fish survival at the Wanapum, Rocky Reach, and Rock Island Dams.

One of the major activities of DOE's Hydropower Program is the development of fish-friendly turbines under the Advanced Hydropower Turbine System (AHTS) Program. The AHTS Program began in 1994 by supporting the development of conceptual designs for advanced turbines by the Alden Research Laboratory, Inc./Northern Research and Engineering Corporation (ARL/NREC) and Voith Hydro, Inc. (Voith). The ARL/NREC concept is a new turbine runner designed to minimize fish injury and mortality. The new runner, based on the shape of a pump impeller, minimizes the number of blade leading edges, reduces the pressure-versus-time and the velocity-versus-distance gradients within the runner, minimizes clearance between the runner and runner housing, and maximizes the size of flow passages, all with minimal penalty on turbine efficiency. The Voith concept explored how existing turbines can be modified to both improve efficiency and reduce environmental effects. Design concepts for improved fish passage survival in Kaplan and Francis turbines (as well as designs for boosting dissolved oxygen levels in discharges from Francis turbines) were developed. Both the ARL/NREC and Voith turbines can be used for rehabilitation/upgrading of existing projects or for new installations. Subsequent

work in the AHTS program has focused on the development of biocriteria for turbine design and proof-of-concept testing of the ARL/NREC runner.

Other organizations that have supported turbine passage survival research include federal agencies (Bonneville Power Administration, U.S. Bureau of Reclamation, National Marine Fisheries Service, U.S. Geological Survey) and research and engineering firms (Electric Power Research Institute, Alden Research Laboratory, Inc. and Voith Hydro, Inc.). Their recent efforts are summarized in this report.

Improvements in field, laboratory, statistical, and modeling techniques for assessing turbine-passage survival have greatly added to our understanding of the downstream fish passage issue at hydroelectric power plants. Nevertheless, gaps remain that can be addressed by future R&D, and some of the studies have given conflicting results. In the final section we to draw conclusions from the completed studies, identify important gaps and contradictions, answer the most frequently asked questions about turbine passage survival, and suggest future research to help resolve the turbine-passage issue.

ACKNOWLEDGEMENTS

We thank the Technical Committee of the DOE Advanced Hydropower Turbine System Program, Rod Wittinger (COE), and Dick Fisher (Voith Hydro, Inc.) for their reviews. Preparation of this report was supported by the Office of Biopower and Hydropower Technologies, U.S. Department of Energy under contract DE-AC05-00OR22725 with University of Tennessee-Battelle LLC and contract DE-AC07-99ID13727 with Bechtel BWXT Idaho, LLC.

CONTENTS

FIGURES

TABLES

Hydropower R&D: Recent Advances in Turbine Passage Technology

1. INTRODUCTION

One of the major environmental issues for hydroelectric power production is turbine-passage fish mortality. Downstream-moving fish may be drawn into the intake (entrainment) and suffer injury or mortality when passing through the turbine. The consequence of this source of mortality to fish populations can be serious, especially among anadromous species (such as salmon, steelhead, American shad) and eels that must pass downstream to the sea to complete their life cycle. Turbine-passage losses might be mitigated by reducing the numbers of entrained fish (e.g., by improved fish screens or other diversion measures). Alternatively, mortality among entrained fish may be lessened by improving passage conditions within the turbine by increasing the size of passages and/or decreasing pressure changes, cavitation, shear stresses, or probability of strike.

A variety of organizations are conducting a considerable amount of research to improve the survival of turbine-passed fish. Downstream passage research performed at Columbia River Basin hydropower projects up to the mid-1990s is summarized in Whitney et al. (1997). The purpose of this report is to describe the recent and planned R&D activities across the U.S. related to survival of fish entrained in hydroelectric turbines. In this report, we have considered studies that are intended to develop new information that can be used to mitigate turbine-passage mortality. We have not attempted to summarize the numerous entrainment studies performed solely to estimate the existing level of turbine-passage mortality at a particular site for licensing purposes. Nor does this report consider in detail the widespread efforts to reduce the numbers of fish that are entrained, for example, through the application of intake screens, surface bypass structures, or behavioral barriers (although a few examples of planned screening and bypass studies are noted). This review focuses on the effects on fish of physical or operational modifications to turbines, comparisons to survival in other downstream passage routes (e.g, bypass systems and spillways), and applications of new modeling, experimental, and technological approaches to develop a greater understanding of the stresses associated with turbine passage. In addition, the emphasis is on biological studies, as opposed to the engineering studies (e.g., turbine index testing) that are often carried out in support of fish passage mitigation efforts.

In the following sections we briefly summarize the purpose and results of the studies, draw conclusions from the results to date, and suggest further R&D that are needed to resolve the turbine-passage issue.

2. SUMMARY OF ONGOING AND PLANNED STUDIES

Many of the turbine passage studies summarized here have been carried out in the Columbia River Basin, which has numerous mainstream dams (Figure 1) and large, but declining, populations of salmon and steelhead which must negotiate these dams. A variety of organizations are supporting these studies, including power producers and marketers (U.S. Army Corps of Engineers, Public Utility Districts, Bonneville Power Administration, and U.S. Bureau of Reclamation), research organizations (U.S. Department of Energy, National Marine Fisheries Service, U.S. Geological Survey, Electric Power Research Institute), and engineering firms (Alden Research Laboratory, Inc, and Voith Hydro, Inc.). See Appendix A for a list of contacts.

2.1 U.S. Army Corps of Engineers (COE)

The U.S. Army Corps of Engineers (COE) operates eight multipurpose dams on the lower Columbia and Snake rivers as part of the Federal Columbia River Power System. The COE's Columbia River Fish Mitigation program focuses on improving the passage of adult and juvenile salmon around these dams. The COE estimates that it will spend $1.4 billion implementing its fish mitigation program (GAO 1998). About $908 million of this total will be spent on the construction of fish passage projects and related studies from fiscal year 1999 through the scheduled completion of the program in fiscal year 2007.

The COE has put considerable effort into improving turbine passage survival in response to the Northwest Power Planning Council's request to enhance the survival of migrating adult and juvenile salmonids passing the Columbia and Snake River projects, as well as the National Marine Fisheries Service's (NMFS's) 1995 Biological Opinion on the operation of the federal Columbia River power system (NMFS 1995). The NMFS Biological Opinion recommends that the COE develop a program to comprehensively study engineering and biological aspects of juvenile fish passage through turbines, develop biologically based turbine design criteria, and evaluate how well various prototype designs and modifications improve juvenile fish survival through Kaplan turbines (Conservation Recommendation No. 5). Further, Reasonable and Prudent Alternatives recommended by NMFS (1995) to improve the operation and configuration of the hydropower system include operating turbines within 1% of peak efficiency during the juvenile and adult migration season and attaining 95% fish passage survival at each dam.

The COE Turbine Passage Survival Program (TSP) was developed to investigate means to improve the survival of juvenile salmon as they pass through Kaplan turbines located at Columbia and Snake River dams (COE 1998). The TSP is one part of the COE's multi-faceted Columbia River Fish Mitigation Program. Objectives of the TSP are to (1) develop modifications to the way that existing Kaplan turbines are operated to improve fish passage survivability as they pass through existing turbines; (2) identify biological design criteria that will provide the basis for the development of improved turbine designs; (3) investigate improved fish passage turbine designs or modifications to existing designs that could be implemented to assist the recovery of Columbia and Snake River salmon stocks; and (4) provide information on turbine passage survival which can be factored into decisions about the configuration of the basin's hydropower system.

The TSP is organized along three functional elements that are integrated to achieve the objectives: biological studies of turbine passage at field sites, hydraulic model investigations, and engineering studies in support of the other two elements and to optimize turbine operations. The biological field studies that have been conducted or are planned are summarized here (Table 1); the other two elements of the TSP is summarized in COE (1998). Examples of the laboratory and modeling studies conducted by the COE are provided in Table 2.

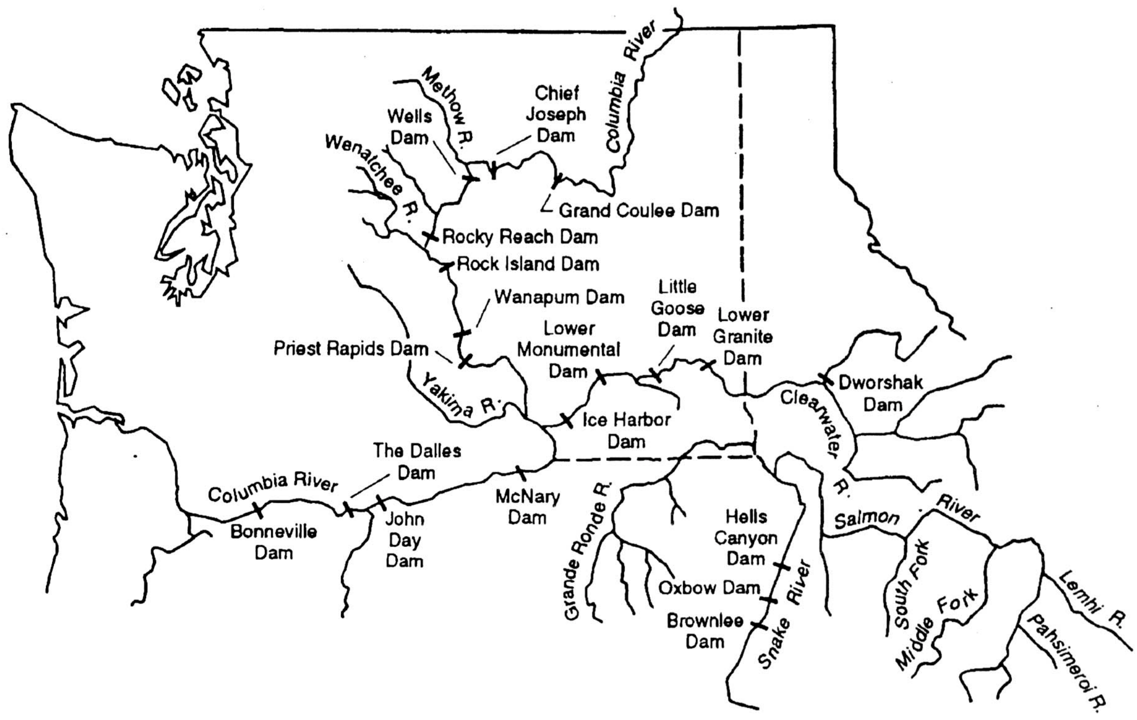

Figure 1. Hydroelectric projects in the Columbia River basin. Modified from Raymond (1988).

Table 1. Hydroelectric projects in the United States with recently completed, ongoing, or planned field studies of downstream fish passage mitigation.

Hydroelectric Project	Type of Biological Study						
	Turbine Passage with Physical Modifications	Turbine Passage with Operational Modifications	Screens and Other Exclusion Devices	Surface Collectors	Spill Passage	Fish Bypass and Release	Fish Distribution Within The Turbine
Bonneville	Comparison of fish survival through Bonneville I Unit 5 (conventional Kaplan) and Unit 6 (Minimum Gap Runner)	Also, this study will examine operational mods? - RKF		Modification of a prototype surface bypass at Bonneville I	Comparison of smolt survival in spillways with and without flow deflectors	New fish bypass and release system at the 2^{nd} powerhouse; plans and specifications for system at Bonneville I	Analysis of fish trajectories using video cameras
The Dalles				Surface bypass study	Spillway and sluiceway survival studies		
John Day			Testing of extended length screens		Spill efficiency and survival		
McNary	Comparison of survival of fish released in 4 locations within Unit 9		Testing of extended length screens				Analysis of fish trajectories using ultrasonic transmitters and video cameras
Ice Harbor							
Lower Monumental							
Little Goose							
Lower Granite		Comparison of survivals of fish released into Unit 4 in 4 locations and 3 operating conditions		Tests of prototype surface collector and behavioral guidance structures			
Priest Rapids							
Wanapum		Comparison of survivals of fish released into Unit 9 in 2 locations and 4 operating conditions			Comparison of smolt survivals through modified and unmodified spillbays	Smolt survivals through the ice/trash sluiceway	Predict the path of turbine-passed fish by CFD model

Table 1. (continued).

Hydroelectric Project	Type of Biological Study						
	Turbine Passage with Physical Modifications	Turbine Passage with Operational Modifications	Screens and Other Exclusion Devices	Surface Collectors	Spill Passage	Fish Bypass and Release	Fish Distribution Within The Turbine
Rock Island	Comparison of smolt survivals through 3 different turbine types				Comparison of smolt survivals through modified and unmodified spillbays		
Rocky Reach	Comparison of smolt survivals through conventional and reduced-gap runners						
Wells							
Buffalo Bill			Test of strobe lights at deep water intake				
Grand Coulee			Test of strobe lights at deep water intake				
Shasta			Test of multi-level outlet to reduce entrainment				

Table 2. Laboratory and modeling studies in support of fish passage mitigation.

Organization	Study
U.S. Department of Energy Hydropower Program	1) Biological Studies to Determine the Effects of Shear and Turbulence Stresses on Turbine-Passed Fish 2) Laboratory Studies of the Effects of Pressure on Turbine-Passed Fish 3) Workshop and laboratory studies to examine the role of turbulence in reservoir and turbine passage 4) Research and development of new instrumentation to track fish through turbine systems and during the entire life cycle
Georgia Institute of Technology/Voith Hydro	Computational Fluid Dynamics (CFD) modeling in support of laboratory shear stress studies and field studies turbine passage survival (partially funded by DOE Hydropower Program)
U.S. Army Corps of Engineers	1) Additional testing of Lower Granite model to explore stay vane - wicket gate relationships (partially funded by the DOE Hydropower Program) 2) Hydraulic modeling studies at Waterways Experiment Station 3) Set up computer model of fish distribution during turbine passage 4) In-turbine fish trajectory mapping through the development of ultrasonic and video imaging techniques (partially funded by DOE Hydropower Program) 5) Develop statistical model that combines survival, fish trajectory, and vertical distribution data to estimate overall turbine passage survival probabilities for the entire fish population 6) Characterize turbine environment in terms of environmental imaging (using information provided by Grant Co. PUD) and water passage pressure distribution (funding from EPRI)
Alden Research Laboratory, Inc.	Construction and testing of ARL/NREC Pilot Scale Fish-Friendly Turbine (funded by DOE Hydropower Program)
Pacific Northwest National Laboratory	Development and testing of sensor fish (partially funded by DOE Hydropower Program)
Voith Hydro, Inc.	1) Development of Virtual Fish model 2) Development of Minimum Gap Runner (MGR) designs for Bonneville and Wanapum 3) Development of zonal fish passage survival estimating methodology 4) Development of advanced instrumentation systems for controlling plant operation to optimize fish passage survival

2.1.1 Bonneville First Powerhouse

The COE plans to install minimum gap runners (MGR) on all ten units at the Bonneville I powerhouse (Chenoweth 1999). MGRs incorporate some of the fish-friendly features that Voith Hydro, Inc. is developing (Section 2.11). As the name implies, compared to a conventional Kaplan runner, the MGR reduces the gaps between the adjustable blade and the hub, and between the blade tip and the discharge ring (Figure 2). It is has been suggested that these modifications would reduce the fish injury caused by pinching, cavitation, shear stress and turbulence associated with the gaps found on conventional Kaplan runners. The first units to be replaced are Unit 6 (put into commercial operation on July 27, 1999) and Unit 4 (September 1999). The remaining eight units will be rehabilitated at the rate of one per year through 2008.

Beginning in November 1999, Normandeau Associates began biological testing of Unit 6 to determine the unit's ability to pass juvenile salmon safely. The survival of turbine-passed fish through Unit 6 was compared to the survival of fish passed through Unit 5, an adjacent, conventional Kaplan turbine (Figure 2). The goal of the biological testing was to determine if the MGR is at least equivalent to the existing machine in terms of fish passage mortality (i.e., it will do no harm). The biological tests, funded by the COE, Grant County Public Utility District No. 2, U.S. Department of Energy, and the Bonneville Power Administration, were conducted between November 15, 1999 and January 31, 2000. Using releases of a total of 7,200 balloon-tagged fish, the study produced 24 survival estimates, one for each of the two turbines at four operating conditions with three release points. Considerable effort was devoted to releasing fish in areas that would cause them to pass near the hub, at the mid-blade region, and near the blade tip.

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

The COE hopes to conduct a second year of biological testing, using run-of-river fish during a normal passage season. One of the reasons for delaying the tests until November was to take advantage of "improved biological conditions" (cooler water + fewer predators = more balloon-tagged fish recovered in the tailrace = better statistics for the survival estimates). This makes the comparison of different passage routes better, but may not produce representative estimates of turbine-passage mortality under more typical smolt passage conditions.

Sensor fish were used in the Bonneville I study as well. The smolt-sized artificial fish was developed by Pacific Northwest National Laboratory to better understand, in physical terms, the passage conditions that occur within a turbine. The sensor fish is instrumented to measure and record pressures, strain, temperature, bending moments, acceleration and other hydraulic parameters experienced during passage. Like real fish, it was attached to a balloon tag, introduced into the turbine flow, and recovered downstream.

In an effort to reduce the number of fish that pass through the turbines, a prototype vertical slot surface collector has been erected across four units of the Bonneville First Powerhouse (Takabayashi and Clarke 1999). Testing will begin in April 2000 to compare the new collector with the existing bypass

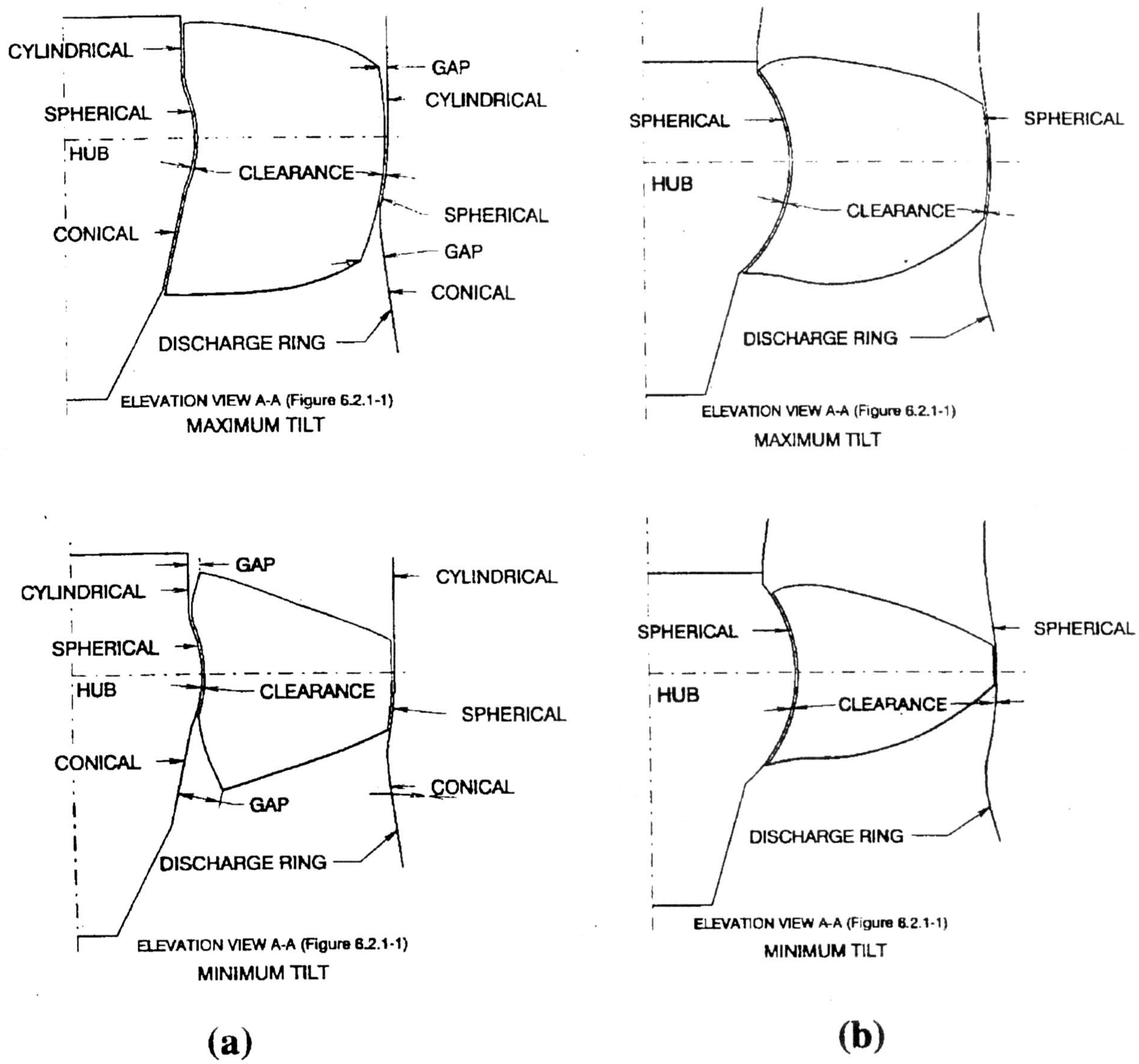

Figure 2. Comparison of (a) a conventional Kaplan turbine runners and (b) a Minimum Gap Runner (MGR). Source: Odeh (1999).

system that relies on submerged intake (gatewell) screens. If successful, the surface collector could replace the screen bypass system.

2.1.2 Bonneville Second Powerhouse

The original systems for screening and bypassing downstream migrants were installed at Bonneville First and Second Powerhouses in the early 1980s. Evaluations indicated that the bypass systems did not divert as many fish as expected, contributed to injury and stress, and returned the bypassed fish to an area of the tailrace where they were vulnerable to predators. COE studies suggested that survival rates were lower for fish using the bypass system than for fish passing through the turbine.

Upgrade of the bypass system was prompted by the NMFS Biological Opinion (NMFS 1995), which called on the COE to take reasonable and prudent actions to relocate the downstream outfall at the Bonneville Second Powerhouse by 1999, provide advanced monitoring facilities for downstream migrating juvenile salmon, and improve hydraulic conditions in the bypass system by 2000. The Second Powerhouse bypass system was rehabilitated and became operational in March 1999 (Takabayashi and Clarke 1999). Upgrades to the bypass system include modifications to the internal piping and collection channel system, construction of a new bypass pipe and flume that delivers bypassed fish to a safe outfall area 2 miles downstream, and construction of a juvenile fish monitoring facility.

A major component of the upgrade, the 4-foot-diameter, 2-mile-long transportation flume, releases bypassed fish into deep, fast-moving water where they are less likely to be preyed upon by birds and fish (Takabayashi and Clarke 1999). Juvenile chinook salmon traverse the flume in 40 to 45 minutes and steelhead in about an hour; preliminary data collected in 1999 indicate that the fish sustain virtually no injuries during the trip. The COE plans to conduct a 3-year study of salmon survival, beginning in March, 2000 (Peters 1999).

The COE is designing a surface collector to augment the intake screens used to reduce turbine passage at the Bonneville Second Powerhouse.

2.1.3 Bonneville Dam Spillway

It is generally assumed that passage over the spillway, rather than through the turbines, will result in higher survival of downstream-migrating fish. Survival rates of 98% or more among spillway-passed fish have been reported (Normandeau et al. 1996a). A concern associated with spillway passage is the potential damage to fish posed by flow deflectors that are located on the spillways of some hydropower plants. Flow deflectors are concrete sills installed on the downstream face of a spillway to direct spilled water along the surface of the tailrace. The deflectors prevent the plunging of spilled water to the bottom of the stilling basin, which can force atmospheric gases into solution and cause nitrogen supersaturation. Flow deflectors (also called flip lip deflectors) were installed below 13 of the 18 spillbays along the Bonneville Dam spillway in 1975 to reduce gas supersaturation (Figure 3). In addition, a row of 6-foot-high concrete dentates extends along the stilling basin downstream from the spillways; these dentates serve to dissipate the energy of spilled water.

The COE evaluated the survival and injury rates of Chinook salmon smolts that passed through particular spillbays with and without flow deflectors (Normandeau et al. 1996a). Flow rate through each spillbay was 12,000 cfs; at this flow, the tops of the concrete dentates were about 26 feet below the surface of the stilling basin. Both control fish and treatment fish released into the flow-deflector-equipped spillbay were directed along the surface of the stilling basin and would not be expected to interact with the submerged concrete dentates. However, treatment fish that passed through the other spillbay (without flow deflectors) may have been carried deeper into the stilling basin and encountered

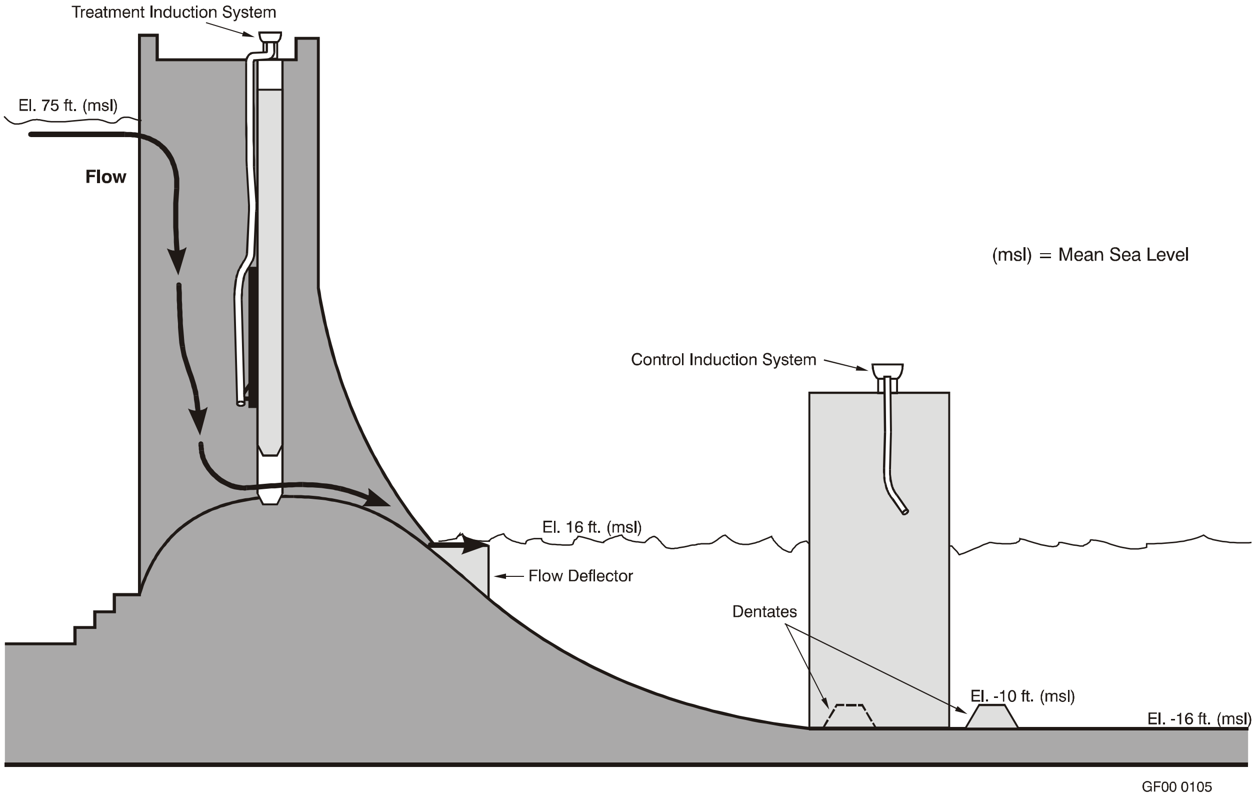

Figure 3. Bonneville Dam spillbay with flow deflector and dentates. Source: Normandeau et al. (1996a).

the dentates before being recovered. In any event, no adverse effects of spillbay passage and the flow deflectors were observed; 1-hour and 48-hour survival probabilities were estimated to be 1.0, whether or not the spillbay was equipped with a flow deflector. Injury rates were low for both treatment groups. There was some indication of a loss of equilibrium among fish that passed through the spillbay without a flow deflector; 4 fish out of 280 displayed loss of equilibrium, compared to none for the flow-deflector-equipped spillbay. The effects of spillway passage on susceptibility to predation (indirect mortality) was not studied, nor were concurrent turbine-passage studies conducted to compare the relative effects of turbine-passage and spillbay-passage on fish survival**.**

2.1.4 The Dalles Spillbay

As noted earlier, it is generally assumed that passage over the spillway will result in higher survival of downstream-migrating fish than passage through the turbines. Effective spillway passage is a function of both the numbers of fish that utilize this route and their subsequent survival. There are considerable differences among dams in the hydraulic and physical conditions of their spillways which can affect both spill effectiveness (number of fish passed over the spillway) and fish survival. For example, many spillbays are equipped with bottom-opening tainter gates, whose operation forces surface-oriented fish to sound as much as 40 feet in order to exit via spill (Normandeau et al. 1996b). The need to swim to greater depths in order to pass downstream of the dam is contrary to the natural behavior of salmon smolts and may reduce the number of fish that pass through the spillbays. This concern motivated the development of surface bypass collection systems that are being tested at many dams in the Columbia River basin (Takabayashi and Clarke 1999).

The COE compared the survivals of Chinook salmon smolts passing through three different spillbay configurations (Figure 4) at The Dalles Dam (Normandeau et al. 1996b). The three configurations were (1) the unmodified tainter gate, in which fish must descend as much as 40 feet from the surface to pass through the bottom opening; (2) a spillbay modified by a bulkhead (upstream from the tainter gate) in which water passed through an I-shaped opening (I-slot) at shallower depths; and (3) a spillbay modified by a bulkhead such that the bottom half of the bay was blocked and all water passing through the tainter gate passed through the top 20 feet (overflow weir). These tests did not attempt to quantify the numbers of naturally emigrating fish that utilized the different configurations, but rather sought to compare the relative survivals of test fish introduced to the three routes. In all three configurations, water and fish plunged approximately 50 feet into the stilling basin, which has a row of concrete baffles to dissipate energy and another energy dissipation structure (end sill) about 45 feet downstream from the baffles.

Survival probabilities and injuries were estimated at 1 hour and 48 hours after release. Flow through the unmodified and I-slot spillbays was 10,500 cfs during the tests, a flow rate that is typically used to bypass emigrants (Normandeau et al. 1996b). However, because of vibration problems, flow through the overflow weir configuration had to be limited to 4,500 cfs. There did not appear to be significant effects of spillway configuration on survival probabilities; 48-hour survival probabilities associated with passage through the unmodified, I-slot, and overflow weir spillbays were 0.955, 0.993, and 0.990, respectively. The authors suggested that most of the observed injuries (bulging/hemorrhaging eyes, hemorrhaging gills, and bruises/scrapes on the head) may have been due to collision with baffles, boulders, or the vertical end sill in the stilling basin. No concurrent turbine-passage studies were conducted to compare the relative effects of turbine-passage and spillbay-passage on fish survival.

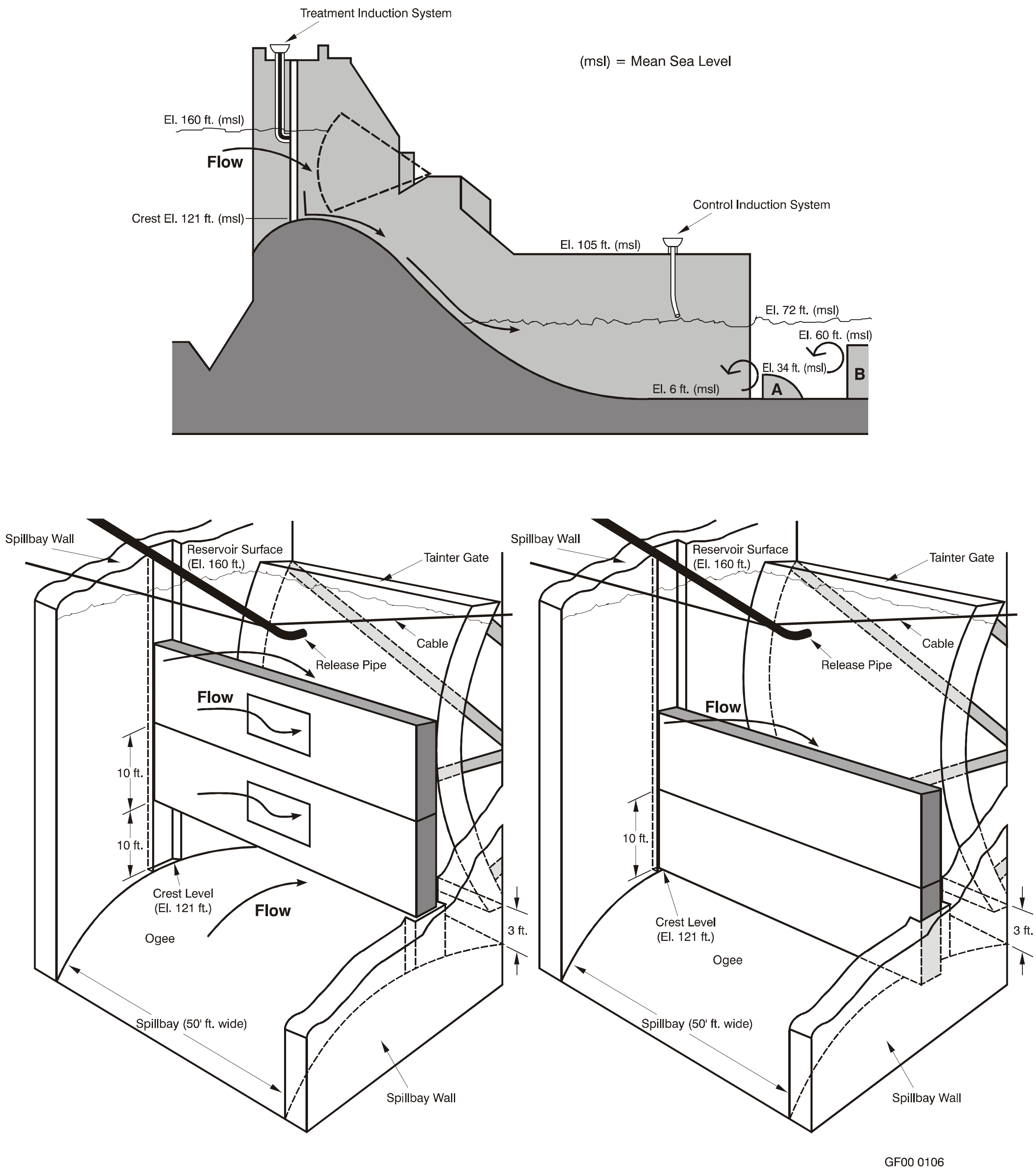

Figure 4. Spillbay configurations at The Dalles Dam. The three tested configurations were (1) the unmodified tainter gate; (2) a spillbay modified by a bulkhead in which water passed through an I-shaped opening (I-slot) at shallower depths; and (3) a spillbay modified by a bulkhead such that the bottom half of the bay was blocked and all water passing through the tainter gate passed through the top 20 feet (overflow weir). Source: Normandeau et al. (1996b).

2.1.5 McNary Dam

In 1999, the COE supported a study of the survival and injury rates of chinook salmon smolts that passed through a conventional Kaplan turbine, Unit 9 at McNary Dam on the Columbia River (Normandeau et al. 1999). Their goal was to determine the relative survivals of salmon smolts that followed different routes through the turbine. Fish were released at four locations in the turbine: (1) near the hub, (2) at mid-blade, (3) near the tip, and (4) at the wicket gates/stay vanes. These locations were chosen to test the idea that fish that passed through the runner in the mid-blade region would experience fewer injuries and higher survival than fish that passed near the runner hub or the blade tip. Fish were introduced at the hub, mid-blade, and tip locations in a way that they would not encounter the wicket gates and stay vanes.

Biological testing of McNary Unit 9 was completed during May-June 1999. All tests were conducted at the same operating condition: at a wicket gate opening of 42.6 degrees, a runner blade angle of 25.2 degrees, and the unit operating within 1% of maximum efficiency. At this blade angle, the hub gaps were 1.0 and 2.0 inches at the leading and trailing edges, respectively, and the blade tip gaps were 1.5 and 4.5 inches at the leading and trailing edges, respectively.

Between 309 and 330 fish were released at each of the locations; a total of 1264 fish were released, of which 1209 were recovered. Of the 1209 recovered, 35 were dead (2.9%), and other fish died over the 48-hour post-recovery holding period. There were no control releases, so test results were expressed as ratios which describe the relative survival rates among the four passage routes. The main conclusions of the study were:

1. There were no significant differences among the passage routes in terms of fish survivals after 1 hour (the best data). That is, in terms of short-term survival, it didn't matter whether the fish passed through the mid-blade region or through a route that was expected to be more dangerous (along the hub or blade tip).

2. The authors suggested that injury rates were slightly higher among fish that passed near the blade tip (5.1%) than over other routes (3.0% for wicket gate group and 3.8% for hub and mid-blade groups). However, statistical tests were not applied to these observations, so the suggested differences may not be significant.

3. The authors suggested that types of injuries were different among different routes. The dominant injury types were: hemorrhage/bruise for hub-passed fish, bruises and eye-damage for mid-blade fish, severed body and bruises for blade-tip fish, and severed body for wicket gate fish. No statistical tests were applied to judge the significance of these observations.

4. There were no differences between active smolts and immobilized smolts (alive, but anaesthetized) in terms of recapture times, recapture rates, or injury rates.

The authors concluded with the following cautionary statement - "The lack of differences in *relative* survival probabilities and injury rates between the release locations should not be construed as typical of the McNary site because only a single turbine operating point was tested." This was considered a pilot test to better delineate fish injury mechanisms, and to evaluate the experimental protocols and fish release systems for future experiments. The COE plans to conduct a second year of biological testing.

2.1.6 Lower Granite Dam

The effects of different operating conditions (turbine discharges) on survival of turbine-passed spring chinook salmon were examined at the Lower Granite Dam on the Snake River (Normandeau et al. 1995). Additional goals of the study were to develop information on the survival of fish passing through each of three intake bays to Unit 4 (conventional Kaplan turbine), and the effects of prototype extended length intake screens on the survival of turbine-passed fish. Three operating conditions were tested: 18,000 cfs (normal efficiency range), 13,500 cfs (normal efficiency range), and 19,000 cfs (cavitation mode). Also, test fish were released near the top and at mid-elevation in the three intake bays. The cavitation mode was created by "overgating" the turbine, which caused moderate cavitation; however, this condition produced less cavitation than would be created at full output.

Overall short-term (1-hour) survival among the juvenile spring chinook averaged 96.1%; at 120 hours post-test, pooled survival averaged 94.8%. No statistically significant differences were observed in the survivals of turbine-passed spring Chinook salmon smolts among the six test scenarios (combinations of turbine discharge and release location). The hypothesis that survival of turbine-passed fish may be greatest at discharges within 1% of peak turbine efficiency could not be supported by this study. In fact, survivals of turbine-passed fish under moderate cavitating conditions were not significantly different from survivals at highest efficiency. The extended length intake screens were kept in place throughout the tests, so the effects of the screens on passage routes and survival of fish under different operating conditions and release locations could not be determined.

2.2 U.S. Department of Energy

One of the major activities of the U.S. Department of Energy (DOE) Hydropower Program is the development of fish-friendly turbines under the Advanced Hydropower Turbine System (AHTS) Program. The AHTS Program is exploring innovative solutions, developing new concepts, applying cutting-edge technology and utilizing applied engineering to develop new turbine equipment. The new designs will be installed and demonstrated in operating power plants.

The AHTS Program is coordinated with related activities being conducted by industry and other agencies, such as Public Utility District No. 2 of Grant County, Electric Power Research Institute, the COE, U.S. Bureau of Reclamation, Bonneville Power Administration, and National Marine Fisheries Service. Members of these organizations advise DOE by participating in its Technical Review Committee.

The AHTS Program began in 1994 with a request for proposals for conceptual designs for advanced turbines. Proposals were evaluated by the Technical Review Committee and contracts awarded to Alden Research Laboratory, Inc./Northern Research and Engineering Corporation (ARL/NREC) and Voith Hydro, Inc. (Voith) in October 1995. Conceptual design reports were completed by both ARL/NREC (Cook et al. 1997) and Voith (Franke et al. 1997), and summarized by Odeh (1999).

The ARL/NREC conceptual design focused on the development of a new turbine runner to minimize fish injury and mortality. The new runner, based on the shape of a pump impeller, minimizes the number of blade leading edges, reduces the pressure-versus-time and the velocity-versus-distance gradients within the runner, minimizes clearance between the runner and runner housing, and maximizes the size of flow passages, all with minimal penalty on turbine efficiency. The flow characteristics of the new runner were analyzed using two-dimensional and three-dimensional Computational Fluid Dynamic (CFD) models.

The Voith conceptual designs examined how existing turbine designs can be modified to improve efficiency and reduce environmental effects. Design concepts for improved fish passage survival in Kaplan and Francis turbines (as well as designs for boosting dissolved oxygen levels in discharges from Francis turbines) were developed. These concepts can be incorporated into rehabilitation of or upgrading existing projects or into new installations.

During the development of conceptual designs, it became clear that there were significant gaps in knowledge of fish responses to physical stresses experienced during turbine passage. Consequently, the Technical Review Committee recommended that subsequent R&D by the AHTS Program be broadened to include studies to develop biological criteria for turbines. In response, the AHTS Program is presently involved in two broad areas: the development of biological criteria and proof-of-concept testing of one of the conceptual turbine designs, the ARL/NREC runner (see Table 2 for description and Appendix B for illustration). A longer-term goal is to support the testing of full-sized prototypes of promising advanced turbine designs.

2.2.1 Development of Biological Criteria for Advanced Turbines

Design of advanced, environmentally friendly hydroelectric turbines requires quantification of the physical stresses (injury mechanisms) that impinge on entrained fish and the fish's tolerance to these stresses. Instrumentation of turbines and the increasing use of CFD modeling can provide considerable information about the levels of each of these potential injury mechanisms that can be expected within the turbine. Frequently missing, however, are data on the responses of fish to these levels of stress.

DOE is supporting research to determine the biological effects of the physical stresses. The research is conducted under controlled laboratory conditions and coupled with physical and numerical modeling that will relate test conditions to levels encountered during passage through a hydropower turbine. To accomplish this, experimental apparatuses have been designed and constructed that are intended to (a) create quantifiable and reproducible amounts of stresses that are representative of those encountered in a hydropower turbine; (b) expose a variety of fish species and sizes to those levels of stresses; (c) as appropriate, record the behavioral response of fish to stresses during the test; and (d) allow for the post-test assessment of survival, injury, and susceptibility to predation.

A recent literature review concluded that among the injury mechanisms associated with turbine passage (water pressure changes, cavitation, shear, turbulence, strike, and grinding), shear and turbulence are considered the least understood (Čada et al. 1997). DOE has funded the Pacific Northwest National Laboratory (PNNL) to conduct laboratory tests needed to develop the biological criteria for shear and turbulence. Further, DOE is supporting studies of the complicating effects of nitrogen gas supersaturation (a common water quality problem in the Columbia River basin) on the fish's response to pressure changes associated with turbine passage.

2.2.2 Proof of Concept of the ARL/NREC Runner

ARL/NREC developed a new concept for a more fish-tolerant turbine runner under the initial phase of the AHTS Program (Cook et al. 1997). This runner will be tested under controlled, replicable conditions in a laboratory facility. See Section 2.10 for a description of this effort.

2.3 Public Utility District No. 2 of Grant County

The survivals of Coho salmon entrained at two depths and at four turbine discharge rates were compared at the Wanapum Dam on the Columbia River (Normandeau et al.1996c). Some of the objectives were to (1) obtain baseline fish survival and condition data for use in turbine design modifications; (2) evaluate the effects of turbine operation efficiency (as indexed by turbine discharge data and theoretical avoidable loss calculations) and entrainment depth on fish survival; (3) correlate survival estimates at Wanapum to available laboratory model results; and (4) provide survival data for future CFD calculations in the vicinity of runner blades and draft tubes. All tests were run at Unit 9, a conventional Kaplan turbine.

A total of 160 tagged fish (40 fish per trial, 4 trials) were released at each depth (10 feet and 30 feet below the intake ceiling) and turbine discharge (9,000 cfs, 11,000 cfs, 15,000 cfs, and 17,000 cfs). From lowest to highest, the four turbine discharges were equivalent to turbine efficiencies of 93.51%, 94.23% (peak efficiency), 92.75%, and 88.57% (cavitation range of operation). Recovery of tagged fish exceeded 88% for all trials. The highest rate of tag dislodgement occurred among fish that passed near the hub at the highest discharge, and was attributed to excessive hydraulic turbulence.

At the two highest discharges, survival probabilities were significantly lower among fish introduced at the 10-ft depth than among those released at the 30-ft depth. Average 48-hour survival estimates were 0.914 and 0.971 for smolts at the 10-ft and 30-ft releases depths, respectively. Because the actual paths of the turbine-passed fish could not be determined, CFD modeling was used to predict the paths of coho salmon introduced at the different depths and discharges. The CFD model results suggested that fish introduced at the 10-ft depth passed near the hub, whereas those introduced at 30-ft depth passed near mid-blade. The authors speculated that, compared to mid-blade-passed fish, fish passing near the hub may be subjected to greater turbulence, exposure to a cavitation zone, swirling flows, and sharp-edged gaps between the runner blades and the hub. With regard to operating conditions, the highest probabilities of fish survival occurred at a turbine discharge of 15,000 cfs (turbine operating efficiency of 92.75%). The highest turbine operating efficiency tested (94.23% at 11,000 cfs) did not coincide with the highest estimated fish survivals. However, the differences in survival probabilities at different discharges (efficiencies) were not statistically significant.

Public Utility District No. 2 of Grant County also supported a study of spillway and sluiceway passage at Wanapum Dam (Normandeau et al. 1996d). The purpose of the study was to estimate the survival probabilities of chinook salmon smolts that passed through (1) a spillbay modified with a flow deflector; (2) an unmodified spillbay (without a flow deflector); (3) a spillbay equipped with an overflow weir (actually a submerged opening near the surface); and (4) the ice trash sluiceway. The flow deflector is used to reduce gas supersaturation, and the overflow weir is believed to increase the numbers of surface-oriented smolts that pass through the submerged tainter gate opening and out the spillbay (see Section 2.1.4 and Figure 5).

None of the passage routes provided 100% survival. The estimated 48-hour survival probability of Chinook salmon smolts was significantly greater for the unmodified spillbay (0.996) than for the spillbay equipped with a flow deflector (0.957). Also, the estimated survival probability was greater for fish that passed through the ice/trash sluiceway (0.974) than for fish that used the spillbay fitted with the overflow weir (0.920 and 0.969, depending on flow). Fish injury rates were higher for the unmodified spillbay and the overflow weir than for the other two downstream passage routes. The effect of spillway passage on susceptibility to predation (indirect mortality) was not studied. Turbine-passage studies were conducted between April 23 and May 11, 1996 at Wanapum (see above). However, different salmon species were used (coho vs. chinook) and the studies were not carried out concurrently with the spillway study (April 2 to April 18), so it is not possible to compare the relative effects of turbine-passage and spillbay- or sluiceway-passage on fish survival at this site.

2.4 Public Utility District No. 1 of Chelan County

2.4.1 Rocky Reach Dam

The Public Utility District No. 1 of Chelan County (Chelan County PUD) supported a study of injury rates and types among juvenile fall chinook salmon passed through Rocky Reach Unit 7, a conventional, adjustable-blade Kaplan turbine (RMC 1994). Probabilities of survival were not estimated because of an insufficient number of suitable test fish. Recovery rates of tagged fish that were released through the turbine were lower than expected, probably because of predation by Northern pikeminnow. Ten percent of the recaptured turbine-passed fish had some type of injury, including scale loss, bruises, lacerations, missing eyes, and severed bodies. The authors attributed all of the injuries to mechanical causes resulting from a direct strike or collision with structural components. They suggested that the gaps between the runner blade and the hub may have been a particularly important source of injury.

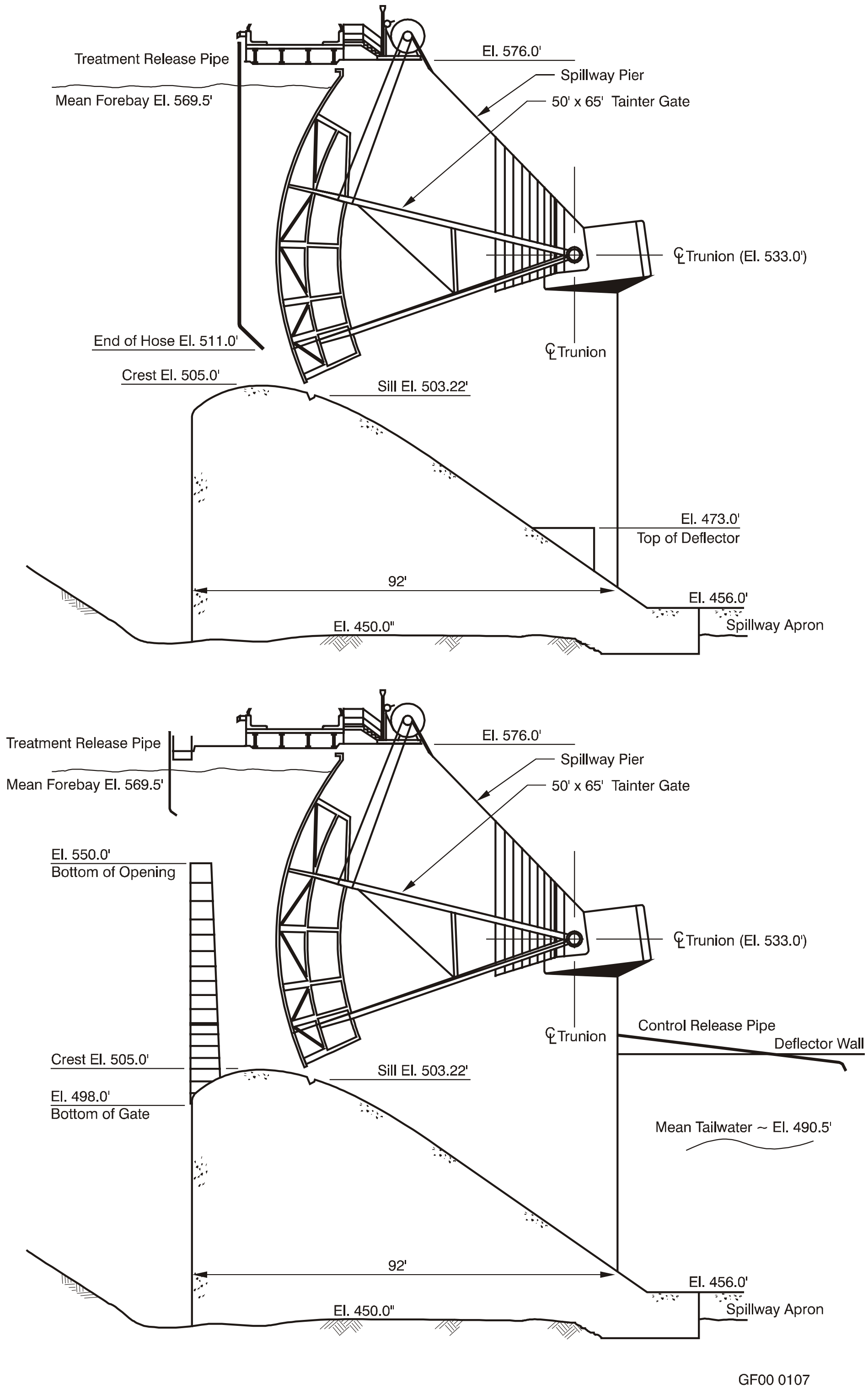

Figure 5. Spillbays at Wanapum Dam equipped with (1) flow deflector, or (2) overflow weir. Source: Normandeau et al. (1996d).

Based on these and other studies, Chelan County PUD replaced the old Kaplan turbine in Unit 6 with a Kaplan turbine with a new runner blade design. In the new design, the gaps between the blade and the hub were essentially closed by means of a recessed pocket in the hub to allow blade movement. The benefits of this new runner design were examined by estimating the survival probabilities of chinook salmon passed through the new turbine in Unit 6 at three power loads and two release depths (Normandeau and Skalski 1996). Survival probabilities were compared to those in Unit 5, an adjacent conventional Kaplan.

Overall survival probabilities were not significantly different between the two turbines: 0.958 for old Unit 5 and 0.950 for new Unit 6. Consistent, statistically significant patterns in survival related to power level and release depth were not apparent for either turbine. Although turbine efficiency values were not reported, the absence of differences in estimated survivals among the three power levels (60 MW, 80 MW, and 100 MW) did not suggest that fish passage survival is highest at the highest operating efficiencies. Surprisingly, the survival of fish that were expected to pass near the hub (10-ft release depth) was significantly lower in Unit 6 than in Unit 5. It was proposed that this unexpected result was due to the gap between the hub and the trailing edge of the blade in Unit 6. A temporary steel wedge was used in later tests to close that gap, which reduced injury rates (Normandeau and Skalski 1996). There appeared to be an improvement in survival following closure of the hub gap, but because controls were not used, the significance of this benefit could not be determined.

2.4.2 Rock Island Dam

Chelan County PUD compared the survival of chinook salmon smolts that passed through three types of turbines at the Rock Island Dam (Normandeau and Skalski 1997). Survival probabilities were estimated for passage through a fixed blade propeller turbine, a Kaplan (adjustable blade) turbine, and a bulb turbine. The turbines were operated at constant discharges throughout the tests (each turbine at its normal peak efficiency), but fish were passed through the turbines at two depths: near the ceiling and near mid-depth. Only direct mortalities were estimated; the effects of indirect mortality (e.g., susceptibility to predation) were not studied.

The estimated 48-hour survival probabilities were 0.932, 0.961, and 0.957 for the fixed blade, Kaplan, and bulb turbines respectively. The survival probability estimates were not significantly different among either turbine type or entrainment depth. The authors attributed most injuries from the fixed blade and Kaplan turbines to mechanical causes (direct contact with runner blades or other structures; passage through gaps). On the other hand, injuries from passage through the bulb turbine were believed to be pressure-related (Normandeau and Skalski 1997).

At the same time that the turbine passage tests were being conducted, Chelan County PUD also compared the relative survivals of chinook salmon smolts that passed over modified and unmodified spillbays (Normandeau and Skalski 1998). Instead of a plunge pool, both of the tested spillbays have an exposed flat concrete sill that extends 15 feet downstream from the wall (Figure 6). Depending on the volume of spill, fish have the potential of striking the concrete sill. Each spillbay has two or three crest gates that are stacked on top of each other. By fully raising the top crest gate, a spill flow of about 10,000 cfs through each spillbay can be released. Several of the crest gates were modified to spill only 1,850 cfs by cutting a notch in the center of the gate (slotted crest gate).

The spillway passage study did not include a separate group of control fish, so absolute estimates of spill passage survival could not be developed. Rather, the relative survival of smolts passed through modified and unmodified spillbays was estimated (Normandeau and Skalski 1998). Four of the 250 fish released through the unmodified spillbay died during the 48-hour post test holding period, compared to 16 of the 250 fish released through the modified spillbay. Relative to the unmodified spillbay, survival of

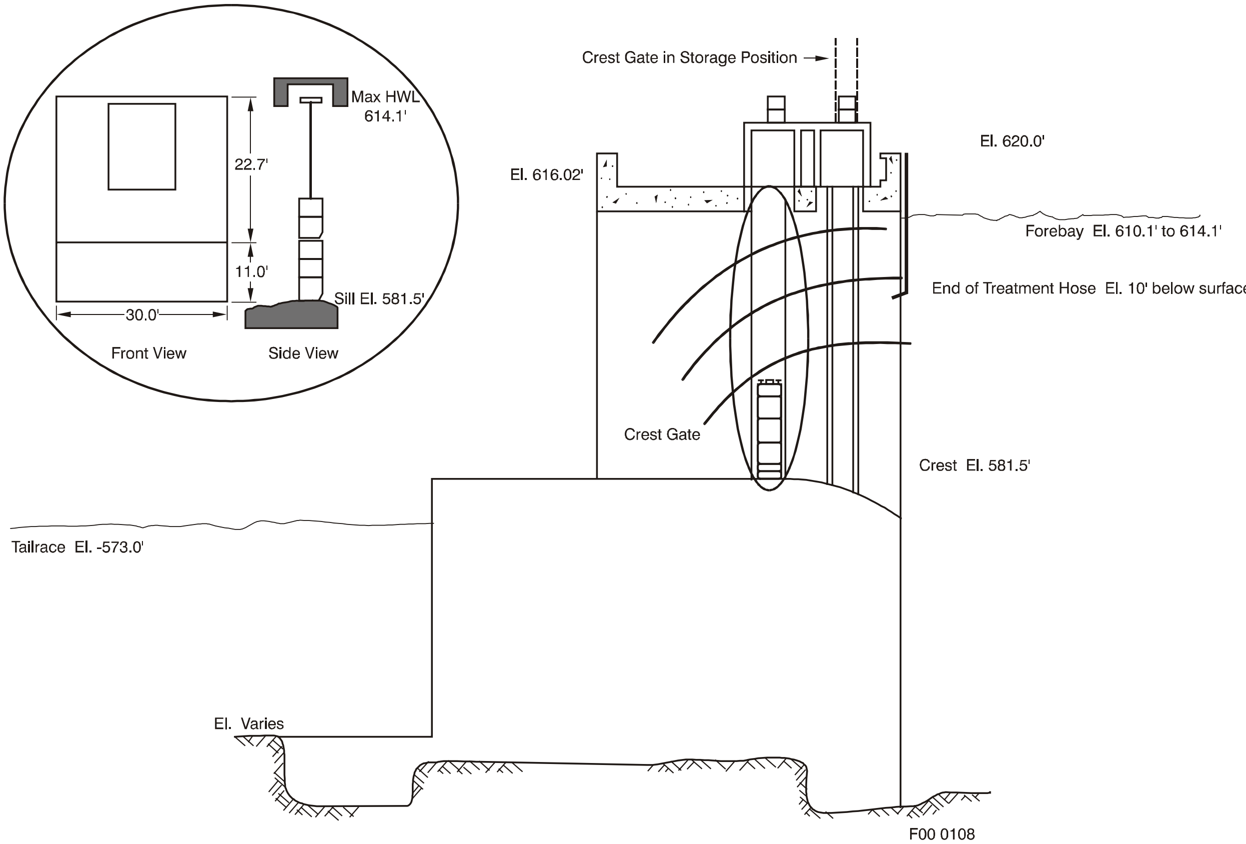

Figure 6. Cross-section of a spillbay at Rock Island dam, showing locations of crest gates and concrete sill. Source: Normandeau and Skalski (1998).

smolts passing through the modified (slotted crest gate) spillbay was significantly lower, 0.951, at 48 hours after release. The rate of injury was also significantly higher among fish passed through modified spillbay. The lower survival and higher injury rate through the modified spillbay was attributed to the lower spill volume (1,850 cfs), which caused the spilled water to drop onto the concrete sill at an impact velocity estimated to be about 51 ft/s. The higher spill flow of 10,000 cfs through the unmodified spillbay created a greater "water cushion," and at least one half of the flow projected farther out beyond the sill into the downstream plunge pool. Normandeau and Skalski (1998) suggested that fish passing through the unmodified spillbay had a smaller chance of directly striking the concrete sill. Because the spillway tests lacked controls, the absolute values of direct survival could not be estimated.

2.5 Bonneville Power Administration

The Bonneville Power Administration (BPA) is an agency of the U.S. Department of Energy. It wholesales electric power produced at 29 federal dams located in the Columbia-Snake River Basin in the northwestern U.S., as well as the power from one non-federal nuclear plant.

A major goal of the 1980 Northwest Power Planning and Conservation Act is to address the impacts that the region's hydroelectric dams have had on fish and wildlife. The Act directed the formation of the Northwest Power Planning Council (NPPC) to develop and implement a program for protection of all anadromous and resident fish and wildlife in the Columbia Basin. The Columbia Basin Fish and Wildlife Program includes measures that BPA and other federal agencies can implement to protect, mitigate, and enhance fish and wildlife affected by hydroelectric dams; objectives for developing and operating hydroelectric dams in a way designed to protect, mitigate and enhance fish and wildlife; and coordination and funding of fish and wildlife management, research and development.

In September 1996, the Clinton administration signed an agreement with federal agencies that established BPA's fish and wildlife budget for the subsequent 6 years at the following amount: $252 million per year for capital improvements, such as fish ladders and screens at the dams, and other projects; and $183 million (when water supplies in the Columbia River Basin are average) for lost hydropower income as the result of storing water during winter for release during the spring and summer to aid salmon migration. The total, in an average water year, is $435 million.

BPA directs a portion of this funding to support downstream passage research, often through cost-sharing with other organizations. For example, BPA contributed funds to the study that compared fish survival through a conventional Kaplan and an MGR turbine at the Bonneville First Powerhouse (Section 2.1.1). Since 1982, BPA has funded research by the National Biological Service to assess the vulnerability of juvenile salmonids to predation and to develop measures to protect outmigrating juveniles from resident fish predators, e.g., Northern pikeminnow, in the reservoirs of the Lower Snake and Columbia Rivers. All of the turbine passage-related research supported with BPA funding is reported in other sections of this report.

2.6 U.S. Bureau of Reclamation

The U.S. Bureau of Reclamation (Reclamation) is not presently conducting research into the survival of turbine-passed fish. Rather, their ongoing and planned research is directed toward developing measures to prevent turbine entrainment and to balance the need for fish protection with downstream water temperature requirements (Charles Liston, Reclamation, personal communication). Examples of this agency's fish passage R&D are provided below.

2.6.1 Buffalo Bill Reservoir, Shoshone River, Wyoming

Reclamation has initiated a study to determine if flash (strobe light) technology applied in front of a deep hydropower intake (150 ft depth) at Buffalo Bill Reservoir can minimize fish entrainment by causing an avoidance response among fish. A net sampling the total outflow (approx. 1200 cfs) allows for direct comparisons of "lights on" and "lights off" periods. Earlier entrainment netting (1991-95) provides extensive pre-study baseline information to assist in the interpretation of results. Initial testing in September 1999 indicated that the technology may work successfully. Replicated studies are planned for years 2000 and 2001. If successful, this technology may be useful in preventing entrainment of lake trout and other salmonid species (in particular, bull trout) at other hydropower dams where deep intakes operate in dark recessed waters of deep reservoirs. Studies are supported mainly by Reclamation's Research and Technology Transfer Program (Commissioners Office) with assistance from project offices and the Wyoming Game and Fish Department.

2.6.2 Grand Coulee Dam, Washington

A study is planned for 2002-2005 to apply underwater flash (strobe light) technology above the third power house at Grand Coulee Dam to determine if this technology can minimize rainbow trout and kokanee entrainment into power generators. Lights will be suspended from barges in front of the inlet leading to the third powerhouse forebay. Extensive hydroacoustic sampling will be undertaken within the forebay and at inlets of two of the penstocks to assess effectiveness of the behavioral exclusion device. Water current profiles and vertical and horizontal patterns will be discerned using doppler technology. This will be a cooperative program among Reclamation, U.S. Geological Survey, and private concerns.

2.6.3 Shasta Dam, Sacramento River, California

Since 1996, Reclamation has been assessing fish entrainment through turbines receiving flows from various levels in Shasta Lake in order to ascertain the gate settings that could minimize fish entrainment. A new multi-level structure is used to alter vertical withdrawal zones for maintaining salmonid rearing temperature downstream. This study will integrate information from entrainment studies to attempt to prescribe management scenarios that meet both downstream temperature requirements and fish protection needs for reservoir fishes.

2.7 National Marine Fisheries Service

The National Marine Fisheries Service (NMFS) conducts relatively little turbine-passage research. Instead, much of the research supported by the NMFS's Northwest Fisheries Science Center (NWFSC) is aimed at measures to keep salmon and steelhead from entering the turbines. For example, NWFSC scientists evaluate the efficiency of screening, collection, and bypass systems for diverting juveniles salmon away from turbines and assess the benefits of transporting juvenile salmon downstream in trucks and barges.

As the Federal agency responsible for protecting anadromous fish, many NMFS regulatory actions set the agenda for turbine-passage R&D carried out by other organizations. For example, since 1995, the COE's efforts to mitigate the decline of salmon stocks on the lower Columbia and Snake rivers have been guided by the NMFS's 1995 Biological Opinion. Many of the monitoring, evaluation, research, design, and construction projects identified in the Biological Opinion are included in the COE's Columbia River Fish Mitigation program (GAO 1998).

2.8 U.S. Geological Survey

Most of the fish passage research in the U.S. Geological Survey is performed at either the Conte Anadromous Fish Research Center (CAFRC) or the Western Fisheries Research Center (WFRC), Columbia River Research Laboratory in Cook, Washington. Information about ongoing and planned studies of the CAFRC was provided by Mufeed Odeh (CAFRC; personal communication).

2.8.1 Effects of hydraulic phenomena on downstream migrating fish (CAFRC)

Downstream migrating fish can experience damaging hydraulic and physical phenomena in rivers, over dams, and through hydropower turbine systems. The development of biological and engineering design criteria for use in new turbine designs or retrofitting existing ones to become fish friendly is essential. Flow characteristics will be studied and biological evaluation will be performed in an accurately controlled laboratory model of a control volume in the flow field near localized potential damage zones; the model will be made large enough to accommodate migratory fish for testing without adverse effects from surrounding boundaries. This apparatus, called "Bio-Hydraulic Turbine Test Stand," will be made modular to accommodate simulation of flow behavior near various turbine components for biological testing. Design criteria will be based on micro- and macro-injuries sustained by fish, instantaneous and delayed. Micro-injuries may include scale and mucous loss, local cuts and bruises, damaged fins, and bleeding eyes. Macro damage may include popped eye, torn operculum, severed head, observed torsion and twisting, and severed body. Also, internal injuries and delayed behavior and mortality will be documented and considered in the data analysis. Test configurations may include simulations of stay vane, stay vane and wicket gate, leading and trailing edges, draft tube piers, and wicket gate/discharge ring overhang.

2.8.2 Migratory behaviors and passage technologies for anguillid eels (CAFRC)

Recruitment of catadromous freshwater eels (*Anguilla rostrata*) to freshwater in North America is declining, although the causes are unknown. Passage facilities for upstream and downstream migrant eels are lacking at hundreds of hydroelectric and other dams along rivers and tributaries of the Atlantic coast, reducing recruitment of eels into upstream habitats. Provision for upstream passage of eels has been shown to enhance recruitment to historic habitats in upstream sections of rivers currently blocked by dams. The technologies required for eel passage have not been extensively tested or implemented in the U.S. Several aspects of eel passage are being investigated in this study, including development of prototypes for upstream passes; age, growth, and life history traits in upstream rearing habitats; downstream migratory behavior; and technologies to reduce turbine entrainment and mortality. These focus areas are critical for providing sound biological data, design criteria and evaluation of passage structures, and a basis for future eel mitigation efforts and enhancement of populations on a coast wide scale. Data concerning techniques, general behaviors, and passage structure design have been made available for fisheries scientists and engineers designing new or modifying existing downstream fish passage structures.

2.8.3 Estimation of Atlantic salmon smolt passage and outmigration in the Connecticut River by remote acoustic telemetry (CAFRC)

Increased effort in stocking Atlantic salmon smolts and fry in the Connecticut River has not resulted in increased adult returns, indicating decreases in return rates of hatchery and stream-reared smolts. The poor return rate may be a result of losses of smolts during downstream migration due to delays caused by dam impoundments, turbine mortality, or predation. However, these losses have not been quantified and summarized on a cumulative, basin-wide level. This study investigates movements of acoustically telemetered fry-stocked smolts throughout the mainstem of the lower Connecticut River.

The technique employs arrays of data logging receivers sited at locations above and below the three lowermost hydroelectric dams. The collected data yield information on migratory rates in dammed and undammed mainstem reaches (e.g., delays), progressive losses of smolts due to turbine mortality or predation, and behaviors upon entry into the estuarine and marine environment. The information gained from the study will be valuable to fisheries managers and biologists with respect to determination of the presence or absence of major losses of smolts within the lower Connecticut River. Results from 1999 studies have provided a better overall understanding of downstream migratory behavior and timing of Atlantic salmon smolts.

2.8.4 Juvenile Salmon Research in the Pacific Northwest (WFRC)

The Western Fisheries Research Center (WFRC) in Cook, Washington performs little research into turbine-passage effects directly, but rather studies the ecological relationships of salmon and steelhead as they are altered by operations of the Columbia River basin hydroelectric system. For example, WFRC scientists have recently studied the bypass/collector devices at Bonneville Dam, the effects of spill patterns on juvenile salmonid movements in the tailrace of John Day Dam, physiological condition of smolts transported through the new Bonneville Dam juvenile bypass system, the effectiveness of the surface bypass collector and behavioral guidance system at Lower Granite Dam, and the effects of different hydropower operations on predation by Northern pikeminnow and smallmouth bass. This research is performed with the cooperation and support of other organizations, including COE, BPA, Washington Department of Fish and Wildlife, and NMFS.

2.9 Electric Power Research Institute

The Electric Power Research Institute (EPRI) has a long history of research and mitigation of intake structure effects. These activities have included literature reviews (EPRI 1986; 1987; 1992a; 1993a; 1998) and laboratory and field studies of physical/behavioral screening measures (EPRI 1992b;1993b). EPRI is presently supporting a comprehensive review of downstream passage of eels, including the potential effects of turbine passage.[a]

2.10 Alden Research Laboratory, Inc./Northern Research and Engineering Corporation

As part of Phase I of the DOE AHTS program (Section 2.2), Alden Research Laboratory, Inc./Northern Research and Engineering Corporation (ARL/NREC) developed a conceptual design for a new turbine runner that minimizes the number of blade leading edges, reduces the pressure versus time and the velocity versus distance gradients within the runner, minimizes clearance between the runner and runner housing, and maximizes the size of flow passages, all with minimal penalty on turbine efficiency. The flow characteristics of the new runner were analyzed using two-dimensional and three-dimensional Computational Fluid Dynamic (CFD) models (Cook et al. 1997; Hecker et al. 1997).

Based on the Phase I conceptual designs, ARL/NREC is now refining the design of a three-bladed runner. When the design is optimized, a 3.5-foot diameter (pilot scale) runner will be installed in a test loop. The subsequent test program will quantify the effects on fish passing through the runner and verify the basic hydraulic characteristics of the turbine runner.

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[a] Doug Dixon, EPRI, personal communication.

2.11 Voith Hydro, Inc.

In an effort to develop fish-friendly turbines, Voith Hydro, Inc. (Voith) has focused on modifications to Kaplan turbines. In part, these efforts have been supported by DOE (Section 2.2), and COE/Grant County PUD (Section 2.1.1); in the latter case, tests of an advanced Kaplan design (MGR) have recently been completed. Ellis et al. (1999) suggested that for the redesign of turbine systems it is important to understand fish-passage mortality as a function of the unique combinations of mechanical and fluid stresses at particular zones within the turbine. The full range of design modifications that Voith has suggested is summarized in Franke et al. (1997).

Voith and Georgia Institute of Technology (GA Tech) are employing CFD simulations of turbulent jets to better understand the fluid stresses that fish experience as they pass through hydroelectric turbines. Voith will use the same CFD model (AEA Tascflow) to relate measured velocity fields in an experimental flume used to expose fish to shear and turbulence (Section 2.2.1) to predicted velocity fields in a turbine at the Wanapum Dam on the Columbia River (Section 2.3). GA Tech's portion of the joint effort is to apply two versions of advanced CFD software to the velocity data from the experimental flume in order to provide insight into the model error associated with turbine design. Additional software (Voith's Virtual Fish model) will be used to estimate flow-induced loads on both flume-passed and turbine-passed fish.

3. CONCLUSIONS

Research on downstream fish passage at hydroelectric dams has accelerated in the latter half of the 1990s, largely in response to the need to explore all possible means of protecting declining salmon and steelhead stocks. This research has included investigations into operational and structural measures to improve the survival of turbine-passed fish. The primary organizations supporting turbine-passage R&D have been power producers in the Pacific Northwest (COE and Public Utility Districts) and the DOE Hydropower Program. Both the COE and DOE rely on technical advisory groups to ensure that proper issues are being investigated, that the research is sound, and duplication with the studies of other organizations is avoided. The COE's Turbine Working Group is comprised of representatives of various COE branches, DOE, BPA, NMFS, and PUDs. Similarly, the DOE AHTS Program relies on the guidance of its Technical Committee, made up of representatives of NMFS, USGS, PUDs and other utilities, EPRI, COE, engineering and consulting firms, BPA, Reclamation, and Tribes. DOE routinely obtains technical peer reviews of draft reports from specialists in environmental groups, academia, and other federal agencies (U.S. Fish and Wildlife Service and the Federal Energy Regulatory Commission). These coordination and integration activities have been essential to moving turbine-passage R&D forward under limited budgets and time frames.

Improvements in field, statistical, and modeling techniques for assessing turbine-passage survival have greatly added to our understanding of the downstream fish passage issue at hydroelectric power plants. Nevertheless, gaps remain that can be addressed by future R&D, and some of the studies have given conflicting results. For example, turbine-passage survival at Lower Granite Dam was not affected by operating conditions, including cavitating conditions characteristic of deep drawdown of the reservoir. On the other hand, significant differences in survival were related to discharge conditions (turbine efficiencies) at Wanapum Dam. Regarding the presumed route of passage through the turbine, the Wanapum Dam studies showed a significant effect of release location, whereas McNary Dam and Lower Granite Dam studies did not. In this section we attempt to draw conclusions from the completed studies, identify important gaps and contradictions, and suggest future R&D to help resolve the turbine-passage issue.

3.1 Top 10 Frequently Asked Questions (FAQs) about turbine-passage survival:

1. What is the range of survival among turbine-passed fish?

The survival of turbine-passed fish depends greatly on characteristics of both the hydropower plant (e.g., the type and size of the turbine, environmental setting, and the mode of operation) and the entrained fish (species, size, physiological condition). Some small turbines designed for high-head installations (e.g., Pelton turbines) probably cause complete mortality. On the other hand, fish-passage survival for turbine types with larger water passages (e.g., Kaplan, Francis, and bulb turbines) is commonly 70% or greater. Among the most "fish-friendly" conventional turbines, e.g., Kaplan and bulb turbines that are used at the mainstem Columbia and Snake Rivers dams, survival may range from 88% to as high as 95%. Testing of new designs with fish friendly features (e.g. MGR) may demonstrate even higher survival probabilities. A goal of the DOE AHTS Program is to develop turbines that achieve 98% survival of turbine-passed fish, a value that would put turbine passage on a par with other downstream passage routes.

2. Does turbine efficiency have an effect on fish survival?

Within a broad range, yes. At the ends of the turbine operating range, pressure changes, shear stresses, and turbulence become very severe, and cavitation can occur. Because these are all sources of injury to fish, it is expected that survival will be reduced under conditions of very low operating efficiency. However, within a narrower range, but perhaps broader than the "within 1% of peak efficiency" target that is employed in the Columbia River basin, there may not be a direct relationship between turbine operating efficiency and survival. Turbine-passage survival is a complicated function of gap sizes, runner blade angles, wicket gate openings and overhang, and water passageway flow patterns. Many of these factors constitute a source of mechanical injury to fish (from strike, pinching, and grinding), and they also produce localized fluid forces (shear stress, turbulence, vortices) that may cause injury. Fisher et al. (1997) proposed that large-scale turbulent energy caused by flow incidence on structures (e.g., stay vanes, wicket gates, and runner blades) may be a significant source of injury to fish within the turbine. These investigators suggested that the optimum configuration of factors which minimizes the chances of mechanical damage and the magnitude of fluid stresses may not necessarily coincide with highest operating efficiency.

A number of studies have been performed to ascertain whether modifications to the way that existing Kaplan turbines are operated would improve fish passage survival. The fish-passage studies at Lower Granite, Rocky Reach, and Wanapum dams have all failed to detect a direct relationship between turbine efficiency and probability of survival. In fact, survivals of spring chinook salmon at Lower Granite under moderately cavitating conditions were not significantly different from survivals at highest efficiency. A useful research question would be to determine whether highest fish-passage survival might lie outside of the +/- 1% efficiency range for some turbines, or could occur at a wider range encompassing the 1% criterion. Preliminary analyses of the recently completed Bonneville I tests suggest that for the MGR turbine, high fish survival can also be achieved outside of the 1% range.

3. Does passage route through the turbine have an influence on the types of injuries and probability of survival?

Because different routes of passage through the turbine impose different combinations of fluid and mechanical stresses on fish, it is reasonable to suppose that injury rates and survivals would also be affected. We cannot watch a fish passing through the turbine runner and out the draft tube, so we can only estimate the path that each fish takes, based on where it was introduced into the intake and assuming that its path generally follows flow lines described by hydraulic models. Considerable effort has been devoted to developing fish introduction systems that will place the fish in areas of the intake where flows will take them along a desired route past the runner; recent entrainment studies have been more successful at this than earlier studies. It has been generally believed that a fish passing the runner near the mid-blade will suffer less injury than one passing near the hub or blade tip. This is because the hub and blade tip zones pose a greater risk of mechanical damage (collision with walls as well as the blade; pinching in the blade-tip and hub gaps) and probably fluid damage (high-energy shear stress and turbulent vortices associated with blade-tip and hub gaps). Consistent with this idea, it appears that different passage routes result in different frequencies of injury types. The McNary Dam studies suggest that injury rates were slightly higher among chinook salmon smolts that passed near the blade tip than over other routes, and that types of injuries differed as well, but it is not known whether these differences are statistically significant.

In terms of survival, studies of turbine passage routes yielded mixed results. For example, the study at Wanapum Dam indicated that the release location (and presumed path of the fish through the turbine) had a significant effect. Fish that were believed to have passed near the runner hub had lower probabilities of survival than fish that passed through the runner in the mid-blade region. On the other hand, introducing fish in different locations had no significant effect on survival at McNary, Lower Granite, and Rock Island dams. The recently completed Bonneville I tests suggest that hub passage resulted in high fish survival for both conventional Kaplan and MGR turbines, whereas blade-tip passage was the route with lowest and most variable survival.

4. Do intake screens have an effect on survival of turbine-passed fish?

Because a comparison of fish passage survival in adjacent screened and unscreened turbines has not been made, this question cannot be answered. Submerged intake screens will divert a portion of the fish to bypass systems, through which they can be safely released downstream. However, these screens filter only the top portion of the water entering the intake. Fish entering the intake at greater depths may not be screened, but rather may be diverted to lower, possibly more injurious, areas of the water passage. For example, fish that might pass through the mid-blade region of the runner in an unscreened turbine bay may, in a screened bay, be diverted toward the blade-tip area by screen-induced flow patterns. Alternatively, screens cause a mixing of flow that may move undiverted fish closer to the ceiling than in an unscreened intake. Screens that project into the turbine flow cause a loss of efficiency and create areas of high fluid energy (strong velocity gradients and turbulent vortices) which may be injurious to fish. Until the path of unscreened fish and the severity of screen-caused turbulence and shear stress have been studied, the significance of these concerns cannot be determined.

5. Do the modifications associated with Minimum Gap Runners (reduced gaps at the hub and blade tips) result in higher survivals of turbine-passed fish?

The survivals of fish that pass through an MGR and conventional Kaplan turbine are presently being compared at the Bonneville I powerhouse. Preliminary analyses suggest that the MGR yielded higher survival than the adjacent conventional Kaplan overall, and was particularly beneficial for improving survival of fish that pass near the runner blade tips. There is good reason to expect that reducing gaps will improve survival. Modifications characteristic of MGRs should reduce the chance of pinching, cavitation, shear stress and turbulence associated with the hub and blade-tip gaps on conventional Kaplan runners. However, the fish-passage tests at Rocky Reach Dam did not support this idea. Although the new runner tested at Rocky Reach Unit 6 was not an MGR, it closed the gap between the hub and the leading edge of the blade with a recessed pocket. Contrary to expectations, this modification seemed to lower survival among test fish that passed near the hub. Subsequent modifications to also reduce the gap between the hub and the trailing edge of the blade seemed to reduce injuries.

In addition to modifications to the runners represented by the MGR design, additional changes have been suggested in the design of stay vanes, wicket gates, and the draft tube to reduce gaps and overhangs that may cause mechanical and hydraulic stresses (Franke et al. 1997). It is theorized that resulting reductions in mechanical and fluid stresses would improve fish survival.

6. Is indirect mortality significant for turbine-passed fish?

Indirect mortality is the term used to describe mortality among fish that experience low (sublethal) levels of stress during dam passage, but subsequently die because of increased susceptibility to disease or predation. Predation in the tailrace is the most immediate source of indirect mortality to downstream-migrating fish. Fish that pass through turbines and spillways are exposed to shear and turbulence, pressure changes, and potentially abrasion and collision with structures. These stresses cause loss of equilibrium and disorientation which may make the fish at least temporarily more susceptible to predators in the tailrace. Fish that pass through properly functioning screening and bypass systems probably experience lower levels of these stresses, but may be concentrated at the bypass release site below the dam and be more vulnerable to waiting predators. Proper outfall design and avian exclusion measures are needed to minimize predation losses of bypassed fish.

Indirect mortality has not been rigorously studied in the field. However, recent laboratory experiments supported by DOE demonstrated that rainbow trout exposed to levels of shear and turbulence that do not cause obvious physical damage may nonetheless suffer significantly greater predation than controls. Because fish using any of the downstream passage routes will experience some level of sublethal stress or increased vulnerability to predators, the survival probabilities estimated by existing studies are likely to be too high by an unknown amount. Whereas the direct mortality studies indicate that probability of survival is often higher among spillway-passed fish than among turbine-passed fish, subsequent losses to predation and disease could potentially reduce these differences.

7. How do the survivals of fish passing hydroelectric dams via different routes (turbine, screening and bypass, spill, barging) compare?

Concurrent studies of fish survival through each of these routes have not been conducted. Spillway-passage survivals were compared to sluiceway-passage survivals at Wanapum, and in a separate study turbine-passage survival was estimated; however, different species were used for the two sets of tests. At the Rock Island Dam, passage survivals through three turbine types were estimated at the same time as a spillway survival study. Unfortunately, the spillway tests lacked controls, so it was not possible to make absolute estimates of survival for the spillway-passed fish for comparison to turbine passage.

Although strict comparisons cannot be made because concurrent tests are lacking, in separate tests (independent estimates of survival probabilities), survival through spillways appears to be higher than through turbines. For example, no mortality attributable to spillway passage was detected in a study at the Bonneville Dam. Probabilities of survival at The Dalles spillbays ranged from 0.955 to 0.993, and at Wanapum Dam the estimates ranged from 0.920 to 0.996. But the adverse effects of gas supersaturation that may accompany spilling are not always considered. The effects of loss of equilibrium and disorientation that has been noted among fish passed through some spillway configurations have not been studied. Potentially, these sublethal effects could lead to increased indirect mortality from predation and reduce the benefits of spillway passage.

8. How can the stresses experienced by fish passing through turbines be quantified?

Although pressure changes, shear stresses, and turbulence that occur in different areas of a turbine can be estimated with models, actual measurements must be made to calibrate and validate the models. Available instruments can be used to make these measurements in some parts of the turbine (e.g., along the walls of the forebay, intake, or draft tube), but the magnitude of fluid forces in the center of the water passages or near the runner have not been measured. It is likely that shear and turbulence are most extreme in localized areas near the hub, blade tips, wicket gates, and stay vanes, and these areas are the most difficult to instrument. Development of devices such as the sensor fish, which can measure and record some of these fish injury mechanisms as it passes through the turbine, is needed to quantify turbine-passage stresses. Actual measurements made with sensor fish and other such devices can be correlated with CFD and VF numerical simulations to estimate the magnitudes of stresses throughout the turbine passage.

9. How can the stresses experienced by turbine-passed fish be reduced?

Generally, reduction of turbine-passage mortality could be accomplished by the following sequence: (1) quantify the stresses that impact turbine-passed fish; (2) determine at what levels these stresses are injurious by means of controlled, laboratory bioassays; and (3) redesign the turbine or modify its operation to reduce the stresses to safe levels.

Quantification of fish injury mechanisms in a turbine has often been based more on model predictions than actual measurements because it is difficult to install instruments in the areas where these mechanisms are likely to be most severe. Once quantified, the values could be put into perspective by performing controlled laboratory studies of the response of fish to the injury mechanisms. Ideally, such studies would examine each of the stresses in isolation, i.e., the bioassay would not be complicated by combinations of different stresses as occurs in field studies. The bioassays would apply the stresses in relevant ways (similar to the way the stress impinges on turbine-passed fish) and would encompass the full range of values that are encountered in a turbine (or other downstream passage route). The fish responses (disorientation, injury, and mortality) can be expressed as a function of the magnitude of the stress, and different stresses can be compared to determine which should receive greatest consideration in the redesign of turbines.

When safe levels for each turbine-passage stress have been established, measurements and model studies can be reexamined to ascertain the locations within the turbine where the level of the stress is too high. Further modeling can be used to redesign the turbine or to suggest changes in operation to reduce these areas. Ultimately, field studies will be needed to determine whether the new designs and operational modifications increase turbine-passage survival.

10. What research is needed to help resolve these turbine passage issues?

There are a number of short- and long-term studies that could be performed to develop a better understanding of the risk of turbine-passage and other downstream passage routes. These include:

Comparison of MGR and a conventional Kaplan turbine at the Bonneville First Powerhouse using run-of-river fish during the normal passage season (Section 2.1.1). Similar side-by-side comparisons of existing turbines to other advanced turbines should be made to assess their value for improving fish survival.

Comparison of turbine passage with other routes of downstream passage at dams (Section 1.2). Ideally, these comparisons would be made not only for immediate, direct mortality, but also over the entire life cycle of the fish. For example, test groups of screened, turbine-passed, and spillway-passed fish could be implanted with passive integrated transponder (PIT) tags that would allow them to be detected several years in the future when they return from the sea to spawn.

Additional laboratory studies to establish the responses of a range of fish species to individual turbine-passage stresses. New studies might include tests to assess the velocities at which fish strike the runner or fixed structures, the effects of the fish orientation at strike, the effects of flow fields that carry fish around a structure, and the mortality associated with localized conditions near gaps.

Studies of disorientation or loss of equilibrium (if any) caused by any of the downstream passage routes, and assessment of the resulting loss of smolts to predation (Section 2.1.3). In general, there is a need for better understanding of indirect mortality (increased levels of predation or disease from sublethal stresses) associated with all of the downstream passage routes. Is indirect mortality a significant additional source of mortality to downstream migrating fish? What effect does indirect mortality have on the ranking of different passage routes? How can draft tubes and tailraces be redesigned to minimize disorienting turbulence? How can tailraces and bypass outfall locations be redesigned to reduce physical and hydraulic cover for predaceous fish?

More comparisons of turbine-passage survival through different turbine zones under a range of operating conditions (Section 2.1.5).

Field and laboratory measurements to refine, calibrate, and validate predictive models. Developing a better understanding of turbine-passage effects on fish involves integrating knowledge from three general areas: (1) field studies (e.g., fish passage survival studies and physical measurements); (2) laboratory studies (both biological tests and physical models); and (3) computational studies (e.g., CFD and VF models). The general goal of these studies is to ensure that the computational models are valid representations of conditions within the turbine and can be used to predict the effects on fish of design and operational modifications. For example, refinement of existing CFD and Virtual Fish (VF) models (Section 2.11) could include correlation of the DOE shear and turbulence tests with computational models using VF, correlation of observations of real fish and sensor fish at Bonneville I with VF computations, and correlation of predictive fish survival models with observed fish survivals at Bonneville I.

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Appendix A

List of Contacts

Appendix A

List of Contacts

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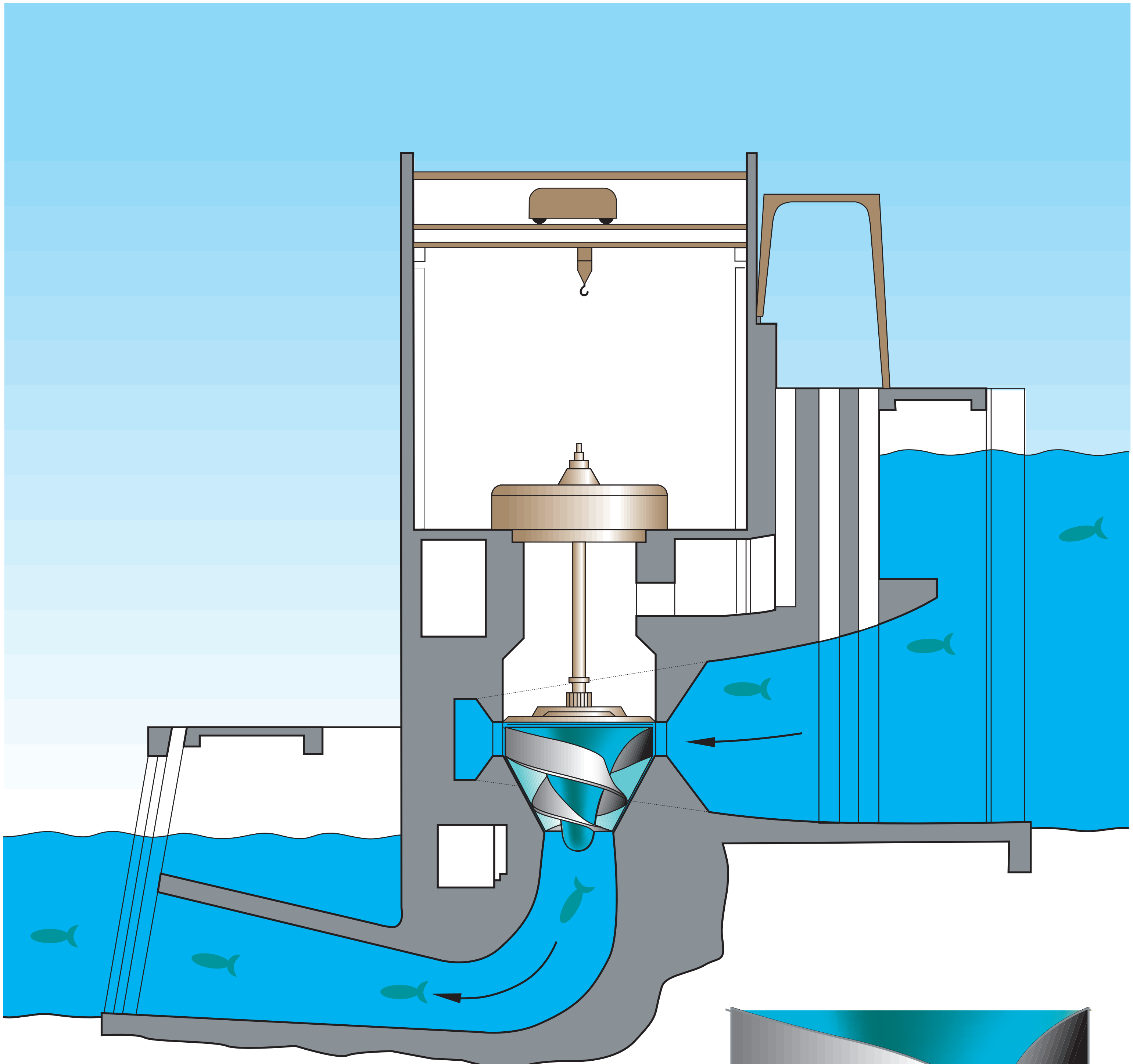
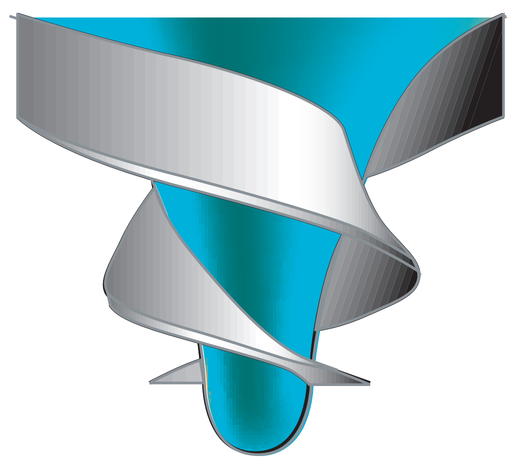
Appendix B

ARL/NREC Turbine Runner





ALDEN/NREC Fish Friendly Turbine

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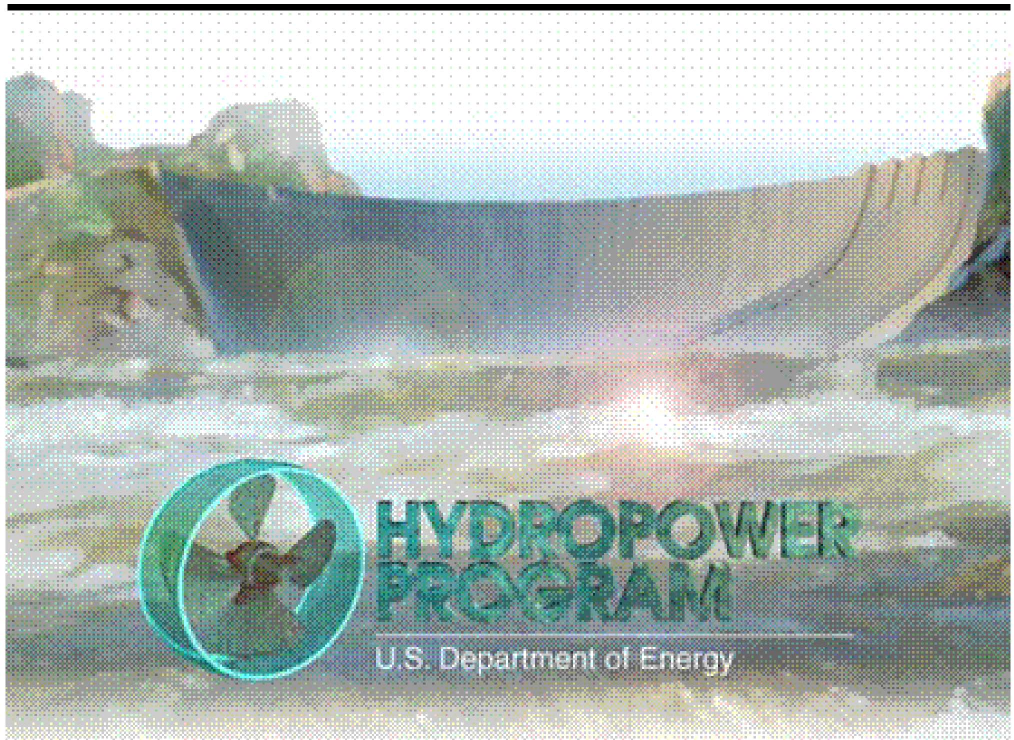

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The mission of the U.S. Department of Energy's (DOE's) Hydropower Program is to develop, conduct, and coordinate research and development with industry and other Federal agencies to improve the technical, societal, and environmental benefits of hydropower. The Office of Biopower and Hydropower Technologies administers the program through the DOE Idaho Operations Office.

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