TURBINE SURVIVAL PROGRAM (TSP)
PHASE I REPORT
1997-2003

FEBRUARY 27, 2004

Prepared By:

U.S. Army Corps of Engineers
Portland District
Walla Walla District
Hydroelectric Design Center
Engineer Research & Development Center-Waterways Experiment Station

Table of Contents

Glossary

References

List of Tables

List of Figures

List of Abbreviations

ACAD – Advanced Computer Aided Design

AHTS – Advanced Hydropower Turbine System program

B1 – Bonneville First Powerhouse

B2 – Bonneville Second Powerhouse

BiOp – Biological Opinion

BIT – Biological Index Testing

BPA – Bonneville Power Administration

CENWW – Corps of Engineers, Walla Walla District

CENWP – Corps of Engineers, Portland District

CFD – Computational Fluid Dynamics

CFS – Cubic Feet per Second

CI – Confidence Interval

COE – Corps of Engineers

CRFM – Columbia River Fish Mitigation

DACS – Data Acquisition Control System

DOE AHTS – Department of Energy Advanced Hydropower Turbine System

ECU – Electronic Control Unit

ERDC – Engineer Research and Development Center

ESBS – Extended-Length Submerged Bar Screens

FCRPS – Federal Columbia River Power System

FFDRWG – Fish Facilities Design Review Work Group

FGE – Fish Guidance Efficiency

FPE – Fish Passage Efficiency

FPOM - Fish Passage Operations and Maintenance Coordination Team

GBT – Gas Bubble Trauma

GDACS – Generic Data Acquisition and Control System

HDC – Hydroelectric Design Center

kPa – kilopascals

LDV – Laser Doppler Velocimeter

MGR – Minimum Gap Runner

NMFS – National Marine Fisheries Service

NOAA – National Oceanic and Atmospheric Administration

NWPPC – Northwest Power Planning Council (Renamed the Northwest Power and Conservation Council - NPCC in July 2003)

NWD – Corps of Engineers, Northwestern Division

ORNL – Oak Ridge National Laboratory

PIT – Passive Integrated Transponder

PNNL – Pacific Northwest National Laboratory

psi – pounds per square inch

RCC – Reservoir Control Center

RPA – Reasonable and Prudent Alternative

SE – Standard Error

SIMPAS – Simulated Passage Model

STS – Submerged Traveling Screen

TIE – Turbine Intake Extension

TSP – Turbine Passage Survival Program

TWG – Turbine Working Group

USACE – United States Army Corps of Engineers

VBS – Vertical Barrier Screen

WES – Waterways Experiment Station

Executive Summary

The U.S. Army Corps of Engineer's (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 first phase (Phase I) of this study includes four main objectives:

- Evaluate and recommend operational criteria to improve the survival of fish passing through the Kaplan turbine units.
- Identify the biological design criteria for the design of new modifications to the existing turbines.
- Investigate modifications to the existing designs that have the potential to increase survival of fish passing through the Kaplan turbine units.
- Recommend a course of action for turbine rehabilitation or replacement that incorporates improvements for fish passage survival.

As the COE makes decisions to replace or rehabilitate aging turbine units it is important that these objectives be met so knowledgeable decisions can be made to enhance fish passage survival while maintaining cost effectiveness. Rehabilitation of a number of Corps projects is already underway. New Kaplan turbines are being installed into the Bonneville First Powerhouse (B1) and new turbine designs are being developed for the McNary Project. Unit 2 of Ice Harbor will be replaced in 2005 and a rehabilitation plan is being considered for The Dalles Project. Other Corps Projects on the Lower Snake and Columbia rivers have been in service for more than 30 years and will soon require rehabilitation. It is critical to long-term operations that the rehabilitation process considers and includes, where feasible, modifications or new designs that improve fish condition and survival as they pass through the turbines.

This report documents the major work accomplished and results obtained during Phase I of the TSP and represents the completion of Phase I activities. The following paragraphs highlight some of the more significant results of Phase I of the TSP.

Hydraulic Model Evaluations

Three hydraulic model techniques have been used to evaluate and investigate the existing turbine environment and turbine modifications to increase fish survival and turbine efficiencies. These include Froude and Reynolds physical hydraulic modeling and numerical modeling. Froude model testing was conducted at the Corps of Engineers' Engineer Research and Development Center at the Waterways Experiment Station (ERDC-WES), and Reynolds, Froude, and numerical model investigations were conducted by turbine manufacturing companies. The models at ERDC-WES are made primarily of clear acrylic to allow for visual observation of the entire water passageway and the collection of detailed velocity measurements. The Reynolds models or high-head performance models tested by the turbine manufacturers are constructed of steel. The ERDC-WES turbine models have been used extensively to design fish screens for the turbine intakes and to evaluate modifications of the design and operation of the turbines.

Many of the turbine modifications tested in the ERDC-WES models were also tested in high-head performance test stands. These modifications include evaluation of design changes to the wicket gate and stay vane assembly, the runner and the draft-tubes. The results of these studies indicate modifications made to improve fish passage conditions will likely also increase turbine efficiencies.

The ERDC-WES models have shown that flow through the draft-tubes of the McNary, Lower Granite and Bonneville turbines, under the current one percent operating restriction, is very non-uniform and turbulent. In many cases there is reverse flow along the draft-tube ceilings. As turbine flows increase, the draft-tube flow becomes more streamlined. The biologists have identified this non-uniform turbulent flow to be detrimental to fish passing through the turbines, because those conditions likely result in further disorientation, poor egress, and increased predation.

Based on general observations of the turbine models, the best operating conditions for fish passage is likely related to turbine geometry and discharge rather than turbine efficiency. The best alignment of the stay vane and wicket gates with the greatest turbine blade angle minimizes the potential for impact and exposure to hydraulic shear. The increased discharge through the turbine reduces turbulence and streamlines flow through the draft-tube, providing for improved egress conditions. Another potential danger to fish is the wicket gate overhang. Under some operating conditions, the wicket gate extends beyond the discharge ring into the flow path to the runner. The interaction of turbulence generated at the trailing edge of the wicket gate with the leading edge and wake of the runner blades has the potential to severely injure fish. This danger may be reduced by operational changes and wicket gate design modifications.

A key finding of the TSP was a comparison of high head to low head turbine performance tests. To assure proper modeling techniques are used for performance testing of turbines with intake screens, turbine performance cam curves were developed for high head and low head (Froude or scaled head) model conditions. This study showed that for existing turbines the low head performance tests with fish screens in place better matched the prototype field index test results than high head performance tests. Future model testing of existing or rehabilitated turbines with intake fish screens in place should be conducted using both high head and low head model conditions.

A numerical model was used to design a variety of stay vane and wicket gate modifications. The best designs were then tested in both the ERDC-WES low head models and a manufacturer’s high head performance model. These models showed a decrease in the potential for fish to strike upon the leading edges of those structures and an increase in turbine efficiency. As numerical model techniques continue to improve, they will become a valuable component in turbine design.

Combining the three model techniques has proven to be an invaluable component of the TSP in the evaluation of the turbine environment. Physical hydraulic and numerical model investigations should be required in any turbine rehabilitation to evaluate the existing conditions, to identify potential areas of concern, and to determine the benefits that may be gained from modifications. Before these tools can be used to estimate biological benefits, a stronger link must be developed between the data collected in the models and the biological field data. For example, the bead and velocity data collected from the hydraulic models can indicate the potential for impact and exposure, but neither data set can be used to estimate an increase or decrease in fish mortality or injury. They can, however, be effectively used to make relative comparisons of design alternatives.

Engineering Evaluations

The engineering evaluations focused primarily on the turbine operating components and conditions thought to cause direct mortality. The primary areas of investigation consisted of model and prototype studies, which centered on developing measurement tools to evaluate operational improvements, flow, biological testing designs, turbine runner designs, turbine geometry, and the effects of turbine modifications on turbine performance and potential fish passage improvements.

To address turbine operations and the impact of those operations on fish survival, a complete understanding of turbine design and operation is required. Both the mechanics and hydraulics of the turbine operation must be defined. How the turbines were designed to operate and how they actually operate must be evaluated. In addition, the impact of fish diversion screens and other structures that alter flow patterns through the turbine intakes must be considered. Turbine model studies and prototype investigations were conducted to address these issues. The investigations resulted in improvements to some mechanical operating systems and development of new cam curves for turbine operations both with and without intake screens. These improvements ensure the operating requirements specified by the Biological Opinion (BiOp) are met. However, sufficient error still exists in many of the existing control systems, resulting in uncertainty of actual operating condition of those turbines. A regular inspection and evaluation of all control systems is needed and improvements, where necessary, should be made.

The BiOp currently requires that all turbines operate within a range of one percent from the best operating efficiency point. This operating requirement is based on the assumption that fish survival is directly related to turbine efficiencies. This assumption has not been validated. Field studies indicate that turbine operating condition and geometry may be more important than turbine efficiency for safe fish passage. Although a direct relationship of fish passage survival to turbine operations has not yet been established, defining the mechanical and hydraulic operating parameters is a critical first step in evaluating survival as function of turbine operations.

Through the TSP’s evaluation and inspection of several turbine units it was noted that many had corroded surfaces, which will require resurfacing. It was also reported that there were many unnecessary objects projecting into the water passageways, such as temporary handrails, access ladders, and exposed pressure relief pipes that extend into the flow path from the base of the draft-tubes at John Day. Every turbine unit should be inspected for such projections and these should be removed where possible.

Biological Evaluations

A number of biological studies were conducted as elements of the TSP and in coordination with other agency programs. These included both field investigations and laboratory investigations. The investigations were structured to evaluate both direct and indirect losses. Direct survival was associated with the passage from the turbine intake to the exit of the turbine draft-tube and indirect survival was for passage from the draft-tube exit through the powerhouse tailrace. In general, biological studies of fish passing through Kaplan turbines of Columbia and Snake River dams and other similarly sized turbines have shown direct survival to be relatively high. Studies of fish passing through specific routes of the turbine runner have found that fish passing through the mid-blade and hub locations have a significantly higher survival rate than those near the blade perimeter. However, the distribution of fish as they pass through the turbine runner has not yet been determined. Indirect survival appears to vary with many factors resulting in increased predation on turbine-passed fish. Biological studies have found indirect mortality to vary from very low rates to rates two to three times the rate of direct mortality.

The vestibular disruption resulting from the exposure of fish to harsh hydraulic conditions and contact with structural elements, and the negative buoyancy resulting from exposure to rapid pressure change during turbine passage, have been identified as sub-lethal biological mechanisms that might make turbine-passed fish more vulnerable to predation in the powerhouse tailrace. Tailrace hydraulic conditions that enhance tailrace egress for fish and provide time for recovery from sub-lethal effects of turbine passage may provide one of the best means to enhance total turbine passage survival at mainstem dams. Information about the time required for recovery from sub-lethal injuries could help assess the benefits of tailrace hydraulics alternatives with different fish egress potential. Fish survival benefits from changes to the design, structure, and operation of individual turbine units may not be fully realized without treatment of indirect turbine passage mortality. This requires consideration of project operations that enhance tailrace egress conditions for turbine-passed fish. Turbine operations that more efficiently use turbine draft-tubes and/or modifications of draft-tubes may enhance tailrace egress conditions for fish resulting in an increase in overall turbine passage survival.

The results of biological studies of juvenile salmonids passing through turbines do not show a statistically significant relationship between either absolute or relative turbine operating efficiency and juvenile salmonid direct turbine passage survival rate. Retrospective analysis of turbine operating efficiency and juvenile salmonid direct survival has shown differences up to 3.2 percent between maximum survival and survival at peak operating efficiency for passage of juvenile salmonids through large mainstem Columbia and Snake River Kaplan turbines. At three of the four dams included in the analysis, maximum survival did occur within one percent of peak turbine operating efficiency. It has become clear that operating mainstem Kaplan turbines within ±1 percent of peak operating efficiency does not assure maximum turbine passage survival. Research results have consistently demonstrated the need to focus on maximization of fish survival rather than turbine operating efficiency in efforts to optimize the turbine passage survival of juvenile salmonids and other fish. Further research focused on maximization of fish turbine passage survival, unconstrained by current operating rules, is needed to identify turbine-operating rules that will minimize risk of death or injury for the full range in size and species of fish passing through turbines.

The biological benefits of new turbine designs that close gaps at the tip and hub of turbine runner blades are only partially defined. Unresolved issues include accurate estimates for the reduction in gap-related injury for fish passing in gap regions as well as the assessment of the proportion of the run-of-the-river fish that may pass through turbine runner zones where exposure to gaps is possible. In addition, lack of information about the distribution of run-of-the-river juvenile fish at passage through the turbine wicket gates has prevented use of route-specific survival estimates to estimate survival for the run-of-the-river fish population. Until adequate fish distribution data are available, release strategies that broadly distribute test fish upstream of the wicket gates will best provide estimates of direct and total turbine passage survival.

A gap in understanding the effect of rapid pressure change on fish passing through turbines has been identified. Field and laboratory studies of the effects of pressure changes on juvenile fish have been conducted using surface-acclimated fish only. The rate and absolute range of pressure change during turbine passage would be greatest for depth-acclimated fish passing through a turbine operating at high discharge. Although the pressure changes do not appear to negatively impact the near surface-acclimated test fish, the consequences, if any, for depth-acclimated fish is still unknown.

While it is well known that the consequences of turbine passage vary with fish size, almost all of the direct turbine passage survival studies have been conducted using yearling juvenile salmon because of the inability to adequately tag smaller fish. This limitation must be considered when using results of direct turbine passage studies to make decisions about turbine designs and operations. Methods for evaluating total turbine passage survival, such as using radio and PIT tagging have improved and can be applied to subyearling as well as yearling juvenile fish.

Conclusions and Recommendations

Significant progress has been made toward meeting the four objectives of the TSP. Although much more work is needed to fully achieve those objectives, a number of conclusions and recommendations can be made, and a process for rehabilitation of the aging turbine units developed.

Conclusions

1) The distribution of fish passing through a turbine unit has not yet been defined.
2) Route-specific areas of the turbine can be biologically tested for impacts on direct survival.
3) The passage route near the runner blade tips poses a greater hazard to fish than passage near the mid-blade or hub.
4) The hydraulic performance of most Lower Snake and Columbia River Project draft-tubes, in terms of streamlined flow, improves as discharge increases.
5) Bead investigations indicate the greatest exposure to severe hydraulic conditions occur at the trailing edges of the wicket gates and runner blades, below the runner hub within the hub "rope" and near the leading edges of the draft-tube splitter walls.
6) The turbine intake screens influence turbine performance by creating head losses **and** altering the distribution of flow to the turbine unit distributor. Froude (scale head) model testing appears to replicate turbine performance with screens in place.
7) Some turbine operation improvements have been made, however sufficient error exists in many of the existing control systems, such that there is very little certainty as to the actual operating conditions of the turbine.

8) Analysis of the results of the last decade of direct and total turbine passage mortality studies shows that a statistically valid relationship between turbine operating efficiency and fish survival does not appear to exist.

9) Turbulence through existing turbines is higher with lower turbine discharge operations and the passage time of beads (emulating fish) is longer.

10) Sensor fish records indicate that the turbine passage route has a shorter duration and is less severe than that observed in spillway stilling basins.

11) The rate of bead strike on model turbine structure is several times the rate of physical injury observed for live test fish passing through the prototype turbines.

12) Physical models of turbines are essential to design turbine passage biological tests and to help interpret the results of those biological tests.

13) Given uncertainty about the distribution of run-of-the-river migrants passing through turbine intakes, indirect passage mortality for a turbine unit is currently estimated using test fish release strategies that result in test fish being vertically distributed more uniformly as they pass through turbine wicket gates.

14) While mechanical injury is the highest direct mortality component, indirect mortality may be a more significant problem than presently assumed.

Recommendations

1) Continue biological index testing of each family of turbine units to identify the safest operating range with respect to both direct and indirect survival.

2) Existing turbine controls should be improved.

3) Physical model investigations should be conducted prior to turbine rehabilitations to evaluate existing conditions and to make recommendations for design modifications if needed.

4) Continue to develop and improve biological test protocols for turbine passage.

5) Conduct a comprehensive interrogation of existing information and biological test data sets.

6) Develop an engineering and biological linkage between hydraulic model data and prototype biological test data.

7) Continue to develop numerical modeling capabilities.

8) Further evaluate adult passage through turbines.

9) Formalize biological design criteria for future rehabilitations.

Turbine Rehabilitation Decision Framework

Phase I of the Turbine Survival Program has resulted in the development of unique investigative tools to characterize the fish passage environment. These tools consist of physical models, route-specific test fish injection systems, sensor fish, and protocols for use of balloon-tagged and radio-tagged live test fish, to estimate total fish passage mortality and to separate this mortality into direct and indirect components. The development and use of these tools will help assess the biological benefits and justification during the rehabilitation process and to assess alternative designs.

Systematic application of basic engineering design methods, with the addition of biological assessment, can achieve rehabilitated turbines that meet engineering design objectives, such as increased power production efficiency, while providing biological benefits, such as increased direct and total turbine passage survival for fish. A product of Phase I of the TSP is a framework for making decisions prior to, during, and following turbine rehabilitation that can optimize both the biological and economic benefits of rehabilitation. This framework consists of a series of stages with the following objectives:

Stage 1 Objective: Define the physical condition, operational characteristics, and biological performance of the existing turbine.

Stage 2 Objective: Identify turbine design features that have the potential to improve turbine efficiency and fish passage survival, to determine if turbine designs or modifications other than “replacement in kind” should be considered.

Stage 3 Objective: Evaluate promising turbine design alternatives using physical hydraulic models, including turbine performance models, to measure the performance of the alternative designs, and the ERDC-WES hydraulic models to assess turbine passage conditions that affect fish.

Stage 4 Objective: Document the results of the alternative turbine design analyses. Use the findings and recommendation reports completed for the regional coordination processes to prepare specifications, schedule, and budget documents for procurement and installation of a prototype unit.

Stage 5 Objective: Measure the biological performance and power performance of the new design prototype unit.

Stage 6 Objective: Evaluate the biological performance data and power performance data acquired in stage 5 and review model testing data acquired in stage 3. Weigh the benefits against the cost, then make a decision about procurement of additional units.

Section 1. Introduction

1.1 Turbine Survival Program (TSP) Background

1.1.1 Problem Definition

Much of the hydropower in the Pacific Northwest is generated by hydro turbines installed within the many dams located throughout the Columbia River Basin (Figure 1). With the increase in regional power demands, these turbines must be more efficiently operated, and in doing so, a significant portion of migrating fish will continue to pass through them.

The fish species of concern are the threatened and endangered stocks of salmonid species. Salmon and steelhead are anadromous fish, which undertake extensive migrations both as juveniles and again as adults. Anadromous fish spend most of their lives in the ocean, but spawn in fresh water. The Federal dams on the Columbia and Snake rivers must be passed by salmonids during their upstream migration as adults to spawning grounds and during downstream migration to the ocean as juveniles (smolt) and post-spawned steelhead trout (kelts). Unlike Pacific salmon, steelhead trout are capable of repeat spawning and therefore may also migrate downriver as post-spawned adults. Salmonid species include salmon, graylings, whitefish, and trout. The salmonid lifecycle spans approxi

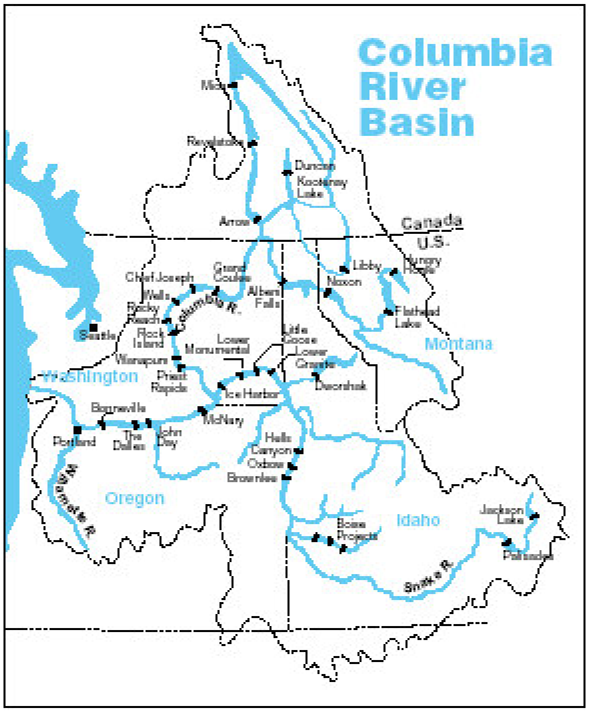


Figure 1. Dams of the Columbia River Basin

To date, only a pilot study (Normandeau 2003) has been performed to estimate the turbine passage survival of adult salmonids. However, considerable effort has been expended to estimate the survival and injury rates for juvenile salmonids passing through turbines. In understanding the issues associated with turbine passage of migrating 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. A recently completed meta analysis (Bickford and Skalski 2000) of turbine passage survival studies conducted within the Columbia River basin between 1971 and 1996 estimated the overall mean total turbine passage route survival for Kaplan turbines to be 0.873 (SE 0.0152 and a within-year standard deviation of 0.108). This same study estimated overall direct turbine passage survival for Kaplan turbines to be 0.933 (SE 0.0047).

The basic strategy for restoring Columbia River salmonid stocks has been the implementation of turbine bypass alternatives with the objective of reducing the portion of migrants passing through turbines to a very low level. However, because significant numbers of juvenile fish will continue to pass through turbines, improving turbine passage for fish remains a desirable goal. The Turbine Survival Program (TSP) was established to achieve this goal, incorporating a study plan divided into two phases. Phase I of the TSP was to identify where and how juvenile fish are injured when passing through a turbine. The Phase I studies were designed to partition direct turbine passage mortality to identify specific turbine structures and operations dangerous to fish. The primary objective of Phase II is the modification of the turbine environment to improve fish survival. This report denotes the end of the Phase I portion of this program.

1.1.2 Authorization

Primary funding authority for the TSP has been through the Congressionally approved Columbia River Fish Mitigation Program. Appropriation for the Columbia River Fish Mitigation, Washington, Oregon, and Idaho (CRFM) falls under the title of Construction General – Multiple Purpose Power. Authorization for CRFM has been established over a period of years: 1933 Federal Emergency Administration of Public Works; 1935, 1945 and 1950 River and Harbor Acts; 1937 Bonneville Project Act; the 1950 Flood Control Act, and WRDA 1999, Section 582. This mitigation consists of: (1) Adult and juvenile fish bypass improvements at Lower Granite, Little Goose, Lower Monumental, and Ice Harbor on the Snake River; McNary, John Day, The Dalles, and Bonneville on the Columbia River, avian predation controls, and salmon survival research and development in the Lower Columbia River estuary and near-ocean environments, (2) A mitigation analysis, prepared in cooperation with regional interests, to evaluate additional measures to increase fish survival in the Columbia and Snake Rivers. The mitigation analysis provides the analytical process for consideration and implementation of Federal actions necessary to support regional initiatives and Federal salmon and resident fish ESA requirements. The Turbine Survival Program is one of many programs that are currently addressing CRFM issues.

1.1.3 Project History

The Corps of Engineers' (COE's) Turbine Survival Program addresses the Northwest Power Planning Council's (NWPPC) 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 (NMFS) 1995 Biological Opinion for system operations, into its ongoing studies for various improvements to these projects, undertaken as a result of the following legislation:

- Conservation Measure No. 5 – to develop a program to study/improve fish passage through turbine.
- Reasonable and Prudent Alternative (RPA) No. 6 – to maintain operation of turbines within one-percent peak efficiency.
- Reasonable and Prudent Alternative No. 15 – to improve fish passage with a goal of 95 percent survival through each project.

The activity that largely led to the development of the Turbine Survival Program was the Turbine Passage Survival Workshop held in Portland, Oregon, May 31- June 1, 1995. The workshop was comprised of a 20-member panel of engineering and biological experts from government, industry and universities, along with over 50 non-panel participants. The major goals of this workshop were to:

1) Determine how to deliver fish from the turbine to the tailrace environment in a condition allowing them to readily cope with the river environment.
2) Focus on those uncertainties that prevent closure on developing biological turbine design criteria.
3) Identify and prioritize the causal agents of turbine mortality.

The workshop concluded that the highest priority studies were to:

1) Recognizing the need for the optimization of fish survival, look at engineering options currently available to modify both turbine operation and design.
2) Conduct mechanical injury studies as the next highest priority.
3) Conduct research into other direct and indirect mechanisms that are limiting further turbine fish-passage improvements. (USACE-Portland District 1995)

Following the workshop the TSP identified a turbine unit with generic characteristics that could be used as the experimental base for the program. The base case report, entitled *Turbine Passage Survival Baseline Turbine Report*, was completed on January 19, 1996. (Summit Technology Consulting Engineers 1996) A number of factors were evaluated in determining which site would be selected, including powerhouse capacity and the ability to use the selected unit without largely interfering with hydrosystem operations. With Regional coordination, the COE selected McNary Dam's Unit 5 powerhouse as the base case prototype test site for the TSP. However, a generator failure at Unit 5 resulted in using Unit 9 as a substitute in the initial TSP biological testing.

The 2000 Federal Columbia River Power System (FCRPS) Biological Opinion provided additional guidance for actions needed to improve fish survival in turbines. The TSP provided available information on turbine passage survival to agencies. The following reasonable and prudent actions (RPA's) included both studies and operations guidance to help minimize risk to fish passing through turbines.

- RPA #58 – The Corps and Bonneville Power Administration (BPA), in coordination with the Fish Passage Operations and Maintenance Coordination Team (FPOM), shall operate all turbine units at FCRPS dams for optimum fish passage survival. Methods to achieve this objective shall include, but are not limited to, activities outlined in the following:
    - Operate turbines within one-percent peak efficiency during the juvenile and adult migration seasons (March 15 through October 31 in the Columbia River and March 15 through November 30 in the Snake River). Operating turbines at peak efficiency is believed to provide the highest survival of anadromous species during passage through a turbine (Bell 1981 and Eicher 1987).

  - Continue efforts to index-test all families of turbine units specific to each project in the FCRPS to ensure that peak efficiency tables are developed and are included in the annual fish passage plan.

- RPA # 59 – The Action Agencies in coordination with the Regional forum shall determine the appropriate operating range of turbines equipped with minimum gap runners (MGRs) to increase survival of juvenile migrants passing through these new turbine designs.
- RPA #64 – The Corps shall continue the investigation of minimum gap runners at the Bonneville First Powerhouse.
- RPA #88 – The Corps and BPA in coordination with the Fish Facility Design Review Work Group (FFDRWG), shall continue the program to improve turbine survival of juvenile and adult salmonids.
- RPA #89 – The Action Agencies shall investigate hydraulic and behavioral aspects of turbine passage by juvenile steelhead and salmon through turbines to develop biologically based turbine design and operating criteria. The Corps shall submit a report to NMFS stating the findings of the first phase of the Turbine Survival Program by October 2001. Annual progress reports will be provided after this date.
- RPA #90 – The Action Agencies shall examine the effects of draft-tubes and powerhouse tailraces on the survival of fish passing through turbines.
- RPA #91 – The Action Agencies shall remove all unnecessary obstructions in the higher velocity areas of the intake-to-draft-tube sections of the turbine units.
- RPA #92 – The Action Agencies shall consider all state-of-the-art turbine design technologies to decrease fish injury and mortality before the implementation of any future turbine rehabilitation program (including any major repair programs, the ongoing rehabilitation program at The Dalles, and any future program at Ice Harbor Dam). The Action Agencies shall coordinate within the annual planning process before making decisions that would preclude the use of fish-friendly technologies and to minimize any adverse effects of project downtime.
- RPA #93 – The Action Agencies shall determine the number of adults passed through turbines, then, if warranted, investigate the survival of adult salmonid passage through turbines (including steelhead kelts).
- RPA #111 – The Corps shall investigate and enumerate fallback of upstream migrant salmonids through turbines at all lower Snake and Columbia River dams. The Corps shall implement corrective measures to reduce mortality, as warranted.

In 2000, a second workshop was held (USACE-Portland District 2000). Workshop participants presented the significant findings of the program studies up to that time. Methods to study elements of the runner environment had been developed and used to obtain estimates of the route-specific survival of juvenile Chinook salmon passing through a test unit.

1.1.4 TSP Coordination

The TSP Phase I Program was initiated in response to the National Marine Fisheries Service Biological Opinion and through the Northwest Power and Conservation Councils

Fish and Wildlife Program. Although the primary funding authority was in the Congressionally approved CRFM, other Federal agencies such as the Department of Energy (DOE), and Public Utility Districts (PUD's) have assisted and provided funding for various aspects of the TSP program. Due to the regional and national nature of these efforts, new coordination processes were developed in addition to existing forums. This was important to ensure coordination and to minimize duplication between the Corps, and the DOE programs and to maximize the use of the available funding. These efforts share the common goal to improve the survival of fish passing through turbines. The Turbine Working Group (TWG) was organized by the Corps' Northwestern Division using the Corps Hydroelectric Design Centers existing national mission coordination responsibilities to provide an informal forum for coordination, elimination of duplicate efforts, and to allow information sharing on a broad technical level. The TWG includes various COE, DOE, several PUD's, NMFS, Electric Power Research Institute (EPRI), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and BPA engineering and biological participants. Voluntary monthly meetings have been held since 1994, to share technical information and coordinate activities between the respective agencies, groups, and programs. The TWG has also provided a broad forum for cost sharing, review and evaluation of proposed fish passage improvement investigations and lessons learned from the combined results and experience of the group. In addition, several TSP team members are actively involved in the DOE's national Advanced Hydro Turbine System (AHTS) program, which allows for close coordination with efforts going on outside the Columbia River Basin.

The TSP has been coordinated within the regional forum as part of the 1995 and 2000 FCRPS Biological Opinion. This forum consists of the System Configuration Team (SCT), which prioritizes and suggests funding for the CRFM program, and the Anadromous Fish Evaluation Program (AFEP). The purpose of the AFEP is to produce scientific information to assist the Corps in making engineering, design, and operations decisions for the eight mainstem Columbia and Snake River Dams. Three working groups are formed within the AFEP program and include the Studies Review Work Group (SRWG), which is primarily responsible for initiating and coordinating studies for the program, the FFDRWG, which focuses on design of fish passage structures, and FPOM, which oversees operations of the fish facilities. Each of these work groups is composed of members from the U.S. Fish and Wildlife Service, NMFS, BPA, COE, Oregon Department of Fish and Wildlife, Washington Department of Fish and Wildlife, Idaho Department of Fish and Wildlife, NWPCC, and Columbia River Inter-Tribal Fish Commission. The Regional forum also consists of the Implementation Team (IT), which focuses on conflict resolution as the need arises within the other coordination groups. The coordination process provides input to all aspects of the program including development of the initial action plan, review of biological and modeling studies, and review of all periodic and final reports.

Corps TSP members also coordinate on a different level within the various FCRPS groups to assure operational improvements to existing turbine equipment are consistent with Regional fish passage improvement goals and requirements. This may be done through the turbine rehabilitation study teams, the Hydro Optimization Team (HOT), operation and maintenance teams and field-testing teams. These diverse groups may provide assistance to the TSP for various biological or engineering implementations, investigations, and to address operational improvements to the existing or potential turbine rehabilitations.

1.1.5 Scope

The TSP goal was to gather information allowing an accurate evaluation of fish passage benefits associated with turbine operational changes and improved turbine design concepts. The program was organized along two time frames, short-term (Phase I) and long-term (Phase II). Phase I of the scope of work consisted of using base case turbine information/data and McNary Unit 5 for engineering and biological prototype testing. The purposes of these tests were to:

- Explore methods to evaluate and understand fishery impacts caused by turbine operation.
- Develop turbine operational changes to improve fish passage through turbines.
- Identify biological criteria for use in turbine re-design.
- Develop recommendations for future turbine studies. (These recommendations will be implemented during Phase II.)

1.1.6 Study Approach

Phase I of the TSP relied on the integration of hydraulic turbine model studies, engineering studies, and biological studies to develop new turbine design criteria, to evaluate operational and physical modifications of existing turbines, and to provide a study of cost-effective alternatives to improve fish passage survival through turbines.

1.1.6.1 Turbine Hydraulic Model Studies

Physical hydraulic models have been used to evaluate the hydraulic conditions within the turbine passageway, and to evaluate power performance characteristics. Two types of hydraulic models were used: observational models and performance models. The models best used to evaluate the hydraulic characteristics through the turbine are the observational models constructed and tested at the COE Engineer Research and Development Center at Vicksburg, Mississippi (ERDC-WES hydraulic models). These models are made primarily of clear acrylic material, which allows visual access to nearly the entire water passageway. Beads 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-WES hydraulic models are tested using Froude similitude. Froude similitude relates the scale model test data to prototype using a linear scale relationship. The total turbine head used in Froude testing is a direct scale relationship to the prototype head; as a result these models are often referred to as Froude or low-head models.

The performance turbine models are used to measure flow, power, and other turbine performance characteristics such as cavitation. These models are generally tested using Reynolds similitude. Reynolds similitude relates model test data to prototype data by a ratio of inertia to gravitational forces. Performance models are generally tested under high-head conditions for increased accuracy of model measurements. Because of this, the performance models are constructed mostly of steel with limited visual access to the water passageways. The turbine blade angles, wicket gate angles, and turbine speeds necessary to set a given flow condition for the ERDC-WES hydraulic models are developed in the performance turbine models constructed by turbine manufacturing companies. These models are often referred to as Reynolds or high-head models.

The ERDC-WES hydraulic models and the turbine performance models have been used to evaluate existing turbine conditions, including the performance of turbines with and without intake diversion screens. They have also been used to evaluate turbine modifications with the potential to improve fish passage survival and turbine efficiencies. Some of the turbine modifications that were evaluated include modified runner designs, modified stay vane and wicket gate assemblies, and draft-tube modifications. The ERDC-WES hydraulic models have also been used extensively to aid in the design of biological test equipment, to establish biological test parameters, and to evaluate the biological test data.

See Section 2 for a more complete discussion of the model investigations conducted in support of the TSP Phase I.

1.1.6.2 Engineering Studies

Initial TSP engineering studies included a number of physical hydraulic model and field investigations to ensure prototype turbine-operating conditions were consistent with the design and current operating parameters. 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 (Appendix A.4) for McNary, Bonneville First Powerhouse (B1), The Dalles (Units 1 to 22), John Day (Units 1 to 16), Lower Monumental (1 to 6), and Lower Granite (Units 4 to 6). 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 (Appendix B).

Investigations involving engineering and biological tests to compare an existing Bonneville First Powerhouse Kaplan turbine runner to a new MGR turbine runner were added to the TSP in 1997. The MGR incorporated design features that were expected to improve turbine efficiency and reduce likely sources of turbine juvenile fish injury or mortality. The tests were designed to evaluate the effects of the MGR on juvenile fish passage and to determine if MGRs should be considered in future turbine rehabilitation programs. The engineering support for these tests included: index testing (tuning) of Unit 5 (existing) and Unit 6 (rehabilitated); the preparation of optimized turbine operating tables for both units with and without fish screens installed; a test plan; design and installation of a fish pipe release system; video imaging; design and installation of a monitoring system; and performing the necessary calibrations to achieve refined control of the two turbine units simultaneously. Similar efforts were necessary for the McNary Unit 9 biological tests of 1999 and 2002. The engineering measurements made during these biological tests were documented in the Hydroelectric Design Center (HDC) report, Biological Test. Turbine Operating Conditions. Unit 9.

More detailed information on these and other engineering studies completed for the TSP Phase I can be found in Section 3.

1.1.6.3 Biological Studies

Biological studies conducted during Phase I of the TSP focused on:

1) Investigation of direct mortality and the types of injuries to fish during passage through specific turbine routes under specific turbine operations.

2) Studies to obtain initial estimates of indirect turbine passage mortality.
3) Evaluation of the biological benefits of turbine structural modifications.
4) Investigation to determine the extent to which observations of beads in turbine physical models can be used to estimate the trajectories, probability of strike, and other measures of passage conditions for fish during turbine passage.
5) Description and evaluation of the physical environment to which fish are exposed during turbine passage.

Studies and other activities designed to address these items included the following:

- TSP biological studies were coordinated with biological studies conducted by the US Department of Energy in their AHTS program. The AHTS program supported laboratory studies of the effects on juvenile salmonids of exposure to shear and turbulence (Neitzel et al. 2000). It also supported studies of the combined effects of exposure to supersaturated total dissolved gas conditions and studies of simulated turbine passage pressure time histories. (Abernethy et al. 2001) (Abernethy et al. 2002)
- Biological studies to estimate direct and indirect mortality rates were conducted using Hi-Z Turb'n Tag (balloon tag) (Heisey et al. 1992) and radio tracking (Skalski et. al. 1998) technologies. Balloon tagging techniques permit fish to be recovered immediately following turbine passage. Since the fish can be recovered, determining their condition (alive, dead, injured, uninjured) and the types of injuries they sustained during turbine passage is possible. Radio-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. Both 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. Also, both technologies permit isolation of regions of interest to aid partitioning of survival and injury rate estimates to segments of the total turbine passage route.
- Most of the biological studies conducted during Phase I of the TSP required innovation in development of injection systems to place test and reference release fish in specific locations within the turbine passage environment. This resulted in unique fish injection systems that will be discussed in Section 3.2.1.6.5 and Appendix A.1.4.
- Route-specific studies were conducted at McNary Dam (May and June 1999) to estimate the mortality and injury rates and to identify the types of injuries fish sustained during turbine passage. In this study, balloon-tagged fish were injected into the turbine intake at specific locations and recovered in the tailrace.
- In September 1999 and July 2000, studies were conducted using a short baseline ultrasonic, three-dimensional tracking technique to observe the trajectories of juvenile steelhead trout and Chinook salmon, released upstream in the turbine intake, as they approached the turbine wicket gates. The trajectories of the juvenile fish were compared to that of drogues that were carried passively by flow through the turbine intake.
- In 1999 a new MGR was installed at turbine Unit 6 in Bonneville First Powerhouse. Over the winter of 1999-2000, a biological study using balloon tag methods and various types of fish was conducted to determine the turbine route-specific survival and injury rates

sustained by passing through the MGR runner. These were compared to the same information obtained for passage through the original design runner, located in adjacent turbine Unit 5. The MGR design eliminates large gaps at the tip and hub of turbine runner blades. These gaps had been implicated as a source of injury to fish (Normandeau 1996). During this study, a sensor developed under the DOE AHTS program was used to obtain measurements of the time history of turbulence response and pressure experienced by fish during turbine passage.

In 2002, radio-tracking studies were conducted at both McNary and Bonneville Dams. These studies were conducted with reference fish releases so that mortality rates could be estimated between the time test fish were injected into the turbine environment and the time they reached the end of the powerhouse tailrace.

Outside of the TSP, other turbine passage studies have been conducted by the COE and others. In 1994-5, balloon tag studies were conducted at Lower Granite Dam. In addition, the Mid-Columbia utilities conducted balloon tag studies of fish turbine passage survival at Rocky Reach Dam in 1993 and again in 1996, at Wanapum Dam in 1996 and at Rock Island Dam in 1997. In addition to balloon tag and radio-tracking studies, other studies that have used Passive Integrated Transponder (PIT) tags and other mark/recapture methods have been conducted at mainstem Columbia River dams. The results of many of these studies were included in the meta-survival analysis conducted by Bickford and Skalski (2000).

Additional information on biological studies can be found in Section 4.

1.2 General Information

1.2.1 Dam Passage

Salmonid populations in the Columbia River Basin have been on the decline in recent years, which has resulted in 12 Evolutionary Significant Units being placed on the endangered species list. Contributing to the decline of the salmonid population is a variety of naturally occurring and manmade hazards. Major contributors include water pollution, predation, harvest, and watershed modification through farming and increasing urbanization and dams. Dams are readily identifiable sources of impact to salmonid populations and, for this reason, have been the focus of considerable attention during efforts to restore threatened and endangered stocks, and to maintain healthy stocks of anadromous fish. Fish have several options for passing dams. Originally, juvenile fish moved downstream through turbines, through ice-trash sluiceways if available, or through spillways. Fish ladders were provided at the projects for upstream migrating adult fish. Later, it became apparent that downstream migrating juvenile salmonids needed additional assistance in passing mainstem hydroelectric facilities. Considerable effort and funds have been spent in recent years to improve juvenile survival through dams. Adult salmonids are known to occasionally “fall back” through turbines during upstream migration and kelts, downstream migrating spawned out steelhead, may also pass through turbines. Studies are currently underway to evaluate the rates of passage through turbines by these adult fish and the consequences of that passage. Methods include design and construction of screened juvenile bypass systems, transportation of juveniles, use of voluntary spill, modifying turbines and their operation, and developing new passage technologies such as surface collection facilities.

The National Marine Fisheries Service issued Biological Opinions for the FCRPS in both 1995 and 2000. Under the reasonable and prudent measures identified in the 1995 and 2000 FCRPS Biological Opinions, the region is currently evaluating a wide range of different passage strategies for restoring the anadromous fish runs on the Snake and Columbia Rivers. The COE, through the regional process, is evaluating and making improvements to existing juvenile passage facilities and initiating studies and methods for designing new passage technologies at the mainstem dams. The Biological Opinions recognized that significant improvements have been made to juvenile passage facilities at large mainstem dams and suggested where additional improvements should be implemented. This included improvements to Kaplan turbines, since it was recognized that, while bypass systems have been installed at most projects, none of the systems collect all the migrating fish. As turbine rehabilitations are considered, the volume of fish passing through the units should be determined, and, if justified, safer passage provided.

1.2.2 Turbine Passage Environment

1.2.2.1 Original Plant Physical Characteristics

The major civil facilities on the Columbia and Snake River system were constructed to meet existing regional demands for flood control, transportation and power production. Sites were selected based upon balancing civil engineering limitations and economic considerations. Included in these was the incorporation of hydropower generation. The basic civil engineering limitations such as dam height, excavation limitations and historical hydrology, defined the basic parameters of the site for turbine design. Once these limitations were defined, a turbine design was selected for that site. For the Columbia and Snake River system, the sites with Kaplan turbines are listed in Table 1.

Table 1. Corps of Engineers General Plant Characteristics

PLANT	LOCATION		TYPE OF PLANT	AUTHORIZED PURPOSE	TYPE OF TURBINE	SERVICE START	NUMBER OF UNITS	TOTAL CAPACITY		
	City	River/Lake						Nameplate Capacity (MW)	Maximum Capacity (MW)	Hydraulic (cfs)
Bonneville I	Bonneville, OR	Columbia River	Run-of-river	Power, Navigation	Kaplan	1938	10	518.4	596.16	136,000
Bonneville II	Bonneville, OR	Columbia River	Run-of-river	Power, Navigation	Kaplan	1982	8	532	612	152,000
Ice Harbor	Pasco, WA	Snake River	Run-of-river	Power, Navigation	Kaplan	1962	6	603	693	106,000
John Day	Rufus, OR	Columbia River	Storage	Flood Control, Power, Navigation	Kaplan	1971	16	2160	2484.8	322,000
Little Goose	Starbuck, WA	Snake River	Run-of-river	Power, Navigation	Kaplan	1970-1978	6	810	931.8	130,000
Lower Granite	Almota, WA	Snake River	Run-of-river	Power, Navigation	Kaplan	1975-1978	6	810	931.8	130,000
Lower Monumental	Matthaw, WA	Snake River	Run-of-river	Power, Navigation	Kaplan	1970-1978	6	810	930	130,000
McNary	Umatilla, OR	Columbia River	Run-of-river	Power, Navigation	Kaplan	1957	14	980	1127	232,000
The Dalles	The Dalles, OR	Columbia River	Run-of-river	Power, Navigation	Kaplan	1960-1973	22	1780	2052	375,000

Note: Information above obtained from Columbia River and Tributaries Study, Book 1, July 1989, US Army Corps of Engineers and Tabulation of Generator and Turbine Data.xls, US Army Corps of Engineers, HDC

1.2.2.1.1 Original Environmental Considerations

Original turbine environmental requirements were to prevent oil leakage and prevent cavitation; provide controlled inflow and outflow conditions to prevent erosion; provide a navigable system; and use the resource safely and efficiently. Initial design criteria of the civil structures may have incorporated features to allow consideration of adult upstream migration and other potential environmental protections.

1.2.2.1.2 Specific Turbine Selection

Selecting turbines for a site is an iterative process of meeting the site limitations economically. When these sites were constructed, the selection process had already been completed—with inherent uncertainties concerning the actual hydrological conditions at the site (e.g., 100-year flood was not known, only estimated). The project flow for storage, power, and flood control was determined using historical information. Power flow was determined from river flow and civil flood control limitations. Regional dependable electrical capacity requirements were established. The civil limitations for dam height (flood control), transportation requirements (locks) and dam location dictated the general footprint of the powerhouse and discharge area in relation to the spillway and other uses. The civil considerations for excavation, non-overflow, site access, unit size and number (largest physically sized machines in the fewest number to meet site flow requirements) defined the basic powerhouse. The following influenced the turbine design:

- Cavitation – The setting of the machine or the excavation of the powerhouse is dictated by cavitation requirements and submergence. This, in turn, is balanced by economics and hydraulic conditions.
- Size – The number of units is based on physical size limitations, civil constraints, flow capacity and duration, pool and tailwater constraints and durations, cavitation constraints and dependable capacity required.
- Water passages – The design of the water passages is limited by civil constraints. The manufacturer of the turbine, in collaboration with Corps hydraulic and structural design guidance and experience, established the water passage design meeting the minimum requirements to design goals.

1.2.2.2 Existing Plant Physical Characteristics

1.2.2.2.1 Existing Turbines

Almost all of the turbines installed at Federal dams on the Columbia and Snake rivers are Kaplan turbines. These turbines are of the axial flow type and primarily of the vertical shaft design. In general, the designs of the turbines vary; they have been procured and installed over approximately forty years, incorporating technological advances in design and materials. As of the publication date of this report, the Bonneville First Powerhouse turbines are being rehabilitated with modern Kaplan turbine runners designed to incorporate possible environmental improvements. The Dalles turbines 1 to 14 are scheduled for rehabilitation in the near future. McNary turbines are presently being investigated for replacement with fixed blade turbine runners incorporating environmental improvements. Rehabilitation of the turbine in Ice Harbor Unit 2 is being planned to incorporate the replacement of a Kaplan turbine with environmental enhancements. Table 2 lists the existing turbines and their design families with some identifying characteristics.

Table 2. Corps of Engineers Families of Turbines

FAMILY	DATE OF SERVICE	TURBINE MANUFACTURER	NUMBER OF BLADES	NUMBER OF STAY VANES	NUMBER OF WICKET GATES	RUNNER DIAMETER (IN)	SPEED (RPM)	UNITS	PROJECT
1	1938	S. Morgan Smith	5	17	20	280	75	1-10	Bonneville I (MGR)
2	1982	Allis-Chalmers	5	23	24	331.2	69.2	11-18	Bonneville II
3	1960	Baldwin-Lima-Hamilton	6	23	24	280	85.7	1-14	The Dalles
4	1973	Baldwin-Lima-Hamilton	6	22	24	300	80	15-22	The Dalles
5	1971	Baldwin-Lima-Hamilton	6	22	24	312	90	1-16	John Day
6	1957	S. Morgan Smith	6	19	20	280	85.7	1-14	McNary
7	1962	Allis-Chalmers	6	19	20	280	90	1-3	Ice Harbor
8	1976	Allis-Chalmers	6	19	20	300	85.7	4-6	Ice Harbor
9	1970	Baldwin-Lima-Hamilton	6	22	24	312	90	1-3	Lower Monumental
	1970	Baldwin-Lima-Hamilton	6	22	24	312	90	1-3	Little Goose
	1975	Baldwin-Lima-Hamilton	6	22	24	312	90	1-3	Lower Granite
10	1978	Allis-Chalmers	6	19	20	312	90	4-6	Lower Monumental
	1978	Allis-Chalmers	6	19	20	312	90	4-6	Little Goose
	1978	Allis-Chalmers	6	19	20	312	90	4-6	Lower Granite

Appendix A.4 contains the current one-percent operating tables.

The original turbines installed at the Corps powerhouses were installed without fish diversion structures in the turbine water passages. The concept of using various devices to divert fish from passing through the turbines was developed in the 1970’s and has been refined over the years to the present configuration. Currently, many of the powerhouses have fish screens installed during much of the year (approximately 9 months) during migration of juvenile salmon returning to the ocean. Various configurations of fish diversion devices have been installed in an attempt to provide sustainable returns of the endangered or threatened fish species. The installation of these structures affects the turbine’s operating characteristics by causing disruptions in the flow field entering the turbine distributor. Recent field and model tests have quantified the effect of fish diversion screens and other structures, such as surface collectors, on the turbine performance. Care must be taken when designing these types structures to minimize the impact on the turbine, and, when installed, they may require a re-synchronization of the runner blade to wicket gate position for optimum performance. Based upon existing field-test information the following diversion devices cause the indicated efficiency losses to turbine performance:

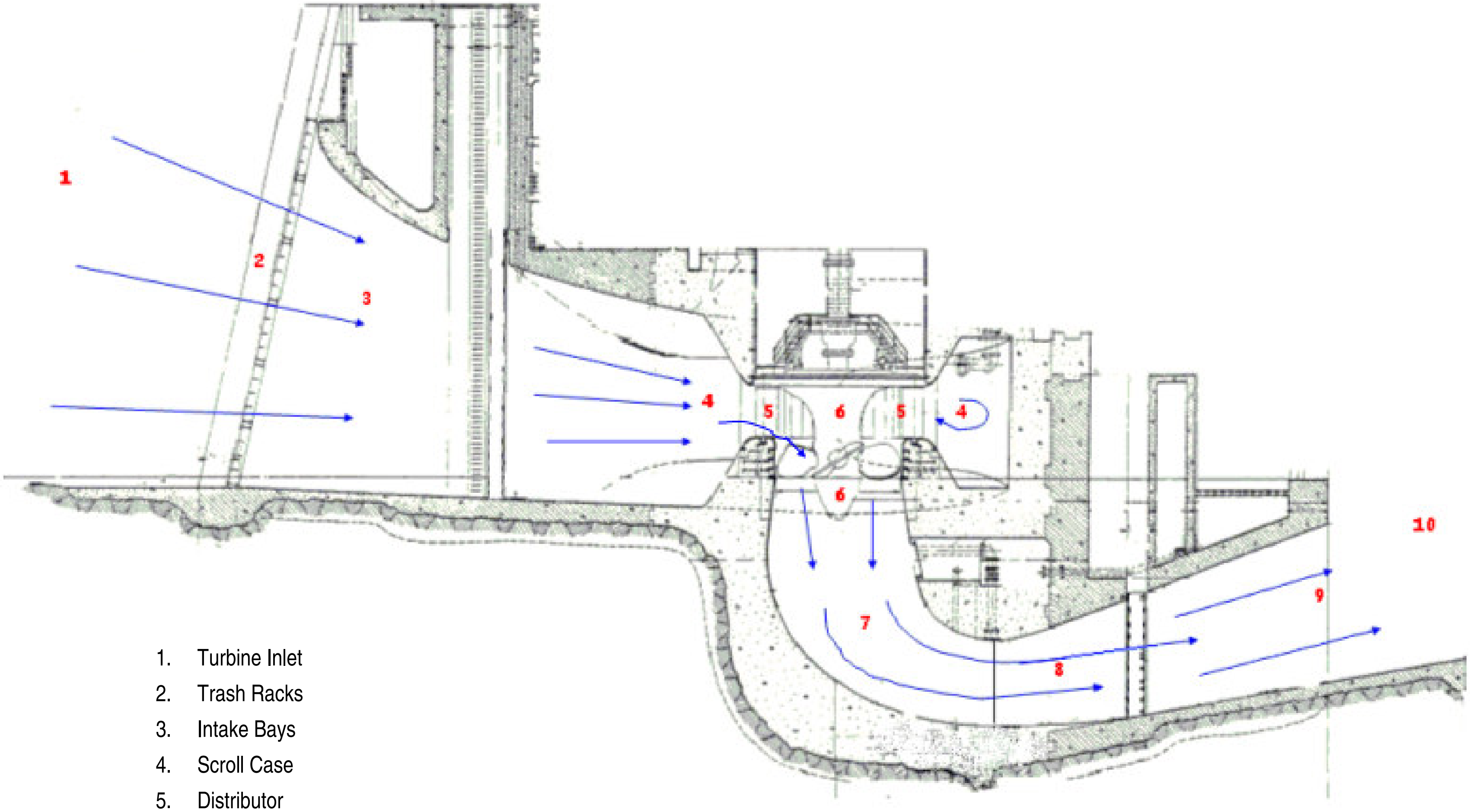
- Submerged Traveling Screens (STS) – 0.75 to 1.3 percent
- Extended-length Submerged Bar Screens (ESBS) – 1.0 to 4.0 percent
- Surface Collectors – 2.0 to 6.0 percent
- Trash Rack Blockages – 1.0 to 10.0 percent

All of the mainstem projects, except for the Dalles, have turbine intake screens. Three of the projects have extended-length submerged bar screens (ESBS) that extend approximately 40 feet into the intake. The other projects have submerged traveling screens (STS) that extend 20 feet into the intake.

1.2.2.2.2 Description of Turbine Environment

The turbines selected for installation on the Columbia and Snake rivers are generally termed *Kaplan turbines*. Kaplan turbines are a reaction-type, vertical shaft turbine, with adjustable blades designed to optimize turbine performance and operate over a relatively wide flow and head range, from about 100 feet to as little as 20 feet of head. The turbine design and the number of adjustable blades are defined by the head and flow range of operation. The environment of the Kaplan turbine can further be characterized by dividing it into zones. These zones are shown on Figure 2, summarized in Table 3, and described as follows:

- <u>Turbine Inlet (1)</u> **–** The flow enters a specific turbine inlet from the pool and is affected by conditions or events associated with project operation for both power and other uses. The inflow conditions can be greatly affected by the civil works, underwater topography, trash or ice, number of units in operation, the location of units in operation, the level of power operation, spill conditions and the general relationship of the river flow to the turbine inlet. Any of these, or a combination thereof, can cause fluctuating flow and oblique approach conditions resulting in unsteady conditions in the intake.
- <u>Trash Racks (2)</u> – Trash racks have been installed in each bay to prevent large trash or debris from entering the turbine and causing damage or operational blockages. These devices are a removable, rigid design with little streamlining to improve flow conditions. The design maximum water velocity through the racks is about 5.5 ft/sec or they are designed for a head loss in the range of 0.5 feet near rated conditions. However, losses can approach 2.0 feet depending on the inlet flow and actual operating condition. The trash racks tend to straighten the inlet flow to the intake.



1. Turbine Inlet
2. Trash Racks
3. Intake Bays
4. Scroll Case
5. Distributor
6. Runner Chamber
7. Draft-tube and Elbow
8. Draft-tube Barrels
9. Draft-tube Exit
10. Downstream Discharge Area

Figure 2. Turbine zones.

- Intake Bays (3) – In general, the three bays are designed with equal areas and contain a set of bulkhead slots and emergency gates as well as air vents. Under normal operating conditions, the flow distribution in each bay is somewhat different, ranging from about 30 to 37 percent depending on inflow conditions and turbine operation. The original intake designs attempted to provide a smooth flow transition from the trash racks to the scroll case. The current configuration at many plants is to have fish diversion devices installed in the upstream bulkhead slot. The installation of these devices results in flow disruptions and turbulence as the flow enters the scroll case and increased frictional losses and hydraulic losses. The velocity distribution to the scroll case is severely affected by the devices, resulting in non-uniform flow conditions, often with large-scale turbulence, entering the scroll case.
- Scroll Case (4) – The scroll case accepts the flow from the intake and is designed (without fish screens) to equally and smoothly distribute the flow to the turbine distributor near a constant radial velocity and impart a pre-whirl to the water as it enters the turbine. The closure of the scroll case is often called the "crotch" section and should have equal flow on each side.
- Distributor (5) **–** The distributor is composed of stay vanes, nose vane, and wicket gates. Stay vanes are stationary, structural elements shaped to guide flow to the wicket gates and runner. The number of stay vanes is normally less than the number of wicket gates. The nose vane forms the convergence of the scroll case. The stay vane angle is based on the selected design flow to impart a direction to the flow to effectively intersect the turbine runner. On most of the existing machines the angle is constant for most of the stay vanes. The angle in modern designs is better defined through the use of computational fluid dynamics and results in different angles at various locations in the distributor. The wicket gates are shaped like a wing and often are tapered from top to bottom. They are moveable and move simultaneously in a "cascade". They are used to throttle the water to the turbine. The movement of the runner blades is coordinated with the movement of the wicket gates to result in optimum (on cam) efficiency. The wicket gates adjust the flow to the turbine runner and have approximately equal velocity between adjacent pairs at any on cam gate opening.
- Runner Chamber (6) **–** The runner chamber is composed of discharge ring, head cover turbine runner, runner cone, and the draft-tube liner. The discharge ring surrounds the runner blades and provides a guide for the water. The head cover is an axisymmetric structural member and provides guidance for the water on to the turbine runner. The turbine runner rotates and, to optimize the conversion of potential energy to shaft power, the pitch angle of its adjustable blades matches the inlet water velocity vector angle from the distributor. The adjustable blades optimize performance over a wide flow and head range. The maximum water pressure is above the runner and the minimum pressure is just below the runner. The maximum water velocity occurs in the runner chamber. To eliminate flow separation, the runner provides a residual whirl in the discharge to the draft-tube liner. The upper draft-tube steel liner is the upper part of the draft-tube, which is a conical diffuser and protects the concrete from the high water velocity.

- Draft-tube and Elbow (7) – The draft-tube elbow or foot is a diffuser in the form of an elbow used to convert the direction of the water from a vertical to horizontal direction. The draft-tube is used to reduce the velocity and recover the residual velocity head to the runner. The height and expansion is designed to increase uniformly in areas without flow separation. Flow in this area can be severely turbulent depending on the turbine operating point. The draft-tube in most cases was designed for optimum operation at high flow conditions and is linked to the runner design to produce the desired performance. The design is also linked to the economics because the lower the elbow, the greater the civil excavation required.
- Draft-tube Barrels (8) – The draft-tube is normally segmented into two barrels by an intermediate pier. The cross-sectional area of each barrel is continually expanding and is shaped to preclude flow separations. A central pier provides structural support to the turbine and civil works, and is located to cause the least effect on the change in area. A set of slots is provided in each barrel to allow bulkheads or stop logs to be installed to permit dewatering of the turbine water passage. The flow angle at the exit is slightly upward to minimize scour of the river bottom. The flow through each barrel can vary significantly depending on the turbine operating condition and site hydraulics. Turbulence and velocity in some areas can be high and unsteady resulting in a "pulsing" phenomenon.
- Draft-tube Exit (9) – The exit area of the draft-tube is designed as large as is reasonable and with a 6 to 8 ft/sec average water velocity. The roof elevation is selected to provide sufficient submergence of the draft-tube during the most infrequent minimum operating conditions. Discharge flow is best distributed at high flow conditions. Instability may occur at partial load conditions resulting in undesirable velocity distributions.
- Downstream Discharge Area (10) – The downstream discharge area is often referred to as "the boil". This area is subject to existing river hydraulic conditions, but it is desired to provide a smooth discharge transition from the draft-tube exit to general river conditions. The discharge must contain enough energy to ensure flow downstream without disruptive river conditions. The conditions in the discharge area can vary widely depending on operating conditions. Tailwater levels and directions of flow vary with number of units on line, lockages, downstream operating effects and spill.

Table 3. Summary of Turbine Zones

ZONE	DESCRIPTION
1. Turbine Inlet	The region upstream of the dam from which the turbine pulls water.
2. Trash Racks	Steel grating to keep trash from damaging the turbine.
3. Intake Bays	Three bays to distribute flow to the turbine scroll case
4. Scroll Case	A volute-shaped chamber directing water uniformly to the distributor.
5. Distributor	A ring around a turbine runner composed of the stay vanes and wicket gates. The stay vanes carry the structural weight and the wicket gates rotate to adjust the flow.
6. Runner Chamber	The zone containing the stationary and rotating components of the turbine, which converts waterpower to shaft power. It is composed of the discharge ring, head cover, runner blades, hub and cone.
7. Draft-tube and Elbow	A shaped diffuser tube below the turbine runner in which velocity and pressure heads are recovered.
8. Draft-tube Barrels	A structural pier that separates the draft-tube into two sections to direct discharge in a downstream direction.
9. Draft-tube Exit	The exit area of the draft-tube where discharge expands to the tailwater level.
10. Downstream Discharge Area	The chaotic region, a short distance downstream from the draft-tube exit, where turbine discharge returns to river conditions.

1.2.2.3 Existing Plant Operational Characteristics

The majority of powerhouses on the Columbia and Snake rivers operate as “run of the river” projects. This means existing river flow at a particular time is passed through the project with little storage available. The river flow is passed downstream through the spillway, turbines and other minor routes such as ice and trash sluiceways. River flow is adjusted by the Reservoir Control Center (RCC) to match inflow conditions or other regional requirements. Flow at a project is somewhat regulated by the power demands but conforms to operational requirements such as the annual Fish Passage Plan.

Kaplan turbines have a coordinated system of movable flow distribution devices, called wicket gates, and adjustable blades, which optimize efficiency for the desired operating condition. The wicket gates and runner blades must be coordinated geometrically to produce the optimum operating condition. This relationship is termed “on cam” operation and is established from engineering data and field-testing measurements. The adjustments to establish or monitor on cam conditions are measured externally to the water passage through the use of moving mechanical components in the turbine. These mechanical components convert the mechanical movement to an electronic signal that is monitored by the governor. The governor checks power, speed and head to ensure correct positioning. If a change is needed to maintain optimum operation, the turbine is mechanically adjusted (blade-gate) to achieve the optimum condition. The establishment of this on cam blade-gate relationship is a difficult engineering challenge because this relationship changes for head and power changes. A tabular set of information is developed which must be fine-tuned to account for the idiosyncrasies of each machine. This tabular set of data is derived through model test information and field-test information. The field-test information is obtained through an *index test*, which is discussed in more detail in Section 3.4.3.2.

1.2.2.4 Fish Passage Injury

For juvenile fish using the mainstem Columbia and Snake rivers as a migration corridor, the primary evaluation method for determining the biological impact of an action is simulation modeling of the proposed action on the action area biological requirements. The Biological Effects Team agreed to use NMFS' Simulated Passage (SIMPAS) model to evaluate the biological benefits of juvenile salmonid passage measures. The spreadsheet model, developed by staff in the Hydro Program of NMFS' Northwest Region, is a fish passage accounting model that apportions the run to various passage routes (i.e., turbines, fish bypass system, sluiceway/surface bypass, spillway, and/or fish transportation) based on empirical data and input assumptions for fish passage parameters. The model accounts for successful fish passage (survival) and losses (mortalities) through each of the alternative passage routes to estimate survival past each project. In addition, it accounts for the proportions of juvenile fish transported and left to migrate upriver. The model also provides survival estimates at each project (dam plus pool) and throughout the system (from the head of Lower Granite Reservoir to the tailrace of Bonneville Dam).

The data used in SIMPAS, obtained from Appendix D of the NMFS 2000 Biological Opinion are shown in Table 4. The table contains estimates for the fish guidance efficiency (FGE) of turbine intake fish diversion screens, which are expressed as a percentage of the fish entering the intake that are successfully guided by screens into juvenile bypass systems. Unguided fish pass through turbines. The table also shows the estimates of survival for turbine, spillway, and bypass dam passage routes for yearling and subyearling Chinook smolt for Federal lower Columbia River and Snake River dams. Over the past several years, research emphasis has been placed on improving fish diversion from turbines and providing alternatives to turbines for dam passage. As a result considerable effort has gone into measuring the guidance efficiency of turbine intake screens. Only recently has more research effort gone into obtaining estimates for dam passage route survival. For this reason, many of the passage route survival estimates in Table 4 are not based on specific studies, but are extrapolated from studies conducted at dams with similar structures and operations. The estimates in Table 4 will be replaced as studies provide better fish passage survival information.

Table 4. Estimates of passage parameters for yearling Chinook salmon and Steelhead and subyearling Chinook salmon*

PROJECT	SPECIES	FGE	TURBINE	SPILLWAY	BYPASS
BON I	Yearling Chinook	39%	90%	98%	90%
	Yearling Steelhead	41%	90%	98%	90%
	Subyearling Chinook	9%	90%	98%	82%
BON II	Yearling Chinook	48%	90%	98%	98%
	Yearling Steelhead	48%	90%	98%	98%
	Subyearling Chinook	28%	94%	98%	98%
IHR	Yearling Chinook	54%	90%	98%	98%
	Yearling Steelhead	93%	90%	98%	98%
	Subyearling Chinook	54%	90%	98%	98%
JDA	Yearling Chinook	73%	90%	98%	98%
	Yearling Steelhead	85%	90%	98%	98%
	Subyearling Chinook	32%	90%	98%	98%
LGS	Yearling Chinook	78%	92%	100%	99%
	Yearling Steelhead	81%	92%	100%	95%
	Subyearling Chinook	53%	90%	98%	98%
LWG	Yearling Chinook	75%	93%	98%	98%
	Yearling Steelhead	81%	93%	98%	98%
	Subyearling Chinook	53%	90%	98%	98%
LMN	Yearling Chinook	49%	92%	97%	95%
	Yearling Steelhead	82%	93%	97%	93%
	Subyearling Chinook	49%	90%	98%	98%
MCN	Yearling Chinook	83%	90%	98%	98%
	Yearling Steelhead	89%	90%	98%	98%
	Subyearling Chinook	62%	90%	98%	97%
TDA	Yearling Chinook	3%	90%	90%	n/a
	Yearling Steelhead	3%	90%	90%	n/a
	Subyearling Chinook	3%	90%	88%	n/a

*Data from Appendix D NMFS 2000 Biological Opinion

Under Phase I of the Turbine Survival Program the Corps has begun to obtain fish survival and injury estimates for turbine passage at Federal dams. This information is presented in Section 4.

The mortality rate of fish passing through a turbine is broken into two components, direct and indirect. Direct turbine passage mortality is the result of injuries fish experience during turbine passage, although death may occur hours or days later in the river downstream. Mechanisms of injury include strike, pinching, scraping, shear, pressure, turbulence, and various combinations. Direct injuries are those that can be readily observed upon recovery of a fish following passage. Typically direct injuries can only be estimated using a mark/recapture method such as balloon tags. Examples of direct injuries are decapitation, severed body, cuts, bruises, bloody eyes, opercular damage, fin damage, and disorientation or loss of equilibrium. Autopsy of fish showing external signs of injury can result in identification of other internal injuries. Only a portion of fish showing direct injuries is dead upon recovery or dies during a holding period following recovery. Rates of direct injury and mortality from direct injury can vary considerably as a function of turbine passage route and other factors. Phase I of the Turbine Survival Program has mainly focused on direct injury and mortality of turbine-passed fish with the intent of identifying structural and operational modifications to turbines that could decrease injury and mortality rates.

Indirect turbine passage route mortality is that portion of total mortality that occurs in the powerhouse tailrace and is not simply the result of obvious injuries as described previously. While it is generally assumed that injuries to fish and, particularly, temporary disability such as vestibular system disruption contribute to indirect mortality, cause and effect has not been substantiated. Other factors such as disease that might reduce the fitness of fish and make them more vulnerable to predation are likewise not considered because of the extreme difficulty of demonstrating cause and effect. Therefore, indirect mortality is generally defined as predation of juvenile, turbine-passed fish, of whatever degree of fitness, by birds and piscivorous fish in the tailrace. Indirect mortality, which is infrequently directly measured but estimated by subtracting direct turbine passage mortality from total turbine passage mortality, has been observed to be at least equal to or higher than direct mortality. While Phase I of the TSP has focused on direct turbine mortality, the need to address indirect mortality is evident and is an element of TSP Phase II. Turbine passage survival studies conducted between 1988 and 2002 at mainstem COE dams are discussed in Section 4.1.1. A summary of the survival estimates obtained in these studies is presented in a series of tables organized by dam in Section 4.1.1.4.3.

TSP Phase I research into turbine passage has shown that identification of turbine environment features affecting the safety of fish requires assessment of fish injury. Because of this, considerable emphasis has been placed on learning how to better classify fish injuries to the most likely causal mechanism. Direct physical injury is discussed in detail in Section 4.2.

Section 2. Turbine Hydraulic Modeling

2.1 Modeling Introduction

The primary objective of the turbine hydraulic modeling efforts was to develop model capabilities, and to use those capabilities to better design and evaluate turbine improvements and improve turbine operations. Prior to the TSP, the Corps of Engineers relied heavily on the use of physical hydraulic models at the Engineer Research and Development Center – Waterways Experiment Station (ERDC-WES) to design turbine intake screens to keep fish out of the turbines. The TSP combined the ERDC-WES hydraulic model test capabilities with the manufacturer's performance model test capabilities and developed a program to design and test turbine models to improve fish passage survival and turbine efficiency.

A tremendous amount of turbine model development and testing was completed in support of the TSP. Some of this work was completed through the Kaplan Turbine Improvement Program (KTIP) funded by the BPA, and the AHTS program with funding from DOE, the remainder was funded by the Columbia River Fish Mitigation program. All of the work was coordinated with TSP to meet TSP and other study objectives. The physical turbine model studies included performance testing at the VA TECH laboratory in Linz, Austria, and hydraulic model testing at ERDC-WES, in Vicksburg, Mississippi.

The turbine hydraulic model studies performed under Phase I cover three distinct modeling types.

- Turbine performance model testing
- ERDC-WES hydraulic modeling
- Computer numerical modeling

In general, the performance model testing allows for measurement of power and efficiency and an evaluation of cavitation, while the hydraulic model testing at ERDC-WES allows for visual observations and the collection of velocity and particle path data throughout the turbine unit. As illustrated by Table 5, a number of physical hydraulic models representing prototype turbines of the FCRPS projects have been constructed and tested.

These investigations incorporated turbine performance model testing, turbine hydraulic modeling, and numerical modeling with prototype field measurements to define, in engineering terms, the physical conditions within a turbine water passage. Engineering and biological judgment was then used to identify potentially dangerous or unsatisfactory conditions for fish passage. Design modifications for improving fish passage conditions were identified and incorporated into the models for additional evaluation. Some of the modifications were then tested in a turbine performance model to evaluate for power, efficiency and cavitation. The successful design modifications may be incorporated into an existing prototype design, and field-tested to determine improvements in fish passage survival as part of Phase II of the TSP program.

Phase I of the TSP included the investigations of three Kaplan model turbines replicating turbine units of the McNary, Bonneville I, and Lower Granite projects. The first objective was to define basic turbine model performance for existing designs. The investigations included examining the effects of fish screens on turbine operation to understand conflicting and often confounding prototype turbine performance information. In addition, the relationship of existing prototype performance, Reynolds performance model testing and Froude hydraulic model testing at ERDC-WES was investigated to determine if the modeling techniques were transferable between the prototype, Reynolds model and Froude model.

Table 5. Physical Hydraulic Models Constructed and Tested

MODEL	SCALE	TYPE	TEST	PURPOSE
McNary ERDC-WES Hydraulic Without Runner	1:25	Low-Head/ERDC	Froude	1. Extended screen design development
McNary ERDC-WES Hydraulic With Runner	1:25	Low-Head /ERDC	Froude	1. Comparison of velocity data from pre-runner to post runner model 2. Investigation of potential hazard zones 3. Development of techniques to investigate turbine environment 4. Bead investigation to pick release points for biological prototype tests 5. Draft-tube modifications
McNary ERDC-WES Hydraulic Intake	1:12	Low-Head/ERDC	Froude	1. Vertical barrier screen design 2. Vertical barrier screen debris investigation 3. Orifice investigations
McNary Turbine Performance	1:25	High-Head and Low-Head Performance/VA TECH	Reynolds Froude	1. Development of model cam curves for ERDC-WES model 2. Development of prototype cam curves using Froude technique 3. Development of prototype cam curves using Reynolds technique 4. Comparison of Froude and Reynolds technique for developing prototype cam curves 5. Investigations of the effects of draft-tube modifications on turbine performance 6. Investigations of MGR designs
Lower Granite ERDC-WES Hydraulic Without Runner	1:25	Low-Head/ERDC	Froude	1. Extended screen design development 2. Surface collector investigations 3. River drawdown
Lower Granite ERDC-WES Hydraulic With Runner	1:25	Low-Head /ERDC	Froude	1. Comparison of velocity data from pre-turbine to post turbine model 2. Draft-tube modifications 3. Stay vane modifications

Table 5. Physical Hydraulic Models Constructed and Tested

MODEL	SCALE	TYPE	TEST	PURPOSE
Lower Granite ERDC-WES Hydraulic Intake	1:12	Low-Head/ERDC	Froude	1. Vertical barrier screen design 2. Vertical barrier screen debris investigation
Lower Granite Turbine Performance	1:25	High-Head and Low-Head Performance/VA TECH	Reynolds Froude	1. Development of model cam curves for ERDC model 2. Development of prototype cam curves using Froude technique 3. Development of prototype cam curves using Reynolds technique 4. Comparison of Froude and Reynolds technique for developing prototype cam curves 5. Investigation of effects of surface collector on turbine performance 6. Investigations of effects of draft-tube modifications on turbine performance 7. Design of stay-vanes and wicket gates to improve fish passage 8. MGR development 9. Investigations of drawdown effects
Bonneville First ERDC-WES Hydraulic Without Runner	1:25	Low-Head/ERDC	Froude	1. Extended screen design development 2. Streamlined trash rack design development 3. Surface collector design development 4. Release point picks for prototype biological tests
Bonneville First ERDC-WES Hydraulic With Runner	1:25	Low-Head /ERDC	Froude	1. Biological release point verification for original runner 2. Biological release point verification for MGR
Bonneville First ERDC-WES Hydraulic Intake	1:12	Low-Head/ERDC	Froude	1. Vertical barrier screen design
Bonneville First Turbine Performance	1:25	High-Head and Low-Head Performance/Voith Hydro	Reynolds Froude	1. Development of MGR using Reynolds technique 2. Investigation of the influence of ESBS on turbine performance using Froude-head 3. Investigation of influence of surface collector on turbine performance using Reynolds technique

2.2 Physical Turbine Hydraulic Model Studies

All turbine hydraulic models constructed and tested at ERDC-WES rely on Froude similitude for prototype relationship. These models are sometimes referred to as observational models because of the plexiglass construction, and are sometimes called low-head models because the differential head across the model is related to prototype head by the geometric scale. For this report, these models will be referred to as *ERDC-WES hydraulic models*. The turbine performance models used by industry to design prototype runners rely on Reynolds similitude; these models are typically referred to as performance or high-head models. For this report, these models will be referred to as *turbine performance models*. All models built for TSP investigations were constructed at 1:25 scale. To acquire similitude in the high-head turbine performance model, the flow through the model is increased for increased velocity and runner speed. The velocity in the Reynolds-head turbine performance model is directly dependent on the test head and can be as much as five times greater than that tested in the Froude model of the same physical scale.

The physical model studies are based on scientific methods using scale relationships defined by Froude and Reynolds similitude. Numerical modeling is based on theoretical and mathematical techniques to compute expected results. Froude model testing is representative of the actual scale but is considered to be less accurate at measuring turbine performance and cannot measure cavitation phenomena. Reynolds modeling is based on the ratio of inertia to gravitational forces. Froude is normally used with water surfaces open to atmosphere while Reynolds is used for closed systems and is usually tested at high-heads. Numerical modeling is representative of inviscous flow (no fluid viscosity) and uses the Navier-Stokes equations.

2.2.1 Froude Modeling

Froude hydraulic model techniques have been used at ERDC-WES for many years in the design of fish diversion screens as well as many other fish passage investigations. The accepted equations of hydraulic similitude for a 1:25-scale model, based on the Froudian relations, are used to express mathematical relations between the dimensions and hydraulic quantities of the model and prototype. General relations for the transfer of model data to prototype equivalents, or vice versa, are presented in Table 6.

Where:

H = head, r = ratio (Hr = head ratio of model to prototype).
L = length, (Lr = scale ratio of model to prototype).
A = area, (Ar= area ratio of model to prototype).
V = velocity, (Vr = velocity ratio of model to prototype).
Q = discharge, (Qr = discharge ratio of model to prototype).
N = speed of rotation, (Nr = speed ratio of model to prototype).

Table 6. General Froude Relations for Transferring Between Model Data and Prototype Equivalents Geometric Scale 1:25		
DIMENSION	**RATIO**	**MODEL : PROTOTYPE SCALE RELATIONS**
Head	Hr = Lr	1:25
Length	Lr = L	1:25
Area	$Ar = Lr^{2}$	1:625
Velocity	$Vr = Lr^{0.5}$	1:5
Discharge	$Qr = Lr^{2.5}$	1:3125
Runner speed	$Nr = 1/Lr^{0.5}$	1:0.2

Using Froude model similitude for performance model testing is not an industry practice because of the inability to accurately measure small differences in power and efficiency. For example, the accuracy of a Reynolds high-head model test is in the range of 0.15 to 0.3 percent. Using the same measurement equipment Froude scale accuracy would be in the range of 1.5 to 2.5 percent. Performance model test codes require an accuracy of test measurement equipment of about 0.1 percent. Measuring the Froude scale values is difficult because model test head is low, resulting in the inability to accurately measure small differences in power and efficiency. However, Froude performance testing was conducted using Lower Granite and McNary performance models at VA TECH. These Froude turbine performance models achieved accuracies of 0.3 to 0.5 percent, which is a significant accomplishment. Even though these tests are called Froude, they are exactly the same experiments as those conducted using Reynolds similitude except they were tested at a lower head and, therefore, a lower Reynolds number. The Reynolds number used for Froude performance testing is on the order of $3x10^{5}$ compared to Reynolds performance testing of $1.3x10^{6}$ and the prototype of $6x10^{7}$.

2.2.2 Reynolds Performance Modeling

The relationship of model to prototype using Reynolds similitude is shown in Table 7 for a 1:25 scale. These relationships are not truly Reynolds similitude, as true Reynolds similitude would be impractical, requiring model test heads in the 30,000-foot head range, however the Reynolds equations can still be used for making model to prototype conversions as long as the Reynolds numbers are within acceptable ranges.

Where:

H = head, r = ratio (Hr = head ratio of model to prototype).
L = length, (Lr = scale ratio of model to prototype).
A = area, (Ar = area ratio of model to prototype).
V = velocity, (Vr = velocity ratio of model to prototype).
Q = discharge, (Qr = discharge ratio of model to prototype).
N = speed of rotation, (Nr = speed ratio of model to prototype).

Table 7. General Reynolds Relations for Transferring Between Model Data and Prototype Equivalents For Reference Head (Prototype Head used as Model Head)

DIMENSION	RATIO	MODEL : PROTOTYPE SCALE RELATIONS
Head	Hr = 1	1:1
Length	Lr = L	1:25
Area	$Ar = Lr^2$	1:625
Velocity	Vr = 1	1:1
Discharge	$Qr = Lr^2$	1:625
Runner speed	Nr = Lr	1:25

Table 7 provides the conversion between model and prototype values if the prototype head is used in the model. However, this is not the case in most performance models; the test head in the performance models is limited by the model design and test stand capabilities. The conversions have to be adjusted accordingly.

2.2.3 Comparing Froude and Reynolds Modeling

Scale model and prototype turbine velocity profiles and performance were evaluated using two different modeling methods: Froude and Reynolds. The applications of the two modeling methods are shown in Table 8.

Table 8. Froude and Reynolds Modeling

CHARACTERISTIC	FROUDE	REYNOLDS
System Type	Open to Atmosphere	Closed to Atmosphere
Error Band	Higher (at low head) for turbine performance Low for velocity measurements	Low (at higher head) High for velocity measurements
Measures	Velocity Profiles Turbine performance with test stand improvements Bead impacts	Turbine Performance Cavitation Pressure Pulsations

The two methods were applied to the manufacturer’s steel high-head models (turbine performance models) and the scale model at ERDC-WES (ERDC-WES hydraulic models).

2.2.4 Data Collection Methods for ERDC-WES Hydraulic Modeling

The initial part of the TSP model program was to develop tools and methods that could be used to investigate models for fish passage issues. The following is a brief description of the tools investigated:

- Laser Doppler Velocity System (LDV) – ERDC-WES used a three-beam, two-color laser LDV (Figure 3) to measure velocities in both the pre-runner and post-runner models. This system consists of a 4-watt Argon laser, optics to split and color-separate the laser beam

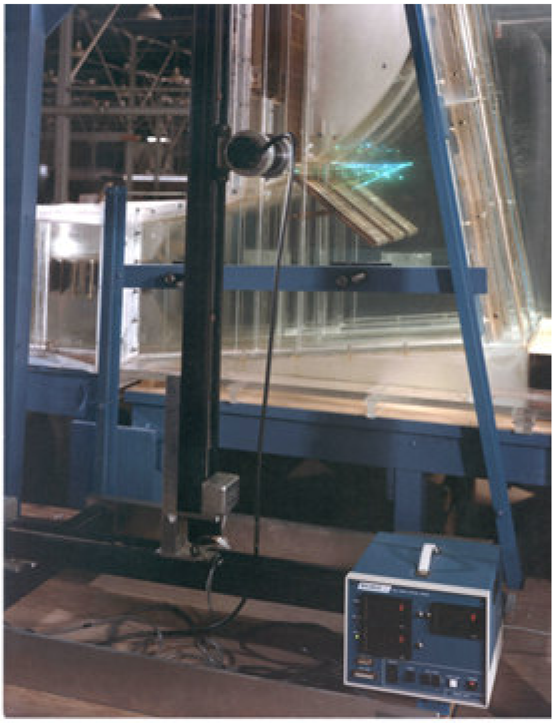


Figure 3. Laser Doppler velocity system.

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 measures two components of the flow field. The LDV system is a critical tool for defining flow distributions, velocity magnitudes and direction, turbulence, and for investigations of shear.

- Dye – Dye is used to aid the observation of flow paths through the model. It is a useful tool in the area around the trash racks to just downstream of the ESBS. It shows the effect of the screens on flow distribution and the turbulence that the ESBS imparts to the flow. It is also useful for showing the reverse flow that occurs in the draft-tube for various operating conditions. However, the dye disperses quickly in the turbulent flow which occurs downstream of the fish screens and makes it difficult to define flowlines into the stay-vane wicket gate arrangement. Dye is not useful in the immediate vicinity of the runner because of dispersion and high velocities.
- Bead development – Flow downstream of the ESBS is highly turbulent. Normal dye disperses too quickly to obtain detailed information in the vicinity of the stay vanes, wicket gates, runner, and in the draft-tube. As a result, nearly neutrally buoyant beads were investigated as tools to look at flow lines, the interaction of flow to the stay vane and wicket gate arrangement, and the turbine environment. A great deal of research was performed to find a bead with the same density as water. At least ten different bead types with varying specific gravities were investigated. Two bead types were picked from this investigation. The first was a white polystyrene bead with a specific gravity of 0.98 and a yellow polystyrene bead with a specific gravity of 1.02. These beads are raw materials

used in plastic injection modeling. Initially a bead type that had a specific gravity of water (1.0) could not be found and, in conversations with bead manufacturers, it would be very difficult to find or manufacture a bead with the same specific gravity as water. During TSP experiments ERDC-WES continued to search for beads with a specific gravity of 1.0. Finally in October of 2001 a plastic bead with a specific gravity of 1.0 was located.

- Normal color photography – This is a useful tool for documenting flow conditions such as disturbances caused by flow passing under the ESBS. It is also useful for documenting physical differences of designs (such as size and shape).
- Black light experiments – Experiments were conducted to attempt to trace bead paths with fluorescent beads and black lights. Plastic beads were painted with assorted fluorescent colors and injected into the model upstream of the ESBS. Black lights illuminated the beads and the paths of the beads were tracked with time-lapse photography. The quality of the final products was insufficient for justifying continuation of this type of flow visualization.
- High-speed digital still photography – Digital still photography is useful for looking at snapshots of beads as they pass the stay vanes, wicket gates and the turbine runner blades.
- VHS and 8-mm video – While of no use in the turbine environment, video is an excellent tool for documenting the location at which beads pass the stay vanes as well as where they pass through the draft-tube.
- High-speed film-video – High-speed film cameras (Figure 4) were used to document bead paths through the stay vanes, wicket gates, and runner environment. These cameras are capable of capturing images at a rate of 10,000 frames per second. The images are stored on 18-mm film, which is developed and then transferred to VHS format. Turn-around time for film development is approximately 2 to 3 weeks; until then, it is not known if the video is acceptable. As a result, a large number of experiments were necessary to determine appropriate speed rates for the different parts of the model. It was determined that a speed of 250 frames per second works best for the stay vane, wicket gate and draft-tube elbow areas. A camera speed of 1,000 frames per second is required for the turbine environment because the opaque blades obscure the region.
- High-speed digital video – High-speed digital video was used for the TSP models beginning in 2002, when the Department of Energy lent two cameras to ERDC-WES to be used on the existing turbine models. The advantage of high-speed digital video (over high-speed film video) is that there is no developing time. The digital video is stored on the computer and can be immediately reviewed to ensure that the video captures the desired footage. The downside of the DOE digital video is that the resolution is not comparable to the high-speed film. ERDC-WES is researching high-speed digital video with higher resolution.

Figure 4. Setup of high-speed film cameras.

2.3 Numerical Turbine Hydraulic Model Studies

Computer numerical modeling, called computational fluid dynamics (CFD), has been used by the industry for years to develop preliminary turbine designs for actual hydraulic turbine performance model testing. The DOE AHTS used the CFD analysis beyond the design of Kaplan turbine runner blades to investigate the suitability of CFD use for water passages. The initial work, outlined under Phase I of this program, was procuring services to develop the McNary Unit 5 and Bonneville First Powerhouse Units 5 and 6 CFD models. These models would be calibrated and tested using model and prototype measurements. After development of an acceptable CFD model, the existing numerical turbine model design could be modified and used to assess the hydraulic and turbine performance impacts resulting from design modifications.

During Phase I, the accuracy and availability of existing CFD methods were investigated. This resulted in the development of draft plans and specifications to procure the work. Legal concerns regarding intellectual property rights, poor results from other ongoing CFD work, lack of available funding, and lack of necessary detail have significantly reduced efforts in this area. However, a separate effort, funded by BPA for development of a CFD model of the Lower Granite intake, was performed with limited success (see Appendix

B.5.1). At the time of this publication, final information to compare to the ERDC-WES model measurement was unavailable. Figure 5 is a preliminary view of the entire CFD model for Lower Granite Dam. Figure 6 is an example of flowline paths predicted by the CFD model. It should be noted that fish diversion devices are not included in this computer model because the present state of the art has not reached the capability to model such devices. This model will be coordinated with ongoing TSP activities at ERDC-WES to test its validity. The state of the art is improving and will be considered for inclusion in future TSP studies.

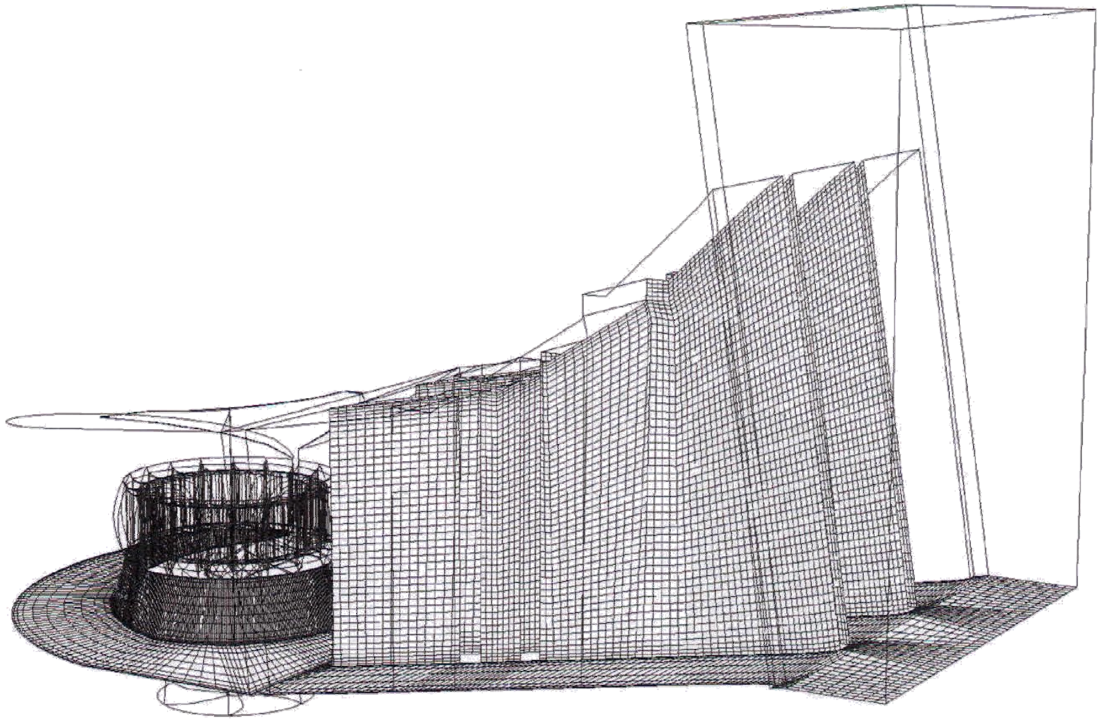


Figure 5. Lower Granite CFD intake grid (Habertheurer 2002)

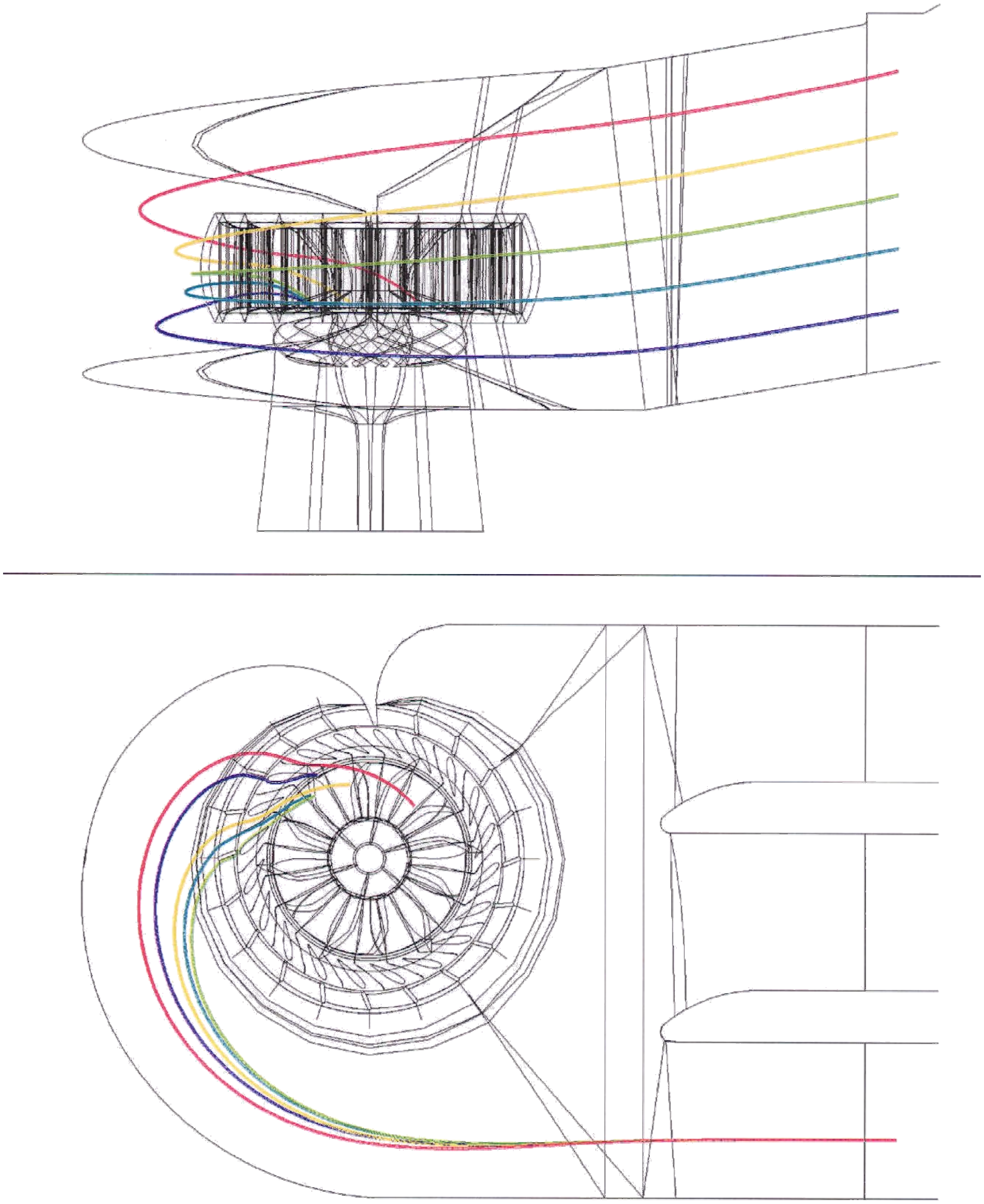


Figure 6. CFD streamlines from Lower Granite model (without screens). (Habertheurer 2002)

2.4 McNary Physical Hydraulic Models

2.4.1 Construction of McNary Models

Two models, an ERDC-WES hydraulic model and a VA TECH turbine performance model, replicating the McNary turbines at a 1:25 scale, were constructed and tested as part of the TSP and other programs. The first model was constructed at ERDC-WES in 1988 for low-head Froude hydraulic model testing. This model was built to aid in the design and evaluation of fish diversion screens located in each of three turbine intake bays. The original model included an approach flume, all three bays of the intake structure, scroll case, and distributor including the stay vane and wicket assembly and cascade. It did not include the draft-tube or a turbine runner, and the wicket gates were set at a fixed full open position. The model discharged into a pipe with return to the sump.

The ERDC-WES McNary model structure was constructed of acrylic, except for the stay vanes, wicket gates and turbine runner. This provides visual access to the entire water passage route from the trash racks through the turbine runner to the exit of the draft-tube. The clear acrylic also allows for Laser Doppler Velocimeter (LDV) measurements throughout the water passage.

The initial model investigations lead to the design and installation of 40-foot extended-length submerged bars screens (ESBS), replacing the previously installed STSs.

In 1992 it was decided to rebuild the McNary turbine model for TSP investigations. The new model could be used for the comparison of Froude test results in the ERDC-WES hydraulic model to Reynolds test results in the turbine performance model. A contract was awarded to VA TECH to construct and test a 1:25 scale high-head turbine performance model of the McNary turbine, and to build an additional turbine runner with adjustable blades for installation into the existing ERDC-WES hydraulic model. A motor and controller to accurately adjust and control the turbine speed were also provided. To rebuild the structure, the existing model was disassembled. The outer walls of the intake structure, the scroll case and the supports for the upper flume and structure were rebuilt. The wicket gates and stay vanes were replaced and provisions were made to allow the wicket gates to be adjustable from fully open to fully closed without disassembling the model. The discharge ring, wicket gate ring and draft-tube were fabricated from acrylic. A downstream flume was added for water to discharge from the draft-tube. The model was assembled and the supplied runner was installed (Figure 7).

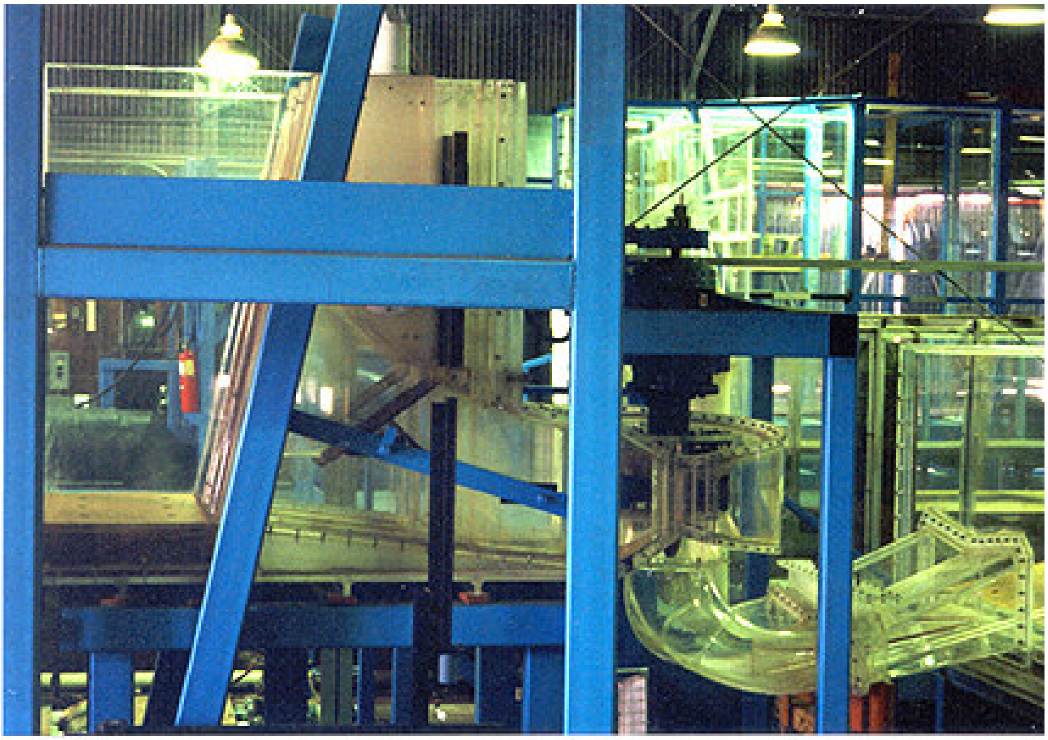


Figure 7. ERDC-WES McNary model with installed runner assembly.

Figure 8. ERDC-WES McNary model with model runner and control instrumentation.

The 1:25-scale McNary turbine performance model (Figures 9 and 10) was built to develop cam curves with ESBSs in place. VA TECH built the model, which included the full intake scroll case, distributor, runner and draft-tube. The construction of the turbine performance model was based upon actual field measurements of Unit 5 and existing as-built drawings. It was made of steel to allow for the high-head turbine performance investigations. Acrylic viewing ports were added for visual access to the intake structure, turbine runner area, draft-tube and the tailrace area. They also allowed for LDV measurements. The complete model was installed and tested in VA TECH’s model test stand which is equipped to measure turbine power and efficiency. These models are generally tested at high-head to increase the model Reynolds number, making it much easier to obtain high precision when measuring large values of head and torque.

2.4.2 McNary Physical Hydraulic Model Investigations

The two 1:25 scale McNary models were used for a number of investigations. The turbine performance model investigations using the VA TECH high-head turbine performance model included:

1) Froude testing in the high-head turbine performance model to evaluate turbine model performance with the intake screen in place to develop new cam curves for prototype operations with screens in place.
2) Froude testing in the high-head turbine performance model to develop cam curves to be used with the runner installed in the ERDC-WES hydraulic model.
3) Reynolds testing in the high-head turbine performance model to develop new cam curves for prototype operations with screens in place and to compare Froude and Reynolds performance modeling techniques.
4) Comparison of velocity data collected from ERDC-WES McNary hydraulic model of the original condition without the turbine runner, to the rebuilt model, which includes the operating turbine runner.

Investigations using the ERDC-WES hydraulic model included:

1) Comparison of velocity data from pre-runner to post-runner model.
2) Investigation of potential hazard zones for fish passage.
3) Development of techniques to better investigate turbine environment.
4) Bead investigations to pick release points for biological prototype tests.
5) Draft-tube modifications.

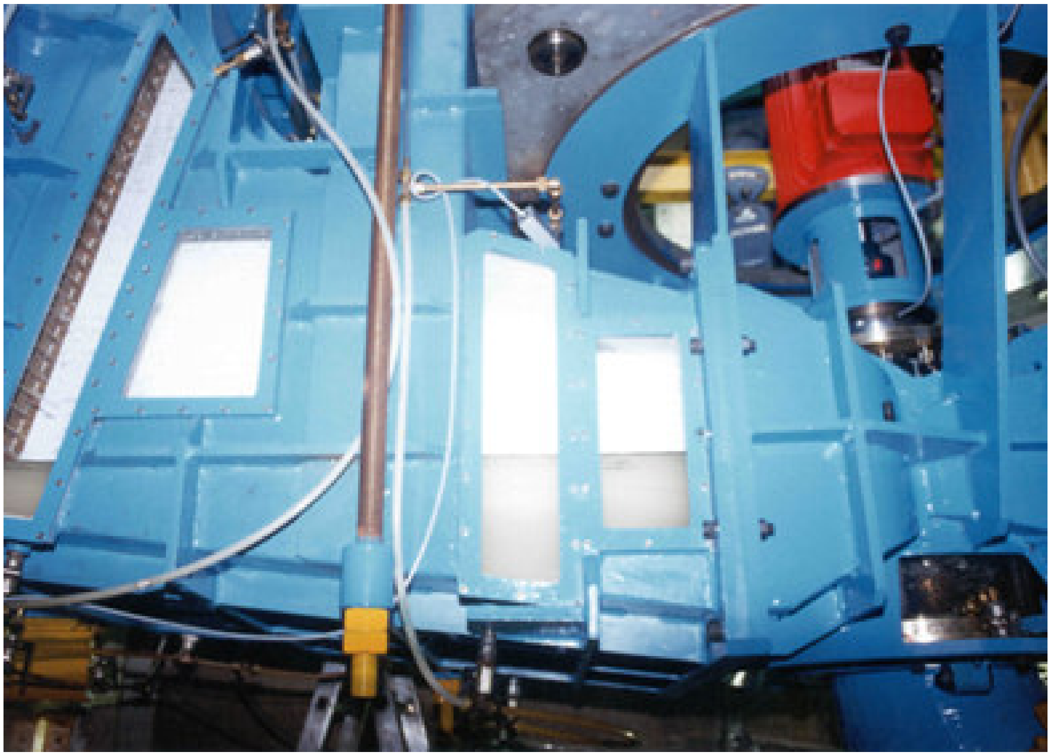


Figure 9. 1:25-scale McNary Performance Model

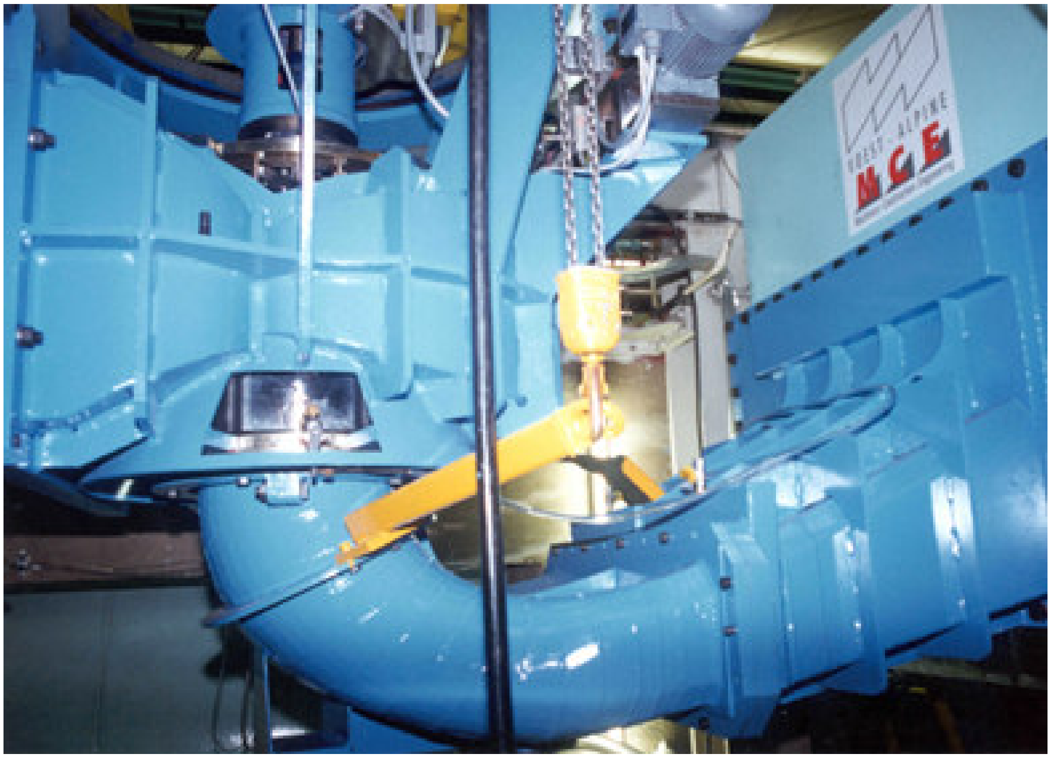


Figure 10. 1:25-scale McNary performance model.

2.4.2.1 McNary Turbine Performance Model Testing

2.4.2.1.1 Froude-head Turbine Performance Testing

A concern with using model components in the flow path (diversion screens and trash-racks) developed from the ERDC-WES Froude-head hydraulic models, in the Reynolds high-head turbine performance models, prompted the initial turbine performance model investigations to be conducted at Froude-head. Because the velocity in a high-head turbine performance model is significantly greater when compared to Froude-head models, it was believed the Froude test would better replicate the severe flow disruption caused by the ESBSs (Figure 11). The disrupted flow from the ESBSs tries to normalize in the intake downstream of the screens but the distance from the screens to the stay vane and wicket gate cascade is too short. As a result, head loss continues to develop even as flow enters the stay vane and wicket gate arrangement. The turbine performance model Reynolds number for Froude-head experiments was on the order of $3x10^5$, comparatively, the Reynolds number in the prototype was $6x10^7$. Even though these experiments are called Froude-head, they are exactly the same experiments as Reynolds-head experiments, only at a lower Reynolds number. The Reynolds number for a model-head (Reynolds-head) of 56.5 feet would be on the order of $1.3x10^6$.

The Froude-head experiments were conducted in the turbine performance model to develop cam curves without screens in place, with 20-foot-long STSs in place and with ESBSs in place. Trash racks were installed in the model for all experiments. LDV measurements were also taken for two discharges of each of the following conditions: without screens, with ESBSs installed, and with STSs installed. Velocity measurements were taken in each bay of the intake at twelve elevations and at three lateral positions for each elevation. The velocity data were collected for two reasons: (1) checking the contractor’s model to ensure that the flow distribution in the intake was not being influenced by inadequate inflow baffling, or by the actual design of the approach flume and (2) to provide data sets that could be used to compare the contractor’s turbine performance model with the hydraulic model of McNary at ERDC-WES.

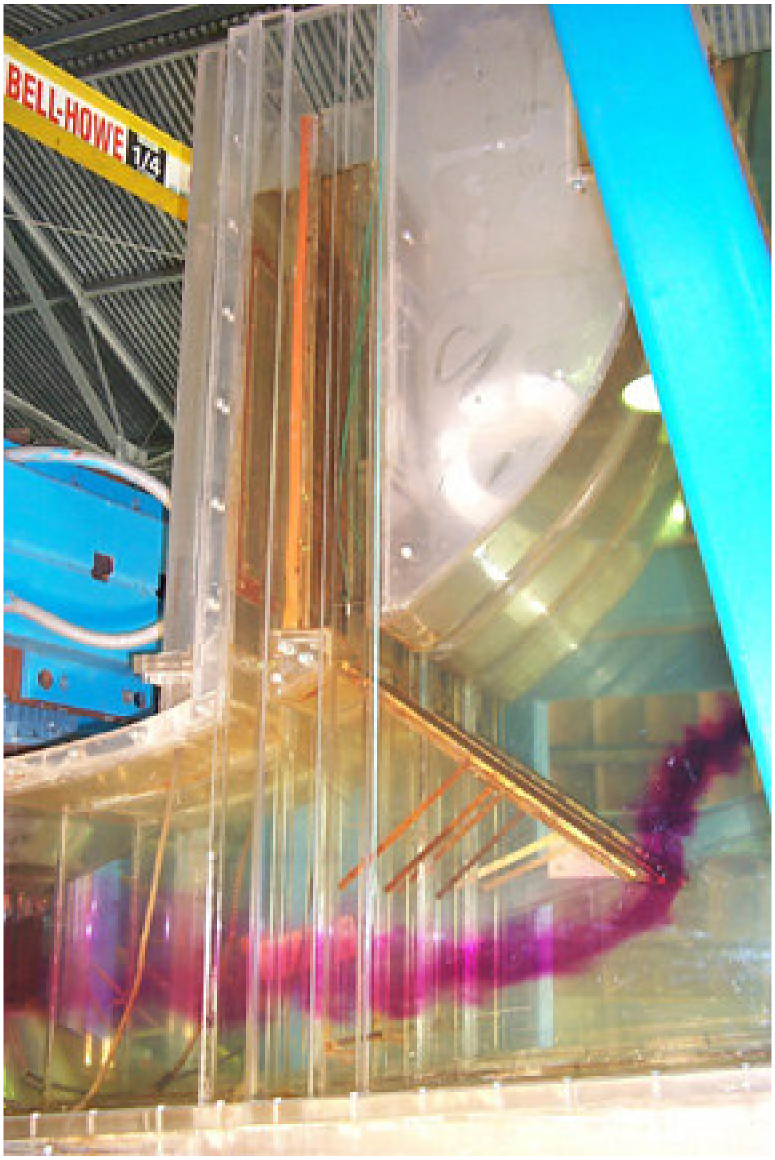


Figure 11. Disruption of flow due to ESBS.

Current regional direction requires that prototype turbines be operated within one percent of the peak efficiency for a given head. The cam curves that were used to set the prototype turbines were developed from a turbine performance model that was conducted without screens or trash racks. As a result of the influence of the screens on turbine performance and because the effect of the screens is more than just straight head loss, it was not possible to set the turbines within the desired one-percent operating range. In other words, the turbines were being operated off cam with the screens in place.

The experiments in this model were initially required to be conducted at a Froude-head. This was done for two reasons. The first was that the screens to be used in the turbine performance model were developed at ERDC-WES for Froude-head hydraulic models. The development of these screens consisted of flume experiments on prototype screen materials to determine its loss characteristics and then conducting flume experiments with model materials to match these data to the prototype screen loss characteristics. This will be discussed in more detail in later paragraphs. The second reason for conducting the experiments at Froude-head was that the turbine contractor was required to supply a 1:25-scale operating turbine runner for installation in the McNary hydraulic model at ERDC-WES. To determine where to operate the ERDC-WES turbine, it is necessary to develop model cam curves. Since a Reynolds-head model normally operates at a higher Reynolds number, it was not possible to accurately develop Froude-head model cam curves from high-head testing. Hence, the requirement to operate the turbine performance model at Froude-head.

McNary turbine performance modeling was the first attempt to define the interrelationship between prototype field information and model information. The investigations were broken into phases to allow milestones to be completed and data evaluated prior to executing additional optional testing. Phase I was the model duplication of a field Index test taken on the prototype turbine to compare results and determine if the uncertainty of the Froude performance modeling and velocity measurement techniques were significantly reduced using modern measurement technology. If successful, Phase II would be the development of the full operating range. Phase I was successful (Figure 12), Phase II was implemented to determine the model performance over the full operating range of the McNary project with no screens installed, with STS screens installed and with ESBS screens installed. Summary model test results are in Appendix B.1. After completing the Phase II Froude testing, additional model testing was performed in a high-head test stand. The model was disassembled and the intake and discharge tanks were modified to accommodate high-head (Reynolds) testing. Section 2.4.2.1.2 discusses the results of that testing.

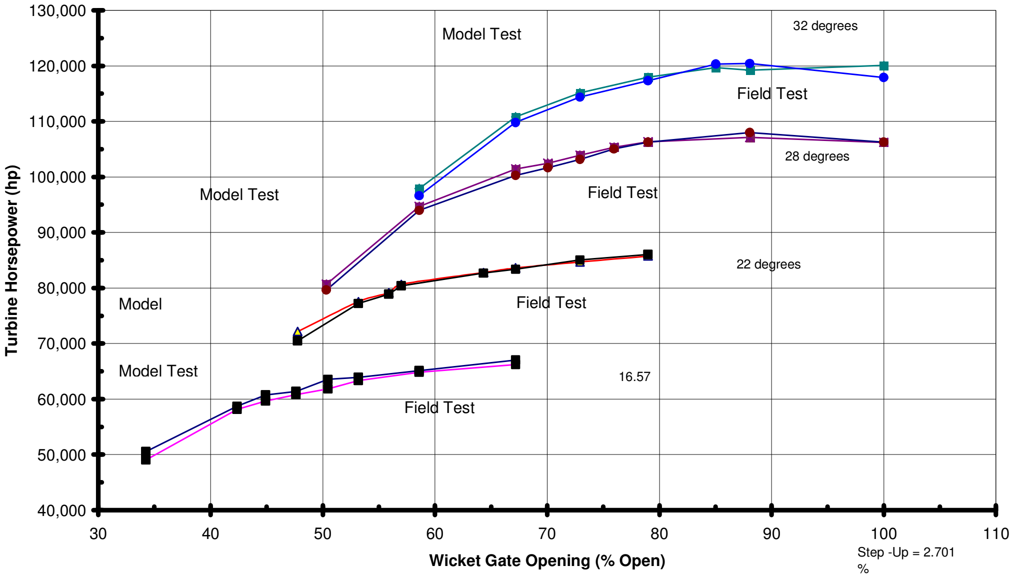


Figure 12. McNary performance comparison – field index test results versus Froude model test results.

2.4.2.1.2 Reynolds-head Turbine Performance Testing

The maximum total uncertainty for the Phase II high-head testing (Abfalterer, J. 1997) is 0.33 percent in efficiency with the average uncertainty of less than 0.2 percent. The testing was satisfactorily performed and provided model turbine performance and cavitation information for the existing design with comparisons to field-test data, without fish screens, with STS screens, and with ESBS screens. In summary, the best model efficiency at 75 feet of head was found to be: without screens = 89.85 percent, with STS screens = 89.65 percent, with ESBS screens = 89.05 percent. As an example of cavitation behavior with ESBS screens installed, Figure 13 is provided which demonstrates the full range of the head and flow of the existing turbines operation. In the normal range of on cam operation for all conditions only very minor cavitation existed at the extreme ranges of operation. Figure 14 shows a comparison of the turbine performance of the field test and the Reynolds model test.

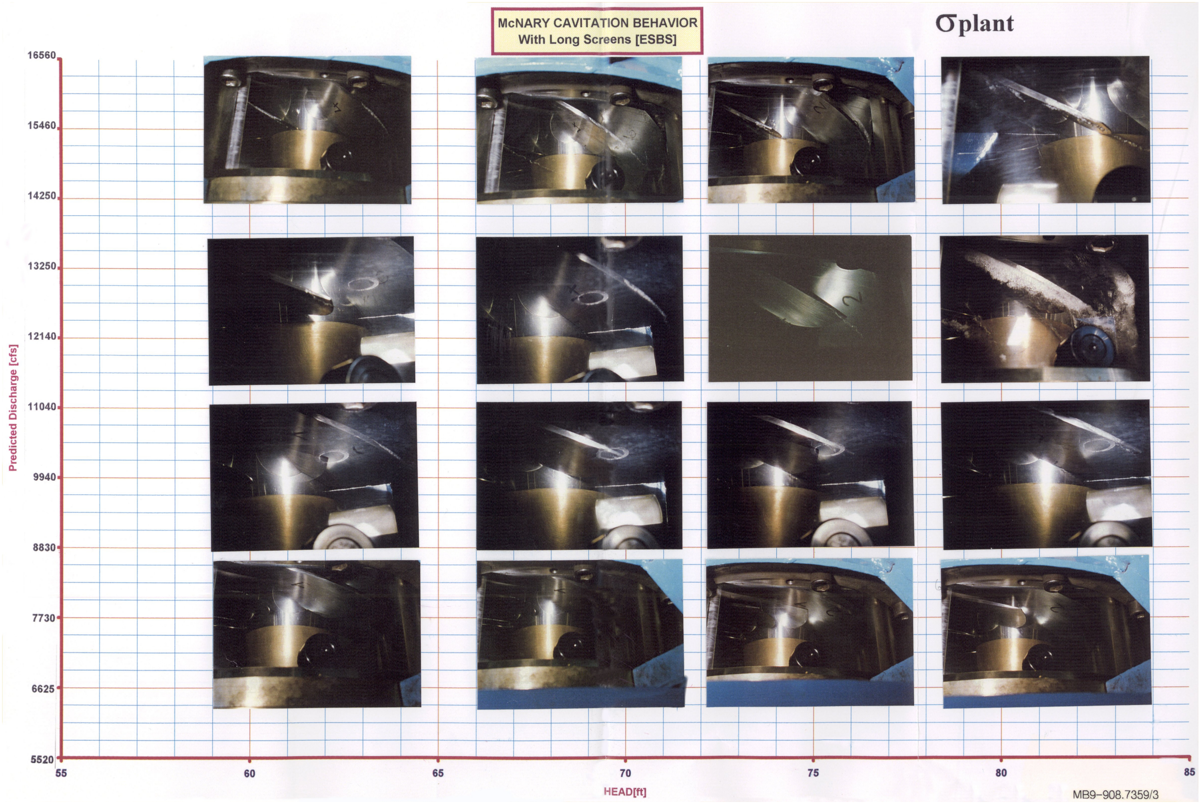


Figure 13. McNary cavitation behavior with ESBS screens installed.

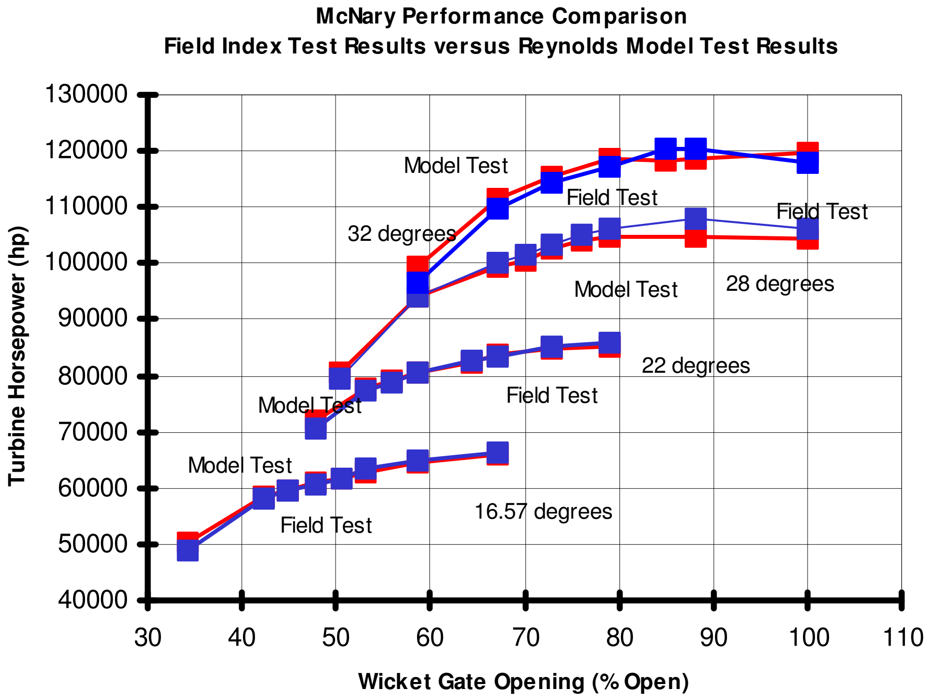


Figure 14. McNary performance comparison – field index test results versus Reynolds model test results.

2.4.2.2 McNary ERDC-WES Hydraulic Model Testing

2.4.2.2.1 Initial TSP Experiments in the ERDC-WES Hydraulic Model

TSP Model Experimental Conditions. The McNary model turbine speed was set at 428.5 revolutions per minute (rpm). This is comparable to the prototype turbine speed of 85.7 rpm. Permanent markers were used on the stay vanes to number them and to add grids (dividing vanes vertically into four equal sections) to aid in identifying the location of bead passage through the vanes. Turbine blades were also numbered in this manner. While grids were originally tried on the blades, this was abandoned in favor of a two-camera system, which shows three-dimensional bead locations through the turbine.

All investigations were completed with the model set to the following conditions unless otherwise indicated:

Table 9. Model Experiment Conditions

TURBINE ELEMENT	CONDITION
Turbine flow	12,400 cfs
Turbine blade angle	25.75 degrees
Wicket gate angle	39 degrees
Forebay elevation	340 feet mean sea level (fmsl)
Tailwater elevation	265 fmsl

Comparison of ERDC-WES Pre-runner and ERDC-WES Post-runner Velocity Profiles. Velocities had previously been obtained in the original ERDC-WES hydraulic model (pre-runner) for three conditions at a discharge of 16,000 cubic feet per second (cfs). The three conditions were: without screens, with STS in place, and with the ESBS in place. These velocities were measured at the same spatial position as the velocities that were obtained in the contractor’s turbine performance model. The velocity experiments were repeated with the turbine runner installed (post-runner). The comparison of ERDC-WES's velocity data (pre-runner to post-runner) indicated that the addition of a turbine runner did not affect the velocity profiles in the vicinity of the screening devices. Therefore, the data obtained before the addition of the turbine are valid. Some effect in the velocity profiles nearer the turbine would be expected. However, this was not investigated and has no bearing on previously completed experiments in the ERDC-WES hydraulic model. This is important because the design of the ESBS and the vertical barrier screen was based on the premise that it was not necessary to have a turbine runner to develop correct flow conditions in the vicinity of the screens.

Comparison of Post-runner ERDC-WES Hydraulic Model with Turbine Performance Model Velocity Profiles. Six velocity experiments were performed in both the ERDC-WES hydraulic model and the turbine performance model at Froude-head. Velocities were measured at the same spatial position in both models for the same discharges to develop a profile. Upon comparison the velocity profiles obtained in the ERDC-WES hydraulic model and the turbine performance model at Froude-head showed a reasonable correlation. This shows that the two models develop similar velocity profiles in the intake structure and the cam curves developed by the contractor can be used in the ERDC-WES hydraulic model.

Determination of Areas of Study Interest. The intake passageway was divided into eight zones for study; these zones correspond to the areas shown in Figure 2 (see Section 1.2.2). The following is a description of what was learned during initial bead, dye and velocity experiments. These base investigations gave direction to the following TSP model studies.

- <u>Intake entrance to intake gate slot (1)</u> – This area was intensively studied during the development of the ESBS. For a turbine loading of 12,400 cfs (upper one-percent discharge) the velocity at the upstream face of the trash rack would be in the range of 2-4 ft/sec. The average velocity of flow passing under the ESBS is approximately 5.3 ft/sec with the velocity at the tip of the screen being 6.2 ft/sec. The ESBS is designed to safely pass juvenile salmon. This design cannot be changed to enhance fish passage through the turbine. The ESBS causes an acceleration of flow around the tip of the screen. It also imparts a great deal of turbulence into the flow. Velocity shear occurs downstream of the screen, but this shear is well below the level that would cause injury to the fish. One potential improvement to this area would be changing the current trash rack design to a streamlined arrangement. This would result in less head loss and would have the potential for improving the efficiency of the current bypass system.
- <u>Intake gate slot through start of scroll case (2-4)</u> – In this area the main issues are the turbulence and the skewed velocity distribution of flow passing through this region. This is caused by the flow passing the ESBS. The other item that is of interest is the reverse flow that occurs downstream of the emergency closure slot along the roofline of all three bays of the intake. The major cause of the flow reversal is the downward flow exiting the emergency closure gate slot. This flow is approximately 9 percent of the flow passing through the intake and is necessary for maximizing the efficiency of the ESBS for attracting and bypassing juvenile salmon. This flow reversal is the most severe in Bay C (the intake bay with the shortest flow path). While these flow reversals do not directly harm fish, they allow for a large space for juvenile salmon to hold. It is not clear what effect these flow reversals have on turbine performance. One way to eliminate these holding areas would be to add fill-in material to eliminate the area for the flow reversals to occur. It is possible that this may also improve the efficiency of the turbine. These fill-in shapes would need to be designed using the ERDC-WES hydraulic model and put into a turbine performance model to determine their effect on performance.
- <u>Scroll case (4)</u> – No areas of concern were identified in the scroll case.
- <u>Stay vanes, wicket gates, and turn into turbine area (5)</u> – For a turbine loading of 12,400 cfs, the average velocity at the leading edge of the stay vane would be approximately 9 ft/sec. The flow accelerates to 14 ft/sec at the trailing edge of the stay vane and to 29 ft/sec at the controlling point of the wicket gate opening. These values are estimated by dividing the discharge by the flow area. The localized velocity magnitudes may actually be 40 percent higher than these average values. This is especially true with ESBSs in place. During initial bead experiments a significant number of beads struck the stay vanes. In addition, a significant number of beads passed though the gap between the trailing edge of the stay vane and the leading edge of the wicket gates; several became lodged in this gap. A number of beads were observed to strike the leading edge of the

stay vane (at the top) and pass downward along the downstream side of the stay vane, then pass along the surface of the wicket gate and top of the stay ring. These beads show the potential for juvenile salmon to strike the bottom edge of the wicket gate, which would have the potential to injure them. This zone was identified as a major area of concern with potential for improvement.

- Turbine runner and hub (6) – Velocities in this area are the highest that the fish will experience in the powerhouse. The average flow velocity at the hub would be approximately 38 ft/sec, with the actual velocity magnitude being 40 percent higher than the average. Juvenile salmon can withstand this velocity magnitude by itself; however, the hazards occur when the rotating blades cause gaps, large enough for juvenile salmon, between the blade and hub and the blade tip and discharge ring. As fish pass adjacent to these gaps, the tangential velocity of the blade at its outer blade tip would be approximately 104.5 ft/sec and the tangential speed of the blade at the hub would be on the order of 50.5 ft/sec. A number of beads were observed to make sudden changes in directions, an indication of shear, after passing through the turbine. For these reasons this zone was identified as an area needing improvement and further study.
- Draft-tube expansion and elbow to pier nose (7) – Flow exits the runner with an average velocity of 38 ft/sec and decelerates to an average velocity of 11 ft/sec at the draft-tube splitter pier nose. There are several areas of concern in this region. Velocity shear is a concern in this area since beads made sudden changes in direction indicating high shear zones in this region during initial bead experiments. Also, a large number of beads were observed striking the draft-tube splitter pier nose and a number of beads made contact with the draft-tube elbow. This contact may be an indicator of abrasion potential for fish passing though this area.
- Draft-tube pier nose to exit (8-9) – Flow in this zone was observed to be very turbulent and somewhat chaotic. Also, the flow distribution between the two barrels of the draft-tube was observed to be unequal and the velocity in each barrel was not uniform. Modifications to the runner or the draft-tube elbow may improve these flow distributions. In this region, the flow decelerates from 11 ft/sec at the splitter pier nose, to an average velocity of 7 ft/sec at the draft-tube exit. These are average values based purely on flow area and turbine discharge.
- Draft-tube exit into tailrace (9-10) – Large number of beads became entrained into a backroller that exists downstream and above the draft-tube exit. While this backroller may not directly hurt fish, it has the potential to permit high rates of predation while the juvenile salmon are becoming re-oriented to their surroundings. This is an area that needs further study in the prototype and in the models.

2.4.2.2.2 Determination of Release Points for Biological Studies

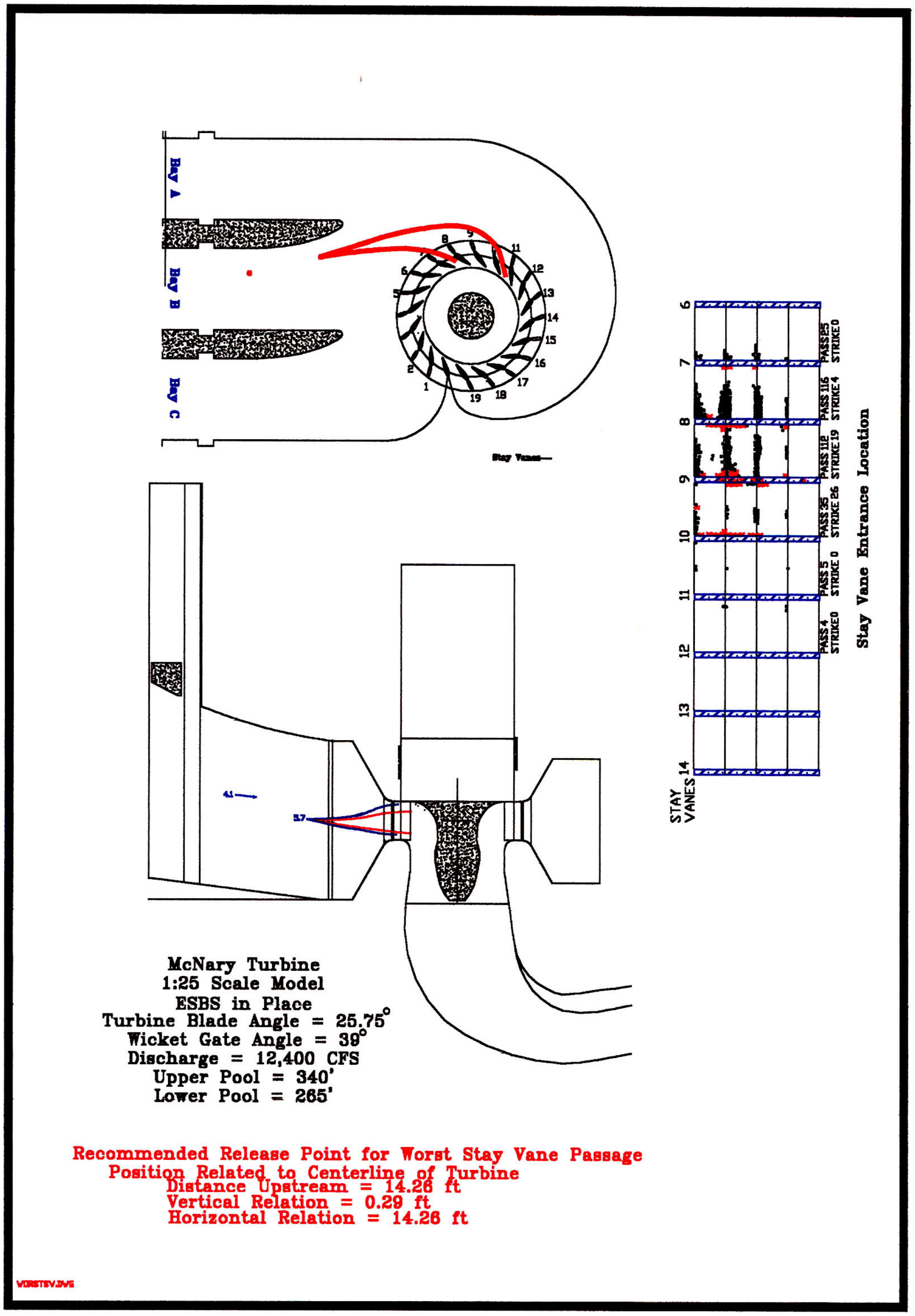
Previous bead experiments identified several zones in the turbine environment and draft-tube that have a potential for causing fish injury.

Based on intensive bead experiments, distinct zones were identified as having greatly varying potential for fish injury. Specifically, four areas of the turbine, and one area downstream of the turbine, were identified as having, relatively, either the highest potential for fish injury or the lowest potential for fish injury (sweet spot). These zones were: stay vanes zone, tip of blade zone, runner hub zone, center of blade zone (sweet spot) and the draft-tube splitter nose zone. These are the zones that were biologically evaluated in the field at the McNary Project (see Section 4.1.1.2). Efforts in the model were directed toward identifying the optimum release position to put fish through these zones.

Stay Vane Release Point. The stay vanes and wicket gate represent a variety of hazards. As they are stationary objects in the flow, there may be a high incidence of fish strikes on the vanes or gates. The gap between the vanes and gates influences flow patterns and bead experiments indicate the potential for fish to pass through this gap. Abrasion injuries along the vanes and the gates are likely, as are strike injuries and velocity shear injuries.

Bead experiments were conducted to determine which stay vanes sequence exposed the fish to the highest potential for injury. This sequence was determined to be stay vanes 7-11. Stay vanes were numbered beginning with the stay vane closest to the intake wall in Bay C and increased in numeric value in a clockwise direction.

Bead release experiments were conducted to determine a position in the model to release beads that would consistently pass through stay vanes 7-11. The first position tested was at the closure gate slot in Bay B. A copper release tube was inserted into the model through the closure gate slot. It was moved laterally and vertically while releasing beads and an optimum position was obtained. Because of the effect of the ESBS on the stability of the flowlines, this release point did not provide a consistent flow path to stay vanes 7-11. The release point was moved downstream and the above procedure was repeated. Once again the effect of the screen, along with confluence of flow between Bays A and B, resulted in an inconsistent flow path. The release point was moved downstream to a point were beads passed through only stay vanes 7-11. The lateral and vertical position was adjusted to obtain the most consistent flow path. This release point position can be seen in Figure 15.



McNary Turbine
1:25 Scale Model
ESBS in Place
Turbine Blade Angle = 25.75°
Wicket Gate Angle = 39°
Discharge = 12,400 CFS
Upper Pool = 340'
Lower Pool = 265'

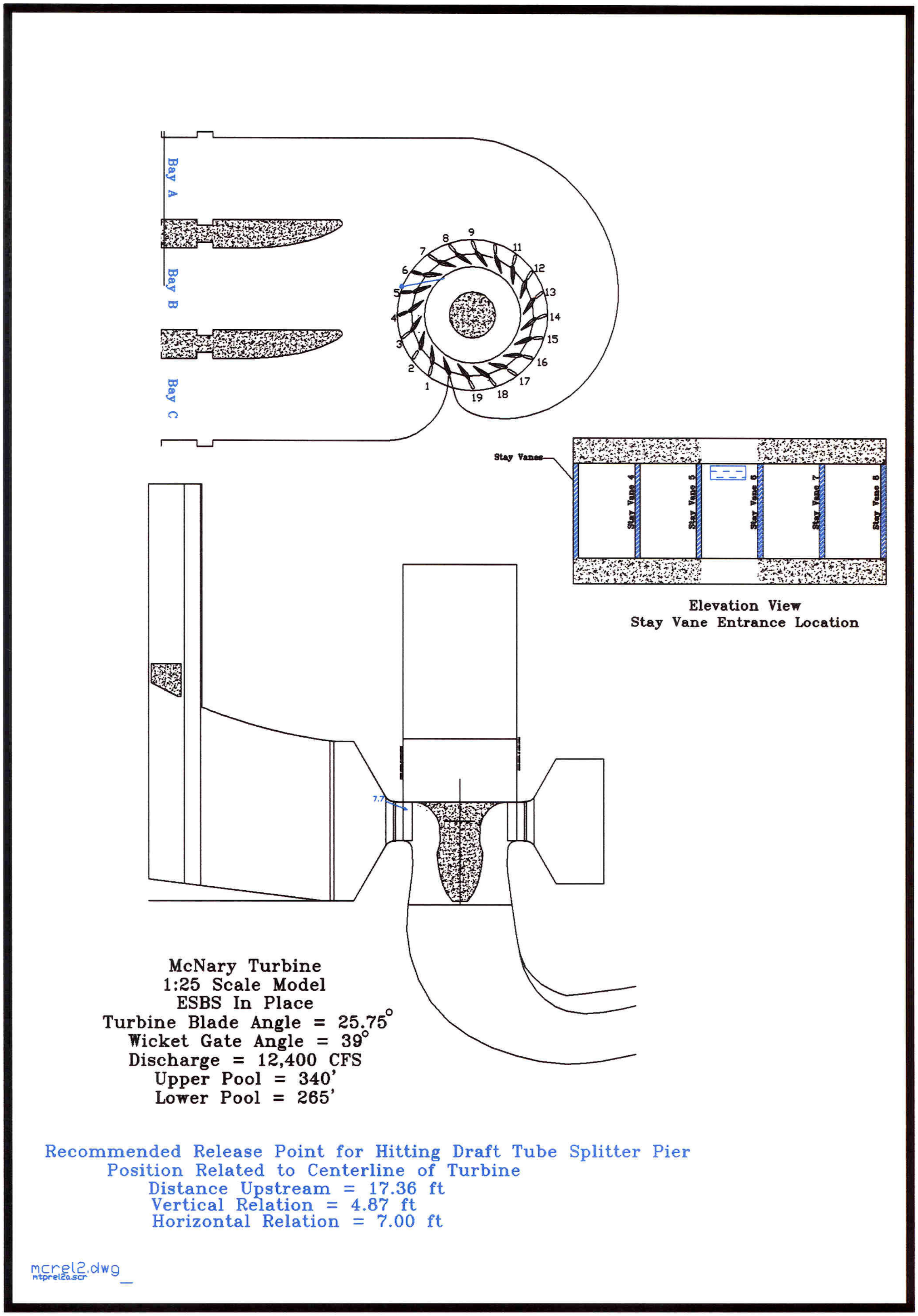
Recommended Release Point for Worst Stay Vane Passage
Position Related to Centerline of Turbine
Distance Upstream = 14.26 ft
Vertical Relation = 0.29 ft
Horizontal Relation = 14.26 ft

Figure 15. Recommended stay vane release position.

Runner Hub (Top) Release Point. A gap exists between the turbine blades and the hub of the turbine. The range of the gap changes as the angle of the blade changes. Injuries in this area could be caused by pressure changes across the gap, and/or abrasion as high velocity flows cross the blades and the hub.

Bead experiments were conducted to determine which bay of the intake would offer the highest potential for beads to pass near the top of the stay vanes and wicket gates, with minimal impact, and thus pass near the runner hub gap. It was determined that Bay C offered the best path to the turbine with the flowlines nearly aligned with the stay vanes and wicket gates.

Bead release experiments were conducted to determine a position in the model to release beads to consistently pass near the top of a minimal number of stay vanes. The first position tested was at the closure gate slot in Bay C. A copper release tube was inserted into the model through the closure gate slot. It was moved laterally and vertically while releasing beads. An optimum position was obtained. Because of the effect of the ESBS on the stability of the flowlines, this release point did not provide a consistent flow path. The release point was moved downstream and the above procedure was repeated. Once again the effect of the screen, along with confluence of flow between Bays B and C, resulted in an inconsistent flow path. The above procedure was repeated until a position was found that allowed the majority of the beads to pass through the top one-quarter of four stay vane pairs. Since, the beads passed through so many stay vane pairs it was decided that the release point should be moved to a position near the stay vane. This would greatly reduce the variation in flow path caused by the ESBS and would eliminate any stay vane or wicket gate contact. Bead experiments were conducted to determine the optimum position. This was found to be between stay vanes 5 and 6 and can be seen in Figure 16.



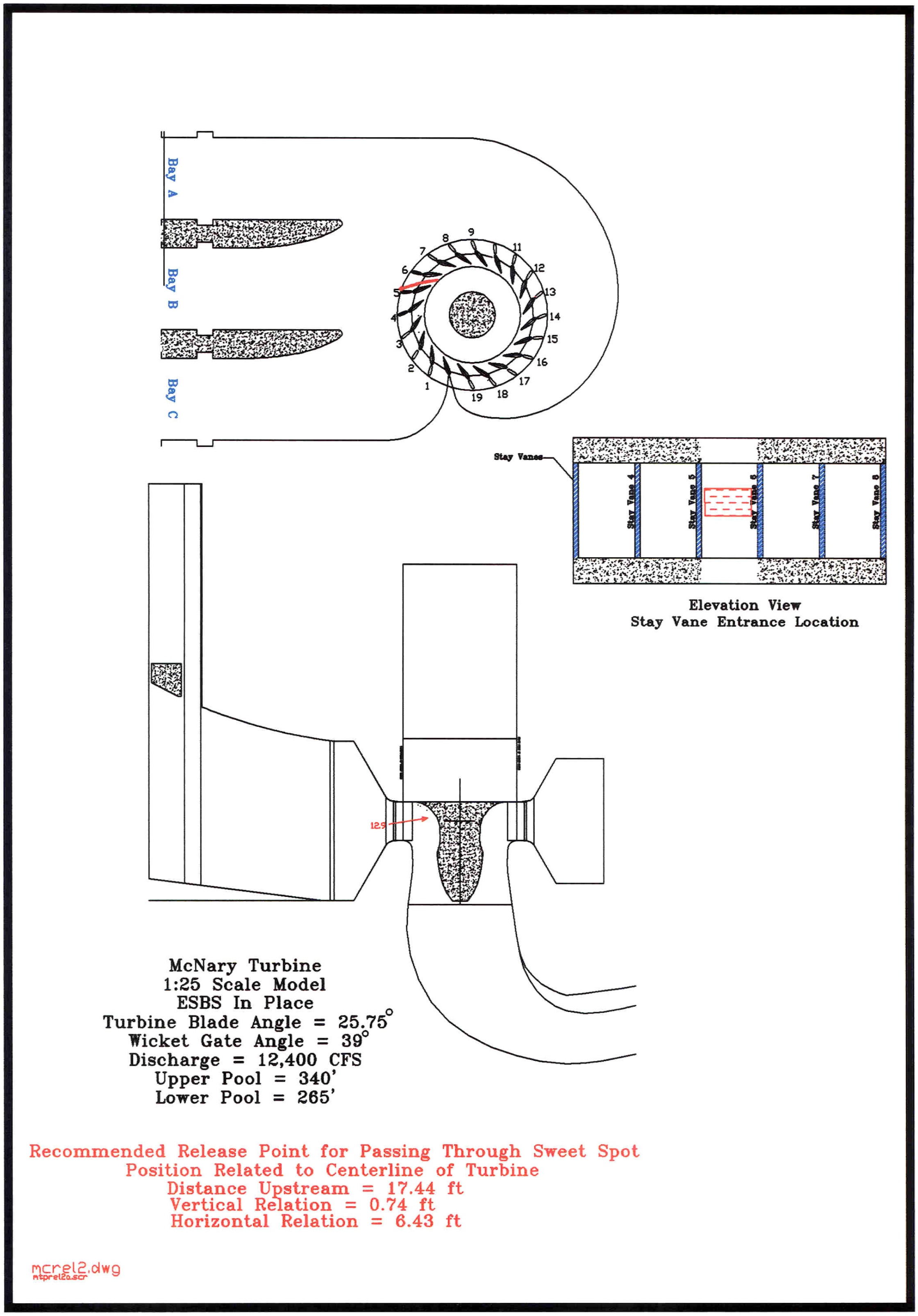
McNary Turbine
1:25 Scale Model
ESBS In Place
Turbine Blade Angle = 25.75°
Wicket Gate Angle = 39°
Discharge = 12,400 CFS
Upper Pool = 340'
Lower Pool = 265'

Recommended Release Point for Hitting Draft Tube Splitter Pier
Position Related to Centerline of Turbine
Distance Upstream = 17.36 ft
Vertical Relation = 4.87 ft
Horizontal Relation = 7.00 ft

Figure 16. Recommended runner hub release position.

Best Path Release Point (Middle of Blades). The assumed best path was defined as the flow path through the turbine and draft-tube with the lowest potential for fish injury. This flow path occurs where there is minimal impact on the stay vane and wicket gate. It passes the mid-blade region then through the draft-tube away from the draft-tube splitter pier.

As with the hub release point, it was difficult to find a release point in the intake within Bays B and C. The turbulence caused by the ESBS created a wide variation in the bead path to the turbine. To reduce the effect of the ESBS and eliminate stay vane and wicket gate contact, efforts were directed toward finding a release point at the stay vanes. The recommended release point was the mid-point between stay vanes 5 and 6. This release point can be seen in Figure 17.



McNary Turbine
1:25 Scale Model
ESBS In Place
Turbine Blade Angle = 25.75°
Wicket Gate Angle = 39°
Discharge = 12,400 CFS
Upper Pool = 340'
Lower Pool = 265'

Recommended Release Point for Passing Through Sweet Spot
Position Related to Centerline of Turbine
Distance Upstream = 17.44 ft
Vertical Relation = 0.74 ft
Horizontal Relation = 6.43 ft

Figure 17. Recommended mid-blade release position.

Tip of Blade Release Point. The outside of the turbine blades spins tightly against the discharge ring. The range in gap between the blades and the discharge ring varies as the angle of the blade is changed. In addition, water is passing vertically through the turbine. The outside edge of the turbine is an area with a high likelihood of fish injury. Abrasion caused by high velocities in the area, as well as rapid pressure changes at the gaps between the turbine blade and the discharge ring, could result in fish injury.

As with the hub and best path release points, a great deal of effort was undertaken to find a release point in the intake within Bays B and C, but because of the influence of the ESBS, there was great deal of variation in bead path to the turbine. To reduce the effect of the ESBS and eliminate stay vane and wicket gate contact, efforts were directed toward finding a release point at the stay vanes. The recommended release point was at the bottom of the stay vanes (between stay vanes 5 and 6). This release point can be seen in Figure 18.

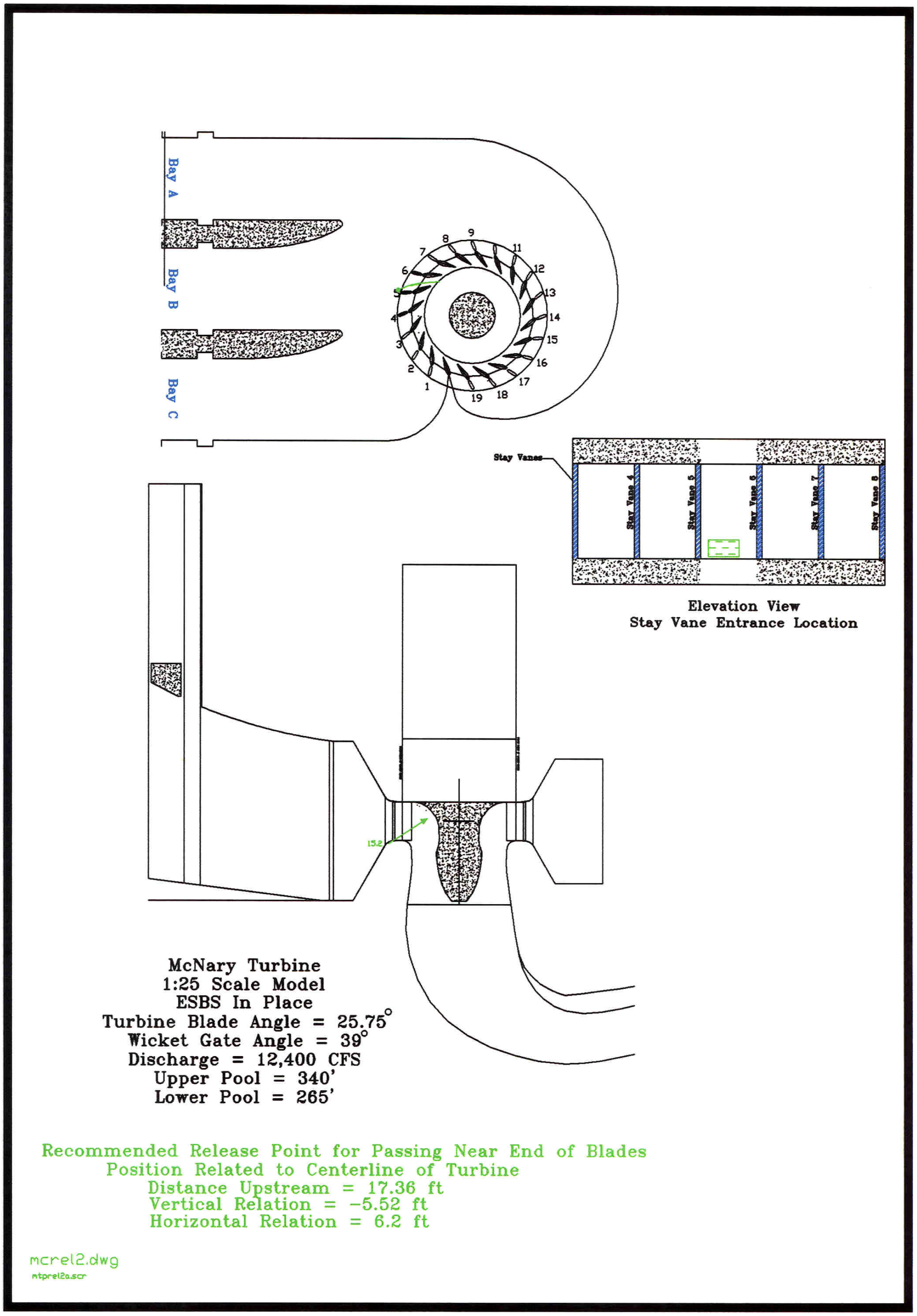


Figure 18. Recommended blade-tip release position.

Draft-tube Splitter Release Point. After flow exits the turbine, it is turned at the draft-tube elbow and continues to expand through the draft-tube. The draft-tube splitter pier divides the flow into two paths. Impact and abrasion injuries are possible in this area. The hub release passed more beads at the nose of the draft-tube splitter pier than the mid or top releases, but had a fairly wide distribution. Turbulence at the splitter pier nose could cause disorientation and additional abrasion injuries from the unstable flow.

It was not possible to obtain a release point upstream of the turbine that would allow the beads to be subjected to only the draft-tube environment. Fish injuries from this zone would be included in the other four release points.

2.4.2.2.3 Velocity Information

Numerous velocity experiments were performed in support of the bead release experiments. These experiments consisted of obtaining velocity profiles at various cross-sections through the intake structure. These velocity profiles aided in the structural design of the fish prototype release system as well as identified what fish release exit velocity and flow direction would be needed to match the surrounding velocity profile.

2.4.2.2.4 Model Bead Release Experiments to Compare with Prototype Biological Studies

Fish survival studies were conducted at McNary by releasing fish into the prototype turbine at the four selected positions: worst stay vane release, hub release, tip of blade release and assumed best path release (middle of blade). Follow-up bead experiments were conducted in the model to compare the bead strikes, abrasion, and shear, to fish injury data obtained from the prototype biological tests. At each of the four release locations, 350 beads were released. The test beads have a prototype equivalent length of 4 inches and are 2.2 prototype inches thick with a specific gravity of 1.02. Beads passing through the stay vane area were filmed with 8-mm cameras. Beads in the turbine environment and in the draft-tube were photographed at 1,000 and 250 frames per second with 16-mm film. Each bead was tracked to identify bead contacts with surfaces in the turbine and draft-tube environments. A subjective 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

In addition, each bead was evaluated for exposure to shear by watching for abrupt changes in bead direction. The subjective grading system for bead change in direction included:

1 = Severe sudden change in direction

2 = Moderate sudden change in direction

3 = Small sudden change in direction

4 = No sudden change in direction

Model Results for Worst Stay-Vane Release. The beads spread vertically as they approached the stay-vane cascade. They were distributed at the middle three-quarters of the stay-vane height and entered mainly through four stay-vane openings. Of 350 beads that were released, 76.4 percent passed the wicket gate stay-vane assembly without touching any surface or suffering a sudden change in direction. A moderate change in direction or minor contact was experienced by 21.7 percent of the beads. Significant contact with the stay vane leading edge affected 1.9 percent of the beads. Several of the beads that made contact slid downward along the surface of the vane and passed through the wicket gate overhang. Beads from this release were captured as they passed through the turbine environment. Only 1.7 percent of the beads were severely impacted by the runner blades with 76 percent passing without contact with a surface or a sudden change in direction.

During other bead observational experiments, a number of beads became lodged in the gap between the trailing edge of the stay-vane and the leading edge of the wicket gate. This was true for all gaps around the stay-vane wicket gate cascade. This becomes more apparent at higher turbine loadings. The experiment above was performed at 12,400 cfs. Further investigation in the model of the wicket gate to stay vane relationship is warranted, at different discharges, around the entire wicket gate and stay vane cascade. This is an area that has potential for improvement.

Model Results for Top Release (Hub). Of the 350 beads passing near the hub, 2.9 percent were significantly impacted (graded as 1 for strike and 1 for change in direction), 30.6 percent had a moderate change in direction without any surface contact, and 66.6 percent passed through this region with no surface contact or significant change in direction.

Beads observed passing through the draft-tube traveled in a nearly even distribution between the two barrels of the draft-tube. Flow in the draft-tube elbow is turbulent and somewhat chaotic at this discharge. Flow is decelerating from an average of 38 ft/sec to 11 ft/sec. Nearly 73 percent of the beads did not contact a surface in the draft-tube elbow while 15.6 percent of the 350 beads had moderate to severe contact with either the draft-tube splitter pier or perimeter of the draft-tube elbow.

Model Results for Mid-Release (Middle of Blades – Best Path). Beads injected at the mid-point of the stay-vane passed through the middle area of the runner blades. Most of the beads, 87.1 percent, passed through this area without impacting a surface or without any changes in direction, and 11.1 percent of the beads had a moderate change in direction but no contact with the runner blades. Only 1.7 percent of the beads had a severe contact with the runner blades. These results are similar to the worst stay-vane release of beads passing the turbine environment.

These beads were tracked through the draft-tube elbow environment and 56 percent of the beads passed through the left draft-tube barrel (looking downstream). Flow in the draft-tube elbow is turbulent and somewhat chaotic at this discharge. Flow is decelerating from an average of 38 ft/sec to 11 ft/sec. Beads rated as having severe contact with a surface, including a severe change in direction, accounted for 3.4 percent. A total of 20 percent of the beads made contact with some surface in this area.

Model Results for Bottom-Release (Tip of Blades). Bead experiments for this zone indicated that this area of the runner has a higher potential for injuring juvenile salmon than does the mid-blade or hub zones at this discharge. Of the beads passing through this zone, 71.8 percent passed through without coming into contact with the discharge ring or blades and without sudden changes in direction. Beads making contact with the blades accounted for 11.1 percent, and of this 11.1 percent, 1.1 percent were graded as being very severe strikes with severe changes in direction and 8.3 percent were graded as being severe strikes. An additional 17.3 percent were graded with moderate changes in direction without striking the blade. This is an indicator of shear as beads passed through the wake of the runner blades.

Three hundred and fifty beads passing through the draft-tube elbow were imaged. Of these beads, 85 percent passed through the left barrel of the draft-tube (looking downstream), 87.9 percent of the beads passed through the draft-tube elbow without touching any surface or experiencing significant changes in direction. Only 3.6 percent of the beads were observed to have experienced severe strikes and changes in direction. This release point seemed to pass the beads through a better part of the draft-tube compared to the mid and top releases. However, this is only one operating point. Further investigation of the draft-tube should be conducted at different operating points. Again, beads are not fish and are only indicators for comparing different areas of the flow passage as well as different operating points.

Draft-tube Observations. Flow conditions were observed in the draft-tube for three different operating points using beads and dye. The first was at the peak efficiency point for 75 feet of head, 10,200 cfs. Beads passing through the elbow were erratic, making sudden twirling moves. A number of beads started down one barrel of the draft-tube, then traveled upstream and passed through the other barrel of the draft-tube. It was obvious that there was a flow imbalance between the two barrels. Also, flow reversals were observed along the roofline of both barrels near the draft-tube exit. Downstream of the draft-tube exit a number of beads became entrained in backflow above the draft-tube exit. This may be an area where juvenile salmon would be subject to predation after passing through the turbine. Beads were observed to strike the draft-tube splitter pier nose as well as the surfaces of the perimeter of the draft-tube. While it appears that the draft-tube environment may not directly injure fish in large numbers (from field biological experiments), it most certainly has the effect of disorienting fish, which may contribute to delayed mortality as well as making the salmon subject to greater levels of predation.

The second operating point corresponded to the high discharge side of the one-percent peak efficiency for 75 feet of head (12,400 cfs). Flow was still somewhat erratic and a flow imbalance between the barrels was observed. Some flow reversals were observed along the roof of the right draft-tube barrel (looking downstream). An initial set of velocities was obtained 7 feet upstream of the draft-tube exit in both barrels of the draft-tube. These velocities show that the velocities are not distributed evenly within each of the two barrels of the draft-tube and that there are unequal flow distributions between the two draft-tube barrels. Beads also were entrained into the backroller downstream of the draft-tube exit.

The third operating point was for a turbine loading of 16,450 cfs. Beads passed through the draft-tube without delay. Draft-tubes are designed to operate efficiently at high discharges. Impacts of beads were observed on the splitter pier nose. Flow was not as erratic as it was for 12,400 cfs. Contact with the draft-tube wall surfaces was also observed, but, unlike the previous two discharges, the surface contact was not direct strikes, but tended to be rubbing. Very few beads were entrained in the backroll occurring downstream of the draft-tube exit. In fact, most of the beads exited the tailrace area of the model quickly. Overall, this draft-tube condition seems to have hydraulic advantages when compared to the previous two turbine settings. The only disadvantage in the draft-tube for this turbine loading would be that the velocity magnitudes would be on the order of 30 percent higher for this condition than at 12,400 cfs.

A more detailed investigation into the draft-tube conditions for these discharges is needed and will be performed in support of the McNary Modernization Project.

2.4.2.2.5 Bead Experiments in Support of 2002 Biological Experiments

Biological prototype experiments performed in 2002 were performed at different turbine operating points. It was decided to release fish at the emergency closure gate slot to have information on turbine passage that could be related to the overall population passing through the intake structure, but not guided by the ESBS. In preparation for these biological experiments, beads were released in the model intake at elevations 245.6 feet and 239.6 feet in all three bays (at the mid-point) at the emergency closure bulkhead slot for two flow conditions. The high and low flows corresponded to the prototype test discharges of 16,450 cfs and 10,220 cfs. The two elevations correspond to the mid-height of the intake at the emergency closure gate slot and the approximate flow path elevation of flow passing the tip of the ESBS.

Beads were imaged as they passed through the stay-vane wicket gate cascade. Eight-millimeter cameras were set-up to capture every pair of stay-vane/wicket gates. The beads released in Bay A (for both discharges and elevations) entered the stay-vane cascade between stay-vanes 8 and 19. The beads released in Bay B (center bay) entered the cascade between stay-vanes 7 and 16 with the majority entering between 7 and 11 (for both operating conditions and elevations). The majority of the beads released in Bay C entered between the stay-vane cascade and stay-vanes 1 and 5 with some entering as far around the cascade as pair 10-11. Almost all the beads for every release entered the stay-vane cascade in the upper ¾ of its height. This would indicate that very few beads would pass the tip of the blades. This prototype biological experiment would not be valid for exploring the survival rate of the entire turbine; however, this experiment was performed to look at the survival of the population of the salmon passing through the intake. It is unclear what the actual distribution of fish are after they pass the ESBS or how much they re-distribute between the tip of the ESBS and the stay-vane\wicket gate cascade.

2.4.2.2.6 Froude-head Model Validation

Flow Scintillation Experiments. Originally velocity experiments were conducted in the pre-runner ERDC-WES hydraulic model to determine the position and number of prototype velocity measurements required to define the velocity profile in the intake so that accurate discharge calculations could be performed. It was determined that a minimum of ten velocity measurements would be required.

The flow scintillation method was chosen as the means to obtain the velocity measurements at the prototype structure. Because the boundary layer can significantly affect the discharge calculation (for index testing), it became necessary to attempt to define the expected prototype boundary layer profile. Velocities were obtained in the post-runner ERDC-WES hydraulic model at the closure gate slot exit and near the invert of the structure (corresponds to the location of the prototype scintillation frame). Once the measurements were obtained, the information was supplied to the contractor performing the scintillation measurements for adjustments to his flow calculations.

Comparison of Scintillation Measurements to Froude-head Model Velocities. Scintillation measurements were performed at the prototype structure in 1998 with ESBSs in place as well as without any screen in place. Measurements at the prototype structure were made in all three bays of the intake at ten elevations in each bay at the emergency closure bulkhead slot. Flow scintillation measures and averages the velocity across the width of the bay. Table 10 compares the flow distribution between the three bays of the intake structure (with the ESBS in place) and the flow distribution calculated from velocity information in both the ERDC-WES hydraulic and contractor's turbine performance model. This is a very good correlation and indicates that the prototype structure and Froude model have nearly the same flow distribution (between the three intake bays) in the intake structure. This also indicates that the ESBS is modeled correctly for Froude experiments.

Table 10. Flow Distribution Comparison

BAY	INTAKE STRUCTURE	ERDC AND CONTRACTOR MODELS
BAY A	36.5%	36.6%
BAY B	34.4%	35.4%
BAY C	29.1%	28.1%

Two discharges from the prototype scintillation measurements were selected for observation in the post-runner ERDC-WES hydraulic model with the ESBS in place. Velocities were measured in Bay A in the model at the same elevations as the prototype measurements. The horizontal velocity components for the prototype and model were plotted on the same plot (Figures 19 and 20). The data showed a very good correlation. This indicates that the Froude model with the ESBS in place has the same flow distribution in the individual bay as the prototype (downstream of the ESBS), and that Froude-head models the prototype very well. This also shows that the ESBS is modeled correctly.

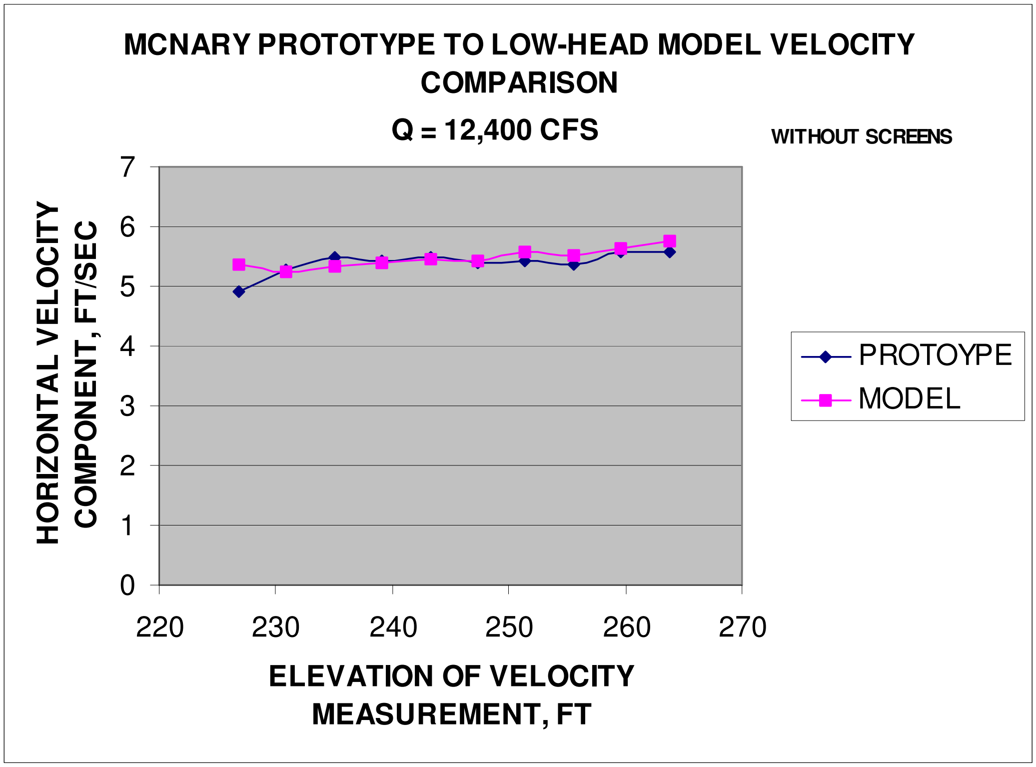


Figure 19. McNary prototype to model velocity comparison.

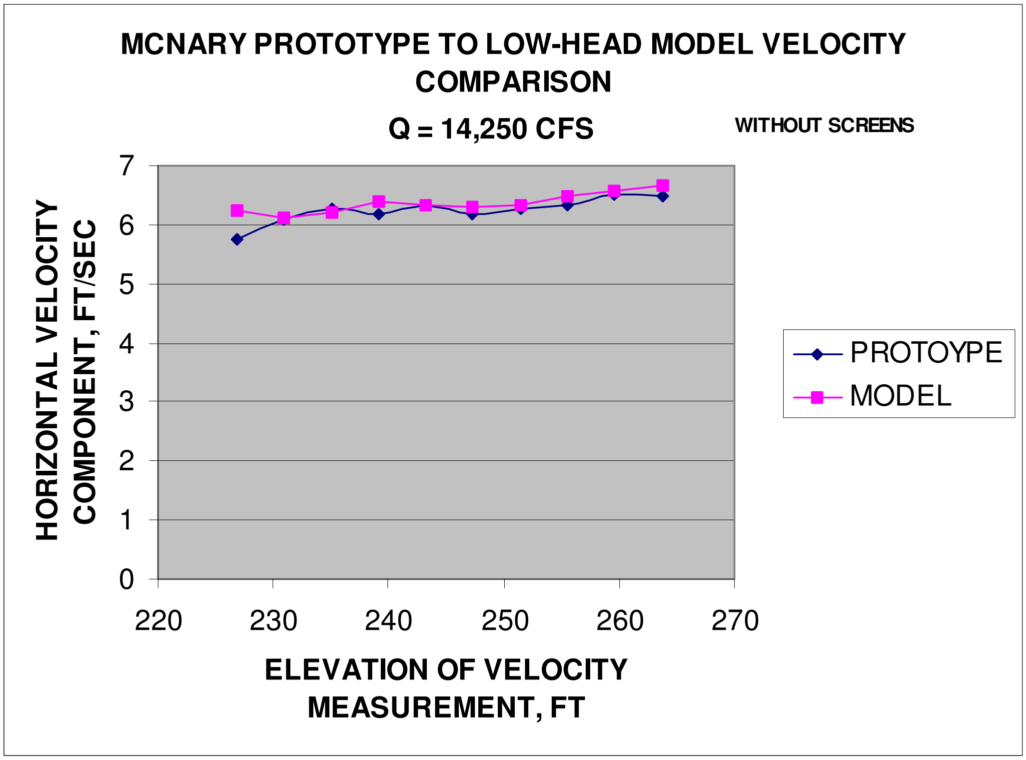


Figure 20. McNary prototype to model velocity comparison.

2.4.3 Findings of the McNary Turbine Model Studies

Fish diversion screens have a significant impact on turbine performance. This was documented both in turbine performance model and in prototype field index testing. Prototype cam curves, with ESBSs in place, were developed through turbine performance model tests both at Froude- and Reynolds-head. The Froude-head cam curves matched the cam curves developed in the field using flow scintillation. Froude modeling techniques can be used to develop cam curves for prototype turbine operations with intake screens installed.

The1:25 scale hydraulic turbine model at ERDC-WES was used to investigate and identify potential hazard zones in the intake, turbine and draft-tube. The model was then used to locate release points in the intake that would put neutrally buoyant beads (fish) through specific areas of the turbine and draft-tube in support of biological tests conducted at the prototype structure. Beads were released in the model at the selected release points and their path through the turbine was captured, using high-speed photography. The beads were evaluated by the severity of contact they made with surfaces and by any sudden changes in direction. The results from these experiments indicate that the extent of bead contacts were significantly greater than the extent of fish injuries detected during the prototype biological tests. This would indicate that bead contacts within the model either overestimate fish contacts or strikes upon turbine structures or that most surface contacts that fish make with surfaces as they pass through the turbine and draft-tube do not cause direct injury to fish. There may be other reasons for this lack of correlation, thus requiring the need for future studies to better tie the bead analysis data to biological data. A significant number of beads were observed to pass through the gap between the trailing edge of the stay vane and the leading edge of the wicket gate. This area has a potential for fish injury and should be evaluated further.

Flow in draft-tubes is erratic and at low discharges can be unstable. An uneven flow distribution between the two barrels of the draft-tube exists within the one-percent operating zone. This is also true for the distribution of flow within each of the draft-tube barrels. Higher flow outside the one-percent zone tends to equalize the flow between the draft-tube barrels as well as improves the flow distribution within the draft-tube barrels. While the draft-tube environment may not cause a high level of direct injury it can have a significant effect on the indirect survival of the migrating juvenile salmon. Draft-tube modifications can improve turbine performance as well as improve conditions for migrating salmon.

2.5 Lower Granite Physical Hydraulic Models

2.5.1 Construction of Lower Granite Models

Model investigations of the Lower Granite turbine were conducted similar to those of the McNary turbine. Two different models were built replicating the Lower Granite turbine Units 4, 5 and 6 at a 1:25 scale. The first model was constructed at ERDC-WES in 1990 (Figures 21 and 22). It included 600 feet of approach flume, three bays of one turbine unit, the scroll case, a full set of wicket gates, and stay vanes. The wicket gates were not adjustable and were set in a full open position. The intake structure and approach flume were constructed of acrylic to allow viewing of the flow conditions and the measurement of water velocities. The trash racks, STSs and the vertical barrier screens (VBSs) were geometrically reproduced at the scale of 1:25. The purpose of the original model was much the same as the McNary model, to aid in the design of extended-length submerged bar screens (ESBSs). The model investigations lead to final design and installation of 40-ft ESBSs at the Lower Granite Project. These screens successfully divert juvenile fish away from the turbine. The model was also used to study a prototype surface collector for the Lower Granite Project, which was intended to collect and bypass fish around the powerhouse.

Following the success of the McNary model testing, the Corps decided to rebuild the original Lower Granite turbine model to test and compare Froude model performance with Reynolds model performance. A contract was awarded to VA TECH to construct and test a 1:25 scale high-head turbine performance model of the Lower Granite turbine, and to build an additional turbine runner with adjustable blades for installation into the existing ERDC-WES hydraulic model (Figure 23). The contractor provided the runner and a motor with controls to set and regulate the runner speed. The existing ERDC-WES model was disassembled and re-built. The new scroll case, discharge ring, draft-tube and a flume downstream of the draft-tube exit were constructed of clear acrylic. The stay vanes and wicket gates were machined from brass. Provisions were made for adjusting the wicket gates to any desired opening without disassembly of the model. After assembly, the model was calibrated in preparation for experiments. The calibration of the model consisted of inflow meter volumetric calibration, wicket gate opening calibration, runner blade angle calibration and runner speed calibration.

The 1:25-scale Lower Granite turbine performance model built and tested by VA TECH included the full intake, scroll case, distributor, runner and draft-tube. The construction of the performance model was based upon actual field measurements of Lower Granite Unit 4 and existing as-built drawings. It was made of steel to allow for the high-head turbine performance investigations. Acrylic viewing ports were added for visual access to the intake structure, turbine runner area, draft-tube and the tailrace area. They also allowed for LDV measurements. The complete model was installed and tested in two of VA TECH's model test stands which were equipped to measure turbine power and efficiency under both low-head and high-head conditions.

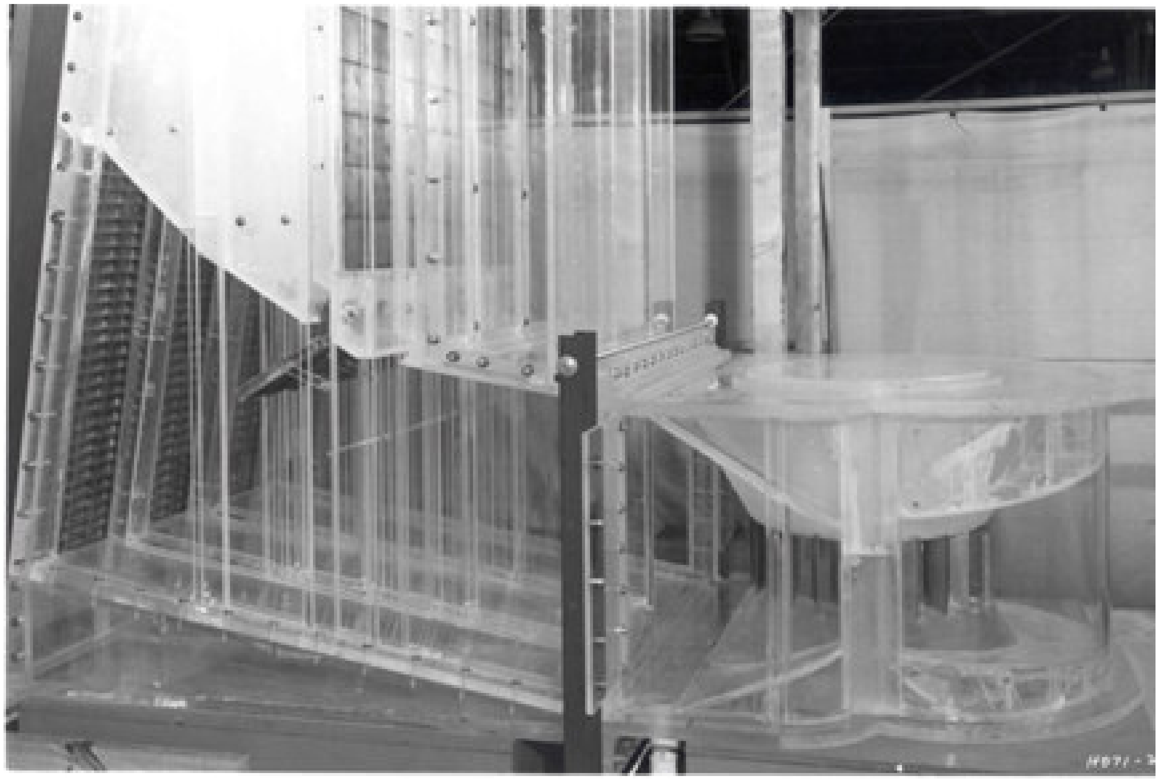


Figure 21. Original Lower Granite 1:25-scale model intake structure.

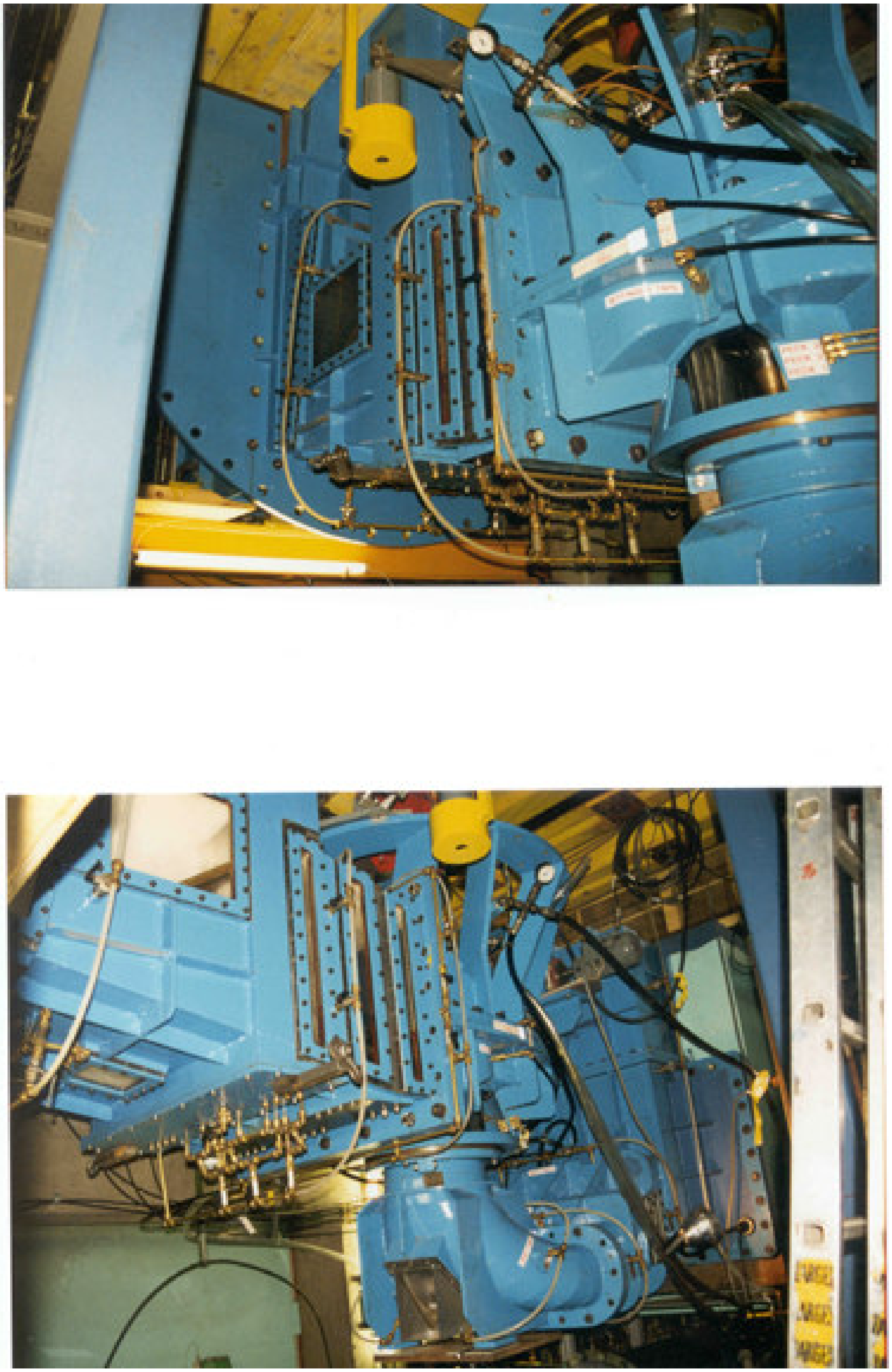


Figure 22. 1:25-scale Lower Granite performance model.

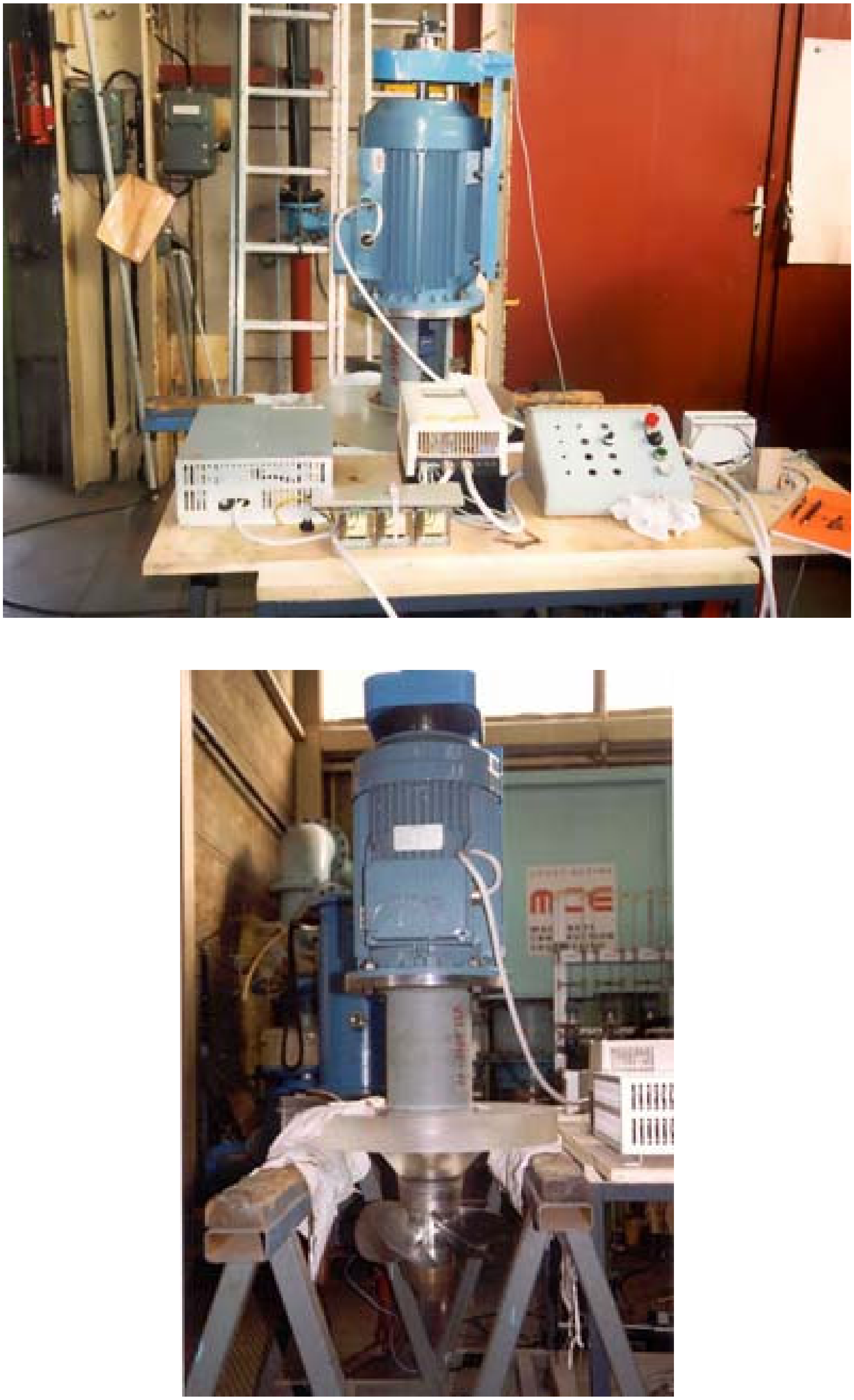


Figure 23. Lower Granite model turbine runner assembly and control instrumentation.

2.5.2 Lower Granite Physical Hydraulic Model Investigations

The two 1:25 scale Lower Granite models were used for a number of investigations. The performance model investigations using the VA TECH high-head model included:

1) Froude testing to evaluate model performance with the intake screen in place.
2) Froude testing to develop cam curves to be used with the runner installed in the ERDC-WES hydraulic model.
3) Reynolds and Froude testing in the high-head turbine performance model to develop new cam curves for prototype operations with screens in place.
4) Comparison of velocity data from the Froude and Reynolds testing with data collected from ERDC-WES Lower Granite hydraulic model of the original condition without the turbine runner, and the rebuilt model with an operating turbine runner.

Investigations using the ERDC-WES Froude-head hydraulic model included:

1) Comparison of velocity data from pre-runner to post-runner model.
2) Draft-tube modifications.
3) Stay vane and wicket gate modifications.

2.5.2.1 Lower Granite Turbine Performance Model Testing

As with the McNary turbine, ESBSs influence performance of Lower Granite turbines. The effect is a combination of head loss across the screen and skewed velocity distribution and turbulence downstream of the screen as flow attempts to normalize. With screens installed, prototype turbines were operating off cam because the original cam curves were developed from the performance test conducted without trash racks or screens. Although the McNary model showed the effect of ESBSs on cam curves, information obtained from McNary tests cannot be used to adjust Lower Granite prototype cam curves due to differences in ESBS design, turbine unit geometry and turbine discharge.

The performance investigations were initially divided into two parts. The first was the development of cam curves using Froude-head techniques. The second part was developing cams curves using Reynolds-head techniques. Both of the two modeling techniques provide for fully turbulent flow. These two experimental investigations were conducted to develop cam curves for comparing the two modeling techniques to each other and then to prototype performance index experiments. After the initial testing, the turbine performance model was removed from the test stand used for Froude-head experiments and placed into a modified test more suited for Reynolds-head experiments. Additional performance tests were conducted to develop cam curves and the complete turbine performance over the operating head range. These were completed for three different test conditions: no screens, with ESBSs, and with the originally designed STSs in place.

2.5.2.1.1 Froude-head Turbine Performance Testing

Performance experiments were performed at Froude-head to develop cam curves for three screen conditions: without screens, with STSs in place and with ESBSs in place. The trash racks were in place for all experiments.

In addition to performance experiments, velocity experiments were conducted at two turbine-operating points for each of the three screen conditions. The first operating point corresponded to prototype index experiments conducted before the construction of the performance model. The second operating point corresponded to the high side of the one-percent peak efficiency zone as defined from the model performance curves.

Velocity measurements were made in Bay A at one cross-section immediately downstream of the trash racks, one cross-section in the flow passage at the emergency closure bulkhead slot, and one cross-section near the end of the pier that separates Bays A and B. Velocity measurements were also obtained at one cross-section downstream of the emergency closure bulkhead slot in Bays B and C.

2.5.2.1.2 Reynolds-head Turbine Performance Testing

Velocity experiments were conducted for two operating points. These operating points corresponded to the high-discharge side of the one-percent operating zone (as determined from the high-head performance model) and to the same operating point where velocities were obtained in the Froude-head experiments for duplication of prototype index experiments. The velocities were obtained at the same spatial position as the velocities measured in the Froude-head experiments.

Lower Granite Unit 4 was selected for evaluation in a turbine performance model to investigate Froude and Reynolds techniques in more detail and the effects of other fish diversion devices on smaller intakes and more common draft-tube designs. In addition, effects of drawdown, surface collectors, draft-tube modifications, stop log closure, trash rack effects, piezometric tap stability, stay vane wicket gate design and alignment, and MGR designs were investigated. A turbine manufacturer performed the turbine performance model testing of the Lower Granite turbine. The drawings for construction of the Lower Granite model were based upon actual field measurements of Unit 4 and the existing manufacturer drawings. The turbine model was constructed out of steel with windows for visually observing and measuring the trash racks and fish screens for water velocity, turbulence and cavitation measurements Figure 24. More information about the Lower Granite model is contained in Appendix B. The same basic model was used in both the Froude and the Reynolds testing with the exception of the inlet and discharge tanks being different. The maximum total uncertainty for the Lower Granite Phase II high-head testing (Abfalterer, J. 2000) is 0.143 percent in efficiency. The testing was satisfactorily performed and provided model turbine performance and cavitation information for the existing design (Figure 25) without fish screens, with STS screens and with ESBS screens. In summary, the best model efficiency at 105 feet of head was found to be: without screens = 90.2 percent, with STS screens = 89.85 percent, with ESBS screens = 89.15 percent.

As an example of cavitation behavior with ESBS screens installed, Figure 26 is provided which demonstrates the full range of the head and flow of the existing turbines operation, including draw down. In the normal range of on cam operation for all conditions only very minor cavitation existed at the extreme ranges of operation.

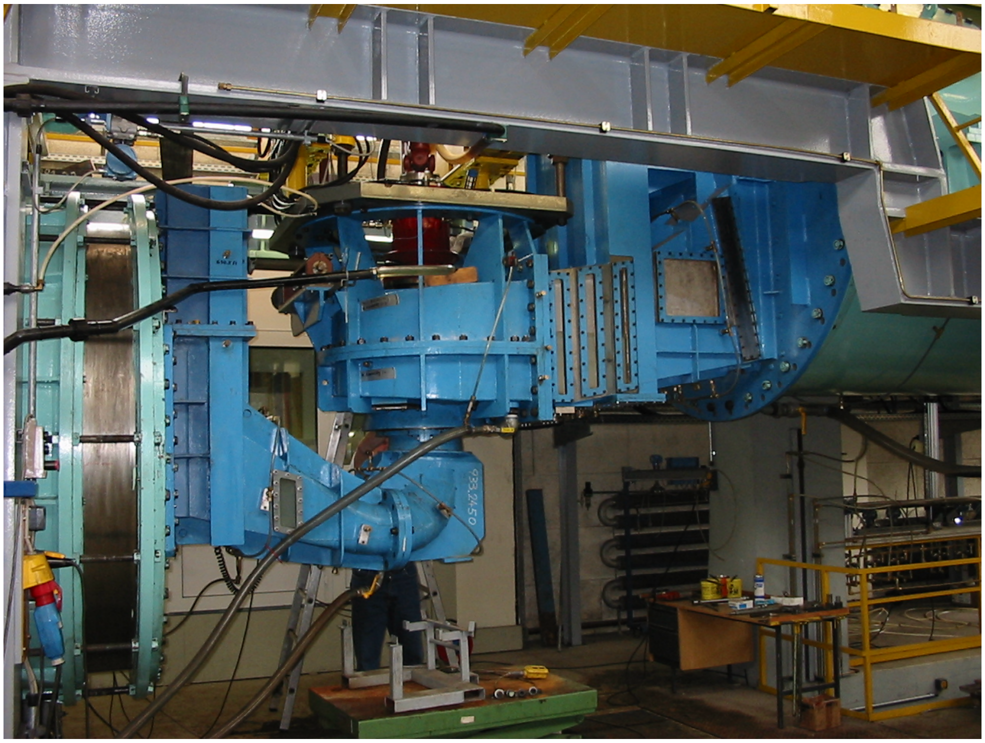


Figure 24. Lower Granite high-head performance model water passage (blue).

Figure 25. Existing Lower Granite model turbine runner.

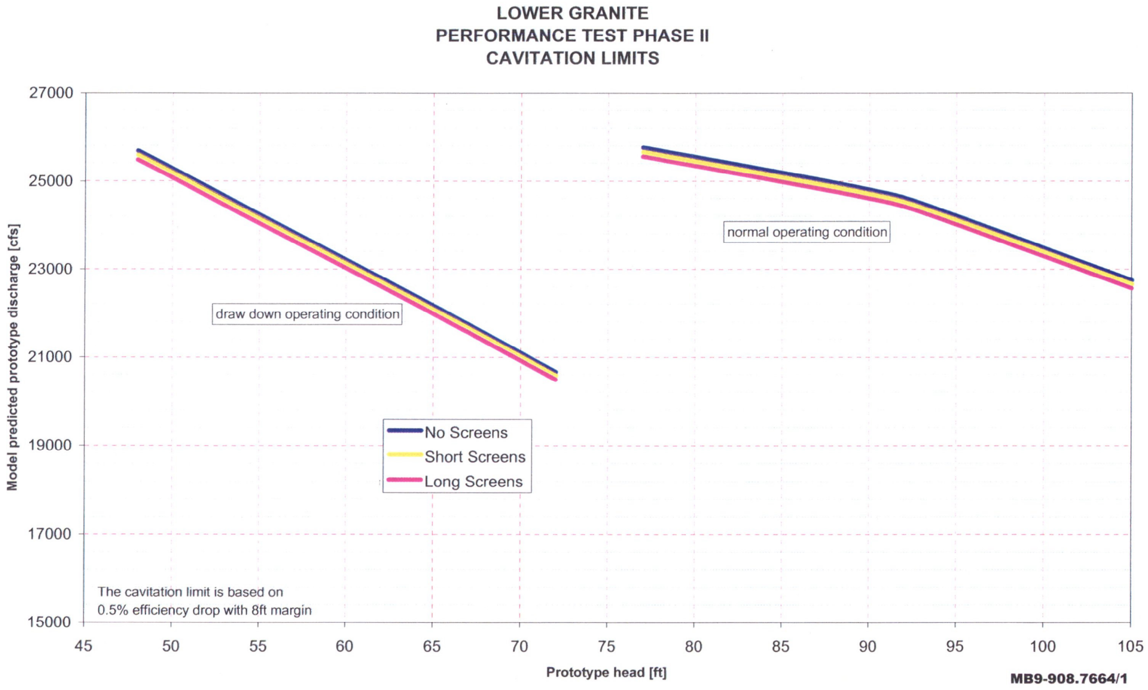


Figure 26. Cavitation graph of existing Lower Granite model turbine.

2.5.2.2 Lower Granite ERDC-WES Hydraulic Model Testing

2.5.2.2.1 Comparison of Froude and Reynolds-head Experiments

The ESBS for the Lower Granite project was developed at ERDC-WES in a Froude-head model. The material for the model ESBS was developed by comparing model and prototype screen materials to find a model material that would match the prototype screen head loss characteristics. The same logic was used for this model as was used in the McNary project. The ESBS significantly affects the velocity distribution approaching the turbine and imparts a great deal of turbulence to the flow. The velocity magnitude in a Reynolds-head performance model could be as much as five times greater for the same operating point than that of a Froude-head model. The velocity downstream of the ESBS would be expected to be different for the two modeling techniques and the performance curves would also be different since the velocity distributions do not have a sufficient distance to normalize before flow enters the turbine.

Velocity profiles obtained for the two modeling techniques were compared. The distribution of flow downstream of the screens was different for the same operating point in each bay of the intake for the two modeling techniques. This shows that the influence of the screens on the velocity distribution is different for the two modeling techniques. This would also indicate that the head loss, turbulence, and velocity distribution of flow at the turbine entrance would also be different, and some effect on the model-determined cam curves would be expected.

Comparison of ERDC-WES's Pre-runner Model and Post-runner Model. Measurements of velocity were obtained in the pre-and post-runner ERDC-WES hydraulic model at two operating points for all three screen conditions. The velocities were measured at the same spatial positions as the ones obtained in the contractor's turbine performance model.

The velocity profiles obtained in the pre-runner ERDC-WES hydraulic model were compared to the post-runner ERDC-WES hydraulic model. The velocity profiles for the pre-runner and post-runner model showed a reasonable agreement for each of the three screen conditions. This comparison indicates the operating turbine runner did not significantly affect the velocity field in the vicinity of the screens, validating the pre-runner model data used for design of the ESBSs.

Comparison of Contractor's Turbine Performance Model to ERDC-WES Hydraulic Model. Velocities obtained during Froude-head experiments in the contractor's turbine performance model, at two operating points for each of the three screen conditions, were compared to model velocities obtained in the post-runner ERDC-WES hydraulic model. This comparison showed a reasonable correlation between the two models' velocity profiles of all three screen conditions indicating cam curves generated from the Froude-head performance test can be used appropriately to set operating conditions for the ERDC-WES hydraulic model.

Comparison of Model Velocities to Prototype Velocities (Flow Scintillation). Velocities were measured at ten elevations (flow scintillation method) in Bay A of the intake at the emergency closure bulkhead slot during index experiments at the prototype in 1998. These velocity measurements were performed for a large number of operating points. Two of these operating points, with the ESBS in place, closely corresponded to the two operating points at which velocities were obtained in the Froude-head and Reynolds-head turbine performance model. Horizontal components of velocities obtained for both performance-modeling techniques were plotted with the velocity information obtained in the prototype structure for an operating point with a turbine loading of approximately 17,600 cfs. This plot is provided in Figure 27. With the exception of one measurement near the bottom of the intake, the velocity profile for the Froude-head model and the prototype measurement match fairly well. The Reynolds-head velocity doesn't match the prototype velocity as well. This indicates that the Froude-head modeling technique models the prototype better with screens in place than does the Reynolds-head technique.

The second operating point corresponded to a turbine loading of approximately 23,375 cfs. Once again, the horizontal component of the velocity profiles for the Froude-head turbine performance model, Reynolds-head turbine performance model and the prototype-measured velocities were plotted together. This plot is provided in Figure 28. Again, the Froude-head model velocity information matched the prototype velocity profile better than the Reynolds-head model velocity information.

Based on this information, the assumption that the Reynolds-head turbine performance model would not yield a correct velocity profile downstream of the screens was correct. Any future performance modeling with screens in place should be conducted at Froude-head. However, model performance test stands capable of the required Froude conditions are not generally available because turbine performance testing requires cavitation testing. In addition, the uncertainty of turbine model testing at Froude conditions for turbine performance is greater than is currently acceptable to industry. A combination of the two testing techniques can be used to better define prototype turbine performance and expected prototype velocity profiles during the design phase of a turbine replacement or rehabilitation. Appendix B, Sections B.2.1 and B.2.2 contains more information.

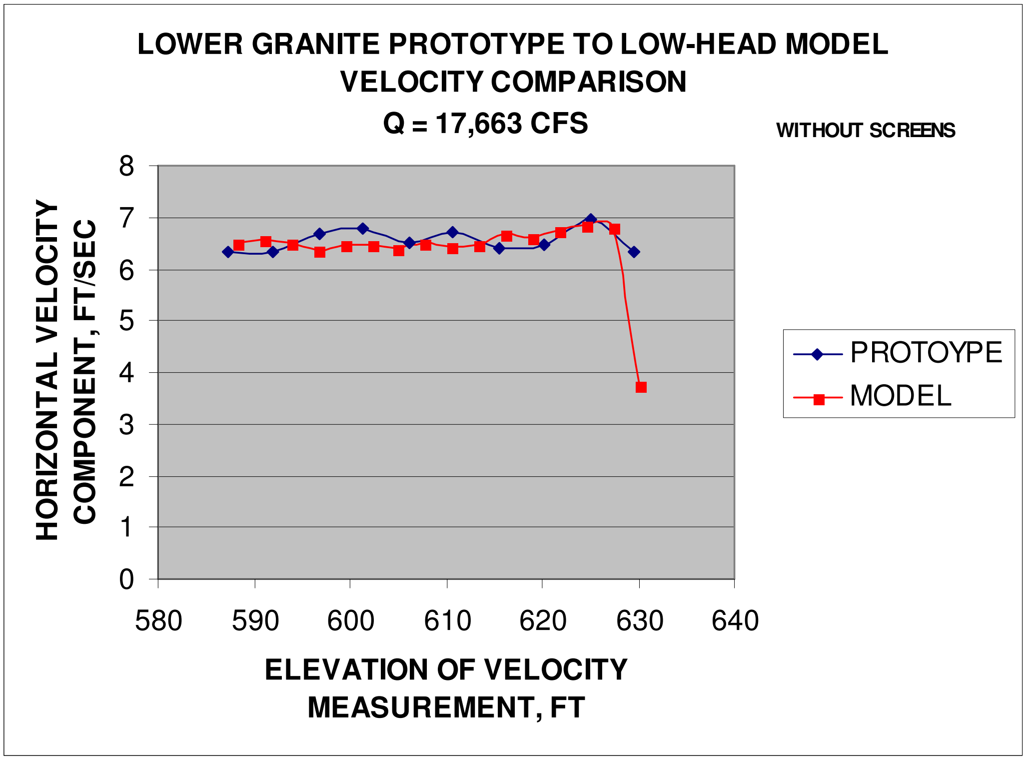


Figure 27. Lower Granite model and prototype velocity profile comparison.

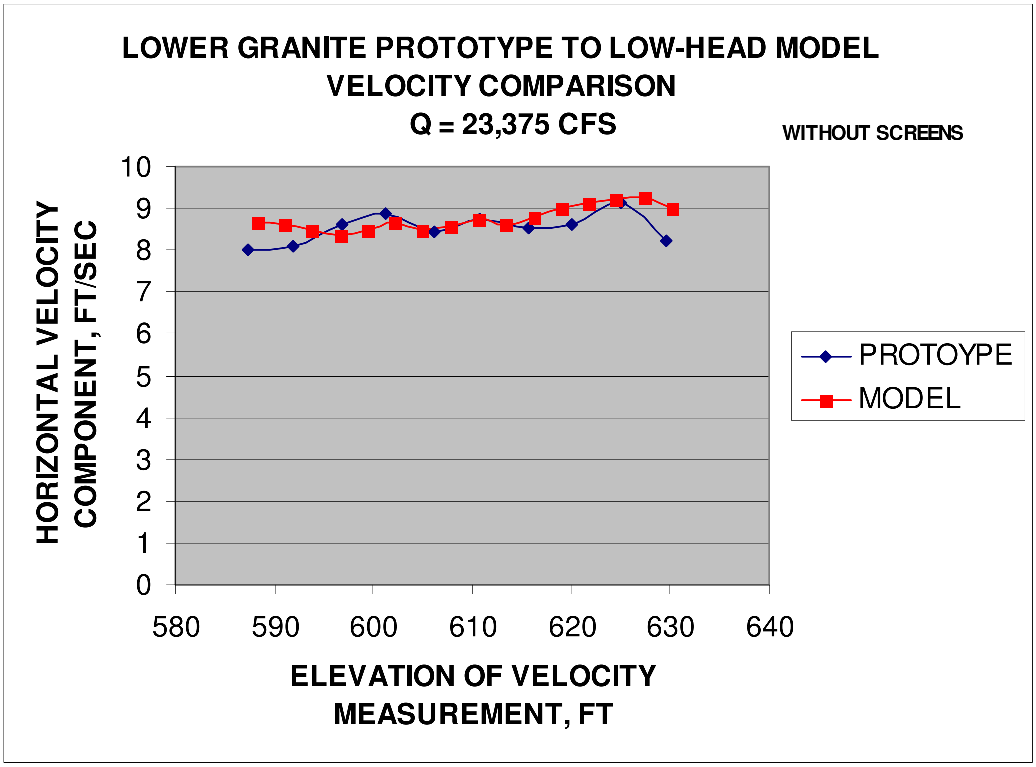


Figure 28. Lower Granite model and prototype velocity profile comparison.

2.5.2.2.2 *Preliminary Bead Experiments in the ERDC-WES Hydraulic Model*

Preliminary bead experiments were performed to ensure that the bead release methods used on the McNary turbine model worked well in the Lower Granite model. This bead release method worked well for the Lower Granite Turbine model as well.

2.5.2.2.3 *Initial Bead Range Finding Experiments*

Neutrally buoyant beads were released along the centerline of each of the three bays of the intake at the emergency closure bulkhead slot, for six elevations at a turbine loading of 17,663 cfs. The ESBS was in place for this experiment. The release of the beads was carried out at one location at a time and the position at which the beads passed through the stay-vane and wicket gate cascade was captured with 8-mm video. This video was reviewed and the position of the beads passing through the stay-vane cascade was scaled and transferred into an ACAD plot. It is apparent that the beads pass through a number of stay-vanes from each release point as well as a significant vertical spread. This is an indicator of the turbulence imparted to the flow by the ESBS. Even if fish followed flowlines, it would be difficult to predict the path a fish would travel from a release point at the emergency closure bulkhead slot to the turbine entrance, and then what passage route the fish would take through the runner and draft-tube. This is consistent with observations in the McNary model.

Duplication of 1995 Biological Test (Beads). Biological experiments were conducted at the prototype structure in 1994-1995 to determine survival rates of juvenile salmon through the Lower Granite turbine. Fish were released in each bay of the intake structure at the emergency closure bulkhead slot for three different turbine-operating points, which corresponded to turbine discharges of 13,570 cfs, 18,040 cfs and 19,700 cfs.

In 1998 the same prototype operating conditions were run in the model. For a turbine loading of 13,570 cfs, beads were released in the model at a corresponding prototype elevation of 603 feet in each of the three bays; fish were released in the same position in the prototype structure. The beads released in Bay A passed between stay vanes 9 and 17, but mainly between stay vanes 10 to 14. The vertical distribution was mainly the center one-half of the stay vane, which indicate a mid-blade passage. The beads released in Bay B passed mainly between stay vanes 5 and 8 in the top one-half of the stay-vane, indicating the beads would pass mid-blade to the hub area of the runner. This was also true for the Bay C release.

Bead results for the other two operating points were similar. These results indicate that few fish released in the biological experiment would pass through the tip of the runner and, therefore, these releases would not give a true assessment of fish survival through the entire turbine environment. This assumes that fish follow flowlines. However, these release points may actually represent the population of the salmon passing through the intake that are not guided away from the turbine by the ESBS. The release point at elevation 603 feet would represent the approximate flowline that passes just underneath the tip of the ESBS. To assess the validity of these release points to represent the population of juvenile salmon passing through the intake, the actual distribution of fish passing through the intake in all three bays would need to be determined.

2.5.2.2.4 Draft-tube Experiments

Baseline Experiments. Observations of flow in the draft-tube performed with dye and beads, for a turbine loading of 17,600 cfs, indicated that flow through the draft-tube is turbulent and not uniform. A flow imbalance seemed to exist between the two draft-tube barrels. In addition, flow conditions downstream from the draft-tube exit were chaotic with large areas of reverse flow occurring on the right side of the model (looking downstream) and a large backroller above the exit of the draft-tube. Large numbers of beads became entrained into these reverse flow areas and tended to circulate in this area for extended periods of time. This entrainment process was more severe than for the same areas observed in the McNary model. Juvenile salmon in the prototype draft-tube have a high potential for being entrained into these areas and may become easy targets for predation.

Experiments were conducted in an effort to research possible modifications to the draft-tube to improve or remove this entrainment area. For a turbine loading of 17,660 cfs, velocities were obtained at two cross-sections in each barrel of the draft-tube, as well as at several locations downstream of the draft-tube exit. The flow split between the barrels of the draft-tube was calculated from velocity information as 69.8 percent for barrel A and 30.2 percent for barrel C. Velocities obtained 6.25 feet upstream of the draft-tube exit showed a non-uniform velocity distribution in both barrels of the draft-tube (Figure 29). In barrel C there was reverse flow in the center of the barrel. In addition, a large backroller formed above, and downstream of, the draft-tube exit. The turbine loading was increased to 22,750 cfs and the velocity measurements were repeated. The distribution of the flow between the two barrels was improved to 61 percent for barrel A and 39 percent for barrel C. The velocity distribution within each barrel was improved, however some reverse flow was documented along the roofline in both barrels (Figure 30). The backroller was still present above the draft-tube exit.

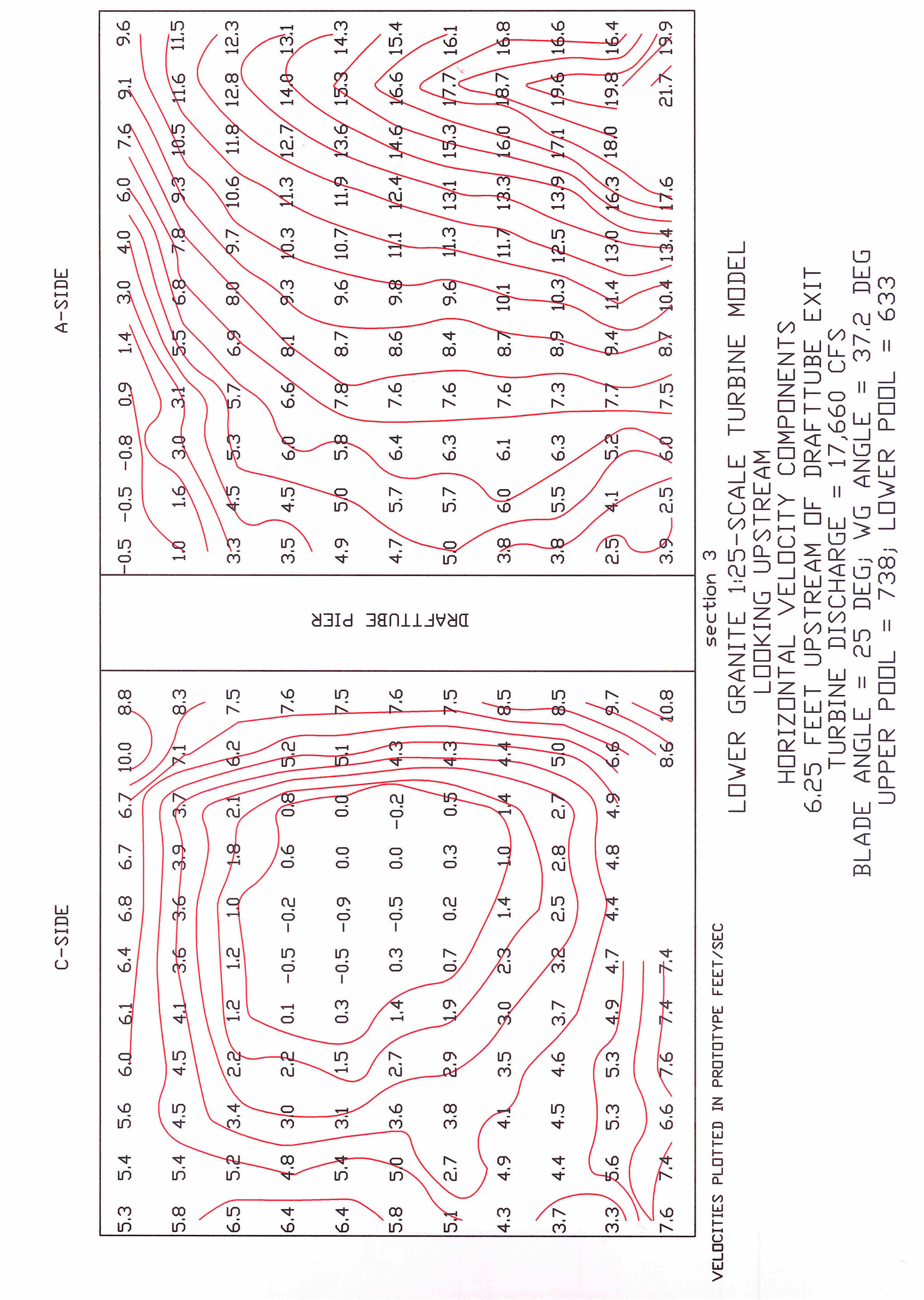
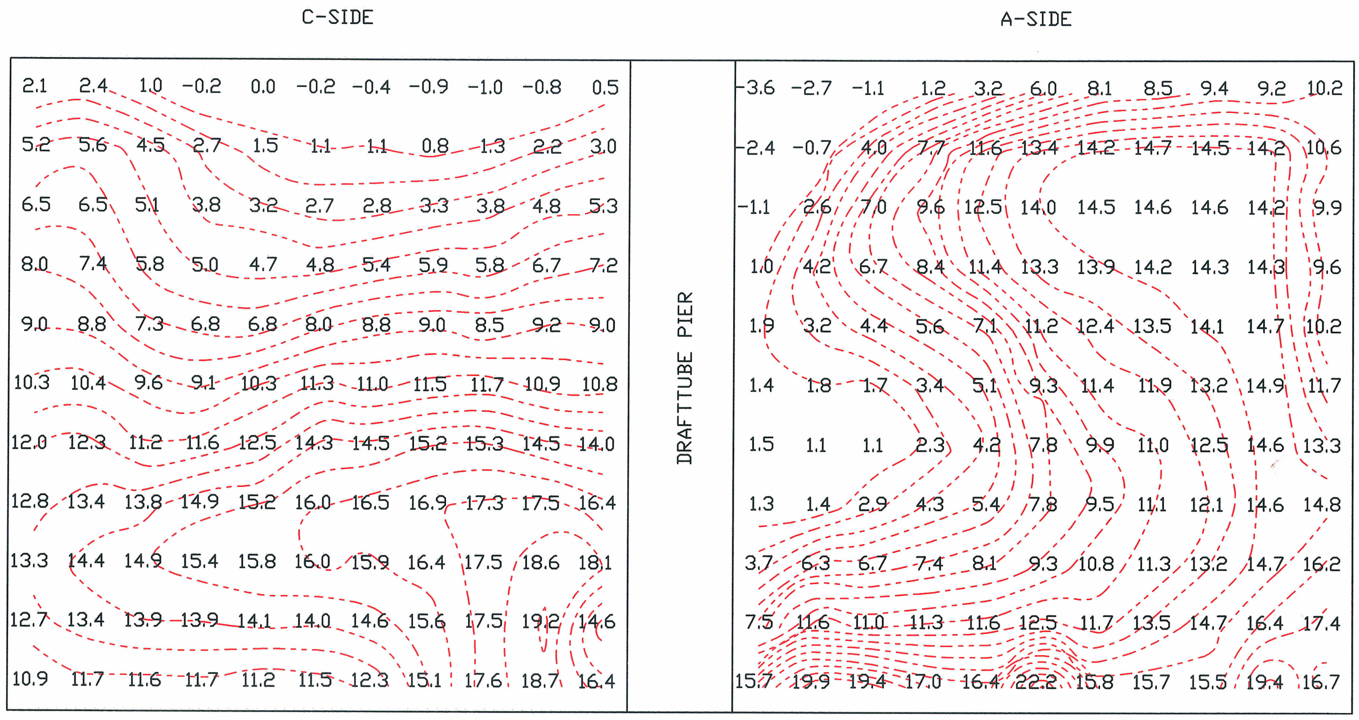


Figure 29. Lower Granite velocity cross-section near the draft-tube exit.



C-SIDE

2.1	2.4	1.0	-0.2	0.0	-0.2	-0.4	-0.9	-1.0	-0.8	0.5
5.2	5.6	4.5	2.7	1.5	1.1	1.1	0.8	1.3	2.2	3.0
6.5	6.5	5.1	3.8	3.2	2.7	2.8	3.3	3.8	4.8	5.3
8.0	7.4	5.8	5.0	4.7	4.8	5.4	5.9	5.8	6.7	7.2
9.0	8.8	7.3	6.8	6.8	8.0	8.8	9.0	8.5	9.2	9.0
10.3	10.4	9.6	9.1	10.3	11.3	11.0	11.5	11.7	10.9	10.8
12.0	12.3	11.2	11.6	12.5	14.3	14.5	15.2	15.3	14.5	14.0
12.8	13.4	13.8	14.9	15.2	16.0	16.5	16.9	17.3	17.5	16.4
13.3	14.4	14.9	15.4	15.8	16.0	15.9	16.4	17.5	18.6	18.1
12.7	13.4	13.9	13.9	14.1	14.0	14.6	15.6	17.5	19.2	14.6
10.9	11.7	11.6	11.7	11.2	11.5	12.3	15.1	17.6	18.7	16.4

A-SIDE

-3.6	-2.7	-1.1	1.2	3.2	6.0	8.1	8.5	9.4	9.2	10.2
-2.4	-0.7	4.0	7.7	11.6	13.4	14.2	14.7	14.5	14.2	10.6
-1.1	2.6	7.0	9.6	12.5	14.0	14.5	14.6	14.6	14.2	9.9
1.0	4.2	6.7	8.4	11.4	13.3	13.9	14.2	14.3	14.3	9.6
1.9	3.2	4.4	5.6	7.1	11.2	12.4	13.5	14.1	14.7	10.2
1.4	1.8	1.7	3.4	5.1	9.3	11.4	11.9	13.2	14.9	11.7
1.5	1.1	1.1	2.3	4.2	7.8	9.9	11.0	12.5	14.6	13.3
1.3	1.4	2.9	4.3	5.4	7.8	9.5	11.1	12.1	14.6	14.8
3.7	6.3	6.7	7.4	8.1	9.3	10.8	11.3	13.2	14.7	16.2
7.5	11.6	11.0	11.3	11.6	12.5	11.7	13.5	14.7	16.4	17.4
15.7	19.9	19.4	17.0	16.4	22.2	15.8	15.7	15.5	19.4	16.7

VELOCITIES PLOTTED IN PROTOTYPE FEET/SEC

section 3

LOWER GRANITE 1:25-SCALE TURBINE MODEL
LOOKING UPSTREAM
HORIZONTAL VELOCITY COMPONENTS
6.25 FEET UPSTREAM OF DRAFTTUBE EXIT
TURBINE DISCHARGE = 22,750 CFS
BLADE ANGLE = 32 DEG; WG ANGLE = 40.5 DEG
UPPER POOL = 738; LOWER POOL = 633

Figure 30. Lower Granite velocity cross-section near the draft-tube exit.

Long Draft-tube Extension. Experiments were conducted with modifications to the model in an attempt to improve the velocity distribution in each barrel of the draft-tube and to reduce the downstream backroller. A large draft-tube extension, basically a ceiling extending from the original exit to the water surface, was placed above the draft-tube exit. This extension extended 77.4 feet downstream (Figure 31) and extended above the downstream water surface. This modification had no effect on the distribution of flow in the draft-tube barrels, but did fully eliminate the downstream backroller. This was true for both discharges of 17,660 and 22,750 cfs. This draft-tube extension was installed in the contractor's performance model. Performance experiments were performed at Reynolds-head and it was determined that this extension would not degrade the performance of the turbine(Appendix B.4).

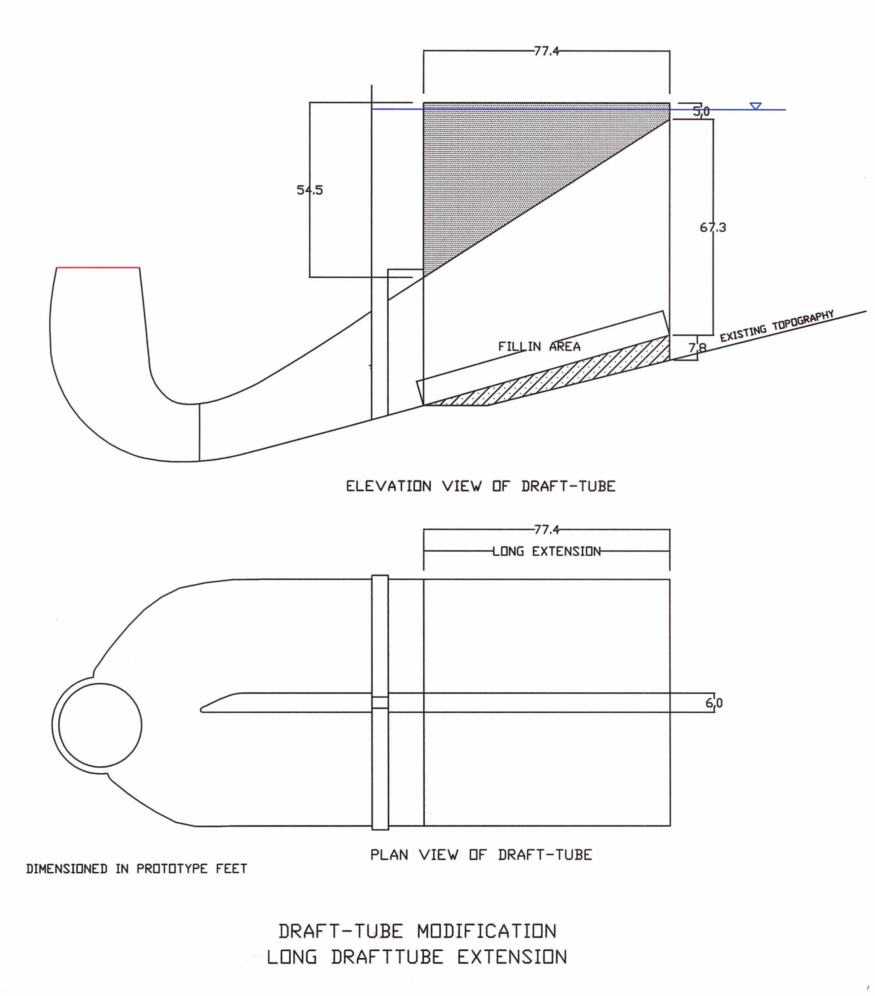


Figure 31. Draft-tube modification – long draft-tube extension.

Short Draft-tube Extension. A shorter draft-tube extension was installed in the ERDC-WES hydraulic model as an alternative to the larger draft-tube extension. This draft-tube extension extended the draft-tube by 54.0 feet (Figure 32). It was concluded (from observations of beads and velocity experiments) that this draft-tube extension had little effect on the flow distribution between the two barrels of the draft-tube, or on the flow distribution within each barrel of the draft-tube, when compared to data obtained without any draft-tube modifications. It did reduce the size of the downstream backroller. However, the top of this extension was 18 feet below the water surface. This area above the draft-tube extension allowed for beads to circulate awhile, which would be an indicator that juvenile salmon may become entrained into this area after passing the draft-tube exit. This draft-tube extension was not looked at in the performance model, however no impact on turbine performance would be expected with this draft-tube extension.

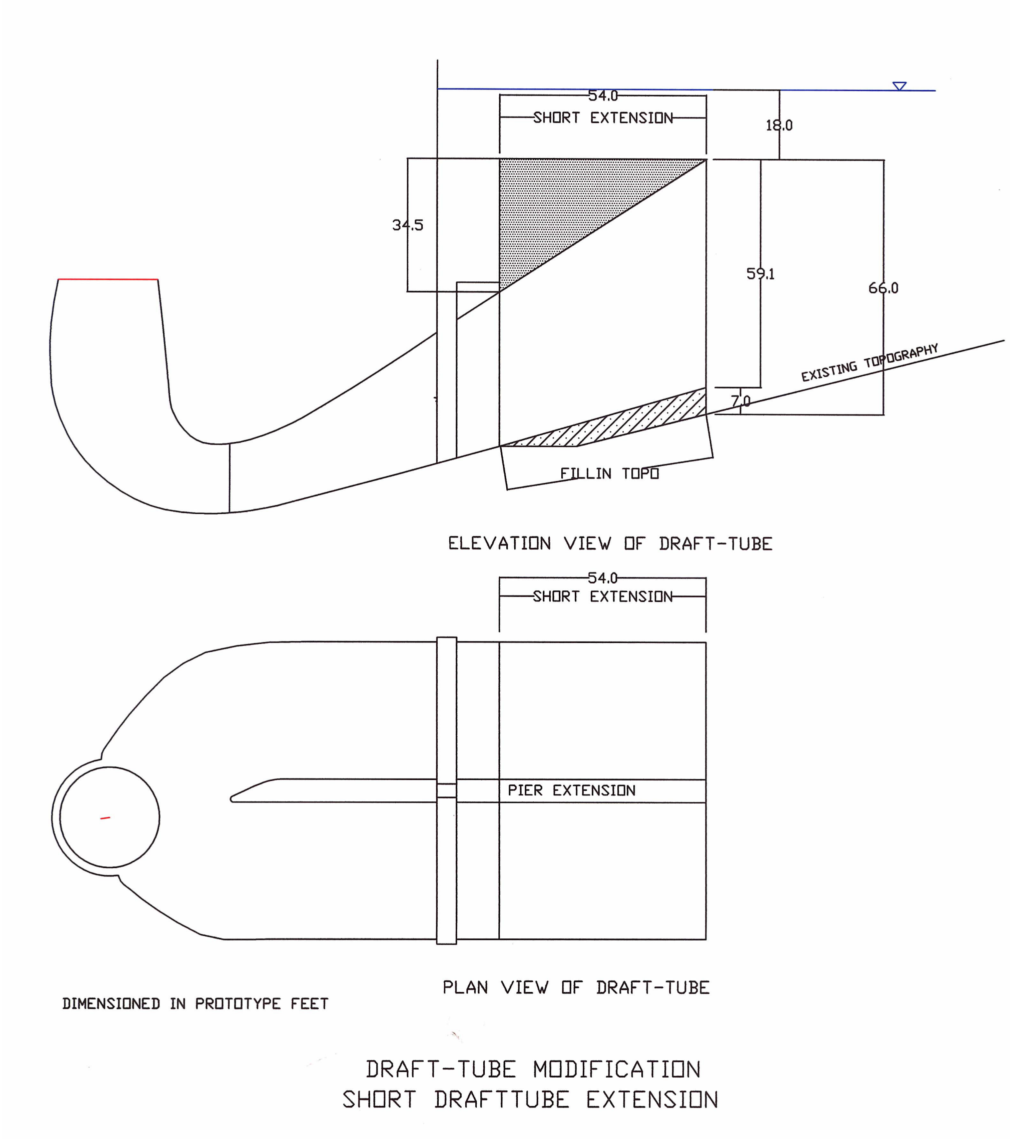


Figure 32. Draft-tube modification – short draft-tube extension.

Long Draft-tube Extension with Asymmetric Floor. The flow area in barrel C of the draft-tube does not have full barrel flow for a high turbine loading of 17,660 cfs. One method of eliminating flow reversals in this barrel would be to reduce its cross-sectional area, thereby reducing the available area for flow to pass. To accomplish this, the floor of the draft-tube of barrel C was raised. Beginning at the draft-tube invert at section 14, the invert of the draft-tube was sloped to a point 6 feet higher than the existing draft-tube exit invert. This provided a 15-percent reduction in flow area at the existing draft-tube exit. From the existing draft-tube exit, the slope of the invert was continued upstream to a point corresponding to the downstream edge of the long draft-tube extension. Barrel A was left with its original area. The long draft-tube extension was placed in the model with the asymmetric floor. A diagram of this arrangement is provided in Figure 33. In the long draft-tube extension a pier divided barrels A and C. This arrangement allows the draft-tube to be extended 77.4 feet. Velocity experiments, conducted at a turbine loading of 17,660 cfs with this arrangement, indicated that the flow reversal in barrel C was fully eliminated. A low velocity area occurred at the center of the barrel at the same location where the flow reversal occurred before the addition of the raised invert in barrel C. This is an improvement. There was not an effect on flow distribution between the barrels of the draft-tube. Consequently, a significant change in performance of the prototype turbine would not be expected. The turbine loading was increased to 22,750 cfs and the velocity experiments were repeated. This arrangement did not affect the distribution of flow between the two barrels of the draft-tube. When compared to previous experiments, differences in the velocity distributions in barrel C were noted for this condition. The flow reversals along the roofline were eliminated and the overall flow distribution within this barrel was more uniform.

This arrangement was installed in the contractor's performance model and performance experiments were run (Appendix B.4). These experiments indicated that this arrangement would not degrade the performance of the turbine. In fact, the trend at the higher blade angles showed a slight improvement. The higher blade angles would correspond to higher turbine loadings.

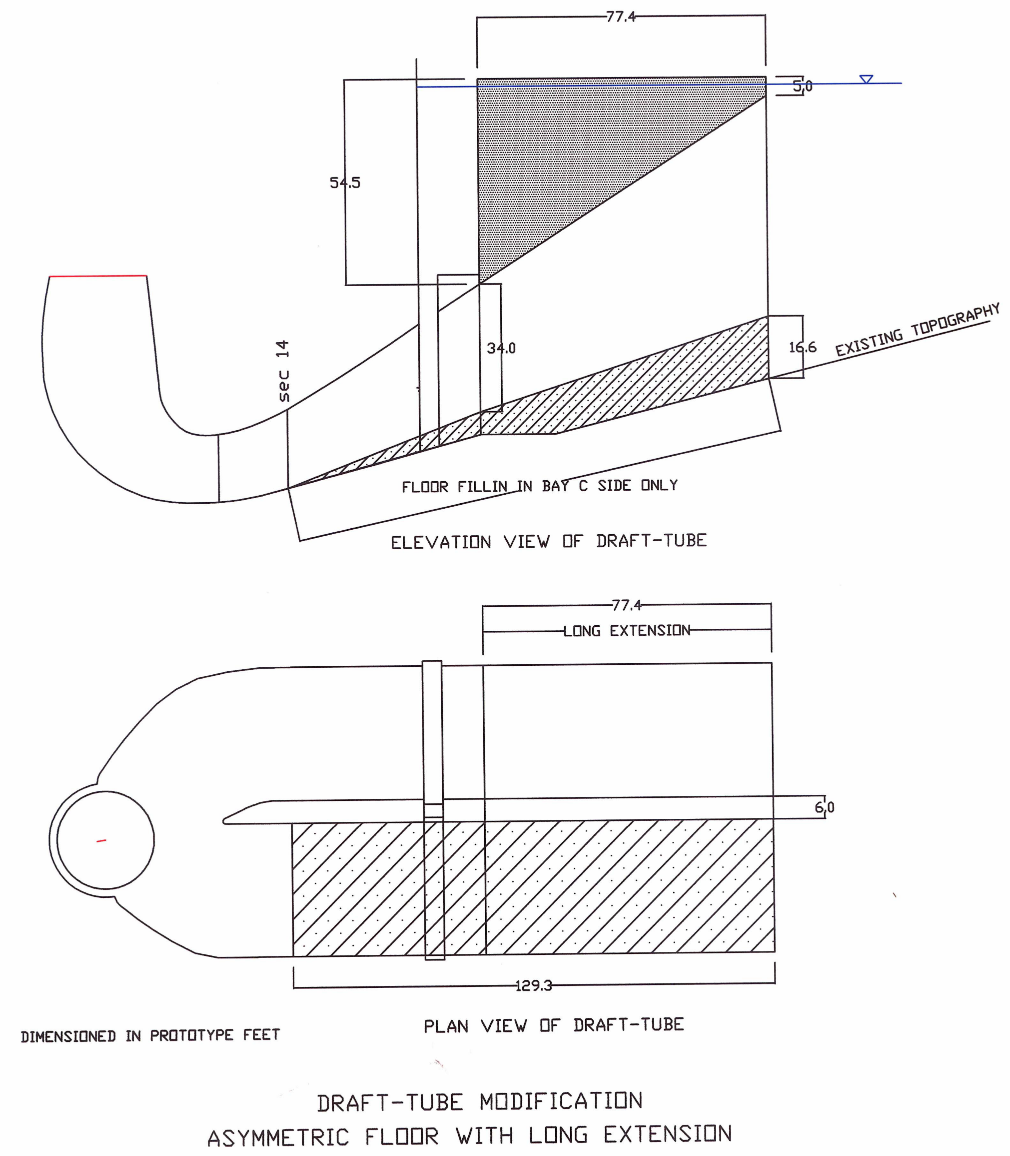


Figure 33. Draft-tube modification – asymmetric draft-tube extension.

Horizontal Splitter Piers with Vertical Dividers. Another method of changing the distribution of flow within each barrel of the draft-tube would be to put structures within the draft-tube barrels to guide the flow. Horizontal and vertical splitter piers were installed in each barrel of the draft-tube. The horizontal splitter in barrel C extended along the centerline from the nose of the existing draft-tube pier to just upstream of the draft-tube bulkhead slot. A vertical pier divided the area below the horizontal splitter into two equal areas. Barrel A had a similar arrangement except it started 12.3 feet downstream of the existing draft-tube pier. A diagram showing this arrangement is provided in Figure 34. Velocities obtained within each draft-tube barrel showed that this arrangement significantly affects the velocity distribution in each barrel of the draft-tube. When compared to previous draft-tube modifications, the overall velocity was more uniform. At a turbine loading of 17,660 cfs, the distribution of flow between the two barrels of the draft-tube was calculated from velocity information as 70.5 percent for barrel A and 29.5 for barrel C. This is very similar to values obtained for the other experiments conducted at this discharge. This indicates that this draft-tube modification had little affect on the distribution of flow between the draft-tube barrels. This experiment was repeated for a discharge of 22,750 cfs. Velocity information obtained for this experiment showed a change in the velocity distribution within each barrel of the draft-tube and a slight improvement in the flow distribution between the two barrels. The percent of flow in barrel A for this experiment was 59.4 percent compared to 61.0 percent in previous experiments at this turbine loading.

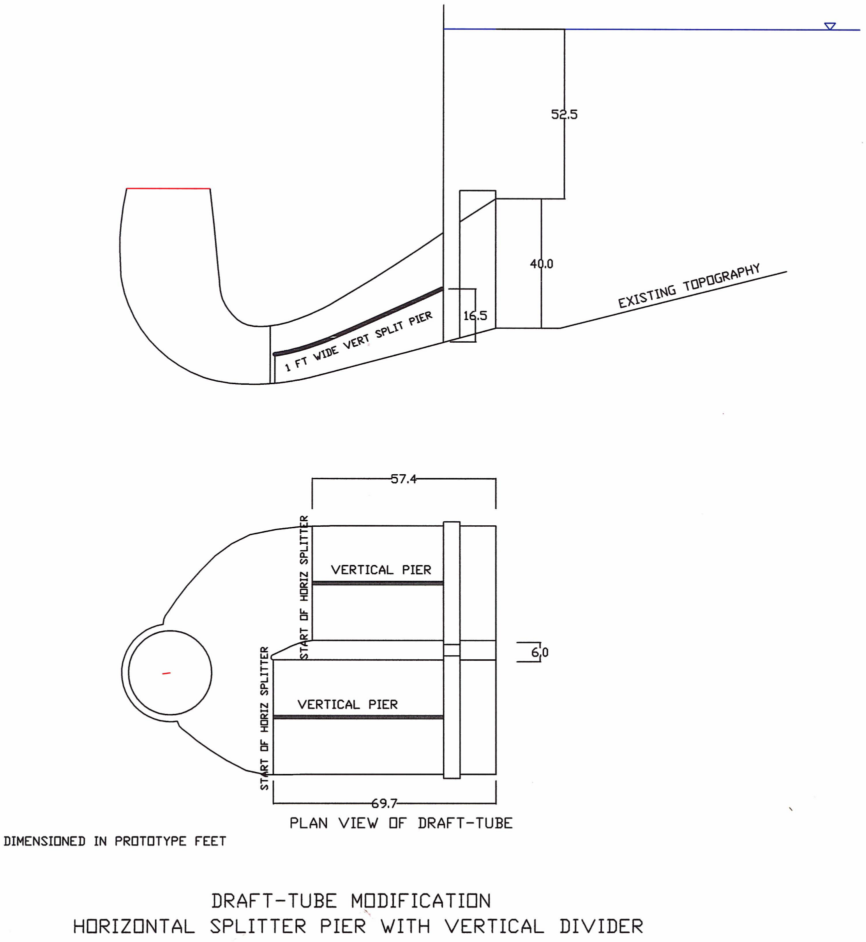


Figure 34. Draft-tube modification – horizontal splitter pier with vertical divider.

This draft-tube modification type has potential for improving the flow characteristics of the flow through the draft-tube and thus improving the flow in the area downstream of the draft-tube. The experiment in the ERDC-WES hydraulic model was to see if this type of modification would have a beneficial impact on fish passage. To proceed with this type of modification, more research would be needed to determine the correct position, shape, and elevation of a horizontal splitter pier for a given operating range. It would be doubtful that one shape would be optimum for all operating points. This would need to be researched in the ERDC-WES hydraulic model with the final one or two designs tested in a performance model. This draft-tube modification has the potential for affecting the performance of the turbine. One drawback of this type of draft-tube modification is that an additional object and surface is being placed into the flow field; some juvenile salmon would come into contact with it. It is unclear if fish would be injured by the leading edge of the horizontal splitter piers, but Bonneville First Powerhouse units have horizontal as well as vertical splitter piers and these do not seem to cause excessive direct injury to juvenile salmon.

2.5.3 Findings of the Lower Granite Turbine Model Studies

High (Reynolds) and low-head (Froude) turbine performance model tests were conducted to evaluate the impact of fish diversion screens on turbine performance, and it was determined that fish screens have a significant impact on turbine performance. New cam curves were developed with screens in place using both Froude and Reynolds techniques on turbine performance models. Froude model cam curves matched prototype field index tests better than Reynolds-head developed cam curves. One reason for this is the fish diversion screens used in the performance model were developed at ERDC-WES for use in the Froude-head FGE models (ERDC-WES hydraulic models) and not high-head and high discharge models (turbine performance models). Velocity profiles obtained in both Reynolds and Froude performance models indicate that head loss and velocity distributions develop differently downstream of the screens, therefore the model-measured turbine performance will be different. Comparisons of these model results with prototype velocity measurements show the low-head or Froude model techniques better replicate intake flow conditions when fish intake screens are in place.

Each of the modeling techniques has inherent challenges in the accurate modeling of the prototype. For example, forebay inflow conditions must be assumed because only one unit is modeled when, in fact, adjacent units exist and affect the actual inflow conditions. In addition, some scale adjustments are necessary to make a model usable. These adjustments are due to the tight clearances for the moving parts in the prototype that cannot be duplicated in a model. The surface roughness conditions in a prototype cannot be duplicated in a model and simplifications of complex designs must be made to approximate prototype conditions (fish screens are an example). Small shape changes to hydraulic designs caused by years of service and maintenance can only be approximated. These simplifications and adjustments and other potential uncertainties must be and have been considered when examining modeling results and evaluating findings.

Model cam curves were developed in the Froude-head turbine performance model to be used at ERDC-WES in its hydraulic turbine model. A turbine runner was supplied by a turbine contractor and successfully installed in the ERDC-WES hydraulic model. Initial velocity experiments conducted in the hydraulic model showed a good correlation to velocity profiles obtained in the contractor’s Froude-head turbine performance model. This indicates both models develop similar velocity profiles upstream of the turbine and that the cam curves developed in the Froude-head turbine performance model could be used for the ERDC-WES hydraulic model. In addition, velocities obtained in the hydraulic model before the model runner showed good correlation to velocities obtained at the same spatial position as velocities obtained after the addition of the turbine runner. This indicates that model results used to design fish diversion screens (before the addition of the model turbine runner) are valid.

Neutrally buoyant beads released in the downstream bulkhead slot in the ERDC-WES hydraulic model, with a fish diversion screen in place, are highly distributed by the time they enter the stay-vane and wicket gate. Thus they would have a highly varied path through the runner environment and the draft-tube region. It would be expected for fish to redistribute after passing beneath the screens but it is not known to what extent. Although fish may not actually follow the flow paths as the neutrally buoyant beads do, these studies do indicate that the areas downstream of the screens are highly turbulent and will have a significant affect on fish distribution as they pass through the runner region

A significant number of beads were observed to pass through the gap between the stay vane and wicket gate in the ERDC-WES hydraulic model. Also, flow separation was observed at the leading edge of the stay vane for several discharges. Based on these model observations, Reynolds-head turbine performance experiments were conducted to determine the effects of reshaping the stay-vanes and reducing the gap between the wicket gate and stay vane. It was found that it would have a positive influence on turbine performance. Closing the gap and streamlining the stay-vane would be beneficial for both performance and fish passage.

Velocity and bead experiments conducted in the ERDC-WES hydraulic model indicate that flow in the draft-tube is highly turbulent and that an uneven flow distribution exists between the two barrels of the draft-tube for the upper end of the one-percent operating zone. Also, the flow distribution between each barrel of the draft-tube is also unevenly distributed with reverse flow occurring on one draft-tube barrel. The distribution of flow existing in the draft-tube can potentially affect fish survival by placing fish in zones downstream of the turbine exit where more predation can occur. Several draft-tube modifications were tested in the ERDC-WES hydraulic model and it was determined that the flow distribution between the barrels and within each barrel can be improved by physically modifying the draft-tube. The best of the modifications investigated at ERDC-WES was placed and evaluated in the Reynolds-head turbine performance model. A slight improvement in turbine performance was documented.

2.6 Bonneville First Powerhouse Physical Hydraulic Models

2.6.1 Construction of Bonneville First Powerhouse Models

Three Bonneville First Powerhouse turbine models were built at a 1:25 scale. The first model was built for the design and evaluation of ESBSs, streamlined trash racks and to investigate the surface bypass collection at the Bonneville project. It consisted of 800 feet of approach flume and topography, three intake flow bays, trash racks, STSs, ESBSs, VBSs, scroll case, stay vanes and wicket gates (Figure 35). Like the original McNary and Lower Granite turbine models, this model did not include an operating turbine runner. The wicket gates were set at a full open position for all screen and surface bypass collector experiments. The model was constructed of acrylic to allow for visual observations and measurement of velocities within the structure.

Voith Hydro constructed the second turbine model as part of Government contract DACW57-95-C-0002. This high-head turbine performance model was used to develop the turbine replacement design for the Bonneville First Powerhouse. The model testing resulted in the design and installation of an MGR. Uncertainties of a fish passage survival test conducted on the new prototype MGR at Bonneville lead to construction of a second model at ERDC-WES. This model was constructed to accommodate either of two operating turbine runners (existing and MGR) provided by Voith Hydro. Both runners were geometrically reproduced at the 1:25 scale.

Due to ongoing and potential research using the original ERDC-WES Bonneville First Powerhouse turbine hydraulic model, Portland District decided not to modify this model, but to construct a complete new model. The new 1:25 scale Bonneville First Powerhouse turbine model geometrically reproduced one powerhouse unit including the three intake bays, scroll case, stay vane and wicket gate cascade, draft-tube, trash racks, screening devices, and vertical barrier screens, approximately 800 feet of approach topography and 300 feet of downstream topography. The model was constructed of acrylic to allow for visual observations and measurement of velocities within the structure. The 1:25 scale replicates the existing runners and MGR that were manufactured by Voith Hydro and delivered to ERDC-WES. Voith Hydro also provided a motor and instrumentation to control the speed of the turbine runners. Figures 36 and 37 show the newly constructed model.

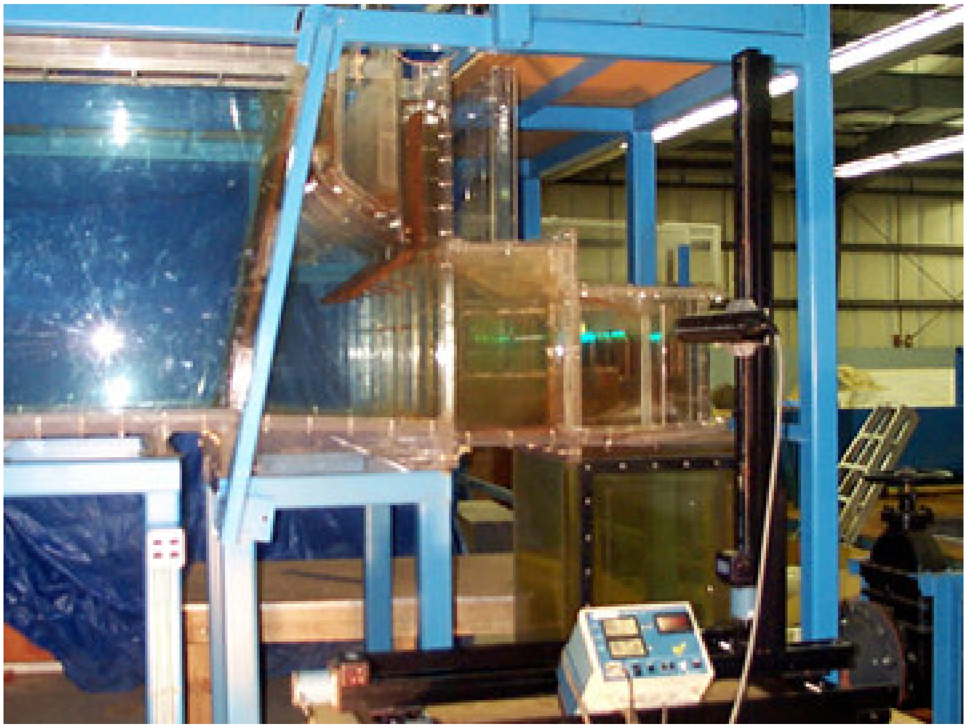


Figure 35. Original Bonneville First Powerhouse 1:25-scale model.

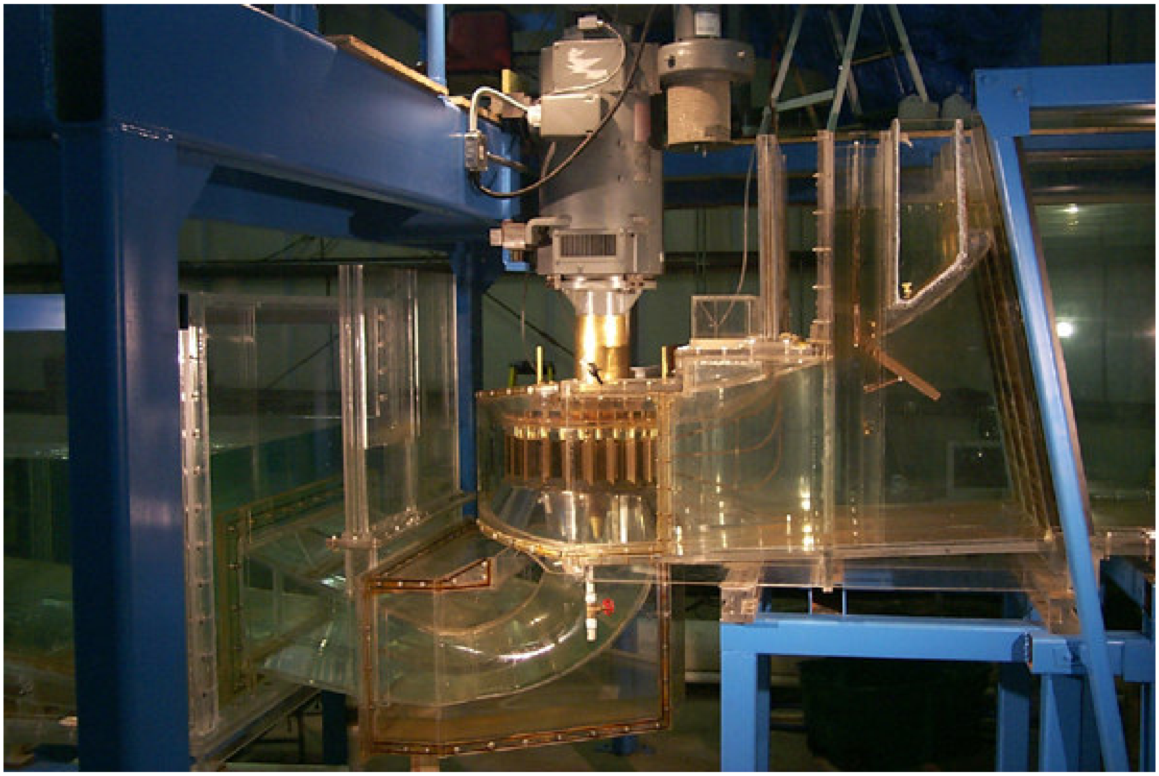


Figure 36. Bonneville First Powerhouse 1:25-scale model with model runner installed.

Figure 37. General view of new Bonneville 1:25-scale model.

2.6.2 Bonneville First Powerhouse Physical Hydraulic Model Investigations

The Bonneville First Powerhouse turbine model investigations supported by TSP focused on the design and evaluation of the original and MGR runners. These investigations included the high-head turbine performance testing conducted by Voith Hydro for design and evaluation of a new runner, and testing of the two ERDC-WES low-head hydraulic models. The ERDC-WES investigations using the original model were conducted to help design the biological test plan for two prototype units (existing and MGR) and for design of the test fish release pipes. The new ERDC-WES Bonneville First Powerhouse turbine hydraulic model was primarily used to support the evaluation the fish passage or biological test results.

2.6.2.1 Bonneville First Powerhouse Turbine Performance Model Testing (Voith Hydro)

The contract with Voith Hydro included the design and model testing of a new replacement runner for Bonneville First Powerhouse, and evaluation of baseline conditions including model testing of the existing runner. The first phase was to define the baseline turbine performance to establish minimum requirements for the powerhouse turbine rehabilitation. As information became available, options within the contract were exercised to investigate potential turbine performance and environmental improvements. This led to a mutually selected design concept for further development. This MGR design was developed and tested. The design provided good cavitation characteristics and exceeded the baseline design performance within the one-percent operating limitations. The model efficiencies at the best operating point were: baseline = 91.46 percent, MGR = 92.78 percent with the MGR having an improved cavitation safety margin of 50 percent over the baseline test without screens. Based on the performance of the MGR turbine model, the MGR was determined to be economically acceptable when compared to the existing. The Corps verified the final design and ordered the prototype MGRs. The first MGR was installed in Bonneville First Powerhouse Unit 6 and tested for fish passage survival and index tested for performance. Figure 38 shows a comparison of the designs and Figure 39 is a photograph of the turbine model runner.

2.6.2.2 Bonneville First Powerhouse ERDC-WES Hydraulic Model Testing

As part of the Corps rehabilitation program, the Kaplan runner at Unit 6 was replaced with an MGR in 1997. In determining whether this new design could be implemented for the entire First Powerhouse, the MGR had to be verified biologically as providing turbine passage no worse for juvenile salmon than the existing Bonneville runner.

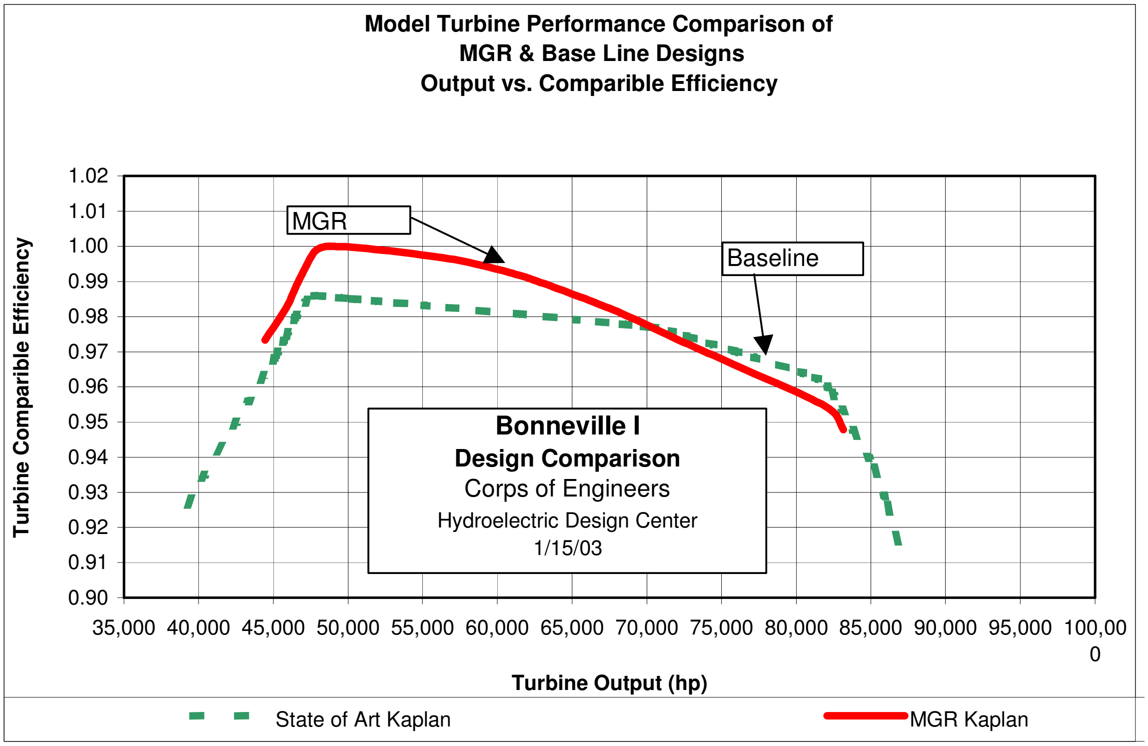


Figure 38. Performance comparison MGR to baseline.

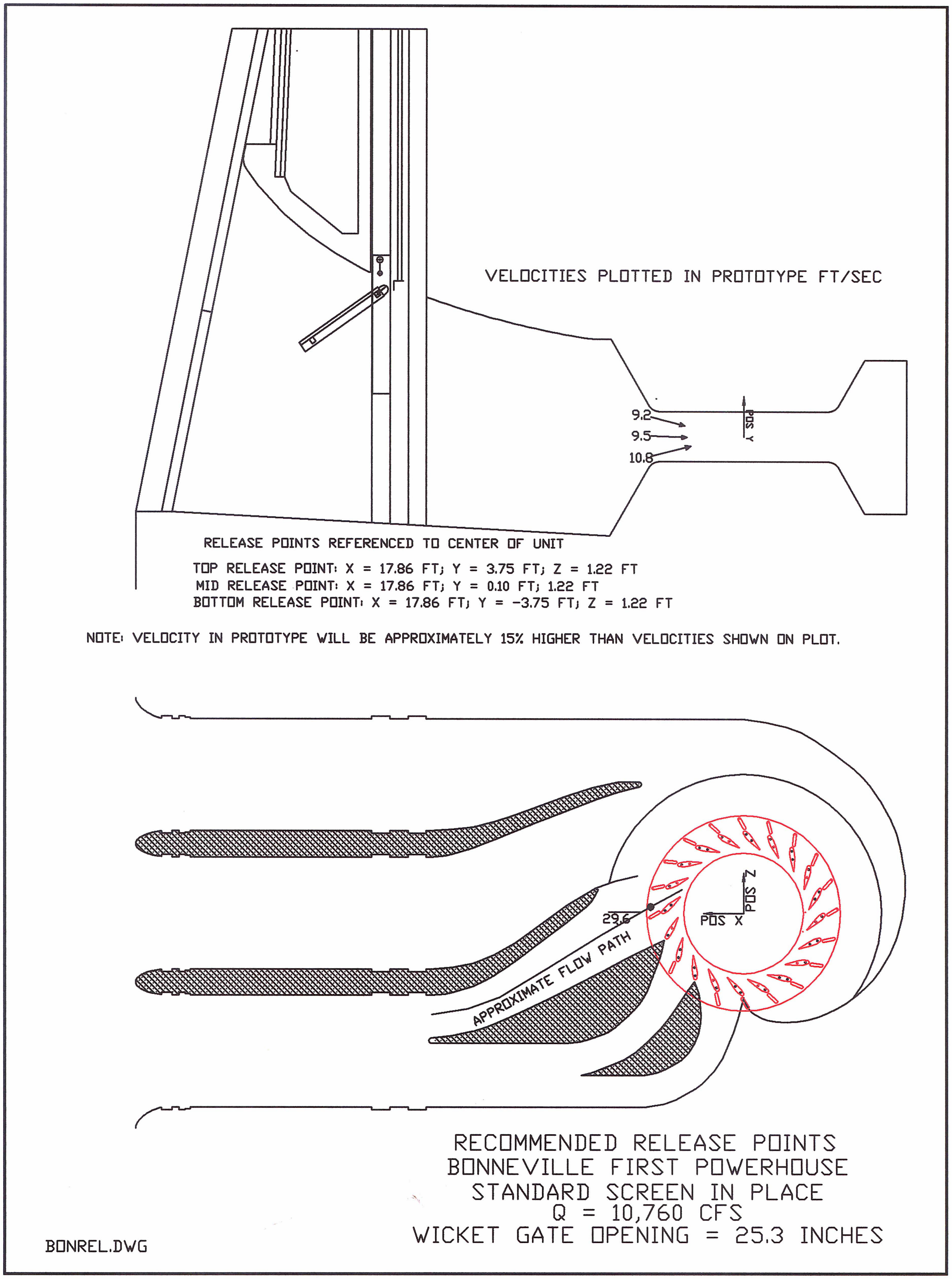
Figure 39. Photograph of the model B1 MGR.

2.6.2.2.1 Bonneville First Powerhouse ERDC-WES Hydraulic Model (without runner)

The ERDC-WES hydraulic model investigations included testing of the original model, without the turbine runner, to establish a method of testing fish passage survival through the turbine. The tests were designed to release tagged fish at specific locations so they would pass through one of three main areas: the gap near the hub of the runner, the mid-blade region of the runner, and the gap near the tip of the runner. As this model was originally intended for screen designs, some adjustments to the model were required. The model in the area of the scroll case and wicket stay vane cascade was disassembled. The wicket gate opening was changed to an opening that would represent a turbine loading of 10,760 cfs. This discharge would represent the high discharge side of the one-percent peak efficiency zone for the existing (original) prototype unit. The components of the model were cleaned and re-assembled. The bead path tracking techniques developed for the McNary model investigations were used to locate the best release points for biological tests.

Model Bead Release Experiments. The goal of these experiments was to locate release points in the model that would pass beads through target zones of the turbine: near the tip of the blades (within 12 to 14 inches prototype), near the middle of the blades, and near the hub (within 12 to 14 inches prototype). Beads were released at a range of elevations in each of the three bays of the intake structure at the emergency closure bulkhead slot. From this position in the model, it was obvious that it would not be possible to have a consistent flow path to pass beads through specific zones of the turbine. The release points were moved closer to the stay vanes in Bays B and C. Bay A was not considered because it had the greater variability in the number of stay vanes the beads passed through as well as a large vertical spread. Once again, a flow path was not found that would be consistent enough to pass the beads through a tight area of the stay vane arrangement. Several more release positions in Bays B and C were investigated and it became obvious that it would be necessary to release beads at the stay vanes to pass them through a specific area of the turbine. This is consistent with findings from the McNary model in investigating specific areas of the turbine. Stays vanes downstream of Bay B and in Bay C were investigated and a release in Bay C at the stay vane was determined to be the most desirable release position. This is because it has the shortest length from the emergency closure gate slot to the stay vane entrance (making it the least expensive) and because the flow in the first barrel of Bay C guides the flow into the stay vane arrangement. This allows for the least amount of turbulence, which should yield the most consistent flow path. The final recommended release points for passing fish through the tip of the blades, middle of the blades and near the hub can be seen in a diagram provided in Figure 40.

In addition to locating the best release points, measurements were taken in Bay C of the model to define the velocity flow field. These data were used for the structural design of the release pipes. Velocities were also measured at the three recommended release points such that the exit velocities of the prototype release system could be designed to match to the velocity of the ambient flow. This was necessary to eliminate potential shear on the fish as they ejected from the release pipes.



VELOCITIES PLOTTED IN PROTOTYPE FT/SEC

RELEASE POINTS REFERENCED TO CENTER OF UNIT

TOP RELEASE POINT: X = 17.86 FT; Y = 3.75 FT; Z = 1.22 FT
MID RELEASE POINT: X = 17.86 FT; Y = 0.10 FT; 1.22 FT
BOTTOM RELEASE POINT: X = 17.86 FT; Y = -3.75 FT; Z = 1.22 FT

NOTE: VELOCITY IN PROTOTYPE WILL BE APPROXIMATELY 15% HIGHER THAN VELOCITIES SHOWN ON PLOT.

RECOMMENDED RELEASE POINTS
BONNEVILLE FIRST POWERHOUSE
STANDARD SCREEN IN PLACE
Q = 10,760 CFS
WICKET GATE OPENING = 25.3 INCHES

Figure 40. Bonneville final recommended release points.

2.6.2.2.2 Bonneville First Powerhouse ERDC-WES Hydraulic Model (with runner – original and MGR)

During the biological experiments in the winter of 1999 to 2000, fish were released at three locations at the stay vane entrance in Bay C at the prototype structure in Units 5 and 6. These fish were released at positions based on information from the runnerless ERDC-WES hydraulic model as discussed above. Since these release points were determined from a model without a runner, there was some uncertainty as to whether the fish actually went where they were intended to go. In addition, the release points were chosen based on one operating point. Prototype tests were conducted at four operating points for each runner type. These operating points corresponded to the low and the high discharge side of the one-percent peak efficiency zone for the original runner and the MGR. Each condition would have a different discharge, wicket gate opening, and runner blade angle. The path of the fish would be expected to vary based on these differences. The runner type may also impart some difference in the path of the fish. Because of these uncertainties, it was decided a Bonneville First Powerhouse turbine model with an operating turbine would be necessary to establish where the fish actually passed through the prototype unit for each of the four operating conditions of each runner design.

Experimental Conditions. The original runner was biologically tested under four operating conditions. These include the low and high discharge sides of the one-percent peak efficiency zone of the existing runner and at discharge levels corresponding to the MGR discharges when at the low and high discharge sides of its one-percent peak efficiency zone.

The MGR was biologically evaluated in a similar manner. It was tested at operating points corresponding to the low and high sides of the one-percent drop in efficiency and at two additional operating points corresponding to discharges of the original runner when operating at its low and high discharge sides of the one-percent drop from peak efficiency.

During the prototype biological experiments, the conditions for each operating point varied (mainly due to head fluctuations). This means that the wicket gate, blade angle, head, and turbine discharge varied throughout the time that was required to introduce enough fish to evaluate each operating point. At each operating point, fish were released at three positions at the stay vanes to investigate three different zones of the turbine runner (blade-tip, mid-blade and hub). It was not feasible to vary the head, wicket opening and blade angle for each operating point during experiments performed in the model. The Hydroelectric Design Center (HDC) supplied ERDC-WES with a file that had all the settings of the turbine (head, discharge, wicket gate opening and blade angle) that was used for the prototype biological evaluation for each operating point. These values were averaged. An actual operating point, used during the prototype experiment, was chosen that was close to the average values. This was done to be sure that an on cam point was chosen during the model evaluations. This method for determining model experimental conditions was repeated for each of the eight operating conditions used to evaluate the original runner and the MGR. These experimental conditions are provided in Table 11.

Table 11. Bonneville First Powerhouse Operating Conditions for Model Experiments*

HEAD WATER FMSL	TEST DATE	HEAD FT	WICKET GATE %SS	BLADE ANGLE, DEG	GENERATION MW	EFFICIENCY	DISCHARGE CFS	MODEL Q, CFM	WICKET GATE, PRO IN
UNIT 5 (EXISTING)	**BLADE AND SETTING EQUATION**								
73.9	1/11/2000	55.48	47.03	13.05	25072.36	0.87	6205.90	119.15	20.59
73	1/26/2000	55.69	49.72	15.72	29128.43	0.87	7148.42	137.25	21.86
74	1/18/2000	54.72	65.85	24.94	42857.18	0.87	10809.70	207.55	29.43
73.9	11/23/1999	59.16	68.46	29.71	53290.38	0.86	12110.77	232.53	30.63
UNIT 6 (MGR)	**BLADE AND SETTING EQUATION**								
72.7	12/13/1999	55.63	42.32	16.11	24951.49	0.86	6207.07	119.18	18.37
74.3	12/6/1999	57.8	47.73	16.12	30849,82	0.91	6907.91	132.63	20.92
72.3	1/6/2000	54.87	63.85	24.01	42834.52	0.90	10351.04	198.74	28.50
73.8	1/22/2000	56.13	68.05	27.14	29219.87	0.90	11691.87	224.48	30.44

*Actual test conditions that approximate average values.

2.6.2.2.3 Bead Results from the ERDC-WES Bonneville Turbine Model

Bead Release System Set-up. The release point locations for the prototype biological experiments were developed in the existing Bonneville First Powerhouse hydraulic model at ERDC-WES and provided to the Portland District where a prototype release system was designed (Figure 41). This design allowed fish to be introduced through a pressurized pipe system that injected the fish at the stay vane entrance at an angle and velocity that matched velocity measurements obtained in the ERDC-WES hydraulic model for a turbine loading of 10,200 cfs.

When the new Bonneville turbine hydraulic model was constructed, 1/8-inch holes were drilled into the bottom and top stay ring by means of a computer-controlled milling machine. A brass rod was inserted into these two holes and served as a guide for the model release tubes. The release tubes were inserted through a slot that was added to the model for this study. The exact routing shape of each of the three release tubes was routed into a 1-inch-thick piece of acrylic. The model tubes were fabricated from soft copper tubing. The tubing was shaped by forcing it into the acrylic, and 1/8-inch rods were soldered to the three tubes to ensure the desired shapes of the release tubes were maintained. This assembly was inserted into the model and tied to the rod at the entrance to the stay vane at the correct elevation (the elevation had been pre-marked on the rod). This method ensured that the beads would be released at the exact elevation and angle as fish were released during the prototype biological experiments. Figure 42 shows the release tube mounting arrangement in the model. In addition to ensuring that the spatial position for the model matched the prototype release, it also was important to match the release velocity for each tube. The water is supplied to the model release tube by a cylinder. The beads are placed into this cylinder and allowed to pass into the release tube. The elevation of the cylinder was set and the exit velocity at the release tube exit was measured by means of an LDV system. This was repeated until an elevation was found that closely matched the desired release tube exit velocity.

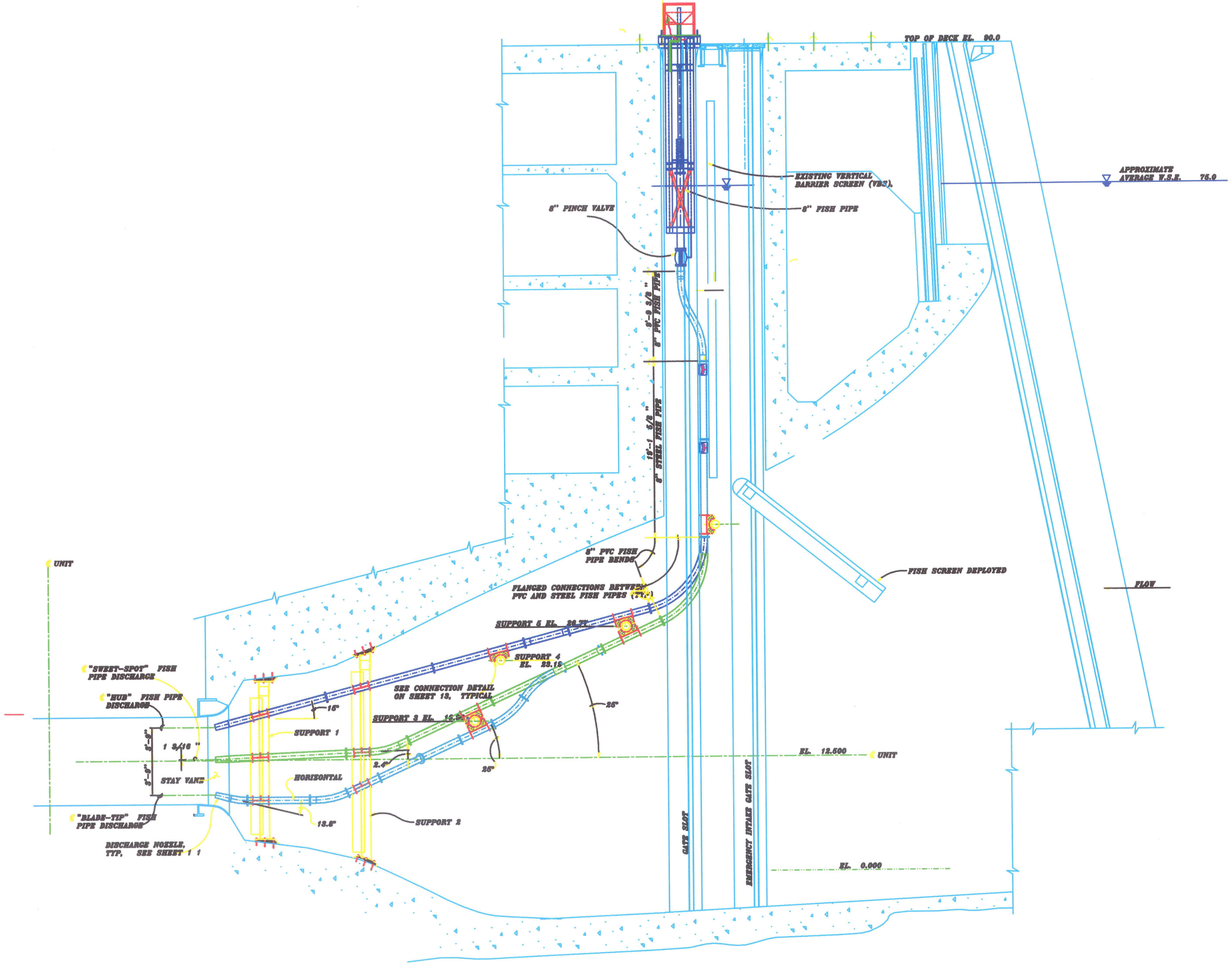


Figure 41. Diagram of the fish release system used at the prototype project.

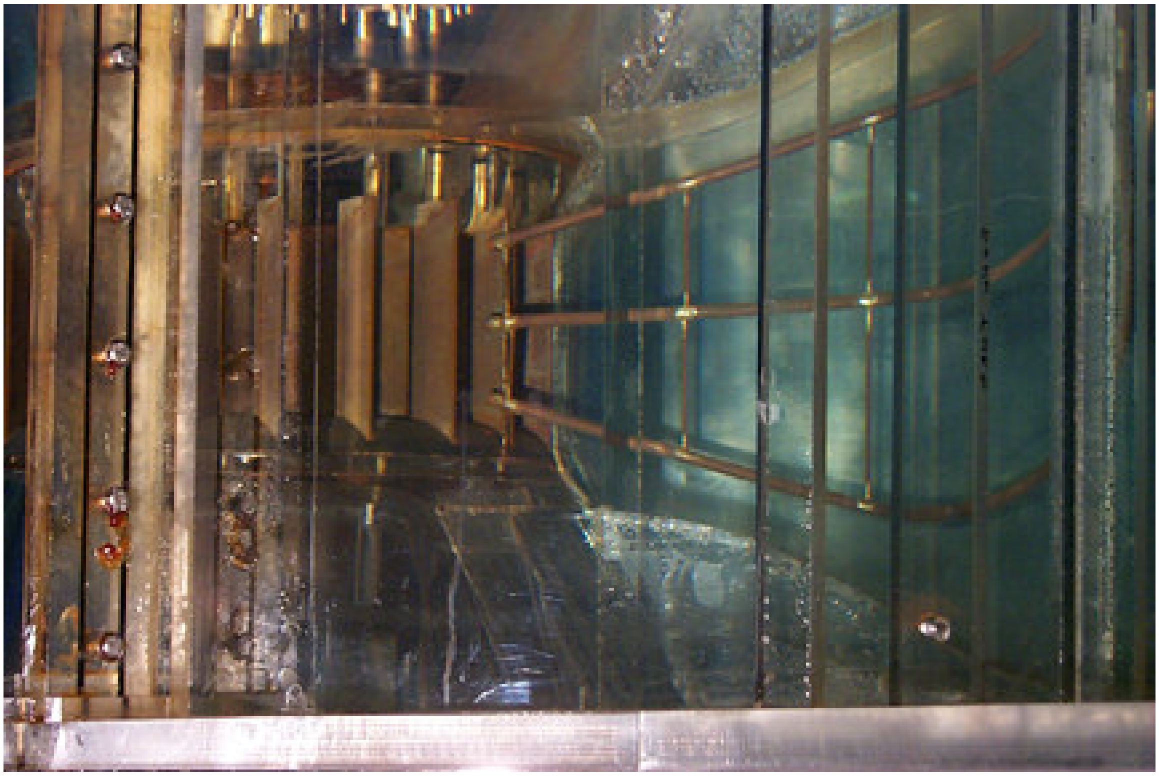


Figure 42. Bead release tubes used in the Bonneville model.

Low Discharge Side of One-percent Efficiency Drop for the Original Runner - Original Runner Bead Results. The model was set to represent a prototype turbine discharge of 6,207 cfs. Since these model experiments were being conducted at Froude-head, and had the same model to prototype scale as the McNary model, the scaling relationship between the model and prototype was the same as the McNary ERDC-WES turbine hydraulic model. The runner blade angle for this experiment was set at 13 degrees. The model head across the turbine represented a prototype head of 55.5 feet.

Beads released at the top release (hub release) were imaged as they passed through the turbine environment with two Red-Lake digital high-speed camera systems. The capture rate for these bead experiments was set at 1,000 frames per second. One camera was set under the model to capture the location of the bead passage. The other camera was set to obtain elevation view footage that would be used to determine strike and shear information for each bead. Numerous beads were released (approximately 250 beads) through the top release tube and were imaged in the turbine environment. Of the 250 beads, only roughly 100 were useful for analysis. When multiple beads are captured passing through the turbine at the same time, then they are not used for the analysis. This is to ensure that bead interactions are not affecting the paths of the bead. This was true for all Bonneville bead experiments. The position where they passed the runner blade was scaled from the digital file from the camera that was mounted below the turbine runner; these positions were then plotted. The beads had a scatter of approximately ¼ of the turbine diameter. The average distance between beads and the hub for this experiment was 14.4 inches. The maximum gap between the runner blade and the hub for this blade angle was 9.7 inches. This means that the average bead was not subjected to the gap at the hub for this release point at this operating point. In fact, only 32 percent of the beads passed within 9.7 inches of the hub.

Beads released from the mid-release (mid-blade) all passed near the middle of the blade; none of the beads passed through the hub or tip blade gaps.

Beads released at the bottom of the stay vane (blade-tip release) passed though the blades in a fairly confined area. The average distance from the bead to the tip of the blades was 13.7 inches. The maximum distance from the blade tip to the discharge ring for this blade angle is 2.1 inches. None of the beads passed through the gap area at the tip of the blades for this operating point.

Low Discharge Side of One-percent Efficiency Drop for the Original Runner - MGR Bead Results. The discharge for the MGR equivalent to the original runner's discharge at its low discharge side of the one-percent drop in efficiency was 6,207 cfs (based on average prototype settings). The blade angle for the MGR was set at 16.1 degrees. Beads released at the top of the stay-vane were imaged with the digital video system. The average bead passed at a distance of 22.8 inches from the hub. With the MGR there is not a gap between the blades and the runner hub. The beads were highly dispersed around the entire perimeter of the runner (Figure 43). In fact, the beads seemed to pass almost everywhere around the diameter of the runner. This would indicate a highly erratic and turbulent flow area in the vicinity of the MGR runner for this operating point. Several beads captured with an elevation view camera were observed to pass through the blades then stop, seemingly attached to the runner cone (rotating with the runner cone), then move vertically upward toward the runner blade. When they reached the runner blade they were pushed downward by the wake of the blade and then they finally moved into the draft-tube. This is an indication of unstable flow that results from the spherical runner hub. It should be noted that this operating point would be below the low discharge side of the one-percent drop in efficiency for the MGR, but is also an indicator that low discharges should be avoided with the MGR. Beads released at the top release for the MGR had a larger scatter around the perimeter of the turbine runner when compared to the original runner as well as passing at a greater distance away from the runner hub.

Beads released through the mid-release tube passed through the runner near the middle of the runner. This is comparable with the mid-release for the original runner.

The evaluation of beads released at the bottom of the stay vane indicated that the average bead released from this point would pass 17.4 inches away from the tip of the MGR runner blade. This is farther than beads released from the same location for the original runner (13.7 inches). Also, the beads passed through a larger area of the turbine for the MGR runner than the original runner. The gap for the MGR at this blade angle is not significant.

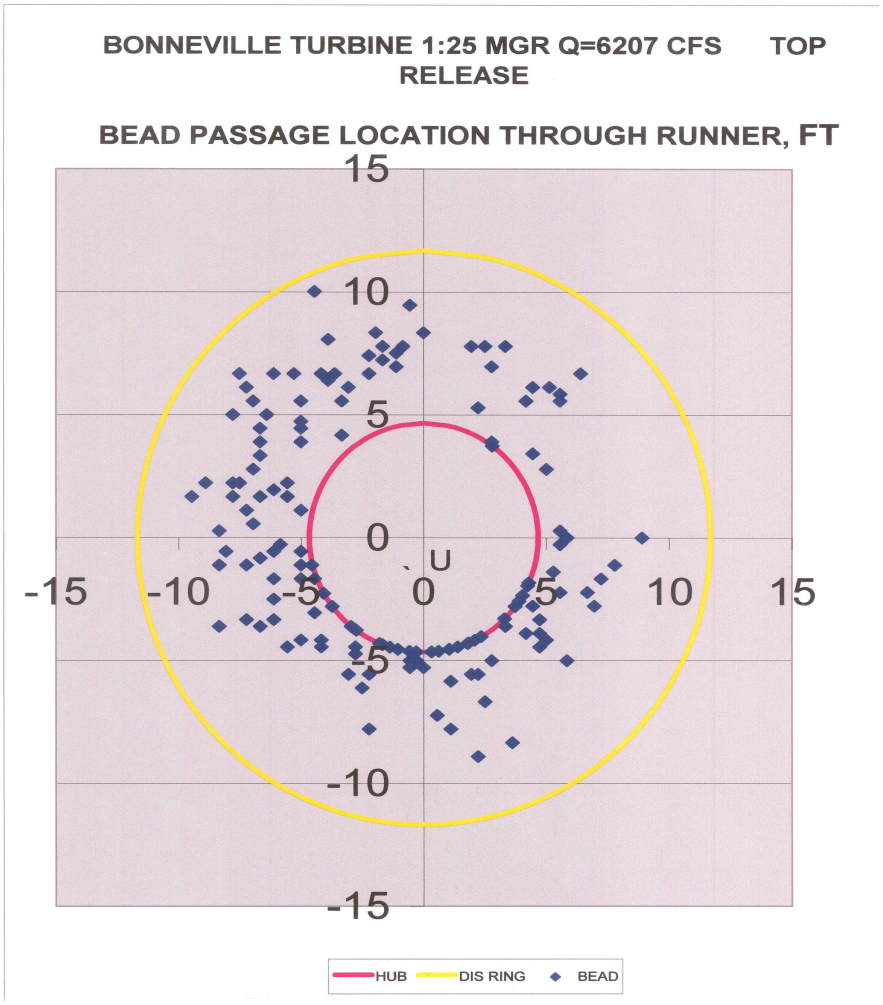


Figure 43. Bead distribution through the Bonneville runner for a hub release.

High Discharge Side of the One-percent Efficiency Drop for the Original Runner - Original Runner Bead Results. Based on average biological experiments conducted at the prototype structure, the model discharge was set at a discharge representing a prototype discharge of 12,110 cfs (high discharge side of the one-percent efficiency drop). The runner blade was set at 29.7 degrees. Beads were released through the top release tube. The average bead passed through the runner an average distance of 16.6 inches away from the hub. The maximum gap between the runner blade and the runner hub for this blade angle was 4.8 inches. The average bead would not be subjected to the gap area of the hub and blade. In fact only 16.6 percent of the beads passed within 4.8 inches of the hub. The beads were dispersed around ¼ of the perimeter of the runner.

The average bead released through the mid-release tube passed within 12 inches of the center of the runner blades and tended to be more toward the tip of the blade than the hub.

The beads released through the bottom release (tip of blade release), on average, passed within 8.4 inches of the tip of the runner blade. The maximum gap between the tip of the runner blade and the discharge ring for this blade angle is 8.4 inches. This would mean that the average bead released through the bottom release point for this operating point would have the opportunity to pass through the gap area at the tip of the blade. This does not mean that all beads passing within 8.4 inches of the discharge ring would pass through the gaps. Most of the beads would pass between the blades and not through the gap area. It does mean that the beads went where they were intended to go for this operating point. The beads also had a tight spread pattern as they passed the runner blades.

High Discharge Side of the One-percent Efficiency Drop for the Original Runner - MGR Bead Results. A turbine loading of 11,690 cfs was the MGR discharge that matched the average discharge that occurred during the prototype biological experiment of the MGR operating point. This point would be compared to the original runner at its high discharge side of the one-percent efficiency drop operating point. The MGR runner blade angle was set at 27.1 degrees. Beads that were released through the top release tube were observed to have a similar spread through the runner when compared to the similar operating point of the original runner. The average bead passed through the runner at a distance of 16.3 inches from the MGR runner hub. This is comparable to the original runner. There is not a gap between the runner blade and the MGR hub for this blade angle.

Beads released through the middle release tube passed near the middle of the runner blade. This was also comparable to what was observed at the similar operating point for the original runner.

The maximum gap between the tip of the blades and the discharge ring for this blade angle is 2.7 inches. No beads passed within 2.7 inches of the discharge ring. This means that the majority of the beads would not pass through the gap area at the tip of the blades. The average bead released from the bottom release tube passed through the runner at a distance of 20.6 inches from the tip of the blades. The spread of the beads for this operating point was similar for the MGR when compared to the original runner. However, the beads for the original runner, on average, passed much closer to the tip of the runner blades than for the MGR.

Low Discharge Side of the One-percent Efficiency Drop for the MGR - MGR Bead Results. The discharge through the model was set at 6,908 cfs for an MGR blade angle of 16.1 degrees at a head of 57.8 feet. This model set-up simulates an average experimental condition that existed during the biological verification of the low discharge side one-percent efficiency drop for the MGR. The average bead released near the top of the stay-vane (top-release) passed at a distance of 28.6 inches from the hub surface. The MGR does not have a gap at the hub. This distance is well outside the average target distance of 12 inches from the hub. The beads were highly dispersed around ¾ of the diameter of the runner.

The average beads released through the middle release tube passed 14.6 inches from the center of the MGR blades (toward the tip). However, this would still pass the beads away from the tip of the blades and the hub area of the MGR. The beads were dispersed around ¼ of the diameter of the runner.

Beads released through the bottom release tube (on average) passed within 11 inches of the tip of the runner blade. This meant the average bead passed through the area in which they were intended. The beads were dispersed around ¼ of the diameter of the runner. The gap between the runner blade and the discharge ring was on the order of 0.375 inches at this blade angle.

Low Discharge Side of the One-percent Efficiency Drop for the MGR - Original Runner Results.

With the original runner in place, the turbine discharge was set at 7,149 cfs for a runner blade angle of 15.7 degrees. The head across the turbine was set at a prototype equivalent head of 55.7 feet. This model condition would represent the average conditions encountered in the prototype biological experiments with the original runner that corresponded to the low discharge side of the one-percent efficiency drop for the MGR.

Numerous beads were released (approximately 250 beads) through the top release tube and were imaged in the turbine environment in a manner described in previous paragraphs. Again, of the 250 beads, only around 100 were useful for analysis. The average distance from the original runner hub to the beads passing for this release was 3.0 inches. This meant that the majority of the beads passed close to the hub and had an opportunity to pass through the hub gap, which is 9.1 inches at this blade angle. Fifty-five percent of the beads passed within 9 inches of the runner hub. This does not necessarily mean that the beads passed through the gaps, but that they passed through the area of the hub where the blade-to-hub gaps exist. Most of the beads passed through this region between the blades away from the gaps. The beads were dispersed around ¼ of the diameter of the runner.

The average bead released through the mid-release tube passed within 9.5 inches of the middle of the runner blade.

Beads released through the bottom release tube (tip-release) passed, on average, within 12 inches of the tip of the runner blade. This was approximately the position that was targeted. The gap between the tip of the runner blade and the discharge ring is approximately 2.5 inches at this blade angle. None of the beads released passed through this area.

High-discharge Side of One-percent Efficiency Drop for the MGR - MGR Bead Results.

The high-discharge side of the one-percent efficiency drop for the MGR was biologically evaluated in the field. The average discharge and blade angle used during this evaluation was 10,351 cfs and 24 degrees. These conditions were reproduced in the model for an equivalent head across the turbine of 54.9 feet. Beads were released at the entrance to the stay-vane at three release points. These release points have been identified in earlier paragraphs.

The beads released through the top release tube passed at an average distance of 20.4 inches from the hub. This is farther than the desired 12 to 14 inches. Only 20.8 percent of the beads passed within 12 inches of the hub. There is not a gap between the MGR runner blade and the hub. Therefore, it was not possible to pass beads or fish through a non-existent gap.

The average beads released through the middle tube passed within approximately 3 inches of the center of the runner blades.

Fish were released through the bottom release tube during prototype experiments to examine the effects of gaps at the tip of the blades on injury rates caused by the flow conditions in this area. The maximum gap between the tip of the runner blade and the discharge ring for this blade angle is approximately 2 inches. Of the beads released through the bottom release tube in the model, 24.7 percent passed within 2 inches of the discharge ring. The average bead passed within 7.2 inches of the discharge ring and 80.6 percent passed within 12 inches. This indicated that the bottom release tube for this operating point (MGR) would probably put fish into the desired area to evaluate the tip of the MGR blade region.

High-discharge Side of One-percent Efficiency Drop for the MGR - Original Runner Results. The average prototype discharge, with the original runner in place to simulate the high discharge of the one-percent efficiency, was 10,809 cfs and occurred at a blade angle of 24.9 degrees. These conditions were reproduced in the model with an equivalent head across the turbine of 54.7 feet.

Beads released through the top release tube were captured and their position was obtained from digital video files. The average distance of the bead in relation to the runner hub was calculated to be 16.6 inches. The maximum gap between the runner blade and the runner hub is approximately 6 inches for this blade angle. Only 13.6 percent of the beads were determined to pass within 6 inches of the hub and 38.8 passed within 12 inches. This indicated that the top release position for this operating condition did not put fish in the proper location to evaluate fish passing through the hub-gap area.

Beads released through the middle tube tended to pass near the mid-point of the runner blade.

Beads released through the bottom tube had a consistent and confined area where they passed through the runner. The bead spread was only about 1/8 of the runner diameter. The average bead passed within 9 inches of the blade tip. This is within the targeted 12 inches. In fact, 75.7 percent of the beads passed within 12 inches of the discharge ring. However, only 14 percent of the beads passed within 6.5 inches of the discharge ring surface. The maximum gap between the runner blade and the discharge ring for this blade angle is approximately 6.5 inches. This would indicate that even though the beads passed through the targeted area, very few would have the opportunity to pass through the blade-tip gap. Of the 14 percent that passed though this area, most would pass through the area between the blades and not through the gaps themselves.

2.6.3 Summary and Findings of the Bonneville First Powerhouse Turbine Model Studies

A high-head turbine performance model study was conducted to support the rehabilitation of the existing prototype turbines. During this study a decision was made to investigate a runner design that would eliminate or minimize gaps that occur between the tip of the blades and the discharge ring and the blade and the runner hub. Minimizing gaps would reduce the potential for injuring fish passing through tip and hub regions of the turbine. A MGR design was completed and a prototype MGR was installed in Unit 6 at Bonneville Dam. As a part of the deployment of the MGR they would have to be biologically evaluated to ensure they were at least as safe for passing fish as the existing runner. This evaluation took place during 2002 when both the existing runner and MGR were biologically evaluated.

To perform the biological evaluation of the MGR, fish would need to be released at certain locations that would potentially pass fish through specific locations in the turbine. A model of one intake unit of the First Powerhouse had previously been constructed at ERDC-WES to investigate fish bypass screens and surface collectors. This model reproduced the intake structure down to the wicket gate and stay-vanes. It did not have an operating turbine or draft-tube. Through bead experiments, this model was used to locate release points at the stay-vane and wicket gates that would potentially put fish near the tip of the blades, middle of the blades and near the runner hub.

The effects of not having a turbine on the bead path were a concern. The existing model was rebuilt and an operating model turbine (both existing runner and MGR) and draft-tube was included in the new model. This was done after the 2002 biological tests were completed. Bead experiments were conducted in the model to determine what zones of the runner the fish were exposed to during the 2002 biological tests. Results from the model indicated that fish released to pass through the mid-blade region should have passed through the mid-blade region of the prototype turbine for both runner types. For the other blade-tip release and hub release there was less success in passing beads through the desired area. Higher discharges passed more beads near the tip of the blades.

Observed flow through the draft-tube was highly turbulent. This was especially true for low discharges where the flow was observed to be erratic with reverse flow occurring in both barrels of the draft-tube. Reverse flow from the draft-tube barrels to the trailing edge of the runner at the hub was observed for the MGR. Flow within each draft-tube barrel was uneven. Additional investigations of the draft-tube should be conducted to evaluate the interaction of beads with the draft-tube splitter piers and the influence of the erratic and uneven flow on fish survival. From the ERDC-WES model investigations it appears that the draft-tube conditions will improve if the turbine is operated at high discharge.

2.7 Conclusions

2.7.1 Use of Physical Hydraulic Models in Support of Biological Studies

Physical hydraulic models of the McNary, Lower Granite, and Bonneville turbines have been successfully used in support of biological studies of the prototype turbine units. They are necessary to establish targeted operating conditions and appropriate release locations of test fish, and in the analysis of the biological test results. These models are necessary to fully understand the geometric and hydraulic conditions that result from turbine operations and to identify the operations and conditions that are favorable or unfavorable for fish passage. The inclusion of both types of hydraulic models should be required in the development of future turbine rehabilitation plans for the Region. The ERDC-WES (low-head Froude) hydraulic models constructed of clear acrylic plastics allow for visual observation of flow through the entire turbine environment including the intake, scroll case, stay-vane wicket gate assemblies, cascade, runner and draft-tube. The visual observations combined with a method of analyses using LDV measurements and high-speed digital imaging are important to the biological evaluation of existing turbine units and for the design of fish passage improvements. The LDV measurements provide velocity magnitude, direction, flow distribution, velocity gradients and turbulence intensity. Analyses using high-speed digital imaging of neutrally buoyant beads are used to define and classify bead path as well as interaction of beads with turbine structure and regions of extreme hydraulic conditions.

2.7.2 Use of Physical Hydraulic Models for Design of Turbine Improvements

Both the high-head (Reynolds) and low-head (Froude) turbine models are necessary to design turbines with improved power performance and safer fish passage. Design improvements for safe fish passage will most likely result in increased turbine performance efficiency. Likewise improvements for turbine performance will most likely result in fish improvements. These models are used to evaluate any potential improvement without the high cost of prototype testing and design by trial and error. Any number of design alternatives can be evaluated for potential fish passage improvements as well as performance improvements. Through an iterative approach, an optimum design for both fish passage and performance can be developed. Using the models to evaluate existing conditions will help to identify potential design improvements, which can then be incorporated into both models to determine potential benefits.

2.7.3 Conclusions from the TSP Phase I Hydraulic Model Investigations

Conclusions derived from the physical hydraulic model investigations conducted throughout the course of the TSP Phase I study are identified below. They are in a numerical order for reference only, not to imply any order or importance.

Conclusions from the ERDC-WES hydraulic models include:

1) Flow conditions downstream of the turbine intake screens are highly turbulent and significantly impact the distribution of flow as it enters the scroll case, and as it approaches the wicket gate/stay-vane cascade. The head losses created by the screens as well as the non-uniform distribution of flow reduce turbine efficiency.

2) The influence of the disrupted flow caused by the intake screens on fish survival has not been determined. There is a potential for fish to be caught in reverse flow along the intake ceiling downstream of the screens, and for the fish to be more vertically distributed as they approach the wicket gates, possibly subjecting more fish to the blade tip region.

3) Small neutrally buoyant beads provide an excellent method of investigating the conditions through the turbine unit. They can be used to identify areas of concern and to evaluate potential turbine improvements, such as improvements to the stay vane-wicket gate assembly, runner blade and draft-tube.

4) High-speed digital imaging has been successfully used to capture and evaluate bead passage through the ERDC-WES model turbines.

5) A significant number of beads contact surfaces during their passage through the wicket gate cascade, runner region and draft-tube. The majority of those bead contacts are not severe and may not imply fish injury.

6) Beads released from a single point at the stay-vane have a widely variable path through the runner.

7) Operation of the Bonneville MGRs at low discharges should be avoided. Beads were observed to pass through the runner into the draft-tube elbow and then back upstream to the runner blade region. This is not necessarily an indication of direct mortality but may have an effect on indirect mortality.

8) With low turbine discharges flow becomes less streamlined and more turbulent in the turbine environment. The environment from the entry to the stay vane-wicket gate cascade to the leading edge of the turbine runner blades is more turbulent. These conditions may result in increased retention time and the potential injury to fish.
9) Model observations indicate fish may spend as long as one revolution of the runner within the immediate runner environment with low discharge operations.
10) Flow conditions within the draft-tube are variable and turbulent. Lower discharges impart more variability as well as reverse flow within the draft-tube.
11) For turbine units that have been studied, operating within the one-percent zone as required by the BiOp imparts an unequal flow distribution between the draft-tube barrels with a non-uniform distribution of flow through the individual draft-tube barrels.
12) Operating turbines at high discharge results in a more balanced flow distribution between draft-tube barrels and a more uniform flow within each draft-tube barrel.
13) Bead investigations have shown a significant number of beads are exposed to the gap between the stay vanes and wicket gates. These beads can experience extreme turbulence, shear and impact with the stay-vane and wicket gate.
14) Streamlining the stay vane and wicket gate configuration by modifying the leading and trailing edge of the stay vane reduces flow separation and turbulence. It also reduces the potential for and severity of bead strike.
15) Minimizing the gap between the stay vanes and wicket gates can significantly reduce or eliminate the potential for beads to pass through the gap under specifically designed operating ranges.
16) The draft-tubes can be structurally modified by asymmetrically raising the draft-tube floor and/or with installation of horizontal flow splitter piers to improve flow conditions for fish. Draft-tube extensions can be added to reduce the backroll eddy to improve fish egress conditions.

Conclusions from the turbine performance model testing include:

1) Reynolds performance models and Froude performance models develop different velocity profiles downstream of the intake screens.
2) Turbine performance cam curves developed from Froude models with screens in place, match prototype cam curves (developed from index testing) better than cam curves developed from Reynolds model testing.
3) Streamlining the stay vane and wicket gate configuration by modifying the leading and trailing edge of the stay vane, and minimizing the gap between the stay vane and wicket gates will increase turbine efficiency.
4) Draft-tube modifications that streamline flow can increase turbine efficiency.
5) Draft-tube extensions can increase turbine efficiency.
6) Surface finish improvements can increase turbine efficiency.
7) Draft-tube stop log closure can increase turbine efficiency.

Section 3. Engineering Studies

3.1 Engineering Introduction

The engineering evaluation of turbine fish passage encompassed a wide range of efforts to investigate Kaplan turbine designs for causes of fish mortality. These efforts have focused primarily on the turbine environment and direct mortality components. Initial work endeavored to establish or develop tools to probe the turbine and its water passage to determine potential causal agents for direct turbine passage mortality. In coordination with biologists, the turbine environment was investigated to examine if the potential causal agents were quantifiable. The studies conducted under this program are combined with complementing studies, performed under other programs, to investigate the possibility of improving turbine fish passage and turbine design.

The primary areas of investigation consisted of model and prototype studies, which centered on developing measurement tools for evaluating operational improvements, flow measurement, biological testing design, turbine runner designs, turbine geometry, and the effects of modifications to existing turbine designs on turbine performance. The detailed information and data are contained in Appendix A (Prototype Studies) and Appendix B (Performance Model Studies), and results are provided in this Section. As efforts of the TSP program provided information on turbine operation and the biological effects of that operation or condition, actions have been taken to implement improvements in the Corps' mainstem powerhouses. These actions have primarily consisted of operational improvements to turbine mechanical operation to achieve the requirements of the one-percent efficiency operating limits. The challenge of the variability of the turbine designs and hydraulic operating conditions, along with environmental requirements, has resulted in investigations into multiple areas not normally considered valuable in the turbine industry. These investigations have resulted in improvements in turbine fish passage and provided guidance for Phase II of the program.

3.2 Evaluation of the Turbine Passage

3.2.1 Background

Most of the direct injuries detected on turbine passed fish appear to be mechanically related. These types of injuries result from severe strikes upon the turbine structures or pinching between moving components. There is also evidence that the hydraulic conditions, such as hydraulic shear and turbulence, have an effect on fish passage mortality and injury. Investigations in the turbine modeling performed under this and other programs have provided insights into the internal conditions of turbine operation and fish passage.

3.2.1.1 Strike

Fish may strike or impact a stationary or moving component in the turbine. It is also possible that a moving component of the turbine runner can impact a passing fish. The following paragraphs describe possible locations of strike within a turbine and its water passage.

Intake. Inflow conditions can present flow characteristics, which may induce direct injury. Inflow conditions from the pool through trash racks and fish screens can be affected by adjacent unit operation, ice, and trash, which create flow conditions that may position fish in dangerous locations. Model studies indicate that trash racks and their supports pose obstacles that may cause direct injury. Flow turbulence and distribution downstream of the fish screens may have zones that are detrimental to fish passage.

Scroll Case. Flow entering the scroll case from the intake is redistributed and begins to normalize. Model studies indicate that, other than access holes, projections or gratings in the prototype, there appear to be no apparent direct injury locations beyond the fixed boundaries of the water passage. At some low flow conditions within the one-percent operating limitation, dead zones may develop where fish can hold (or become entrained) for extended periods of time. It is unknown if these dead zones are detrimental to fish. The crotch or baffle section of the scroll case creates an unstable zone because water enters from two intake bays at somewhat different angles. Under these conditions, fish have some ability to control and vary their path toward the turbine.

Stay Vane-Wicket Gates. Often called the distributor, the stay vane wicket gate cascade presents cross-sectional areas and shapes that can injure fish. The water flow is accelerating and turning to enter the turbine runner chamber. The flow entering the smallest plane between the wicket gates is generally at constant velocity regardless of the wicket gate opening. The wicket gates move and the openings between them vary while the stay vanes remain in a fixed geometry. There are also clearance gaps between the stay vane trailing edge and the leading edge of the wicket gates. These gaps are affected by the position or opening of the wicket gates. Modeling studies have indicated that the stay vane wicket gate cascade has a high potential for strike and abrasion. Also noted is the existence of a flow disruption from the bottom of the wicket gate as it opens wide enough for the trailing edge to overhang the turbine runner blades; there is also a sharp edge on the bottom of the wicket gate. This area also appears to be a zone with high shear conditions. The wicket gate cascade presents the smallest individual water passage opening in the turbine. Once a juvenile fish enters the cascade, it has limited independent movement because the water velocity is increasing and its direction is changing. Figure 44 shows the cascade and potential areas of concern.

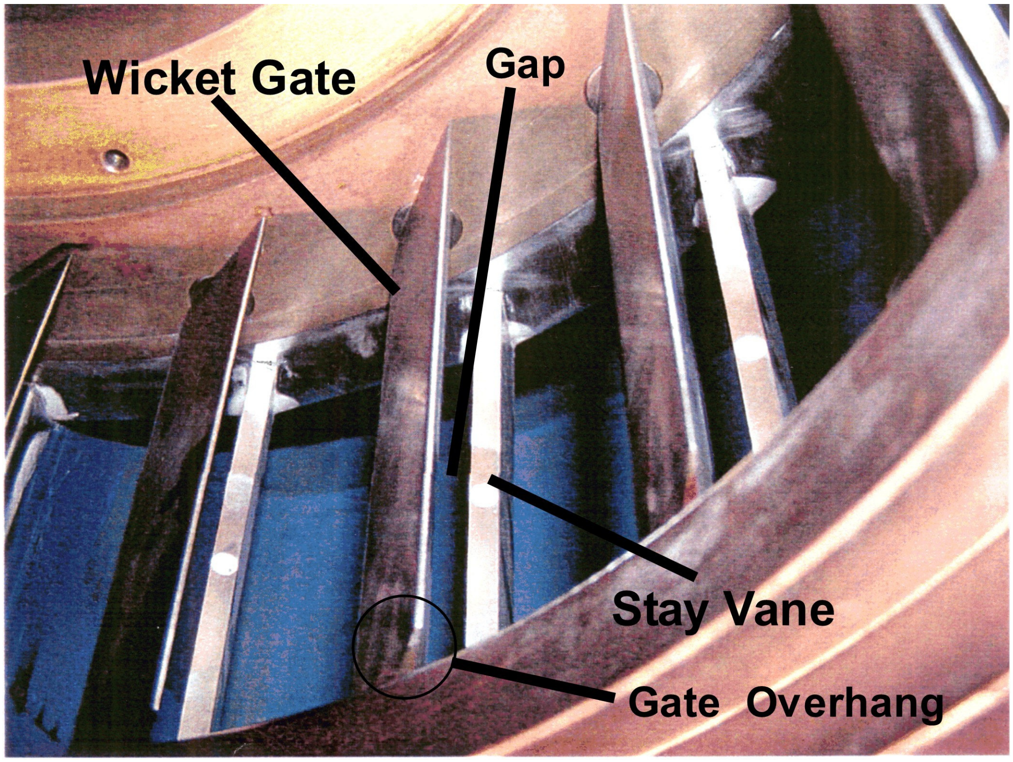


Figure 44. Model photograph of stay vane-wicket gate relationship.

Turbine Runner Chamber. The turbine runner, hub and cone are rotating while the turbine operates. Flow enters the runner chamber at an angle directed by the wicket gates and head cover on to the turbine runner blades that are angled to coincide with the direction of water flow. As the turbine runner rotates, it passes each of the wicket gate openings. Unstable flow through the wicket gates (poor distribution of flow to the runner) can cause pulsing and shear in the runner chamber. Modeling studies have indicated that sources of direct injury can include the runner blade leading edge, blade pressure surface, the clearance gaps at the periphery and hub as well as projections on the head cover. Flow entering a wicket gate opening may pass the turbine runner on the opposite side or make a rotational circuit depending on the point of entry. The axis of the turbine runner blade rotation presents the smallest total area for unit discharge and the fastest velocity. The velocity of the flow is sufficient (greater than 30 ft/sec) and the distance small enough, 8 to 10 feet, that fish have a very limited voluntary movement.

Under Runner. The pressure on the underside of the runner is relatively low, approaching half an atmosphere. The water flow has a twirl as it leaves the runner to prevent flow separation from the discharge ring and draft-tube throat. Cavitation may occur in this area and can take several forms. Cavitation can occur on fixed and rotational components and there may be leakage at the gaps; surface cavitation may not be attached to a surface at all. Model studies have indicated that cavitation does not appear to directly cause injury since the turbines are not operated in a cavitation zone. They have also indicated the twirl may consist of turbulence and shear forces that can twist and turn fish, disorient or cause impacts and abrasion with fixed surfaces because of centrifugal forces.

Draft-tube Elbow. The draft-tube elbow presents some risks of impact with the structure, shear and a turbulent condition, which may result in direct injury. It is also possible that fish may experience disorientation in this region. The water flow is changing direction from a vertical orientation to a more horizontal orientation. The water is decelerating, recovering velocity head and creating a zone in which pressure is beginning to return to atmospheric. Depending on the turbine operating condition, the changes occurring can be chaotic to smooth. In general, discharge tends to be smoother at higher, rather than lower turbine discharges. Turbulence and twirl can be both large scale and small scale with zones of varying turbulence depending on the flow distribution to the turbine runner. It is also possible that a vortex or rope can occur with zones of low pressure, shear, and turbulence. The potential for fish striking or contacting rough surfaces exists. The turbine runner and draft-tube are linked in a design. The two must work well together or poor conditions such as pressure pulsations, flow separation, and unbalanced flow may result. This component is also examined closely in a turbine performance model to ensure that flow separations and severe shear zones are avoided.

Draft-tube Barrels. The draft-tube barrels form a transition from the draft-tube elbow to the tailwater environment. In large turbines, such as in the Columbia River system, the draft-tubes are large and require structural support by the use of a splitter pier that divides the draft-tube into two barrels. The cross-sectional areas are increasing, which allows the discharge to decelerate to the exit area and tailwater. Typically, a maximum velocity of 8 ft/sec at the exit is expected under high flow conditions, however, substantially higher velocities can exist in certain segments of the draft-tube depending on the turbine operating point. (See Figure 29) The draft-tube is normally designed for optimum performance at high flow conditions. The geometry changes from a round shape at the discharge of the turbine to a rectangular shape in the draft-tube barrels. The draft-tube exit must be submerged to provide sufficient backpressure to reduce the potential for cavitation. Possible direct injury could result from impact with rough surfaces and abrasion, large or small-scale turbulence, or shear conditions. Fish may experience reverse flow conditions and may get entrained in the stop log slots used to dewater the draft-tube for repair or inspection, or in dead areas where velocity is low. The floor of the draft-tube normally has piezometric relief holes to relieve uplift pressures under the powerhouse structure. These pipes may project into the draft-tube posing potential impact obstacles. Draft-tube surging or pulsing can occur if an unequal flow distribution exists between the barrels is present. The design and length of the draft-tube was defined in the initial design of the powerhouse structure without considering fish passage.

3.2.1.2 Cavitation

It has not yet been proven that cavitation of the turbine runner results in direct injury or mortality. Although turbines are designed to operate under normal conditions without cavitation, a biological test was conducted of a Lower Granite turbine unit intentionally operating within a cavitation zone. This test did not reveal any unusual biological results when compared to other operating conditions. However, there may be localized cavitating areas, such as at the runner blade clearance gaps or discharge ring, which pose a hazard. Cavitation may be more of a concern as gas saturation levels increase due to spill through the dam spillways. It is not known, but cavitation may have more effects on indirect fish passage than direct injury.

3.2.1.3 Gaps

Kaplan turbines have clearance gaps on the leading and trailing edge of the runner blades at both the periphery and at the hub to allow runner blade movement. The maximum gap at the blade periphery occurs at the maximum runner blade angle and the maximum hub gap occurs at the minimum runner blade angle. Appendix A.3.2 provides gap measurements of various turbines that have been recorded as part of this program. Provided in Figure 45 is an illustration of the location of the measurements; there is also an example (Table 12) of the gaps for the Bonneville First Powerhouse Unit 6 MGR in various positions of the runner blades for the biological testing. In Figures 46 and 47, photographs of the periphery of the blade at the maximum blade angle are provided to demonstrate the size of the opening. These gaps are thought to provide a zone where fish may be killed or injured.

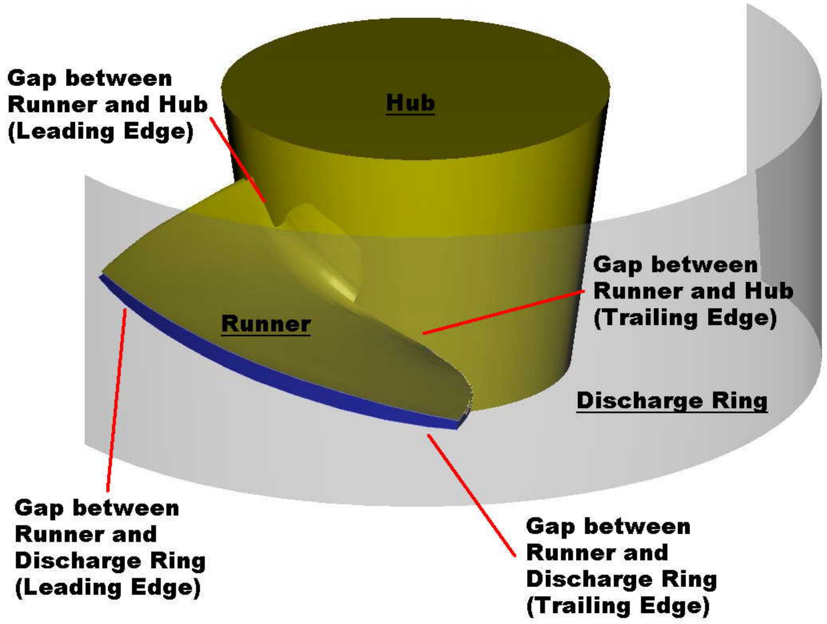


Figure 45. Anatomy of a runner blade.

Measured gaps between the blade and discharge ring of Bonneville Unit 6 with Minimum Gap Runner installed.

FLAT (As Measured)		STEEP (As Measured)		CONDITION #1		CONDITION #2		CONDITION #3		CONDITION #4	
16.01 Blade Angle		31.21 Blade Angle		16.1 Blade Angle		16.3 Blade Angle		24.2 Blade Angle		27.6 Blade Angle	
Distance from Leading Edge (inches)	**Gap Measurement (inches)**	**Distance from Leading Edge (inches)**	**Gap Measurement (inches)**	**Distance from Leading Edge (inches)**	**Gap Measurement (inches)**	**Distance from Leading Edge (inches)**	**Gap Measurement (inches)**	**Distance from Leading Edge (inches)**	**Gap Measurement (inches)**	**Distance from Leading Edge (inches)**	**Gap Measurement (inches)**
0	0.25	0	3.375	0	0.27	0	0.31	0	1.93	0	2.63
4	0.23	4	2.5	4	0.25	4	0.28	4	1.45	4	1.96
8	0.21	8	1.5	8	0.22	8	0.24	8	0.91	8	1.19
12	0.20	12	0.875	12	0.20	12	0.21	12	0.56	12	0.71
16	0.18	16	0.375	16	0.18	16	0.18	16	0.28	16	0.33
20	0.16	20	0.25	20	0.16	20	0.16	20	0.21	20	0.23
24	0.14	24	0.1875	24	0.14	24	0.14	24	0.17	24	0.18
28	0.125	28	0.1875	28	0.13	28	0.13	28	0.16	28	0.17
32	0.125	32	0.125	32	0.13	32	0.13	32	0.13	32	0.13
Dist from Trailing Edge (inches)	**Gap Measurement** (inches)	**Dist from Trailing Edge** (inches)	**Gap Measurement** (inches)	**Dist from Trailing Edge** (inches)	**Gap Measurement** (inches)	**Dist from Trailing Edge** (inches)	**Gap Measurement** (inches)	**Dist from Trailing Edge** (inches)	**Gap Measurement** (inches)	**Dist from Trailing Edge** (inches)	**Gap Measurement** (inches)
0	0.375	0	3.375	0	0.39	0	0.43	0	1.99	0	2.66
4	0.25	4	3.25	4	0.27	4	0.31	4	1.87	4	2.54
8	0.23	8	2.875	8	0.24	8	0.28	8	1.65	8	2.25
12	0.21	12	2.25	12	0.22	12	0.25	12	1.31	12	1.77
16	0.19	16	1.875	16	0.20	16	0.22	16	1.10	16	1.47
20	0.17	20	1.5	20	0.17	20	0.19	20	0.89	20	1.18
24	0.15	24	1	24	0.15	24	0.16	24	0.61	24	0.80
28	0.125	28	0.75	28	0.13	28	0.14	28	0.46	28	0.60
32	0.125	32	0.625	32	0.13	32	0.13	32	0.39	32	0.51
36	0.125	36	0.375	36	0.13	36	0.13	36	0.26	36	0.32
40	0.125	40	0.25	40	0.13	40	0.13	40	0.19	40	0.22
44	0.125	44	0.1875	44	0.13	44	0.13	44	0.16	44	0.17
48	0.125	48	0.125	48	0.13	48	0.13	48	0.13	48	0.13

* The minimum gap runner does not have a measurable gap between the blade and the hub

Table 12. Blade gap measurements. (Bonneville MGR – see Figure 56)

Figure 46. Leading edge gap at the maximum blade angle.

Figure 47. Trailing edge gap at the maximum blade angle.

3.2.2 Turbine Design Studies

As mentioned previously in Section 2.1, Phase I of the TSP included investigative work using three different model techniques: performance testing, ERDC-WES model testing and numerical model testing. This section discusses the performance model tests conducted under the TSP and other regionally coordinated programs to help design equipment for use in biological field tests and to make improvements in turbine design.

3.2.2.1 Turbine Performance Model Testing

During Phase I, results of turbine performance model tests (Appendix B) were incorporated into the turbine hydraulic modeling at ERDC-WES. Data obtained from these tests were also used to develop prototype test plans for the Phase I engineering and biological field-tests at McNary and Bonneville. The performance model testing of the McNary model was completed and the actual model is now being used to support the development and selection of a potentially new turbine runner for McNary. The Lower Granite and Bonneville First Powerhouse model testing is also completed and the models have been placed in storage.

Turbine performance modeling has indicated that modeling turbine performance at Froude conditions is very difficult and has less accuracy in performance measurements than normally accepted in the turbine industry. The flow profiles measured under high-head conditions in the performance test stand matched well with the flow profiles measured at ERDC-WES for test conditions without fish screens. However, when diversion screens are placed into the intake, the velocity profiles downstream of the screens are different (between the two performance modeling techniques) indicating that the two different modeling techniques deliver different flow conditions at the entrance to the turbine. This is discussed in Section 2 in more detail. Cavitation evaluation at Froude conditions is not possible and is normally performed under high-head Reynolds turbine modeling conditions. Turbine design alterations may be evaluated for turbine performance effects in the high-pressure (Reynolds) models; this evaluation is the standard accepted by industry. However, if diversion screens will be used in the intake structure, low-head performance modeling techniques could be used to evaluate the effect of the screens turbine performance and to develop cam curves with prototype index testing to verify the cam curves. The potential biological benefits of these alterations may also be evaluated in the low-head (Froude) hydraulic models at ERDC-WES. The models are related in engineering terms for performance, but it is not yet known if the biological evaluation is transferable to a prototype. It is clear that potential benefits to improved fish passage can result from these modeling investigations and should be undertaken for all CRFM program projects related to turbine passage and installation of fish diversion devices.

Programs other than the TSP have funded the construction of the hydraulic turbine models tested. These other efforts have had various purposes, many of which are related to this program.

3.2.2.1.1 McNary Turbine Performance Model Testing

McNary turbine performance model testing began in 1993 to determine the affect of fish diversion screens on turbine performance and to develop new cam curves for operations with the intake screens in place. This would be done through comparisons of the low-head (Froude) and high-head (Reynolds) model techniques to prototype measurements. Turbine performance modeling is traditionally performed under high-head conditions to emulate prototype hydraulic conditions for head, power, flow and efficiency, whereas Froude modeling is done in hydraulically-scaled conditions. Vast improvements in instrumentation technology allowed consideration of turbine performance model testing to be done at Froude conditions. This permits the evaluation of turbine performance in addition to comparisons of hydraulic conditions. A turbine performance model was built based upon actual field measurements and a duplicate turbine runner was manufactured and provided for testing the ERDC-WES model. Both models were built to the same 1:25 scale. A model test was performed to duplicate the prototype index test of McNary Unit 5 and the results were duplicated within measurement accuracy.

3.2.2.1.2 Lower Granite Turbine Performance Model Testing

The positive results of the pilot McNary model testing resulted in the decision by Walla Walla District to perform turbine performance model testing under Froude and Reynolds conditions on a Lower Granite model. This testing was designed to be more definitive in comparing the two turbine performance-modeling techniques. This testing was also to investigate the effects of surface collectors on model turbine performance. The success of the performance modeling encouraged other investigations of turbine performance with design modifications and other investigations. The success of the prototype Bonneville First Powerhouse MGR and the ERDC-WES Lower Granite hydraulic model investigation encouraged additional modeling investigations into: relative flow measurements, draft-tube modifications, MGR designs, operational changes, stop log slot closure effects, CFD analysis and stay vane to wicket gate relationships and design. The three separate model tests indicated the importance of careful design analysis for both turbine performance and environmental improvements in future Powerhouse Rehabilitation programs. Others provided the primary funding for these efforts.

3.2.2.1.3 Bonneville First Powerhouse Turbine Performance Model Testing

Performance model testing of the Bonneville replacement turbine runner was performed and funded in 1997 as part of the Bonneville Powerhouse Major Rehabilitation Program. The purpose of this testing was to confirm that the design proposed by the contractor met contractual requirements for turbine performance. During this period advances in turbine design were taking place and this program recognized potential improvements for fish passage that could be applied. A proposal was made to the Portland District by HDC to investigate an alternate turbine runner design incorporating design features which reduced the clearance gaps of the runner blades, reduced the operating range of the turbines, incorporated a spherical discharge ring and altered the shape of the runner hub and cone. These were model tested with significant improvements in performance (approximately 1 to 2 percent in efficiency) near the best operating points but with reductions in performance at higher power levels. Additional tests were performed to evaluate the effects of fish screens and some testing was performed to attempt to replicate Froude hydraulic modeling conditions. This attempt was only marginally successful because the model was not designed to accommodate this type of testing. These investigations resulted in the installation of the modified turbine runner called the MGR. See Section 3.2.1.6.1 for more discussion and information. The design was field-tested and proven both for turbine performance and fish passage.

3.2.3 Related Engineering Studies

The following studies were conducted to improve both the power and biological performance of Kaplan turbines. They were coordinated with the TSP, but were not funded by the CRFM program.

3.2.3.1.1 MGR Studies

The clearance gaps of the Kaplan turbine units have been identified as a potential cause for fish injury and mortality. Engineering investigations of the gaps were undertaken to evaluate the significance of the gaps at the turbine runner periphery and at the runner hubs. Four turbine designs were examined for the potential of gap closure and effects on turbine performance. The blade rotation angle, perpendicularity of blades to the centerline of shaft rotation, and minimum blade operating angle each affect the size of the gap and the engineering necessary to affect a change in the geometry to reduce the gap. Model turbine runners were redesigned with smaller gaps and tested to determine the effect on turbine performance. See Appendix B.3 for more detailed information. Figure 48 presents the results of the model design investigations to date, reduced to the same conditions to be comparable. It is clear that a progression in turbine design improvements incorporating MGR features has occurred. The potential improvement in juvenile fish passage is, as yet, unproven for all the design features, however, the Bonneville First Powerhouse 1999 biological evaluation of the MGR 1st generation design indicated (see Section 4.1.1.3) fish passage benefits.

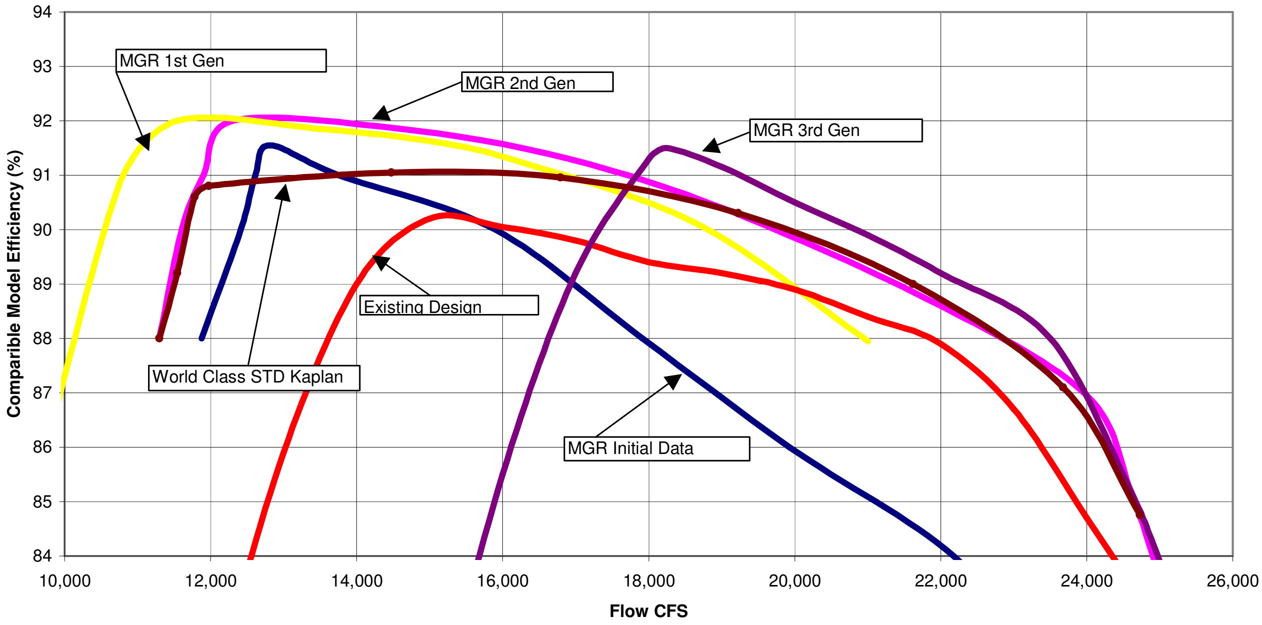


Figure 48. Estimated efficiency curves comparison of MGR designs.

3.2.3.1.2 Draft-tube Modifications

Draft-tube design modifications have been used in the industry to improve turbine performance. The draft-tube is a key energy recovery component and as much as 15 percent of the energy produced results from a well-designed draft-tube. The extent of the modifications on existing structures has normally been limited to shape alterations by minimum removal of material and addition of filled-in areas or horizontal splitter piers. In the original designs of prototypes, the draft-tube and the runner designs were coupled as a unit. The typical design of draft-tubes provided the optimum water passage flow at high flow conditions. Performance model testing is necessary because of the complex and turbulent nature of flow in the draft-tube, especially at operating conditions away from optimum (part load).

ERDC-WES turbine model investigations indicated unsteady flow conditions existed in the part load operating range of the McNary, Lower Granite, and Bonneville models (see Section 2). There did not appear to be conditions that would cause a direct injury or mortality to fish, but the turbulence within the draft-tubes and the extent of the turbine boil at the exit of the draft-tubes may have a significant impact on indirect mortality caused by further disorientation of the fish and poor egress conditions leading to increased predation. Model studies were initiated to improve the draft-tube conditions both to provide a safer environment and improved egress for fish and to improve turbine efficiencies.

Alternatives investigated on the McNary and Lower Granite turbine models were changes to the geometry of the draft-tube. These changes centered on extending the draft-tubes to provide a more downstream-directed water velocity pattern. Results indicate turbine performance may increase, with the flow becoming more streamlined and more uniformly distributed within and between the draft-tubes. The effect on turbine performance for reshaping and extending the draft-tube of McNary is estimated to be a 1.5 percent turbine efficiency improvement. The two draft-tube modifications/extensions of the Lower Granite model testing indicated a performance improvement of about 0.5 percent at higher flow conditions without closure of the draft-tube stop log slots. Closure of the Lower Granite stop log slots indicate a turbine performance improvement of about 0.3 percent in turbine efficiency near the best operating point of the turbine. Figure 49 below presents the results of the McNary model studies for two different draft-tube modifications, and indicates improvements in turbine performance and possibly fish passage can result from draft-tube modifications; however, the effects of adjacent unit operation confound the effect of the modifications. Appendix B.4 contains more detailed information.

The alteration or modification of the draft-tube and exit can significantly alter the downstream flow conditions of a turbine. If future investigations reveal the discharge area of the turbines does not provide adequately safe fish passage, more detailed investigations should be performed to better identify alternatives to modify the existing turbine discharge conditions.

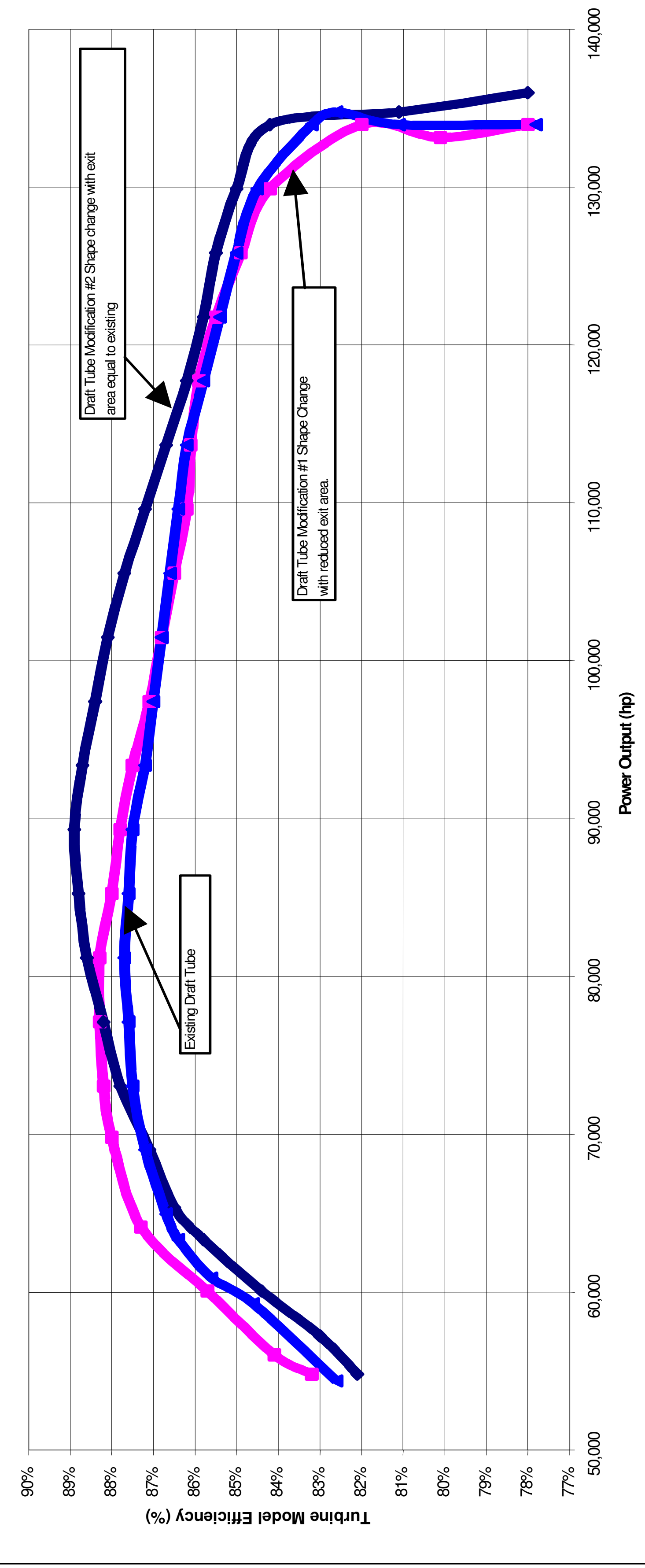


Figure 49. Draft-tube modifications – McNary model test.

3.2.3.1.3 Modified Stay Vane and Wicket Gate Designs and Alignment

Observations of the ERDC-WES hydraulic models show that a poor alignment of the stay vanes to the wicket gates has the potential to injure fish. The 1995 biological evaluation of the McNary prototype biological test investigating wicket gate and stay vane effects was inconclusive. However, as more beads and flow paths were observed on the ERDC-WES McNary, Lower Granite, and Bonneville First Powerhouse hydraulic models, it became apparent that the relationship of the components, their shapes, and designs affected both bead impacts and flow paths within the turbine runner environment. The stay vane and wicket gate arrangement and shapes are designed to cover a wide range of operation. Reducing the desired operating range provides the opportunity to optimize the cascade for specific conditions. A computational fluid dynamics model (CFD) was used to re-design and evaluate the design of the stay vane and wicket gate assembly of a Lower Granite turbine. The goal was to improve the alignment and streamline the shape of the stay vanes and wicket gates to provide minimum cross-sectional areas for possible impacts while having no effect on improved turbine performance. Different combinations were examined with potential performance and geometric improvements. A design was selected and tested for power performance with three different runners. The test results show a significant improvement in performance. Figure 50 illustrates the performance achieved with the design compared to the existing stay vane wicket gate arrangement. Figure 51 shows a potential optimum modification. See Appendix B.5 for more information.

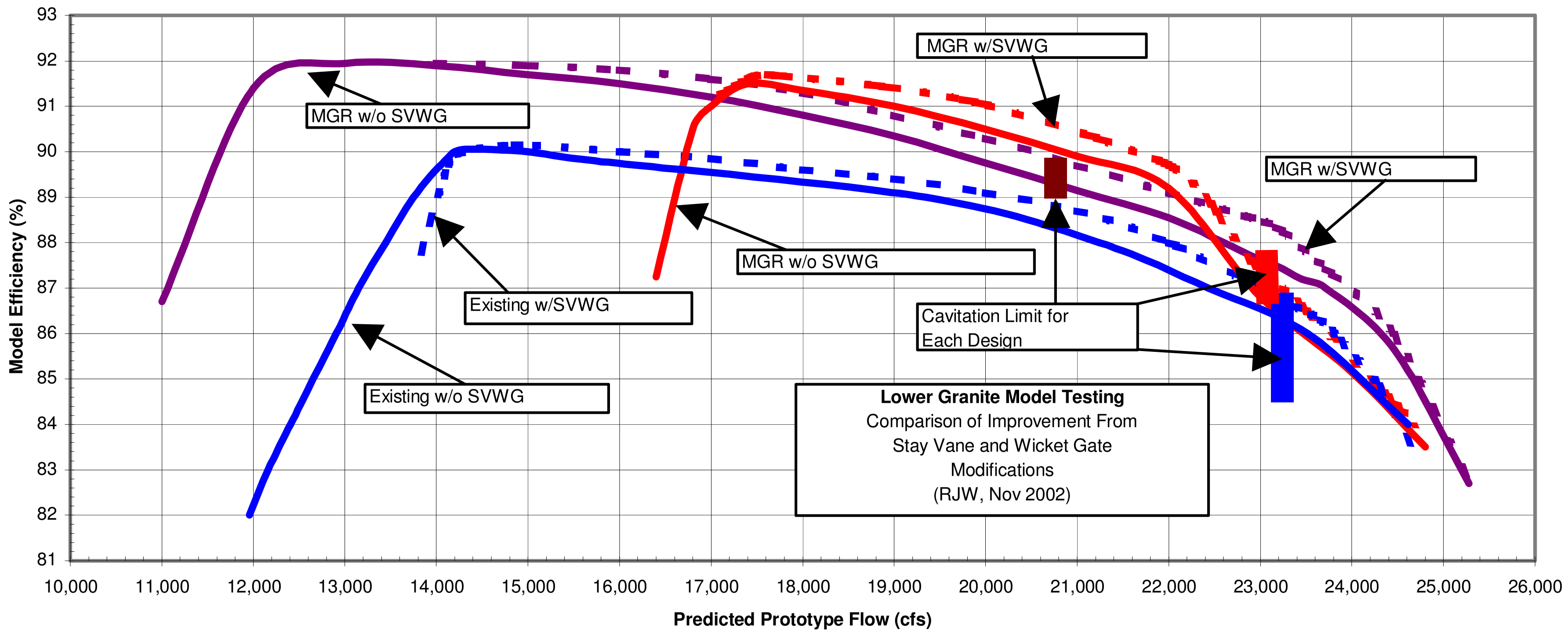


Figure 50. Performance comparison with and without stay vane-wicket gate (SVWG) modification.

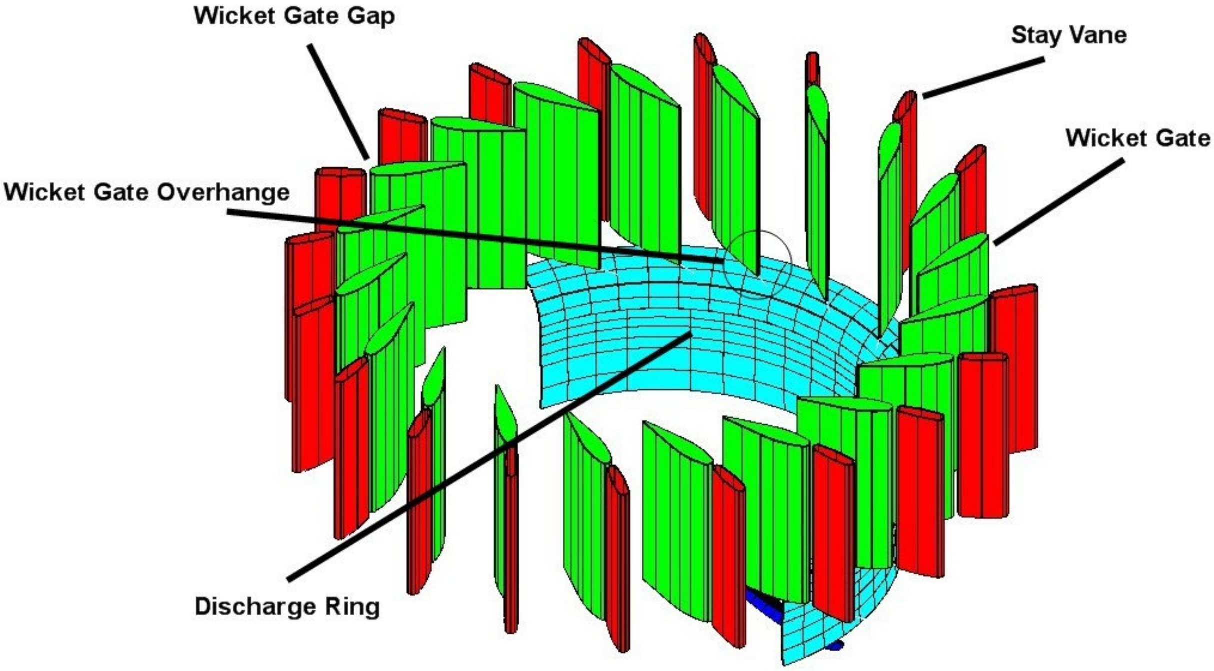


Figure 51. Potential optimum stay vane and wicket gate modification.

3.2.3.1.4 Relative Flow Studies

The measurement of flow in a prototype turbine is complicated and difficult. Adding fish diversion devices makes the measurement even more difficult. Field-testing indicated that, with fish screens installed, the uncertainty of the existing relative flow measurement system called *Winter-Kennedy* was unreliable. In an attempt to understand the erratic and unreliable measurements, investigations of alternate methods were included in the model studies. Alternate locations of measurement, in varying combinations, were investigated in both the McNary and Lower Granite model studies. The locations investigated were the existing Winter-Kennedy tap locations, six *Peck* tap locations, and new locations called *Wittinger* taps. Information on the investigations can be found in Appendix B.6. The results of the investigation concluded that the existing Winter-Kennedy taps provided information more consistent than other alternatives and could be used to develop on cam curves, but significant uncertainty remained in defining the performance of the turbine.

3.2.3.1.5 Fish Pipe Release Design

To release fish within the turbine environment, a system of pipes and injection devices was developed to place fish near locations of suspected injury (see Figure 41). The design of these systems was a significant accomplishment of the TSP program and was successfully demonstrated in biological tests at both the McNary and Bonneville First Powerhouse projects. The design was coordinated with NMFS, ERDC-WES and other agencies to achieve release of juvenile fish at specific locations within the turbine; it is also designed to accommodate the releases of adult salmon. Adult salmon were successfully released in a pilot study at the McNary project. The system operated from the elevation of the intake deck to release the fish at an elevation and water velocity similar to the existing turbine runner environment.

3.2.4 Turbine Environment Studies

3.2.4.1 General

The purpose of these studies was to better define, in engineering terms, the existing conditions within the turbine water passage environment. The studies consisted of quantifying conditions within a turbine during operation. Both laboratory and prototype work was performed to attempt to identify hydraulic and engineering design criteria limits. These limits could then be biologically evaluated to determine if a causal effect between the turbine environment and fish mortality existed. Three areas to be investigated under the turbine environment studies included: (1) turbine environmental imaging, (2) prototype pressure distribution, and (3) coordination with ERDC-WES hydraulic studies.

3.2.4.2 Turbine Environmental Imaging

The purpose of turbine environmental imaging was to investigate the interior of a turbine water passage and estimate how juvenile fish respond to the hydraulic and operating conditions within the turbine environment. Initially, environmental imaging was to be investigated under a DOE program examining advanced turbine designs known as DOE AHTS. The results of these studies would be incorporated into the planned biological testing at McNary and Bonneville.

As schedules and priorities were set, it was evident that final results from the DOE AHTS program would not be available in time for the COE planned biological testing. The TSP team coordinated with the DOE AHTS team to attempt a pilot investigation into video imaging within the turbine environment at McNary.

Low light video cameras, underwater housings and the necessary appurtenances were obtained and installed to permit a trial during the McNary biological tests conducted in 1999. Initial trials during the commissioning of the equipment at McNary showed that the test methods used for the video imaging were suitable and applicable for the intended purpose. However, the equipment was not protected well enough and an apparent trash impact made the system inoperable. After completing the biological test, it was found that the video and power cables had been destroyed. This information was accounted for in the design of the mounting and cabling system for the biological test at Bonneville. This study was not continued after the initial McNary and Bonneville First Powerhouse pilot investigations due to reduced funding. Similar imaging studies were performed on the DOE AHTS turbine design at the Alden Laboratory. The results of the observations indicate fish tend to orient head first into the flow (approach turbine tail first) until a close approach to the wicket gates is sensed. The fish then tended to turn and to enter the turbine runner headfirst. Cameras were successfully installed in Unit 6 at Bonneville First Powerhouse (MGR) to evaluate the distribution of fish within the intake; this information was analyzed by ERDC-WES and presented in a report (Carlson, T.J. and M.A. Weiland 2001). More discussion of this is found in Section 4. Continued investigations on imaging within a prototype turbine are recommended for Phase II of the TSP program.

3.2.4.3 Pressure Distribution

During Phase I, six water passage sections were measured in a model turbine test on the Lower Granite model Kaplan turbine. Some initial information on pressure was obtained from the preliminary sensor fish work at McNary. A redesign of the measurement capabilities of the sensor fish was completed and the sensor fish were passed through the Bonneville First Powerhouse turbines and through the McNary turbines. The results of these investigations are explained in Section 4.2.4 and a distribution is shown in Figure 61. As part of the turbine modeling efforts, pressure and pressure pulsation were measured. This information is presented in Appendix B.4.2. Examples of the model draft-tube pressure pulsations are shown in Figure 52 and Figure 53. However, a correlation of the model measurements to sensor fish has not been made in Phase I of the TSP program. If possible, this correlation should be examined in Phase II of the program.

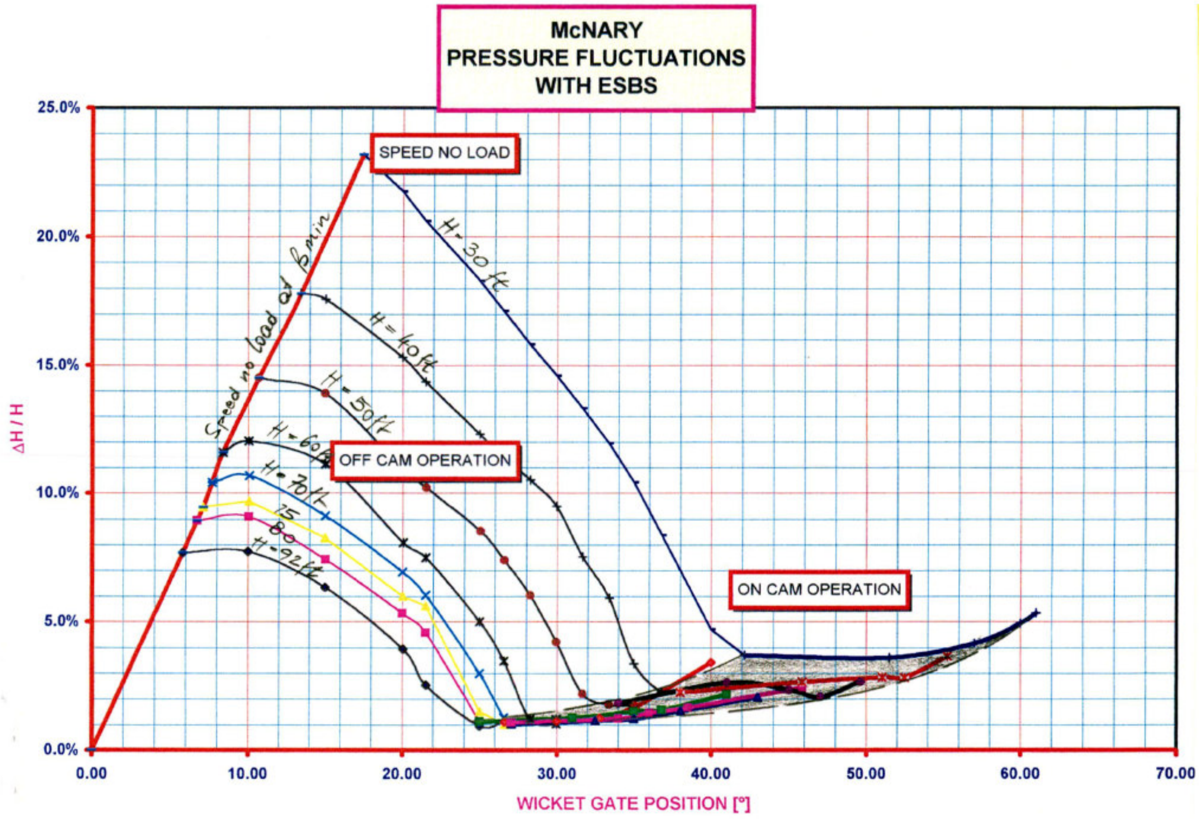


Figure 52. An example of model draft-tube pressure fluctuations.

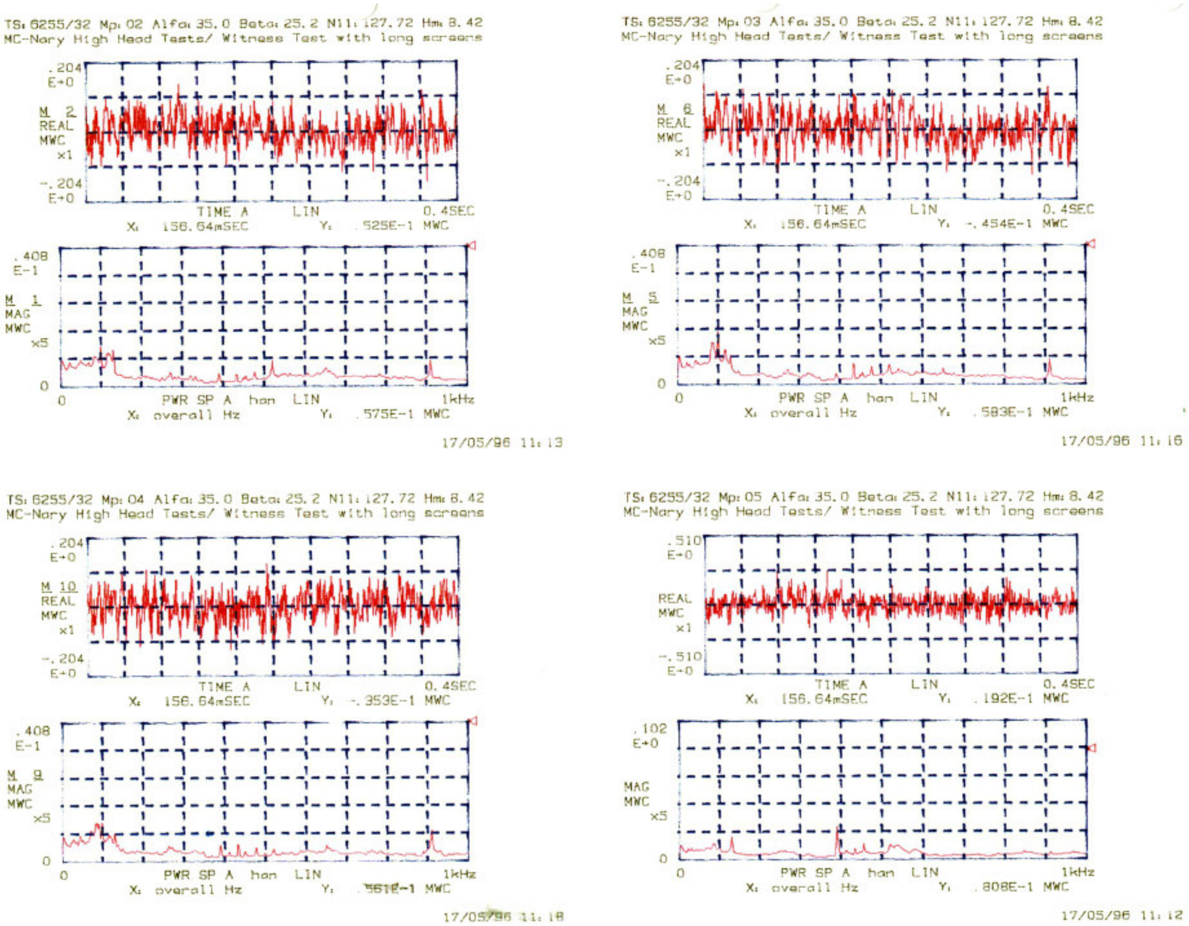


Figure 53. An example of McNary draft-tube pulsation data.

3.2.4.4 Coordination with Biological Test Designs

In Phase I, observational testing was performed at ERDC-WES to determine what, where and how to measure water passage parameters of engineering and biological interest. This information was coordinated with the engineering required in the equipment and systems development to release fish at the desired location within the turbine environment to meet the biological test designs.

3.2.4.4.1 Lower Granite Unit 4 Direct Survival Tests (1994 and 1995)

The 1995 Lower Granite biological test (see also Appendix A.1.3) consisted of pilot investigations of turbine operations with simultaneous release of fish through a turbine. The release points were on the horizontal centerline of each bay. Two elevations were used with one elevation approximately 5 feet below the bottom of the fish screen (Elevation 606.0 feet) for five of the six conditions tested. The other elevation was a top release, approximately mid-point in the extended screen (Elevation 624.0 feet). Four out of the six releases were in Bay A with one each in Bays B and C. Four of the conditions were at the upper end of the one-percent operating limit, one at the lower end of one-percent and a special case with off cam operation at the one-percent limit with cavitation present. The turbine had been tuned (operationally optimized) just prior to the biological test by index testing and the development of correct on cam blade gate positioning. This tuning resulted in approximately a 3-percent efficiency improvement. The biological statistical precision level was not rigorous; this resulted in difficulty establishing statistically significant differences in the conditions tested since the survival rate was high, greater than 95 percent. This testing indicated that the statistical test design needed improvement, specific release locations may be required, and that release techniques needed improvement. It also indicated that turbine tuning trended toward higher fish survival, confirmed the viability of simultaneous coordination of turbine operations and biological releases, and showed that cavitating turbine operating conditions were not statistically different from non-cavitating conditions. This testing formed the baseline for much of the Turbine Survival Program from the indications that there were potential biological benefits associated with improvements in turbine operation and that the turbine environment could also be probed for improvements. The 1994 test was performed without monitoring the turbine, making detailed comparisons difficult. A report on the 1995 testing was published (RMC Environmental Services, Inc. 1994 and Hydroelectric Design Center 1998). (See Section 4.1.1 for the biological evaluation). Figure 54 shows the improvements from tuning a turbine. Biological testing was performed at three approximate turbine discharges 13,570 cfs, 18,040 cfs, and 19,700 cfs. The TSP request to fund a detailed study of turbine operation and biological results was postponed by the Region until the ERDC-WES studies could be performed. Completion of the engineering evaluation will be included in Phase II studies.

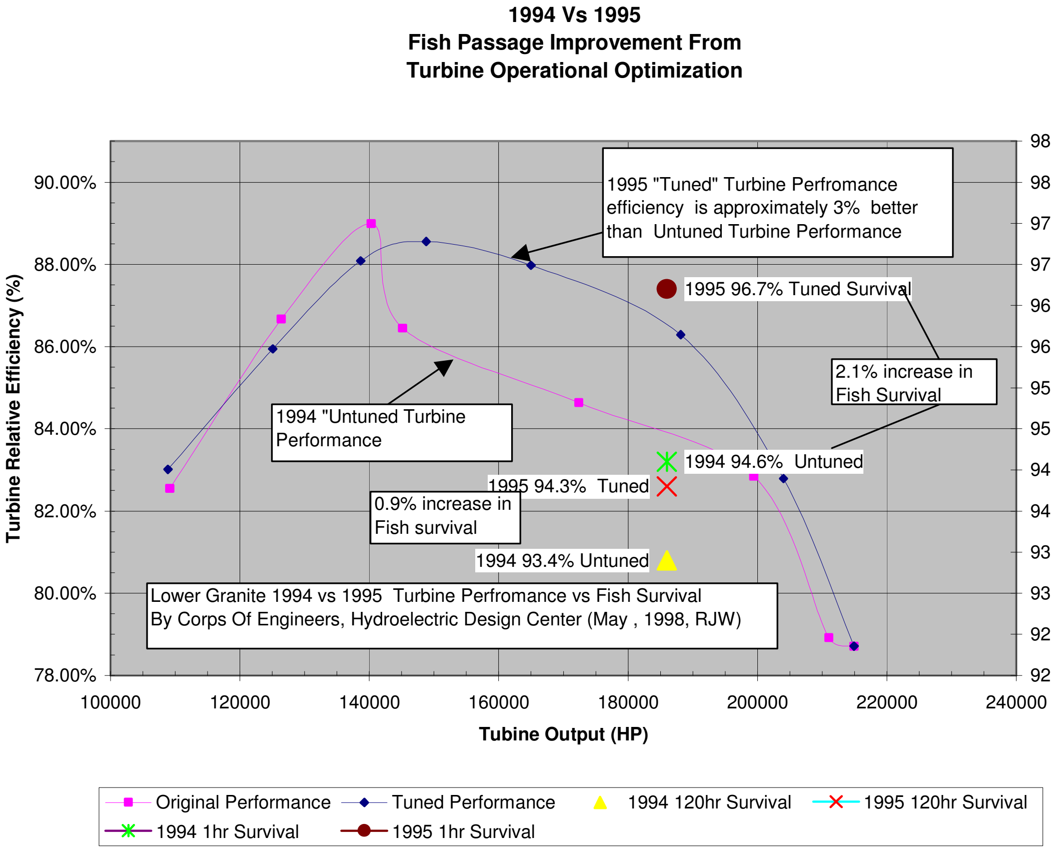


Figure 54. Improvements from tuning a Lower Granite turbine.

3.2.4.4.2 McNary Unit 9 Relative Passage Direct Survival (1999)

Observations at ERDC-WES were used to identify potential locations of injury and mortality within the turbine environment. Please refer to Section 2.4 describing the observations and Appendix A.1.1. A significant engineering effort was required to place juvenile fish in the turbine areas desired for evaluation of potential injury and mortality. This consisted of developing a suitable injection system and distribution system to reach the desired release points (see Appendix A.1.4). For this test, four release points were selected based on the ERDC-WES observations. These four points were identified as near the top of the stay ring or distributor, at the vertical midpoint of the stay ring, near the bottom of the stay ring and a location near the vertical midpoint of the stay ring, approximately 20 feet upstream of the distributor. This biological evaluation was performed at a single operating point (upper end of the one-percent, approximately 12,400 cfs) and the test was considered a pilot study to determine if release piping and systems could successfully be used to release fish near a desired location. The turbine was monitored to ensure correct operation and settings during the testing and a report on the operation during the testing was prepared (Wittinger et al. 1999). Figure 55 below shows the test point of the biological test. (See Section 4.1.1 for the biological evaluation).

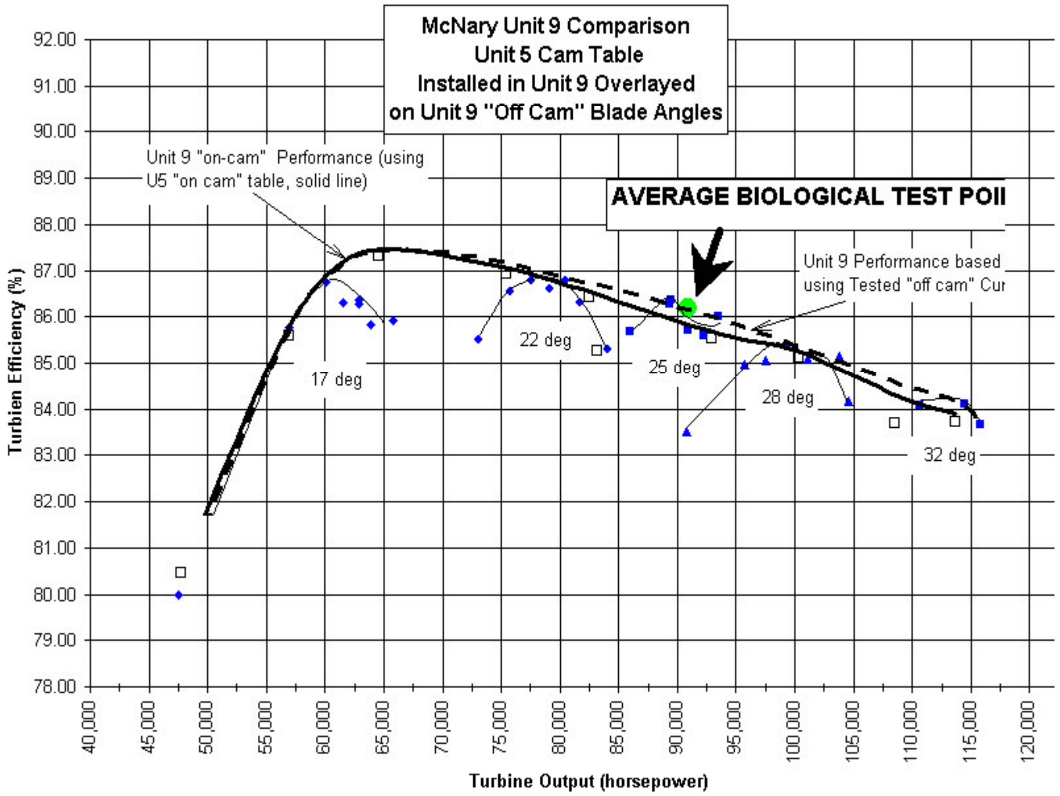


Figure 55. Average biological test point (12,400 cfs) and turbine performance.

3.2.4.4.3 Bonneville First Powerhouse Units 5 and 6 Survival Test (2000)

This test consisted of engineering efforts similar to the McNary Unit 9 test. Fish release pipes and injection systems were designed, installed and tested in the intakes of these units. The experience gained from the McNary test was applied to these designs. Three release pipes were installed in each unit for evaluation of the replacement MGR (Unit 6) and the existing (Unit 5) design. The location of the release points was established using an ERDC-WES hydraulic model of the Bonneville First Powerhouse intake without a turbine installed. The testing occurred over four basic operating points requiring careful consideration of the water velocity at the discharge of each of the release points. The four tests points were at one-percent efficiency points in both turbines. The corresponding approximate flows are:

#1: Unit 5 - 6,200 cfs and Unit 6 - 6,200 cfs.

#2: Unit 5 - 7,150 cfs and Unit 6 - 6,900 cfs.

#3: Unit 5 - 10,800 cfs and Unit 6 - 10,350 cfs.

#4: Unit 5 - 12,100 cfs and Unit 6 - 11,700 cfs.

The turbines were monitored during the testing for correct operation and a report prepared documenting the operations during the 60 days of testing. (Wittinger, R. and D. Ramirez 2000) Figure 56 below shows the test conditions actually tested. See Section 4.1.1 for the biological evaluation and Appendix A.1.2.

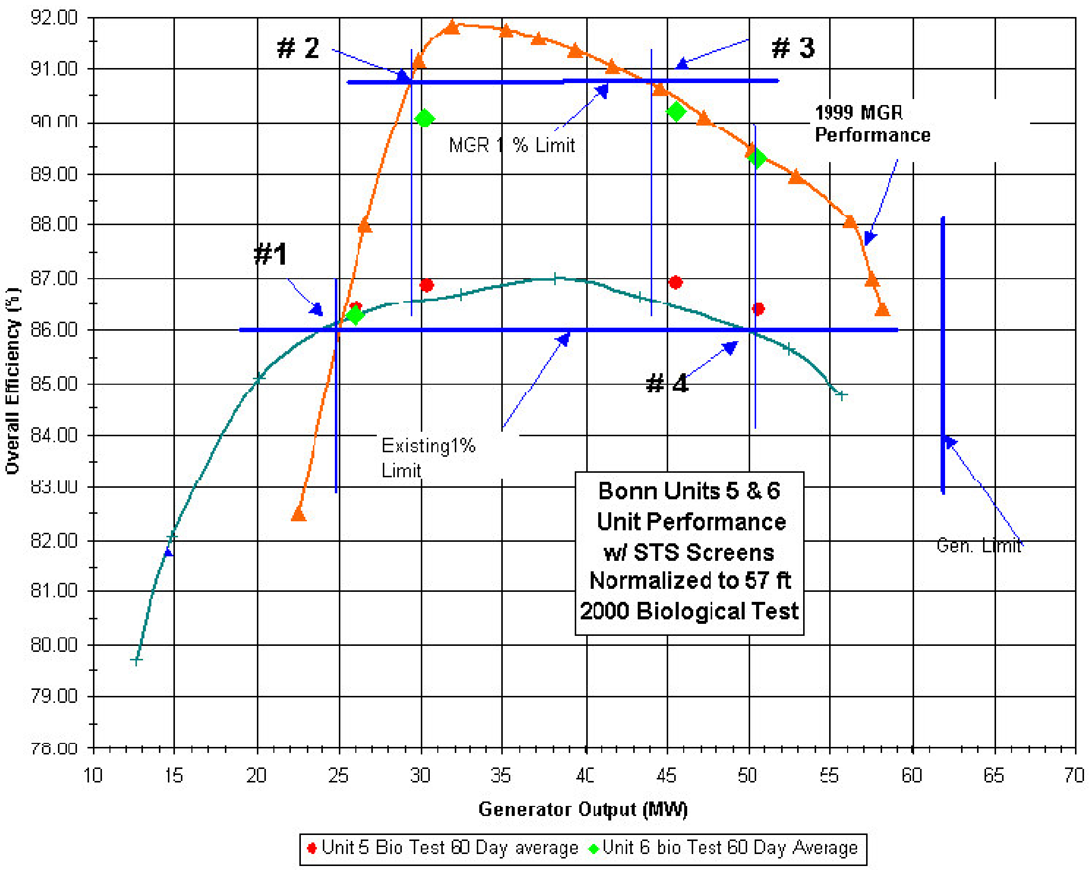


Figure 56. Actual versus desired operating conditions.

3.2.4.4.4 McNary Unit 9 Survival Test (2002)

The engineering in this test centered on the fish injection systems and positioning of the turbine to the desired geometry. The goal was to investigate turbine geometry at different operating conditions. Based on ERDC-WES studies of the previous two tests, it was desired to maintain the turbine at a fixed operating point near the lower and upper end of the one-percent operating limit, at about a 2-percent drop from the best operating point and at the maximum on cam blade position. These test points required daily setting of the turbine to the correct on cam blade gate relationship for the head existing at the time of adjustment. Hence, there is some variation in the positioning over the test period and head fluctuations for the day of testing. The corresponding approximate flows are:

#1:	8,000 cfs.
#2:	11,200 cfs.
#3:	14,000 cfs.
#4:	16,400 cfs.

The turbine was monitored during the testing and a report prepared documenting the operation of the turbine during the fish releases (Wittinger, R. and C. Polinski 2002). Figure 57 shows the average actual test points and the desired test points. See Section 4.1.1 for the biological evaluation.

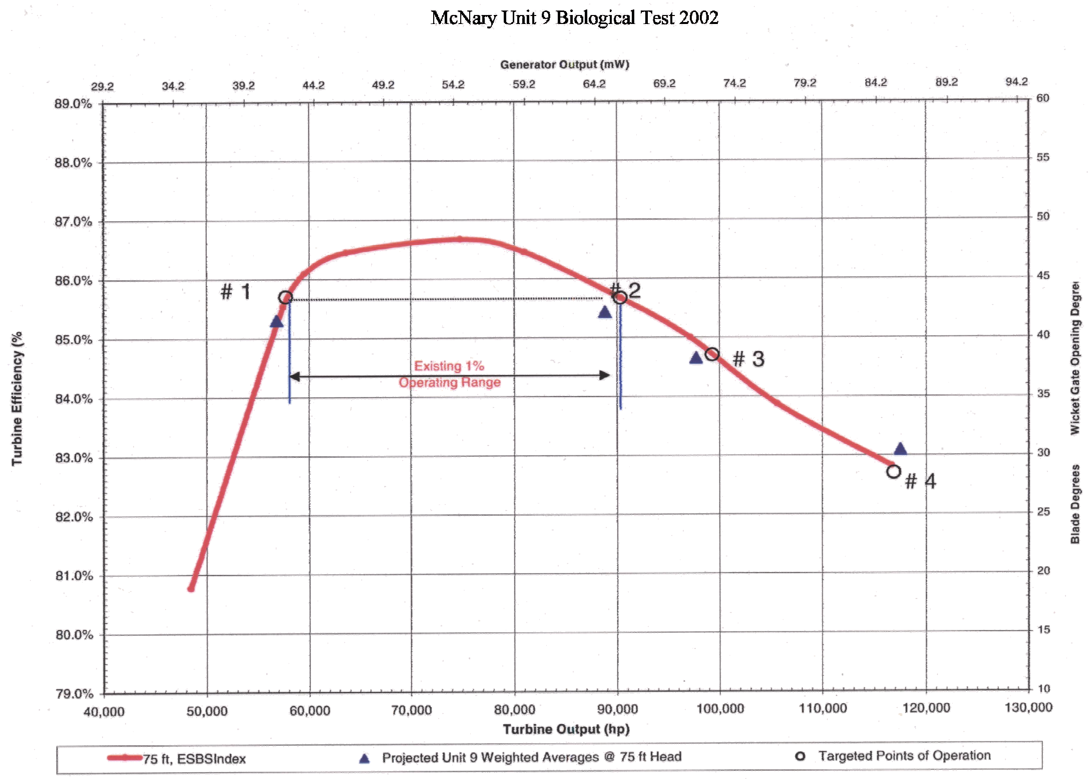


Figure 57. Actual versus desired operating conditions.

3.3 Evaluating Turbine Operations

3.3.1 General

Investigations revealed existing turbines do not actually operate as required by the Region. This is a result of efforts to divert fish from entering the turbines without considering the effect on actual turbine operations. The turbines and their operation have been considered by many as a kind of “black box” with little understanding of how the physical changes to the turbine intakes affect actual turbine operation. The TSP program addressed turbine operations through various operational investigations and identified operational optimization opportunities. The investigations included examining the actual turbine operating assumptions, index testing, one-percent operating limits and other topics. Many opportunities for improvements have been recognized and are being implemented by other programs. The implementation of these opportunities requires significant coordination within the Region and consequently has not been timely in implementation; as the understanding of potential improvements grows, it is expected that the work necessary to obtain and maintain operational optimization will occur on a regular basis.

3.3.2 Absolute and Relative Efficiency

In this report, several references are made to *efficiency*. Depending on the context, however, the term efficiency can refer to different concepts. For the purposes of clarifying the meaning of the word, as used in engineering terms, it is necessary to describe the different measures of efficiency used in the discipline. There are distinctions based on four separate issues. The first is absolute efficiency, which is the measured value of the ability of an individual component to convert what is potentially available to what is actually produced. The second is relative efficiency (before and after comparison), which is based on techniques to obtain a relative value because not all of the elements necessary to determine *absolute* efficiency can be easily measured. The third is the location of the measurement from the source of conversion of waterpower to electrical power. The fourth is the difference in performance that can be expected in comparing a model to a prototype machine. The efficiency of hydroelectric generation is the conversion of the fluid power to mechanical power. However, where and how the measurements are obtained can have a significant effect on the magnitude of the efficiency value identified.

3.3.2.1 Absolute Turbine Efficiency

The term *absolute* in hydroturbines means Power Out/Power In. It is a measure of the conversion of available hydraulic power to mechanical shaft power. For a turbine this is typically taken at the turbine shaft coupling to the output device, normally a generator. It typically takes the form of:

Turbine Efficiency = C1*(Power)/(Head)*(Flow)

Where:

C1= Conversion Factor—Waterpower to Horsepower

(550/water density, where density is in lbs/ft^3.)

Power = The Measured Power (Horsepower)

Head = Measured Available Head in Feet (Forebay – Tailwater)

Flow = Measured Turbine Flow Used (CFS) to Produce Power

Each of the above terms has variations depending on the measurements available. For example, turbine efficiency in a model turbine can be closely measured because each of the component measurements can be precisely measured. While in a prototype turbine, all but the flow rate can be precisely measured. Currently the only known absolute flow measurement is the *current meter* method (although not Code approved), which is not applicable with fish diversion devices installed. Other techniques or methods are currently under investigation, however their precision is presently unknown.

The prototype inherently requires adjustments to arrive at a specific efficiency level. These include: net head and gross head, flow and generator losses.

3.3.2.2 Relative Turbine Efficiency

The term *relative* in hydroturbines means a comparable efficiency to some selected baseline. A metric for turbine flow must be assumed. The value of relative efficiency can take the form of a number relating the measurement of power, head and the selected term for flow. These values are compared to a baseline definition/calibration of the term used for flow measurement. In the FCRPS Kaplan turbine, relative efficiency is normally assigned to a pressure difference between a pair of piezometric taps called *Winter-Kennedy* taps, which really measure the changes in angular momentum of the water. This differential pressure is theoretically proportional to the square of the discharge. The use of these taps and their geometric relationship has been used for decades. It normally takes the form of:

Relative Efficiency = C2*(Power)/(Head)*(Relative Flow)

Where:

C2 = Conversion Factor – Waterpower to Horsepower

Power = The Measured Power (Generator Output)

Head = Measured Available Head in Feet (Forebay – Tailwater)

Relative Flow = $K*(D)^n$ (K =Constant, D=Differential Pressure, n=Exponent)

The form of the equation above can take many forms depending on the testing requirements. Each of the above terms has variations depending on the measurements available. The prototype inherently requires adjustments to arrive at a specific efficiency level. These include: net head and gross head, a flow metric and generator losses. The existing prototype Kaplan turbines in the FCRPS use a relative unit efficiency based on gross head and generator output.

3.3.2.3 Overall Unit Efficiency

Overall unit efficiency is the water-to-wire efficiency, which includes losses outside the turbine. These include generator losses and may include other electrical losses from equipment such as an exciter and transformer. The determination of one-percent operating limits is based upon turbine relative efficiency using gross head and generator output.

3.3.3 Operational Investigations

Operational investigations included basic turbine operation assumptions and their applications to the existing operation of the turbines; index testing and how turbine performance is affected; the existing requirements of the one-percent operating limitations and how this requirement is met; investigations of prototype flow measurement techniques; investigations of standardizing mechanical adjustment to aid on-site staff in maintaining optimum turbine operation; and potential improvements from improved surface finishes.

3.3.3.1 Actual Turbine Conditions

3.3.3.1.1 Actual Turbine Operation Assumptions

The following assumptions are made in the development of the on cam curves and performance curves for a particular powerhouse:

- Original performance model tests and recent performance model tests correctly reflect the existing design and operation of the installed prototype.
- In a particular powerhouse, field index testing of one turbine of the same design as others in the powerhouse is sufficient to develop on cam operating curves for all machines in that powerhouse of that design.
- Prototype turbines of the same design at the same site operate identically both mechanically and hydraulically.
- Turbines and controls work correctly and are mechanically and electrically calibrated.
- The input variable to the control system is a required power output. The wicket gates move to the desired power area and the turbine runner blades adjust to match the wicket gate position.
- The hydraulic head measurement at a unit is accurate.
- The powerhouse parameters existing at the site are as presented in Table 13 below.

Table 13. Project Powerhouse Parameters

POWER PLANT	MEAN TAILWATER OPERATION* FT (MSL)	AVERAGE HEAD RANGE FT	AVERAGE FLOW RANGE 1000 CFS
Bonneville	15	55-61	125-175
Ice Harbor	341	95-99	20-60
John Day	161	99-103	110-240
Little Goose	540	93-98	15-80
Lower Granite	637	96-101	15-80
Lower Monumental	440	97-100	40-90
McNary	266	70-75	75-200
The Dalles	77	77-82	50-190

*Mean Tailwater was found by using the Tailwater Duration Curve for each Plant

3.3.3.1.2 Governors

Each of the turbines is equipped with a speed control governor that controls the operation of the machine through the use of hydraulic fluid power. Sensors and feedback devices control the operation of the hydraulic pressure system to obtain the desired operating condition requested. Included in the system are mechanical fail-safe functions to operate the machine in automatic, manual and in testing modes:

- <u>Existing Governors</u> – The existing governors are termed *cabinet oil actuator* type. These governors were originally mechanical governors, which used mechanical means through a feedback system to control operation of the turbine unit. Metal cams are used to position the runner blades to the wicket gate position. Over time, these governors have been modernized to some degree. This includes the addition of 3-D cam electronic units to position the turbines to the correct blade gate relationship for the existing head and power requested.
- <u>Digital Governors</u> – Digital governors are currently replacing the existing mechanical controls. The motive forces to physically operate the turbines remain essentially the same, but electronic devices are replacing the existing mechanical “brains”.
- <u>Hard Cams</u> – The governors in the system have been procured from different manufacturers. Hard cams (metal plates or parts) were machined for the specific site based on the original model test data and field index test date of one unit. The number of cam plates varied for each design based on the required head operating range. While the turbine was operated in a certain hydraulic head zone, the operator would manually select the cam (inside each unit’s governor cabinet) for turbine operation. This system is prone to “wear and tear” and maladjustment. In the 1980’s most of these control systems were replaced with electronic control units called 3-D cams.
- <u>3-D Cams</u> – Three-dimensional (3-D) cams represent the coordination of three variables for positioning of the wicket gates and runner blades. The three variables used are existing head, wicket gate position and runner blade position. This coordination is initiated by the adjustment of the wicket gates by the operator or control system to achieve a desired power. The electronic control unit (ECU) (see Appendix A.2) takes the electronic input values from the wicket gates and head measurement systems and goes to an electronic table to find the wicket gate position and the measured head. When the head is located for that wicket gate position, a corresponding blade position is selected. The ECU then moves the runner blades to that position. The power output is checked and the adjustment is repeated until all parameters are in agreement. This process is carried out through the use of software and feed back systems. Existing 3-D cam systems are being replaced because they are obsolete and electronic spare parts are no longer available. The ECU contains on cam tables for both with and without fish diversion devices in place and the condition is selected by the operator.

3.3.3.1.3 *Automated Operation*

The control system monitors a machine operation in a supervisory manner to keep the operator and system informed as to the operation of each machine and of the powerhouse. As part of this supervisory system, limitations on the operation of the machines are overlaid on the current operation of the machine to ensure limitations are not being violated, any violations are reported to the operator for correction. These limitations include: the one-percent efficiency operating limits or one-percent tables, flow computation tables which estimate the flow through a unit and/or the powerhouse, cavitation limitations and power limitations. Other parameters are monitored indicating the condition of the machine for continued operation such as temperatures, speed, etc. Currently, the previous Data Acquisition Control System (DACS) is being replaced with a new Generic Data Acquisition Control System (GDACS), which standardizes control functions in the Region.

3.3.3.1.4 *Variables Effecting Turbine Performance*

- <u>Inlet Flow Conditions</u> – Effects of inflow conditions on turbine performance are estimated to be about one-percent in efficiency when flow approaches the turbine intake obliquely. Losses can be substantially more with trash accumulations and fish diversion devices installed.
- <u>Runner Blade Position</u> – Differences between blades on the same machine can be as much as ± 1 degree of rotation. This variation is due to "wear and tear" on the operating mechanism of the turbines. The setting of the turbine runner blades is based on a single average runner blade angle. Originally, the supplier of the turbine defined runner blade angles. Those blade angles were used until about 1990 when the Corps recognized that original 3-D cam on cam tables were offset from the desired manufacturer's blade angles because of "wear and tear" and inconsistent maintenance activities. The Corps currently uses a standard method to establish blade angle to permit consistency in on cam table development and operation (Appendix A.3.1). The Corps method uses the existing turbine blades and defines blade angle from the horizontal at the full flat over-travel position. This angle is then related to the original manufacturer's settings and a consistent relationship is established by direct manual measurements and calibrations at the oil head and position indicators. In some cases, blade shape and angle have been altered from the original design by maintenance activities and corrosion.
- <u>Wicket Gate Position</u> – The turbine wicket gates regulate the flow into the turbine chamber. There are two ways of measuring wicket gate positions external to the water passage. These are a wicket gate opening position correlated to movement of the wicket gate operating devices (servomotors) and direct measurement of wicket gate rotation. The wicket gate physical opening must be manually measured directly with a turbine dewatered. These openings can then be correlated to the external measuring devices (Appendix A.3.3). Experience has indicated that the use of the servomotors is subject to large uncertainties because the servomotor to wicket gate mechanism relationship is subject to maintenance activities that can significantly alter the correlations. The direct measurement of wicket gate angle is not subject to these uncertainties. The Corps is presently modifying the method of indicating wicket gate position, from servomotor movement to direct measurement of wicket gate angles.

- Operating Head – The operating head on a turbine fluctuates as operating conditions change. The head acting on a turbine is the difference in elevation between the forebay and tailwater. These elevations can substantially change due to project and unit operations. The head signal is an input to the 3-D cam control system for wicket gate and runner blade positioning (Appendix A.3.4). Currently, the source of the head signal to the governors is from a signal source located in the original design of the powerhouse. The quality of the signal can vary significantly depending on location and equipment providing the signal. Recent investigations have indicated the error in head measurement may approach 2 feet. A Corps/BPA program is underway to improve this signal to have a maximum uncertainty of 0.4 feet of error at any location within a powerhouse.
- Cavitation Damage and Repair – Depending on a powerhouse and specific unit, the amount of cavitation damage can vary substantially. A normal repair cycle is every 5 years. The amount of repair work varies between turbines of the same design and depends on accurate calibrations and operating conditions. The repairs are normally weld repairs to the blades, hub and discharge ring to return them to original condition. However, experience has indicated that the repair process can alter the original design's hydraulic contours, creating significant differences in actual turbine performance between machines. Existing operational cavitation limits, and one-percent efficiency operating limits effective during fish passage seasons, limit the amount of damage. In most cases the damage is restricted to a type of cavitation called *leakage cavitation*. This cavitation takes place between the runner blades and discharge ring and the runner blades and hub. It occurs in a small zone roughly 2 to 6 inches from the blade periphery and may burrow horizontally into the thickness of the blades. This zone can be transferred to a circumferential zone about 18 inches wide around the discharge ring. Over time, stainless steel weld repairs have significantly reduced the recurring damage to a point that, if a turbine is being operated on cam, major repairs are unlikely.
- Wetted Surface Roughness – In most cases, the originally installed turbines were not painted with a long-term coating. The wetted parts were coated with a red lead preservative over the raw metal surfaces. This preservative was lost over time and corrosion of the steel surfaces began. Standard Corps maintenance practices are not to maintain surfaces. This has resulted in substantial corrosion on the wetted steel surfaces. Recent investigations have indicated that turbine performance losses approaching 3-percent in efficiency may be the result of the increased surface roughness (Appendix A.5). These investigations have also found that different on cam positioning information (re-tuning) is required when surface finish is improved.

3.3.3.2 Index Testing

Field index testing is used to optimize the turbine operation by positioning the turbine wicket gates and runner blades to produce the best operating efficiency of a turbine for the requested turbine output. This is referred to as on cam operation and the testing results in a data table of geometric relationships used by the control system to keep the unit on cam or in a tuned condition of optimum performance. Appendix A.2 contains an explanation of the process and its application to a turbine, as well as a significant amount of supporting engineering information indicating the need to perform regular testing to ensure optimum operation. The field-testing performed under the TSP program and other programs revealed gross inconsistencies in the actual mechanical operation of the existing turbines tested. The index testing revealed that the addition of fish diversion devices require the development of a separate on cam data set for operation with these devices. The testing also revealed wearing, maladjustments and errors preventing the turbines from operating within desired Fish Passage Plan parameters. Other evidence (see Section 3.2.2.4) suggests higher fish survival with tuned turbines. The field-tested turbine performance evidence indicates that turbine performance improvements of 1 to 5 percent can be achieved on individual turbines. Other programs have recognized the importance of tuning and attempts have been made to perform more index tests and establish a perpetual plan to index test and regularly adjust turbines for optimum performance. However, the region has normally permitted this type of activity intermittently and restricted index testing to about a 3-month window annually. Index testing and adjustments should be performed on a regular basis at each powerhouse and on each family of turbine designs. The results of various investigations have indicated the following.

1) Kaplan turbines should be regularly index tested.
2) Kaplan turbine mechanical positioning should be calibrated on a regular basis to ensure mechanical and electronic systems are coordinated and accurate.
3) The on cam relationships of blade to gate must be developed both with and without fish diversion devices installed in the intake.
4) The control system inputs for the 3-D cam operation of a Kaplan turbine need to be modernized to achieve operation within required operational limitations.

3.3.3.3 One-Percent Operating Limits

During the 1960’s, studies were performed in an attempt to determine the effects of turbine operation on fish passage and mortality through the turbines. The results of these studies were compiled in a 1981 report submitted by Milo C. Bell and a subsequent report recommended operation within one-percent of best operating condition. These studies were based on a single set of survival tests performed at the single unit Big Cliff project on the North Santiam River. The turbine tested is about one-half the size and twice the rotation speed of the Columbia and Snake River turbines. The original one-percent recommendation contained in the 1981 report *Recommendation for Turbine Generator Loadings and Blade Gate Relationships for the Best Survival of Juvenile Migrants at the Eight Columbia Basin Dams Operated by the Corps of Engineers* made the following assumptions:

- “…success levels can be based on the efficiency of an operating unit at the time when the small fish pass through that unit.”
- “A single point of efficiency does not satisfy the operating range needed to meet the load demands, a band of efficiency at one percent less than the maximum efficiency…during seaward migration”
- .“A recommendation would be that the turbines be operated within the range shown for the heads as indicated….” The one-percent operating range.
- “…it is recommended that the telemetry equipment be checked against measurable openings for blade angles and for wicket gates to ensure that this equipment is recording precisely these relationships.”
- No fish diversion devices were installed at the time these recommendations were made.

- No reference is made to the one-percent efficiency reference being an absolute or relative efficiency or turbine or unit efficiency.

The Region and the Corps implemented this one-percent recommendation in subsequent operation of the Corps facilities. The existing Corps turbines are required to operate within one-percent efficiency of their best operating point at the head existing across the turbine. This is accomplished through the use of tables listing the allowable operating range for a turbine. These tables are published in the annual Corps of Engineers Fish Passage Plan (Table 14). They identify the allowable power output and the corresponding flow being passed through the turbines at a specific head. These values are estimated based on index testing and historical model test information. Current one-percent tables are contained in Appendix A.4.

3.3.3.3.1 Fish Diversion Devices

The addition of fish diversion devices in the intake of the existing turbines affects the performance of the turbine and the optimum on cam blade gate relationship. The various arrangements of fish diversion devices each require index testing to determine both the performance and the optimum cam curves. The fish diversion devices disrupt the flow into the turbine by causing additional frictional losses and turbulent losses. It is unknown at this time if the presence of fish diversion devices caused additional juvenile or adult fish mortality than existed without the devices installed. It is also unclear if the original assumptions used in establishing the one-percent efficiency operating limits apply to operation with fish diversion devices installed.

3.3.3.3.2 Discussion

The significance of the one-percent operating limit on fish survival should be evaluated for continued use for operating purposes. This operating requirement may not be optimum for fish passage survival of both juveniles and adults. Each turbine design family likely has a particular operating zone in which fish passage survival is optimum. This zone may not lie within the existing one-percent operational limitations. Improvements in statistical evaluation of previous and recent biological field-testing information indicated that there is not a strong direct relationship between turbine efficiency and fish survival (2000 Workshop, Skalski Presentation). There is evidence that at low flows (RMC Environmental Services, Inc. et al. 1994) survival may be better for juvenile fish passage. However, biological evidence is mounting that turbine operating conditions at higher flows and geometric openings than are presently allowed by the one-percent operation limitation may be desirable to improve fish passage for both juveniles and adults. It may be necessary to “biologically index test” existing and replacement turbine designs to define the best operating range as it corresponds to safer passage of both juveniles and adults. Turbine passage fish survival is likely site-specific and turbine operational limitations for best fish survival may be required for individual projects and/or specific turbine designs. There is preliminary evidence (Normandeau Associates, Inc. et al. 2002) that a turbine geometric condition with better flow characteristics, should be defined for operation with fish diversion devices installed. A reevaluation of current operational limitations should be made for each project including emergency actions should a fish diversion device cause a catastrophic turbine failure.

Table 14. Corps of Engineers One-Percent Limitations

POWER PLANT		UNITS	RATED HEAD (FT)	DISCHARGE DIAMETER (IN)	GENERATOR POWER (KW)	WITHOUT SCREENS		WITH SCREENS	
						LOWER 1% LIMIT @ RATED HEAD (KW)	UPPER 1% LIMIT @ RATED HEAD (KW)	LOWER 1% LIMIT @ RATED HEAD (KW)	UPPER 1% LIMIT @ RATED HEAD (KW)
1	Bonneville 1	2	50	280	49,680	21,700	48,200	20,900	45,400
		1	50	280	49,680	21,700	48,200	20,900	45,400
		3-6	60	280	62,100	21,700	48,200	20,900	45,400
		7-10	60	280	62,100	32,700	48,200	20,900	45,400
	Bonneville 2	11-14	52	331.2	66,500	40,100	65,000	41,000	68,200
		15-18	52	331.2	66,500	40,100	65,000	41,000	68,200
2	Ice Harbor	1-3	89	280	94,737	53,700	82,600	54,100	92,100
		4-6	89	300	116,800	64,000	109,100	61,700	114,100
3	John Day	1-16	94	312	155,250	87,400	155,250	82,000	151,000
4	Little Goose	1-3	93	312	155,250	81,000	150,000	79,000	147,000
		4-6	93	312	155,250	93,600	126,200	91,600	118,100
5	Lower Granite	1-3	93	312	155,250	81,000	150,000	79,000	147,000
		4-6	93	312	155,250	93,600	126,200	91,600	118,100
6	Lower Monumental	1-3	94	312	155,250	87,000	150,000	81,000	150,000
		4-6	93	312	155,250	93,600	126,200	91,600	118,100
7	McNary	1-12	80	280	80,500	45,400	70,300	45,200	68,900
		13 & 14	80	280	80,500	45,400	70,300	45,200	68,900
8	The Dalles	1-14	81	280	89,000	51,400	75,400	No Screens	
		15-22	73	300	99,000	46,800	82,500		

3.3.3.4 Kaplan Turbine Flow Measurement

To determine turbine operational improvements, it is necessary to define a flow measurement for the determination of efficiency, be it relative or absolute flow. The measurement of flow is very difficult without fish diversion devices installed; with the fish diversion devices installed it becomes extremely difficult. Prior to the installation of fish screens, Winter-Kennedy differential pressure taps were used for the purpose of flow measurement. These taps, when calibrated with an absolute flow measurement technique called current meter, can be used to compare turbine discharges in a *relative* manner by calibrating the Winter-Kennedy taps. This was done in the 1960's for many of the hydropower plants. However, with the insertion of fish screens in the turbine intake the reliability of the Winter-Kennedy predictions using historical information methods became suspect. This is important as the regional requirement for operating turbines within one percent of their best operating condition required some accurate method of flow determination so an efficiency term could be identified. It should be noted that the original regional requirement for the one-percent operating limitation was based on turbine operation without fish diversion screens installed and no consideration of the effects on the turbine of various devices was made or research performed.

As part of the Phase I investigations, an alternate method of determining either relative or absolute flow was attempted. Two initial alternatives called Scintillation and Accusonics, both of which use acoustics, were investigated. Results of the investigations have revealed that most Winter-Kennedy taps, when properly calibrated, can provide relative flow results suitable for establishment of the one-percent operation limitation. However, each turbine would need to be calibrated both with and without fish diversion devices installed. This means that for every fish diversion device installed, a different calibration would have to be performed. This calibration would be through a form of index testing (see Section 3.4.3.2). Appendix B.6 contains additional information on Winter-Kennedy, Scintillation, Accusonics (time of travel) and current meter flow measurements. There is still considerable uncertainty in measuring absolute flow with fish screens installed. Currently efforts are underway to establish the uncertainty associated with the various flow measurement techniques.

3.3.3.5 Mechanical Adjustments

One issue that the Phase I studies made immediately apparent was that, over time and by adding more modern control equipment to improve operation, the relationship of the turbine mechanical moving parts to the electronic control systems became disjointed. The electronic and mechanical adjustments of the turbines were often based on design information no longer valid or on erroneous physical scales and measurements. The operations staff made both mechanical and electronic adjustments to keep the turbines operating, but often the control and turbine response to control were far from the optimum operating conditions and not actually within the desired one-percent operating limitation range. This resulted in many turbines operating off cam in an efficiency range from 2- to 5-percent below the desired one-percent operating limitation. It is important to note that, while the multiple adjustments could be the cause of the mis-operation, it is not directly physically apparent that this is the case. Phase I investigations recognized this problem and proposed procedures for improvement and coordination of mechanical and electronic calibrations. The goal of these adjustments was to have the turbine mechanically operate at the best on cam geometry it can regardless of the electronic control instructions for power production the turbine receives. Under the TSP program and other ongoing programs most of the turbines have been mechanically adjusted (66 of 94 Kaplan turbines as of this report). These adjustments have resulted in improved operation and in potentially improved fish passage. Refer to Appendix A.3 for detailed discussion of adjustments to the governor, runner blade and wicket gate controls, and head measurements.

3.3.3.6 Existing Turbine Surface Roughness

The Kaplan turbines in the region are approaching 50 years of age. The turbines when installed were not normally finish-painted. Instead, the surfaces were coated with a red lead primer when installed and little surface finish repair has been done since. As Kaplan turbine rehabilitations have been performed the corroded surfaces have been sandblasted, lead removed, and painted, however, this has not entirely removed the roughness. Approximately half of the existing turbines have had the lead removed, but little has been done to improve surface finish. Research has indicated that the remaining roughness is not even near the newly installed condition. Evidence indicates that a substantial Kaplan turbine performance loss may result from rough corroded surfaces of the metal wetted turbine parts. Although there is no direct evidence that rough irregular surfaces injure migrating fish, the rough surfaces may cause turbine performance losses and increased boundary layer turbulence effects. It is not known if these hydraulic disruptions are detrimental to fish passage. Figures 58 and 59 below are photographs of *as found* and rehabilitated surfaces. Appendix A.5 contains more detailed information on surface roughness. In future Kaplan rehabilitations, the wetted metal surfaces should be painted and returned closer to a “like new” condition roughness of 150 to 300 micro inches.

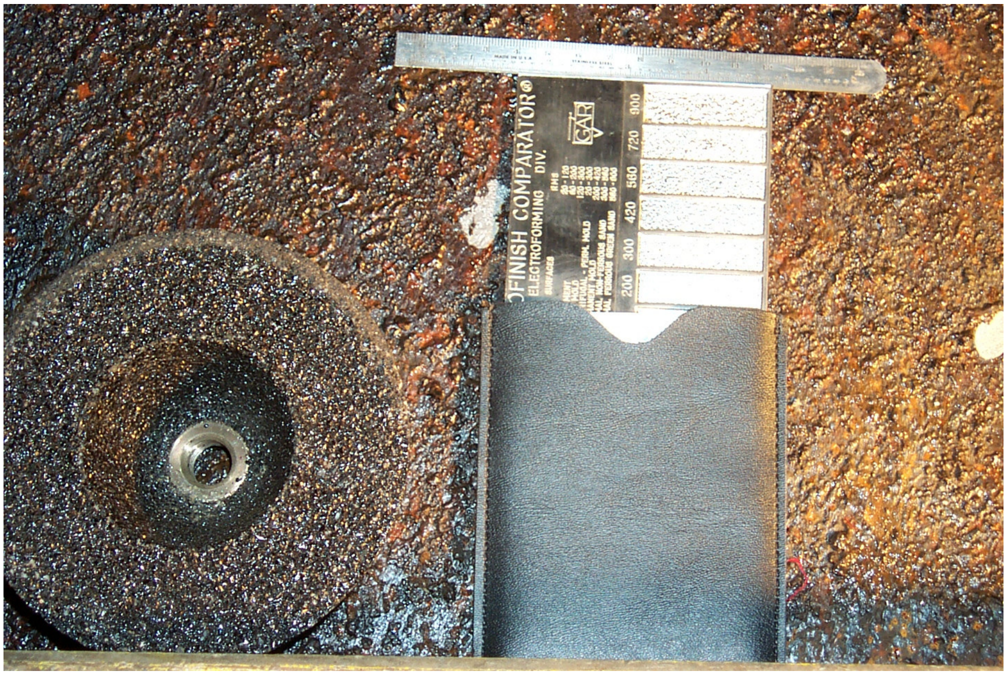


Figure 58. An as found runner blade.

Figure 59. A rehabilitated blade.

3.3.4 Operational Optimization

The operational optimization of McNary Units 5 and 9 and Bonneville Units 5 and 6 consisted of performing turbine field-testing to identify operating conditions consistent with the design and present operating parameters. This testing ensures that the turbine(s) are operating as efficiently as possible prior to actual biological testing. Field index testing was performed in FY98, FY99, and FY00 both with and without fish diversion devices in place. Prior to field-testing, the following areas of work were completed:

- Procurement and installation of dedicated field-testing equipment for performance of a standard field index test.
- Procurement and installation of flow measurement equipment to calibrate existing relative flow measurement piezometric taps and establish the optimum turbine on cam runner blade to wicket gate relationship.
- Development of optimized on cam relationships from known field and model test data, suitable for use in the existing and redesigned 3-D cam controller units.

During optimization, historical methods and existing operational criteria were determined to be insufficient for operation consistently within the one-percent range. Inadequacies in existing control equipment, measurement equipment, techniques and computational routines prompted a re-examination of these features to achieve the required level of operational accuracy (Appendix A.3.5). This was especially true with the different fish screens installed.

The development of new technologies, designs and methods engendered the confidence necessary to allow permitting of comprehensive operational optimization of the turbines. These new developments were then applied to satisfactorily optimize the machines for field-testing. The success of these methods resulted in the development of a preliminary plan to address operational optimization of the COE Columbia and Snake River power plants. The BPA is funding the preliminary implementation plan proposed by the COE. However, there is still considerable uncertainty in establishing turbine performance accuracy to the level required by the Region. The implementation of any plan developed for operational optimization of COE plants is outside the scope of the TSP program. Table 15 outlines the ten field-tests remaining that are required to achieve an initial level of confidence, which indicates that existing turbines are operationally optimized.

Table 15. Field-Tests Needed for Operational Optimization*

SNAKE AND COLUMBIA	NUMBER OF FAMILIES	UNIT NUMBERS	TYPE OF SCREEN INSTALLED	SCINTILLATION TEST NEEDED?		
				NO SCREENS	STS SCREENS	ESBS SCREENS
Bonneville	Exist	1-10	STS	No	No	N/A
	MGR	1-10	STS	No	No	N/A
Bonneville	1	11-18	STS	Yes	Yes	N/A
Ice Harbor	2	1-3	STS	Yes	Yes	N/A
		4-6	STS	Yes	Yes	N/A
John Day	1	1-16	STS	No	No	N/A
Little Goose	2	1-3	ESBS	No	N/A	No
		4-6	ESBS	No	N/A	No
Lower Granite	2	1-3	ESBS	Yes	N/A	Yes
		4-6	ESBS	Yes	N/A	Yes
Lower Monumental	2	1-3	STS	No	No	N/A
		4-6	STS	No	No	N/A
McNary	1	1-14	ESBS	No	N/A	No
The Dalles	2	1-14	NONE	No	N/A	N/A
		15-22	NONE	No	N/A	N/A

3.4 Draft-tube Tail Log Slots

The Bonneville First Powerhouse 2000 biological test indicated a significant fraction of test fish were trapped in the tail log slot of the Bonneville First Powerhouse (see Section 4.5). The biological testing at McNary in 1998 had some observed but undocumented test fish trapped in the McNary stop log slots. Both projects have similar stop log arrangements with openings well inside the draft-tube. The TSP investigated a possible closure-streamlining device and developed a design to close the Bonneville First Powerhouse stop log slots. The TSP investigated the other Corps projects (Hydroelectric Design Center 2002) to determine the configurations at the existing powerhouses. This survey found that the remaining Kaplan turbines have the draft-tube stop log slots at the exit of the draft-tube and are open to the tailwater allowing fish to escape the slots. Model turbine performance model testing indicated an improvement in turbine performance could result from closure of the slots. This testing was performed on Lower Granite, which has the slots at the end of the draft-tube. Appendix A.6 contains the detailed information of the design for Bonneville First Powerhouse and the findings of the survey report. Closure of the slots may be beneficial for fish passage at the Corps Columbia and Snake facilities. Recent biological testing at McNary (2002) indicates that closure of the slots at McNary may not be necessary because fish do not appear to be trapped in the slots. However, it appears at this time that closure of the Bonneville First Powerhouse draft-tube stop log slots would be beneficial.

3.5 Conclusions

3.5.1 General

The following is a consolidation of the conclusions and recommendations drawn from Phase I and other engineering investigations. In addition, Phase II possible engineering actions necessary to bring closure to the TSP program are provided. In general, the conclusion can be drawn that Kaplan turbines can be designed and operated to improve fish passage to achieve direct mortality levels nearly equal to or better than alternate passage routes.

3.5.2 Phase I Engineering Design Studies Conclusions

The following engineering conclusions have been reached on the basis of existing information and data. These engineering conclusions are presented in no particular order.

1) It may be necessary to “biologically index test” existing and replacement turbine designs to define the best operating range as it corresponds to safer passage of both juveniles and adults.
2) The proportion of in river fish passing through turbines and their direct and indirect survival rate are site specific and turbine operational limitations may be required for individual projects and/or specific turbine designs.
3) Fish diversion devices severely affect the flow distribution to Kaplan turbines causing efficiency loss; making engineering measurements and potential solutions for turbine improvements difficult to evaluate.
4) The clearance gaps can be reduced on Kaplan turbines and result in improved turbine performance.
5) The state-of-the-art of CFD is improving, but is still insufficient for evaluating the biological performance of existing or new turbine designs.
6) Different fish screens or fish diversion devices require separate on cam relationships to meet NMFS BiOp turbine operations requirements.
7) Should a Kaplan turbine control system fail with fish screens installed (runaway), model testing with fish screens indicates that the fish screens will structurally fail possibly causing severe structural damage.
8) A quantifiable relationship between the ERDC-WES hydraulic model studies and prototype biological results has yet to be established. Establishing this relationship may identify specific hazard zones within the turbine environment.

9) Turbine design alterations may be evaluated for turbine performance effects in the high-pressure (Reynolds) models. The potential biological benefits of these alterations may be evaluated in the low-head (Froude) hydraulic models at ERDC-WES.

10) The MGR turbine design for the Bonneville First Powerhouse Rehabilitation was an engineering and biological success.

11) The evaluation of surface roughness of existing turbines (rough) to rehabilitated turbines (smooth) indicates the flow boundary conditions are different, which implies that smoothing the surfaces of existing turbines may result in turbine performance improvement.

12) Improvements in turbine performance and possibly fish passage can result from draft-tube modifications. The effects of the operation of adjacent units, however, confound the effect of modifications to a single unit.

13) Turbine hydraulic conditions vary significantly from chaotic to smooth as a function of the turbine operating condition, flow, and geometry.

14) The unmodified draft-tubes investigated in Phase I provide a better flow distribution at higher flow conditions.

15) Runners and draft-tubes are a coupled design that may extend beyond the normal performance model's range of evaluation and well into the egress areas of a powerhouse.

16) Studies of modified stay vane and wicket gate designs and alignments indicate that significant turbine performance improvements can be obtained. However, the risks to fish of contact with stay vanes and wicket gates or exposure to hydraulic conditions near and in the wake of the structures remains unclear.

17) Relative flow studies with and without intake screens installed have concluded that the existing Winter-Kennedy taps can provide flow information reasonably consistent and can be used to develop on cam curves, but significant uncertainty remains in defining the absolute performance of the turbine.

18) Imaging technological advances indicate that the potential for imaging within the Kaplan turbine runner chamber is possible.

19) The range and rate of change of turbine pressure fluctuations vary with turbine discharge. At high discharge, the pressure time history is lowest and the rate of change in pressure through the runner is highest.

20) It is possible to release fish where desired in the intake of a Kaplan turbine to evaluate improvements or danger areas.

21) Turbines should be closely monitored for correct operation during biological testing to ensure the desired test parameters are maintained.

22) Closure of the draft-tube stop log slots will improve turbine performance and may improve turbine fish passage.

23) The geometrical relationships of the physical water passage components of a turbine may be very important in defining turbine operation for optimum fish passage.

24) The studies of alternate turbine runner designs and biological features have indicated that the potential for “win-win” situations exist for both turbine performance improvements and improved fish passage.

3.5.3 Phase I Engineering Design Studies Recommendations

The engineering design study recommendations that follow are presented in a numbered format for reference only and not to imply an order or importance.

1) Index test Kaplan turbines regularly to meet NMFS BiOp objectives.

2) A turbine geometric condition with better flow characteristics should be considered for operation with fish diversion devices installed in lieu of the existing one-percent limitation.

3) A Turbine Fish Passage Workshop should be held in 2005 to coordinate within the Region turbine fish passage advances and research for rehabilitation of existing units.

4) Calibrate Kaplan turbine mechanical positioning linkages on a regular basis to ensure mechanical and electronic systems are coordinated and accurate.

5) Modernize the control system inputs for the 3-D cam operation of a Kaplan turbine to achieve operation within required NMFS BiOp operational limitations.

6) Remove existing projections that may be harmful to fish from the turbine water passage.

7) Allow regional flexibility in accelerating the scheduling of turbine index testing and adjusting turbines to meet NMFS BiOp goals. This is necessary for implementing operational fish passage improvements in the Corps’ existing 94 Kaplan turbines.

8) Establish the uncertainty associated with turbine flow measurement techniques as necessary to meet the NMFS BiOp.

9) Smooth and paint the rough surfaces of existing Kaplan turbine metal wetted surfaces. This can result in a zero to 2 percent turbine performance improvement with unknown environmental benefits.

10) Evaluate the geometrical operational range of existing Kaplan turbines for current system actual operational requirements. If inappropriate for current hydraulic site conditions, the geometrical operational range should be restricted to an alternative range acceptable for continuous operation during fish passage season.

11) Perform individual unit and powerhouse turbine optimization to prioritize turbine operation for project fish passage improvement.

12) Establish a Project and unit priority for turbine improvements based on total project mortality rates.

13) Draft-tubes and tailrace outflow conditions should be investigated in detail to determine relationships to total project flow and fish passage.

14) Kaplan turbine runner chamber imaging is possible and should be investigated and implemented.

15) The pressure history of the twelve existing prototype turbine designs should be obtained using sensor fish.

3.5.4 Phase II Engineering Possible Actions

The following are suggested new or continued actions to reach closure of the Turbine Survival Program. These suggestions are an extension and application of the conclusions of Phase I to better identify, quantify and implement fish passage improvements in Kaplan turbines for Phase II and in the future. They are presented here in a numerical format for reference only, not to imply a ranking.

1) The state of the art of CFD is improving and should be considered for evaluation and inclusion in future Phase II TSP studies.
2) The relationship of model studies to biological results, the relationship of direct to indirect survival, and adult passage turbine effects, need to be defined in Phase II.
3) Physical modeling investigations (performance and hydraulic) should be undertaken for CRFM program projects to evaluate potential turbine fish passage improvements.
4) Incorporate findings from Phase I and Phase II investigations into ongoing, planned, and future turbine rehabilitations.
5) Ensure operational improvements identified in Phase I are implemented.
6) Should Phase II investigations reveal the discharge area of the turbines does not provide adequately safe fish passage, more detailed investigations should be performed to better identify alternatives to modify the existing turbine discharge conditions.
7) Determine potential draft-tube design modifications for fish passage improvement.
8) Investigate and quantify the fish passage effects of stay vane and wicket gate modifications.
9) The correlation of the turbine model measurements to prototype “sensor” fish measurement should be done in Phase II to establish the pressure relationship of models to prototypes.
10) Phase II should rank the Corps system of Kaplan turbines from high biological risk to low biological risk to facilitate execution of turbine fish passage improvements.
11) Perform biological testing of the necessary turbines to obtain a turbine survival rate for each design.
12) Complete the evaluation of the effects of stop log slots on fish passage.
13) The existing blade operating rotational range of Kaplan runner blades should be investigated to determine if a more limited blade operating range would be beneficial for fish passage.
14) Define the geometrical relationships of the physical water passage components of a turbine and their effects on fish mortality.
15) Continue investigations of alternate turbine runner designs and design features with the potential to improve fish passage.
16) Initiate studies on near real time monitoring of turbine operation to identify the internal hydraulic operation condition of a turbine. This study would be in preparation for in-place biological index testing without the need to biologically field-test many turbines.

17) Continue investigations on fish distribution throughout the turbine environment.

18) Consolidate known information into a turbine design and procure, install and test a prototype to evaluate improvements.

19) Complete the evaluation of turbine tuning through a comprehensive engineering and biological test at Lower Granite Unit 4.

20) Initiate investigations on intake and scroll case structural modifications to provide an operating range with improved fish passage and flow distribution to the turbine.

21) Complete measurements and investigations on the determination of absolute and relative flow measurement tools to quantify actual or relative turbine operating efficiency in relation to BiOp operating efficiency limitations.

Section 4. Biological Studies

4.1 Biological Introduction

The biological performance of turbines has been a concern since shortly after the first turbine was installed in the Columbia River. However, little has been learned about turbine passage in the first 50+ years of operation. As a result, it was a focus of the TSP Phase I studies to learn more about the mechanisms that cause injury to fish during turbine passage. These studies have included engineering assessment of the turbine environment using physical models and prototype units. New methods to assess the biological performance of turbines were developed emphasizing methods allowing partitioning of the turbine environment so that specific areas, like the tip region of turbine runner blades, could be studied in more detail. Also an element of Phase I was the use of a "sensor fish" device, an autonomous sensor in a prototype scale fish that can acquire tri-axial acceleration and pressure time histories, to characterize the conditions fish may experience during turbine passage.

In addition to the engineering physical model studies and the prototype field engineering, live fish, and sensor fish studies conducted by the Corps, laboratory studies were conducted within the DOE's Advanced Hydropower Turbine System program. These laboratory studies investigated the effects of shear, turbulence, pressure, and pressure along with total dissolved gas supersaturation exposure on fish. The COE TSP and the DOE AHTS program were coordinated by various means including a technical working group chaired by the COE.

This section provides an overview of biological studies conducted by the COE prior to and during the TSP, and selected studies conducted within the DOE AHTS program.

4.1.1 Fish Condition/Survival Testing

4.1.1.1 Historical Turbine Passage Studies Prior to the Turbine Survival Program

Passage of fish through turbines has long been of interest to the Corps of Engineers. Initial turbine passage study results and their application to the design and operation of Columbia River dams are presented in a series of publications beginning with Bell et al. 1967 and continuing through Bell et al. 1972 and 1981. These studies documented the first systematic investigation of fish survival as a function of biological and turbine design and operational features. One of the most significant conclusions of this early work was that "The fish survival rate for Kaplans follows the general efficiency curve as it does for the Francis wheels. The highest survival occurred at the point of highest total efficiency in both types of turbines." (Bell et al. 1967). The conclusion that fish survival follows efficiency and that best survival occurs at peak efficiency leads to implementation of turbine operating rules based on efficiency. While a relationship between efficiency and fish survival may exist for the Big Cliff and Foster Dam turbines, where the fish survival studies resulting in the finding were conducted, fish turbine passage survival studies at large Kaplan turbines on the Columbia and Snake Rivers have not produced similar results. The reviews by Bell and his co-authors did, however, set the stage for the turbine passage investigations subsequently conducted at mainstem Columbia and Snake River dams. Interestingly, these early studies on projects with significantly different features than the mainstem Columbia and Snake Kaplan turbines have a greater influence on the operation of the large Kaplan units than a significant amount of more precise work performed more recently.

4.1.1.1.1 Lower Granite Pool and Turbine Survival Study, 1987 (Untuned Turbine)

PIT tagged yearling spring Chinook salmon were released into the intake of turbine Unit 3 at an elevation just below that of the toe of the turbine's submerged traveling screen (Giorgi and Stuehrenberg 1988). Reference fish were released just downstream from the test turbine discharge boil. Turbine releases were made at night between 2100 and 2200 hours. Reference releases were made at dusk approximately 2000 hours. Recovery ratios of treatment and reference releases observed at Little Goose Dam were used to estimate survival. Turbine relative survival was estimated to be 0.831 with a 95% confidence interval of 0.741 to 0.922.

4.1.1.1.2 Survival Estimates for the Passage of Juvenile Chinook Salmon through Snake River Dams and Reservoirs (Untuned Turbine)

As part of a pilot study to investigate various experimental models to estimate hydropower system survival, Iwamoto et al. (1994) released PIT tagged hatchery yearling Chinook salmon into the intakes of test turbines at both Lower Granite and Little Goose Dams. At both dams reference releases of tagged fish were made in the river main channel about the same river mile as that of the dams' juvenile collection facility locations. At both dams the survival of three treatment groups was estimated. The weighted averages of these estimates produced total turbine passage survival estimates of 0.823 (SE 0.025) and 0.920 (SE 0.025) for Lower Granite and Little Goose dams respectively.

4.1.1.1.3 Turbine Passage Survival at Lower Granite Dam, April-May 1994 (Untuned Turbine)

The survival of spring migrant Chinook salmon smolts (average fork length of 134 millimeters) following passage through a Kaplan turbine (Unit #4) at Lower Granite Dam on the Snake River was estimated using balloon tagging methods (RMC Environmental Services, Inc. et al. 1994) The study was conducted in April-May 1994 at water temperatures of 50 to 57.2°F, concurrently with a PIT tag survival study undertaken by National Marine Fisheries Service and the University of Washington. The study used the HI-Z Turb'N Tag-recapture technique (balloon tag). The primary objectives of the study were to estimate (1) the immediate (1-hour) and delayed (120-hour) turbine passage survival of Chinook salmon juveniles with a precision level of ±5 percent at a 90 percent confidence level: (2) the types of injury/mortality; and (3) the statistical power to detect differences in turbine passage survival rates between normal and reservoir drawdown conditions.

Fish for the study were obtained from the juvenile fish collection facility located downstream of the dam. Treatment releases totaled 820 fish introduced about 4 feet below the STS in the turbine intake while 821 fish were released at the turbine draft-tube discharge as controls.

The recapture rates of test fish were 94.5 percent for the treatment group (alive and dead) and 98.8 percent for the control group. The average recapture times were similar for control and treatment fish, 5.3±3.4 minutes for treatment and 5.7±6.8 (standard deviation) minutes for controls. The recapture probabilities were significantly different ($P<0.05$) among control trials but not among the treatment trials. One control trial (number 6) caused the heterogeneity: predation was suspected. Consequently, survival estimates and their associated variances were calculated using both the most generalized model ($H_A:P_A \neq P_D$) for the pooled data and also by weighting the estimates for each trial by the inverse of the respective variance. Ignoring the heterogeneity of the control trials, the estimated immediate survival (1-hour) was 94.6 percent (90 percent CI=92.8 to 96.3 percent); the 120-hour survival was 93.4 percent (90 percent CI=90.7 to 96.5 percent). The weighted survival estimates (96-hour survival=92.3 percent, SE=1.5 percent), considering heterogeneity, were virtually identical to those ignoring heterogeneity among control trials (96-hour survival=92.3 percent, SE=1.5 percent). Thus, the pooled survival estimates (immediate survival of 94.6 percent <±2 percent, and 120-hour survival of 93.4 percent <±3.2 percent) as calculated by the generalized model, were estimated for Lower Granite Dam.

The mortality of Chinook at 120 hours, though similar in both the treatment and control groups and acceptable from experimental view point, particularly up to 96 hours, was somewhat higher than expected and increased in trials 11 to 17. In trials 1 to 10 the mortality of treatment groups at 120 hours was 5.6 percent, in trials 11 to17 it was 17.1 percent. The pooled mortality over the treatment trials was 10.3 percent. Among control trials 1 to 10, the 120-hour mortality was 4 percent, in trials 11 to 17 it was 15.9 percent. The pooled mortality at 120 hours over the control trials was 9.1 percent. Many of the Chinook were in poor condition when obtained from the juvenile fish collection facility. The added stress of handling and tagging, compounded by the long holding period in less than ideal water quality may have contributed to higher than expected holding mortality. Many of the fish that died over the 120-hour holding period had developed fungal infection.

The physical injury rate was low and almost all the injuries (severed body, lacerations) appeared due to mechanical causes (e.g., contact or collision with structural components). Decapitation could have been caused by either mechanical injury or by shear.

4.1.1.1.4 Turbine Passage Survival at Lower Granite Dam, April-June 1995 (Tuned Turbine)

Following installation of extended length turbine intake screens over the winter of 1994-1995, balloon tag studies to estimate the direct survival and injury rate for turbine-passed fish were conducted during April-June 1995 (Normandeau Associates, Inc. et al. 1995). The study was conducted at water temperatures of 47.3 to 56.3°F. Test fish were spring migrant Chinook salmon obtained from the juvenile fish collection facility located downstream of the dam. Six turbine operation and release location scenarios were tested. Scenarios 1 and 4 were for fish released near upper (elevation 623 feet) and midlevel (elevation 603 feet) points in intake 4A at a turbine discharge of 18 kcfs. In test scenarios 2 and 3 test fish were released at midlevel elevations in intake bays 4B and 4C at a turbine discharge of 18 kcfs. For test scenario 5, test fish were released at midlevel elevation in intake bay 4A at a turbine discharge of 13.5 kcfs. Finally, for test scenario 6, test fish were released at the mid-level elevation in intake bay 4A with the turbine operating in a cavitation mode at a discharge of 19 kcfs. Control fish were released into the turbine tailrace at the exit of the test unit draft-tube at elevation 540.5 feet.

The estimated immediate (1-hour) survival probabilities were high (>0.94) for each of the test scenarios but point estimates differed somewhat among the test scenarios. Survival probability ranged from 0.972 to 0.975 (90 percent CI = ±0.045) for test scenarios 2, 3, and 5. Survival probabilities were 0.946 to 0.953 (90 percent CI = ±0.045) for the other three test scenarios. Overall turbine passage survival, estimated using pooled data, was 0.948 (90% CI 0.931 to 0.965).

Survival probabilities for the test scenarios are given in the Table 16 below.

Table 16. Survival Probabilities

TEST SCENARIO	RELEASE LOCATION	TURBINE OPERATIONS	SURVIVAL PROBABILITY	
			1 HOUR	120 HOUR
1	Bay A Upper	18 kcfs	0.949 (0.925-0.970)	0.959*(0.919-1.0)
2	Bay B Mid	18 kcfs	0.975 (0.955-0.992)	0.940 (0.901-0.979)
3	Bay c Mid	18 kcfs	0.975 (0.955-0.992)	0.954 (0.916-0.992)
4	Bay A Mid	18 kcfs	0.953 (0.928-0.973)	0.936 (0.893-0.978)
5	Bay A Mid	13.5 kcfs	0.972 (0.949-0.989)	0.987**(0.944-1.0)
6	Bay A Mid	19 kcfs	0.946 (0.922-0.965)	0.941 (0.909-0.972)
Pooled			0.961 (0.951-0.969)	0.948 (0.931-0.965)

* Survival established at 0.949 because 120-hour survival cannot exceed 1-hour survival.

** Survival established at 0.972 because 120-hour survival cannot exceed 1-hour survival.

The hypothesis that survival is highest for turbine operation within one percent of peak efficiency was not supported by the study's results. The highest 120-hour survival was observed at the lower end of the one-percent operating range, and survival at 19 kcfs discharge above the upper end of the one-percent operating range was not significantly different that estimated survival rates within the one-percent operating range.

The probable mechanisms for physical injuries observed during the study were mechanical (50 percent of injured fish), pressure (18.8 percent), shear (14.1 percent), and multiple mechanisms (17.1 percent).

4.1.1.1.5 Project Survival of Juvenile Salmonids Passing through the Bypass System, Turbines, and Spillways With and Without Flow Deflectors at Little Goose Dam, 1997 (Untuned Turbine)

In another PIT tag study conducted in 1997 at Little Goose Dam, relative survival of juvenile hatchery steelhead was estimated for passage through an unmodified spillbay (1.004, SE 0.0150), a spillbay with a deflector (0.972, SE 0.0145), the juvenile bypass system (0.953, SE 0.0162), and through a test turbine (0.934, SE 0.0156). All survival estimates were relative to the survival of test fish released in the tailrace of the dam. (Muir et al. 1998.)

4.1.1.1.6 Relative Survival of Subyearling Chinook at Bonneville Dam 1987-1990 (Untuned Turbine)

Between 1987 and 1990, NMFS conducted a series of studies to investigate the relative survival of subyearling fall Chinook passing the Bonneville Second Powerhouse (B2) by turbine, juvenile bypass, and through the dam's spillway. (Ledgerwood et al. 1990) (Ledgerwood et al. l991) Test fish were hatchery subyearling Chinook, marked with coded wire tags, fin clips, and freeze brands, released to pass through the various dam passage routes then recovered downstream of the dam at Jones Beach. Reference release locations were immediately downstream of the turbine discharge boil (turbine discharge front roll) and in the river 1.5 miles downstream of the dam. In 1989 alone, a total of 2.1 million fish were marked and released.

Test fish were released into the turbine in two locations under two different turbine intake conditions. One release location was near the ceiling of turbine Unit 17 intake bay B (elevation 21.3 feet), without a fish diversion screen in place, through a pipe routed through the turbine intake upstream gatewell. The other release location was at elevation 7.8 feet, with a STS installed in the intake bay. For this release, fish were routed through a pipeinstalled in the upstream gatewell of turbine Unit 17 intake Bay A.

Conclusions drawn from studies conducted between 1987 and 1989 included:

- Test fish passing through the bypass system were recovered at Jones Beach in significantly lower percentages than fish passing through turbines,
- Upper versus lower turbine release locations showed no significant differences in recovery percentages, and
- Spillway released test fish had the higher recovery percentages.

Additional conclusions drawn at the end of the 1990 study included:

- Increased turbine operation (from four to eight units) may have diminished abundance and predator effectiveness of northern pikeminnow near the bypass outlet.
- Tailwater elevation may be an important factor in explaining differences in turbine versus bypass passage survival; generally, the relative survival of bypass fish increased with increased tailwater surface elevation.

These studies were the first turbine passage studies to indicate that tailrace conditions, and the potential effect of these conditions on predatory effectiveness in the powerhouse tailrace, likely contribute to the magnitude of indirect mortality experienced by turbine-passed fish.

4.1.1.2 McNary TSP Test Unit Biological Test – 1999 (Tuned Turbine)

A turbine survival study was conducted at McNary Dam in May and June 1999. (Normandeau Associates, Inc. et al. 1999) The goals of the test were to better determine where major fish injury occurs within a turbine, and the types and causes of the fish injuries and mortalities taking place. Physical modeling of the McNary turbine indicated several points where injuries were likely to occur. A set of four fish release pipes were designed, constructed and installed in Unit 9 at McNary (see Sections 3.2.1.6.5, 3.2.2.4, and Appendix A.1.4). The pipes were located to release fish into the three turbine areas of interest (see Section 2.4.2.2.2). These three areas included the runner hub, the blade tip and a release point upstream of the turbine stay vane-wicket gate cascade from which fish were likely to contact the wicket gates or stay vanes. The fourth pipe was positioned to release fish so that they would pass through the turbine near the middle of the blade. This route was expected to be a passage route with the smallest chance of injury or mortality.

Fish were released in lots of ten at each release point, with the lots being randomly distributed throughout each day. Fish recovered in the tailrace were brought to shore and placed in holding tubs for observation and 48-hour mortality checks. High spill during the test hampered fish recovery efforts, but not substantially. The recovery boats were able to intercept the fish farther downstream. However, many turbine-passed fish were entrained in spill flow, which may have resulted in injuries or other effects that confounded observed injuries and mortalities of turbine-passed fish. Table 17 summarizes fish releases, recoveries and 48-hour holding information.

Table 17. Fish Release and Recovery*

RELEASE LOCATION	HUB	MID	TIP	GATE
Number Released	330	310	309	315
Number Recaptured Alive	309 (0.936)	288 (0.929)	284 (0.919)	293 (0.930)
Number Recaptured Dead	10 (0.030)	5 (0.016)	10 (0.032)	10 (0.032)
Tag Separation	5 (0.015)	3 (0.010)	3 (0.010)	5 (0.016)
Unknown (Nothing Recovered)	6 (0.018)	14 (0.045)	12 (0.039)	7 (0.022)
Number Held	309 (0.936)	288 (0.929)	284 (0.919)	293 (0.930)
Number Alive (48 hr)	306 (0.927)	284 (0.916)	281 (0.909)	291 (0.924)

* Preliminary summary tag-recapture data on fish introduced into McNary Dam Unit 9, May–June 1999. Proportions are in parentheses. For example, 5 test fish or 0.015 of the 330 total test fish experienced separation of balloons from their bodies.

The “Number Released” row indicates the number of fish that were tagged and released in each location. The “Number Recaptured Alive” and “Number Recaptured Dead” rows are self-explanatory. “Tag Separation” refers to tags that were recovered without fish attached to them. These are assumed to be direct mortalities. The “Unknown”, “Number Held” and “Number Alive” categories indicate fish that had no radio signal and were never recovered, live fish placed in holding tanks after recovery, and fish alive after 48 hours holding, respectively. The “Unknown” category has a few more fish than usual for this type of study. This is most likely the result of unfavorable tailrace conditions for fish recovery (high spill levels). These fish are removed from the data set when calculating survival estimates. The low number of fish that died during the 48-hour holding period is typical for this type of study.

The survival probabilities for test fish that passed near the hub, the tip of the turbine runner, and near the turbine wicket gates are shown in Table 18. The probabilities shown are relative to fish survival through the mid-blade region of the turbine runner. The design for this study did not use controls, so effects on fish injury and survival such as tagging, release mechanism, and other experimental factors could not be identified and separated from the data and results. In addition, in the following table some 48-hour holding period survival estimates are higher than the 1-hour survival estimates. This is due to more of the mid-blade release fish dying during holding than fish experiencing other treatments.

Table 18. 1 hour and 48 hour relative survival probabilities for fish introduced near the hub, blade tip, and wicket gate of turbine unit 9 at McNary Dam, 1999. The 90% confidence intervals for the estimates are given in parentheses.

HOLDING PERIOD	RELEASE LOCATION		
	NEAR RUNNER HUB	NEAR RUNNER TIP	WICKET GATE
1 hour	0.980 (0.955-1.005)	0.983 (0.957-1.008)	0.978 (0.952-1.004)
48 hours*	0.984 (0.955-1.014)	0.986 (0.956-1.016)	0.985 (0.955-1.014)

* 48-hour survival cannot exceed 1-hour survival, thus survival for the study is established at 1-hour.

As can be seen from the numbers, survival was relatively high through all routes. Statistically, the survival rates for the three passage routes are not different, as is obvious from the almost total overlap of the estimates' confidence intervals. The 1-hour survival estimates are the final estimates for the study because the longer holding period, 48-hour, survival estimates cannot logically be higher than the 1-hour holding period. The slight increase in survival difference between the 1-hour and 48-hour survival estimates was due to a very small difference in the proportion of holding period mortality between the reference release group and the other treatment groups. Since the study focused on the differences between the release points, particularly the differences between the mid-blade release and the other three, there was no control release for this study. All three of the other release points had survivals between 98 and 99 percent relative to the mid-blade release. The expectation that mid-blade passage survival would be best was realized since all relative survivals, which were calculated relative to survival for fish passing mid-blade, were less than 1.0. One reason for these high survival values, along with the small differences in survival between release points, may have been that the test was conducted under only one set of turbine settings. Blade and wicket gate angles were fixed throughout the test.

During equipment removal following the test, fish balloons were found in the draft-tube slot, indicating that some fish may have been trapped there during the study. This indicated the possibility that some fish get trapped in an area that is predictable.

4.1.1.3 Bonneville First Powerhouse MGR Biological Evaluation 1999-2000 (Tuned Turbine)

As part of the Corps' Turbine Survival Program, survival probabilities were estimated for hatchery-reared Chinook salmon (*Oncorhynchus tshawytscha),* average total length of approximately 6.54 inches, which passed through Units 5 (existing) and 6 (MGR) at Bonneville Dam in November 1999 through January 2000. (Normandeau Associates, Inc. et al. 2000) The new MGR runner was designed to minimize the gap between the blade and hub and the blade tip and discharge ring. This design improves the turbine efficiency at most operating points and has the potential to improve fish survival. The study's primary objective was to test whether passage survival through the MGR unit equals or exceeds that through the original design runner. Secondary objectives were to determine (1) whether the peak turbine operating efficiency is correlated with turbine passage survival; (2) the effectiveness of gap minimization in reducing fish injury and mortality rates; and (3) the injury mechanisms in turbine areas where fish injuries occur. The study was designed as a two-by-three-by-four factorial design (two turbines x three release locations x four power levels).

Sufficient numbers of fish were to be released so that the resulting survival probabilities would be less than or equal to ±3 percent, 90 percent of the time.

The study objectives were accomplished by releasing fish through an induction system (see Figure 41 and Appendix A.1.4) designed to pass fish near the blade tip, mid-blade, and hub regions in each turbine, at four discrete power levels. The four power levels at Unit 5 and the corresponding operating efficiencies for Unit 5 were:

- Power level 1 – near the lower end of the one-percent operating limit
- Power level 2 – slightly below the peak operating efficiency
- Power level 3 – beyond the peak operating efficiency
- Power level 4 – near the upper one-percent operating limit

The same power levels were tested for the MGR unit, but at Unit 6 the turbine operating efficiencies were different than those for Unit 5, the turbine efficiencies for Unit 6 at each power level were:

- Power level 1 – below the lower one-percent operating limit
- Power level 2 – slightly below the peak operating efficiency but within the one-percent operating limit
- Power level 3 – beyond the peak operating efficiency but within the one-percent operating efficiency
- Power level 4 – beyond the upper one-percent operating limit

The power levels and efficiencies for both Unit 5 and 6 are shown in Figure 56 in Section 3.2.2.4.3.

The absolute efficiency of the MGR was greater than or equal to that of the existing unit at all test points. While there were efficiency differences between the test units, the study was designed so that discharge through the units would be as similar as possible. Target discharges for the four power levels were 6.2, 7.0, 10.5, and 12.0 kcfs respectively. Three separate metrics of fish survival were used to assess the effectiveness of the MGR in fish passage: (1) the estimation of turbine released fish survival relative to the survival of control fish released downstream into the turbine discharge (this included fish that were alive at 1 hour and 48 hours, regardless of their condition); (2) estimation of safe passage or unaffected fish (all injured fish and those showing loss of equilibrium were assumed dead and were considered as not safely passing the turbine) and (3) estimation of relative survival (based on estimating survival of blade tip and hub released fish relative to the survival of fish released near the mid-blade region). The latter estimation procedure was identical to that used in the recent study completed at McNary Dam, also a part of the Corps' Turbine Survival Program. Estimates apply only to the direct effects of the turbine runner and draft-tube passage because the fish were released downstream of the stay vanes.

Recapture rates (physical retrieval of alive and dead fish) were high and met the pre-specified expectation used for sample size calculations prior to initiating the study. Recapture rates of treatment fish mostly exceeded 95 percent (range 94.6 to 99.1 percent) and those of controls were greater than 97 percent (range 97.6 to 100.0 percent). Most fish were recaptured within 500 yards downstream of the powerhouse; recapture times for controls averaged less than 7 minutes in any sample block (range 5.1 to 6.6 min) while those for the treatment fish were higher (average range 7.2 to 15.4 min). Treatment fish were generally retrieved at greater distances from the powerhouse than the controls.

The study established that fish passage survival through the new MGR Unit 6 was equal to or better than through an existing unit. This was most evident for blade tip released fish. Depending upon the power level, absolute survival of the blade tip released fish in Unit 6 was up to 3-percent higher than for those passing near the blade tip in the existing Unit 5. Survival probabilities of mid-blade released fish were similar in both units except at power level 1 in MGR Unit 6 where survival was 2.2 percent higher than in Unit 5 (97.1 versus 94.9 percent). Survival probabilities of hub released fish were mostly greater than 0.98 in both units.

Of the 24 independent 48-hour absolute survival estimates (Table 19, survival estimates' standard errors are in parentheses), twenty were ≥0.95, two were 0.94, and two were 0.91 to 0.92. The lowest point survival rates were observed for the blade tip released fish in Unit 5 at power levels 2 and 4. Overall, significant differences (P<0.05) in survival were observed between release locations but not between turbines (P>0.05); the 48-hour survival of blade tip released fish was lower than for the mid-blade and hub released fish. Survival between hub released and mid-blade release locations was not significantly different (P>0.05). The estimates of absolute survival can be categorized as having an increasing gradient from blade tip to mid-blade to hub. The 24 independent estimates of absolute survival are summarized as follows (probabilities ≤0.92 are highlighted):

Table 19. Independent Estimates of Absolute Survival – 48-hour. Standard Errors in Parentheses

RELEASE LOCATION	POWER LEVEL 1	POWER LEVEL 2	POWER LEVEL 3	POWER LEVEL 4
	Unit 5 (Existing)			
Blade tip	0.945 (0.018)	0.920 (0.020)	0.957 (0.017)	0.908 (0.020)
Mid-blade	0.949 (0.019)	0.955 (0.015)	0.970 (0.015)	0.971 (0.015)
Hub	0.988 (0.013)	1.017 (0.078)	0.970 (0.017)	1.012 (0.007)
	Unit 6 (MGR)			
Blade tip	0.948 (0.017)	0.943 (0.018)	0.976 (0.014)	0.939 (0.017)
Mid-blade	0.971 (0.016)	0.954 (0.016)	0.961 (0.016)	0.966 (0.016)
Hub	0.982 (0.015)	0.982 (0.015)	0.982 (0.015)	0.982 (0.015)

Blade tip survival differences between units became more magnified when the safe fish passage metric was used (Table 20). Safe fish passage estimates include both injury and mortality while absolute survival estimates are based on mortality alone. Safe passage was 1.9 to 3.1 percent higher for blade tip passed fish in MGR Unit 6 than for Unit 5 blade tip fish. Safe passage estimates for mid-blade fish in both units were similar (range of 0.948 to 0.960 in Unit 5 and 0.947 to 0.965 in Unit 6). However, except for power level 3, safe passage for hub-released fish in Unit 5 was 2.4 to 3.6 percent higher than in Unit 6. The 48-hour estimates of safe passage are summarized in Table 20 (the estimates' standard errors are in parentheses), with survival probabilities <0.92 highlighted:

Table 20. Estimates of Safe Passage – 48 hour. Standard Errors in Parentheses				
RELEASE LOCATION	**POWER LEVEL 1**	**POWER LEVEL 2**	**POWER LEVEL 3**	**POWER LEVEL 4**
	Unit 5 (Existing)			
Blade tip	0.918 (0.023)	0.915 (0.021)	0.947 (0.078)	0.900 (0.022)
Mid-blade	0.948 (0.020)	0.948 (0.017)	0.960 (0.017)	0.956 (0.017)
Hub	0.988 (0.014)	0.998 (0.011)	0.968 (0.017)	0.998 (0.011)
	Unit 6 (MGR)			
Blade tip	0.948 (0.019)	0.934 (0.019)	0.970 (0.015)	0.931 (0.019)
Mid-blade	0.952 (0.020)	0.947 (0.016)	0.951 (0.017)	0.965 (0.016)
Hub	0.956 (0.019)	0.962 (0.019)	0.982 (0.014)	0.974 (0.016)

With respect to the results of relative survival probabilities, hub-released fish had higher survival relative to the survival of mid-blade fish in both units (1.04 in Unit 5 and 1.02 in Unit 6) while the survival of blade tip fish was lower than that of mid-blade released fish (0.97 in Unit 5 and 0.99 in Unit 6). Estimates of route-specific relative mortality were made for comparison with the results of the McNary Dam 1999 turbine passage survival study. Survival estimates for the McNary Dam 1999 study were made relative to the survival of fish passing through the mid-blade region of the turbine runner.

No statistically significant correlation was found between fish passage survival and turbine operating efficiency in either turbine. However, the highest point estimates of both absolute and safe passage survival in both units, at each of the release locations, occurred at power level 3 (beyond the peak efficiency and towards the upper one-percent operating limit); 48-hour survival probabilities for this power level equaled or exceeded 0.96 (range 0.96 to 0.98).

The incidence of fish injury was lower for fish passing through the MGR Unit than through the existing Unit 5. Incidence of injury was reduced by approximately 40 percent in the MGR unit (2.5 percent for Unit 5 and 1.4 percent for MGR). Reduction in injury was evident for blade tip passed fish (existing runner fish had a 3.9 percent injury rate versus 1.9 percent for the MGR) and the mid-blade region (2.3 percent in Unit 5 versus 1.0 percent in MGR). Very few hub-released fish were injured in either turbine (0.7 percent for Unit 5 and 1.0 percent for Unit 6).

At both turbines, most injuries were attributed to shear and mechanical forces. Shear inflicted injuries were primarily characterized by partial decapitation, hemorrhaged or ruptured eye, and damaged gill or operculum. Mechanical injuries were primarily lacerations, severed body or external bruises. The presence of some severely injured MGR passed fish indicates that some hazardous features are still present, though at a reduced level, and further investigations may be needed to better identify what other areas within the turbine environment could be improved.

Although experience from other sites shows that hub gap minimization is beneficial to safe fish passage, its effectiveness at the Bonneville Dam MGR Unit 6 could not be fully verified because the terminus of the pipe for hub releases may have actually passed fish some distance away from the hub and along the blade region. This was supported by low fish injury rate and high survival rate in Unit 5 and the absence of pinching type injuries typical of gap-related damage. Unfortunately, these findings came to light too late for corrective actions to be implemented in the midst of the field experiment. Since the effectiveness of closing the hub gaps in the MGR unit may not have been fully evaluated in the present study, additional fish releases known to specifically pass the hub gaps would be beneficial. High survival (0.97 to 1.0) and low injury (≤1.0 percent) rates of hub passed fish in both units, however, suggest that duplicating the localized hydraulic conditions found elsewhere in the turbine environment, could further enhance safe fish passage over a wide range of operating conditions.

Subsequent investigations were conducted using the Bonneville ERDC-WES physical turbine model (see section 2.6.2.2.2) to evaluate whether or not test fish were likely to pass through the test turbines where they would be exposed to blade tip and hub gaps. The results varied with discharge, but the overall result was that beads did not consistently pass through the two runners in regions where they would be exposed to turbine runner gaps (only the original runner has appreciable gaps at the runner hub and tip). Under the assumption that test fish passage through prototype units would be similar to that of beads through physical models, it was concluded that the study was inconclusive regarding the biological benefits of turbine runner gap closure, particularly that at the turbine runner hub.

Finally, the study revealed a previously unknown passage issue which, when resolved, may also add to the overall fish survival enhancement. About 2.3 percent of the released fish, primarily blade tip and mid-blade, were entrapped in the tailrace stop log slots. Entrapment in these highly turbulent areas may cause delay for fish in exiting the draft-tube, transport fish into a backroll like environment or abrasive areas, and subject fish to stress, which may lead to predation. The magnitude of this potential problem and its possible solution could be ascertained by sampling naturally entrained fish in the tailrace stop log slots. It is unknown whether this issue is site-specific to Bonneville or relevant to other projects as well.

As in the case of exposure to gaps at the tip and hub of runner blades, studies conducted subsequent to this study provide additional information about exposure of migrating fish to the turbine draft-tube tail log slot at Bonneville Dam's First Powerhouse. This finding of this study (USGS 2002 AFEP Annual Review PowerPoint Presentation) relative to tail log slot entrainment is presented in Section 4.5. While entrainment was observed, the study was not able to evaluate the consequence of entrainment on fish health. Therefore, the impact, if any, of tail log slot entrainment on the health of migrating juvenile salmonids remains unresolved.

4.1.1.4 McNary TSP Test Unit 2002: Biological Tests of Direct and Indirect Turbine Passage Survival and Sensor Fish Device Estimation of Turbine Passage Conditions (Tuned Turbine)

4.1.1.4.1 Balloon Tag Testing of Direct Turbine Passage Survival

The biological performance of a test turbine unit at McNary Dam was evaluated in the spring of 2002 (Normandeau Associates, Inc. et al. 2002). Balloon tag and radio-tagging methods were used to obtain estimates of direct and total turbine passage mortality respectively. In addition to these biological tests, sensor fish devices were used to characterize the passage conditions experienced by fish during turbine passage.

The experiment using the HI-Z tag-recapture technique (balloon tag) was designed to estimate survival probabilities (1 hour and 48 hour) of hatchery-reared Chinook salmon, *Oncorhynchus tshawytscha* (average total lengths about 6 to 6.2 inches in April and 5.6 inches in May), in passage through turbine Unit 9 at McNary Dam at four operating conditions corresponding to the following power outputs:

Condition 1: lower end of one-percent operating limit for Unit 9

Condition 2: upper end of one-percent operating limit for Unit 9

Condition 3: 2-percent drop (additional one-percent beyond upper one-percent) for Unit 9

Condition 4: maximum on cam blade position for Unit 9

These four conditions are referenced as discharge levels 8,000, 11,200, 14,000, and 16,400 cfs. All four discharge levels were tested in April; only the 11,200 and 16,400 cfs discharges were tested in May. The actual four discharges tested during the April fish releases averaged 7,700, 12,000, 13,400, and 16,600 cfs. Peak operating efficiency occurs near 11,200 cfs. The May fish releases were contingent upon the acceptability of the April results at 11,200 and 16,400 cfs and were to coincide with releases of radio-tagged fish to obtain direct, as well as indirect, effects of passage. The balloon tag-recapture technique was to provide an estimate of the direct effects of passage, and radio telemetry was to provide an estimate of the total effects of passage. Survival probabilities, particularly for the April releases, were to be estimated within ≤±0.03, 90 percent of the time.

Although fish were released in each of the three intake bays of turbine Unit 9, the objective was to obtain composite survival estimates for the four operational levels. Model studies at ERDC-WES had indicated that beads released just below the fish diversion screens in the intake would be broadly distributed during turbine passage. See Section 2.4.2.2.2 for additional information.

Recapture rates (physical retrieval of alive and dead fish) ranged from 91 to 99 percent for treatment groups and from 97 to 100 percent for controls. The percentage of fish classified as dead or to unknown status was higher for the May releases than for the April releases, for treatment groups it ranged from 0.7 to 5.4 percent in April and from 8.4 to 8.9 percent in May. The respective ranges for controls were 0 to 3.3 percent and 2.3 to 3.1 percent. The actual percentage of dead fish recaptured was generally ≤2 percent for any treatment group; control dead fish percentages were 0.0 to 1.7 percent. The spill volume and its attendant unique flow patterns may have contributed to the higher than expected percentage of fish classified dead or to unknown status. Hydrological conditions differed between the April and May releases since spill was more prevalent in the May releases than in April.

Retrieval times were similar within treatment and control groups in both months. However, retrieval times for treatment groups (average 9 to 14 minutes) were twice those for controls, particularly during periods of spill (when more of the treatment fish were carried laterally across the face of the powerhouse or into a deeper channel prior to balloon inflation and subsequent recapture). Maximum spill rates during testing in April and May were 160,000 and 102,000 cfs, respectively.

All 48-hour survival probabilities equaled or exceeded 0.93; the lowest survival (0.93, 90 percent CI=0.90 to 0.97) occurred at 11,200 cfs (near peak efficiency) in May. The highest survival (0.983, 90 percent CI=0.957 to 1.00) occurred at 14,000 cfs, a discharge beyond the one-percent peak efficiency discharge.

Direct effects appear reproducible, as observed from the similarity in 48-hour probabilities at two discharges (11,200 and 16,400 cfs) tested in both April and May. At 11,200 cfs in April survival was estimated at 0.955 (90 percent CI=0.931 to 0.982) and in May at 0.930 (90 percent CI=0.900 to 0.970). At 16,400 cfs the estimated survival was virtually identical (0.945, 90 percent CI=0.925 to 0.964 in April and 0.953, 90 percent CI=0.918 to 0.994 in May). The lower estimate in May at the 11,200 cfs discharge could have resulted from more fish either experiencing dislodgment of tags or increased predation. Indirect evidence suggests that some predation may have been caused by sturgeon.

The hypothesis that the highest survival is correlated with peak turbine operating efficiency was not supported by the results of the present study. The highest survival (0.983) occurred at a discharge higher (14,000 cfs) than at the discharge associated with peak efficiency (11,200 cfs) (0.93 to 0.955). In fact, survival probabilities (0.944 to 0.953) at other discharges (8,000 and 16,400 cfs) were more similar to those at the peak efficiency discharge than at 14,000 cfs.

Estimated 48-hour survival probabilities and 90 percent confidence intervals in April and May are summarized in Table 21.

Table 21. Estimated 48-hour Survival Probabilities and 90% Confidence Intervals

	8,000 CFS	**11,200 CFS**	**14,000 CFS**	**16,400 CFS**
April	0.944 (0.914-0.977)	0.955 (0.931-0.982)	0.983 (0.957-1.00)	0.945 (0.925-0.964)
May	--	0.930 (0.90-0.97)	--	0.953 (0.918-0.994)

Injury rates for examined fish at the flow conditions tested in April and May were 2.6 and 2.3 percent, respectively. When April and May data are combined, the most prevalent injury was severance or decapitation of the body (0.94 percent) followed by hemorrhaged/damaged eyes (0.70 percent). Eight of the twenty severance injuries appear to be pinch related and seem to be more prevalent at the highest discharge level. This may be related to the larger gap dimensions at the blade tip when the blade angle is steep.

4.1.1.4.2 Estimation of Total Turbine Passage Survival using Radio Telemetry

Radio telemetry was used to evaluate the relative survival of juvenile yearling Chinook salmon passing through Turbine Unit 9 at McNary Dam under two operating conditions (Absolon et al. 2002). Test conditions were 11,200 cfs and 16,400 cfs, which represent power generations of 58 and 80 megawatts, respectively. Additional information about the test points can be found in Section 3.2.2.4.4. Run-of-the-river hatchery yearling Chinook salmon were collected at the McNary Dam Juvenile Fish Facility. After being held for 24 hours, test fish were surgically tagged with both a radio and a PIT tag. Prior to release, fish were held for an additional 24 hours to monitor for post-tagging mortality and/or tag loss. Releases were made from 5 May through 11 June.

A total of 589 fish were released through the turbine at the 16,400 cfs load, 588 at the 11,200 load, and 581 were released at a reference release location approximately 4 kilometers downstream of McNary Dam (approximately 500 meters upstream of the I-82 bridge). Three releases of 36 fish each were made daily, including one group released under each turbine operating condition and the third group released at the downstream reference release location. The initial turbine operating condition was alternated daily, and each turbine group was equally divided between the three intake bays of the test unit. Fish were released directly into turbine intake bays through induction pipes installed for this study and concurrent balloon tag and sensor fish studies conducted by Normandeau Associates, Inc. and Battelle's Pacific Northwest Division respectively. Downstream reference releases were made from a boat and spread throughout the daily periods of turbine releases.

Three telemetry receivers and air antenna arrays were used to detect radio-tagged fish as they migrated downstream. Receiving antenna arrays were located at Irrigon, Crow Butte East, and Crow Butte West, and were approximately 6.2, 25.5, and 28.6 miles downstream of McNary Dam, respectively. PIT tag detections at John Day and Bonneville Dams provided additional information.

Estimates of relative survival include survival through the turbine and the 2.5 miles of tailrace immediately downstream of McNary Dam. The point estimate of relative survival (SE) was 83.7 percent (0.013) and 84.9 percent (0.015) at the 16,400 and 11,200 cfs operation, respectively. NMFS concluded there was no difference in survival through Turbine Unit 9 when operated at 16,400 and 11,200 cfs.

4.1.1.4.3 *Summary Tables of Turbine Passage Survival Estimates for Columbia and Snake River Mainstem Dams*

Table 22. Turbine Passage Survival Estimates for Lower Granite Dam

YEAR	REPORT	STUDY METHOD	TEST FISH	TREATMENT RELEASE LOCATION	REFERENCE RELEASE LOCATION	TURBINE OPERATION	RELATIVE DIRECT TURBINE PASSAGE SURVIVAL	RELATIVE TOTAL PASSAGE ROUTE SURVIVAL
1988	Giorgi et al. 1988	PIT	Yearling Chinook	Point release in turbine intake	Downstream from Unit 3 turbine boil	Normal Load Response	0.831 (95% CI 0.741-0.922)	Not Estimated
1993	Iwamoto et al. 1994	PIT	Yearling Chinook	Point release in turbine intake	Lower tailrace midriver off juvenile bypass outfall	Normal Load Response	Not Estimated	0.823 (SE 0.025)
1994	RMC Environmental 1994	Balloon Tag	Yearling Chinook	Point release in turbine intake EL 623'	Draft-tube exit	Normal Load Response	0.946 (90% CI 0.955-0.992) 1 hr survival	Not Estimated
1995	Normandeau 1995	Balloon Tag	Yearling Chinook	Point release in turbine intake EL 603'	Draft-tube exit	18 kcfs Discharge	0.975 (90% CI 0.955-0.992) 1 hr survival	Not Estimated
				Point release in turbine intake EL 603'			0.975 (90% CI 0.955-0.992) 1 hr survival	
				Point release in turbine intake EL 603'			0.953 (90% CI 0.928-0.973) 1 hr survival	
				Point release in turbine intake EL 603'			0.972(90% CI 0.949-0.989) 1 hr survival	
				Point release in turbine intake EL 603'		13.5 kcfs Discharge	0.946 (90% CI 0.922-0.965) 1 hr survival	
				Point release in turbine intake EL 603'		19 kcfs Discharge	0.949(90% CI 0.925-0.979) 1 hr survival	
				Pooled		0.961 (90% CI 0.951-0.969) 1 hr survival		

Table 23. Turbine Passage Survival Estimates for Little Goose Dam								
YEAR	**REPORT**	**STUDY METHOD**	**TEST FISH**	**TREATMENT RELEASE LOCATION**	**REFERENCE RELEASE LOCATION**	**TURBINE OPERATION**	**RELATIVE DIRECT TURBINE PASSAGE SURVIVAL**	**RELATIVE TOTAL PASSAGE ROUTE SURVIVAL**
1993	Iwamoto et al. 1994	PIT	Yearling Chinook	Point release in turbine intake	Lower tailrace midriver off juvenile bypass outfall	Normal Load Response	Not Estimated	0.920 (SE 0.025)
1997	Muir et al. 1998	PIT	Yearling Chinook	Point release in turbine intake	Lower tailrace midriver downstream of juvenile bypass outfall	Normal Load Response	Not Estimated	0.934 (SE 0.016)

Table 24. Turbine Passage Survival Estimates for McNary Dam								
YEAR	**REPORT**	**STUDY METHOD**	**TEST FISH**	**TREATMENT RELEASE LOCATION**	**REFERENCE RELEASE LOCATION**	**TURBINE OPERATION**	**RELATIVE DIRECT TURBINE PASSAGE SURVIVAL**	**RELATIVE TOTAL PASSAGE ROUTE SURVIVAL**
1999	Normandeau 1999	Balloon Tag	Yearling Chinook	Turbine intake upstream of wicket gate	Stay vane – mid runner blade	12 kcfs	0.98(90% CI 0.955-1.005) 1 hr survival	Not Estimated
				Stay vane – runner tip			0.98(90% CI 0.955-1.005) 1 hr survival	
				Stay vane – runner hub			0.978(90% CI 0.952-1.004) 1 hr survival	
2002	Normandeau 2002	Balloon Tag	Yearling Chinook	Point release all three intake bays	Draft-tube exit	8 kcfs	0.944 (90% CI 0.914-0.977) 1 hr survival - April	Not Estimated

Table 24. Turbine Passage Survival Estimates for McNary Dam (cont.)

YEAR	REPORT	STUDY METHOD	TEST FISH	TREATMENT RELEASE LOCATION	REFERENCE RELEASE LOCATION	TURBINE OPERATION	RELATIVE DIRECT TURBINE PASSAGE SURVIVAL	RELATIVE TOTAL PASSAGE ROUTE SURVIVAL
						11.2 kcfs	0.955 (90% CI 0.931-0.982) 1 hr survival - April	
							0.930 (90% CI 0.900-0.970) 1 hr survival - May	
							0.944 (90% CI 0.914-0.977) 1 hr survival - April	
						16.4 kcfs	0.945 (90% CI 0.945-0.964) 1 hr survival - April	
							0.953 (90% CI 0.918-0.994) 1 hr survival - April	
2002	Absolon et al. 2002	Radio Telemetry	Yearling Chinook	Point release all three intake bays	Tailrace 2 km below dam	11.2 kcfs	Not Estimated	0.837 (SE 0.013)
						16.4 kcfs		0.849 (SE 0.015)

Table 25. Turbine Passage Survival Estimates for John Day Dam

YEAR	REPORT	STUDY METHOD	TEST FISH	TREATMENT RELEASE LOCATION	REFERENCE RELEASE LOCATION	TURBINE OPERATION	RELATIVE DIRECT TURBINE PASSAGE SURVIVAL	RELATIVE TOTAL PASSAGE ROUTE SURVIVAL
2002	Counihan et al. Draft Final	Radio Telemetry	Yearling Chinook	Point release turbine intake	Tailrace 1 km downstream from dam	Normal Load Response	Not Estimated	0.778 (SE 0.051) 0%day/60%
								0.832 (SE 0.042) 30%day/30%
2003	Counihan et al. Draft Final	Radio Telemetry	Yearling Chinook	Point release turbine intake	Tailrace 1 km downstream from dam	Normal Load Response	Not Estimated	0.820 (SE 0.043) 0%day/60%
								0.764 (SE 0.046) day/45%night
			Sub-Yearling Chinook					0.719 (SE 0.024) 0%day/60%
								0.722 (SE 0.024) day/30%night

Table 26. Turbine Passage Survival Estimates for The Dalles Dam

YEAR	REPORT	STUDY METHOD	TEST FISH	TREATMENT RELEASE LOCATION	REFERENCE RELEASE LOCATION	TURBINE OPERATION	RELATIVE DIRECT TURBINE PASSAGE SURVIVAL	RELATIVE TOTAL PASSAGE ROUTE SURVIVAL
2000	Counihan et al. 2002	Radio Telemetry	Yearling Chinook	Point release into several turbine intakes	Downstream of dam at proposed bypass outfall	Normal Load Response	Not Estimated	0.869 (95% CI 0.718-1.020)
2000	Absolon et al. 2002	PIT	Yearling Chinook and Coho – Spring Study Period	Point release into several turbine intakes	Downstream of dam at proposed bypass outfall	Normal Load Response	Not Estimated	0.790 (95% CI 0.748-0.834) day
								0.830 (95% CI 0.785-0.878) night
			Sub-Yearling Chinook – Summer Study Period					0.791 (95% CI 0.703-0.890) day
								0.889 (95% CI 0.790-1.000) night

Table 27. Turbine Passage Survival Estimates for Bonneville Dam Second Powerhouse*							
YEAR	REPORT	STUDY METHOD	TEST FISH	TREATMENT RELEASE LOCATION	REFERENCE RELEASE LOCATION	TURBINE OPERATION	PERCENTAGE OF MARKED FISH RECOVERED AT JONES BEACH
1987	Ledgerwood et al. 1990	Coded Wire Tag and Cold Brand	Sub-Yearling Chinook	Upper Turbine – 1 m below gate slot	Tailrace 2.5 km and turbine discharge frontroll	Normal Load Response	Upper Turbine 0.6402; Lower Turbine 0.6528; Frontroll no releases; Tailrace 0.5567
				Lower Turbine – 1 m below tip of STS			
1988				Upper Turbine – 1 m below gate slot			Upper Turbine 0.5024; Lower Turbine 0.5104; Frontroll 0.5095; Tailrace 0.5690
				Lower Turbine – 1 m below tip of STS			
1989				Upper Turbine – 1 m below gate slot			Upper Turbine 0.8298; Lower Turbine 0.8256; Frontroll 0.8637; Tailrace 0.9061
				Lower Turbine – 1 m below tip of STS			

* Recovery percentages for subyearling Chinook salmon release into a turbine intake, the turbine discharge frontroll, and 2.5 km downstream of Bonneville's Second Powerhouse.

Table 28. Turbine Passage Survival Estimates for Bonneville Dam First Powerhouse								
YEAR	REPORT	STUDY METHOD	TEST FISH	TREATMENT RELEASE LOCATION	REFERENCE RELEASE LOCATION	TURBINE OPERATION	RELATIVE DIRECT TURBINE PASSAGE SURVIVAL	RELATIVE TOTAL PASSAGE ROUTE SURVIVAL
1999-2000	Normandeau 2000	Balloon Tag	Yearling Chinook	Stay Vane – Blade Tip	Draft-tube exit	Original Kaplan 6.2 kcfs	0.947 (SE 0.0164	Not Estimated
				Stay Vane – Mid-blade			0.964 (SE 0.0144	
				Stay Vane – Blade Hub			0.986 (SE 0.019	
				Stay Vane – Blade Tip		Original Kaplan 7.0 kcfs	0.933 (SE 0.0166	
				Stay Vane – Mid-blade			0.959 (SE 0.0137	
				Stay Vane – Blade Hub			1.009 (SE 0.077	
				Stay Vane – Blade Tip		Original Kaplan 10.5 kcfs	0.963 (SE 0.0145	
				Stay Vane – Mid-blade			0.986 (SE 0.0106	
				Stay Vane – Blade Hub			0.968 (SE 0.016	
				Stay Vane – Blade Tip		Original Kaplan 12.0 kcfs	0.909 (SE 0.0189	
				Stay Vane – Mid-blade			0.968 (SE 0.0139	
				Stay Vane – Blade Hub			1.004 (SE 0.0063	
				Stay Vane – Blade Tip	Draft-tube exit	MGR Kaplan 6.2 kcfs	0.955 (SE 0.0155	Not Estimated
				Stay Vane – Mid-blade			0.981 (SE 0.0116	
				Stay Vane – Blade Hub			0.986 (SE 0.018	
				Stay Vane – Blade Tip		MGR Kaplan 7.0 kcfs	0.949 (SE 0.0149	
				Stay Vane – Mid-blade			0.963 (SE 0.0134	
				Stay Vane – Blade Hub			0.974 (SE 0.0144	
				Stay Vane – Blade Tip		MGR Kaplan 10.5	0.977 (SE 0.0122	

Table 28. Turbine Passage Survival Estimates for Bonneville Dam First Powerhouse (cont.)

YEAR	REPORT	STUDY METHOD	TEST FISH	TREATMENT RELEASE LOCATION	REFERENCE RELEASE LOCATION	TURBINE OPERATION	RELATIVE DIRECT TURBINE PASSAGE SURVIVAL	RELATIVE TOTAL PASSAGE ROUTE SURVIVAL
				Stay Vane – Mid-blade		kcfs	0.977 (SE 0.0123	
				Stay Vane – Blade Hub			0.986 (SE 0.0119	
				Stay Vane – Blade Tip		MGR Kaplan 12.0 kcfs	0.947 (SE 0.0153	
				Stay Vane – Mid-blade			0.977 (SE 0.0124	
				Stay Vane – Blade Hub			0.980 (SE 0.0132	
2002	Counihan et al. 2003	Radio Telemetry	Yearling Chinook	Point release turbine intake	Tailrace downstream of turbine discharge frontroll	Normal Load Response	1.06 (95% CI +/- 0.057)	Not Estimated
					Tailrace downstream of PH 2 JBS outfall		Not Estimated	1.01 (95% CI +/- 0.031)

4.1.1.4.4 *Characterization of McNary Turbine Passage Conditions Using Sensor Fish Devices*

Sensor Fish Devices were used to study passage conditions for juvenile spring Chinook salmon at McNary Dam in spring 2002 (Carlson, T.J. and J.P. Duncan 2003). The study was conducted by Battelle, Pacific Northwest Division, for the U.S. Army Corps of Engineers and was carried out concurrently with balloon tag studies of passage survival conducted by Normandeau and Associates and radio-tag studies by the National Marine Fisheries Service (NOAA Fisheries). The Battelle study used the sensor fish device, a waterproof nearly neutrally buoyant sensor package, developed by Battelle and DOE, which is sent through operating turbines and spill environments to measure pressure and acceleration changes experienced by live fish during dam passage.

Sensor fish devices (and live fish) were released into turbine Unit 9 at McNary Dam during operation at two target discharges: low (8 kcfs) and high (16.4 kcfs). Differences in the pressure and acceleration time histories and summary statistics for these time histories clearly show that the major features of exposure conditions for fish during turbine passage are a function of turbine discharge.

Acceleration magnitude time histories obtained using sensor fish devices from the time of injection to the completion of data acquisition indicated the following:

- There is little turbulence from the point of injection to the stay vane-wicket gate cascade at both high and low discharge.
- At low discharge, at a time believed to coincide with passage through the stay vane-wicket gate cascade, acceleration impulses indicate a high probability of either strike or scraping of the sensor or response of the sensor to irregular flow conditions (turbulence, shear).
- At both high and low discharge, sensors that are believed to pass high through wicket gate openings measured pulses of acceleration and deceleration. This indicates that flow above the turbine runner may be influenced by interaction between the wicket gates and runner blades. The effect, if any, of these features of exposure conditions on fish safety is unknown.
- No strike events by runner blades were apparent from the acceleration data, indicating, as expected (given the results of physical model investigations and live fish tests at prototype scales), that the probability of blade strike events is low.
- At low discharge the sensor can remain within the immediate turbine runner environment for as long as one revolution (700 milliseconds). The impact of longer durations within the runner environment on fish safety is unknown. These observations are consistent with those made by bead tracking in the McNary 1:25 scale physical turbine model.
- Turbulence experienced during passage through the draft-tubes, from the point of draft-tube entry immediately below the turbine runner to the exit into the powerhouse tailrace, was consistently higher overall at low discharge for sensors injected into intake bay C and consistently lower overall at low discharge for sensors injected into intake bay A. These observations validated the McNary physical model findings of irregular loading of draft-tubes at low discharge and also demonstrated that the exposure history of fish to turbulence at low discharge appears to depend upon the intake bay of entry.
- Turbulence experienced by the sensor during passage through draft-tubes at high discharge was low in magnitude (as indicated by sensor accelerometer data) and more uniform across intake bays.
- A comparison of sensor fish device exposure indices for the McNary turbine at high and low discharge, with those for studies conducted at Bonneville and The Dalles Dam spillways in 2002, suggests that overall turbulence exposure in turbines is lower than in spill. This comparison suggests that the risk of injury from turbulence exposure to turbine-passed fish in draft-tubes may be low.
- Consideration of the magnitudes of exposure indices for draft-tube turbulence, under the worst case conditions observed for the McNary turbine at high and low discharge, compared to exposure indices for spillway stilling basins suggests that the main location for injury to fish passing through the turbine environment is between the stay vane-wicket gate cascade and the trailing edge of the runner blades.

Pressure time histories for turbine passage indicated the following:

- The nadir (lowest pressure point) in the pressure time history from passage of the sensor fish device (from injection into a turbine intake bay, through the stay vane-wicket gate cascade, to exit from the turbine runner), provides a very distinctive pressure signal that can be used as a timing mark to estimate the location of the sensor before and after exit from the turbine runner.
- The rate of change in pressure during passage of the sensor through the runner is less and the nadir in pressure is higher at lower discharge. Observed mean total pressures (measured gage plus estimated atmospheric) over all sensor releases for the nadir at low and high discharge were 21.6 and 14.95 psi (149.219 and 103.059 kilopascals) respectively.
- There is considerable variability in the lowest pressure observed at any discharge. This is a consequence of the complex distribution of pressure within the runner environment and the large number of possible trajectories, and therefore pressure time histories, for sensors and fish passing through a turbine runner. The ranges in nadir total pressures observed for low and high discharge were 12 to 25.9 psi (82.924 to 178.526 kilopascals) and 10.6 to 17.4 psi (73.079 to 119.690 kilopascals) respectively.
- The observed mean rates of change in pressure during the 200 milliseconds immediately prior to the pressure nadir were -215.272 and -736.360 kPa/sec for low and high turbine discharge respectively.
- Minimum and maximum mean rates of change in pressure during the 200 milliseconds immediately prior to pressure nadir were -18.28 and -48.32 psi/sec (-126.036 and -333.121 kPa/sec) at low turbine discharge and –31.22 and 143.7 psi/sec (-526.070 and 990.777 kPa/sec) at high turbine discharge.
- A review of literature describing laboratory and field-testing of juvenile salmonids to simulated and actual turbine pressure time histories indicates that the consequences of exposure of depth-acclimated salmonids to turbine pressure time histories is incomplete and has remained unresolved. Observations of pressure time histories, obtained using the sensor fish device, indicated that pressure nadirs and rates of change exist, particularly at higher turbine discharge. Furthermore, these observations showed that these conditions certainly pose significant risk to physoclistous fish and may also pose risk to depth-acclimated physostomous fish as well.

Comparisons of observed pressure time history nadirs with laboratory observations of the effects of turbine passage on the buoyancy of juvenile fall Chinook, indicated the possibility of negative buoyancy for an unknown portion of the juvenile salmonid population for a period of time following turbine passage. This risk would increase with increasing turbine discharge for existing mainstem Kaplan turbines. A review of laboratory data suggests that a threshold on “burping” of air from the swimbladder, in terms of the ratio of exposure pressure (nadir pressure) to acclimation pressure, may exist for juvenile salmonids. Fish experiencing negative buoyancy in the tailrace might seek to achieve neutral buoyancy by moving to the surface to obtain air to inflate their air bladders. Movement toward the surface might expose migrants to higher predation risk, or, the negative buoyancy may keep them deeper in the water and safe from birds in the first minute after passage.

4.1.2 Fish Distribution

Knowledge of the vertical distribution of fish passing through a turbine intake, particularly at passage through the wicket gate openings, is required to help identify operational and design changes that might benefit the total population of fish passing through the turbine environment. Fish that pass high through the wicket gates pass near the hub, those passing mid-wicket gate pass mid-blade, and those passing near the bottom of the wicket gate pass near the tips of the runner blades. Turbine passage survival conditions vary through each of these routes depending upon the internal geometry of the turbine at a particular operating point and the discharge through the turbine. In general, a passage route causing a relatively high rate of injury to a small number of fish may be less of a concern than another area causing relatively lower rate of injury, but to a much larger proportion of the total population passing through the turbine.

4.1.3 Fish Trajectory Mapping

In studies conducted by Battelle, three-dimensional, ultrasonic tracking was used to observe the spatial and temporal components of trajectories for juvenile steelhead trout, juvenile Chinook salmon, and neutrally buoyant drogues. These studies monitored the fish during passage through the intake of a Kaplan turbine at McNary Dam at two turbine operating conditions: 40 and 60 megawatt loads (Carlson, Weiland, Sutton et al. 2001). The purpose of these studies, conducted in September 1999 and July 2000, was to determine whether particle tracking (of beads) in physical models could be used to accurately estimate the trajectories of fish during transit through a turbine intake.

Carlson, et al. (2001) found that the trajectories of both juvenile steelhead trout and Chinook salmon were significantly different at the $p<0.05$ level from those of drogues at both turbine operating conditions. The trajectories of the fish differed most from those of the drogues in the elevation component of their trajectories. The larger juvenile steelhead trout showed a higher activity level during transit than did the smaller juvenile Chinook salmon. Both species of fish dispersed more than drogues during intake transit; however, dispersion of both fish and drogues was great enough that it is probable that their vertical distribution extended over the full height of the turbine wicket gate openings by the time they transited the intake and approached the stay vane-wicket gate cascade. Activity by fish appeared to account for about half of their observed dispersion during intake transit. Carlson et al. (2001) concluded that particle tracking of passively transported beads in physical models would not accurately depict live fish movement in turbine intakes.

4.2 Direct Physical Injury Mechanisms

Total turbine passage mortality has two components, direct and indirect mortality. Direct mortality is the consequence of injury sustained during passage through the turbine environment. Indirect mortality caused by predation in the powerhouse tailrace is believed to be related to turbine passage, but the relationship is not well understood. Some of the indirect mortality is most likely consumption of injured and temporarily disabled turbine-passed fish by birds and piscivorous fish. Other causes may also be the predation of healthy fish that are rendered more vulnerable by being discharged into a region with a high concentration of predators and poor egress conditions.

Direct physical injuries are those injuries fish experience during passage through the turbine environment. Injuries to test fish are not observed except when the test fish are recovered following turbine passage. At this time only one methodology, balloon tagging, permits recovery of test fish immediately following turbine passage. When fish are recovered following turbine passage, two general categories of injury are noted. These categories are visible external injuries and injuries that affect behavior. Fish recovered, alive or dead, after turbine passage are examined for a variety of physical injuries. Their behavior is also observed and fish that are stunned, disoriented, or unable to swim normally or maintain equilibrium are noted. Fish recovered dead are necropsied to gain additional information about other injuries not externally visible. Fish recovered live are held for a period of time. Those that die during holding are necropsied, the others are released after holding. Experience from a large number of prototype turbine passage studies and laboratory studies of the consequences of exposure to shear, turbulence, strike, scraping, and pressure cycling, enables researchers to classify observed fish injury to the most likely causal mechanism. This is the process that is used to obtain the injury statistics by likely cause reported by researchers.

Figure 60, from Heisey et al. (2000), shows the distribution of injuries observed for juvenile fish that passed through a turbine at Lower Granite Dam (RMC Environmental Services, Inc. et al. 1994). While specific to the Lower Granite study, the injury distribution is typical for juvenile fish passage studies in general.

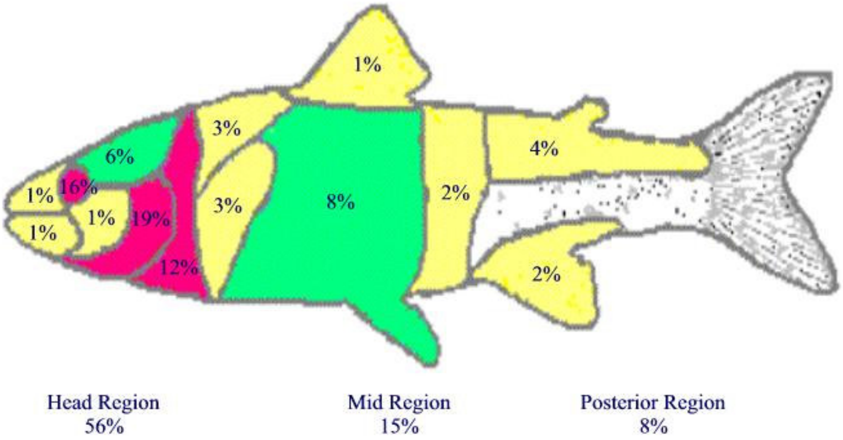


Figure 60. Injury distribution on turbine-passed juvenile salmon passed through Lower Granite Dam. (Heisey et al. 2000)

Since it is not possible to observe the fish during the injury process, it is not possible to classify the cause of injuries observed in turbine-passed fish with absolute certainty; however, experience over a number of turbine studies, coupled with injuries observed in laboratory studies, make it possible to estimate the probable injury mechanism for many injuries. Table 29 (Heisey et al. 2000) lists the percent of injuries by presumed cause for several turbine passage studies conducted between 1994 and 2000 using the balloon tag method.

Table 29. Distribution of Presumed Causes for Observed Turbine Passage Injuries

		MECHANICAL	SHEAR	PRESSURE	COMBINATION
Kaplan Standard	Wanapum	47%	27%	6%	20%
	Rock Island	70%	30%	0%	0%
	Rocky Reach	20%	50%	15%	15%
	McNary	61%	30%	9%	0%
	Bonneville Unit 5	43%	35%	11%	11%
Kaplan Mod.	Rocky Reach	50%	27%	18%	5%
	Bonneville MGR	12%	64%	12%	12%
Fixed Blade	Rock Island	60%	27%	13%	0%
	T.W. Sullivan	64%	13%	13%	10%
Bulb	Rock Island	40%	10%	50%	0%

Table 30 presents an overview of the direct injury mechanisms that are discussed in subsequent sections.

Table 30. Types of Fish Injuries and Locations Within the Turbine Where They Commonly Occur

INJURY	DESCRIPTION	COMMONLY OCCURS
Direct Injuries		
Strike and Scraping	Strike injuries result from fish hitting solid parts of the machine, both moving parts and those that are stationary.	Blades, stay vanes, wicket gates, draft-tube
Pinch	Pinching occurs when salmonids are caught briefly in the gaps between turbine blades or hub.	Blade tips, hub, stay vanes, wicket gates
Shear	Water shear results when two parallel jets of differing velocities of water pass next to or near to each other. Shear injuries may include head damage, torn opercula (gill covers), loss of scales, and damaged or missing eyes. Less severe injuries may include loss of equilibrium and disorientation.	Boundaries (e.g., around turbine blades) and in the periphery of high velocity flows.
Cavitation	Cavitation results when water flow reaches a zone of low pressure where bubbles form, followed by a zone of high pressure that causes the bubbles to collapse. The collapse of these bubbles is violent enough to form very strong localized shock waves, potentially harming nearby fish.	Runner
Differential Velocity	Under sudden acceleration associated with turbulent bursts, the water surrounding a fish can be accelerated more rapidly than the fish. This may result in damage to vulnerable fish tissues such as opercula, gills, and eyes.	Regions of high acceleration
Turbulence	Turbulent flow occurs when fluid particles move in a highly irregular manner, even if the fluid as a whole is traveling in a single direction. That is, there are intense, small-scale motions present in directions other than that of the main, large-scale flow	Throughout the turbine environment.
Pressure	Different regions of pressure exist in the turbine intake and tailrace. Fish passing through the turbine, exposed to this sudden change in pressure, may be harmed.	Turbine runner

4.2.1 Strike and Scraping

Hydroturbines are complex machines with structural features in the flow field required to maintain structural integrity and hydraulic function or hard boundaries such as the concrete walls of the intakes, and draft-tubes. These structural features, because they are in the flow field or contain the flow field, may also be locations for strike and scraping by fish. The use of bead tracking in physical turbine models has helped identify locations where fish may come in contact with turbine structures. Such locations include stay vanes and wicket gates, turbine runner blades, the draft-tube elbow, and the leading edge of draft-tube splitters.

Biological studies conducted at prototypes have not been able to unambiguously identify the locations for strike and scrape injuries observed using live test fish. While there are some types of strike injuries, such as decapitation, that are unlikely to occur by any means other than blade strike (partial decapitation may be caused by shear), there are others that could occur anywhere in the turbine environment. Bead tracking in physical models has been helpful in identifying probable locations for these types of injuries; however, in most studies the incidence of strike and scraping by beads occurs at a much higher rate than the rates of strike and scrape injury observed for live test fish passing through prototypes. It is highly unlikely that 100 percent of fish that come in contact with a turbine surface are injured so it is possible that the rate of contact by beads in the physical model may reflect the rate of surface contact by live test fish in prototypes. A Phase II task of the TSP is to analyze the bead observations in physical models and the biological data from prototype scale tests to learn how to examine physical model data to obtain estimates of fish injury at prototype scales. This type of analysis tool is essential to optimize the use of physical models. The economic gain of improved analysis tools of this type would be substantial. It is significantly cheaper and faster to analyze fish passage conditions of turbine design alternatives using physical models and plastic beads than it is using prototype turbines and live fish.

It seems clear from the prototype fish passage studies conducted to date, along with physical model studies, that there is a low baseline level of fish strike by the leading edge of turbine runner blades. The rate of strike is known to be related to a number of variables such as the runner speed, the number of blades, the angle at which the blades are set, discharge through the unit, and fish length. While all of these factors have an effect on the rate of strike, the fact remains that some small percentage of fish passing through turbines will strike a turbine blade. An ongoing task in TSP Phase II will be the investigation of design alternatives that can reduce the baseline rate of blade strike and that can reduce the probability of injury for fish struck by blades.

4.2.2 Pinching of Fish in Turbine Gaps and Narrow Passageways

In almost every study of fish passage through turbines, test fish are recovered with injuries believed to result from pinching in gaps between structural or mechanical components. Studies using beads in physical models have shown that beads can be caught in gaps at the tip and hub of turbine runner blades and in the spaces between stay vanes and wicket gates. In response to these observations, runners with recessed blade tips and hubs have been built and installed. Such MGRs have very small gaps at their blade tips and hub. Studies of these new runners have shown a decrease in the injury rate of passing fish and almost total elimination of pinching types of injuries (Normandeau Associates, Inc. et al. 2000). On the other hand, prototype scale studies of fish exposed to stay vanes and wicket gates have not been conclusive enough to strongly encourage modification of these structures on units undergoing rehabilitation.

4.2.3 Shear

Shear is believed to be a common cause of injuries in turbine-passed fish showing external visible injury. Shear injuries range from missing eyes to isthmus tears. As an element of their AHTS program the DOE built a flume and other experimental apparatus to create a shear environment and to conduct a series of experiments to investigate the consequences to juvenile fish of exposure to shear. These studies were done with collaboration of scientists and engineers from the COE TSP program. The overall objective of the DOE studies was to specify an index describing the hydraulic force that fish experience when subjected to a shear environment. The following summary of experimental results of exposure of test fish to shear is excerpted from Neitzel et al. 2000.

Elevated levels of shear may result in strain rates that injure or kill fish. At hydroelectric generating facilities, concerns have been expressed that strain rates associated with passage through turbines, spillways, and fish bypass systems may adversely affect migrating fish. Development of safer hydroelectric turbines requires knowledge of the physical forces (injury mechanisms) that impact entrained fish and the fish's tolerance to these forces. It requires up-front, pre-design specifications for the environmental conditions that occur within the turbine system. In other words, determining or assuming conditions known to injure fish will assist engineers in the design of a fish-friendly turbine system. These biological specifications must be carefully and thoroughly documented throughout the design of an advanced turbine. To address the development of biological specifications, DOE researchers designed and built a test facility where juvenile fish could be subjected to a range of shear environments and quantified their biological response.

Test fish included juvenile rainbow trout (*Oncorhynchus mykiss)* spring and fall Chinook salmon (*O. tshawytscha*) and American shad (*Alosa sapidissima).* Fish were exposed to a shear environment produced by a submerged jet over a range of exit velocities from 0 to 21.3 m/s (0 to 70 ft/s). They were introduced in either a headfirst or tailfirst orientation and to the edge of the jet stream (slow-fish-to-fastwater scenario) or within and upstream of the jet stream (fast-fish-to-slow-water scenario). Test fish were captured after leaving the shear environment and specific biological responses noted (i.e., injury and mortality). The behavior or reaction of fish in the shear environment was recorded on high-speed video cameras. Fluid velocities were measured in the jet with a Pitot tube and a Laser Doppler Velocimeter (LDV). Statistical tests were applied to the fish data to estimate the lowest observed effect level and no observed effect level, or the strain rate at which fish were not injured after being subjected to the shear environment. The Pitot tube provided mean velocity information in the axial direction. The mean-flow velocity measurements obtained using the Pitot tube were used to describe the jet centerline velocity and fluid strain rate. This study defined the mean change in water velocity (u) over distance (y) as *strain* rate (e).

$$\text{Exposure Strain Rate} = e = \frac{\partial \bar{u}}{\partial y} \qquad \textbf{(1)}$$

DOE researchers used strain rate as an index of the physical force that fish experience when subjected to the shear environment in our test facility. The rate of strain experienced by test fish varied from 0 cm/s/cm to 1,185 cm/s/cm, based on a spatial resolution of Δy=1.8 centimeters. This interval was based on the minimum width of the salmonids tested. The values reported here are not equivalent to a strain rate computed at a finer scale resolution.

The LDV was used to measure velocity fluctuations and provide information about turbulence intensities. These measurements showed that the turbulence intensity in the area of the jet where fish were subjected to the shear environment was +3 to 6 percent of the estimated strain rate. Test results indicated that fish entering a shear environment may be killed, injured, or their experience may cause increased susceptibility to predation. Fish were subjected to rates of strain up to 1,185 cm/s/cm, $\Delta y=1.8$ centimeters. There were no significant injuries to any fish subjected to rates of strain of less than 517 cm/s/cm, $\Delta y=1.8$ centimeters (Table 31). Of the fish tested, American shad were the most susceptible to injury; steelhead and rainbow trout were the most resistant. Predation susceptibility tests also were conducted with rainbow trout. Rainbow trout only received minor injuries at strain rates near 900 cm/s/cm, $\Delta y=1.8$ centimeters. However, rainbow trout subjected to rates of strain of 688 cm/s/cm, $\Delta y=1.8$ centimeters were more susceptible to predation than control fish in the same test. The test data quantified strain rates and the relationship of these forces to direct and indirect biological effects on fish. The DOE researchers concluded that juvenile salmonids and American shad should survive shear environments where strain rates do not exceed 500 cm/s/cm at a Δy of 1.8 centimeters. Additional studies are planned with sensor fish to better link hydraulic conditions found within the laboratory and field environments.

Table 31. Fish Exposure to Shear Strain

TEST FISH	TEST ORIENTATION	STRAIN RATE (cm/s/cm [ΔY=1.8 cm])		
		NO SIGNIFICANT INJURY	NO SIGNIFICANT MAJOR INJURY	NO SIGNIFICANT DEATHS
Fall Chinook (age-0)	Headfirst	517	852	1008
Fall Chinook (age-1)	Headfirst	517	517	852
Spring Chinook	Headfirst	517	688	1008
Rainbow Trout	Headfirst	688	1008	1008
Steelhead	Headfirst	517	1008	1008
American Shad	Headfirst	517	517	517
Fall Chinook (age-1)	Tailfirst	688	1008	1008
Spring Chinook	Tailfirst	688	1008	1008
Steelhead	Tailfirst	852	1008	1008
Rainbow Trout	Headfirst w/ predators	517	N/A	N/A

The rate of occurrence of shear-like injuries for turbine-passed fish is known from the many turbine passage studies conducted over the last few years. Complementing these data are observations made using physical models of the occurrence of the response of beads and dye to hydraulic conditions believed to be related to shear. However, because the distribution of run-of-the-river fish passing through turbines remains unknown, it is not possible to explain when and where the shear injuries shown by turbine-passed fish occur. It is possible that further analysis of physical model data, the results of biological tests of prototype units, and additional examination of laboratory data will provide information about the location of the shear injuring fish during turbine passage. It is also possible that further development in computational fluid dynamics models will provide another tool to better understand this injury mechanism.

4.2.4 Pressure

As fish pass through a turbine they are exposed to a unique pressure time history. In the case of the large Kaplan turbines at mainstem Columbia River dams, pressure decreases as the fish approach the turbine runner, undergoes a rapid decrease during passage through the runner, then increases as the fish enters the turbine draft-tube and is carried into the tailrace. An example of the pressure time history experienced by fish acquired at McNary Dam using a “sensor fish” is shown in Figure 61 (Carlson and Duncan 2003).

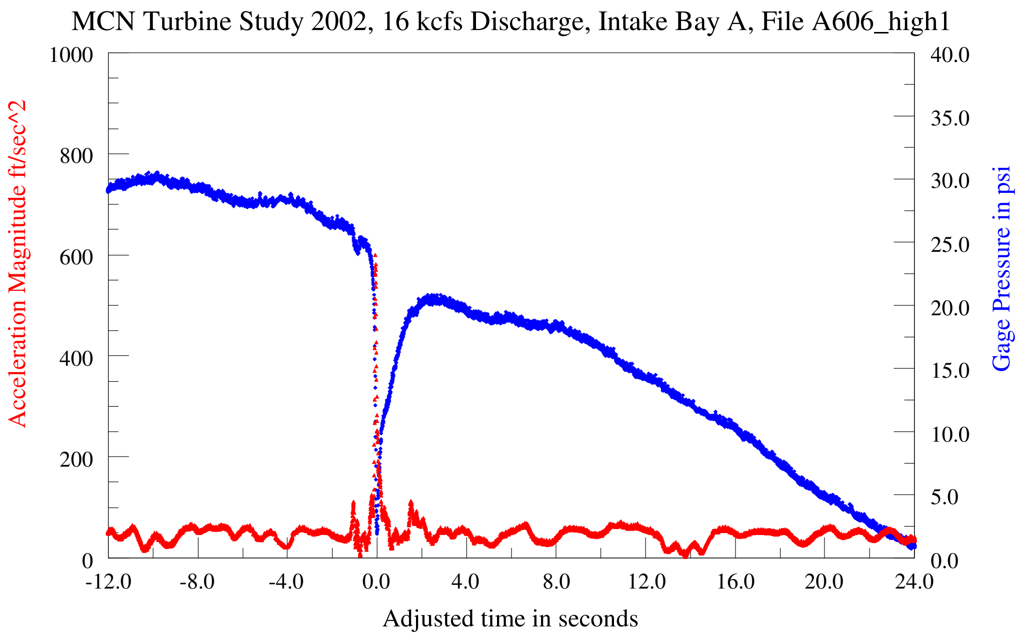


Figure 61. The time history of sensor fish device response to pressure and turbulence during passage through a turbine Unit 9 at McNary Dam at a turbine discharge of 16 kcfs. The blue line is gage pressure in psi. The red line is acceleration magnitude in ft/sec^3. Time zero is when the sensor is immediately below the turbine runner. Exit from the turbine draft tube is estimated at about time +6.0 sec. Time -12 sec is shortly after injection of the sensor into the turbine intake. (Carlson and Duncan 2003).

Exposure of fish to pressure cycles typical of passage through Kaplan turbines has been extensively studied. Since they have a duct leading from the air bladder to the esophagus that permits them to expel air from the bladder, salmonids typically experience a low rate of injury from pressure effects during turbine passage. However the dynamics of air expulsion from their air bladders by salmonids are not well understood and, because of the lack of tests of fully depth-acclimated fish, study of the effects of pressure changes during turbine passage are incomplete. An extensive review of the literature of the response of fish to pressure cycling can be found in Cada et al. 1997.

The DOE AHTS program investigated the effects of simulated turbine passage on both physoclistous and physostomus fish with and without exposure to total dissolved gas supersaturation conditions. Total dissolved gas supersaturation conditions are common in the Columbia and Snake rivers during juvenile salmon outmigration periods because of the extensive use of spill for fish passage past dams. The following information is from Abernethy et al. 2001.

> *The objective of* [the DOE study] *was to examine the relative importance of pressure changes as a source of turbine-passage injury and mortality). Specific tests were designed to quantify the response of fish to rapid pressure changes typical of turbine passage, with and without the complication of the fish being acclimated to gas supersaturated water.*

[DOE] *researchers investigated the responses of rainbow trout (Oncorhynchus mykiss), Chinook salmon (O. tshawytscha), and bluegill sunfish (Lepomis macrochirus) to these two stresses, both singly and in combination.*

[Conclusions reached from the study specific to exposure to pressure time histories typical of Kaplan turbine passage are given below:]

- *The frequency, type, and severity of injuries related to pressure changes during turbine passage vary among species*
    - *Bluegills, and presumably most physoclistous fish, are extremely susceptible to swim bladder rupture when exposed to the sudden pressure change during turbine passage. The total dissolved gas level had only a small additive effect on the injury/death rate due to the pressure spike.*
    - *Fall chinook salmon suffered ruptured swim bladders, but at a much lower rate than bluegills. When acclimated to elevated gas levels at 191 kPa, the turbine passage sequence also caused instantaneous bubble formation in a small number of fish, resulting in immediate death.*
    - *Swim bladder rupture was not observed in rainbow trout, regardless of total dissolved gas (TDG) level or acclimation pressure.*
- *If dissolved gas supersaturation is not a problem, our experiments suggest that the brief low pressure spike to about 0.1 atmosphere downstream from the turbine runner will cause little direct mortality among surface-acclimated salmonids. If fish are entrained from greater depths, such that their swim bladders contain more gas and will expand more during the low-pressure spike, the injury and mortality rates will be higher.*
    - *Injury/mortality rates would likely be reduced or eliminated if the nadir of the turbine pressure spike was higher, as is expected to be the case with new fish-friendly turbine designs. A follow-up series of tests is needed under a modified pressure regime that more closely reflects conditions expected in new turbine designs, or with a nadir of ~50 kPa.* [Follow-up tests have now been completed and have been reported by Abernethy et al. (2002)]
    - *The low-pressure spike is especially a problem if the water is highly supersaturated with gases (well beyond water quality standards), and the fish respond to the supersaturation by depth compensation.*

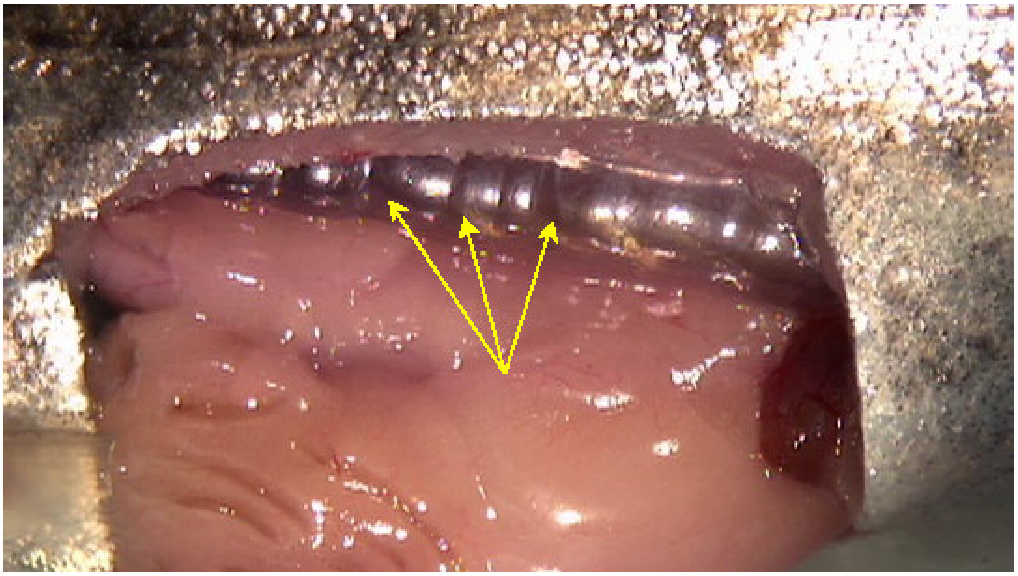


Figure 62. An over-inflated swim bladder ("ropey" appearance) in a rainbow trout 48 hours after the turbine passage sequence. *(*Abernethy et al. 2001)

A potentially significant uncertainty remains concerning the effects of pressure during turbine passage on salmonids. This is the effect on depth-acclimated fish. For various reasons, in laboratory tests to date, while salmonids may be held at pressure for a time prior to exposure to simulate turbine pressure time histories, there is evidence that these fish were not able to achieve neutral buoyancy during the holding period. This indicates that they did not pressure-acclimate by filling their air bladders with sufficient air to compensate for the air bladder compression caused by increased pressure. In addition, little is known about the ability of smaller juveniles (subyearling), in general, to burp air under conditions of very rapid pressure decreases. Also unknown is the state of the air bladder of in river fish passing through turbines.

Abernethy et al. (2001) observed a consequence of exposure to pressure cycling during turbine passage that may affect the behavior of turbine-passed fish. The salmonids that survived turbine passage had voided their swim bladders and were negatively buoyant when returned to holding troughs. The majority of these fish regained neutral buoyancy to shallow depths by swimming to the surface and gulping air into their swim bladders. A small percentage was not able to achieve neutral buoyancy for some reason and remained negatively buoyant throughout the holding period. Salmonids that pass through turbines and become negatively buoyant may be motivated to come to the surface to gulp air to regain neutral buoyancy after entry into the powerhouse tailrace. Consequently, these fish may become significantly more vulnerable to predation. Alternatively, negatively buoyant fish may remain deeper in the water for a longer period of time following entry into the powerhouse tailrace, and may be less susceptible to predation. The inability of fish to regain neutral buoyancy may either result from some internal damage that prevents the gulping of air, or from some other reason. At the present time, it is clear that too little is known about the salmonid response to negative buoyancy following turbine passage to suggest any consequence, positive or negative, of negative buoyancy.

4.2.5 Turbulence

Turbulence is an ever-present feature of flows through turbines. Severe turbulence is believed to be a mechanism for direct physical injury of fish. The following discussion of turbulence (in italics) is from Cada, G.F. and M. Odeh 1999 prepared for the DOE AHTS program and used here with permission of the authors. A review of the literature related to fish injury and turbulence can be found in Cada, G.F. and M. Odeh 1999 as well.

> *At high water velocities, and because of edge effects and surface roughness of structures, given that water is a viscous fluid, flows in a hydropower turbine system are turbulent, rather than laminar. The tendency of water molecules to resist shear forces, due to viscosity, causes them to move irregularly. The shear stresses within a flow field tear the fluid into highly energetic, irregular, and three-dimensional eddies, with scales ranging from the size of the flow passage down to unity (Miller 1990). These eddies exist randomly in space and time in turbulent shear flows (Nezu and Nakagawa 1993). Turbulent flow occurs when fluid particles move in a highly irregular manner, even if the fluid as a whole is traveling in a single direction. That is, there are intense, small-scale motions present in directions other than that of the main, large-scale flow (Vogel 1994). Unlike laminar flow, which is most easily described by linear equations, turbulent flow can only be defined statistically (Gordon et al. 1992; Nezu and Nakagawa 1993); descriptions of the overall motion within turbulent flows cannot be taken as describing the paths of individual particles (Vogel 1994).*
>
> *Within a turbine system, natural river, or laboratory test apparatus, flows are so turbulent it would be difficult to separate the effects of normal forces (that cause pressure) from tangential forces (that cause shear stress), but rather the fluid stress will be a combination of the two. Also the shear stresses are not uniformly applied to a fish; a fish encountering high velocity water head-on is more likely to experience more shear stress on the head than on the tail. Also, resistance of a fish to shear stress may be size-specific; e.g., small rainbow trout may be less resistant than large rainbow trout. Resistance is certainly species-specific (eels are more resistant than shad) and probably life stage-specific (adults are more resistant than larvae; non-smolted chinook salmon juveniles are more resistant than chinook salmon smolts).*
>
> #### Turbulence Intensity
>
> *The pattern of turbulence within a turbulent flow field continuously changes with time (Rouse 1946). Therefore, in order to describe the turbulence in that flow field, a continuous record of the instantaneous velocities at the point of interest must be kept; this is essential to perform the necessary statistical analyses. Using instantaneous velocities, turbulence can be described by a measure called turbulence intensity (Gordon et al. 1992).*

The local velocity in a turbulent region is composed of a temporal mean value plus a component that represents the turbulent fluctuation about the mean. The turbulence intensity is a measure of the magnitude of the turbulent fluctuations about the mean. When a series of instantaneous velocity measurements are made at a point, the turbulence intensity at that point can be expressed as the root mean square of these measured values.

$$\text{Turbulence Intensity} = [\Sigma(v_i\text{-}v_{ave})^2\, n^{-1})]^{-2} \qquad \mathbf{(2)}$$

In this equation v_i *is the instantaneous velocity measurement,* v_{ave} *is the mean velocity of the flow, and n is the number of instantaneous velocity measurements.* Equation 2 *yields a value for turbulence that is expressed in terms of velocity units, e.g., m/s. This formulation has been reported in studies by Pavlov and Tyuryukov (1993) and Skorobogatov et al. (1996).*

Turbulence Scale

The size of the turbulent fluctuations, i.e. turbulence scale, is also an important consideration (Nowell and Jumars 1984; Peters and Redondo 1997). Globally, turbulence of biological interest can occur in scales as large as 10^4 *m or more in the ocean, down to microscopic scales affecting the movements and feeding of individual planktonic organisms. Turbulence exists at a wide variety of scales in a river, from the swirling motion created when a salmon scoops out a redd (scales smaller than the size of the fish) to large pulses of flow in a river (scales much larger than a fish). Similarly, within a hydropower turbine turbulence occurs at different scales* [Figure 63]. *Smaller-scale turbulence, which occurs throughout turbine passage, can distort and compress portions of the fish's body. Larger-scale turbulence may be most pronounced in the draft-tube and tailrace, where water flow is decelerating, expanding into a larger passage, and has a swirl imparted on it by the turbine runner. Fixed structures in the draft-tube (walls and support piers) may cause secondary flows, i.e., flows moving in opposite directions from the main flow moving out of the draft-tube and into the tailrace. Similarly, the configuration of the tailrace can also cause backflows ("tailrace roll") that impede the downstream movement of turbine-passed fish. These chaotic flow conditions (small-scale turbulence, larger-scale flow pulses, vortices, and secondary flows) will distort and spin the fish, and, at the least, may cause disorientation. It has been suggested that this turbulence-caused disorientation, while perhaps not injuring the fish directly, may leave turbine-passed fish more susceptible to predators in the tailrace.*

Shear force, shear stress, and turbulence are inextricably linked. For any but the smallest pipes and lowest velocities (in which laminar flows occur), shear stress will cause turbulent eddies. Similarly, by definition, turbulent flows will create shear forces and shear stress, because parcels of water that are moving in different directions, and with different velocities, will interact.

In terms of adverse effects on fish, there are areas within a turbine in which either shear stress or turbulence predominates. Near a solid-liquid boundary (for example, the runner blade or turbine wall), water velocity decreases very rapidly from the mean velocity of the bulk flow, say 15 m/s, to the non-slip velocity of zero at the solid surface. Some of the energy associated with the large shear stress in this boundary layer is caused less by chaotic motions of water particles (turbulence) than by the fact that a portion of its body is proceeding downstream at a different velocity than another portion, leading to distension, compression, bending, torsion, and localized damage. Turbulence is certainly present in the boundary layer, but its adverse effects are overshadowed by the high values of shear stress [Figures 63a and b].

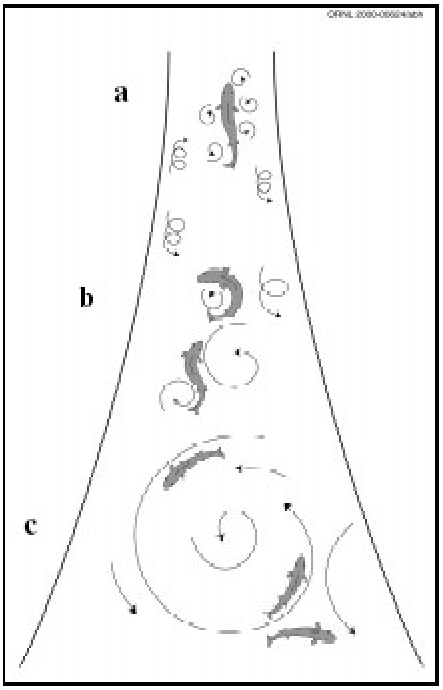


Figure 63. Scales of hydropower turbine turbulence. (Cada and Odeh 1999)

Elsewhere in the turbine system, larger-scale turbulence may overshadow the effects of localized shear stress. In the draft-tube outlet and tailrace, where flow is expanding and slowing, velocity differentials are lower compared to those associated with boundary layers within the turbine. Consequently, the shear stresses will be lower as well and are less likely to exert forces great enough to damage fish. In these areas, however, turbulence may be quite high and of a scale larger than that of the fish. In that case, the motion of the fish's body will also be chaotic, like the water surrounding it. Turbulence scale is important because the forces associated with tiny turbulent eddies will cause localized damage (bruises, scale loss) [Figure 63a]. *Turbulence at a larger scale, e.g. several times the size of the fish, will agitate and spin the fish* [Figure 63c]. *It is believed that residence in an area of large-scale turbulence for enough time will*

> *cause the fish to become disoriented, lose equilibrium, have a reduced swimming capacity, potentially become more susceptible to predators.*
>
> *From these considerations, it can be seen that experiments designed to measure the biological effects of turbulence must take into account not only the intensity of turbulence, but also the scale. Small-scale, high-intensity turbulent vortices may bruise or descale the fish, but are not of sufficient size to spin the fish and cause disorientation. Turbulence scales at about the same length (L) of the fish will tend to bend or twist the fish's body, which may lead to disorientation but may also cause physical injury (creases and internal damage). Scales of turbulence several times larger than the fish, say 5L or 10L, will transport the fish in random (chaotic) motions, possibly leading to disorientation, loss of equilibrium, and diminished swimming capacity. … The forces associated with smaller scale turbulence will compress a portion of the fish's body, causing direct damage. Larger scale turbulence (larger than L) will cause rotation or some form of translational movement; like the flow itself, the fish's movement will be chaotic in terms of direction and velocity.*

The physical models used in Phase I of the TSP have permitted observation of turbulence in turbine passages. Observation has been achieved through the use of dye and also by closely monitoring the movements of beads. A discussion of these models and the associated experimental observations can be found in Section 2.

4.3 Indirect Turbine Passage Injury

Indirect injury is the portion of the total turbine passage mortality that occurs after the fish have left the immediate turbine environment (the turbine draft-tube) and move downstream through the project tailrace. Indirect mortality is believed to result primarily from predation by birds and piscivorous fish. While the mechanisms of indirect mortality may be known (primarily predation), the linkages between turbine passage and indirect mortality are mostly unknown. The rate of occurrence of externally visible physical injuries that may predispose a fish to indirect mortality is too low to explain the high rates of indirect mortality often observed. Indirect mortality appears to be at least as high as direct turbine passage mortality and is frequently much higher (see Section 1.2.2.4). There are other potential sources of injury to fish that are probably as important for predisposition to predation as physical injuries. Such injuries may result in effects such as the temporary disability of the fish's vestibular system, exhibited as stunning or disorienting of the fish that affects its ability to avoid predators. Vestibular disruption can cause fish to revert to their dorsal light reflex to achieve equilibrium. Reversion to the dorsal light reflex causes fish to move toward the surface where they use light to correctly orient in the water column. This movement toward the surface may make the fish more vulnerable to predation by birds and piscivorous fish. This type of injury is only observable in a fish's behavior. Currently, insufficient means exist with which to detect the rate of this type of injury for turbine-passed fish.

In addition, recent laboratory research (Abernethy, et al. 2001) of fish exposed to pressure time histories that simulate turbine passage has found salmonids to be negatively buoyant following exposure. In laboratory settings these fish come to the surface to gulp air to achieve neutral buoyancy. This behavior, which is similar to dorsal light reflex behavior in that it results in fish movement toward the surface, may make turbine-passed fish more susceptible to predation. However, currently there have been no observations of the behavior of turbine-passed fish under field conditions to compare with the behaviors observed under laboratory conditions. Nor are there any studies that link any specific behaviors or conditions of turbine-passed fish with increased susceptibility to predation.

Indirect injury has not been directly addressed in Phase I of the TSP. It is likely that mitigation of this potential source of injury will require assessment of the powerhouse tailrace environment and the way in which turbines are operated. Strategies that optimize tailrace egress conditions and reductions in predator populations for turbine-passed fish will likely provide some improvements in indirect turbine passage survival.

4.4 Turbine Operations

The way a turbine is operated has an effect on the conditions within the turbine environment that may injure fish and therefore offer an opportunity to influence the rates of mortality and injury to turbine-passed fish. While the operation of individual turbine units influences fish passage conditions for that unit, it is becoming clear that optimization to total turbine passage survival will require consideration of how all of the turbines in a powerhouse are operated. Powerhouse operations considered with spill discharge determine dam tailrace conditions and, if experience with management of spill operations to optimize spill passage survival can be applied to turbines, will most likely significantly influence indirect turbine passage mortality and thereby total turbine passage mortality. It is likely that turbine passage survival will not be optimized unless powerhouse tailrace conditions are optimized for safer egress of turbine-passed fish.

4.4.1 One-Percent Operating Limits and Biological Index Testing

Minimum gap runner turbines are currently being installed at Bonneville First Powerhouse. Engineering and biological tests were conducted in 1999-2000 to compare the biological response of juvenile salmonids passing by specific routes (tip, mid-blade, and hub) through turbines equipped with original design and new MGR design runners. This test evaluated only the direct, route-specific survival and injury of juveniles that passed through the two units. In 2002, biological tests were initiated to evaluate the total turbine passage survival (by estimating both direct and indirect components of total turbine passage mortality) of fish passing through test units, incorporating the evaluation of total turbine passage route mortality occurring in the powerhouse tailrace. The effects of turbine operating conditions on turbine passage route survival were not evaluated in 2002. The next phase of turbine biological performance testing is anticipated to determine the operating conditions for the new MGR units that will optimize total turbine passage survival. Observations obtained using turbine physical models, indicate that, at low turbine discharge, tailrace conditions are worse for fish passing through the unit. At low discharge, turbine draft-tubes do not operate with high hydraulic efficiency and the turbine discharge jet is quickly dissipated in the immediate tailrace. This results in hydraulic conditions that retain turbine-passed fish in slowly moving water that may have high concentrations of predators. The juvenile fish mortality associated with the tailrace environment may be as significant or more significant than the direct mortality occurring within the turbine. Birds and piscivorous fish in the tailrace area may prey disproportionately on fish injured or disoriented by turbine passage. Passage through the draft-tube may also inflict injury or mortality, or may disorient fish so they are not immediately able to escape from predators.

Current operating rules for all turbines within the Federal hydropower system restrict operations to a region bounded by turbine efficiency (conversion of the energy in falling water to electricity) that is within one-percent of peak efficiency. Turbines with original design runners have a flat efficiency curve so that operations within one-percent of peak efficiency extend over a wide range of internal geometries, which are defined by the wicket gate opening and the angle of the runner blades. The range of operations extends from blade angles that result in a relatively closed geometry, where the opening between blades is relatively restricted, to blade angles that result in a relatively open geometry with much more opening between blades. The greater the opening between runner blades, the lower the probability that fish will be struck by a blade or pass close to the blades where hydraulic conditions can be severe (Montén 1985). The biological consequences of differences in turbine operating geometry are not well known except for the size range of juvenile fish typically used in balloon, PIT, and Radio Telemetry passage survival studies. With the exception of a limited method feasibility assessment conducted at McNary Dam in 2002 (Normandeau et al. 2003), no field studies of the turbine passage survival of fish the size of downstream migrating steelhead kelt or adult salmon and steelhead upstream migrant fallbacks have been conducted. The limited method feasibility study conducted at McNary dam using adult steelhead indicated direct injury and mortality of adult fish is several times higher than that for juveniles.

The one-percent limit for Bonneville First Powerhouse MGR turbines encompasses a narrower range of turbine settings (combinations of flow and hydraulic head) than that of existing runner turbines, and the absolute efficiency of MGR turbine at peak efficiency is approximately 3-percent higher than the absolute efficiency of the original turbines. Because of this narrower operating range and details of the design of the MGR turbine, under the existing one-percent operating rule the internal geometry of the MGR is slightly less open than the existing turbine runner design at the high end of its operating range, and is less closed at the lower end of the operating range (Wittinger, R. and D. Ramirez, 2000). As in the case of the existing runner design, turbine passage survival information only exists for juvenile fish of a size range of about 150 millimeters.

4.4.2 Tailrace Egress and Powerhouse Operations

Investigation of fish passage through turbines has to consider both the immediate impacts (direct) to fish occurring within the turbine environment that result in mortality or observable injury, as well as those that may not be readily observable but that may reduce the fitness of the fish to cope with the environment downstream of the dam (indirect). Total turbine passage mortality is the sum of direct and indirect mortality rates. Phase I of the Turbine Survival Program has focused on direct effects. However, historical as well as recent fish passage survival studies (see Section 1.2.2.4) have shown that indirect mortality can be larger than direct mortality. The powerhouse tailrace environment is thought to provide good habitat for predators, a portion of fish that pass through turbines are believed to be less able to avoid predators because of sub-lethal injuries, probably to their sensor systems, and turbines may be operated in ways that inhibit the rapid egress of fish through tailrace regions of higher risk. Precedence and examples for such studies are those conducted routinely for spillways to identify spill operating scenarios that optimize the egress of spill-passed fish as they pass through the spill-stilling basin to their reentry into the major downstream flow of the river.

During Phase I studies some effort has been made to better understand the function of turbine draft-tubes and to investigate structural alternatives that would create draft-tube flow conditions aiding egress of fish through the powerhouse tailrace environment (see Section 2). Future study of the turbine fish passage environment will need to consider the powerhouse tailrace region as a whole. Such studies will need to address the operation of the turbine units to identify operations that would help create tailrace environments less attractive to predators and would also provide the opportunity for rapid egress of turbine-passed fish.

4.5 Tail Log Slots

The turbine tail log slot at Bonneville and McNary Dams is an opening to the discharge deck that permits a gate or stop logs to be inserted for dewatering a turbine draft-tube. During normal operation of a turbine there is some flow into and out of this slot. This flow comes from the turbine discharge nearest the draft-tube ceiling. Fish passing through the turbine can be carried with the small amount of turbine discharge flow that enters the tail log slot opening. These fish may then remain in the tail log slot until they choose to exit or are carried by flow back into the turbine draft-tube. Conditions in the tail log slot can be quite turbulent and may expose fish to injury from the turbulence or from scraping on tail log slot walls.

During the Bonneville First Powerhouse MGR studies (Normandeau Associates, Inc. et al. 2000) fish that passed through the mid and blade tip regions were exposed to entrainment in the tailwater stop log slots. About 3.0 percent of the treatment fish introduced at these sites were entrapped. To put this figure into perspective, 78 of the 3,743 fish (2.1 percent) introduced into the blade tip and mid-blade regions in both units were recaptured dead and another 2.2 percent were injured. The minimal entrapment of hub passed fish (0.4 percent) suggests that partial inflation of a small percentage of balloon tags prior to fish exiting the draft-tube was a minor contributing factor to entrapment. Initiation of balloon tag inflation was adjusted to minimize the chance of the balloon tags inflating prior to exiting the turbine. If tagging was not the principal contributory factor, then a potential exists for entrapment of naturally entrained fish. The longer the entrapment time the greater the likelihood of fish experiencing stress and possible death. Secondly, the fish may be transported into a backroll environment, which could make them vulnerable to potential predation upon exiting the draft-tube. These findings resulted in the design of tail log slot closure devices (see Section 3.5).

In 2002, entrainment of radio-tagged fish into turbine draft-tube tail log slots at both Bonneville powerhouses was again studied (USGS 2002 AFEP Annual Review PowerPoint Presentation). This study found that 13 percent of radio-tagged yearling juvenile Chinook salmon detected during passage through the Bonneville First Powerhouse turbine units were entrained in draft-tube stop log slots for a mean time of 18 seconds. For radio tagged fish passing through turbines at the Bonneville Second Powerhouse, 8 percent of monitored juvenile Chinook and 17 percent of monitored juvenile steelhead were found to be entrained for mean times of 18 and 32 seconds respectively. The study investigators were unable to determine the impact of stop log slot entrainment on the health of test fish, but did conclude that the residence time in the stop log slots did not significantly delay the fish.

At the close of the TSP Phase I, the question of whether or not to close draft-tube tail log slots as a means to improve the survival of turbine-passed fish remains unresolved. In future turbine passage studies the tail log slots will be routinely monitored to obtain additional information about their impact on the health of migrating juvenile salmonids.

4.6 Conclusions

The following biological conclusions are presented in a numerical format for reference only and not to imply any order or importance.

1) Route-specific and general distribution direct survival estimates obtained for McNary and Bonneville turbines have indicated that direct survival of test fish is, overall, high. The observed range for turbine passage survival estimates for biological tests conducted during Phase I of the TSP extends from 100 percent for test fish passing nearer the turbine runner hub (but away from gaps between the turbine blades and runner hub) to 91 percent for test fish passing near turbine runner blade tips. Of the 24 direct route passage survival estimates obtained at Bonneville Dam, twenty were ≥ 95 percent, two were 94 percent, and the remaining two were 92 percent and 91 percent.
2) Turbine passage survival testing should be designed to detect a change in survival of ± 2 percent, 90 percent of the time. This level of precision in survival estimates is necessary to distinguish the effects on fish passage conditions of changes in turbine operations or structural modifications given the generally high turbine passage survival through large mainstem Kaplan turbines.
3) The technology to inject test fish into a turbine environment for evaluation of survival through specific passage routes (such as runner blade tip, hub and mid-blade regions) was developed during Phase I of the TSP. During refinement of this technology it was determined that physical model observations are required to correctly place the terminus of injection pipes and to obtain information necessary to correctly interpret study results.
4) Turbine passage survival studies conducted during Phase I of the TSP for on cam turbine operations have not found any statistically significant relationship between test fish survival and turbine discharge or fish survival and absolute or relative turbine efficiency for turbines operating on cam within the range of the lower end of one percent of peak efficiency and maximum on cam discharge.
5) Retrospective statistical analysis of the direct survival of test fish through large Kaplan turbines has not found any statistically significant relationship between turbine operating efficiency and turbine passage survival over the range of operations tested.

6) Direct turbine passage survival studies using route-specific test fish injection technology have found the survival of test fish passing near the tip of turbine runner blades to be statistically significantly lower than the survival of fish passing mid-blade or near the hub of turbine runner blades over the range of operations tested.

7) Turbine passage survival studies have not found fish turbine passage survival to be statistically significantly different for operations within one percent of peak turbine efficiency and operations outside of one percent of peak turbine efficiency.

8) Reference releases of test fish immediately downstream of the test turbine draft-tube exit are necessary to accurately estimate absolute direct turbine passage survival.

9) Recovery of test fish following turbine passage is required to assess the rate or type of injuries to test fish. At this time balloon tagging is the only method that permits recovery of test fish following turbine passage.

10) Classification of observed injuries to the most likely causal mechanism needs additional refinement. Some types of injuries could be caused by either shear or impact. Additional study might identify injury features currently not considered that might make assignment of injuries to mechanism more accurate.

11) Change in pressure during turbine passage appears to cause the majority of salmonids to expel the contents of their air bladder. These fish then enter the powerhouse tailrace negatively buoyant. The need to gulp air at the surface to recover neutral buoyancy may increase the vulnerability of turbine-passed salmonids to predation by birds and piscivorous fish. Observations of the behavior of turbine-passed fish under field conditions are needed to determine if they exhibit the same behaviors as negatively buoyant fish under laboratory conditions.

12) Exposure to turbulence, swirl and other hydraulic events may affect the vestibular sense of fish passing through turbines. Disoriented fish, unable to equilibrate using their inner ear, revert to a dorsal light reflex that causes them to move toward the water surface where they may have increased vulnerability to predation. Methods to detect and measure the severity of this condition under field conditions are needed to fully assess the impact of vestibular disruption on total turbine passage mortality.

13) Direct turbine passage survival is not a good predictor of total turbine passage survival. This is because the indirect mortality component of total turbine passage mortality, which is believed to occur primarily in the powerhouse tailrace by predation upon turbine-passed fish, can be several times higher than the direct mortality and is most likely a function of many factors that may vary significantly between projects.

14) Essentially all direct turbine passage survival studies have been conducted using hatchery yearling Chinook salmon. Therefore, very little information is available about the effects of turbine passage on other sizes and species of salmonids. Laboratory studies conducted by DOE indicate that the same exposure conditions probably result in different rates and types of injuries for other sizes of fish. Therefore, turbine passage survival and injury rates observed for yearling hatchery salmon should not be extrapolated without qualification to other species and sizes of salmonids.

15) The vertical and horizontal distribution of run-of-the-river fish as they pass through the stay vane-wicket gate cascade is unknown. As a result, it is not explicitly known how to

weight route-specific survival rate estimates to obtain direct turbine passage survival estimates for the run at large. As a consequence, it is not feasible at this time to assess the benefits of specific runner modifications, such as blade tip gap closure, for the run at large.

16) Uncertainty about the distribution of fish passing through turbine intakes, including the redistribution of fish passing under turbine intake screens as flow expands downstream of the screens, coupled with differences in the movement of live fish and inanimate beads, suggest that observations of the distribution of beads at the stay vane-wicket gate cascade in physical turbine models (from point releases within the turbine intake) may or may not be representative of the run at large.

17) Tracking of juvenile salmonids bearing micro-acoustic transmitters during passage through the intake of an operating mainstem Kaplan turbine showed that the fish do not behave like passive neutrally buoyant objects during approach to the stay vane-wicket gate cascade, and that fish released at a single point in the turbine intake, downstream of the turbine's intake screen, redistributed to pass through the stay vane wicket gate cascade over the vertical extent of wicket gate openings.

18) Observations of beads passing through ERDC-WES physical turbine models show locations where fish are likely to contact turbine structures. These areas include stay vanes, wicket gates, turbine runner blades, and the elbow and splitter walls within the turbine draft-tubes.

19) Rates of contact by beads on turbine structure surfaces are considerably higher than the rates of injury classified as caused by structural strike observed for live test fish in prototype scale turbine passage studies. Additional analysis of physical model observations and the results of prototype scale studies is needed to identify means the method of use for physical model observations to infer the rate of impact for live fish at prototype scales.

20) Bead analysis and velocity measurements from the ERDC-WES hydraulic models provided the first observations of draft-tube flow conditions under various operating conditions for Bonneville First Powerhouse, McNary, and Lower Granite. Analysis suggests poor flow conditions under lower turbine discharges from the draft-tube, which could have implications for fish survival due to predation in the tailrace (Peak efficiency – much higher numbers of beads in backroll of turbine discharge and draft-tube barrel velocities not uniform). Further analysis is needed on turbine tailrace egress under different operating conditions and relative survival measurements.

21) Comparison of acceleration magnitude time histories of sensor fish response to turbulence during spill passage at Bonneville and The Dalles Dams to that observed for turbine passage at McNary Dam showed the turbulence exposure through the turbine was, in general, significantly less than that observed for spill conditions with very high test fish survival rates. These comparisons suggest that turbulence encountered by fish during turbine passage may not pose a high risk of injury compared to spill. However, the data obtained to date are too limited to draw broad conclusions about the magnitude of turbulence in turbine draft-tubes in general, or the effects of draft-tube turbulence on fish health.

22) Laboratory studies performed by the Pacific Northwest National Laboratory as an element of the DOE AHTS program have developed relationships between the rate of strain in shear flows and the rate of fish injury, both direct injury and mortality, loss of equilibrium, stunning, and increased susceptibility to predation.

23) Sub-lethal effects of turbine passage on juvenile fish that may make turbine-passed fish more susceptible to indirect mortality by predation in powerhouse tailraces have been identified.

    - Disruption of the vestibular system, as a consequence of strike or exposure to turbulence and swirl, is known to cause disorientation, stunning, and loss of equilibrium. Fish responses include attenuated avoidance response and reversion to a dorsal light reflex, which results in fish moving into surface water. Little is known about the rate of occurrence of these conditions or their persistence in afflicted fish.
    - Laboratory studies have found that fish size appears to be important in the rate and type of sub-lethal injury sustained upon exposure to shear and turbulence. Smaller fish appear more likely to experience the full force of turbulence and may be more likely to suffer vestibular impairment but less likely to experience physical injury from inertial effects. The opposite may be true for larger, more massive, juvenile fish.
    - Review of laboratory and field studies of fish passage through turbines, in particular pressure cycling during turbine passage, has found no information on the impact of pressure cycling on depth-acclimated salmonids. As a consequence, current information on pressure cycling could underestimate the rates of injury and mortality of turbine-passed fish due to exposure to pressure cycles.

Section 5. Turbine Rehabilitations

Most of the turbine units within the Federal Columbia River Power System (FCRPS) are reaching the end of their design life and will require some measure of rehabilitation, which may include repair or replacement of the runners. This provides an opportunity to improve turbine efficiency and the survival of fish passing through them. Although turbines of the Lower Snake and Columbia River dams are very similar, there are specific detailed differences in design and operating characteristics. The consequence of these site-specific differences is that runner designs and operations that provide benefits for some of the turbine units may not be the best choice for others. Phase I of the Turbine Survival Program has resulted in the development of unique investigative tools to characterize the fish passage environment of existing and rehabilitated turbine units. These tools should be used to identify opportunities to improve fish passage conditions, prior to the rehabilitation of a turbine unit. These tools consist of physical models, route-specific test fish injection systems, sensor fish, and protocols for use of balloon-tagged and radio-tagged live test fish to estimate total fish passage mortality and to separate this mortality into direct and indirect components.

Systematic application of basic engineering design methods with biological assessments will result in rehabilitated turbines that meet engineering design objectives, such as increased power production efficiency, while providing for safer fish passage. The life-time of a turbine is approximately 35 + years and the cost of turbine rehabilitation is substantial, making the inclusion of the best known fish passage improvements relatively small given the long-term application and potential fish passage benefits. A product of Phase I of the TSP is a framework for making decisions prior to, during, and following turbine rehabilitation that can optimize both biological and economic benefits of rehabilitation. The TSP turbine rehabilitation framework consists of a series of stages of variable length depending upon the nature of the rehabilitation under consideration. Coordination with the various regional authorities will be necessary to establish the funding policy for implementation of these stages. These stages are presented below:

5.1 Stage 1: Baseline Turbine Performance Assessment

The objective of the first stage in turbine rehabilitation is to describe the physical condition, operational characteristics, and biological performance of the existing families of turbines. Assessment of the physical condition of the turbine requires dewatering the turbine and detailed visual inspection of all turbine components. The physical inspection should include the measurement of gaps at the tip and hub of turbine runner blades, wicket gate overhang, surface finish, projections and other turbine structural elements that may influence turbine power production and biological performance.

Assessment of the operational performance of the existing turbine includes index testing to determine the relative efficiency of the turbines under the existing cam curve. Similar assessment of other turbine units in the recent past have found them to be operating well away from optimum values as a consequence of normal wear in control components. Following index testing, new cam curves should be installed for operation of the unit to meet BiOp requirements for protection of turbine-passed fish, but also to make optimum use of available water. Index testing and installation of cam curve corrections should be performed (with and without fish diversion screens in place) prior to assessment of biological performance to ensure that the turbine is operating as efficiently as possible.

The final step in the baseline stage of turbine rehabilitation is the determination of the turbine's biological performance. Biological performance of a turbine unit is determined by two measures, direct and total turbine passage survival. The characteristics and frequency of occurrence of injuries also provide important information about the turbine's biological performance. Direct turbine passage survival and injury rate, and characterization can be estimated using balloon tag methods. Total turbine passage survival can be estimated by telemetry tagging methods. Biological assessment of the turbine should not be restricted to the one-percent BiOp operating range but should extend to the maximum rated discharge for the unit. This allows for science to guide future operating scenarios.

Additional biological assessment may be required if the observed survival rates are unexpectedly low or if injury rates and character are out of the range observed for other original design turbines of similar size and operation. Route-specific assessment of portions of the runner environment may be warranted to better understand the mechanisms of some types of injury and to identify existing turbine features implicated in the injury process. If detailed biological testing of this nature is necessary, construction and use of a fish passage physical model is also necessary. Experience in Phase I of the TSP has shown quite clearly that the design of fish injection systems and the interpretation of the results require the use of physical models to avoid poorly designed tests and proper interpretation of results.

While biological assessment of direct turbine passage survival can be conducted outside of normal fish passage times, indirect assessment must be determined during the normal fish passage season because it is primarily determined by tailrace predation.

5.2 Stage 2: Identification of Turbine Design and Operational Improvements

The objective of stage 2 is to identify turbine design features that have the potential to improve turbine efficiency and fish passage survival. The initial step in stage 2 is to determine if turbine designs other than replacement in kind should be considered. Normally, in the absence of other drivers, the turbine will only be replaced with an identical runner if power production enhancements cannot be economically justified and if the biological performance is at least as good as that expected from a state-of-the-art runner design.

A large number of turbine runner design modifications are possible. Additional design modification of wicket gates, stay vanes, and draft-tube features are also possible. Overall, design modification alternatives are considered in three areas by potential effect: 1) increased turbine efficiency, 2) increased direct turbine passage survival and/or reduced incidence of serious, sub-lethal injury, and 3) improved indirect turbine passage survival.

Increases in turbine efficiency can be achieved by many means; however, particularly important are those that also provide biological performance benefits. Examples of designs that provide both economic and biological benefits are those that eliminate or significantly reduce gaps at the tip and hub of turbine runner blades. Alternatives other than Kaplan type turbines that use fixed blades may provide sufficient economic benefits to encourage turbine runner replacement. Kaplan MGR designs have been built and tested. Such runners can be designed with very significant improvements in economic performance that alone justify runner replacement. Economic analyses should be performed during this stage of the rehabilitation program to identify the result of any design changes on the economic feasibility of a new or modified turbine.

The results of the baseline biological evaluations of the existing runner may provide valuable clues to turbine environment changes providing biological benefits in direct turbine passage survival. Observations of turbine passage conditions using a fish passage physical model with the original design runner installed can help identify potential sources of observed injuries within the turbine environment. For example, injuries attributed to shear could take place in the wake of wicket gates, within or immediately downstream of the turbine runner, or in the turbine draft-tube. Identification of the locations and operating conditions under which potentially deleterious conditions occur can help turbine designers focus on design changes that can reduce the severity or frequency of occurrence of these conditions.

The links between the conditions a fish experiences during turbine passage and susceptibility to predation (indirect turbine passage mortality) in the powerhouse tailrace are at present poorly understood. However, experience gained during implementation of dam fish passage alternatives, such as spill, provides some direction. For example, extensive study of spill has determined indirect spill passage mortality can be reduced in many cases by design of spill operations that provide rapid egress of spill passed fish through the spill stilling basin and into the thalweg of the river thereby bypassing regions of higher predator abundance. The working hypothesis developed during Phase I of the TSP is that operation of individual turbines to minimize exposure to turbulence and duration of passage through the turbine environment, combined with powerhouse operations that minimize egress time through the powerhouse tailrace, offer the best opportunity to optimize total turbine passage survival. Under this hypothesis, studies conducted during TSP Phase I have found that turbine operations that most efficiently load the turbine draft-tubes seem the most promising individual unit operations for improved direct turbine passage survival. Requirements for optimization of total turbine passage mortality, which will require careful assessment of powerhouse operations and resulting powerhouse tailrace conditions, need to be developed and should be an element of any rehabilitation program. This is a key element in Phase II of this program.

5.3 Stage 3: Physical Model Testing to Evaluate Potential Design Improvements

The objective of stage 3 is to evaluate promising turbine design alternatives to identify those to be carried forward to stage 4. A number of tools are available to evaluate this. The most commonly used are physical models to measure the performance of alternative designs and observational models to assess turbine passage conditions that affect fish.

Section 2 of the report provides a review of the types of models and their use. The use of performance models by industry to meet the power production and efficiency goals of a new design is highly evolved with broadly accepted metrics and evaluation criteria. This is not the case for the ERDC-WES observational hydraulic models. However, the design and testing of model turbine runners with intake screens in place is new to the industry. Field and model tests conducted by the Corps and VA-Tech have shown that high-head testing, traditionally used by the industry, is not ideal for testing with turbine intake screens in place. Because the majority of the turbine units on the mainstem Columbia and Snake Rivers operate with intake screens, 75 percent of the time or more, it is critical the design and operation of any rehabilitated or new turbine runners be optimized with these fish screens in place. How to best evaluate model turbine performance with intake screens has not been fully resolved. Testing under lower head conditions will provide more accurate flow conditions and improved test results, if the measuring equipment can attain the necessary precision. Otherwise, it will be necessary to further develop the model screen design such that the model screens will better replicate prototype flow patterns when tested under high-head conditions. Any future evaluation, of existing or new turbine runner designs, must include efforts to improve model test protocols for testing with the fish diversion screens installed within the turbine intakes.

Considerable effort has been expended during TSP Phase I to identify means to obtain metrics to characterize the turbine environment for fish passage. This effort will continue into TSP Phase II and is a focus for the Phase II effort. The present state-of-the-art is relative comparisons in metrics between alternative turbine designs such as the turbine environment with an original design runner versus the environment with a new design runner. The ERDC-WES observational physical hydraulic models permit very rapid comparison of turbine passage conditions over the whole operating range of competing alternative designs. Metrics such as surface contact frequency and contact severity made using observations of beads passing through the model from a specific injection location help identify sometimes subtle differences between designs that may have a significant impact on fish.

Numerical models, while commonly used by turbine designers to address specific design issues, are much less well developed to address fish passage issues. At this time there are no numerical models sufficiently developed to provide reliable fish passage assessment information to aid in the evaluation of turbine design alternatives.

5.4 Stage 4: Findings and Recommendations Report

The objective of stage 4 is to document the results of the various turbine design alternative analyses. Findings summaries of various types are needed for regional coordination processes, and to prepare specifications, schedule, and budget documents required for procurement and installation of a prototype unit.

5.5 Stage 5: Prototype Test (Proof of Biological Performance)

The objective of stage 5 is to measure the biological performance of the new design prototype unit prior to the procurement and installation of any additional units of the same design. Performance testing, to validate power production performance and other aspects of the physical performance of the prototype unit, is conducted prior to prototype testing to assess the unit’s biological performance. Biological performance testing should not be conducted until all aspects of the physical performance of the new unit have been tested and determined to meet specifications. Biological performance testing requires the measurement of direct and total fish passage survival and may also require route specific testing to assess the effectiveness of specific design features.

In general, the first phase of biological performance testing is to obtain assurance that the new design performs at least as well as the original design. Designs that degrade biological performance are generally unacceptable and may have to be removed or only operated under very restricted conditions. In TSP Phase I, experimental designs and methods for side-by-side tests of new and original turbine designs were developed and implemented. This type of testing is the method of choice because it nearly eliminates confounding variables such as test fish condition and environmental factors such as water temperature.

Biological performance testing of new units within the mainstem Columbia and Snake rivers has been conducted up to this time using yearling juvenile salmonids and concurrent sensor fish releases. The combination of live fish and sensors permits observations of the conditions test fish experience during turbine passage that are helpful in explaining observations of visible physical injury, mortality, and sub-lethal injury for live test fish. During this stage it is often helpful to review the results of the ERDC-WES observational hydraulic model tests or to perform additional ERDC-WES testing to gain insight into live fish and sensor fish observations.

New design features of prototype units should be carefully evaluated whenever possible to determine the magnitude of the biological benefit realized from the feature. An example is runner blade tip gap closure in MGR designs. A design feature may be acceptable if it provides economic benefits and is biologically neutral or vice versa.

At this time there are no criteria for the minimum biological benefit for inclusion of a design feature. As more experience is gained with design features and methods to assess their biological benefit, it may eventually become possible to establish criteria that weigh the cost of a feature against its biological benefits.

5.6 Stage 6: Evaluation of Prototype Performance

The objective of stage 6 is to evaluate the biological performance data acquired in stage 5 along with “sensor” fish data, measures of the prototype unit’s physical performance, and review of model testing data acquired during stage 3 and make a decision about the procurement of additional units. Tradeoff analysis for assessment additional unit procurement of the same design as a prototype unit is early in development. Recent procurement decisions have been based on an equivalent biological performance basis. Procurement of additional units of the same design as the prototype have occurred when the prototype was assessed to perform biologically no worse than the original design units. To date, the economic performance of new designs has been the driving factor for acceptance.

Biological performance evaluation criteria are needed to make decisions about the addition of costly turbine design elements. Typically, the physical performance tradeoffs for design elements are made during the turbine design process. Design elements that clearly degrade performance are carefully considered within the context of potential biological performance benefits before inclusion in the prototype unit design. However, making this tradeoff is very difficult in many cases because of limited prototype scale data for the biological performance of specific design features. A focus of TSP Phase II is to progress in quantitative assessment of the biological benefits of turbine design features that also improve physical/economic performance. An additional focus is identification and assessment of turbine structural design and operations that may result in offsetting biological performance. An example of offsetting biological performance is the potential for slightly higher direct injury by one mechanism or another at higher turbine discharges versus improved tailrace egress and potential significant reductions in indirect mortality. Offsetting biological performance questions are likely to occur more frequently in the future as experience with new turbine designs and the importance of total turbine passage mortality increases.

At the close of TSP Phase I, significant progress has been made in the development of physical modeling methods to investigate the probable biological performance of new turbine designs prior to construction of a prototype. The TSP has also made progress in the design and execution of biological tests to determine the overall relative biological performance of original and prototype turbines. The ability to perform tradeoff analyses of biological performance and cost and to obtain measures to perform tradeoff analysis of competing biological benefits and costs is still very limited. Of increasing importance is the need to assess the tradeoffs, if any, between turbine design features differentially affecting direct and indirect turbine passage mortality components of total turbine passage mortality. It has become clear that turbine design features affect indirect and direct survival differently and future designs should balance both.

5.7 Project Rehabilitations in Progress

Although there is no detailed comprehensive rehabilitation plan for the USACE hydropower projects on the lower Snake and Columbia Rivers, there are four rehabilitation plans of various degrees in process. These include plans for the Bonneville First Powerhouse, The Dalles, McNary, and Ice Harbor projects. Each of these plans may contain elements of the TSP's recommended Rehabilitation Process, but none fully incorporate the processes recommended in this report.

5.7.1 Bonneville 1-10 Major Rehabilitation

The Bonneville First Powerhouse is over 60 years old and the turbine generating equipment has exceeded its design life. The turbines and generators have experienced an accelerated rate of failures with major turbine blade failures occurring. The approved Major Rehabilitation plan is to replace the existing turbine runners, rehabilitate remaining equipment and rewind the necessary generators. The site rehabilitation has been underway since 1998 with powerhouse rehabilitation currently about half completed. Initially standard Kaplan type turbine runners were to be installed. A coordinated design effort between the Corps and the vendor resulted in installation of a successful environmentally beneficial turbine design. The new turbines incorporate the minimum gap runner concept, which minimizes the gaps between the runner blade and the runner hub, and the gaps between the tip of the runner blade and discharge ring. Currently economic issues have delayed the installation of the remaining turbines.

5.7.2 The Dalles 1-14 Major Rehabilitation

The Dalles Powerhouse has been producing commercial power since about 1957. The Dalles experienced an increasing number of generator failures of Units 1-14 with availability declining from 96% to 77% in the last decade. The approved Major Rehabilitation plan is to rewind nine generators and replace turbine blades on twelve of the 14 units and refurbishment of the remaining two turbines. The generator rewinds are underway at this time with two remaining generators to be completed in the near future. Currently, turbine blade replacement work has been delayed pending resolution of economic and environmental issues. The Dalles turbine rehabilitation provides an opportunity to employ technologies developed throughout the TSP to improve upon the existing turbine designs for both fish passage and power efficiencies.

5.7.3 McNary 1-14 Major Rehabilitation

The McNary Lock and Dam project was completed in 1953 with all 14 turbine units operational by February of 1957. There have been no significant capital investments made to the units since the installation. The Corps and BPA formed a joint team in the year 2000 to develop and study options to expand the power production capability, improve generation reliability, and increase the hydraulic capacity at McNary Dam, while improving the turbines for safer fish passage. The product of this team effort was the award of individual contracts to four turbine manufacturers, each to design and model test a replacement turbine runner and other turbine modifications to meet specific turbine performance criteria and to improve the fish passage survival. The four competing design proposals will be evaluated for, 1) the potential to improve fish passage survival, 2) technical merits, 3) economic feasibility and 4) the turbine manufacturer's past performance. Hydraulic model testing techniques developed from the TSP, in combination with performance model tests, will be used to select the best design for a prototype installation. If the design is technically, economically and environmentally feasible, the design will be procured and installed. Once installed, the unit will be rigorously tested for fish passage survival and overall performance. The installation of additional units will be dependent upon the success of the test unit.

5.7.4 Ice Harbor Unit 2 Replacement

The Ice Harbor Lock and Dam project was completed in 1976. The powerhouse consists of six Kaplan turbine units. The runners of turbine units 1 through 3 were manufactured and supplied by Baldwin-Lima-Hamilton. They were fully operational by 1962. The runners of turbine Units 4 through 6 were supplied by Allis-Chalmers in 1975. For the past decade the runner of turbine Unit 2 has been leaking oil. A number of attempts have been made to fix the leak, but none have been successful. The BPA and Corps have teamed up to coordinate the replacement of the Unit 2 runner with an oil-less hub design. A contract for the design and installation of a new turbine runner will be awarded in early 2004 with installation beginning in 2006. The proposed design will be evaluated for its potential to improve fish passage survival through testing of a 1:25 scale physical hydraulic model at ERDC-WES and by biologically testing the new unit after it has been installed.

Section 6. Conclusions and Recommendations

6.1 TSP Objectives

The following is a summary of conclusions and recommendations, based on data and information obtained through this study. The new information developed during Phase I of the TSP was integrated with the results of historical studies. In a unique collaboration through the TSP team and the TWG, this new information was also integrated with studies completed within the DOE AHTS program. The combined resources of the COE and DOE programs permitted a wide range of both laboratory and prototype scale field studies to be conducted. The activities of the TSP team and the TWG helped avoid duplication of effort and development of scopes of study that permitted easy integration of research results. The following conclusions address objectives laid out early in the TSP. These objectives are:

- Evaluate and recommend operational criteria to improve the survival of fish passing through the Kaplan turbine units.
- Identify the biological design criteria for the design of new modifications to the existing turbines.
- Investigate modifications to the existing designs that have the potential to increase the survival of fish passing through the Kaplan turbine units.

The study has also identified several new areas that need to be addressed further, prior to fully resolving issues with improved passage of fish through turbines. The conclusions and recommendations listed below are general and identify some of the issues that should be addressed in future studies.

Briefly stated, within the range of the values tested a relationship between either absolute or relative turbine operating efficiency and direct turbine passage survival was not found. TSP findings are consistent with those of others and it appears that, for the large Kaplan turbines found at mainstem Columbia and Snake River dams, there is no statistically significant relationship between turbine operating efficiency and direct turbine passage survival for yearling Chinook salmon for on cam operations over the range from one percent below peak efficiency to maximum on cam discharge. Biological index testing of turbine families is needed to derive turbine operation rules that will protect fish and optimize power production. Additionally, observations made using physical models have found the turbine environment to be more turbulent at lower discharge. Sensor fish observations made for passage through operating turbines have confirmed these observations, but have also found draft-tube turbulence to be less than that found in spill environments where fish passage survival is high. Other observations, such as the duration of turbine passage, which is longer at lower discharge, also indicate that fish passing through a turbine operating at low discharge may face higher risk of injury than when turbine discharge is higher. The study data and information also suggest that a more streamlined trajectory and direction through which fish are introduced into the turbine environment, i.e., the wicket gates, stay vanes and the runner, may 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. While TSP Phase I focused on turbine internal structures and operations affecting direct turbine passage survival, it has become clear that improvements made in direct turbine passage survival may not contribute significantly to total turbine passage survival unless indirect turbine passage mortality is addressed. Turbine structural designs and operations that provide streamlined, low turbulence flow through efficiently operating turbines, combined with powerhouse operations that provide rapid egress through the powerhouse tailrace, appear to be the necessary elements to provide the best conditions for passage of fish through turbines.

6.2 Conclusions and Recommendations

6.2.1 Turbine Efficiency

The TSP did not find a relationship between absolute or relative turbine operating efficiency and the survival of fish passing through the turbines. The highest survival of fish passing through turbines is not necessarily aligned with the one-percent peak operating efficiency. The TSP recommends further biological index testing for each project with a focus on turbine geometry (alignment of wicket gates and stay vanes, wicket gate overhang and blade angle) and turbine discharge. The biological index tests should cover the full operating range of each turbine family to establish safe operating parameters for all sizes and species of fish passing through the turbines. Individual project turbine operations should then be modified accordingly.

6.2.2 Turbine Discharge

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. At low unit discharges the hydraulic conditions from entry to the stay vane-wicket gate cascade to the leading edge of the turbine runner are more turbulent. With lower turbine unit discharges, fish may spend as long as one complete turbine revolution within the immediate runner environment. The performance of the draft-tubes, in terms of more uniform flow distributions, uniform exit velocities, less hydraulic involvement with the backroll, and, in hydraulic models, better movement of beads downstream, is better at discharges near the upper end of the turbine operating range. Biological index testing should include test points near the turbines' upper operating limits to evaluate high flow operations and the significance of less turbulent, more uniform flow on fish passage survival.

6.2.3 Indirect Mortality

Biological tests indicate a greater percentage of total turbine mortality occurs as indirect mortality. The total turbine passage survival cannot be optimized without improving conditions that influence indirect survival. The TSP recommends further investigations of indirect mortality and the influence of tailrace hydraulic conditions on indirect survival. Acoustic and radio telemetry test methods should be used to observe the behavior of fish in the powerhouse tailrace and their survival through the tailrace (indirect survival) in response to tailrace hydraulic conditions. Computational fluid dynamic models and physical hydraulic models should be used to investigate the effects of powerhouse operations on powerhouse tailrace hydraulics and to optimize project operations to produce good tailrace egress conditions for turbine-passed fish.

6.2.4 The Influence of Depth-Acclimation on Biological Studies

A gap in understanding the effect of rapid pressure change on fish passing through turbines has been identified. Field and laboratory studies of the effects of pressure changes on juvenile fish have been conducted using fish that have not demonstrated acclimation to increased pressure after pre-test holding periods. The rate and absolute range of change in pressure during turbine passage would be greatest for depth-acclimated fish passing through a turbine operating at high discharge. Although the pressure changes do not appear to negatively impact the near surface-acclimated test fish, the consequences if any, for depth-acclimated fish are still unknown. The TSP recommends further scrutiny of existing data as well as laboratory and field investigations to address this issue. The investigations are necessary to develop appropriate test protocols for thoroughly evaluating existing operating conditions and future turbine modifications.

6.2.5 Turbine Control and Mechanical Operations

Field-testing indicates that most turbine operating controls, both mechanical and electrical, are not presently capable of setting and controlling the runner blades and wicket gates to meet any specified operational requirement. It is extremely important that turbine unit operations are accurately defined and controlled, when conducting necessary biological tests to determine the safest operating conditions. The TSP recommends that all monitoring and control systems be inspected and improved as necessary to accurately meet the biological test and operational requirements.

6.2.6 Fish Distribution and MGRs

Biological and performance testing of the MGRs installed at Bonneville indicate the MGR designs can improve turbine efficiency while reducing the risk of fish injury and mortality. Results of the biological testing of the Bonneville and McNary turbine runners show a higher rate of injury and death to fish passing near the blade periphery region than among those passing near the mid-blade or hub regions. However, the overall biological benefit of closing the blade tip gaps remains somewhat unresolved, because the distribution of fish as they pass through the turbine runner is still unknown. The TSP recommends an evaluation of the distribution of fish as they pass through the turbine intake, approach the stay vane and wicket gate cascade, and pass the turbine runners. The purpose is to determine the proportion of the run-at-large that is exposed to the gap areas of turbines to better estimate the biological benefits of minimizing the gaps.

6.2.7 Physical Turbine Models

The ERDC-WES physical hydraulic turbine models have been essential to the design of biological testing and the interpretation of test results. The TSP recommends continued development of model techniques and the use of the ERDC-WES hydraulic models to support the biological index testing and to evaluate any pre- and post-turbine modifications as a result of individual turbine replacements or complete project rehabilitations. An interactive design approach using both the ERDC-WES turbine hydraulic models and turbine manufacturers' high-head turbine performance models, will be necessary to design new turbines and turbine modifications that have potential to increase both the efficiency and the safety of fish passing through turbines.

6.2.8 ERDC-WES Model Investigations Bead Impacts

An analysis of beads passing through physical turbine models of existing units show a high rate of bead strikes on the wicket gate and stay vane leading edges as well as on draft-tube splitter walls. The bead investigations also show a high rate of exposure to "severe" hydraulic conditions, particularly at the trailing edges of wicket gates, trailing edge of the runner blades and within the hub rope. The rate of strike and exposure to severe hydraulic conditions is several times the rate of physical injury observed for live test fish passing through prototype turbines. The TSP recommends further analysis of the bead passage data and the biological data to develop a correlation. With this in place, physical hydraulic models can be used more effectively to estimate the biological benefits of specific turbine operational and structural modifications.

6.2.9 Potential and Known Design Improvements

A number of potential and known design improvements have been identified, but not yet field-tested, for biological benefits. They include streamlining and minimizing the gaps between the stay vane and wicket gates, minimizing the clearance gaps of the turbine runner, rounding and smoothing exposed edges, designing draft-tubes that generate more streamlined flow, and minimizing the turbulence generated at the wicket gate overhang by reshaping of the wicket gate profile. Model investigations indicate that such improvements can reduce the potential for bead strike and exposure to severe hydraulic conditions while increasing turbine efficiency. The TSP recommends such modifications be investigated for future rehabilitations. These should be model tested for each specific application and, if warranted, tested as a single prototype for fish benefits before a full implementation.

6.2.10 Stop Log Slot Closures

The McNary and Bonneville turbine survival studies have shown that a moderate proportion of juvenile migrants are entrained in draft-tube stop log slots for short periods of time. The effect of this entrainment on survival or the likelihood of sub-lethal effects resulting from entrainment is unknown. Therefore, it is premature to conclude that closure of draft-tube stop log slots is warranted to improve passage survival. Modeling evidence has indicated that turbine performance improvements will result from slot closure. When project survival studies are conducted at individual projects to fulfill BiOp objectives, tail log slot monitoring is recommended where applicable to assess the biological benefits for slot closure at individual projects. Such monitoring can be easily accomplished by placing appropriate receiving equipment in tail log slots to detect the presence of tagged test fish in the slots and the time they are retained in the slots. Tail log slot monitoring results will be reported as a part of coordination with fish managers. Based on monitoring results and coordination with fish managers, stop log slot closure may be recommended.

6.2.11 Removal of Projections

Through the course of the TSP's evaluation of turbines, a number of turbine units were inspected in preparation of biological tests, turbine performance tests and for prototype measurements needed for model construction. During these inspections it became apparent that many of the turbine units have unnecessary objects projecting into the water passageways, such as temporary handrails and access ladders. Also noted were exposed pressure relief pipes extending into the flow path from the base of the draft-tubes at John Day. Every turbine unit should be inspected during maintenance for such projections and these should be removed where possible.

6.2.12 Intake Diversion Screens

All of the Lower Snake and Columbia River turbines were designed without intake diversion screens. The intake diversion screens that have since been installed create not only additional head loss, but cause a redistribution of flow to the turbines for which they were not designed. The TSP recommends that any future turbine rehabilitation program fully address the influence of fish diversion structures, such as intake screens and/or surface collectors, on the design and performance of new or modified turbines.

6.2.13 Rehabilitation Schedule

New MGRs are being installed at the Bonneville First Powerhouse and a rehabilitation program is in place for McNary. A contract has been prepared to replace Unit 2 at IHR and a rehabilitation plan for The Dalles is currently being considered. Aside from these projects, there is no overall rehabilitation plan or schedule for the Lower Snake and Columbia River hydropower projects. The TSP recommends a schedule be developed that identifies priority projects, turbine families and/or individual turbine units for replacement or rehabilitation. The schedule should be developed based on the age and physical condition of the units with an emphasis on the maintenance history. The schedule should also consider, as a priority, turbine units with low fish passage survival rates. The rehabilitation process will require Regional Agency coordination and must consider fish passage improvements as identified by the NMFS's BiOp.

6.2.14 Continued Index Testing

A continued program of index testing to optimize the performance of the turbines should be implemented to maintain existing turbines at their optimum for fish passage. At least 6 of the about 100 existing units should be index tested annually to maintain a minimum of operationally and biologically tuned units. This will require regional coordination to establish a larger window of time for performance of these tests and to make improvements throughout a year. This process should continue to optimize the performance of the existing and rehabilitated units with and without fish screens or other fish diversion devices installed.

Section 7. Phase II Program

The purpose of this section is to explain the direction in which the Turbine Survival Program is proceeding. Areas of future investigation and any major needs are discussed and a brief schedule for the program is included. The program will continuously adjust to new discoveries and focus areas in order to maximize its effectiveness and expenditure of ever-tightening Federal dollars. Significant effort has been expended in identifying the most critical focus areas for future studies.

Investigations performed during Phase I of the Turbine Survival Program have identified opportunities for changes in the design and operation of turbines to improve the survival and reduce the injuries to fish passing through turbines. A limited number of potentially productive turbine design changes, such as almost total elimination of the gaps at the tip and hub of Kaplan turbine runner blades, have been implemented and subjected to extensive engineering and biological testing during Phase I. Most of the opportunities to improve the survival of fish passing through turbines, which have been identified during Phase I and also meet financial and engineering goals, remain for implementation and evaluation in Phase II of the Turbine Survival Program.

Prioritization of Turbine Survival Program Phase II work plan elements is based on NMFS Biological Opinion reasonable and prudent actions (RPAs). An action of considerable importance is the development of new operating rules for the MGR turbines being installed at Bonneville First Powerhouse. Improvements in fish survival may also be possible by new operating rules for turbines with original design runners. Because operational changes are mechanistically inexpensive to implement, moving quickly during TSP Phase II to determine the biological benefits for all of the families of turbines within the Federal hydropower system is also a Phase II priority for the Turbine Survival Program. The process of developing operating rules for hydro turbines based on biological criteria has been named *biological index testing*.

Biological investigations completed during TSP Phase I have shown that the benefits of improvements in turbine passage conditions cannot be fully realized unless turbine-passed fish can quickly pass through powerhouse tailraces with low exposure to predation. The biological studies completed show that, at most locations studied, the major component of turbine passage mortality occurs in the powerhouse tailrace on fish that have survived turbine passage. For this reason, in Phase II of the Turbine Survival Program emphasis is placed on investigation of means to significantly improve tailrace egress for turbine-passed fish. These investigations will address issues such as the design of draft tubes, the turbine operations that optimize their hydraulic performance, and the powerhouse operations that will improve tailrace hydraulics for fish egress. Also important is the evolution in the design and use of both turbine and general project physical models to provide tools to expedite development of turbine and powerhouse operations to optimize fish egress and total turbine passage survival.

An important product of Phase I investigations was the development of a process to systematically address physical, economic, and biological aspects of turbine modifications during turbine rehabilitation. This process will facilitate implementation of the Biological Opinion RPA to investigate opportunities to improve turbine passage conditions for fish as an element of any turbine rehabilitation action. Currently, turbine rehabilitation is underway at Ice Harbor and McNary Dams. Turbines at The Dalles Dam are also being considered for rehabilitation in the near future. Implementation of the findings of Phase I for the process of making decisions during turbine rehabilitation remain to be merged with the turbine rehabilitation process currently used by the COE and BPA.

An essential, ongoing activity for Phase II is participation in the evolution of turbine designs to improve fish passage conditions with other dam owners, Federal agencies, and private sector turbine design and manufacturing companies. A number of activities including the continuation of the COE as the lead for the Turbine Technical Working Group and participation in DOE's Advanced Hydro Turbine program will keep the COE informed about the progress of others, provide for efficient technology transfer from successful COE projects, and permit the COE to leverage its opportunities and capabilities through joint activities with others interested in improving turbines for fish passage.

Also essential are efforts to communicate to dam operators and their contractors the importance of simple measures, such as elimination of projections in the water path, to improve fish passage conditions. Too frequently, examination of the water path has found remnants of turbine repair and maintenance activities that present injury hazards to fish.

7.1 Biological Index Testing

The goal of biological index testing (BIT) is to identify turbine operations that optimize the total turbine passage survival for all of the fish passing through turbines. These turbine operations will be a subset of the total range of desired turbine operations that are identified during turbine engineering index testing conducted to determine the relationship between, hydraulic head, turbine discharge, turbine mechanical operating geometry, and power production. Engineering index testing identifies those turbine operations that optimize the use of available water for power production. Basic engineering index testing is necessary for BIT. BIT should not be performed for turbines that have not been engineering index tested. Turbines that are operating outside of their best power production range are thought to present a higher risk of injury to fish.

While basic engineering index testing is conducted on an individual turbine unit basis, TSP Phase I study results indicated that BIT cannot be as narrowly defined. Although many of the critical parameters such as turbine mechanical operating geometry can be evaluated on a turbine unit basis, it is the interrelationship of flows from adjacent units and the overall powerhouse operation and relationship to spill that offers the greatest benefits. Operations that result in mechanically open turbine operating geometries, turbine discharges that more optimally use draft-tubes, and the operation of other turbine units plus spill discharge, all appear to be potentially important. While BIT may be complex, the potential for improvement in survival of turbine-passed fish is high. Turbine passage survival studies completed during TSP Phase I have shown that, for most turbine units tested, the major portion of turbine passage mortality occurs in the powerhouse tailrace through predation on fish that would otherwise survive turbine passage. Total survival gains for turbine-passed fish on the order of 10 percent may be achievable.

A strategy for BIT has been developed. The first stage of the strategy depends on the use of engineering index testing and other engineering evaluations to identify the best hydraulic operating point for a turbine. This alignment is typically above (in terms of turbine discharge) the most efficient turbine operating point, is to be used as a pivot point for investigation of BIT. This point appears to match the geometric and hydraulic conditions where inflow to the turbine runner and draft-tube are aligned with the flow distribution from the scroll case. Lessons learned during Phase I indicate that BIT, at the single turbine unit level, is likely to be asymmetrical, biased toward higher discharge and more open turbine mechanical geometries. Additional analysis of existing engineering and biological data during Phase II will further develop testable hypotheses. In particular, the analyses conducted by Skalski, et al. (2002) found that, while peak turbine passage survival did not coincide with peak turbine efficiency for 3 of 4 mainstem Kaplan turbines, peak survival did occur within 1 percent of peak efficiency. These results need to be considered in more detail with emphasis placed on assessment of the operating geometries that corresponded to peak survival and hydraulic conditions at these geometries. In addition, mathematical modeling using strike as a surrogate variable, physical model observations, and reassessment of historical turbine passage survival studies will be used to develop hypotheses for single unit operation (around the identified pivot point to optimize direct turbine passage survival). These hypotheses will be tested at prototype scales using live fish. The final stage of BIT will require the use of physical general project models, computation fluid dynamics models, and fish behavior assessment to identify powerhouse and other project operations needed to optimize the egress of turbine-passed fish through the project tailrace.

Enough information currently exists to undertake the first stage of BIT to develop hypotheses for single turbine unit operations. Completion of BIT for specific projects will require studies similar to those conducted over the past decade to more safely pass fish in spill.

7.1.1 Biological Index Testing at COE Mainstem Dams.

Implementation of BIT will follow NMFS Biological Opinion RPAs with initial focus on the new minimum gap runner turbine units at Bonneville First Powerhouse, and will progress to reassess biological operating criteria for all of the families of turbine units at mainstem Columbia and Snake River Federal dams.

7.1.2 Integration of Physical Turbine Models and Biologic Studies Results.

Physical turbine models and prototype scale biologic tests are important tools for biological index testing as well as other investigations to improve the survival of fish passing through turbines. Qualitative assessment of the results of bead tracking through physical turbine models, and the result of prototype scale biological studies, indicate physical models may potentially be used to quantitatively evaluate the biological performance of turbine environment structural and operational changes. The objective of this work is to statistically assess relationships between observations made using physical models and the results of prototype scale biological studies. The analysis would use existing physical model and biological test results available for Bonneville First Powerhouse and McNary Dam. Incorporation of information available from recently completed numerical modeling completed within the Department of Energy's Advanced Hydropower Turbine System (AHTS) program would also be considered during analysis.

7.1.3 Effects of Pressure Cycling on Depth-Acclimated Salmonids

One of the potential strategies for optimization of total turbine passage survival is the operation of turbine units at the upper end of their range. In the Kaplan turbines installed at COE projects, as turbine discharge increases the nadir in pressure immediately downstream of the runner decreases. In addition, the rate of change in pressure through the runner increases. During TSP Phase I, a deficiency was identified in the understanding of the condition of the swim bladders of run-of-the-river juvenile salmonids and the effects of pressure changes on fish that might be acclimated for neutral buoyancy at greater depths. A review of studies on the effects of pressure on salmonids found no information on pressure acclimation by run-of-the-river fish or the effects of simulated turbine pressure time histories on depth-acclimated fish. This uncertainty affects assessment of the tradeoffs of operating Kaplan turbines at high discharge and of designs that increase discharge through turbine units above that of original design units.

Phase II of the TSP will investigate the physiological state of in-river fish and conduct laboratory studies to evaluate the effects of pressure cycling typical of turbine passage on depth-acclimated juvenile salmonids.

7.1.4 Complete Investigations of Fish Distribution Effects in Turbine

Turbines are designed without fish screens in the intake. With the exception of The Dalles, however, all of the lower Columbia River and Snake River projects currently have fish screens in the intake. Consequently, future designs should consider the impact on flows through the runner created by the fish screens. The distribution of fish entering a turbine intake bay are affected by the fish diversions devices which could result in fish being directed to the worst part of the turbine. Structural changes in the turbine water passages could be made to mitigate these effects. Phase II will investigate and document how screens affect the entry point of juveniles into the runner environment through biological field evaluations and turbine imaging. Studies to correlate the effect of fish diversion devices on adult and juvenile fish distribution at the turbine runner will be prepared.

7.1.5 Turbine Operating Geometry and Hydraulic Conditions at Peak Turbine Passage Survival

The approach to BIT developed during Phase I is predicated on identification of a turbine operating condition where structural geometry and hydraulics provide optimum fish passage conditions. This point would then serve as a pivot for identification of an operating range that would satisfy the various constraints of operational flexibility, power production, and safer fish passage. In this optimization, safer fish passage would be evaluated based on both direct and indirect turbine passage biological effects.

The operating pivot point for BIT appears to be above peak turbine efficiency but further investigation is needed to evaluate this hypothesis. One of the critical activities, to be conducted as early in the Phase II program as possible, is additional analysis of existing turbine passage data with emphasis on identifying the operating geometries for test turbines for operations resulting in maximum direct turbine passage survival. This assessment will require review of biological tests conducted to date to identify the operating conditions at peak fish survival, engineering analysis of the turbines to describe the blade-wicket gate settings at these conditions, and review of any relevant physical model test data or other information that would aid description of the structural and hydraulic conditions that existed at peak survival during the various tests. The expected outcome from this analysis is insight into the conditions necessary for optimum fish direct survival through a turbine that will aid in identification of peak survival pivot points for BIT.

7.2 Turbine Rehabilitation

One of the primary products of the TSP Phase I was the development of a decision process for scheduled turbine rehabilitation that incorporates biological performance with engineering and economic factors. Historically, biological performance has not been included in the assessment of replacement runner design or other turbine modifications that might occur during turbine rehabilitation. However, the listing of salmonid stocks under the Endangered Species Act and the requirements for recovery of these stocks has focused attention on all of the potential passage routes, including turbine passage.

Because of the long planning horizon for turbine rehabilitation projects, rehabilitation planning was already underway for Bonneville First Powerhouse and McNary Dam at the time of initiation of the Turbine Survival Program. Although it is anticipated that turbine rehabilitations will be scheduled solely based on the needs to repair worn and fatigued equipment, evaluation of the replacement equipment should incorporate advances in understanding of the biological effects. Phase II of the TSP includes actions to implement features of the TSP developed turbine rehabilitation decision process at Bonneville, Ice Harbor, The Dalles, and McNary Dams. The action for Bonneville Dam was previously discussed in Section 7.1. TSP contributions to these rehabilitations are presented below.

In all of these cases the intent of the TSP program is to work within rehabilitation programs to help select design and operational modifications that will improve fish passage safety if possible, but, at the very least, will not degrade fish passage conditions. Part of the TSP Phase II work plan is to have TSP work interactively with rehabilitation design groups. Another objective is to provide COE projects and turbine operators with a planned process for scheduling rehabilitation to help ensure that fish passage concerns are addressed and opportunities to improve fish passage conditions are not overlooked.

The coordination efforts to link turbine fish passage improvements to turbine rehabilitation or replacement consistent with National and Regional interests and the TSP Turbine Rehabilitation Decision Framework is envisioned.

7.2.1 Application of the TSP Turbine Rehabilitation Decision Framework to Ice Harbor Dam

The runner for one of the turbine units at Ice Harbor Dam is scheduled for rehabilitation. Problems with turbine runner blades and oil leakage at Unit 2 triggered a rehabilitation action for this unit. The turbine rehabilitation decision process developed by the Turbine Survival Program calls for biological evaluation of existing runner performance to assess the potential biological benefit of turbine runner redesign. Total turbine passage survival studies are being conducted as an element of system wide evaluation of project passage survival. Turbine passage survival studies were conducted at Ice Harbor during FY03 as an element of this work. The results of these studies are pending. When these survival estimates are obtained they will be evaluated to determine the necessity of a direct turbine passage injury and mortality assessment study in FY04. If is found that direct turbine passage assessment is necessary to determine the appropriate path for biological performance optimization of a rehabilitated Ice Harbor turbine, funding will be needed in FY04 to plan and execute the needed study.

7.2.2 Application of the TSP Turbine Rehabilitation Decision Framework to The Dalles Units 1 to 14 Powerhouse Rehabilitation

The rehabilitation program for The Dalles Dam turbines has been delayed and a new schedule has not been determined. The current focus of The Dalles rehabilitation is to evaluate the potential power efficiency increases and biological responses through reconditioning the runner surfaces to near new conditions. Regional discussions are ongoing to acquire additional information on direct turbine survival at The Dalles. Opportunities to obtain turbine passage survival data will occur as project survival studies are conducted at The Dalles Dam over the next several years. As this data becomes available, the TSP will apply the turbine rehabilitation decision framework to the existing TDA rehabilitation plan. It will also coordinate with the sponsoring rehabilitation product delivery team and the Region as necessary. In addition, the TSP will provide regional coordination regarding future TDA rehabilitation plans.

7.2.3 Application of the TSP Turbine Rehabilitation Decision Framework to McNary 1 to 14 Turbine Rehabilitation.

In general, the McNary turbine rehabilitation attempted to conform to the regional requirements through collaboration, without the benefit of the proposed TSP rehabilitation framework. Hence, the work of the TSP is more limited because the process has already been coordinated. However, there is significant TSP involvement providing consultation and evaluation services to the product delivery team. The TSP will provide a lead biologist to participate in biological evaluation of the turbine designs at ERDC and for monitoring and advising on the biological testing as an independent observer. The TSP will provide independent coordination and reporting of progress and results to the Region.

7.2.4 Application of the TSP Turbine Rehabilitation Decision Process to Other Turbine Rehabilitations

A schedule of turbine rehabilitations for Federal mainstem Columbia and Snake River dams, beyond those already mentioned, does not exist. The TSP should be included in the FCRPS Corps rehabilitation planning process. The TSP would provide coordination and communication to the Region regarding rehabilitation plans. In addition, the lack of a system-wide schedule for turbine rehabilitation limits consideration of data needs for assessment of potential biological benefits of turbine redesign. Consequently, acquiring turbine-passed fish survival and condition data, in an efficient and cost-effective manner, to aid in the assessment of turbine design alternatives for rehabilitation may not be realized.

7.3 Turbine Operation Modifications

Significant improvements in existing turbine operation and control systems have occurred, are currently being implemented, or are planned. These improvements need to be coordinated, monitored, checked, and updated as new information or technology becomes available. The following tasks are necessary in Phase II to come to closure on implementing the recommendations resulting from Phase I of the TSP program.

7.3.1 Develop a Plan for Modernizing Turbine Monitoring and Control Systems to Ensure Operation at the Accuracy Required by Biological Criteria

The NMFS Biological Opinion sets rigorous criteria for operation of turbines. These criteria limit turbine operations to within ±1 percent of peak efficiency. In the future, any new biological-based turbine operation criteria will also require close control of turbine operations to remain within criteria. A critical challenge with meeting current and future turbine operations criteria is uncertainty in the ability of turbine operations monitoring and control systems to accurately indicate the turbine operating condition.

During Phase II, the TSP will: (1) Identify current condition and accuracy of monitoring and control systems for all COE Columbia/Snake River dams, (2) Establish necessary operating tolerances for turbine operations needed to meet biological operating criteria for fish survival and compare these specifications to current conditions, and (3) Evaluate and upgrade options for each plant and develop a prioritized incremental plan for upgrading systems to meet required turbine operating tolerances.

7.3.2 Provide Training/Awareness for Identifying and Correcting Projections in the Flow Path

Sharp edges and gaps in the flow path present a hazard to passing fish. These objects are often not part of the original design, but are often devices added to assist maintenance crews and to provide access. As such, they are not included in drawings of the project and are largely unknown until a unit is dewatered for inspection. Training and awareness will be provided to Project and other personnel on identifying/correcting these problems. The criterion to be followed is that no flow path projections are to be within a turbine other than those required for safety and structural and mechanical integrity.

7.3.3 Determine the Need to Provide Draft-tube Stoplog Slot Closure

Biologic studies at Bonneville First Powerhouse and the initial study at McNary indicated that a few percent of the fish were being entrained in the draft-tube stoplog slots. It is unknown what effect this entrainment has on fish survival or condition. Further studies at B2 indicate that temporary entrainment in the stoplog slot is occurring. Again, the effect of this entrainment is unknown. Further evaluation of the effects of this entrainment and identification of the hydraulic conditions that exist resulting in this entrainment are needed. Pending results of the biological investigation, a prioritized list of projects where stoplog slot closure would provide biological benefits will be prepared.

7.3.4 Continue to Evaluate Physical Model Data as a Means for Comparative Measures with Varying Field Conditions

Physical model studies proved to be invaluable in evaluations of areas affecting the passage of fish. Evaluations of future rehabilitations will need to include physical modeling in their assessment of design for hydraulic features impacting biology. Simulations of prototype conditions encountered during biological testing will be performed and compared to biological results to identify conditions impacting survival and injury. These will serve to help identify biological design criteria to be employed on future projects. These physical models will continue to be used to help in development and analysis of biological tests. Physical model reports will be prepared for each study.

7.4 Draft-tube and Egress Investigations

Indirect turbine passage mortality, which occurs in the tailrace environment, is frequently the major component of total turbine passage mortality. Experience with passage of juvenile migrants in spill suggests that the vulnerability of turbine-passed fish in the powerhouse tailrace is related to flow field dynamics, egress of turbine-passed fish through the powerhouse tailrace, and the abundance and behavior of avian and piscivorous predators. Rapid egress through regions with high predator density has been found to enhance survival of fish passing in spill. Investigation of powerhouse tailrace flow field dynamics and the behavior of turbine-passed fish in the region is a priority for TSP Phase II because of the potential to significantly improve total turbine passage survival. Improvement in indirect survival is also necessary to realize increases in direct turbine passage survival and decreases in injury rates realizable through turbine design and operational modifications.

In TSP Phase I very limited work was completed on draft-tubes and egress other than identifying the overall indirect mortality at a few projects and the initial overview of the effect of turbine discharge and draft-tube hydraulic performance on flow field conditions in the immediate powerhouse tailrace. These investigations continue to point out the significance of this portion of this fish passage route.

Phase I studies indicate opportunities to address tailrace hydraulic conditions and potentially reduce indirect turbine passage mortality. For this reason, the Phase II plan of study includes additional study of the hydrodynamics of turbine draft-tubes and physical and numerical modeling to determine project operations to optimize egress conditions for turbine-passed fish. Biological studies of the egress behavior of turbine-passed fish under different project operations will also be conducted to evaluate the effectiveness of project tailrace flow field conditions for rapidly moving fish through the tailrace environment. Behavioral studies will be integrated into future indirect turbine passage survival studies to maximize the information obtained from each study.

7.4.1 Use Turbine and General Project Physical Models to Evaluate the Influence of Draft-tube Flow Dynamics on the Immediate Tailrace Environment and Conditions for Fish Egress through the General Tailrace Environment

Limited analysis to date has determined that juvenile salmonids may have increased tailrace retention time, and higher indirect mortality rates at lower turbine discharges. This appears to be due to draft-tubes being designed for capacity rather than average discharge. The result is that flow within turbine draft-tubes becomes less streamlined and more turbulent at lower discharge. The high mortality that occurs downstream of the draft-tube could be highly influenced by draft-tube flows resulting in longer tailrace retention time, turbulence exposure, entrainment in backroller flows, and generally poorer conditions for egress through the tailrace environment prior to fish entering the main river flow. The primary mechanism of this increased mortality is the increased opportunity for predation.

Using existing turbine physical models, and those for other turbine families that may become available over the next few years, the TSP will investigate hydraulic conditions within turbine draft-tubes with the goal of identifying the range of turbine operations that provide the best hydraulic conditions within existing draft tubes and in the immediate tailrace environment. Measurements of draft-tube discharge characteristics will be validated with measurements made using an Acoustic Doppler Current Profiler (ADCP) or other water velocity measurement technologies at prototype scales. Validated physical model data sets will be used to evaluate the performance of the powerhouse sections of general models needed to investigate the flow dynamics of the general tailrace environments of mainstem projects. Physical model and prototype flow field measurements may also be used as boundary conditions and validation data sets for computation fluid dynamics investigations of tailrace flow field dynamics.

These efforts will be coordinated with the biologic operating point information and biological index testing. Because of the anticipated importance of project tailrace flows to survival of turbine-passed fish, upon completion of this element of TSP Phase II work an interim report will be prepared to include recommendations on modification to turbine best biological operation or, potentially, structural modifications to improve total turbine fish passage survival for juvenile salmonids.

7.4.2 Investigate the Biological Response of Juvenile Salmonids to Tailrace Flow Field Conditions

A limited number of juvenile salmonid survival studies have indicated that loss of fish due to predation in the tailrace environment of mainstem projects is high and appears to be the major component of total turbine passage mortality. TSP researchers theorize that treatment of powerhouse discharge in a manner like that used to optimize the survival of fish passed in spill will decrease tailrace mortality. Evaluation of this hypothesis will require the conduct of biological studies that evaluate tailrace flow conditions as treatments affecting juvenile salmonid survival.

Test treatments will need to be designed to investigate the contributions to tailrace flow field dynamics and consequences for fish egress and survival of spillway flows, back roller, tailrace channel geometry, etc. Conditions to be tested as treatments will be provided by the hydraulic investigations described in the previous TSP Phase II study element.

7.4.3 Investigate Draft-tube Structural Improvements using Physical Turbine Models

Turbine runners and draft-tubes for mainstem dams were originally designed as a system to provide optimal hydraulic performance at a high discharge condition. Operational restrictions, such as the 1 percent operating limit, not envisioned during original design, result in flow in the draft-tubes that is very much imbalanced and irregular and can actually have reverse flow in one barrel.

The draft-tube shape, pier nose, flow characteristics, stop log slots and exit angles need to be examined to determine if better hydraulic conditions for fish passage might be feasible. Physical hydraulic modeling has indicated that flow and velocity distribution can be improved with potential biological and turbine performance improvements. There does not appear to be significant hydraulic danger points in the draft-tubes impacting direct fish survival, but the turbulence may have significant effects on disorientation and through these means affect indirect turbine passage survival.

It is expected that this study element may identify draft-tube structural modifications that could improve draft-tube flow dynamics and thereby positively influence both direct and indirect turbine passage survival. Any such improvements will be identified as potential biological design criteria to be incorporated into turbine rehabilitations.

7.5 Continuing Support

Essential to the continuance of knowledge development in the area of turbine passage is the exchange of developing information with other Federal agencies and PUD's. This allows all of the groups working in this area to learn from each other and to build upon each other's successes. This is accomplished in several forums: conversations between peers, participation in professional conferences, and literature development, but primarily through meetings such as TWG or AHT. The ability to share expertise developed by members of the TSP with others is critical to the success of other studies and design development. This is why TSP members play such an active role in evaluating rehabilitation designs, applying their experience in this very unique field. Working and sharing information with the turbine development industry as experimental concept designs are developed, combined with TSP's knowledge of fish passage, saves considerable development cost and results in fish passage improvements on an international scale.

7.5.1 Communication Plan with Industry, Other Federal Agencies, and PUDs

The initial workshop on fish passage through turbines resulted in the organization of the TSP. Development of concepts to evaluate fish passage through turbines is only one of the many recommendations that were made in this gathering. A later workshop also resulted in further refinement of ideas and agreement on necessary direction of studies. The next workshop will focus on what has been learned to date and consider what is critical for future turbine fish passage improvements.

The Turbine Working Group (TWG) is the primary interface of the Corps of Engineers with industry, other agencies and PUD's for integration of fish survival through turbines issues. Participation is primarily attendance at monthly meetings by TWG members. The format of these meetings is updates and presentations by all members and collaboration between members on ongoing work for any or all members.

The Advanced Hydroturbine Technical Committee (AHT) is the interagency steering committee set up by DOE to help evaluate and provide technical assistance to their turbine fish passage programs. Participation is primarily TSP attendance at meetings, technical reviews and coordination of interagency activities. These meetings are normally held near a project of interest and allow for onsite, shared discussions, evaluations and expert cooperation and collaboration concerning turbine fish passage improvement.

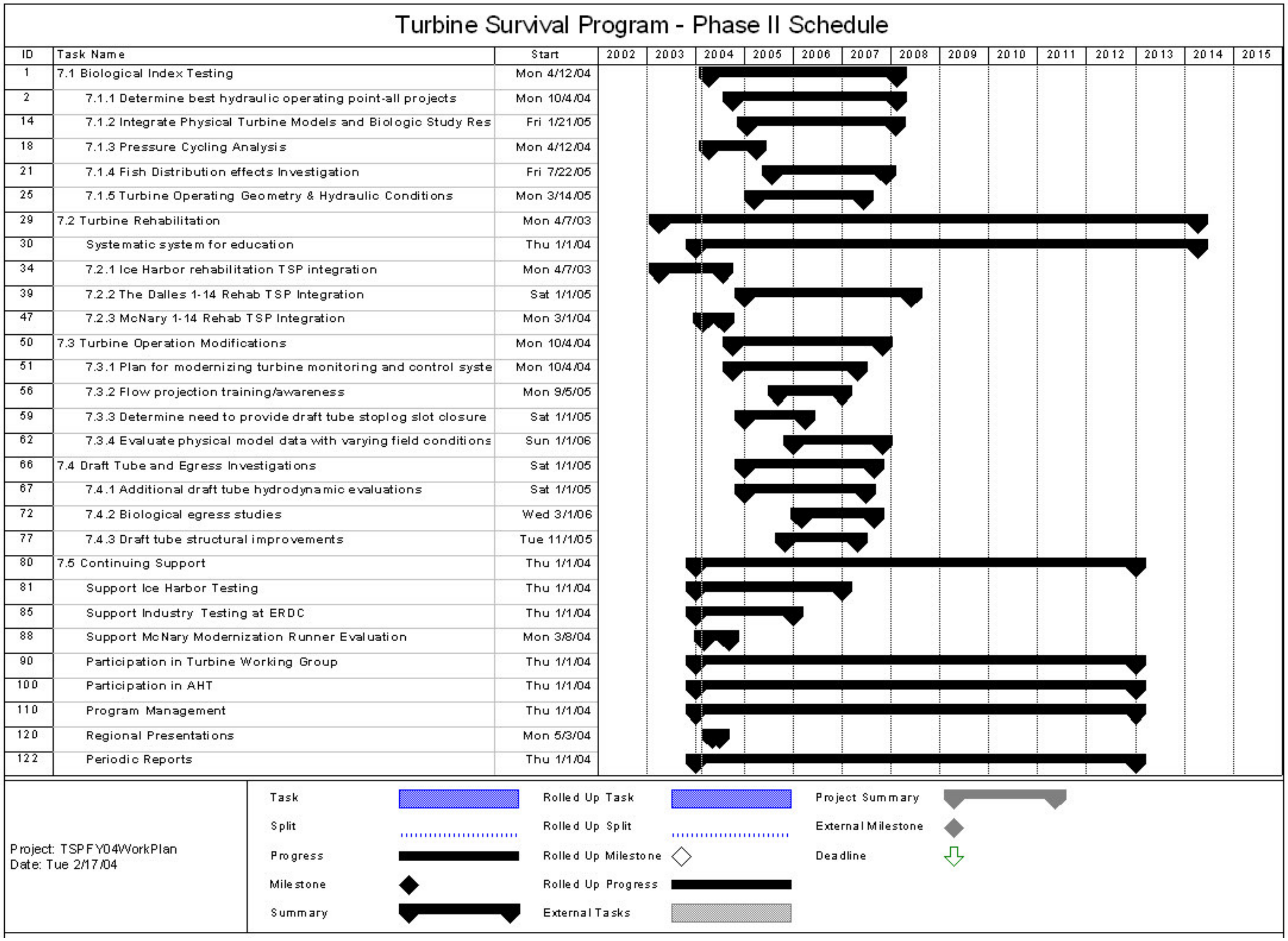
Publication of cutting edge information is accomplished at timely intervals to provide critical information to the diverse audience of regional, national and international representatives. One method used to accomplish this is through regional presentations. A series of presentations to the region is planned to share successes with the program.

Feedback to this program's supporters is considered vital to inform and to maintain regional support of this critical program. Periodic reports of the progress being made are published and distributed to a wide audience. This report represents the third installment of major publications for the TSP. A summary brochure on the TSP program will be prepared and printed. The purpose of this document is to explain the Turbine Survival Program to others and to inform the Region and other agencies of our successes.

Actively participating in the development of designs for ongoing rehabilitations or experimental design development is one of the most beneficial aspects of the TSP. Currently, rehabilitations at Ice Harbor and McNary dam are including TSP in their planning and evaluation phases. As support for these efforts, the COE is constructing a new Ice Harbor turbine model, funded by DOE AHTS, and examining the hydraulic characteristics of the new runner. Hydraulic performance modeling will be performed at the turbine manufacturer's laboratory. The selected design will then be evaluated in the new Ice Harbor Unit 1-3 model at ERDC. Model construction management, supervision, and report out to DOE AHTS is being carried out by the TSP.

Experimental design development is an ongoing activity with industry. However, it is only recently that industry has been asked to improve biological elements of particular turbine design features. The TSP has developed the combined engineering and biological expertise to provide information to industry on potential biological improvements on a cost-shared basis. Currently, an evaluation of a manufacturer's proposed Kaplan turbine design is to be performed in the Lower Granite Model at ERDC. This cost-shared effort requires coordination activities and process review from the TSP as the program coordinators and interface between ERDC, industry, and the DOE. This is a unique opportunity to work closely with engineers, biologists, industry, and other interested agencies (DOE). This opportunity to share knowledge and expertise in such a cooperative environment is unusual in the highly competitive world of turbine design. Industry designs will be compared to the Lower Granite design. Testing will include observing beads, using high-speed video, as well as measurement of velocity distribution in the draft-tube. TSP will provide coordination, oversight and review of ERDC investigations and reports.

7.5.2 Schedule



Turbine Survival Program - Phase II Schedule

ID	Task Name	Start
1	7.1 Biological Index Testing	Mon 4/12/04
2	7.1.1 Determine best hydraulic operating point-all projects	Mon 10/4/04
14	7.1.2 Integrate Physical Turbine Models and Biologic Study Res	Fri 1/21/05
18	7.1.3 Pressure Cycling Analysis	Mon 4/12/04
21	7.1.4 Fish Distribution effects Investigation	Fri 7/22/05
25	7.1.5 Turbine Operating Geometry & Hydraulic Conditions	Mon 3/14/05
29	7.2 Turbine Rehabilitation	Mon 4/7/03
30	Systematic system for education	Thu 1/1/04
34	7.2.1 Ice Harbor rehabilitation TSP integration	Mon 4/7/03
39	7.2.2 The Dalles 1-14 Rehab TSP Integration	Sat 1/1/05
47	7.2.3 McNary 1-14 Rehab TSP Integration	Mon 3/1/04
50	7.3 Turbine Operation Modifications	Mon 10/4/04
51	7.3.1 Plan for modernizing turbine monitoring and control syste	Mon 10/4/04
56	7.3.2 Flow projection training/awareness	Mon 9/5/05
59	7.3.3 Determine need to provide draft tube stoplog slot closure	Sat 1/1/05
62	7.3.4 Evaluate physical model data with varying field conditions	Sun 1/1/06
66	7.4 Draft Tube and Egress Investigations	Sat 1/1/05
67	7.4.1 Additional draft tube hydrodynamic evaluations	Sat 1/1/05
72	7.4.2 Biological egress studies	Wed 3/1/06
77	7.4.3 Draft tube structural improvements	Tue 11/1/05
80	7.5 Continuing Support	Thu 1/1/04
81	Support Ice Harbor Testing	Thu 1/1/04
85	Support Industry Testing at ERDC	Thu 1/1/04
88	Support McNary Modernization Runner Evaluation	Mon 3/8/04
90	Participation in Turbine Working Group	Thu 1/1/04
100	Participation in AHT	Thu 1/1/04
110	Program Management	Thu 1/1/04
120	Regional Presentations	Mon 5/3/04
122	Periodic Reports	Thu 1/1/04

Project: TSPFY04WorkPlan
Date: Tue 2/17/04

Glossary

Absolute Efficiency – The measured value of an individual component's ability to convert what is potentially available to what is actually produced.

Acoustic Doppler Current Profiler (ADCP) – An instrument that measures three-dimensional current velocities by measuring the frequency shift of reflected acoustic energy along the axis of the energy transmission beam. The flow velocity components along the paths of three beams are used to resolve the vector and a fourth beam provides a consistency check.

Advanced Hydropower Turbine System Program (AHTS) – A national DOE program to improve the overall performance and acceptability of hydropower projects by developing and testing advanced turbine technologies that reduce or eliminate adverse environmental effects.

Air Bladder – The organ a fish uses to control its buoyancy in water. To achieve near neutral buoyancy the fish fills its air bladder with gas, which decreases its density until it is nearly that of the surrounding water. See also *Swim Bladder.*

Anadromous – Fish, including all salmon, which spawn in fresh water, but live most of their lives in the ocean.

Alden Laboratory – Located in Holden, Massachusetts, an independent hydraulic laboratory under contract to the DOE-AHTS for performance and biological testing a pilot-scale concept turbine design.

Avian – Of, relating to, or derived from birds.

Backroller – Flow from the tailrace of power plants that surfaces a short distance downstream and flows back toward the powerhouse on the surface.

Balloon Tag – A small balloon attached to a fish containing a capsule of chemicals, which, when activated, create gas that inflates the balloon and brings the fish to the surface for recovery. Recovered fish that have passed through a turbine, spill, or other dam bypass can be examined for injury. Also called Hi-Z Turb'n Tag.

Battelle – The company that operates the Pacific Northwest National Laboratory, located in Richland, Washington for the US Department of Energy.

Bead – A small oblong plastic particle with a specific gravity near one used to visualize features of flow and structure interaction in 1:25 scale physical turbine models and other similarly scaled physical hydraulic models.

Biological Effects Team – Federal agency team that established inputs to the SIMPAS model for the 2000 FCRPS Biological Opinion.

Biological Opinion (BiOp) – Produced by the NMFS, this document is a plan for recovery of threatened and endangered fish stocks that defines which stocks are considered threatened or endangered, and identifies legally enforceable actions that must be taken to achieve recovery of stock.

Bonneville Power Administration (BPA) – A provider of wholesale electricity and transmission to the Pacific Northwest. The BPA also works with other federal agencies to coordinate operations of the Federal Columbia River Power System.

Cavitation – Cavitation results when water flow reaches a zone of low pressure where bubbles form, followed by a zone of high pressure that causes the bubbles to collapse. The collapse of these bubbles is violent enough to form very strong localized shock waves, potentially harming nearby fish.

Computational Fluid Dynamics (CFD) – Numerical models that estimate fluid flow field characteristics.

Corps of Engineers (COE) – A branch of the U.S. Army employing civilian and military personnel to provide engineering services to the country.

Corps of Engineers, Walla Walla (CENWW) – The Walla Walla District of the Corps of Engineers is within the North Pacific Division of the US Army Corps of Engineers. Its offices are located in Walla Walla, WA.

Corps of Engineers, Portland (CENWP) – The Portland District Corps of Engineers is within the North Pacific Division of the US Army Corps of Engineers. Its offices are located in Portland, OR.

Crotch of Turbine - The closure of the scroll case, sometimes referred to as the baffle or nose vane.

Dewater – The act of emptying the water from fluid passageways within the project to provide access for maintenance. (Also termed unwater)

Direct Injury – Those injuries that fish experience within a dam bypass environment such as a turbine. Direct injuries are those that can be readily observed upon recovery of a fish following passage.

Distributor – The part of a turbine that controls the flow of water through the turbine. The distributor acts like a valve. It is composed of the stay vanes and wicket gates. The stay vanes carry the structural weight and the wicket gates rotate to adjust the flow.

Downstream Discharge Area – The chaotic region, a short distance down stream from the draft-tube exit, where turbine discharge returns to river conditions. It is also called "*the boil*".

Draft-tube and Elbow – A shaped diffuser tube below the turbine runner in which velocity and pressure heads are recovered.

Draft-tube Barrels – In most Kaplan turbines the most downstream section of a turbine draft-tube is divided into two sections called barrels by a structural pier. The barrels permit the expansion of turbine discharge and direct the discharge in a downstream direction.

Draft-tube Exit – The exit area of the draft-tube where turbine discharge enters the powerhouse tailrace.

Drogue – A flow measurement device that aids estimation of the direction and velocity of water flow. Many drogues have two parts. One part floats on the surface of the water and is attached by a chain to the second part, which is neutrally buoyant. The drogue is outfitted with ultrasonic transmitters and, sometimes, global positioning system (GPS) transmitters.

Data Acquisition Control System (DACS) – An automated system to gather and report information as well as automatically execute control functions in the operation of the hydropower system.

Electronic Control Unit (ECU) – An isolated turbine control system adjusted for each individual hydro turbines operational characteristics.

Embolism – A bubble of air within an organ or blood vessel. Embolism can cause death by causing obstruction of blood flow.

Engineer Research and Development Center (ERDC) – Part of the Department of Defense laboratory system, the ERDC-WES has as its mission to conceive, plan, study and execute engineering investigations and research and development studies in support of the civil and military missions of the Corps of Engineers and other Federal agencies.

Evolutionary Significant Units – An Evolutionary Significant Unit is a sub-portion of a species that is defined by substantial reproductive isolation from other conspecific units and represents an important component of the evolutionary legacy of the species. (http://www.delta.dfg.ca.gov/afrp/acronym_template.asp?code=ESU)

Extended-Length Submerged Bar Screens (ESBS) – Turbine intake screens that are approximately 40 feet long, which divert fish from the upper portion of the turbine intakes to a juvenile bypass system.

Federal Columbia River Power System (FCRPS) – A collaboration of Federal Agencies (BPA, Corps and the Bureau of Reclamation) in the Pacific Northwest to coordinate the Federal hydropower system and maximize the use of water resources available for power generation, protecting fish and wild life, controlling floods, providing irrigation and navigation, and sustaining cultural resources.

Fish Facility Design Review Work Group (FFDRWG) – A working group that focuses on the design of fish passage structures.

Fish Guidance Efficiency (FGE) – A measure of how efficiently turbine intake screens guide juvenile fish out of turbine intakes. FGE is calculated as gatewell catch (guided fish) divided by the total number of fish (guided + unguided) passing through the turbine.

Fish Passage Efficiency (FPE) – The proportion of fish using non-turbine routes.

Fish Passage Operations and Maintenance Coordination Team (FPOM) – A working group that oversees the operations of fish facilities.

Fish Passage Plan – The Fish Passage Plan is developed by Corps of Engineers in conjunction with BPA and other parties to describe the "year-round project operations necessary to protect and enhance anadromous and resident fish species listed as endangered or threatened under the Endangered Species Act (ESA), as well as other migratory fish species." (FPP 2002)

Froude Modeling – Based on the physical principles of the Froude (Fr) number, a dimensionless number used in studying the motion of a body floating on a fluid with production of surface waves and eddies; equal to the ratio of the square of the relative speed (v) to the product of the acceleration of gravity (g) and a characteristic length (L) of the body.
$Fr = V^2/gL$

Gas Bubble Trauma (GBT) – Injury resulting from gas bubble formation inside fish following exposure to uncompensated total dissolved gas supersaturation conditions. Possible injuries include: over-inflation/rupture of the swim bladder, blockage of blood flow, etc.

Generic Data Acquisition and Control System (GDACS) – A control system using interchangeable parts and computer programs to regionally standardize the DACS system.

Hydroelectric Design Center (HDC) – The Corps Hydroelectric Design Center, an element of the US Army Corps of Engineers located in Portland, OR, has national responsibility to perform engineering and design for the Corps' 75 hydropower and large pump plants, maintains expertise, and develops standards for the US Army Corps of Engineers hydropower projects.

Index Testing – A means of defining, in relative or absolute terms, performance (conversion of the energy in the discharge through a hydro turbine into electrical energy) of a turbine/generator unit, typically for determining the unit's performance over the range of generator output up to full output.

Indirect Mortality – The mortality by predation of fish in the tailrace of passage route such as turbines or spill where the fish may or may not have experienced an injury during passage.

Inlet – The region upstream of the dam from which the turbine pulls water.

Intake Bays – Three bays to distribute flow to the turbine scroll case.

Isthmus – A narrow anatomical part or passage connecting two larger structures or cavities.

Kaplan Turbine - A reaction-type, vertical shaft turbine, with adjustable blades designed to optimize turbine performance and operate over a relatively low-head range, from about 100 feet to 20 feet of head.

Laser Doppler Velocity System (LDV) – An instrument that uses laser beams to measure water velocity. The normal LDV system consists of a two-color, four-beam system for obtaining two-component velocity measurements.

Meta Analysis – The statistical analysis of a large collection of data from many individual studies for the purpose of integrating the findings ("analysis of analyses" Glass, 1976).

Minimum Gap Runner (MGR) – A Kaplan turbine runner designed to almost completely eliminate gaps at the tip and hub of turbine runner blades. These gaps have been implicated as a source of pinching injury to juvenile fish.

Morphology – The form and structure of an organism or any of its parts.

Nadir – As used in this report, it is the lowest point in the pressure time history of a sensor passing through an operating turbine.

National Marine Fisheries Service (NMFS) – An organization within the U.S. National Oceanic and Atmospheric Administration (NOAA) charged with the stewardship of living marine resources.

North Pacific Division (NPD) – Former designation of the North Pacific Regional Headquarters under the Northwestern Division (CENWD) of the U.S. Army Corps of Engineers. The CENWD consists of the Portland, Walla Walla, Seattle, Omaha, and Kansas City districts.

Northwest Power Planning Council (NWPPC) – "The Council develops and maintains a regional power plan and a fish and wildlife program to balance the Northwest's environment and energy needs." (NWPPC website) (Renamed the Northwest Power and Conservation Council - NPCC in July 2003.)

Northwestern Division (NWD) – The Corps of Engineers regional business office providing administrative and coordination services to the Seattle District, Portland District, Walla Walla District, and Omaha District.

Off Cam – Turbine operation not on cam, which results in decreased efficiency due to friction losses inside the machine and incidence effects, which create more turbulence.

On Cam – Turbine operation on an envelope curve in which turbulence is minimized and efficiency (electrical power production per unit if turbine discharge) maximized through unique optimal blade angles and gate openings.

One-Percent (1%) Rule – A turbine operations requirement listed in the NMFS BiOp (1995), which specifies that turbines should be operated within one-percent of peak efficiency. It is based on the theory that the survival of fish through turbines coincides with the highest operating efficiency of the turbine.

Opercula – The covering of the gills of a fish.

Pacific Northwest National Laboratory (PNNL) – A multi-program national laboratory within the U.S. Department of Energy's Office of Science. It is managed for the US Department of Energy by Battelle.

Passive Integrated Transponder (PIT) – An electronic device about the size of a grain of rice that is implanted in juvenile fish. The device provides the fish with a unique identification number and permits it to be tracked during downstream migration through the hydropower system as a juvenile and later upstream as an adult.

Physoclistous – Fish without any connection between the swim bladder and esophagus.

Physostomus – Fish with a connection between the swim bladder and esophagus.

Pinching Injury – Pinching occurs when salmonids are caught in the gaps between runner blade tips and the turbine discharge ring or the runner blade hub and the turbine discharge cone.

Piscivorous Fish – Predatory fish that feed on other fish.

Portland District – See *Corps of Engineers, Portland (CENWP).*

Pressure Injury – When the pressure in the water surrounding a fish changes suddenly, such as occurs when water is passed through a turbine runner, air filled structures within a fish change volume which may cause tissue damage. Both lethal as well as sublethal injuries are possible.

Reasonable and Prudent Alternative (RPA) – Regulations implementing section 7 of the ESA (50 CFR §402) define reasonable and prudent alternatives as alternative actions, identified during formal consultation, that (1) can be implemented in a manner consistent with the intended purpose of the action; (2) can be implemented consistent with the scope of the action agency's legal authority and jurisdiction; (3) are economically and technologically feasible; and (4) would, NMFS believes, avoid the likelihood of jeopardizing the continued existence of listed species or resulting in the destruction or adverse modification of critical habitat.

Relative Efficiency – The power production efficiency of a Kaplan turbine at any head, blade angle, and wicket gate opening relative to the maximum efficiency of the turbine. Relative efficiencies are typically presented as a percentage decrease from maximum efficiency.

Reservoir Control Center (RCC) – A division within the Corps of Engineers Northwest Division responsible for management of the flow of water through USACE dams.

Reynolds Modeling – Scaling the fluid forces exactly so that the ratios remain the same for the scale physical model (1:25) and the full-scale model.

Run-of-the-River – When the existing river flow at a particular time is passed through the project (dam) because little storage is available.

Runner Chamber – The zone containing the stationary and rotating components of the turbine, and converts waterpower to shaft power. It is composed of the discharge ring, head cover, runner blades, hub and cone.

Scraping Injury – Scraping/Abrasion injuries result from fish contacting solid parts of the machine, both moving parts and those that are stationary.

Scroll Case – A volute-shaped chamber directing water uniformly to the distributor.

Shear Injury – Water shear results when two parallel jets of differing velocities of water pass next to or near to each other. Shear injuries may include head damage, torn opercula (gill covers), loss of scales, and damaged or missing eyes. Less severe injuries may include loss of equilibrium and disorientation.

Simulated Passage Model (SIMPAS) – NMFS' Simulated Passage (SIMPAS) model used to evaluate the biological benefits of juvenile salmonid passage measures.

Stay Vanes – Vanes arranged in the stay ring upstream from the wicket gates carrying the structural weight and positioned to operate with the wicket gates.

Stock – A "fish population that spawns in a particular stream, or stream reach, at a particular season and that do not interbreed to a substantial degree with any group spawning in a different place, or in the same place at a different time." (http://www.delta.dfg.ca.gov/afrp/anadfish.html#Stocks)

Stop Log/ Bulkhead – The draft-tube stop log or bulkhead used to isolate the turbine draft-tube from the powerhouse tailrace prior to dewatering of the turbine passage.

Strike Injury – Injuries resulting from fish hitting solid parts of the machine, both moving parts and those that are stationary.

Submerged Traveling Screen (STS) – Turbine intake screens approximately 20 feet long that divert fish from the upper portion of the turbine intakes to a juvenile bypass system. Traveling screens continuously rotate to remove debris from the screen surface. The screens rotate on a frame so that debris lodged on the screen when it is facing upstream are removed when the screen rotates around the frame and faces downstream.

Swath - A long, broad strip of scales.

Swim Bladder – See *Air Bladder*.

System Configuration Study (SCS) – The SCS is a two-phase study of alternatives for physically modifying or reconfiguring the Federal hydropower projects on the Columbia and Snake rivers to better operate for fish.

Tail log slot – The draft-tube slot that houses the gate used to close off the draft-tube from the tailrace when removing water from the draft-tube before repairs are made to the turbine.

Tailrace – The region downstream of the dam, beginning at the downstream end of the stilling basin or a short distance down from the draft-tube exit, where water in the channel becomes shallower and narrower, more riverine in nature.

The Boil – See *Downstream Discharge Area*.

Trash Racks – Steel grating located at the upstream face of turbine intake bay openings to keep large trash from entering the turbine.

Turbine Intake Extension (TIE) – Structures placed at the Bonneville Dam second powerhouse that extend the ceiling intake for the turbines.

Turbine Survival Program (TSP) – A U.S. Army Corps of Engineers program to investigate mechanical and operational changes that can be made to hydropower dam turbines to increase fish passage survival and power production benefits.

Turbine Working Group (TWG) – A National and Regional group tasked with coordinating efforts between agencies and others to improve fish passage through turbines.

Turbulence – A fluid flow in which the velocity at a given point varies erratically in magnitude and direction.

Turbulence Intensity – A measure used in characterizing turbulence through the maintaining a continuous record of the instantaneous velocities at the point of interest.
Turbulence Intensity = $[\sum (v_i - v_{ave})^2 n^{-1})]^{-2}$

Turbulence Scale – The size of the turbulent fluctuations.

United States Army Corps of Engineers (USACE) – A branch of the U.S. Army employing civilian and military personnel to provide engineering services to the country.

Vertical Barrier Screen (VBS) – A screen built from wire mesh or bars that separates the water diverted by in turbine screens from return flow to the turbine intake. The VBS prevents juvenile fish that enter the turbine gatewell with diverted turbine flow from being carried back into the turbine and helps direct them into juvenile bypass orifices that perforate the gatewell wall.

Vestibular – Relating to the sense of equilibrium.

Voith Hydro – An international hydroturbine manufacturer.

Walla Walla District – See *Corps of Engineers, Walla Walla (CENWW).*

Waterways Experiment Station (WES) – Headquarters for the U.S. Army Engineer Research and Development Center (ERDC).

Wicket Gates - A gate in the flow of water to turbine blades that regulates quantity and direction; or a series of movable, flow-regulating, gates that impart a whirling component to axial flow.

Winter Kennedy – A pair of piezometric taps located in a turbine scroll or spiral case that provide a differential pressure that is proportional to flow through a turbine. They provide a relative measure of flow. Flow = (constant for a pair of taps) x (square root of pressure differential)

References

Abernethy, Amidan, and G.F. Cada. Laboratory Studies of the Effects of Pressure and Dissolved Gas Supersaturation on Turbine-passed Fish. Prepared for the US Department of Energy Idaho Operations Office. Idaho Falls, ID: 2001.

Abernethy, Amidan, and G.F. Cada. 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. Report Prepared for the U.S. Department of Energy Idaho Operations Office. Idaho Falls, ID: 2002.

Abfalterer, J. Report on Model Test for McNary Lock and Dam High Head Model Testing: Addendum to Final Phase II Model Test Report. Contract DACW68-93-C-0012. vol 1, rev 1: 1997.

Abfalterer, J. Model Test Report on Lower Granite Dam Project Model Test Phase II for Turbine Model Development and Testing. Contract DACW68-95-C-0017. vol 1, rev 1: 2000.

Absolon, Ferguson, Eppard, and G.A. Axel. Evaluation of Juvenile Salmonid Survival Through Turbines at McNary Dam Under Two Operating Conditions, 2002. Report Prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla WA: 2002.

Absolon, Dawley, Sandford, Ferguson, and D.A. Brege. Relative Survival of Juvneile Salmon Passing Through the Spillway of The Dalles Dam, 1997-2000. Report Prepared for the Portland District of the US Army Corps of Engineers. Portland, OR: 2002.

Alammer, Jeppson, and H. Keady. Fundamental Principles and Applications of Fluid Mechanics. Utah State University. 1982. 356.

Bell, DeLacy, and G.J. Paulik. A Compendium on the Success of Passage of Small Fish through Turbines. Report prepared for the North Pacific Division of the US Army Corps of Engineers. Portland, OR: 1967.

Bell, M.C. and A.C. DeLacy. A Compendium on the Survival of Fish Passing through Spillways and Conduits. Report prepared for the North Pacific Division of the US Army Corps of Engineers. Portland, OR: 1972.

Bell, M.C. and K.J. Bruya. Updated Compendium on the Success of Passage of Small Fish through Turbines. Report prepared for the North Pacific Division of the US Army Corps of Engineers. Portland, OR: 1981.

Bell, M.C. Recommendation for Turbine Generator Loadings and Blade Gate Relationships for the Best Survival of Juvenile Migrants at the Eight Columbia Basin Dams Operated by the Corps of Engineers: 1981.

Bickford and J.R. Skalski. "Reanalysis and Interpretation of 25 Years of Snake-Columbia River Juvenile Salmonid Survival Studies." North American Journal of Fisheries Management 20(2000): 53-68.

Cada, Coutant, and R.R. Whitney. Development of Biological Criteria for the Design of Advanced Hydropower Turbines. Report to the US Department of Energy Advanced Hydropower Turbine System Program. Idaho Falls, ID: 1997.

Cada, G.F. and M. Odeh. Turbulence at Hydroelectric Power Plants and its Potential Effects on Fish. Report Prepared for the US Department of Energy Advanced Hydropower Turbine System Program. Idaho Falls, ID: 1999.

Carlson, Weiland, Sutton, Wirtz, and M. McCaulay. Ultrasonic 3-D Tracking of Fish and Drogues Passing Through a Kaplan Turbine Intake. Report Prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: 2001.

Carlson and J.P. Duncan. Characterization of the McNary Dam Turbine Fish Passage Environment, April 2002. Report Prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: 2003.

Carlson and M.A. Weiland. Light-Emitting Tag Testing in Conjunction with Testing of the Minimum Gap Runner Turbine Design at Bonneville Dam Powerhouse 1. Report Prepared for the US Army Corps of Engineers, Contract DE-AC06-76RLO 1830. USA: January 2001.

Counihan, Felton, and J.H. Petersen. Survival Estimates of Migrant Juvenile Salmonids in the Columbia River from John Day Dam Through Bonneville Dam Using Radio-Telemetry, 2000. Draft Final Report Prepared for the Portland District of the US Army Corps of Engineers. Portland, OR: 2002.

Counihan, Holmberg, Walker, and J.M. Hardiman. Survival Estimates of Migrant Juvenile Salmonids in the Columbia River Through John Day Dam using Radio-Telemetry, 2003. Draft Report Prepared for the Portland District of the US Army Corps of Engineers. Portland, OR: 2003.

Counihan, Holmberg, and J.H. Petersen. Survival Estimates of Migrant Juvenile Salmonids Through Bonneville Dam Using Radio-Telemetry, 2002. Draft Final Report Prepared for the Portland District of the US Army Corps of Engineers. Portland, OR: 2003.

Eicher Associates, Inc. Turbine-Related Fish Mortality: Review and Evaluation of Studies. EPRI AP-5480, Project 2694-4, Final Report, November 1987. Prepared for the Electric Power Research Institute (EPRI). Palo Alto, CA: 1987.

ERDC-CHL. McNary Project ERDC Pre-turbine to Post-turbine Comparison and Voest-Alpine to ERDC Model Comparison. Draft Report.

ERDC-CHL. Lower Granite Project ERDC Pre-turbine to Post-turbine Comparison and Voest-Alpine to ERDC Model Comparison. Draft Report.

Giorgi and L. Stuehrenberg. Lower Granite Pool and Turbine Survival Study, 1997. Report Prepared for the Bonneville Power Administration, Contract DE-A179-87BP34270. Portland, OR: 1988.

Gordon, McMahon, and B.L. Finlayson. Stream Hydrology: An Introduction for Ecologists. John Wiley & Sons, New York, NY: 1992. 526.

Habertheurer, N. Lower Granite Stay Vane Modification – CFD Study. VA TECH: 2002. Figures 3 and 5.

Heisey, Mathur, and T. Rineer. “A Reliable Tag-Recapture Technique for Estimating Turbine Passage Survival: Application to Young-of-the-Year American Shad (*Alosa sapidissima*)”. Canadian Journal of Fisheries and Aquatic Science. 49(1992): 1826-1834.

Heisey, Mathur, Fulmer, and S. Adams. “Analysis and Interpretation of Injuries to Turbine Passed Fish.” Proceedings of the Turbine Passage Survival Workshop. 14-15 June, 2000. Ed. T. Carlson. Portland, OR: 2000.

Heisey, Paul, Normandeau Associates, Inc. Personal interview. July 2002.

Hydroelectric Design Center. Turbine Passage Survival Juvenile Spring Chinook Salmon April 1995 Lower Granite Dam Snake River, Washington. February 1998.

Hydroelectric Design Center. Columbia River and Tributaries Study, Book 1, July 1989, US Army Corps of Engineers. US Army Corps of Engineers, HDC.

Hydroelectric Design Center. Tabulation of Generator and Turbine Data.xls. US Army Corps of Engineers, HDC.

Hydroelectric Design Center. Biological Test Turbine Operating Conditions Unit No.9. Report Prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: 2002.

Hydroelectric Design Center. Columbia and Snake River Turbines Survey of Stoplog Slots and Stop Log Slot Closures. Report Prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: August 2002.

Hydroelectric Design Center. Abbreviated Acoustic Relative Flow Measurement. Report Prepared for the US Army Corps of Engineers: December 2003.

Iwamoto, Muir, Sandfors, McIntyre, Frost, Williams, Smith, and J.R. Skalski. Survival Estimates for the Passage of Juvenile Chinook Salmon Through Snake River Dams and Reservoirs. Report Prepared for the US Department of Energy, Bonneville Power Administration, Division of Fish and Wildlife. Contract DE-A179-93BP10891, Project 93-29: 1993. 139.

Ledgerwood, Dawley, Gilbreath, Bently, Sandford, and M.H. Schiewe. Relative Survival of Subyearling Chinook Salmon Which Have Passed Bonneville Dam via the Spillway, or the Second Powerhouse Turbines or Bypass System in 1989, With Comparisons to 1987 and 1988. Report Prepared for the US Army Corps of Engineers,Contract E8590024/E86890097, 64p. plus Appendixes: 1990.

Ledgerwood, Dawley, Gilbreath, Bentley, Sandford, and M.H. Schiewe. Relative Survival of Subyearling Chinook Salmon That Have Passed Through the Turbines or Bypass System of Bonneville Dam Second Powerhouse, 1990. Report Prepared for the US Army Corps of Engineers, Contract E86900104, 90p: 1991.

Miller, D.S. Internal Flow Systems – Design and Performance Prediction. Second Edition. Gulf Publishing Company. Houston, TX: 1990. 396.

Montén, E. Fish and Turbines: Fish Injuries During Passage Through Power Station Turbines. Norstedts Tryckeri, Stockholm, 111 p. [ISBN 91-7186-247-1]. 1985.

Muir, Smith, McIntyre, and B.P. Sandford. Project Survival of Juvenile Salmonids Passing Through the Bypass System, Turbines, and Spillways With and Without Flow Deflectors at Little Goose Dam, 1997. Report Prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: 1998.

Neitzel, Richmond, Dauble, Mueller, Moursund, Abernethy, Guensch, and G.F. Cada. Laboratory Studies on the Effects of Shear on Fish: Final Report. Report Prepared for the US Department of Energy Idaho Operations Office, Idaho Falls, ID: 2000.

Nezu and H. Nadagawa. Turbulence in Open-Channel Flows. Balkema, Rotterdam, The Netherlands. 1993.

Normandeau Associates, Inc., J.R. Skalski, and Mid Columbia Consulting, Inc. Turbine passage survival of juvenile spring Chinook salmon (*Onchorhynchus tshawytscha*) at Lower Granite Dam, Snake River, Washington. Report Prepared for the Walla Walla District US Army Corps of Engineers, Walla Walla, WA: 1995.

Normandeau Associates, Inc., and J.R. Skalski. 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: 1996.

Normandeau Associates, Inc., J.R. Skalski, and Mid Columbia Consulting, Inc. Relative Passage Survival and Injury Mechanisms for Chinook Salmon Smolts with the Turbine Environment at McNary Lock and Dam, Columbia River. Report Prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: 1999.

Normandeau Associates, Inc, J.R. Skalski, and Mid Columbia Consulting, Inc. 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 the Portland District of the US Army Corps of Engineers. Portland, OR: 2000.

Normandeau Associates, Inc., J.R. Skalski, and Mid Columbia Consulting, Inc. Survival/Condition of Chinook Salmon Smolts Under Different Turbine Operations at McNary Dam, Columbia River. Report Prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: 2002.

Normandeau Associates, Inc. and Mid Columbia Consulting, Inc. Feasibility of Estimating Passage Survival of Adult Salmonids Using the HI-Z Tag-recapture Technique. Report Prepared for the Portland District of the US Army Corps of Engineers. Portland, OR: 2003.

NMFS. 2000 FCRPS Biological Opinion. NMFS-NOAA. Portland, OR: 2000.

Nowell and P.A. Jumars. “Flow Environments of Aquatic Benthos”. Annual Review of Ecology and Systematics. 15(1984): 303-328.

Pavlov, Laupandin, and M.A. Skorobogatov. “Influence of Flow Turbulence on Critical Flow Velocity for Gudgeon (*Gobio gobio*)”. Doklady Biological Sciences 336(1993): 215-217.

Peters and J.M. Redondo. “Turbulence Generation and Measurement: Application to Studies on Plankton”. Scientia Marina 61(1997): suppl. 1, 205-228.

Rouse, H. Elementary Mechanics of Fluids. John Wiley & Sons, New York, NY: 1946. 376.

RMC Environmental Services, Inc., Mid Columbia Consulting, Inc., and J. Skalski. Turbine Passage Survival of Spring Migrant Chinook Salmon (*Onchorhynchus Tshawytscha*) at Lower Granite Dam, Snake River, Washington. Report Prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: 1994.

Skalski, Townsend, and A.E. Giorgi. The Design and Analysis of Salmonid Tagging Studies in the Columbia River Basin, Volume XI, Recommendations on the Design and Analysis of Radiotelemetry Studies of Salmonid Smolts to Estimate Survival and Passage Efficiencies. Report Prepared for the US Department of Energy, Bonneville Power Administration. Division of Fish and Wildlife, Contract DE-B179-90BP02341. 1998.

Skorobogatov, Pavlov, and A.I. Lupandin. “Effects of Current Velocity and Turbulence Intensity on the Distribution of the Roach *Rutilus rutilus* in a Water Stream”. Journal of Ichthyology 36(8): 1996. 654-658.

Summit Technology Consulting Engineers, and Northwest Hydraulic Consultants. Turbine Passage Survival Baseline Turbine Report Report to US Army Corps of Engineers, Contract DACW57-94-D-0002. January 1996.

Thomas, S. “Evaluating Technologies for Improved Fish Passage”. Salmon Passage Notes. USACE-NWD: January 1998.

USACE-Portland District. Proceedings of the Turbine Fish Passage Survival Workshop. US Army Corps of Engineers, Portland District, 31 May- 1 June 1995, Portland, OR: 1995.

USACE-Portland District. Proceedings of the Turbine Fish Passage Survival Workshop. US Army Corps of Engineers, Portland District, 14-15 June 2000, Portland, OR: 2000.

USAED Portland, USAED Walla Walla, ERDC-WES. Turbine Passage Survival Program Annual Report FY 97. Report Prepared for the Northwestern Division of the US Army Corps of Engineers: September 1998.

USAED Portland, USAED Walla Walla, ERDC-WES. Turbine Passage Survival Program Progress Report October 1, 1997 to June 30, 1999. Report Prepared for the Northwestern Division of the US Army Corps of Engineers: 2000.

Vogel, S. Life in Moving Fluids. Princeton University Press, Princeton, New Jersey. ISBN [0-691-03485-0] 1994.

Winter, I.A. “Improved Type of Flow Meter for Hydraulic Turbine”. ASCE Proceedings. (59): April 1933.

Wittinger, Ramirez, Micetic, and C. Roos. McNary Powerhouse Umatilla, Oregon, Biological Test Turbine Operating Conditions Unit No. 9. Report prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: June 1999.

Wittinger, R. and D. Ramirez. Bonneville First Powerhouse, Unit 5 & 6 Biological Test, Turbine Operating Conditions. November 1999 – January 2000.

Wittinger, R. and C. Polinski. McNary Powerhouse Umatilla, Oregon, Biological Test Turbine Operating Conditions Unit No. 9. Report prepared for the Walla Walla District of the US Army Corps of Engineers. Walla Walla, WA: July 2002.