US Army Corps
of Engineers ®

PHASE II MAIN REPORT

TURBINE OPTIMIZATION FOR PASSAGE OF JUVENILE SALMON AT HYDROPOWER PROJECTS ON THE COLUMBIA AND LOWER SNAKE RIVERS

PREPARED BY
U.S. ARMY CORPS OF ENGINEERS
TURBINE SURVIVAL PROGRAM

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REVISION 0

EXECUTIVE SUMMARY

This Phase II Turbine Survival Program (TSP) Report provides discussion regarding the best turbine operating conditions for juvenile salmonids passing through turbines of U.S. Army Corps of Engineers (USACE) hydropower projects on the lower Columbia and Snake rivers. This report also provides recommended guidelines for the operation of turbines at specific projects where adequate data is available. The eight USACE hydropower projects being studied by the TSP include Bonneville (first and second powerhouses) The Dalles, John Day and McNary on the lower Columbia River and Ice Harbor, Lower Monumental, Little Goose and Lower Granite on the lower Snake River. The 2004 TSP Phase I report identified turbine passage conditions that may improve juvenile fish survival, and suggested that the best target operating range (TOR) may not coincide with peak efficiency as previously assumed, but may better correlate to "open turbine geometry." The TSP Phase I report recommended conducting further research to better define the optimum TOR for the eight hydropower projects.

This Phase II report, which addresses the Phase I recommendations, is considered a "working document" as it includes results from studies conducted to date and provides place holders for future project-specific research and analysis. It is recognized that many of the USACE hydropower projects are similar in design and turbine type. Where possible, the TSP has applied study results from one or more specific projects to similar type projects with less available data.

As estimated through biological field studies, the survival of juvenile fish passing through turbines is generally represented by one of two measures: direct survival and total turbine passage survival. Direct survival is typically measured using Hi-Z balloon-tag methods and represents the survival of fish having experienced the most direct effects of turbine passage, mainly the risk of exposure to direct blade strike, hydraulic shear forces, and/or pressure-related injury (barotrauma). Total turbine passage survival is typically measured using telemetry methods relying on use of either radio telemetry tags or acoustic telemetry tags. Total turbine passage survival represents the survival of run-of-the river fish having experienced the complete turbine passage, as well as delayed effects and/or post turbine passage exposures. An example of these delayed or indirect effects is the increased risk of predation resulting from sub-lethal injuries and/or disorientation caused by the turbine passage.

Phase II of the TSP has focused study efforts on identifying turbine and project operations that minimize both direct and indirect causes of turbine mortality. A number of studies including field studies, laboratory studies, physical hydraulic model studies, and numerical model evaluations have been conducted throughout both Phase I and Phase II to provide a basis for turbine optimization. It has become increasingly more apparent that delayed and/or indirect effects of turbine passage can be as significant, if not more significant, than the direct effects. The full benefits of turbine optimization may not be realized unless the turbine egress conditions are also optimized.

The primary causes of direct mortality are strike and impact forces, hydraulic and mechanical shear forces, and extreme pressure changes. In general, the strike/impact and shear forces can be minimized by operating the turbine units in an open geometry, where the wicket gates are well aligned with the stay vanes and the runner blades are at a steep angle. This generally occurs at unit discharges above the peak efficiency point and near or beyond the upper 1% operating limit. The higher flows tend to reduce turbulence and provide for improved draft tube conditions. Turbine pressures, however, tend to become more extreme as turbine flows increase due to the increase in velocity. Turbine unit optimization for fish passage must weigh the benefits of reducing exposure to strike and shear forces against the increase risk of pressure-related injuries (i.e., barotraumas). Although the risk or mortality from barotraumas is very difficult to quantify, the benefits of reducing direct injuries through open geometry are expected to outweigh the risk of barotraumas for most of the USACE hydropower projects on the Snake and Columbia rivers. Based on analysis of past direct tag studies (Hi-Z balloon tag) and the physical hydraulic model studies, it is not unreasonable to expect an approximate 2% increase in direct turbine survival. Without a thorough biological test of turbine operations, it is not reasonable to assume or estimate the increase in "total" turbine passage survival as a result of open geometry operations.

In addition to reducing risk of direct impact and strike, the open geometry operation tends to improve the draft-tube conditions by reducing turbulence and improves egress when multiple turbines are operated adjacent one and another. The open geometry is defined for specific turbine unit families in the 2010 Hydroelectric Design Center report, *Columbia and Snake River Turbines Stay Vane and Wicket Gate Geometry Study*, as well as in further detail in this report.

The TSP also recommends additional research and analysis. A pressure effects risk assessment is necessary to more accurately weigh the risk of pressure related mortality against the benefits of reduce strike/impact when operating in an open geometry. To complete this assessment, additional prototype turbine pressure data is needed and the depth distribution of acclimated fish prior to turbine passage must be well defined.

Based on the available information, the TSP recommends a TOR for improved fish passage for most of the hydropower projects. The TSP plans to update and add to the TORs by updating this document as new information becomes available. As indicated above, turbine passage egress is an important component; thus, the TSP also provides recommendations on target project operations to improve total turbine passage survival. In addition, turbine survival tests should be conducted to verify the TSP-defined TORs and target project operations.

The conclusions in this report are based on current information. The report will be revised as new information becomes available that may change the identified TORs.

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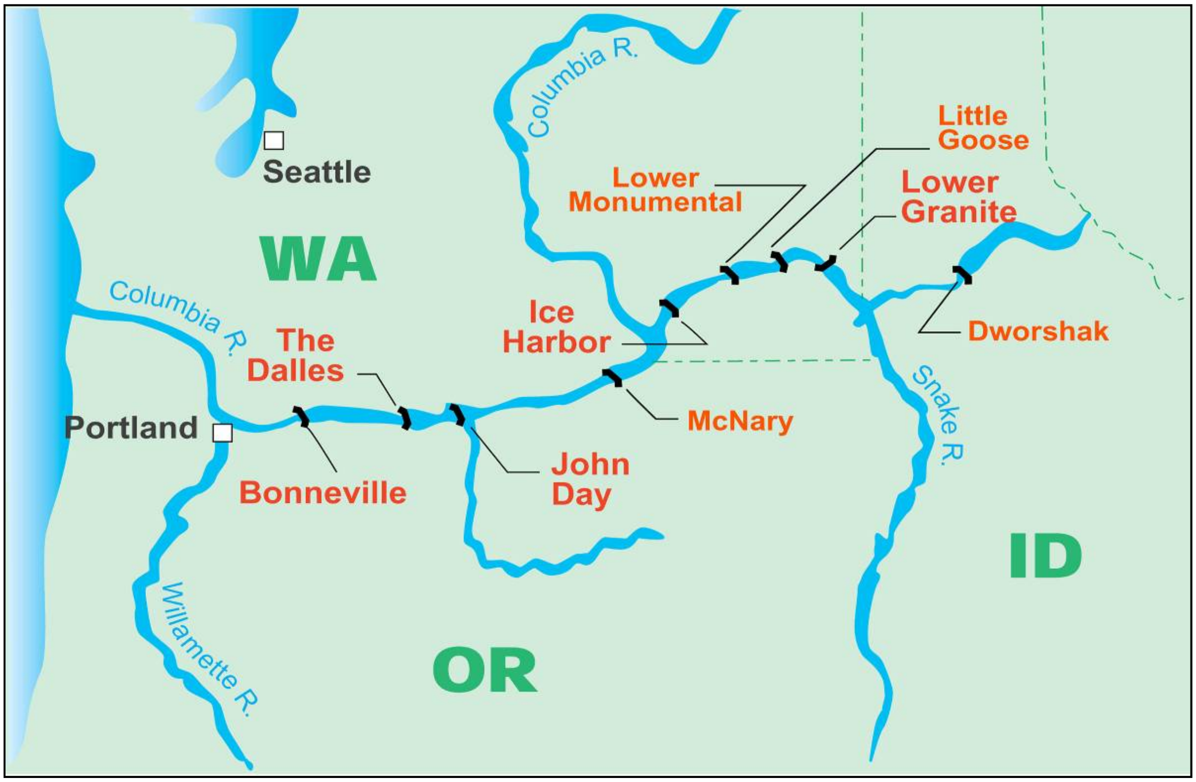
ACRONYMS AND ABBREVIATIONS

AC	Allis-Chalmers (turbine manufacturer)
B1	Bonneville First Powerhouse
B2	Bonneville Second Powerhouse
BiOp	Biological Opinion
BLH	Baldwin-Lima-Hamilton (turbine manufacturer)
BIT	biological index testing
CFD	computational fluid dynamics
cfs	cubic feet per second
CI	confidence interval
cm	centimeter(s)
CRFM	Columbia River Fish Mitigation
ERDC	Engineering Research and Development Center
ESBS	extended submersible barrier screens
FPP	Fish Passage Plan
HDC	Hydroelectric Design Center
JBS	juvenile bypass system
kcfs	thousand cubic feet per second
ft/s	feet (foot) per second
LDV	Laser Doppler Velocimeter
LRP	log ratio of pressures
MABL	Mobile Aquatic Barotrauma Laboratory
MGR	minimum gap runner
MW	megawatt(s)
NOAA	National Oceanic and Atmospheric Administration
PNNL	Pacific Northwest National Laboratory
psia	pounds per square inch absolute
SE	standard error
STS	submersible traveling screens
TOR	target operating range
TSP	Turbine Survival Program
TST	turbine survival testing
USACE	U.S. Army Corps of Engineers
VBS	vertical barrier screen

1. INTRODUCTION

The Turbine Survival Program (TSP) is part of the U.S. Army Corps of Engineers' (USACE) multi-faceted Columbia River Fish Mitigation (CRFM) program. The TSP was developed to evaluate juvenile fish passage through turbines at the eight USACE hydropower projects on the Columbia and lower Snake rivers, with an emphasis on identifying turbine features and conditions that cause injury to fish. These eight projects are Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose, and Lower Granite (Figure 1). These projects are required to have both upstream and downstream fish passage.

Figure 1. Columbia and Snake River Projects



The first phase of the TSP involved developing tools to evaluate the physical conditions fish experience as they pass through the large Kaplan turbines typical of USACE projects on the lower Columbia and Snake rivers. This effort is summarized in the TSP Phase I Report (USACE 2004). In support of the National Oceanic and Atmospheric Administration (NOAA) Fisheries Biological Opinions (BiOps; NOAA 2000, 2004, 2008), the TSP recommends biological index testing (BIT) as a continued Phase II effort. In this report, BIT will be referred to as turbine survival testing (TST).

1.1. TURBINE SURVIVAL TESTING

Survival estimates of juvenile fish passing through turbines generally represent one of two measures: direct survival or total turbine passage survival. Direct survival is typically measured using Hi-Z balloon-tag methods and represents the survival of fish having experienced the most direct effects of turbine passage, mainly the risk of exposure to direct blade strike and extreme mechanical and hydraulic shear forces. Total turbine passage survival is typically measured using telemetry methods relying on use of either radio or acoustic telemetry tags. Total turbine passage survival represents the survival of run-of-the river fish having experienced the complete turbine passage, as well as delayed and/or indirect effects post turbine passage. An example of these delayed or indirect effects is the increased risk of predation resulting from sub-lethal injuries and/or disorientation caused by the turbine passage. The rate of indirect mortality caused by predation can be exacerbated by poor egress conditions from the immediate powerhouse tailrace region. Stagnant or circulating flow patterns caused by the manner in which the spillway and powerhouse are operated can subject juvenile fish to large areas where predatory fish may hold. Stunned or disoriented fish may also rise to the surface where they may be more susceptible to avian predation.

The goal of this Phase II report is to identify turbine operations that optimize the total turbine passage survival by minimizing causes of both direct and indirect mortality of all fish passing through the turbines. The first step in this process is to identify how to operate an individual turbine unit for the best direct turbine survival and best delivery of fish into the tailrace. The TSP team has identified this as the target operating range (TOR). Identifying the TOR involves a number of tools and is discussed in Section 3 of this report.

The second step is an assessment of tailrace conditions given existing powerhouse and spill operations. Operating turbine units at the TOR should improve the draft tube exit conditions for fish entering the tailrace as well as result in less fish injury. However, tailrace conditions are heavily affected by how the overall project is operated. Therefore, this step investigates ways to operate the project for better tailrace conditions in order to improve indirect survival of fish passing turbines.

The third step is a biological field test of turbine and powerhouse operation plans using live juvenile salmonids as test fish. Because of the high cost of biological tests at prototype scales, data from other biological tests are used as much as possible. While this process can provide some additional information, it will not likely provide conclusive evidence. Therefore, the strategy is to use targeted field studies to test specific hypotheses about turbine operations and configurations developed in previous steps that minimize harm to juvenile salmon. If hypotheses tests provide biologically acceptable results, this will validate proposed turbine configuration and operating recommendations.

1.2. DESCRIPTION OF THE PROJECTS

For each USACE hydropower project on the Columbia and lower Snake rivers, a description of the turbine units and a summary of fishery operations is provided in the following sections. Additional information for each project can be found in the project's appendix to this report.

1.2.1. Bonneville Lock and Dam

Bonneville Lock and Dam is located 146 river miles from the mouth of the Columbia River and about 40 miles east of Portland, Oregon (see Figure 1). Bonneville's first powerhouse, spillway and original navigation lock were completed in 1938 (Figure 2). A second powerhouse was completed in 1981 (Figure 3), and a larger navigation lock was completed in 1993. The first powerhouse (B1) is 1,027 feet long and contains 10 S. Morgan Smith Kaplan turbines with a total generating capacity of 680 megawatts (MW). The second powerhouse (B2) is 988 feet long and contains eight Allis-Chalmers (AC) Kaplan turbines with a total generating capacity of 558 MW. The B1 turbines are minimum gap runners (MGR) installed from 1998 to 2010 to replace the original runners for the powerhouse. It should be noted that the turbine intake extensions depicted in Figure 3 were installed to improve FGE; however, they provided only marginal benefit and are no longer in use.

At B2, fish by-pass screens are installed in each of the turbine unit intakes. There are no fish by-pass screens at B1. While the screens are effective in intercepting juvenile steelhead, a significant number of juvenile fish pass through the turbines. Turbines are operated within 1% of the best efficiency in accordance with the current USACE Fish Passage Plan (FPP). The FPP also specifies powerhouse priority and unit priority at each powerhouse to maximize adult and juvenile fish movement. Spill is required from April 10 to August 31 each year for juvenile egress. Additional details of the operational requirements at Bonneville can be found in the FPP and in the project's appendices to this report.

Figure 2. Bonneville First Powerhouse and Bradford Island Fish Ladder

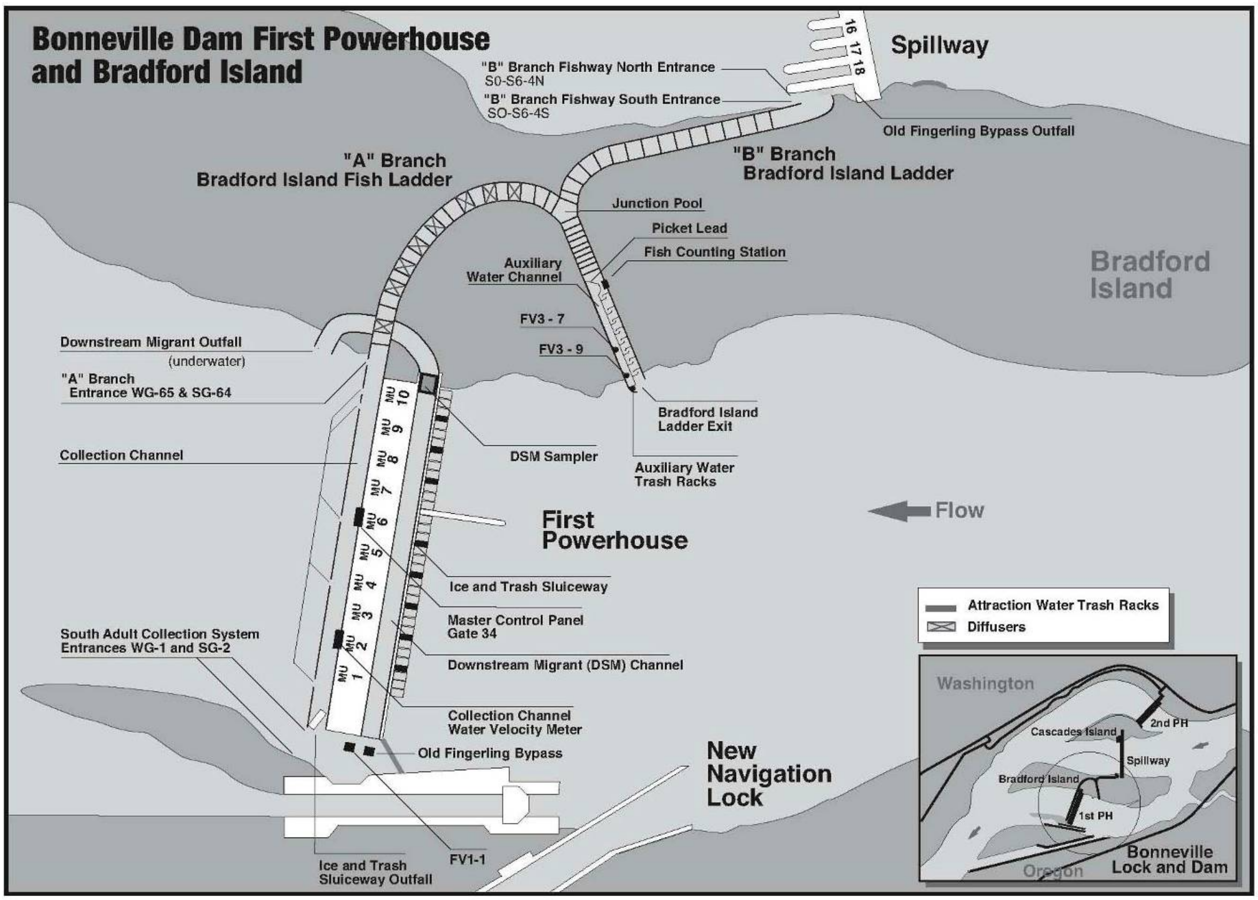
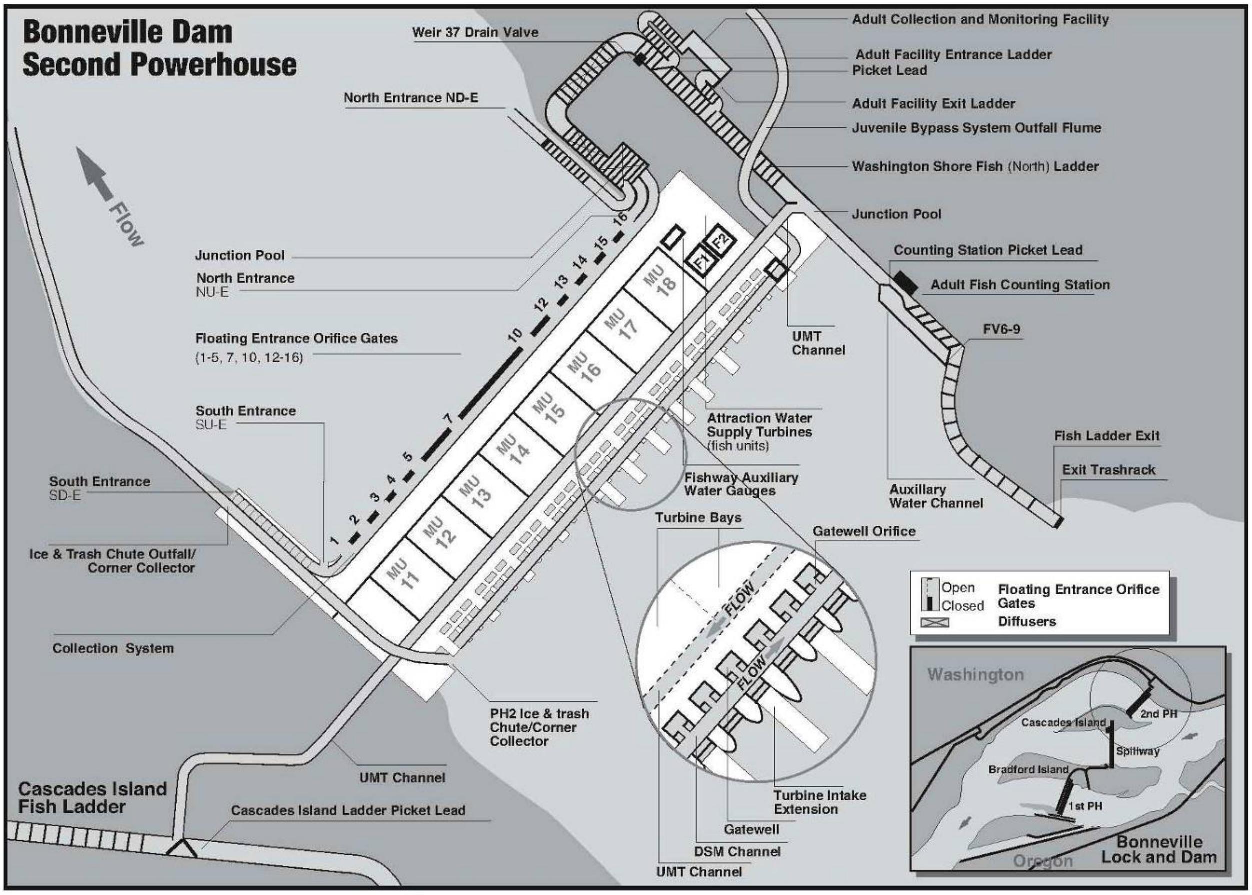


Figure 3. Bonneville Second Powerhouse and North Fish Ladder

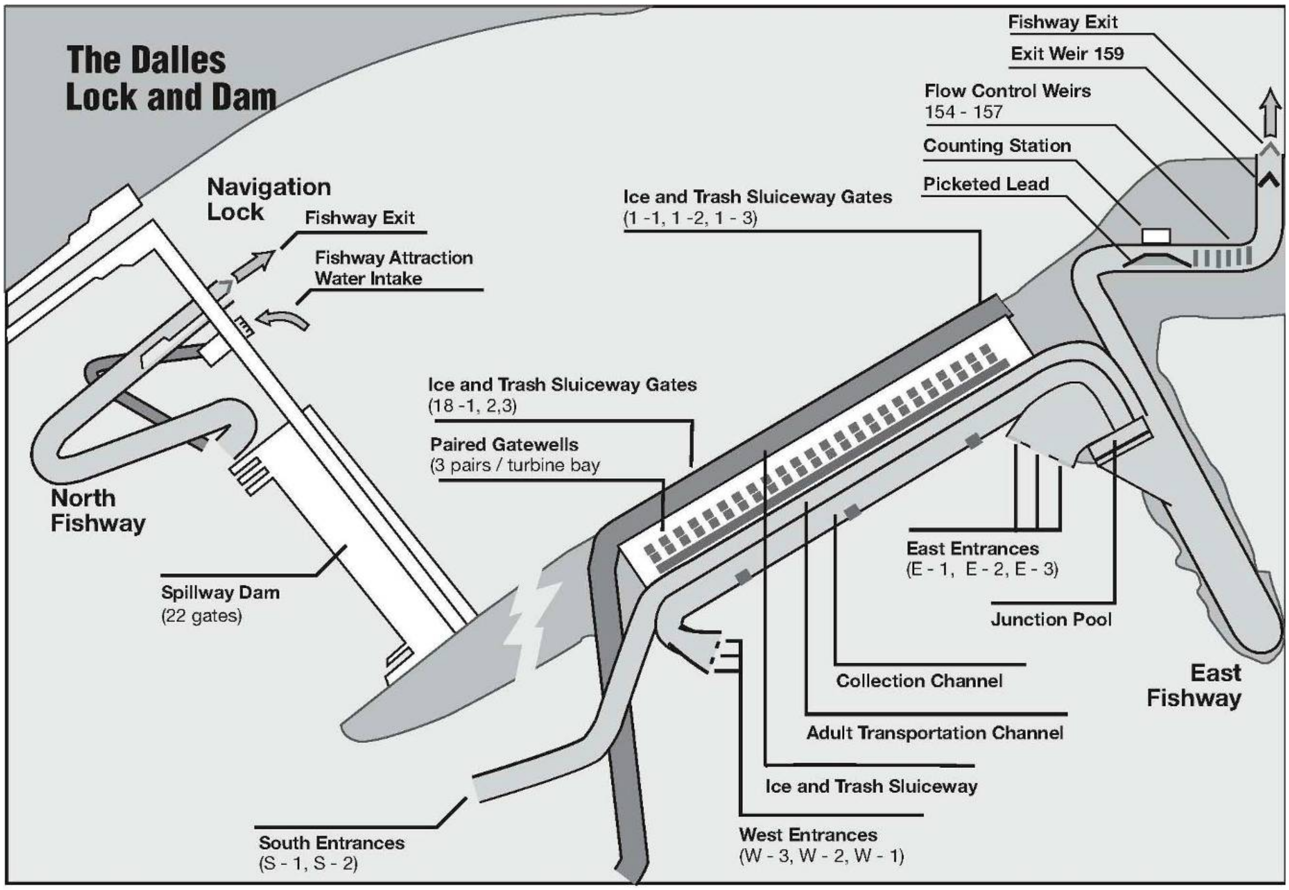


1.2.2. The Dalles Lock and Dam

The Dalles Lock and Dam is 192 miles upriver from the mouth of the Columbia River and 2 miles east of the city of The Dalles, Oregon (see Figure 1). Construction of The Dalles started in 1952 and the project began operating 5 years later. The project consists of a navigation lock, spillway, powerhouse, and fish passage facilities (Figure 4). The powerhouse is 2,089 feet long and contains 22 Baldwin-Lima-Hamilton (BLH) Kaplan turbine units with units 1-14 having 280-inch diameter runners and units 15-22 having 300-inch diameter runners for a total generating capacity of 2,100 MW. Units 1-14 were all operating in 1960, while units 15-22 began operating in 1973. Unlike most turbines in the system which turn clockwise, The Dalles turbine units turn counter-clockwise due to the angle of the incoming flow.

The turbine units at The Dalles are not screened. Juvenile fish passage consists of the ice and trash sluiceway and one 6-inch orifice in each gatewell. Adult fish passage facilities at The Dalles are composed of a north shore fish ladder, which passes fish collected at the north end of the spillway, and an east fish ladder that passes those fish collected at the south end of the spillway and across the downstream face of the powerhouse. The turbines at The Dalles are operated within 1% of the best efficiency in accordance with the current FPP. Additional details of the operational requirements at The Dalles can be found in the FPP and in the project's appendix to this report.

Figure 4. Diagram of The Dalles Lock and Dam



1.2.3. John Day Lock and Dam

John Day Lock and Dam is 216 miles upriver from the mouth of the Columbia River near the city of Rufus, Oregon (see Figure 1). Completed in 1971, the project includes a powerhouse, spillway, navigation lock, and fish passage facilities (Figure 5 and Figure 6). The powerhouse is 1,975-feet long and contains 16 BLH turbines of 155 MW each, for a total generating capacity of 2,480 MW. All turbines are Kaplan, six-blade units operating at 90 revolutions per minute. The last of the 16 generators went on line in November 1971. The north end of the powerhouse has four skeleton bays providing a potential expansion of four additional turbines.

Fish passage facilities include two adult fish ladders and a screened juvenile bypass system (JBS). The north fish ladder has two main entrances located adjacent to spillway bay 1 and exits upstream along the Washington shore. The south fish ladder has three main entrances, one at the south end of the powerhouse and two smaller entrances at its north end. Ten floating orifice-type entrances also are distributed across the downstream powerhouse face. The south fish ladder exits upstream adjacent to the Oregon shore.

The JBS has undergone several modifications in the last 25 years. Currently each main unit intake has a 20-foot submersible traveling screen (STS) that diverts approximately 200 cubic feet per second (cfs) of flow up into a dewatering gate slot. A vertical barrier screen (VBS) located between the dewatering gate slot and the operating gate slot removes all but 14 cfs of this flow. The remaining 14 cfs of water and guided fish are discharged through a 14-inch orifice into a collection channel, and eventually released approximately 600 feet downstream of the powerhouse through an outfall adjacent to the Oregon shore. The JBS also includes a juvenile smolt monitoring facility that was put into operation in 2000.

The John Day turbines are operated within 1% of the best efficiency in accordance with the current FPP. Additional details of the operational requirements at John Day can be found in the FPP and in the project's appendix to this report.

Figure 5. John Day Powerhouse, South Fish Ladder, and Juvenile Fish Bypass System

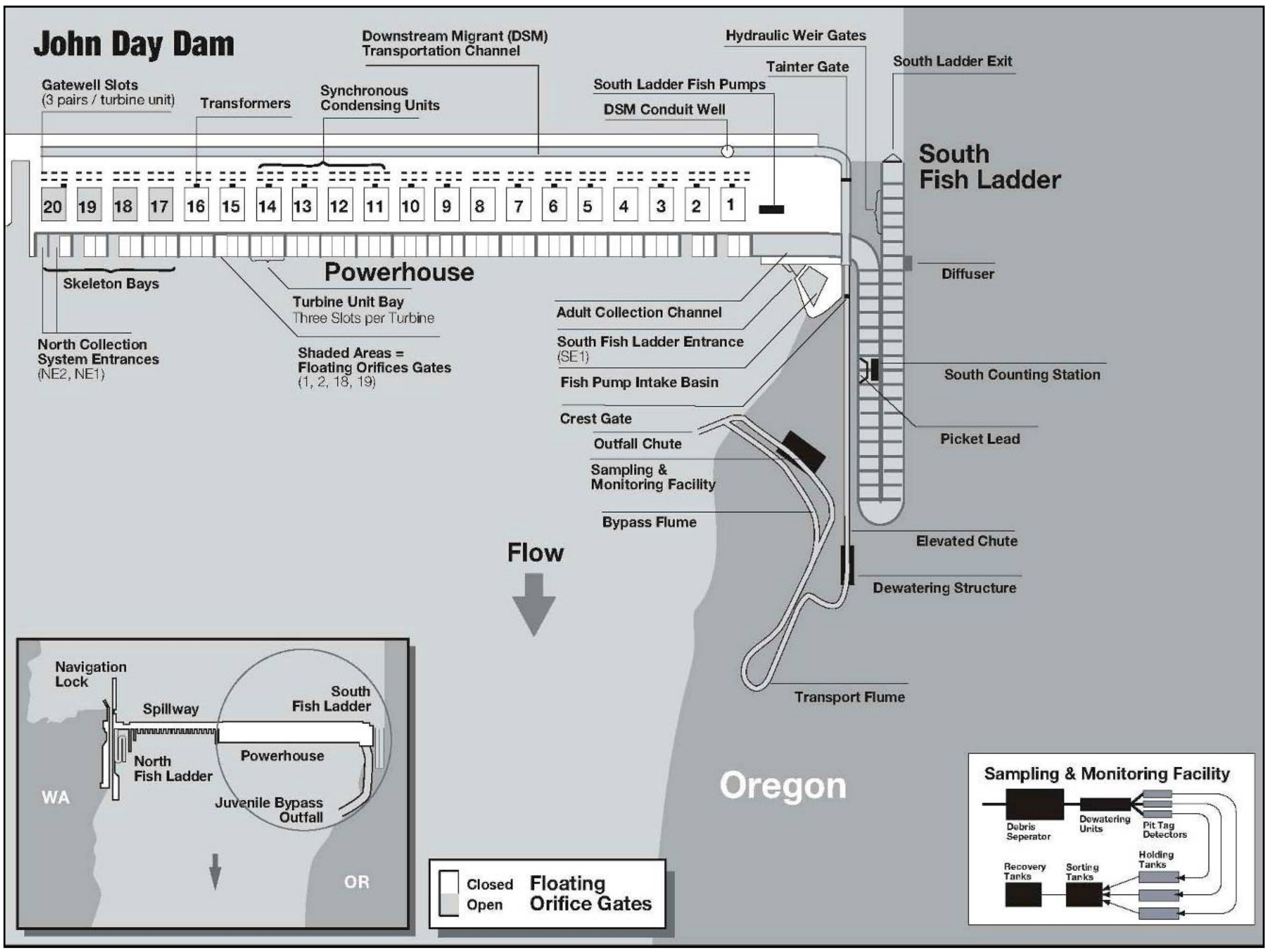
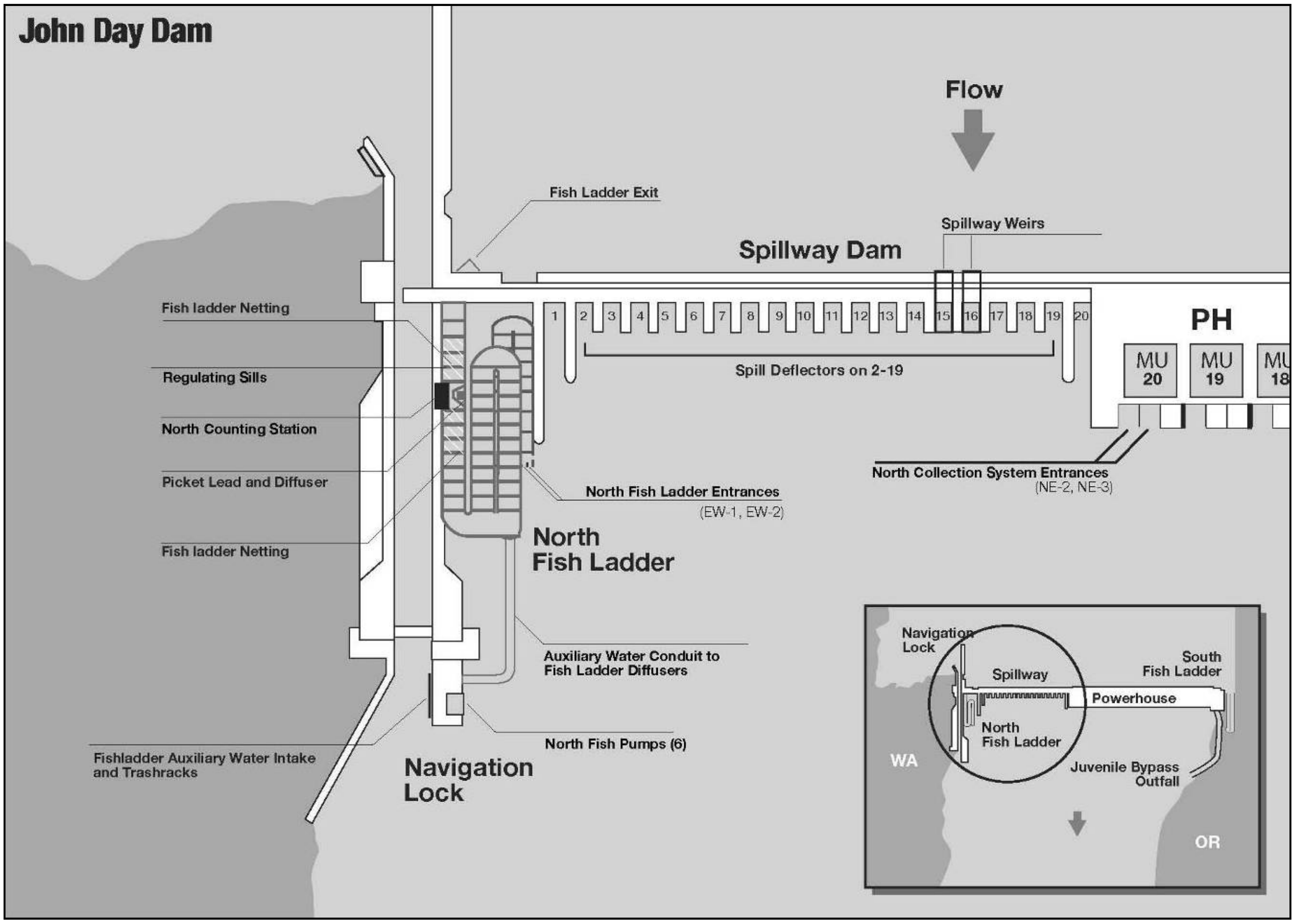


Figure 6. John Day Dam Spillway, Navigation Lock, and North Fish Ladder

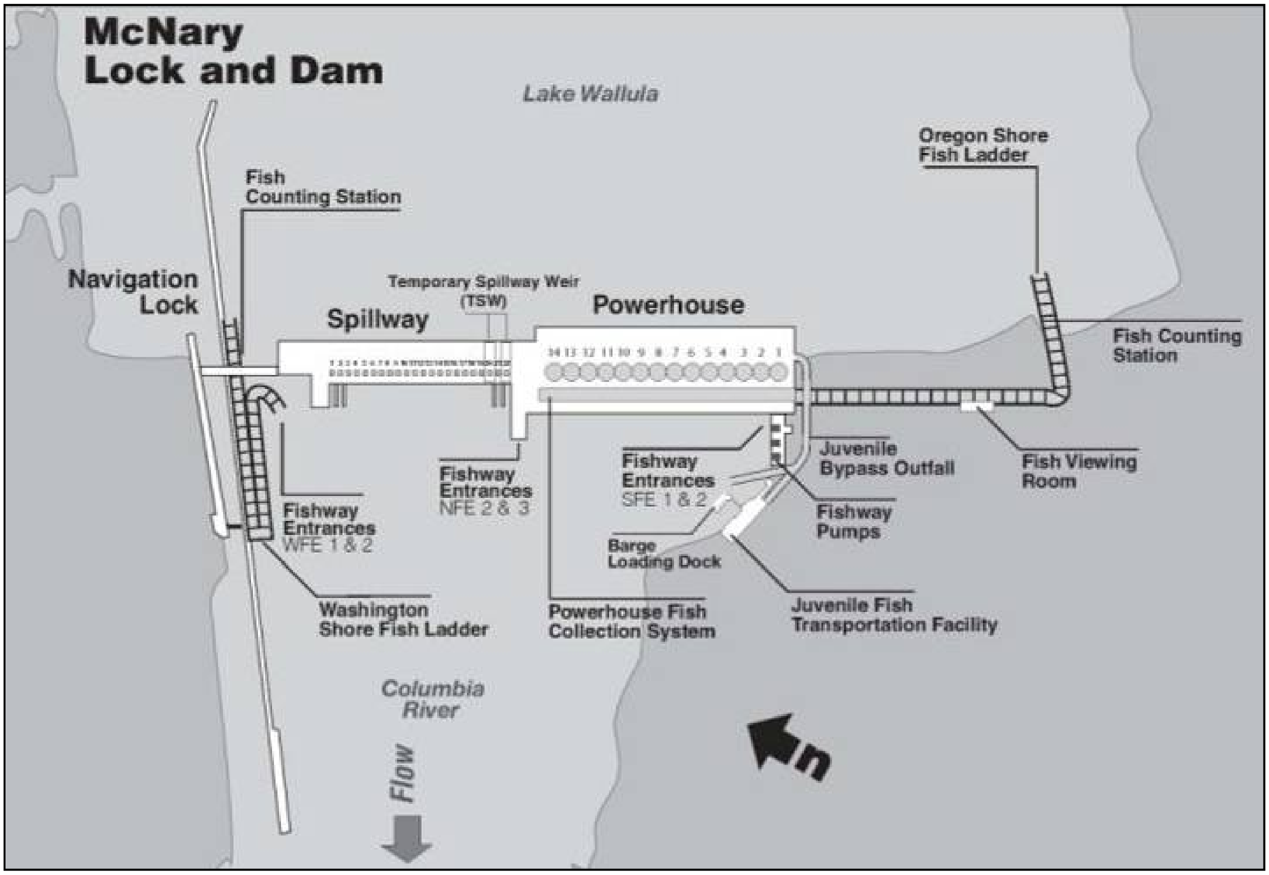


1.2.4. McNary Lock and Dam

McNary Lock and Dam is located about 292 miles upstream from the mouth of the Columbia River and 3 miles east of the town of Umatilla, Oregon (see Figure 1). Completed in 1953, the project includes a powerhouse, spillway, navigation lock, and fish passage facilities (Figure 7). The powerhouse is 1,422 feet in length and contains 14 generating units of 70 MW each, for a total capacity of 980 MW. The Kaplan turbine units manufactured by S. Morgan Smith have a generator capacity of 84.7 MW (USACE 2004). The turbine units were put into service in 1957 and the 280-inch diameter runners were designed to operate at 85.7 revolutions per minute.

Extended submersible barrier screens (ESBS) are installed in each of the turbine unit intakes, and at 40 feet in length they screen a significant portion of the intake. The turbines are operated within 1% of the best efficiency in accordance with the current FPP. The FPP also specifies a turbine operating priority from unit 1 and then unit 14 down to unit 2 that is intended to improve adult fish attraction to the fish ladders. The FPP requires spill during much of the fish passage season, which influences the powerhouse tailrace egress conditions. Additional details of the operational requirements at McNary can be found in the FPP and in the project's appendix to this report.

Figure 7. Diagram of McNary Lock and Dam

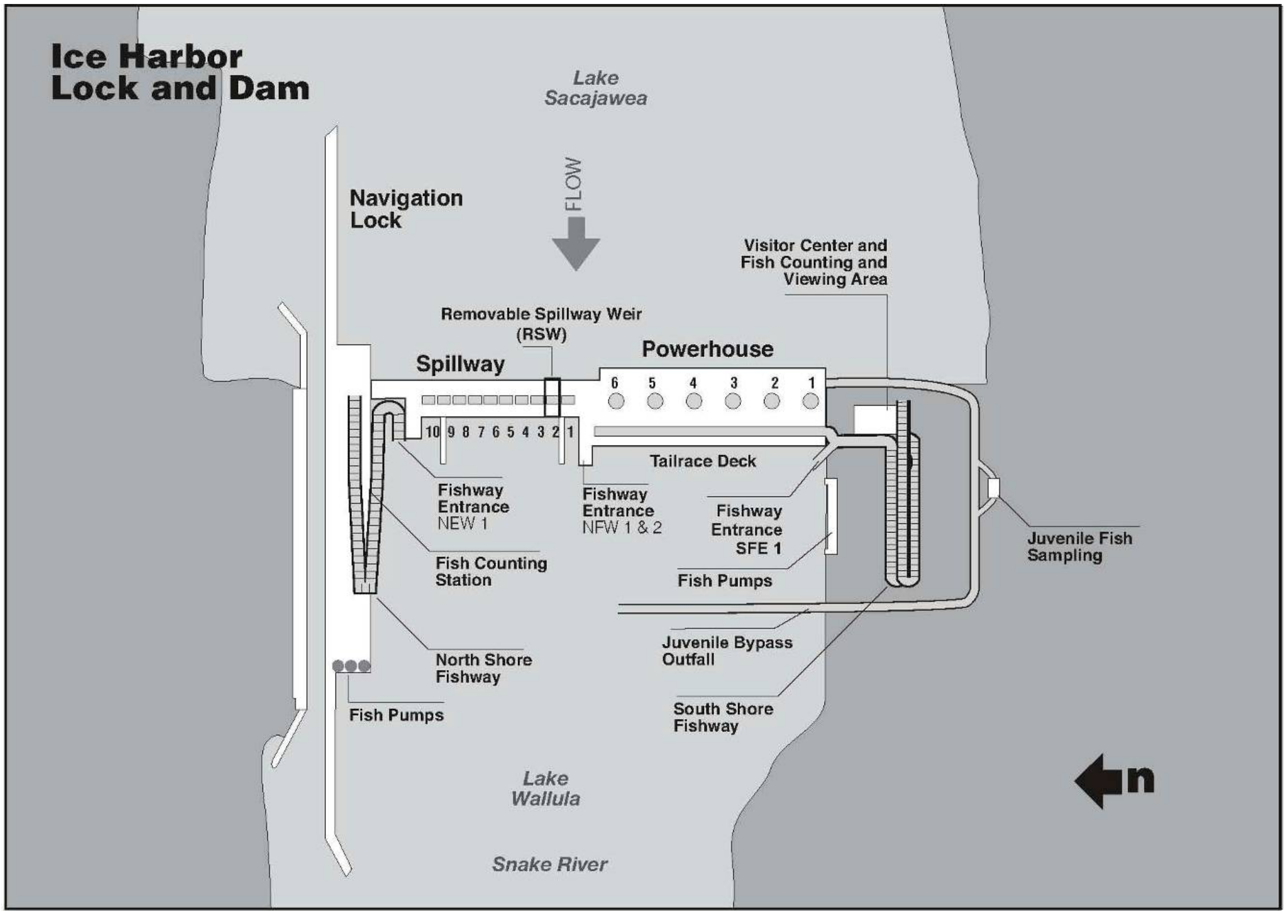


1.2.5. Ice Harbor Lock and Dam

In 1945, Ice Harbor became the first of four dams authorized by Congress for construction on the Snake River. The project is located 9.7 miles upstream from the mouth of the Snake River (see Figure 1). Completed in 1961, the project includes a navigation lock, powerhouse, spillway, fish ladders on each shore, and non-overflow sections (Figure 8). The powerhouse has three 90 MW, 280-inch diameter Kaplan turbines and three 111 MW, 300-inch diameter Kaplan turbines. The six AC turbine units have a total generating capacity of 603 MW. Turbine unit 2 currently operates as a fixed-bladed unit, and plans are underway to replace turbine units 2 (with a new fixed runner) and 3 (with a new adjustable runner) at Ice Harbor with units intended to improve fish passage survival.

All six turbines units are screened with submersible traveling screens (STS). The Ice Harbor turbines are operated within 1% of the best efficiency in accordance with the current FPP. Additional details of the operational requirements at Ice Harbor can be found in the FPP and in the project's appendix to this report.

Figure 8. Diagram of Ice Harbor Lock and Dam

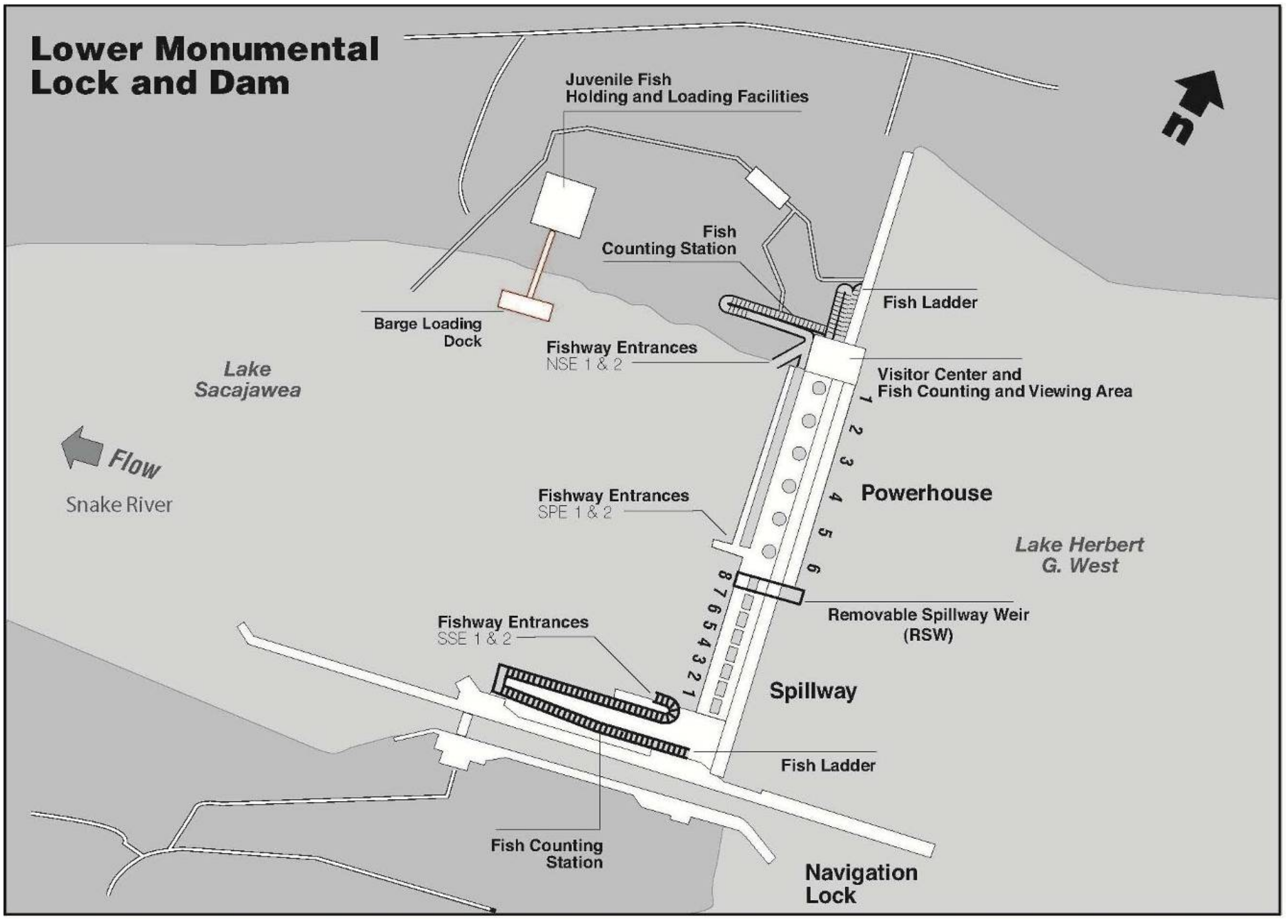


1.2.6. Lower Monumental Lock and Dam

Lower Monumental Lock and Dam is located 41.6 miles upstream from the mouth of the Snake River (see Figure 1). Completed in 1969, the project includes a powerhouse, spillway, navigation lock, and fish passage facilities (Figure 9). The powerhouse contains six 135 MW turbines housed in the 656 feet long concrete powerhouse structure. All turbines units are 312-inch diameter Kaplan, six-blade units operating at 90 revolutions per minute. Three BLH turbines were installed in 1969 as part of the original dam construction. Units 4 through 6 are AC turbines installed in 1979 under the powerhouse expansion contract. Turbine unit 1 is presently welded in a fixed-bladed position, and the remaining five turbines have full Kaplan configuration.

The intakes for all six turbine units are screened with a STS. The Lower Monumental turbines are operated within 1% of the best efficiency in accordance with the current FPP. Additional details of the operational requirements at Lower Monumental can be found in the FPP and in the project's appendix to this report.

Figure 9. Diagram of Lower Monumental Lock and Dam

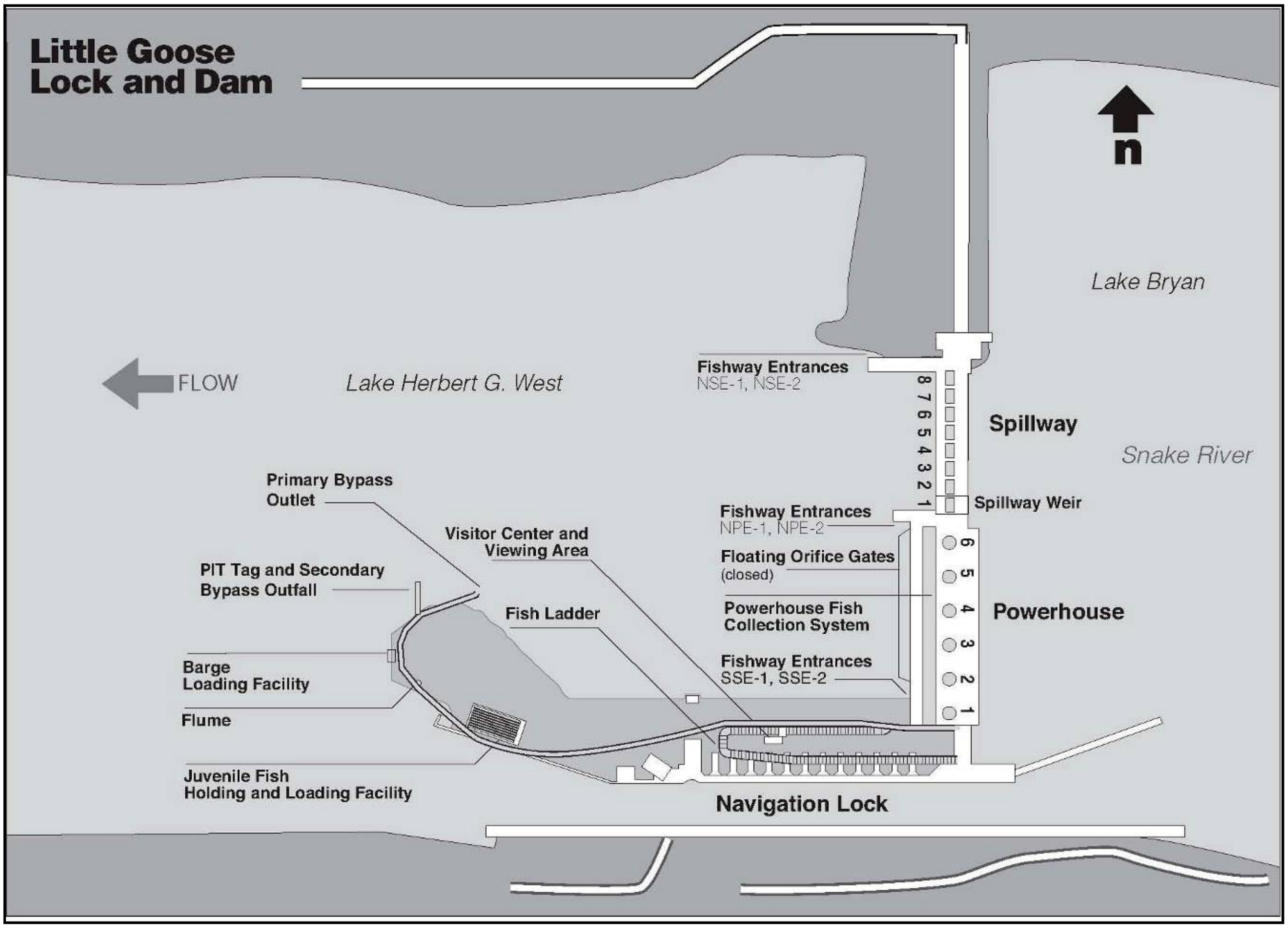


1.2.7. Little Goose Lock and Dam

Little Goose Lock and Dam is located 70.3 miles upstream from the mouth of the Snake River (see Figure 1). Completed in 1970, the project includes a navigation lock, spillway, powerhouse, and fish passage facilities (Figure 10). Little Goose has six turbine units, three BLH units and three AC units. Turbine units 1-3, from south to north, have BLH turbines installed in 1970 as part of original dam construction. Units 4 through 6 are AC turbines installed in 1978 under the powerhouse expansion contract. The turbine runners match the runners installed at Lower Monumental Dam. All turbines presently have full Kaplan configuration.

The intakes for all six turbine units are screened with an ESBS. The Little Goose turbines are operated within 1% of the best efficiency in accordance with the current FPP. Additional details of the operational requirements at Little Goose can be found in the FPP and in the project's appendix to this report.

Figure 10. Diagram of Little Goose Lock and Dam

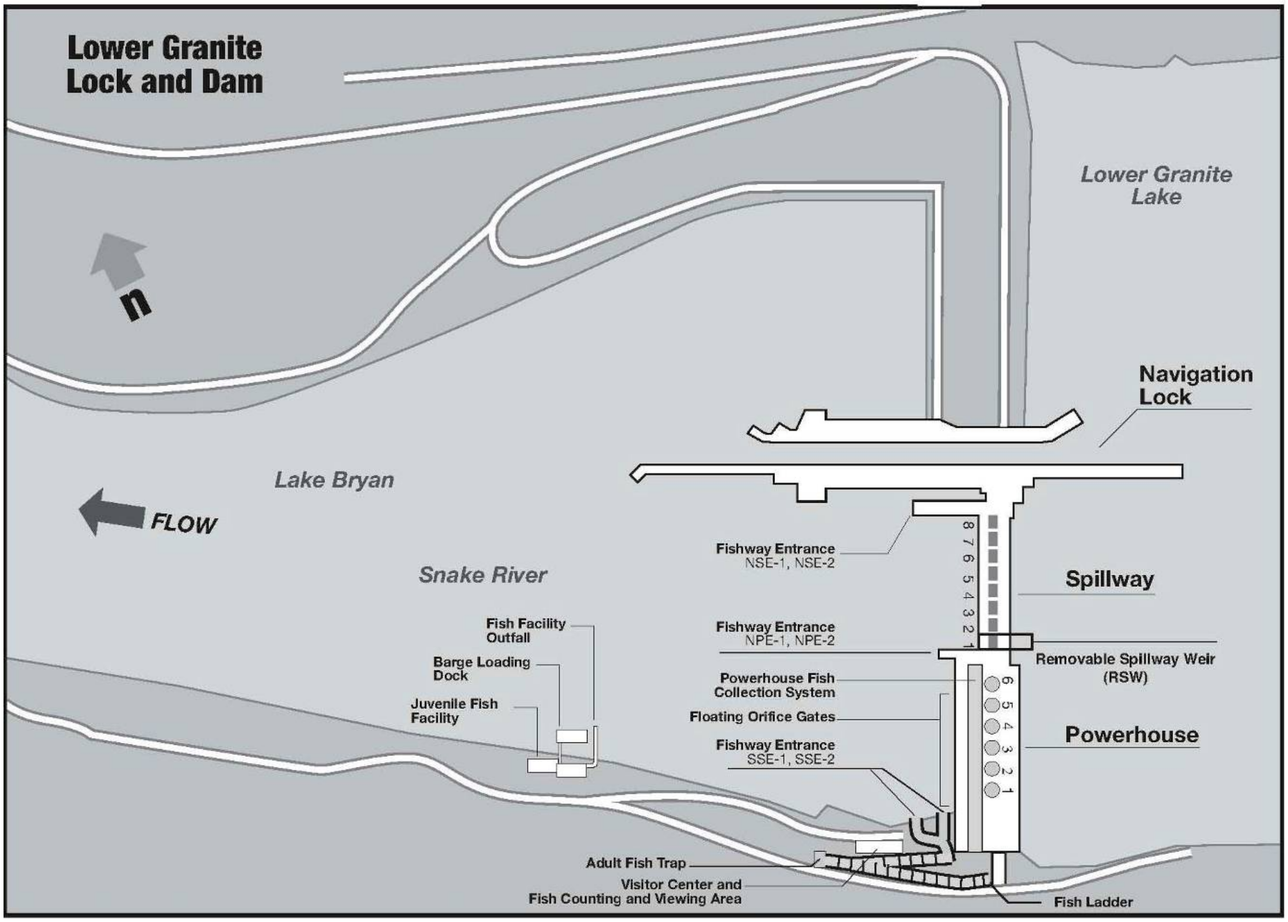


1.2.8. Lower Granite Lock and Dam

Lower Granite Lock and Dam is located 107.5 miles upstream from the mouth of the Snake River (see Figure 1). Construction started in 1965 and the project went into operation 10 years later. The project includes a navigation lock, spillway, powerhouse, and fish passage facilities (Figure 11). Lower Granite has six turbine units. Turbine units 1-3 have BLH turbines, which were installed in 1975 as part of original dam construction. Units 4 through 6 are AC turbines that were installed in 1978 under the powerhouse expansion contract. The turbine runners match the runners installed at Lower Monumental Dam. All turbines presently have full Kaplan configuration.

The intakes for all six turbine units are screened with an ESBS. The Lower Granite turbines are operated within 1% of the best efficiency in accordance with the current FPP. Additional details of the operational requirements at Lower Granite can be found in the FPP and in the project's appendix to this report

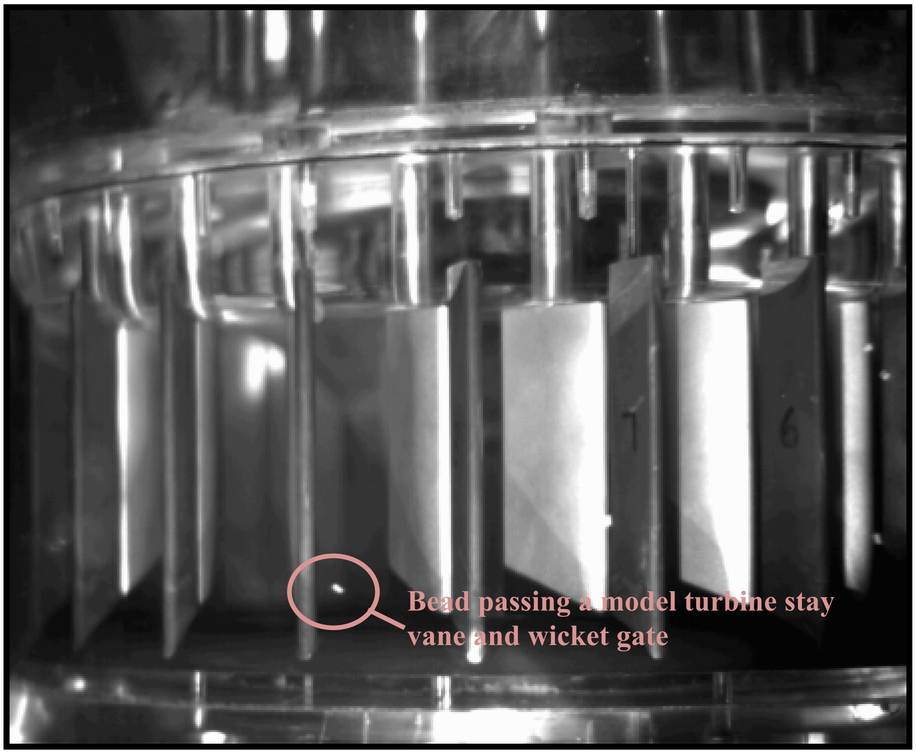
Figure 11. Diagram of Lower Granite Lock and Dam



2. FACTORS IN MORTALITY OF TURBINE-PASSED FISH

The TSP Phase I report (USACE 2004) summarized the suspected causes of direct mortality of turbine-passed fish. Suspected causes of direct turbine mortality were evaluated through laboratory studies, physical hydraulic model studies, and field studies. The injuries sustained during turbine passage are split into mechanical, shear and pressure related injuries. Due to the moving and stationary structures within a turbine environment, striking and scraping of fish passing through this environment will occur. A comparison of field test results with physical model bead strike data indicates not all contact will result in significant injury or mortality. These data also indicate the frequency that fish contact turbine surfaces can be influenced by turbine operational changes. For reference, Figure 12 provides a still image of bead strike data being recorded in the physical hydraulic turbine model.

Figure 12. Passage of Neutrally Buoyant Bead through Physical Turbine Model



Pinching of fish at narrow passageways within the turbine environment can occur. Based on physical model studies this primarily occurs at gaps between the turbine blades and the hub, between the turbine blades and the discharge ring and between the stay vanes and wicket gates. The size of these openings and the frequency of beads getting caught in these openings, which is assumed to correlate to fish injury rate, are also dependent on operation of the turbine.

Shear and turbulence has also been shown to injure fish in laboratory studies and is suspected of being a common cause of external visible injury for turbine passed fish. A study by the Department of Energy at the Pacific Northwest National Laboratory (PNNL) exposed fish to jet velocities up to 70 feet per second (ft/s) to evaluate injury caused by hydraulic shear (Neitzel et al. 2000). This study quantified shear as a strain rate[1] (change in water velocity over distance) based on a spatial resolution of 1.8 centimeters (cm; 0.71 inches), where this spatial interval was based on the minimum width of the salmonids tested. In general, significant injury did not result until approximately 850 cm/s/cm, which corresponds to a jet velocity of approximately 49 feet per second (ft/s) in these experiments. Similar rates of injury were seen whether the fish were pushed out the nozzle (termed fast-fish-to-slow-water) or released into the jet downstream of the nozzle (termed slow-fish-to-fast-water). Specific results do show injury at lower strain rates when introduced headfirst into the jet, as opposed to tail first as seen in Table 1.

Table 1. Fish Injury when Exposed to Shear Strain

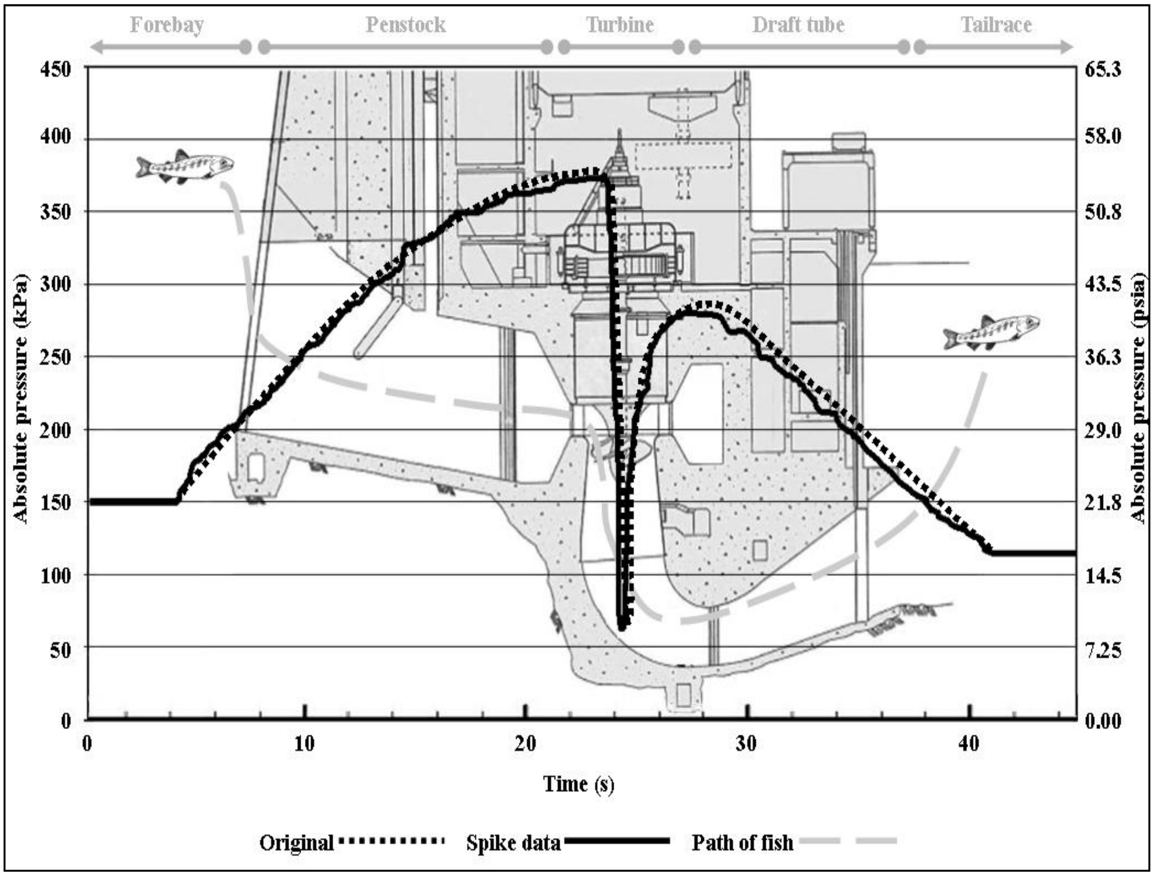
Test Fish	# of Fish Tested	Test Orientation	Strain Rate (cm/s/cm [Δy=1.8 cm])		
			No Significant Injury	No Significant Major Injury	No Significant Deaths
Fall Chinook (age 0)	190	Headfirst	517	852	1008
Fall Chinook (age 1)	300	Headfirst	517	517	852
Spring Chinook	170	Headfirst	517	688	1008
Rainbow Trout	170	Headfirst	688	1008	1008
Steelhead	170	Headfirst	517	1008	1008
American Shad	150	Headfirst	517	517	517
Fall Chinook (age 1)	130	Tail first	688	1008	1008
Spring Chinook	130	Tail first	688	1008	1008
Steelhead	80	Tail first	852	1008	1008
Rainbow Trout	199	Headfirst w/ predators	517	NA	NA

Source: Neitzel et al. 2000

As fish pass through a turbine, they are exposed to a unique pressure time history. Pressure increases as fish approach the turbine runner, then rapidly decreases as they pass through the runner. Immediately following the runner passage, the pressure then increases as the fish enter the turbine draft-tube and flow into the tailrace. The lowest pressure experienced on the downstream or suction side of the runner is called the nadir pressure and is dependent on the turbine design, operating head, discharge, and passage location (Figure 13). Exposure of fish to pressure profiles typical of Kaplan turbines has been extensively studied. A series of laboratory studies were conducted at PNNL, where salmonids were held for 24 hours at various pressures then exposed to simulated turbine pressures (Carlson et al. 2010). Holding the fish at various pressures (termed acclimation pressures) allowed the fish to acclimate both their blood and their swim bladder to the pressure that would exist at various approach depths. These studies found the variable most responsible for injury was the ratio of the acclimation pressure to the nadir pressure. The operation of the turbine influences both distribution and magnitude of the nadir pressure.

[1] The strain rate is presented in units of cm/s/cm (centimeter/second/centimeter) to emphasize that the rate of strain is the mean change in velocity [distance divided by time (cm/s) divided by distance]. When cm/s/cm is carried through algebraically, rate of strain can be represented as 1/s. The units were left as cm/s/cm to emphasize the assumption of strain occurring over a distance of 1.8 cm (average width of the test fish). Additionally, converting the strain rates to English units does not change the numerical value of any calculated strain rates; for example, 1008 cm/s/cm is equal to 1008 in/s/in (inches/second/inches).

Figure 13. Example of Pressure Exposure during Turbine Passage



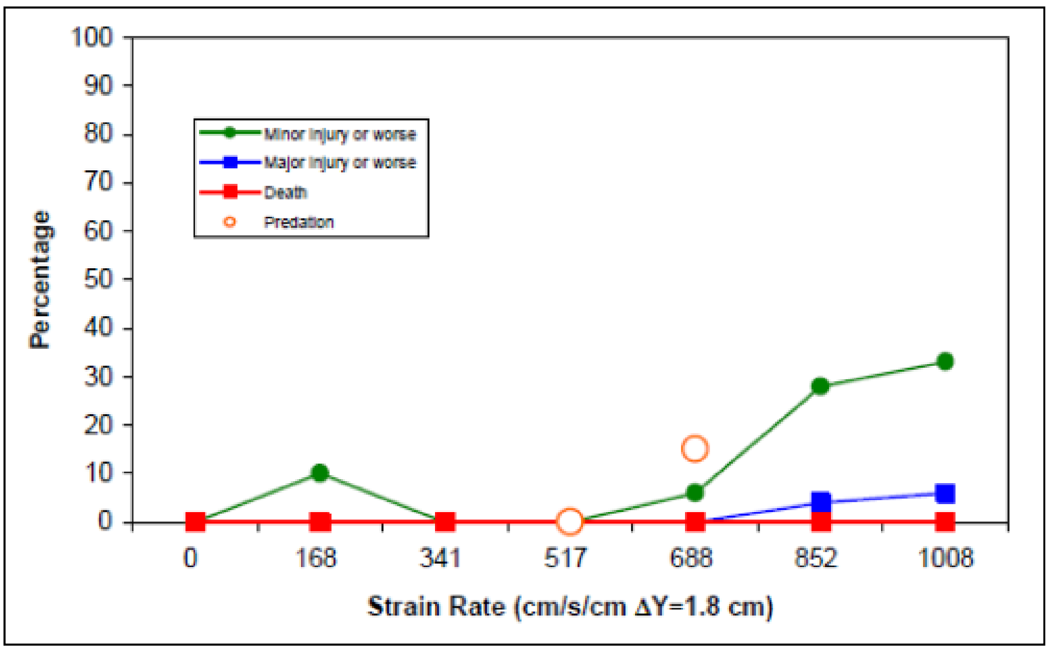
Source: Carlson et al. 2010

While the nadir pressure is a significant part of the equation for pressure related injuries, acclimation pressure is also an influencing factor. In general, juvenile salmonids approach the dams within the upper one-third of the water column during the day but may be deeper or more randomly distributed at night (Coutant and Whitney 2000). Adams and Liedtke (2010) performed studies tracking salmonids in the McNary forebay with acoustic transmitters. At first approach to the dam (approximately 100 feet out), juvenile steelhead were at a mean depth of about 10 feet, yearling Chinook at 18 feet, and subyearling Chinook at 30 feet. A comparison of incoming depth during the day and night found that yearling Chinook did not vary their approach depth much between the day and night, while juvenile steelhead went from a mean approach depth of 10 feet during the day to 18 feet at night. Given the approach depth, the majority of fish were required to dive to pass under the screens and through the turbines (Adams and Liedtke 2010).

While it appears that there is a significant approach depth difference between species, many other factors could affect the approach depth such as tag burden and/or the reservoir temperature profile. The condition of the fish's swim bladder and the dissolved gas levels within the fish's blood and body tissues as it passes through the turbine runner are unknown. Both the dissolved gas in the blood and the condition of the fish's swim bladder will influence the fish's ability to survive pressure changes. For salmon, it is known that there is a limit to the amount of air they can gulp into their swim bladder from the surface; therefore, there is a maximum to the potential depth of acclimation for the swim bladder. A study that attempted to look at this determined that a likely median maximum acclimation depth for juvenile yearling Chinook salmon is 22 feet (Pflugrath 2012).

In addition to the mortal injury that occurs directly within a turbine environment, mortality is known to occur in tailrace following turbine passage. Indirect mortality is believed to result primarily from predation by birds and piscivorous fish. Operation of an individual turbine unit can have effect of the distribution and magnitude of velocity exiting a turbine draft tube. Additionally, reduction of non-mortal injury within the turbine environment would improve the fitness of the fish exiting the draft tube and may result in an increased ability to avoid predators in the tailrace. An indication of this effect was found in the PNNL shear strain rate laboratory studies (Neitzel et al. 2000). Predation challenge studies were performed at two different shear strain rates (Figure 14) and increased predation of jet-exposed fish over control fish for the fish exposed for the higher strain rate (but not the lower strain rate). Therefore, this study indicates that there is likely a relationship between turbine unit operations and indirect mortality (i.e., predation), but due to the limited test and lack of understanding of the strain rate seen within turbine environments, this study does little to quantify the relationship. Additionally, the total powerhouse and total project operations probably have a larger effect on indirect mortality by influencing both the egress from the powerhouse tailrace and affecting the depth, distance from shore and velocity in the tailrace.

Figure 14. Percentage of Juvenile Rainbow Trout Injured when Exposed to Headfirst Jet with Predation Challenge Performed at Two Different Jet Exposures



Source: Neitzel et al. 2000

3. DEFINE TARGET OPERATING RANGE FOR TURBINES

3.1. INTRODUCTION

The following information was used to help estimate the TOR for fish passage survival through the turbines at the lower Columbia and Snake River projects: (1) physical geometry of different operating conditions; (2) physical modeling data of different operating conditions that was guided by physical geometry; (3) pressure information from laboratory and field data; and (4) biological field study information. Because none of this information alone can identify a TOR for survival of fish passing through turbines, it was tied together to provide an estimate of a TOR for each project. A summary description of the information used to help estimate the TOR for fish passage survival at each project is provided below. Additional information can be found in each project's appendix to this report.

3.2. PHYSICAL GEOMETRY CONSIDERATIONS

Field studies of the McNary and John Day turbines indicate a higher probability of survival for juvenile Chinook salmon when passing through a turbine operated with a "more open geometry" (Normandeau 2003, 2007), which is sometimes beyond the current upper 1% operating limit. The turbine unit has an open geometry when the wicket gates are well aligned with the stay vanes, and the runner blades are at a steep rather than flat angle. It is relatively simple to determine and thus, is a good starting point for a particular turbine family. This alignment may be considered a reasonable starting point for optimizing fish survival through turbines. It is predicted that improved geometry will provide for a relatively uniform flow through the runner and minimizes exposure to impact, shear, and turbulence. Alignment of stay vanes with wicket gates also would reduce the wake generated between these structures.

A study of stay vane and wicket gate geometry was performed by the Hydroelectric Design Center (HDC) for the lower Columbia and Snake River hydropower projects (Wittinger et al. 2010). The purpose of the study was to identify the geometry of the different families of turbines to determine the TOR that appears to provide good alignment of the wicket gate opening to the stay vane angular position. Good alignment was considered the presentation of minimal cross-sectional area of the combined wicket gate and stay vane profiles to the flow entering the turbine runner. For comparison, information was also provided for the current operating points with or without fish screens installed.

The best physical alignment of stay vanes and wicket gates for each project is presented in Table 2. However, the goal of minimizing the gap between wicket gate and stay vanes, and maintaining the wicket gate within the hydraulic shadow of the stay vane, is expected to occur within the broader range of a wicket gate angle for each of the projects; thus, Table 3 presents this broader range. For many of the projects, the generator limit factors into the upper range, and the upper range would be compressed for larger than average project heads for these units. The gross head presented is close to the average project head for each project. Over the normal project head, the flow rates indicated would not be expected to vary much, although the power and efficiency, and to a lesser degree the wicket and blade angles, will vary over the normal project head range.

The results of the study by Wittinger and others (2010) indicate that a good geometric relationship is often not found within the existing 1% operating limits. This may indicate that adjustment of current turbine operating criteria is warranted to reduce injury and direct mortality of migrating salmon.

Table 2. Approximate Best Wicket Gate Geometry

Project and Turbine Units	Gross Head (feet)	Approximate Best Geometry				
		Wicket Gate Angle (degrees open)	Blade Angle (degrees open)	Power (horsepower)	Flow (kcfs)	Efficiency (percent)
Bonneville 1st 1-10 New MGR	60	40.50	28.6	69,500	11.0	92.60
Bonneville 2nd 11-18	60	40.86	24.0	105,000	17.3	89.20
The Dalles 1-14	80	41.00	35.0	83,500	10.1	90.80
The Dalles 15-22	80	39.00	33.3	134,000	16.6	89.15
John Day 1-16	95	41.00	31.5	200,500	21.7	85.70
McNary 1-14	75	43.00	26.3	103,000	14.4	84.30
Ice Harbor 1-3	90	40.00	30.7	141,626	17.1	81.10
Ice Harbor 4-6	90	40.50	33.0	173,600	19.8	86.00
Lower Monumental 1-3	100	41.00	32.4	199,000	19.8	88.70
Lower Monumental 4-6	100	42.00	26.5	193,000	18.7	90.90
Little Goose 1-3	95	41.00	31.9	185,000	19.9	86.20
Little Goose 4-6	95	42.00	27.0	187,000	19.4	89.30
Lower Granite 1-3	100	41.00	32.9	200,000	21.2	83.20
Lower Granite 4-6	100	42.00	27.3	192,000	19.7	85.80

kcfs = thousand cubic feet per second

Table 3. Best Wicket Gate Geometry Operating Ranges

Project and Turbine Units	Gross Head (feet)	Best Geometry In		Maximum Design	Best Geometry Operating Range				
		Existing 1% Limits? (Yes/No)	Generator Limits? (Yes/No)	Wicket Gate Operating Angle (degrees open)	Wicket Gate Angle (degrees open)	Blade Angle (degrees open)	Power (horsepower)	Flow (kcfs)	Efficiency (percent)
Bonneville 1st 1-10 New MGR	60	N	Y	61.78	37 to 43	24.0 to 31.0	59,500 to 82,500	9.3-13.4	93.9 to 90.4
Bonneville 2nd 11-18 (see Note)	60	N	N	57.00	N/A	N/A	N/A	N/A	N/A
The Dalles 1-14	80	Y	Y	54.00	37 to 45	30.0 to 35.0	72,500 to 102,500	8.8-12.7	90.2 to 89.9
The Dalles 15-22	80	N	Y	50.00	35 to 39.25	29.3 to 34.3	118,000 to 134,500	14.3-16.6	90.5 to 89.1
John Day 1-16	95	N	Y	50.00	36 to 43	26.2 to 33.6	155,800 to 212,400	16.7-23.1	86.4 to 85.1
McNary 1-14	75	N	Y	61.40	38 to 48	24.0 to 29.8	94,000 to 116,000	12.9-16.4	85.4 to 83.2
Ice Harbor 1-3	90	N	Y	53.50	39 to 40	29.0 to 30.7	136,250 to 141,626	16.3-17.1	81.8 to 81.1
Ice Harbor 4-6	90	N	Y	49.50	39 to 41	32.5 to 33.5	172,900 to 174,000	19.6-19.9	86.1 to 85.8
Lower Monumental 1-3	100	N	Y	50.00	36 to 45	27.5 to 35.0	162,500 to 212,400	16.0-21.4	89.6 to 87.4
Lower Monumental 4-6	100	N	Y	51.23	36 to 44	20.25 to 29.0	155,500 to 212,400	14.9-20.9	91.8 to 89.3
Little Goose 1-3	95	N	Y	50.00	36 to 46	27.3 to 35.0	152,000 to 212,400	15.9-23.5	88.4 to 83.7
Little Goose 4-6	95	N	Y	51.23	36 to 47	22.6 to 31.25	150,000 to 205,000	15.4-21.2	90.5 to 85.8
Lower Granite 1-3	100	N	Y	50.00	36 to 42	26.8 to 34.0	140,000 to 212,400	14.4-22.8	85.5 to 82.2
Lower Granite 4-6	100	N	Y	51.23	36 to 45	21.0 to 29.9	156,000 to 212,400	15.6-22.2	88.1 to 84.3

Note: Bonneville 2nd wicket gates do not shadow the stay vanes.
kcfs = thousand cubic feet per second

3.3. Physical Observational Model Information

3.3.1. Overview

Physical observational model studies have been performed for multiple different turbine designs and different projects at the Engineering Research and Development Center (ERDC) in Vicksburg, Mississippi. The models typically are a 1:25 scale single unit sectional powerhouse observational models used to assess hydraulic passage conditions. These models are constructed primarily of Plexiglas allowing unobstructed views of the flow passage routes. The models are set using the Froude method and can be operated at several different heads. The appropriate scaling of gravitational (mass) and inertial (velocity) forces permits the determination of prototype conditions from model observations. The primary investigation methods include observing dye, neutrally buoyant beads, and air bubble passage through the turbine passage routes. Neutrally buoyant bead passage is observed with high-speed video and scored for both change in direction and contacts to allow a quantitative comparison of fish passage conditions at different operating points. Velocity measurements using a Laser Doppler Velocimeter (LDV) are often taken at several cross sections to obtain important flow distribution information for the turbine passage route. An ERDC technical report for the B1 Turbine Modeling (still in draft) will give more information on a typical turbine modeling effort.

These models allow detailed evaluations of how turbine operations affect impact, shear, and turbulence within the turbine passage environment and when available, provide important information. While several turbine units have been investigated, there are also several turbine units without these Froude-scale physical model investigations.

In an effort to reduce the cost and avoid duplication of building identical turbine models, a geometric and dimensional study of Kaplan turbine water passages was conducted by HDC (2005) to identify the USACE hydropower projects that can utilize the same turbine model with little or no modification. Three design categories for identifying similar families of hydropower units were developed: (1) interchangeable (identical, no modifications to the model), (2) partially interchangeable (some elements identical, only slight or minor modifications to the model), and (3) exclusive (unique design, requires unique model). The study results are shown below.

- **Exclusive:** B1, B2, and McNary turbine units are exclusive and require a unique turbine model.
- **Partially Interchangeable:** The Dalles turbine units 1-14 and units 15-22, and separately Ice Harbor units 1-3 and units 4-6, are partially interchangeable (more investigation required to verify the interchangeability of the different components).
- **Interchangeable:** John Day turbine units 1-16, Little Goose units 1-3, Lower Granite units 1-3, and Lower Monumental units 1-3 are interchangeable. Separately, Little Goose units 4-6, Lower Granite units 4-6, and Lower Monumental units 4-6 are interchangeable.

3.3.2. Bonneville Dam

3.3.2.1. First Powerhouse (B1)

A physical observational model of a single B1 turbine unit was constructed and tested at ERDC. The prototype flow rates fully investigated were 7.5 thousand cubic feet per second (kcfs), 9.7 kcfs, and 11.5

kcfs, while 7.3 kcfs and 13.4 kcfs were only qualitatively investigated. The majority of testing was conducted at 55 feet of head (prototype scale), which is close to the spring fish passage season head, but 60 feet of head was also investigated (~ summer season) with few differences found. These flow rates in relation to the 1% efficiency range are respectively, peak, upper 1%, and upper 2%, while the qualitatively only flow rates represent lower 1% and generator limit, respectively. Testing was performed without intake screens since that is the current field condition.

The first area presenting a chance of strike injury is in the vicinity of the stay vanes and wicket gates. While the contacts and direction changes showed very little change across the operating points, the gap passage decreased with increasing flow and improved alignment. The stay vanes at turbines in B1 are one of the few stay vanes that are shaped, which may explain why little change exists across the operating range for contacts and direction changes. Although the lack of improvement in contacts and direction change dilutes the conclusions, the gap passage improvement would point to higher discharges for improved passage past these structures similar to the wicket gate geometry considerations.

The next area for potential mechanical injury is for fish passing the runner blades of the turbine. In general, contact with the runner was found to decrease with increasing flow rate through the runner with the percentage of severe contacts decreasing from 2.4% to 0.9%. Similarly, the percentage of severe direction changes decreased from 5.9% for the peak operating point to 2.0% for the upper 2% operating point. This corresponded well with the stay vane and wicket gates passage, as well as the blade angle geometry considerations.

Velocity measurements were made at the draft tube exit using a LDV. The draft tube has both a vertical splitter wall that divides the draft tube into two barrels (designated A and C), and a partial length horizontal splitter wall. The velocities at the draft tube exit were used to estimate the flow rate through each of these barrels. Barrel A had a much higher flow rate than barrel C, and this was relatively unaffected by the total turbine discharge. Turbulence intensity was found to decrease with increasing flow for barrel C, while turbulence intensity changed little across the operating range for barrel A.

For this physical model, bead analysis was performed for the contacts and direction changes in the draft tube elbow and around the splitter horizontal and vertical splitter piers. Minimal change was observed across the operating range for severe contacts. However, a significant decrease in severe change in direction was seen with increasing turbine discharge (decreasing from 10% to 5.7%), which agreed with qualitative observations of a vortex occurring beneath the runner for lower discharges that was not present at higher turbine discharges. It can be concluded that increased turbine discharge improves fish passage conditions in the draft tube.

Based on the physical model information for the different areas of the turbine passage all indicated that the mechanical and shear injuries should be significantly reduced by increasing flow rates up to 11.5 kcfs. Although quantitative information was not taken for the generator limit (13.4 kcfs), hydraulic conditions appeared fairly similar to the 11.5 kcfs.

3.3.2.2. Second Powerhouse (B2)

At this time, a physical model of one of the turbine units in B2 has been assembled at ERDC, but testing and observation of the model has not occurred. Since this is an exclusive model, it is unlikely that model information from a different model could be used.

3.3.3. The Dalles Dam

At this time, a runner for turbine units 1-14 at The Dalles has been received by ERDC, but a turbine model for this runner has not been constructed or tested. There are currently plans for a model to be built for The Dalles as part of plans to replace turbine units 1-14. Currently, there is no model runner available for turbine units 15 to 22.

3.3.4. John Day Dam

The John Day physical model is a 1:25 Froude-based scale model of a single turbine unit constructed and tested at ERDC. The first area that presents a chance of strike injury is in the vicinity of the stay vanes and wicket gates. The model showed that the percentage of beads contacting these structures was low. Additionally, the lowest number of contacts and direction changes seem to occur for flows larger than 16.0 kcfs. The percentage of beads passing through the gap between the stay vanes and wicket gates were also analyzed using the high-speed video. Unlike the contacts and direction changes, this percentage appears to increase with flow and be relatively unrelated to the best wicket gate geometry.

The next area for potential mechanical injury is for fish passing the runner blades of the turbine. In general, contact with the runner decreased with increasing flow rate through the runner although at the highest flow there in some increase in contacts. Increasing flow rate of course corresponds to an increase in blade angle and increased open cross-sectional area within the runner environment.

Velocity measurements were made at multiple transects using a LDV. One area that displayed a large difference between the different flow rates tested was the velocity measurements taken near the exit of the draft tube. The draft tube for John Day units has a single vertical splitter wall which divides the draft tube into two barrels (designated A and C) of equal cross-sectional area and length. Barrel A had a much higher flow rate than barrel C at the lower turbine flow rates, but the flow distributes more evenly for flow rates of 16.5 kcfs and higher. Turbulence intensity was found to decrease with increasing flow for both barrels and especially for barrel C, although there is some increase in turbulence intensity at the highest flows. The increased turbulence at lower flow rates could cause fish disorientation. While direct injury or mortality may not result, the disorientation has the potential to increase vulnerability of fish to predation.

Based on physical model information, flow rates above 16.5 kcfs (approximately above peak efficiency) show improved hydraulic conditions over flow rates below 16.5 kcfs. There is some improvement in draft tube conditions for flow rates higher than 16.5 kcfs but marginal improvements in other areas of the runner. While it is expected that mechanical and shear related injuries to fish would be reduced between peak efficiency and generator limit (compared to operating at the low end of the operating range), the collected model information shows little difference within this range.

3.3.5. McNary Dam

Additional information to reduce strike frequency, exposure to shear and turbulent environments comes from a 1:25 Froude-scale model constructed of a McNary turbine unit. The prototype flow rates investigated were 10.2 kcfs (~ best operating efficiency), 12.2 kcfs (~ upper 1% efficiency), 13.4 kcfs (~ 2% drop in efficiency), 16.5 kcfs (~ generator limit) and 17.7 kcfs (~ beyond 100% of generator limit) at approximately 73 feet of prototype-scale head. The percentage of beads with severe contacts to the wicket gate or stay vanes decreased significantly between best operating efficiency and the upper 1% efficiency. Bead contact was lowest at 12.2 kcfs, 13.4 kcfs and 16.5 kcfs and increased slightly at the highest flow rate. For the runner, the percentage of beads with severe contacts and severe direction changes both appeared to have a general decreasing trend with increasing flow rate.

In addition to bead data, velocity data was taken at transects near the runner and at the exit of the draft tube using a LDV. The runner tangential velocity decreases with increasing flow, which shows the increased axial flow angles caused by the steeper blade angle. The draft tube in the McNary turbine units has a single vertical splitter wall that divides the draft tube into two equal sized barrels (designated A and C). While barrel A had a much higher flow rate than barrel C at the lower turbine flow rates, the flow distributes more evenly for flow rates of 13.4 kcfs and higher. Barrel C had high turbulence intensity at low flows, which dropped significantly for flow rates of 13.4 kcfs and higher. The increased turbulence at the lower flow rates could cause fish disorientation. While direct injury or mortality may not result, fish disorientation has the potential to increase vulnerability to predation.

Based on physical model information, flow rates between 13.4 kcfs and 16.5 kcfs (between upper 1% and generator limit) show improved hydraulic conditions and thus, reduced mechanical and shear injuries would be predicted within this range. It is expected that mechanical and shear related fish injuries would be reduced for turbine unit discharges within or near this range (which is above the 1% operating range).

3.3.6. Ice Harbor Dam

While there is no physical model data for Ice Harbor turbine units 4-6, there is significant physical model data collected for units 1-3 as part of the Ice Harbor turbine replacement project. The prototype flow rates investigated were 8.8 kcfs, 11.9 kcfs, 13.4 kcfs, and 14.8 kcfs. All tests were conducted between approximately 96 feet of head (prototype scale), which is close to the average head for the project during fish passage season. These flow rates in relation to the 1% efficiency range are respectively, lower 1%, approximately upper 0.5%, upper 1%, and approximately generator limit (at 96 feet of head). Testing was performed with and without the STS in the intake; however, all model data presented is with the STS installed since that is the current field condition.

The first area presenting a chance of strike injury is in the vicinity of the stay vanes and wicket gates. Modeling showed that while the gap passage increased slightly with increasing flow, the severe contacts and direction changes generally decreased with increasing discharge. Although this information is slightly conflicting, it would point to higher discharges for improved passage past these structures similar to the wicket gate geometry considerations. The next area for potential mechanical injury is for fish passing the turbine runner blades. In general, contact and direction change within the runner were found to increase with increasing flow rate through the runner. This conflicts with the stay vane and wicket gate passage data, as well as with blade angle geometry considerations.

Velocity measurements were made at multiple transects using a LDV. The draft tube for Ice Harbor units 1-3 has a single vertical splitter wall which divides the draft tube into two barrels (designated A and C) of equal cross-sectional area and length. The velocities at the draft tube exit were used to estimate the flow rate through each of these barrels. Barrel A has a much higher flow rate than barrel C at the lower turbine flow rates, but the flow starts to distribute more evenly as the total discharge increases. Turbulence intensity decreased with increasing flow for both barrels and especially for barrel C. The increased turbulence at the lower flow rates could cause fish disorientation. While a direct injury or mortality may not result, the disorientation has the potential to increase vulnerability of fish to predation.

With conflicting information for different areas of turbine passage, it is difficult to determine which turbine unit discharge would be expected to have the best fish passage conditions per the physical model information. Based on the draft tube and distributor information, the 8.8 kcfs discharge would not be the ideal passage conditions and a higher discharge would be preferred. However, due to the high velocities in the runner environment, having good hydraulic conditions in the runner would be considered a priority. Therefore, for the discharges tested, a discharge near 11.8 kcfs would likely have the best fish passage conditions based on physical model information.

3.3.7. Lower Monumental Dam

Lower Monumental operates at a different head than John Day (approximately 100 feet instead 95 feet) but its turbine units 1-3 are the same configuration as the John Day turbine units. Therefore, physical modeling information approximates the conditions in the Lower Monumental turbine units. The conclusions that the hydraulic conditions are improved for discharges above 16.5 kcfs should also apply to turbine units 1-3 at Lower Monumental.

Additionally, Lower Monumental operates at the same head as Lower Granite, and turbines units 4-6 are the same configuration as Lower Granite turbine units 4-6. While an ERDC model has been constructed and operated, only draft tube velocity at some operating points have been investigated; thus, limited conclusions can be made about fish passage from this model.

3.3.8. Little Goose Dam

Little Goose operates at approximately the same head as John Day and its turbine units 1-3 are the same configuration as the John Day turbine units. Therefore, physical modeling information approximates the conditions in the Little Goose turbine units. The conclusions that the hydraulic conditions are improved for discharges above 16.5 kcfs should also apply to turbine units 1-3 at Little Goose.

Additionally, Little Goose operates at different head as Lower Granite (approximately 95 feet instead of 100 feet), but turbine units 4-6 are the same configuration as Lower Granite turbine units 4-6. While an ERDC model has been constructed and operated, only draft tube velocity at some operating points have been investigated; thus, limited conclusions can be made about fish passage from this model.

3.3.9. Lower Granite Dam

Lower Granite operates at a different head than John Day (approximately 100 feet instead 95 feet) but its turbine units 1-3 are the same configuration as the John Day turbine units. Therefore, physical modeling information approximates the conditions in the Lower Granite turbine units. The conclusions that the hydraulic conditions are improved for discharges above 16.5 kcfs should also apply to turbine units 1-3 at Lower Granite.

A 1:25 Froude-scale hydraulic model was constructed at ERDC for a Lower Granite turbine unit 4-6. The primary purpose for constructing this model was to investigate draft tube condition and model possible modifications to the draft tube. The existing draft tube was investigated at discharge 17.6 kcfs (~upper 1%) and 22.8 kcfs (~generator limit). The flow split went from 69.8% in barrel A and 30.2% in barrel C to 53.1% in barrel A and 46.9% in barrel C with the increase in discharge. The turbulence intensity in barrel C decreased with the increased discharge but was still considered high. There was no bead data taken for stay vane cascade or the runner environment. The draft tube information seems to indicate that there are improved hydraulic conditions with increasing discharge; however, without more information, this conclusion is probably premature. The model still exists at ERDC and will likely need to be operated to fully investigate the variation in fish passage conditions over the operating range.

3.4. PRESSURE INFORMATION FROM LABORATORY AND FIELD DATA

3.4.1. Overview

From 2006 to 2010, the USACE funded PNNL to conduct laboratory decompression tests on juvenile Chinook salmon (Carlson et al. 2010). Over 10,000 fish were tested in the Mobile Aquatic Barotrauma Laboratory (MABL) that was developed at PNNL in collaboration with USACE. One of the primary differences with previous decompression testing is that MABL allowed for holding fish at pressure with access to air, which allowed fish to become neutrally buoyant at higher pressures to simulate acclimation in deeper water. In addition, MABL allowed for highly controlled pressure exposures accurately simulating both the rate and magnitude of pressures changes observed in field measurements of turbine pressure profiles (collected with a sensor package exposed to turbine passage).

Although a number of variables were studied, only the rate of pressure change (log ratio of pressures [LRP]) and tag burden were found to be significant variables in determination of mortality due to rapid decompression. The LRP is defined as the log ratio of absolute acclimation pressure to the absolute nadir pressure. Tag burden is defined as the ratio of tag weight in water to fish weight. Equation 1 presents the probability of mortal injury for tagged and untagged Chinook salmon based on the MABL decompression testing. For untagged fish (run-of-river fish), Equation 2 is suggested for use due to the larger data set used in its generation even though the equations are very similar (Carlson and Duncan 2004).

Equation 1:
(for tagged fish)

$$\text{Probability of Mortal Injury} = \frac{e^{-5.997+4.201*\text{LRP}+0.603*\text{Tag Burden}}}{1+e^{-5.997+4.201*\text{LRP}+0.603*\text{Tag Burden}}}$$

Equation 2:
(for untagged fish)

$$\text{Probability of Mortal Injury} = \frac{e^{-5.56+3.85*\text{LRP}}}{1+e^{-5.56+3.85*\text{LRP}}}$$

Graphical representations of Equation 1 and Equation 2 are presented in Figure 15 and Figure 16, respectively. Red- and blue-hashed lines around the predicted fit for Equation 2 represent the 95% confidence intervals for mortal injury due to decompression for both hatchery and run-of-river fish (Figure 16). The hatchery and run-of-river fish had very similar mortal injury rates due to decompression as would be expected (Figure 16). The three-dimensional graphs shown in Figure 15 suggest that tag burden has a significant effect on mortal injury particularly between LRP values between 1 and 2.5.

As can be seen in the above equations, both the acclimation and the nadir pressures play an equally important role in the primary variable of the LRP. At a majority of the projects, the acclimation pressure is not well known since little vertical distribution information exists for fish entering turbines. However, if a robust vertical distribution dataset did exist, then it could only be assumed that the fish were neutrally bouyant as opposed to postively or negatively bouyant when approaching the dam or entering the turbine runner environment. Without good information, a relatively conservative acclimation depth should be used (i.e., one that results in higher mortality). The deepest acclimation depth (or highest acclimation pressure) would result in the highest barotrauma rates.

Figure 15. Decompression Mortality for Tagged Juvenile Chinook (Carlson et al. 2010)

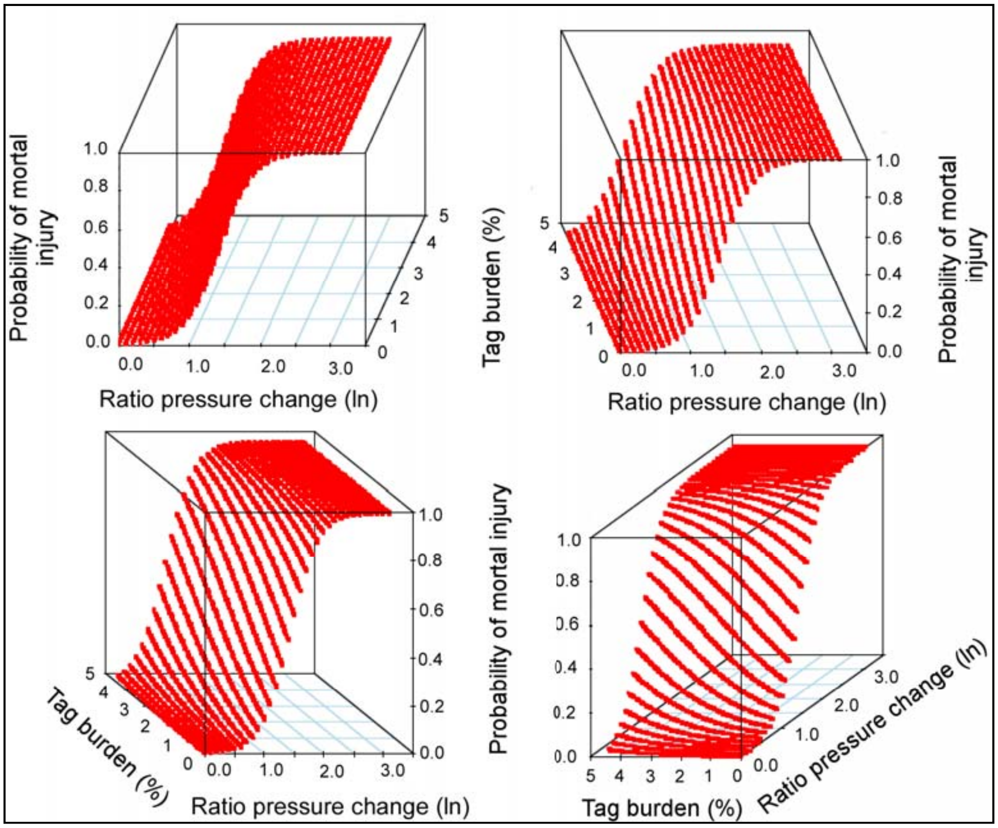
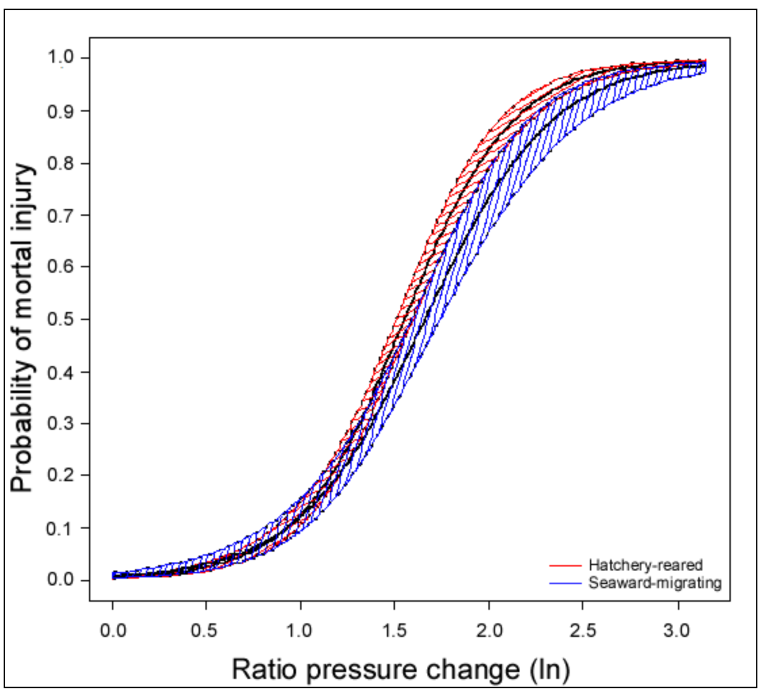


Figure 16. Decompression Mortality for In-river Juvenile Chinook (Carlson et al. 2010)



Additionally, it is known that there is a limit to the amount of air salmon can gulp into their swim bladder from the surface; thus, there is a potential maximum depth of acclimation. A study by PNNL (Pflugrath et al. 2012) looked at three different ways to estimate the deepest acclimation depth for yearling Chinook salmon. The conclusions were that a likely median maximum acclimation depth for juvenile Chinook salmon is 22 feet (Pflugrath et al. 2012). While acclimation depth for a particular project is most likely shallower, to be conservative for barotrauma rates an acclimation depth of 22 feet was used. However, improved information is being pursued for the Lower Monumental forebay, which may allow the use of a field measured acclimation depth distribution. If this information can be collected and then applied at other locations, the calculated mortality could change significantly, which may cause modification of a turbine target operating range.

3.4.2. Bonneville Dam

3.4.2.1. First Powerhouse (B1)

In winter 1999/2000, PNNL released 27 sensor fish into B1 turbine unit 6 to obtain pressure for the new MGR turbine unit and to compare it to existing turbine unit 5 (since replaced). The following four different operating points were tested at approximately 57 feet of head: 6.2 kcfs (below lower 1%), 6.9 kcfs (lower 1%), 10.4 kcfs (between upper 1% and best geometry point) and 11.7 kcfs (between best geometry point and generator limit). By releasing the sensor fish at the stay vanes, the sensor fish targeted tip, mid, and hub locations. The barotrauma mortality was calculated using the mean nadir or a pressure profile and an assumed 22-foot acclimation depth (Table 4).

Table 4. Calculated Barotrauma Mortality for B1 Turbines

Operating Point	Mean Nadir Pressure (psia)	Calculated Mortality using Average Nadir and 22-foot Water Acclimation	Calculated Fish Mortality using Pressure Profile and 22-foot Water Acclimation
6,229 cfs (below lower 1%)	17.74	1.3%	1.3%
6,850 cfs (lower 1%)	18.83	1.0%	1.0%
10,411 cfs (upper 1% to best geometry point)	19.18	0.9%	1.1%
11,693 cfs (best geometry point to generator limit)	14.02	3.1%	4.0%

psia = pounds per square inch absolute

3.4.2.2. Second Powerhouse (B2)

In 2007, PNNL released sensor fish into B2 turbine unit 16 to obtain the pressure profile at three turbine operating conditions (Carlson et al. 2008). The sensor fish were released in intake bays A and B of unit 16 but released at points that targeted either the tip or middle/hub of the turbine blade. Between 20 and 65 were released per test condition over two different discharges, 10.8 kcfs (lower 1%) and 17.6 kcfs (upper 1%). The nadir pressures recorded are summarized in Table 5. The combined data points are the tip and mid/hub data sets combined. Different pressures other than the mean nadir pressure may be experienced by fish; thus, the minimum and maximum nadir pressures are presented as well (Table 5). Based on an acclimation depth at 22 feet, the barotrauma mortality (Table 5) was calculated using the equations generated by PNNL. Note that this acclimation depth is a conservative estimate (see Section 3.4.1).

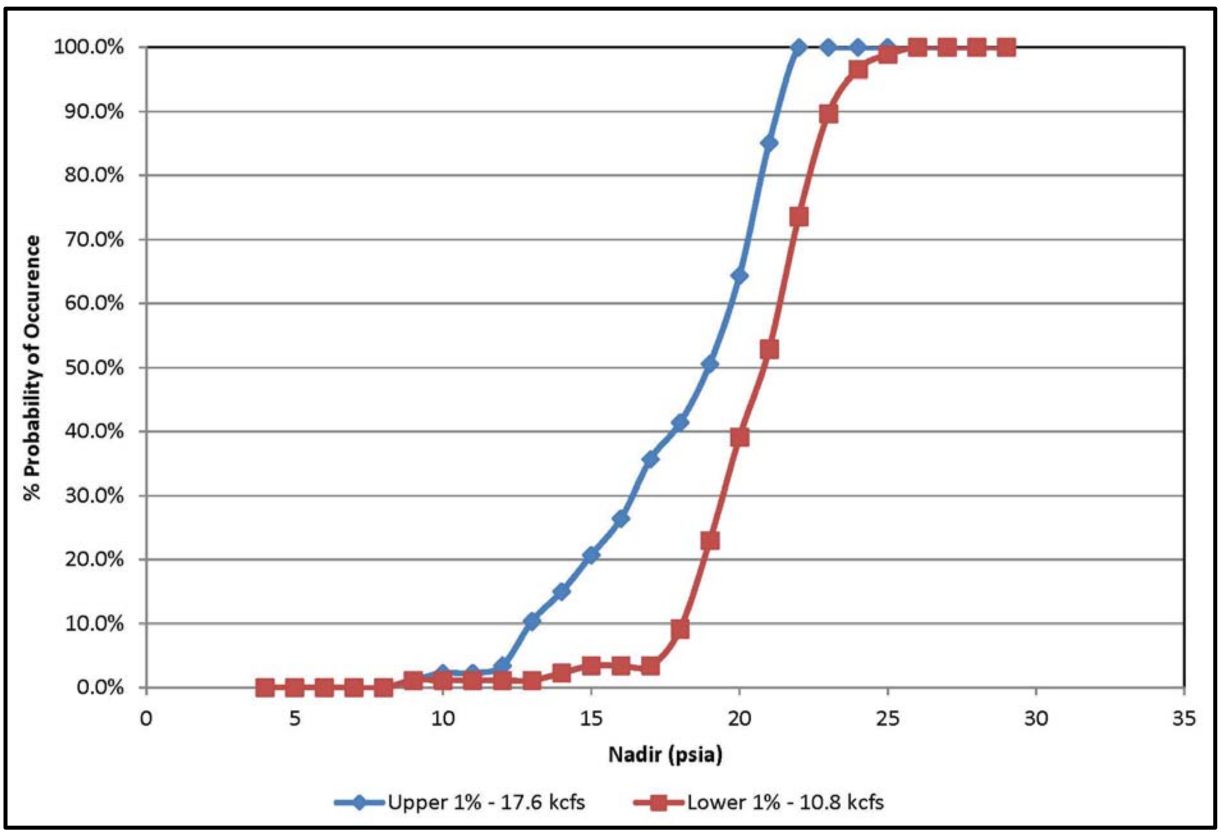
Table 5. Bonneville Turbine Unit 16 Nadir Pressures and Calculated Mortality

Turbine Passage Condition	Turbine Discharge (kcfs)	Median Nadir		Minimum Nadir		Maximum Nadir	
		Nadir (psia)	Calculated Mortality (%)	Nadir (psia)	Calculated Mortality (%)	Nadir (psia)	Calculated Mortality (%)
Lower 1% Combined	10.8	20.46	0.73	8.72	16.45	25.25	0.33
Upper 1% Combined	17.6	17.91	1.22	8.69	16.64	21.95	0.56
Lower 1% Tip	10.8	21.45	0.61	17.67	1.28	25.25	0.33
Upper 1% Tip	17.6	16.27	1.75	8.69	16.64	20.70	0.70

psia = pounds per square inch absolute. Source: Carlson et al. 2008

A pressure probability distribution can be generated that encompasses the range of pressures a fish may experience when passing a turbine runner at a given operations. This pressure distribution provides a more realistic calculation of morality relative to simply using mean nadir pressures. With two different release points, assumptions must be made on the incoming distribution of fish. If all the nadir data points are taken as equal, the resulting incoming distribution is about 75% and would be hub/mid and at 25% would be tip passage. Using this as a basis, the pressure probability distribution for the lower 1% and upper 1% based on the sensor fish data is shown in Figure 17. Based on these pressure probability distributions and 22 feet of acclimation depth, the calculated barotrauma mortality rate is 0.89% for the lower 1% and 1.64% for the upper 1%. These values are relatively close to the mean nadir calculated values and show some increase in barotrauma rate with increasing discharge. However compared to other projects, the nadir pressures are fairly high resulting in fairly low calculated mortality.

Figure 17. B2 Nadir Pressure Probability Distribution based on sensor fish data



3.4.3. The Dalles Dam

There is no pressure information for either turbine units 1-14 or 15-22 at The Dalles.

3.4.4. John Day Dam

There are multiple sources of nadir pressure information for the John Day turbines. Sensor fish releases were conducted by PNNL at John Day in 2006 (Carlson et al. 2008). Following this, a computational fluid dynamics (CFD) model was developed by ENSR/VATECH of the John Day turbine environment. The USACE was then able to perform post-processing of the CFD results to generate a probability of exposure to nadir pressures. This, in turn, was compared to sensor fish and a radial offset correction was applied to the CFD to match sensor fish results (Kiel and Ebner 2011). While it is possible to use sensor fish results directly, the CFD allows for a much smoother probability curve that is not as affected by the less frequent low nadir pressures. With a more robust nadir probability curve, mortality estimates can be calculated for the full range of nadir pressure, rather than simple use of the median sensor fish result. Table 6 presents the results of the calculated mortality estimate at 22 feet of acclimation depth using both the CFD nadir distribution and point estimates from sensor fish. A great deal of variability in estimated mortality associated with the severity of nadir pressures is shown in the table; hence, these estimates should be interpreted as to what may occur at a given operation and nadir pressure. Based on this information, a large increase in estimated mortality occurs between peak and upper 1% operations suggesting that operations remain around peak to reduce the risk of barotrauma.

Table 6. John Day Nadir Pressures and Calculated Mortality

Turbine Passage Condition	Turbine Discharge (kcfs)	Calc. Mort. w/ CFD Nadir Distrib. (%)	Mean Nadir		Minimum Nadir		Maximum Nadir	
			Nadir (psia)	Calc. Mort. (%)	Nadir (psia)	Calc. Mort. (%)	Nadir (psia)	Calc. Mort. (%)
Lower 1%	11.8	0.62	22.19	0.54	0.73	99.96	30.55	0.16
Peak	16.5	1.81	21.97	0.56	14.36	2.81	27.02	0.25
Upper 1%	20.3	6.18	16.08	1.83	0.13	100.00	22.87	0.48

3.4.5. McNary Dam

An assessment of barotrauma mortality risk for McNary turbines was made using relationships established using laboratory testing and field pressure data using sensor fish. For McNary turbines, a limited amount of pressure data is available from sensor fish. In 2002, Carlson and Duncan (2004) released sensor fish in turbine unit 9 at flows of 7.7 kcfs and 16.6 kcfs. In general, the nadir pressures decreased with increasing flow, resulting in mean nadir pressures of 21.64 psia (7.7 kcfs) and 14.95 psia (16.6 kcfs). Based on laboratory studies on juvenile salmonids, 22 feet of acclimation depth for approaching fish was assumed (Pflugrath et al. 2012). Using these pressures and the generated equations, a barotrauma mortality rate without internal tags of 0.6% for 7,667 cfs and 2.4% for 16,567 cfs was calculated. A pressure probability distribution was generated but due to the limited number of sensor fish releases, the distribution was not considered accurate.

3.4.6. Ice Harbor Dam

In 2005, PNNL released sensor fish into Ice Harbor turbine unit 2 to obtain a pressure profile at three turbine operating conditions (Carlson et al. 2008). The sensor fish were released in all three intake bays of turbine unit 2 and released at points that targeted either the tip or middle/hub of the turbine blade. Between 27 and 58 sensor fish were released per test condition over three different discharges: 8.3 kcfs (lower 1%), 13.1 kcfs (upper 1%) and 14.1 kcfs (close to generator limit). The nadir pressures recorded are summarized in Table 7. The combined data points are the tip and mid/hub data sets combined; however, a tip passage was not taken for the generator limit so mid/hub only comparison was included as well. Different pressures other than the mean nadir pressure may be experienced by fish; thus, the minimum and maximum nadir pressures are given in Table 7. Based on an acclimation depth of 22 feet, the barotrauma mortality was calculated using the equations generated by PNNL (Table 7).

Table 7. Ice Harbor Nadir Pressures and Calculated Mortality

Turbine Passage Condition	Turbine Discharge (kcfs)	Median Nadir		Minimum Nadir		Maximum Nadir	
		Nadir (psia)	Calculated Mortality (%)	Nadir (psia)	Calculated Mortality (%)	Nadir (psia)	Calculated Mortality (%)
Lower 1% Combined	8.3	19.54	0.87	14.38	2.79	23.28	0.45
Upper 1% Combined	13.1	14.68	2.58	0.45	99.99	20.35	0.75
Lower 1% Mid-Hub	8.3	19.61	0.86	14.38	2.79	23.28	0.45
Upper 1% Mid-Hub	13.1	15.72	2.00	7.13	29.95	19.48	0.88
Gen. Limit Mid-Hub	14.1	15.44	2.14	6.33	40.33	19.54	0.87

Source: Carlson et al. 2008

As shown in Table 7, barotrauma rate increased with increasing discharge with a large variation from minimum to maximum nadir pressures. Instead of using mean nadirs, a pressure probability distribution can be generated at least for the upper 1% and lower 1% where both tip and mid/hub releases were completed. With two different release points, assumptions were made on the incoming distribution of fish. If all the nadir data points are taken as equal, the resulting incoming distribution is about 66% and would be hub/mid and 33% would be tip passage. Based on these pressure probability distributions and acclimation depth of 22 feet, the calculated barotrauma mortality rate is 0.87% for the lower 1% and 4.96% for the upper 1%. These values are relatively close to the mean nadir calculated values for the lower 1% but significantly higher for the upper 1%, which shows some increase in barotrauma rate with increasing discharge.

There is no pressure information for Ice Harbor turbine units 4-6.

3.4.7. Lower Monumental Dam

Units 1-3 at Lower Monumental are similar to John Day and the pressure information for John Day would likely apply to these units. Although there is no pressure data for units 4-6, there are plans to collect sensor fish information for these units.

3.4.8. Little Goose Dam

Units 1-3 at Little Goose are similar to John Day and the pressure information for John Day would likely apply to these units. Although there is no pressure data for units 4-6, there are plans to collect sensor fish information for Lower Monumental, which also would apply to these units at Little Goose.

3.4.9. Lower Granite Dam

Units 1-3 at Lower Granite are similar to John Day and the pressure information for John Day would likely apply to these units. Although there is no pressure data for units 4-6, there are plans to collect sensor fish information for Lower Monumental, which also would apply to these units at Lower Granite.

3.5. BIOLOGICAL FIELD STUDY INFORMATION

3.5.1. Overview

The majority of biological field tests completed to date for the lower Columbia and Snake River projects have provided estimates of project survival where tagged fish passed through turbines under the full range of turbine operating conditions. Total turbine passage is assigned a survival without accounting for potential survival differences across the operating range. However, a number of tests have been completed to estimate the survival under different operating conditions for the same turbine unit. Information from these tests is invaluable when available; however, there are a number of potential biases, such as that associated with barotrauma, that are factors of methodology and should be acknowledged.

The majority of turbine survival tests were performed by Normandeau using Hi-Z balloon-tag methods. To date, this method has been completed by taking surface acclimated fish and introducing them into the turbine intake under different operating conditions. Since balloon tags are external, the tag burden of internal tags will not increase measured mortality rates. However, the surface acclimation of fish also results in significant underestimation of barotrauma rates. Therefore, balloon-tag tests likely measure the portion of the direct mortality that can be attributed to contact, shear or turbulence but not pressure.

Other biological tests have been completed with internal radio or acoustic tags during turbine passage; however, the addition of an internal tag can result in a significant increase in mortality (Carlson et al. 2010). Again, these studies typically do not estimate survival for different turbine operations. Increased mortality may not be consistent across the operating range due to decreasing nadir pressures and the non-linear relationship of the barotrauma mortality rate.

3.5.2. Bonneville Dam

3.5.2.1. First Powerhouse (B1)

Normandeau Associates (2000) conducted a balloon-tag study at Bonneville Dam to compare the biological performance of a new Kaplan MGR unit to existing Kaplan units. This study compared mortality of balloon-tagged fish passing through a new MGR in unit 6 (current units) to the old Kaplan in unit 5 (has since been replaced). The study was designed as a factorial design (two turbines x three release locations x four operations). Sufficient numbers of fish were to be released so that the resulting survival probabilities would be within ≤ ±3%, 90% of the time, which resulted in 2,593 juvenile Chinook salmon being released through the MGR unit 6 (and approximately the same number for unit 5). These objectives were accomplished by releasing fish through a specially designed induction system for fish to pass them near the blade tip, mid-blade, and hub regions in each turbine at four discrete turbine unit discharges. The study targeted four power levels but the actual average turbine unit discharges tested for the MGR turbine (unit 6) were at 6.2 kcfs (below the lower 1% operating limit); at 6.9 kcfs (approximately the lower 1% operating limit); at 10.4 kcfs (beyond the upper 1% but less than the best geometry point); and at 11.7 kcfs (between best geometry point and the generator limit). The head during the test was approximately 57 feet (same as sensor fish study since they were released at the same time). The 48-hour survival for the MGR turbine unit averaged across the release points was 3.3% (6.2 cfs), 4.3% (6.9 kcfs), 2.7% (10.4 kcfs), and 3.8% (11.7 kcfs). No statistical correlation existed between fish passage survival and turbine unit discharge in either turbine. Qualitatively, however, the highest point estimate of survival for the MGR unit, at all release locations, occurred at power level 3 (approximately 10.4 kcfs operating point).

In addition, a radio-tag study conducted in 2004 estimated direct turbine passage survival with two different control releases downstream (Counihan et al. 2006). However, this study did not separate the results by operating point.

3.5.2.2. Second Powerhouse (B2)

There are no known studies for turbine passage survival at different operating conditions.

3.5.3. The Dalles Dam

There are no known studies for turbine passage survival at different operating conditions.

3.5.4. John Day Dam

Although a number of biological tests have estimated turbine fish passage survival at John Day, they were not designed to provide specific survival estimates at specific operating points. The 2009 Juvenile Salmon Acoustic Telemetry System estimate of survival is 72.8% for subyearling fish and 85.5% for yearling fish. The tag burden for this study was 2.6% for subyearlings and 1.5% for yearlings, which may have resulted in a biased barotrauma injury.

3.5.5. McNary Dam

Although a number of existing biological studies have estimated turbine passage survival at McNary, very few have evaluated fish passage survival relative to turbine operations. In 2002, balloon-tagged fish were introduced into the intake of turbine unit 9 at four different operating conditions (Normandeau Associates 2003). The April releases indicated the lowest mortality occurred at 13.4 kcfs discharge (~2% drop from peak) and survival at 12.0 kcfs discharge (upper 1%) were only slightly better than 7.7 kcfs (lower 1%) and 16.6 kcfs discharges (~ generator limit). Meanwhile, a concurrent radio-tag study was conducted at McNary turbine unit 9 to estimate total turbine mortality of yearling Chinook (direct and indirect) at the 11.2 kcfs (~ between peak and upper 1%) and 16.6 kcfs operating conditions (Absolon et al. 2003).

In 2003, Perry and others (2004) conducted a study to estimate turbine survival of subyearling Chinook salmon carrying gastric implanted radio tags. The purpose of this study was to estimate turbine survival within the 1% operating range, as Skalski and others (2002) suggested that highest survival may be experienced outside the 1% operating range. Turbine operations averaged 11.5 kcfs (~ between peak and upper 1%) during the study. It was determined that survival probability was 77.4% (95% confidence interval [CI]: 70.6% - 84.2%) within the 1% operating range for subyearlings. A 2004 study by Perry and others (2006) attempted to determine a difference in survival for fish passing through turbines operating at high flows outside the 1% operating range (average 15.9 kcfs, near the generator limit), and turbines operating at lower flow inside the 1% operating range (average 11.0 kcfs; ~ between peak and upper 1%). Yearling Chinook salmon and juvenile steelhead were radio tagged with the same techniques as Perry and others (2004). Survival probabilities were highest for yearling Chinook salmon (89% - 98.6%) when turbines were operated within the 1% range and highest for juvenile steelhead (94.3% - 107.4% when turbines were operated beyond the 1% range.

Potential biases in survival estimates derived from the Aboslon and others (2003), Normandeau Associates (2003), and Perry and others (2004) studies may be due to study fish being surface acclimated. Surface acclimated fish are less susceptible to barotrauma; hence, survival estimates derived from surface acclimated fish are likely not representative of actual turbine passage survival. Additionally, the radio tags used in the Absolon and others (2003) and Perry and others (2004) studies added a tag burden of nearly 5% in some cases, which may have further biased survival estimates. The Perry and others (2006) study did allowed natural acclimation of fish by releasing them upstream, but study fish experienced a large tag burden as well (~ 4.5% for yearling Chinook and 2.1% for juvenile steelhead). This study found no significant difference in survival between high and low turbine discharge treatments. Small sample sizes (<100 yearling Chinook and < 30 steelhead per treatment) caused broad confidence intervals around survival estimates, which explains that the data were not robust enough to detect a significant difference in survival between treatments. This study did find an increase in mortality with distance traveled downstream between fish that passed during different discharge treatments, which suggests that turbine discharge may affect survival at McNary Dam.

In 2011, an analysis of data was conducted from tagged juvenile salmonids passing through McNary turbines from 2004 through 2009 (Adams et al. 2011). This analysis found a decrease in survival with increased tag burden for both control and turbine-passed fish, but the effect was more severe for turbine-passed fish. Turbine unit discharge was found to have no effect on fish passage survival; however, very few of the fish passed through turbines under operating conditions above the 1% efficiency range.

3.5.6. Ice Harbor Dam

In 2007, a Hi-Z balloon-tag study was conducted at Ice Harbor turbine unit 3 in all three intake slots (A, B and C) over five different operating conditions (Normandeau Associates 2008). The operating conditions tested were at the lower 1% (8.6 kcfs), at peak efficiency (~9.8 kcfs), between peak and upper 1% (11.4 kcfs), at the upper 1% (12.6 kcfs) and at the generator limit (~14.1 kcfs). The lowest survival was from Slot A for the 8.6 kcfs condition (92.9% survival, standard error [SE]=2.6%), while the highest survival was for Slot C for the 11.4 kcfs condition (99% survival, SE=1%). When all three intake bays were pooled, the survival was 95% (SE=1.3%) for 8.6 kcfs, 96% (SE=1.6%) for 9.8 kcfs, 97.7% (SE=0.9%) for 11.4 kcfs, 96.7% (SE=1.0%) for 12.6 kcfs, and 95% (SE=1.3%) for 14.1 kcfs. Little difference was found across the operating range, but the 11.4 kcfs (between peak and upper 1%) had the highest survival for the pooled estimate. Unfortunately, no studies have been done for turbine units 4-6.

In 2008, Axel and others (2010) conducted a passage and survival study at Ice Harbor Dam. The focus of the study was to evaluate the new removable spillway weir; however, route-specific relative survival metrics were estimated as well. Radio-tagged yearling and subyearling Chinook and juvenile steelhead were released 600 meters upstream of the dam. Fish were released over a period of 27 days (24 April - 27 May). Turbine survival estimates were not operation specific and sample sizes were small, which increased the disparity in confidence intervals; however, survival estimates and confidence intervals were realistic. Survival was estimated at 94.3% (95% CI: 88.9 - 99.6%) for yearling Chinook salmon and 77.8% (95% CI: 68.5 - 87.0%) for subyearling Chinook salmon. Insufficient number of juvenile steelhead passed through turbines to provide survival estimates. Although the final report did not discuss factors influencing turbine survival estimates, subyearlings may have experienced lower survival resulting from tag burden. Summer temperatures may cause higher stress on subyearlings as well; however, fish releases ended in May when temperatures were likely not a factor affecting survival.

3.5.7. Lower Monumental Dam

Passage behavior and survival studies for radio-tagged juvenile Chinook and steelhead were conducted from 2006 through 2009 at Lower Monumental. Yearling Chinook survival rates ranged from 90.9% in 2007 (Hockersmith et al. 2008b) to 100% in 2009 (Hockersmith et al. 2010); juvenile steelhead ranged from 83.8% in 2006 (Hockersmith et al. 2008a) to 100% in 2009 (Hockersmith et al. 2010). The turbine passage survival estimates were not operation or geometry specific, nor were the numbers of fish passing through the turbines during these studies sufficient enough to provide strong survival estimates. These studies focused on spillway survival and spill patterns. Because a small percentage of fish released passed through turbines during the study, turbine passage survival may not be representative of actual survival as indicated by very broad confidence intervals in some cases. Therefore, using John Day information is likely the best surrogate for Lower Monumental BLH turbine units 1-3.

There is limited information for the Lower Monumental AC turbine units 4-6.

3.5.8. Little Goose Dam

Currently, no field studies specific to turbine passage have been conducted at Little Goose Dam.

3.5.9. Lower Granite Dam

Currently, no field studies specific to turbine passage have been conducted at Lower Granite Dam.

3.6. DISCUSSION

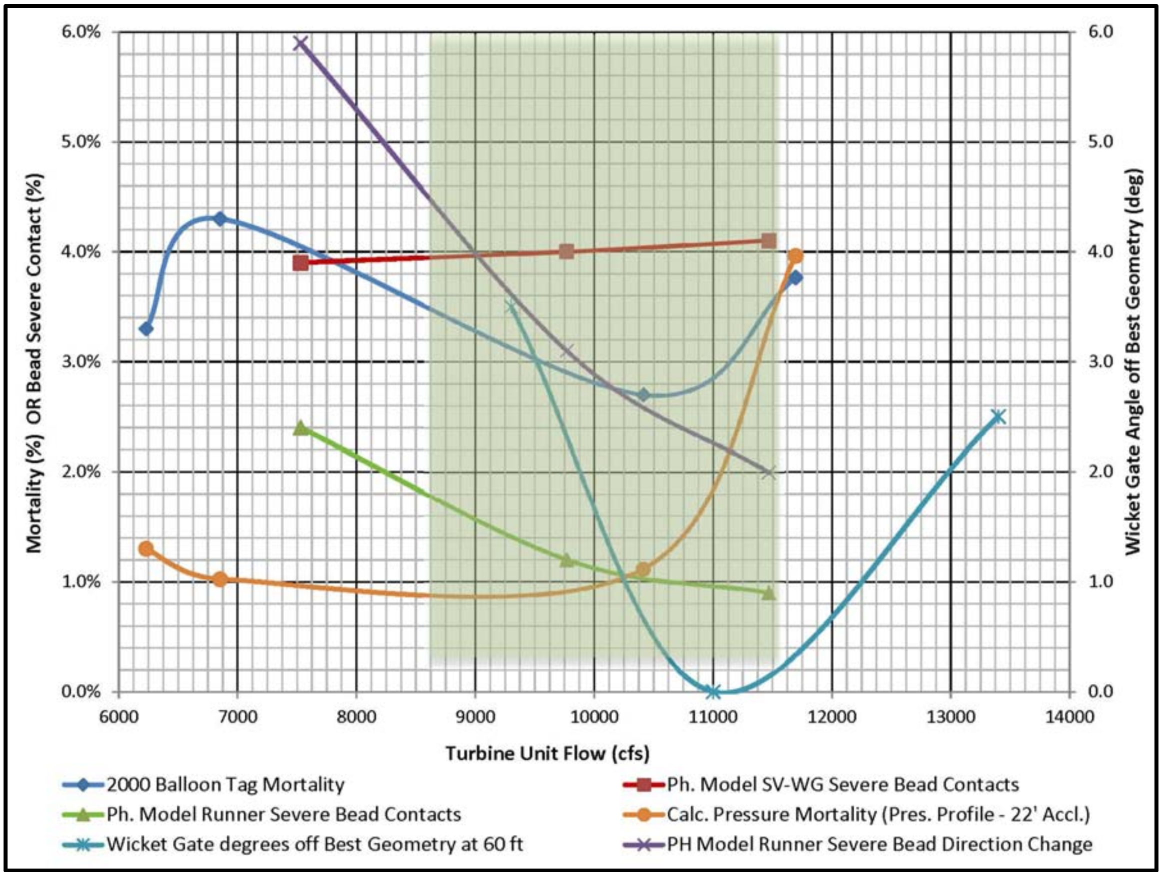
Using the information above, this section identifies a TOR for turbine units with currently installed turbine runners. This is a separate effort than the replacement of turbine runners to improve fish passage survival through turbines. Efforts are underway to replace Ice Harbor runner units 2, 3 and possibly 1 with units that were designed to improve fish passage. Additional turbine runners will be replaced in the future with McNary being the next for turbine replacement. Improving fish passage will continue to be a consideration in this effort. As turbine units are replaced, this document will need to be updated due to the change in operating configuration.

3.6.1. Bonneville Dam

3.6.1.1. First Powerhouse (B1)

A summary of the available information on the primary factors that affect turbine mortality at B1 is shown in Figure 19. At approximately 55 feet of head, physical injury information (physical model bead data and geometry considerations) suggests a lower rate of physical injury and mortality above approximately 8.5 kcfs with lower rates of extending up to the generator limit (13.3 kcfs at 55 feet of head) based on the qualitative assessment. This is supported by the balloon-tag study which indicated a lower mortality at 10.4 kcfs even though there is not a statistically significant difference between the operating points (Normandeau Associates 2000). The only information on potential barotrauma mortality is derived by combining the sensor fish nadir pressure information with the laboratory-based barotrauma mortality equation using assumed acclimation depths. Unfortunately, this is the weakest data but it does indicate there could be an increase in barotrauma mortality at the highest turbine unit discharges. Therefore, based on available information, the proposed TOR for fish passage survival at B1 is defined by the shaded area of Figure 18, which is approximately 8.5 kcfs to 11.5 kcfs at 55 to 60 feet of head.

Figure 18. Combined Information on Direct Turbine Mortality for B1 Turbines



3.6.1.2. Second Powerhouse (B2)

There is limited information on pressure and geometry considerations. An ERDC model has been constructed and information from this model will likely provide additional information to identify a TOR for B2 turbines.

3.6.2. The Dalles Dam

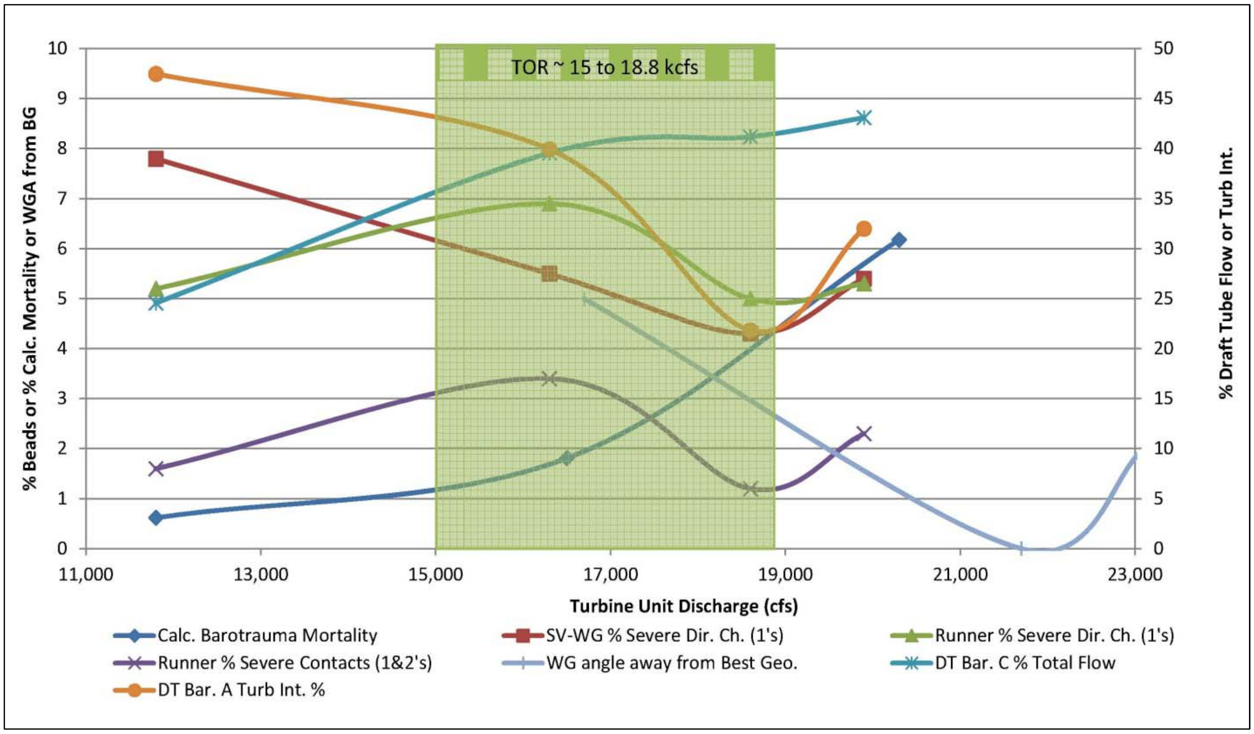
There is only geometry information for both units 1-14 and 15-22 at The Dalles. An ERDC model needs to be constructed and pressure data obtained to be able to identify a TOR for the turbine units.

3.6.3. John Day Dam

A summary of the available information on the primary factors that affect turbine mortality at John Day is shown in Figure 19. Not all of the information on this graph is equal. Calculated pressure mortality and severe contacts would likely be mortalities, while direction changes and draft tube turbulence would only factor into injury and possible mortality. Therefore, by factoring in the significance of different types of information, the proposed TOR for fish passage survival at John Day is approximately 15.0 to 18.8 kcfs at approximately 100 feet of head (shaded area on graph). This is within the current 1% operating range of approximately 11.7 to 20.8 kcfs. Therefore, there are no concerns for gatewell conditions while operating in the more restricted TOR identified.

There is model and geometry information for John Day that points toward higher flows closer to the generator limit; however, the calculated pressure mortality increases significantly between the peak and upper 1% operating range. It is important to remember that the pressure mortality is calculated with a relatively conservative acclimation depth of 22 feet, but the nadir pressures are lower for the upper 1% and mortality will increase toward the upper 1% and generator limit. In selecting a range, it is also prudent to allow reasonable flexibility of operation so that the powerhouse can be operated effectively. Therefore, the low end of the operating range of 15.0 kcfs is intended to reduce the exposure of fish to the poor flow conditions past the turbine structures that appear to occur near the lower 1% operating discharge. The upper end of the operating range of 18.8 kcfs is intended to balance improved flow conditions with the increase barotrauma mortality as the flow increases through the units. It should also be noted that the 29 degree blade angle (where multiple units at John Day are fixed) is within this TOR but it is toward the upper end.

Figure 19. Combined Information for Turbine Mortality at John Day

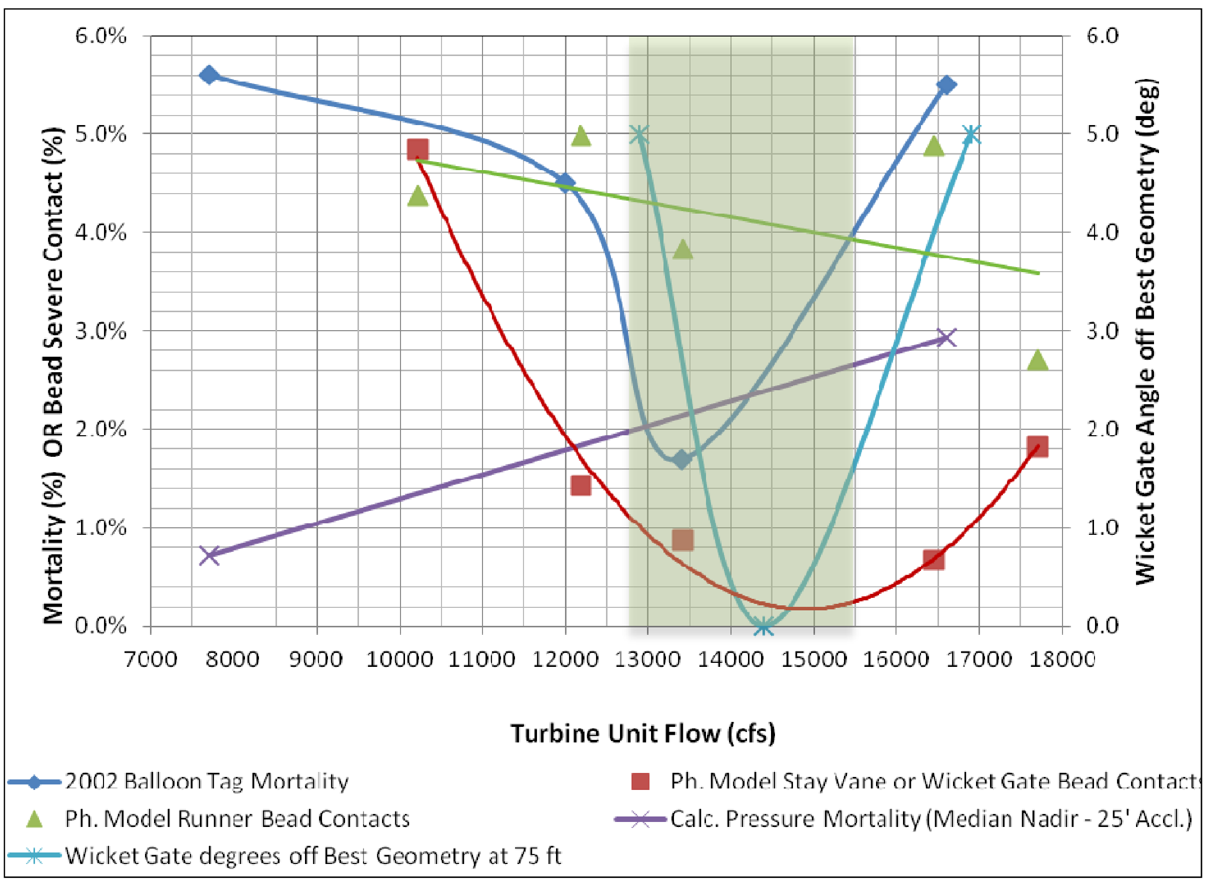


3.6.4. McNary Dam

A summary of the available information on the primary factors that affect turbine mortality at McNary is shown in Figure 20. The proposed TOR for fish passage survival at McNary is approximately 12.8 k to 15.5 kcfs at 75 feet of head (shaded area on graph). At 75 feet of head, this would correspond to a power range of 67.7 to 80.4 MW (85.4% and 83.4% efficiency, respectively), which can be compared to the current 1% efficiency range of 42.2 to 65.8 MW. Since the proposed TOR is an increase in flow rate through a turbine as compared to current operating range, there is concern for increased injury in the JBS due to increased flow up the gatewell. This concern is discussed in more detail in Section **Error! Reference source not found.**. It should be noted that logistic fit curve for turbine mortality (Figure 20) does not indicate a steep increase in mortality within the TOR at flows above approximately 13.5 kcfs. The logistic curve was fitted to four operating points where biological testing provided turbine mortality estimates. The fit may indicate a less abrupt climb in mortality with a more robust dataset of operations within the TOR, although collecting this data is not feasible.

Based on the physical observational model study for McNary, the proposed TOR should also reduced draft tube turbulence and thus, a potential reduction in tailrace predation. While this flow range may vary slightly with changing head, it will not vary significantly within the normal operating range for McNary. This proposed range is above the 1% efficiency operating range for McNary turbines; therefore, longer-term operation within this range would require adjustment to the FPP.

Figure 20. Combined Information for Turbine Mortality at McNary



3.6.5. Ice Harbor Dam

Although CFD data is not yet available for Ice Harbor, sensor fish releases suggest that the lowest nadir pressures occur at the upper 1% and generator limit. Relative survival estimates from Normandeau Associates (2008) suggest that the lowest survival rates (~93%) occurred at the lower 1% and again at the upper 1% and generator limit. The highest survival estimates (~97%) occurred at a point between peak and upper 1%. This appears to compliment physical model data where it was determined that an operation between peak and the upper 1% provided the best passage scenario. The available information suggests that a fish passage benefit may be realized from a TOR near the 11.8 kcfs operation (between peak efficiency and upper 1%) for existing turbine units 1-3. However, pressure information indicates that there may be some increased barotrauma at the upper 1% operating point of around 13.4 kcfs. At this time, a TOR will not be fully developed for units 1-3 because these units will be replaced with new turbine runners developed by the ongoing turbine design process that is attempting to improve fish passage conditions through the units. Units 1-3 will potentially be replaced by 2017. These units may have a TOR other than the 1% and if this is the case, this new TOR will be documented in this report or in other documents as appropriate.

Currently, very little information is available for turbine units 4-6 and no specific TOR is being recommended at this time.

3.6.6. Lower Monumental Dam

Information for John Day is likely the best surrogate for Lower Monumental turbine units 1-3. Figure 19 shows the combined information on direct turbine mortality for John Day. While it is a different dam, there is no additional information for Lower Monumental that would cause a change to this proposed range. No data currently exists for Units 4-6 at Lower Monumental.

3.6.7. Little Goose Dam

Information for John Day is likely the best surrogate for Little Goose turbine units 1-3. Figure 19 shows the combined information on direct turbine mortality for John Day. While it is a different dam, there is no additional information for Little Goose that would cause a change to this proposed range. No data currently exists for Units 4-6 at Little Goose.

3.6.8. Lower Granite Dam

Information for John Day is likely the best surrogate for Lower Granite turbine units 1-3. Figure 19 shows the combined information on direct turbine mortality for John Day. While it is a different dam, there is no additional information for Lower Granite that would cause a change to this proposed range. No data currently exists for turbine units 4-6 at Lower Granite.

4. DEFINE TARGET PROJECT OPERATIONS

The best TOR for direct turbine survival is only one component of total turbine survival. Indirect turbine mortality could be a significant portion of the total mortality and needs to be considered. Indirect mortality of turbine passed fish is thought to result primarily from predation by birds and piscivorous fish (USACE 2004). Primary ideas to reduce the high rates of indirect turbine mortality are to improve the condition of fish (reduce injury rate not just mortality) that are entering the tailrace and to improve the egress conditions out of the tailrace. Operating individual turbine units within the TOR should improve the first objective by improving the draft tube conditions. Typically, the TOR is a higher rate of flow that would provide higher and more evenly distributed velocities exiting a draft tube and thus, possibly better egress directly below a turbine unit. However, the individual turbine unit operation is unlikely to affect the egress of entire powerhouse region of the tailrace, which has much more to do with project operations than individual unit operations. A significant amount of attention has been paid to egress of spillway and JBS outfall discharge and these are the primary focus (in addition to adult fish ladder attraction) for the spill pattern and powerhouse unit priority in the current FPP. Therefore, the subsections below discuss what is information is available about powerhouse egress at each project.

4.1. BONNEVILLE DAM

Bonneville Dam is unique in that each of the powerhouses and the spillway are physically separated by islands, making the egress from each section of the project nearly independent. The turbine unit priority for B1 and B2 in the current FPP attempts to balance adult ladder attraction with powerhouse egress. The B1 turbine unit priority is 1, 10, 3, 6, 2, 4, 5, 8, 7 and 9, while the B2 turbine unit priority is 11, 18, 12, 17, 13, 14, 15, and 16. For both powerhouses, the end units are operated first to provide attraction to adult ladder entrances and other units are added for egress. Typically, B2 is given priority over B1 but at times it switches. Powerhouse egress is already considered as part of the turbine unit priority and operating at the TOR should not degrade egress. Therefore, there are no recommended changes to the turbine unit priority from the current FPP.

4.2. THE DALLES DAM

The Dalles Dam is unique in that the spillway is separated from the powerhouse and the powerhouse draft tube exits are perpendicular to the main river. Water exiting the turbine units turns 90 degrees and then flows in a very deep channel before rejoining the spillway flow. Turbine unit priority in the current FPP prioritizes adult attraction to fish ladder entrance and to the ice and trash sluiceway, while meeting the restrictions of the transmission line needs. Due to current bathymetry and powerhouse orientation, it is not believed that much can be done to improve powerhouse egress.

4.3. JOHN DAY DAM

In March 2012, the powerhouse egress at John Day was evaluated in the 1:80 general model at ERDC. The modeling concluded that the unit priorities identified in the FPP were reasonable. Block loading the powerhouse (north and south ends) does not improve powerhouse egress due to the large area between bulked flows (either powerhouse bulked flow or spillway bulked flow) causing recirculation cells moving flow upstream. When the spillway is in operation, powerhouse egress is reasonable when seven units are operational (at any unit operating point). Direct survival may increase if operating higher in the 1% operating range, but egress would diminish somewhat if that operation resulted in operating less than seven units. Powerhouse egress improves with reduced spill especially at low river flow (< 150.0 kcfs), but spill reduction is not likely due to the significantly higher survival from spill as currently tested.

4.4. McNary Dam

Primary information on powerhouse egress at McNary comes from hydraulic modeling conducted on March 13-15, 2012, using the McNary physical model at ERDC. It was hypothesized that powerhouse egress conditions would improve with higher unit discharge and blocked loading, concentrating tailrace flow to the north near the spillway. This was observed during the modeling for the most part. In general, the velocity downstream of the north end of the powerhouse increased for conditions using the higher unit discharge of the TOR. In most cases, the increase in unit discharge also increased the velocity to over 4 ft/s, which is the generally accepted threshold for eliminating predation habitat.

Several different unit priorities were tested at different river discharges and it was concluded that the north end loading was the best unit priority. The existing turbine unit priority is unit 1 followed by units 14 through 2 in the current FPP. Since unit 1 is still required for attraction flow to the south fish ladder, there is no recommended change to turbine unit priority. Although most of the testing was conducted with existing spill percentages, some testing looked at reduced spill operations. As would be expected, reducing the spill flow improved the powerhouse egress by allowing more discharge out of the powerhouse. There did not appear to be a break point on spill flow by percentage or discharge where spill egress conditions became significantly worse; some 20% spill conditions appeared to have the best project egress.

While the general model is a good tool, there are some portions of the model that do not accurately reflect field conditions, especially for entrainment. Therefore, additional information that can be used is CFD modeling for the McNary tailrace, where entrainment was essentially calibrated using dissolved gas field measurements (Politano 2012). This CFD modeling compared model simulations with the same powerhouse flow that had different unit loading and powerhouse priority – low unit loading with units 1-4, then units 14-5 priority vs. high unit loading (upper 1%) with unit 1, then units 14-2 priority. This modeling resulted in higher velocities in the north part of the powerhouse with a significant portion higher than the 4 ft/s predator habitat criteria. This higher velocity was found to push the point of powerhouse entrainment further downstream of the aerated zone causing a decrease in total river dissolved gas. It can be conjectured that these trends would continue by operating the turbine units within the higher unit loading of the TOR. Therefore, even with the increased entrainment found in the CFD modeling, the north loaded powerhouse with the higher unit flow of the TOR would be expected to result in improved powerhouse egress.

Field measurements and biological tests are needed to verify that current turbine unit priority with units operating at the TOR would improve powerhouse egress.

4.5. Ice Harbor Dam

No information exists for Ice Harbor Dam to support operations different than the current unit priority to improve egress, although further investigations are recommended.

4.6. Lower Monumental Dam

Modeling done as recently as 2011 for the relocated JBS outfall looked at tailrace conditions at river flows from 60.0 to 90.0 kcfs and two different spill patterns (28.0 and 25.0 kcfs for each pattern). The 60.0 and 70.0 kcfs flows had a large eddy downstream of the powerhouse. In addition, data correlation was performed for turbine passage data from 2004-2009 fish survival studies. The number of units operating at Lower Monumental correlated with increased detection of fish downstream. This generally indicates that the more units that are operating, the better the egress and the better the turbine passage survival. The turbine unit of passage at Lower Monumental also correlated with increased detection of fish downstream. Turbine unit 1 is the unit close to shore and unit 6 is closer to the center of the dam. This generally indicates that the closer the unit is to the center of the river, the better the egress and the better the turbine passage survival.

The powerhouse unit priority at Lower Monumental should be adjusted to pass fish through units near the spillway to leverage on the egress conditions created by spill. Unit 1 and possibly unit 2 will continue to be prioritized for adult fish attraction water, but may not be the best for juvenile salmon moving downstream due to the strong reverse eddy associated with that region at the dam. Therefore, a single unit could be used for adult attraction, while subsequent units are prioritized toward the center of the dam. Physical model operation could be used to further justify this change in unit priority.

4.7. LITTLE GOOSE DAM

No information exists for Little Goose Dam to support operations different than the current unit priority to improve egress, although further investigations are recommended.

4.8. LOWER GRANITE DAM

No information exists for Lower Granite Dam to support operations different than the current unit priority to improve egress, although further investigations are recommended.

5. OTHER CONSIDERATIONS

5.1. BONNEVILLE DAM

5.1.1. First Powerhouse (B1)

No further considerations affect the recommended path forward at this time.

5.1.2. Second Powerhouse (B2)

No further considerations affect the recommended path forward at this time. However, less than ideal gatewell conditions may require further operations investigations in the future.

5.2. THE DALLES DAM

No further considerations affect the recommended path forward at this time.

5.3. JOHN DAY DAM

Since the proposed TOR is within the current operating range for John Day, there should be little to no effect on the JBS. There are no other considerations that have been identified for the John Day project at this time.

5.4. MCNARY DAM

The McNary turbines are currently operated with an ESBS installed in front of the turbines. This causes fish to be routed up the bulkhead gatewell slot and into the collection channel through orifices. As long as the ESBS are installed, the effect of the TOR on the gatewell environment needs to be considered in the context of achieving the highest overall project survival and lowest fish injury rates.

There has been concern that increased flow rate through the turbines at McNary may result in decreased fish health and survival in the JBS. The JBS uses the ESBS to route water and fish up the gatewell with the only route for fish to exit the gatewell being orifices that pass into a collection channel in the ice trash sluiceway at McNary. It is known that fish can spend a significant amount of time in the gatewell prior to locating and passing through the orifices. The basis of the concern is that with ESBS installed, increased flow through the turbine results in increased flow up the gatewell. This increase in flow results in both increased velocities and increased turbulence in the gatewell, which may result in increases in fish injury and mortality. Since McNary has significant capacity above the 1% operating range, there have been multiple studies that looked at fish delay, injury and mortality at different turbine unit operating flow rates.

Table 8 summarizes all gatewell studies done to date that looked at high turbine unit loading. Since yearling Chinook was a common thread in the studies, the findings for these fish are reported in Table 8, with some subyearling Chinook data included as well. There is a large degree of variation in the descaling measured by the various studies, and the most likely cause of this variation is debris loading on the trashrack, ESBS, and VBS. Despite the variation, the overall body of data points to an increase in descaling with increased flow through the turbine unit. The quantity of this increase is difficult to determine from the studies done to date, but is probably less than a 5% increase in descaling. It should be noted that a significant portion of the descaling will not result in fish mortality; however, since this relationship is unknown, descaling should be limited to the extent possible. Although not quantified in any of the studies, all studies discussed debris as being a significant contributor to descaling.

Table 8. McNary Gatewell Fish Condition at Different Operating Conditions

Study Year	1997	2002	2004	2005	2006	2010	2010
Reference	(Brege et al. 1998)	(Absolon et al. 2003)	(Absolon et al. 2005)	(Gessel et al. 2006)	(Gessel et al. 2007)	(Axel et al. 2011)	(Axel et al. 2011)
Test Fish	Yearling Chinook	Yearling Chinook	Yearling Chinook	Yearling Chinook	Subyearling Chinook	Yearling Chinook	Subyearling Chinook
High Turbine Unit Flow Results							
High Test Q (kcfs)	16.0	16.4	16.0	16.0	16.0	13.8	13.8
Descaling (%)	17.1	0.2	Incomplete	8.7	2.8	7 to 11	11% for U4 4% for U5
Mortality (%)	---	---	Incomplete	---	1.8	---	---
Orifice Passage	94% OPE in 24 hrs	0.58 hr avg. GW residence time	0.38 days avg. GW residence	---	---	---	---
Low Turbine Unit Flow Results							
Low Test Q (kcfs)	12.0	11.2	12.0	12.2	12.2	12.1	12.1
Descaling (%)	6.7	0.3	Incomplete	7.7	2.5	4 to 7	4.5% for U4 2.5% for U5
Mortality (%)	---	---	Incomplete	---	0.6%	---	---
Orifice Passage	63% OPE in 24 hr	18.7 hr avg. GW residence time	0.51 days avg. GW residence	---	---	---	---

In conclusion, the multiple studies done to date point to an increased risk for fish passed through the JBS when turbines are operated at the predicted TOR (12.8 to 15.5 kcfs at 75 feet of head). However, if debris on the trashracks, ESBS, and VBS are managed appropriately, this increase should be kept to a minimum.

5.5. ICE HARBOR DAM

No further considerations affect the recommended path forward at this time.

5.6. LOWER MONUMENTAL DAM

The standard length traveling screens used at Lower Monumental have several potentially detrimental effects on fish passing beneath them and eventually passing through the turbine. The screens cause turbulence, loss of turbine efficiency, and sometime reverse flows near the ceiling of the intake that can delay and disorient juvenile salmon passing by them. It is not clear that the bypass routes are necessarily better for survival of juvenile salmonids than turbine routes. In spring 2009, juvenile salmon survivals through the bypass system were lower (0.965 for yearling Chinook and 0.939 for juvenile steelhead) than for fish passing through the turbines (1.021 for yearling Chinook and 1.009 for juvenile steelhead). In this instance, the removal of screens during non-transport periods may have provided better survival results than leaving them in. Part of the low survival of through the bypass may have been related to its outfall location, which is not ideal under the current mandated spill patterns. The outfall is currently being relocated downstream where the egress conditions are more favorable. Regardless of the outfall relocation, bypassed fish at Lower Monumental have suffered relatively low smolt-to-adult returns as compared to other routes. It will require time and continued monitoring to determine if the smolt-to-adult returns continue to be low.

5.7. LITTLE GOOSE DAM

No further considerations affect the recommended path forward at this time.

5.8. LOWER GRANITE DAM

No further considerations affect the recommended path forward at this time.

6. RECOMMENDED PATH FORWARD

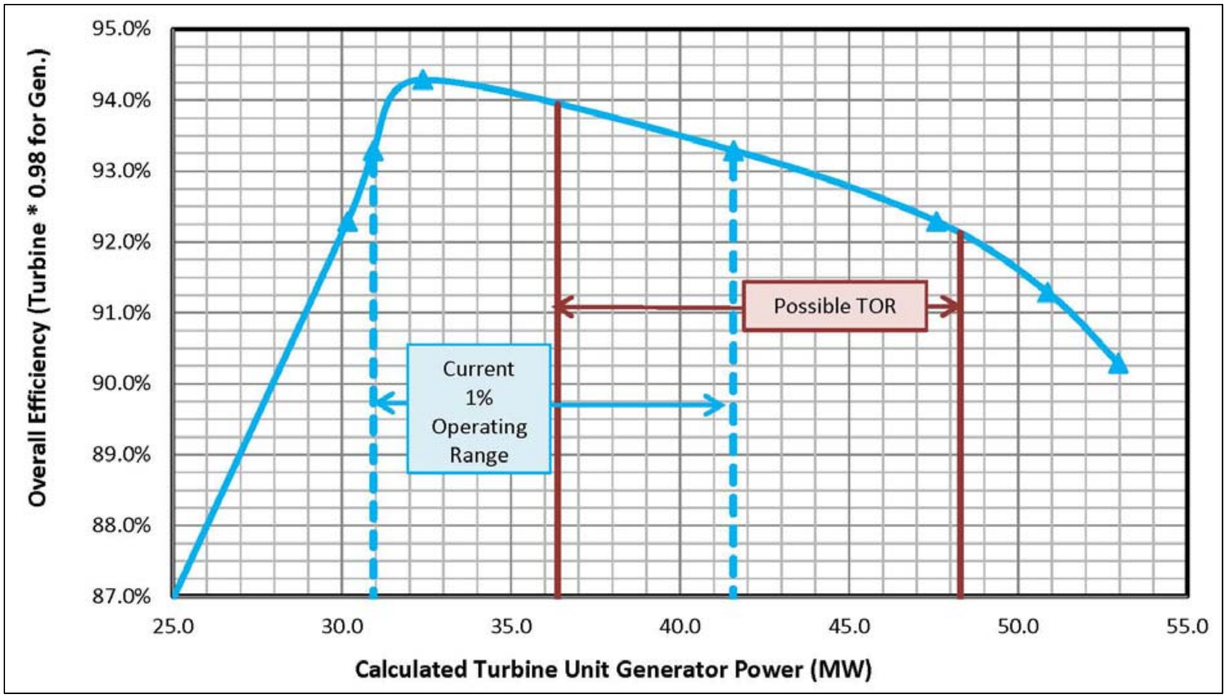
Using the available information, this section recommends turbine unit TORs and target project operations to improve fish passage survival through turbines. For some projects, there is limited information; therefore, as additional information becomes available, this report will be updated to incorporate the information and to revise the recommendations as appropriate.

6.1. BONNEVILLE DAM

6.1.1. First Powerhouse (B1)

The information presented in this report indicates that turbine unit operation may have a significant effect on direct turbine mortality at the B1. Based on the available information, a TOR of 8.5 to 11.5 kcfs at approximately 55 feet of head is proposed. Figure 21 translates this flow range to generator power and efficiency at 55 feet of head, since flow is a calculated value based on power and efficiency.

Figure 21. Proposed Target Operating Range at 55 feet of Head for B1 Turbines



Although the proposed TOR is supported by some field studies, the TSP team believes that additional pressure information is needed to fine-tune the upper end of the operating range. Therefore, either additional sensor fish releases and/or CFD modeling should be conducted to better define the barotrauma risk. This additional information could result in a revision to the TOR. Since Bonneville can have a more significant head variation than the other hydropower projects, it is important to define the TOR at other heads to fully implement this as a new operating range for B1 turbines. For target project operations, the existing turbine unit priority is probably adequate since the B1 powerhouse has a separate tailrace.

6.1.2. Second Powerhouse (B2)

There is not enough information at this time to recommend a different turbine unit operating range than the existing 1% requirements. For target project operations, the existing turbine unit priority is probably adequate since the B2 powerhouse has a separate tailrace.

6.2. The Dalles Dam

There is not enough information at this time to recommend a different turbine unit operating range than the existing 1% requirements. Target project operations have also not been fully investigated although the project configuration may make it difficult to make significant improvements in turbine egress conditions.

6.3. John Day Dam

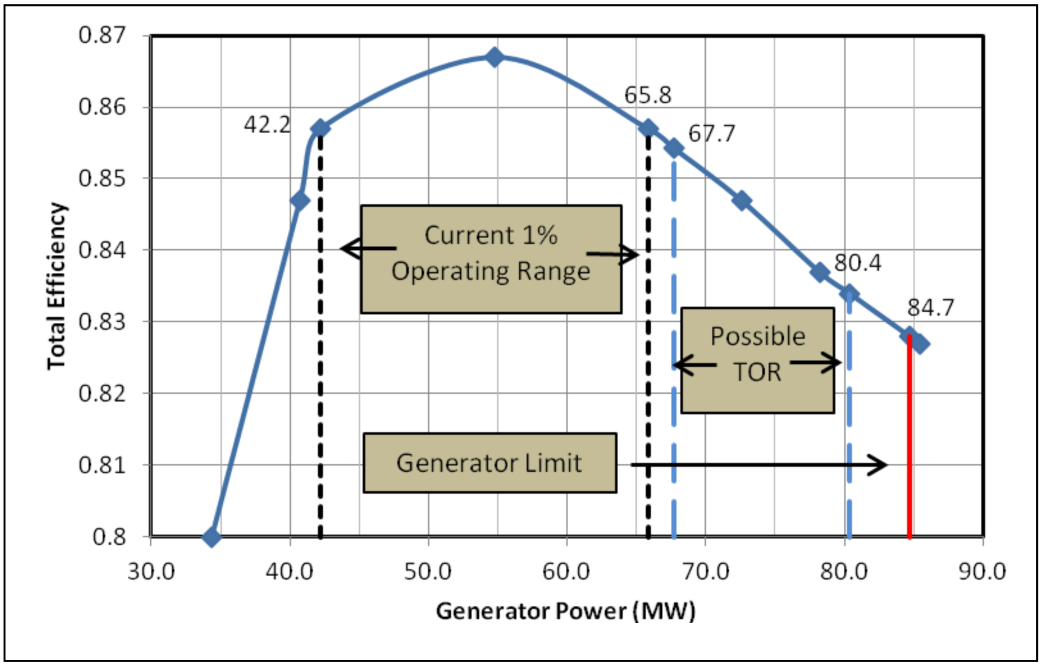
Turbine unit operation may have a significant effect on direct turbine mortality at John Day Dam. The recommended TOR is 15.0 to 18.8 kcfs at approximately 100 feet of head. This TOR is consistent with the most open geometry and with bead strike data and draft tube conditions from the physical model, while accounting for the concerns with barotraumas and low nadir pressures at the higher operating discharges. The existing unit priority seems to give the best turbine egress given currently required spill. If possible with river discharges, operating at least 7 units reduces recirculation below the powerhouse. The TSP team proposes that a thorough turbine survival test be conducted at John Day to establish whether increased survival is seen under the TOR conditions. Indirect mortality (i.e., predation) is considered to be a large portion of total turbine mortality; therefore, any TST must make the project operating conditions as similar as possible while testing the different unit operating conditions.

6.4. McNary Dam

Turbine unit operation may have a significant effect on direct turbine mortality at McNary Dam. Based on available information, a TOR of 12.8 to 15.5 kcfs at 75 feet of head is being proposed for McNary Dam. Figure 22 translates this flow range to generator power and efficiency at 75 feet of head, since flow is a calculated value based on power and efficiency. The TOR may increase the descaling rate of fish diverted by the ESBS into the JBS. With diligent debris management, however, it is expected that the descaling rate should be kept at a minimum. While increased JBS injury is a concern, descaling does not necessarily result in mortality; therefore, the potential benefit in total turbine survival using the TOR of 12.8 to 15.5 kcfs at 75 feet of head is worth exploring.

While the proposed TOR is supported by some field studies, the TSP team believes additional field verification is needed. Therefore, it is recommended that a comprehensive turbine survival test be conducted at McNary within and surrounding the proposed TOR of 12.8 to 15.5 kcfs at 75 feet of head (see Section 6.2). If testing determines that turbine operation at McNary within the TOR can improve the direct survival of turbine-passed fish, the TOR would need to be defined at multiple heads. It is possible to define an operating range at the full range of heads based on efficiency, wicket gate angle, blade angle, discharge or some combination of these variables. The difference in survival shown by testing at the edge of the range, as well as practical operational considerations, will need to be taken into consideration when defining the target fish passage unit operations over a range of heads.

Figure 22. McNary Turbines Proposed Target Operating Range at 75 feet of Head



The next step would look at methods for improving indirect turbine survival. Based on the use of the McNary physical model, the current turbine unit priority (unit 1, then units 14-2), with units operating at the TOR, would improve powerhouse egress. Reductions in required spill would benefit powerhouse egress without harming project egress. Spill reductions are considered unlikely at this time but could be considered as part of the Configuration Operation Plan process. Field velocity measurements and/or biological studies could verify whether further improvements to powerhouse egress and indirect turbine mortality could be made. Finally, field biological studies could be undertaken to look at total turbine survival (direct + indirect).

6.5. ICE HARBOR DAM

For Units 1-3, a fully developed target operating range is not planned to be developed since these units will likely be replaced by 2017 with new units that are intended to improve fish passage. Turbines units 4- 6 are of a different design and there is not enough information at this time to develop a target operating range.

6.6. LOWER MONUMENTAL DAM

Turbine units 1-3 are the same design as John Day and the information from John Day is considered applicable to Lower Monumental. Based on this, the recommended TOR for Lower Monumental turbine units 1-3 is 15.0 to 18.8 kcfs. There is very little information for Lower Monumental units 4-6 for improved fish passage survival. Based on geometry information, a discharge between peak and upper 1% to even higher is recommended; based on unknown pressure mortality, this range should be limited to the upper 1%. The majority of operations within the ±1% of peak efficiency criteria for units 4-6 occur between peak efficiency and the upper 1%. Thus, turbine units 4-6, by default, operate in a preferred manner.

The powerhouse unit priority at Lower Monumental should be adjusted to pass fish through units near the spillway to leverage on the egress conditions created by spill. Unit 1 and possibly unit 2 will continue to be prioritized for adult fish attraction water, but may not be the best for juvenile salmon moving downstream due to the strong reverse eddy associated with that region at the dam. Therefore, a single unit could be used for adult attraction, while subsequent units are prioritized toward the center of the dam. Physical model operation could be used to further justify this change in unit priority.

6.7. LITTLE GOOSE DAM

There is not enough information at this time to recommend a different turbine unit operating range than the existing 1% requirements. Target project operations have also not been fully investigated and therefore there are no recommended changes to project operations at this time.

6.8. LOWER GRANITE DAM

There is not enough information at this time to recommend a different turbine unit operating range than the existing 1% requirements. Target project operations have also not been fully investigated and therefore there are no recommended changes to project operations at this time.

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PHASE II PROJECT APPENDIX

TURBINE OPTIMIZATION FOR PASSAGE OF JUVENILE SALMON AT BONNEVILLE DAM FIRST POWERHOUSE

Bonneville Lock and Dam located on the Columbia River near Umatilla, Oregon.

PREPARED BY
U.S. ARMY CORPS OF ENGINEERS
TURBINE SURVIVAL PROGRAM

JUNE 2013 REVISION 0

EXECUTIVE SUMMARY

This report identifies operating conditions for turbine units in the first powerhouse at Bonneville Dam (B1) on the Columbia River, where turbine fish passage survival is expected to be higher based on using the tools developed by the Turbine Survival Program (TSP). The 2004 TSP Phase I Report indentified that operating conditions of large Kaplan turbine units appear to have a significant effect on the survival of fish passing through them. This appendix involves identifying target operating range (TOR) and the targets for project operations.

To reduce strike injuries, the physical geometry of B1 turbine components was examined. As flow increased, wicket gates opened up and blade angles steepen. The wicket gates achieve the best alignment with the stay vanes at 40.5 degrees open, which corresponds to about 11.0 thousand cubic feet per second (kcfs) at 60 feet of head. Good alignment of the stay vanes and wicket gates are maintained within a wider range of 37 to 43 degrees open, which corresponds to 9.3 kcfs to 13.4 kcfs at 60 feet of head.

Additional information to reduce strike frequency, exposure to shear, and turbulent environments was provided by a physical model of a turbine unit. High-speed video of neutrally buoyant beads was taken to assess the strike frequency and severity. The majority of the bead data was taken at 7.53 kcfs, 9.77 kcfs, and 11.47 kcfs at 55 feet of head. The percentage of beads experiencing severe contacts or direction changes within the runner decreased significantly from 7.53 kcfs to 9.77 kcfs, and decreased further at the 11.47 kcfs operating condition. There was also benefit for increased discharge for reducing the percentage of bead that passed through the gap between the stay vanes and wicket gates. The bead data also indicated that there was a significant reduction in severe direction change in the draft tube elbow between the 7.53 kcfs and the 9.77 kcfs operating conditions. The high percentage of severe direction changes at the peak operating point (7.53 kcfs) qualitatively corresponded to a vortex coming off the runner that was significantly worse at the lower 1% operating condition (approximately 7.27 kcfs). While a quantitative bead assessment was also not performed for the generator limit (approximately 13.25 kcfs), the qualitative assessment was that this operating condition appeared to be as good as or better than the 11.47 kcfs operating condition.

Velocity data was taken at transects near the runner and draft tube exit. The draft tube for B1 turbines has a vertical splitter wall that divides the draft tube into two equal sized barrels (designated A and C) and a horizontal splitter wall splits both of these barrels. Barrel C has high level of turbulence at the 7.53 kcfs discharge which decreases with increasing flow rate. The increased turbulence could cause fish disorientation. While direct injury or mortality may not result, fish disorientation has the potential to increase vulnerability to predation.

Injury and mortality (barotrauma) can also occur to fish passing through turbines due to exposure to low nadir pressures. An assessment of barotrauma mortality risk for B1 turbines was made using relationships established using laboratory testing and field pressure data using sensor fish. Using existing data and generated equations, a calculated barotrauma mortality rate without internal tags was found to be just over 1% for 6.2 kcfs, 6.9 kcfs, and 10.4 kcfs and approximately 4% for 11.7 kcfs. However, these values were calculated using very few sensor fish and additional data is needed to confirm the potential increased barotrauma risk at the highest discharges.

Although a number of existing biological studies have estimated fish passage survival at B1, very few have looked at fish passage survival as related to turbine operations. In 2000, balloon-tagged fish were introduced into the new minimum gap runner in unit 6 and a older runner in unit 5 (since replaced) at four different operating conditions and three different passage areas of the runner (tip, mid and hub). While there was not a statistical difference in fish passage survival for different operating conditions, the lowest mortality rate of 2.7% occurred at approximately 10.4 kcfs.

Based on available information, a TOR of 8.5 kcfs to 11.5 kcfs at 55 feet of head is being proposed for B1 turbine units. While the proposed TOR is supported by some field studies, the TSP team recommends that a comprehensive turbine survival test be conducted at B1 to verify that these operating conditions do improve turbine fish passage survival. Indirect mortality (i.e., predation) is considered to be a large portion of total turbine mortality. However, based on the physical model, there should be some improvement to egress with the increased unit discharge of the TOR. It is expected that the largest reduction in indirect mortality would be associated with increased B1 discharge due to improved egress and reduced predation habitat. However, due to the unique nature of the Bonneville tailrace, there are no changes recommended for unit priority or spill pattern. Operation of the B1 turbines permanently within the proposed TOR will require the TOR to be defined over a full range of operating heads, which is not fully defined at this time.

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ACRONYMS AND ABBREVIATIONS

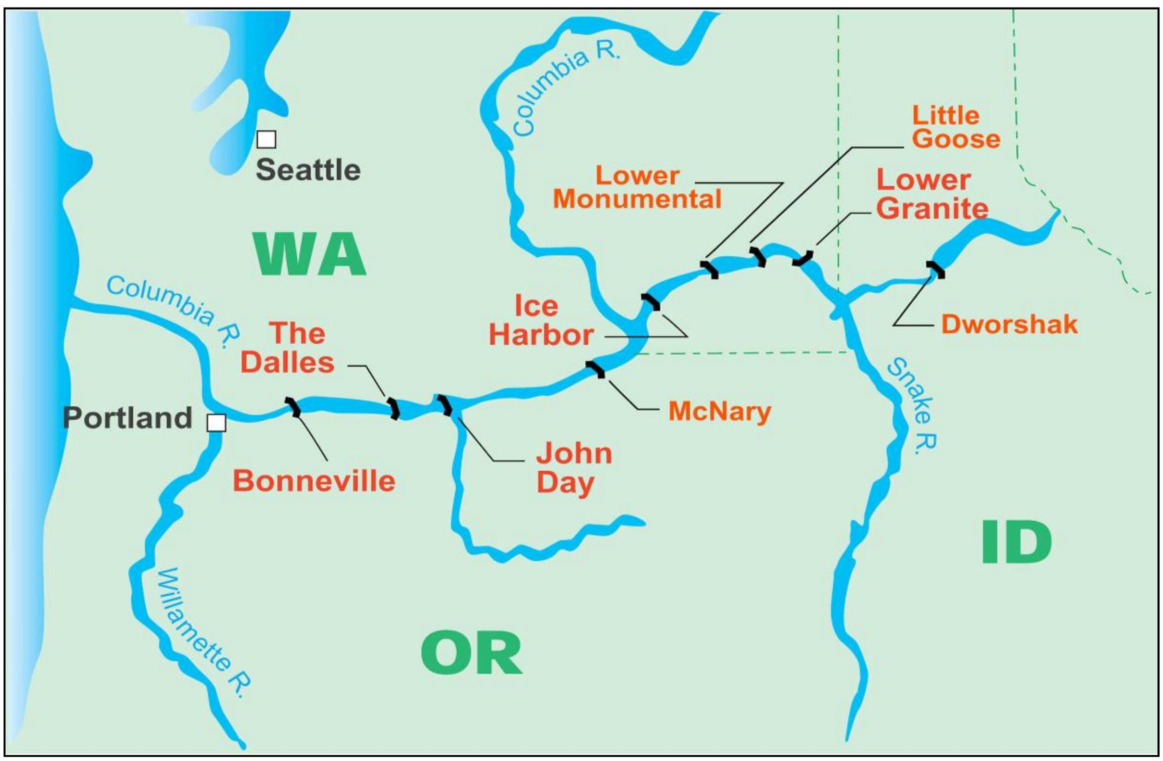
BiOp	Biological Opinion
CFD	computational fluid dynamics
CRFM	Columbia River Fish Mitigation
ERDC	Engineering Research and Development Center
FPP	Fish Passage Plan
hp	horsepower
kcfs	thousand cubic feet per second
ft	feet (foot)
LDV	Laser Doppler Velocimeter
MGR	minimum gap runners
msl	mean sea level
MW	megawatt(s)
NOAA	National Oceanic and Atmospheric Administration
PNNL	Pacific Northwest National Laboratory
psia	pounds per square inch absolute
RM	river mile
TOR	target operating range
TSP	Turbine Survival Program
TST	turbine survival testing
USACE	U.S. Army Corps of Engineers
WGA	wicket gate angle

1. INTRODUCTION

The Turbine Survival Program (TSP) is part of the U.S. Army Corps of Engineers' (USACE) multi-faceted Columbia River Fish Mitigation (CRFM) program. The first phase of the TSP involved developing tools to evaluate the physical conditions fish experience as they pass through large Kaplan turbines typical of USACE projects. The TSP Phase I Report (TSP 2004) indentified that the operating conditions of the large Kaplan turbines appear to have a significant effect on survival of fish passing through them. Phase II of the TSP involves turbine survival testing (or biological index testing) at USACE facilities. This report identifies operating conditions for turbines at Bonneville first powerhouse where fish passage survival is expected to be higher based on the utilization of the tools developed by the TSP program.

Bonneville Dam is the first hydroelectric project from the mouth of the Columbia River located at river mile (RM) 146 (Figure 1). It is the first dam in the Columbia River and influences anadromous fish migrations for all the Columbia basin fish except the Willamette basin fish.

Figure 1. Location of Bonneville Lock and Dam



Bonneville Dam has two powerhouses with the first completed in 1938 and the second added in 1981. The first powerhouse (B1) has 10 units and unlike the second powerhouse (B2), there are no fish bypass screens installed in front of the units. The recent project survival studies included estimates for B1 turbine passage (Ploskey et al. 2011, Ploskey 2012, Skalski et al. 2012). The 2010 study was a single release estimate that also included 81 kilometers of river below the dam. The 2011 study was a virtual paired release study that assessed survival from the face of the dam to the first array a few kilometers below the dam. The 2010 and 2011 B1 turbine survival point estimates for spring Chinook were 98.7%

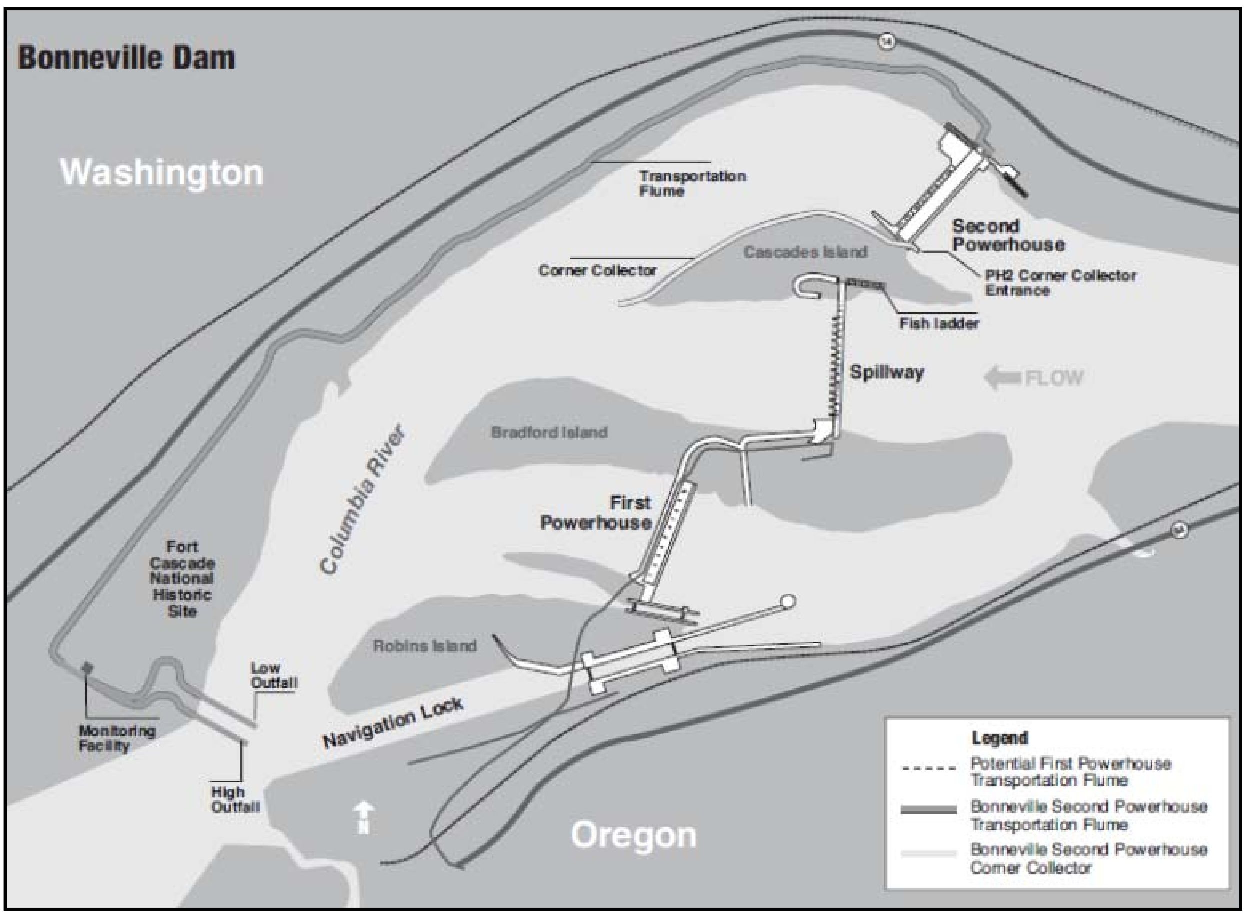
and 96.8%, respectively. The 2010 and 2011 survival point estimates for steelhead were 90.0% and 93.6%, respectively. These studies were telemetry studies that may have a negative bias associated with the surgical implantation of tags (Carlson et al. 2010).

While the recent survival probabilities indicate higher survivals than many other dams (especially considering possible tag bias), the survival probabilities still indicate room for improvement to turbine passage survival. Results of multiple field and laboratory studies indicate that improved fish survival through the B1 turbines may be achieved by changing their operating conditions. The studies included balloon tag, sensor fish pressure, laboratory pressure investigations, and physical hydraulic model investigations. Results from the studies indicate modifying the current operating zone, defined as being within the 1% of peak efficiency, may improve fish passage survival. This report summarizes results from various studies and presents information to support a recommendation to conduct a field test at Bonneville 1st powerhouse for verification of an improved target operating range (TOR) for safer fish passage.

1.1. Project Description

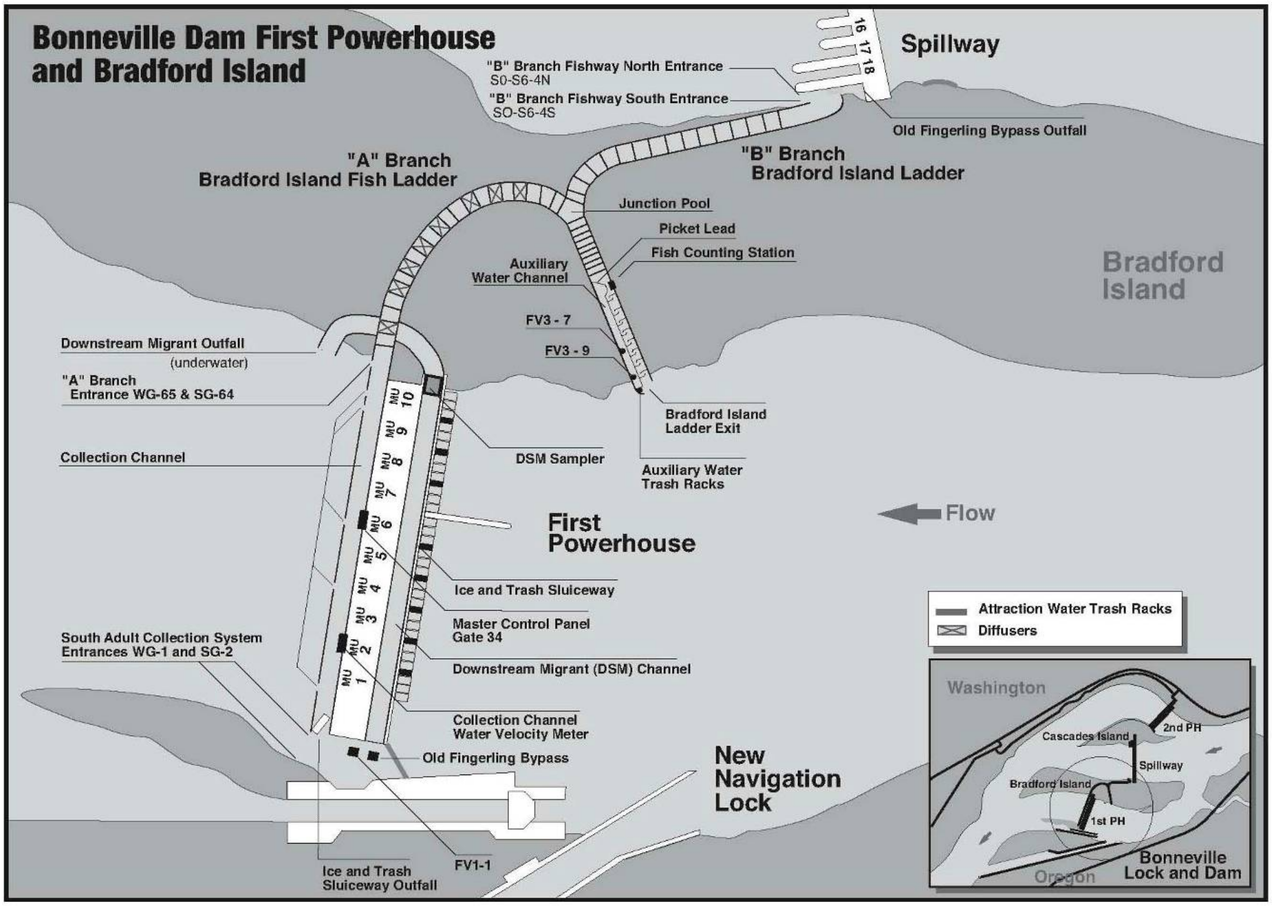
As shown in Figure 2, Bonneville Dam has two powerhouses, a spillway, and a navigation lock that are separated by islands.

Figure 2. Diagram of Bonneville Dam



The first powerhouse (B1) is located near the south shore, is 1,027-feet long, and contains 10 S. Morgan Smith Kaplan turbines with a total generating capacity of 680 megawatts (MW; Figure 3). The B1 turbines are minimum gap runners that were installed from 1998 to 2010 to replace the original runners for the powerhouse (installed in 1938). The current turbine units are 280-inch diameter runners were designed to operate at 75 revolutions per minute. Flows into the turbines are regulated by 20 wicket gates that are accompanied by 17 stay vanes.

Figure 3. Diagram of Bonneville First Powerhouse and Bradford Island Fish Ladder



1.2. PROJECT OPERATIONS

1.2.1. General Project Operations

Bonneville Dam is a run-of-river project. It has no flood control storage, no irrigation storage, and only limited short-term power-peaking functions. Therefore, the forebay pool level is relatively stable, with small daily fluctuations occurring normally from power peaking. However, it is the most downstream dam on the Columbia River and is not influenced by the backwater of another dam, therefore the tailwater elevation can vary significantly with discharge and has some influence by tidal variation.

1.2.2. Turbine Operations

The B1 turbines are operated within 1% of the best efficiency in accordance with the Fish Passage Plan (FPP) developed by the USACE Northwestern Division (USACE 2012), which implements requirements of the National Oceanic and Atmospheric Administration (NOAA) Fisheries Biological Opinion (BiOp; 2000, 2004, 2008). However there have been some efforts to modify this range for B1 turbines and the FPP is updated annually. The approach of restricting turbine operations was formalized in the 2000 BiOp, which requires turbine operations be limited to ± 1% of best operating efficiency. The basis for this rule resulted from research reported by Bell (1981) and Eicher Associates (1987).

A review of turbine survival study results and the 1% operating range was completed by Bickford and Skalski (2000). It was found that highest direct survival did not occur at the best operating efficiency and that direct passage survival did tend to exhibit a curvilinear relationship with increasing turbine discharge. Direct turbine passage survival tests were normally limited to turbine operations within ± 1% of best operating range, highest survival was often found to occur within the 1% operating range, but not always; thus, it cannot be concluded that highest direct turbine survival occurs within 1% of best operating efficiency. Highest direct turbine survival for some turbine units may well occur at untested turbine operations outside the 1% operating range.

The peak efficiency and 1% operating range are dependent on both the head on the turbine and the flow through the turbine. For current B1 turbines with minimum gap runners (MGR), the efficiency versus flow curves are shown in Figure 4 with no screens installed. The 1% operating range is defined by a ±1% drop from peak efficiency at the head at which the turbine is operated.

Figure 4. B1 Turbine Efficiency Curves with no screens Installed

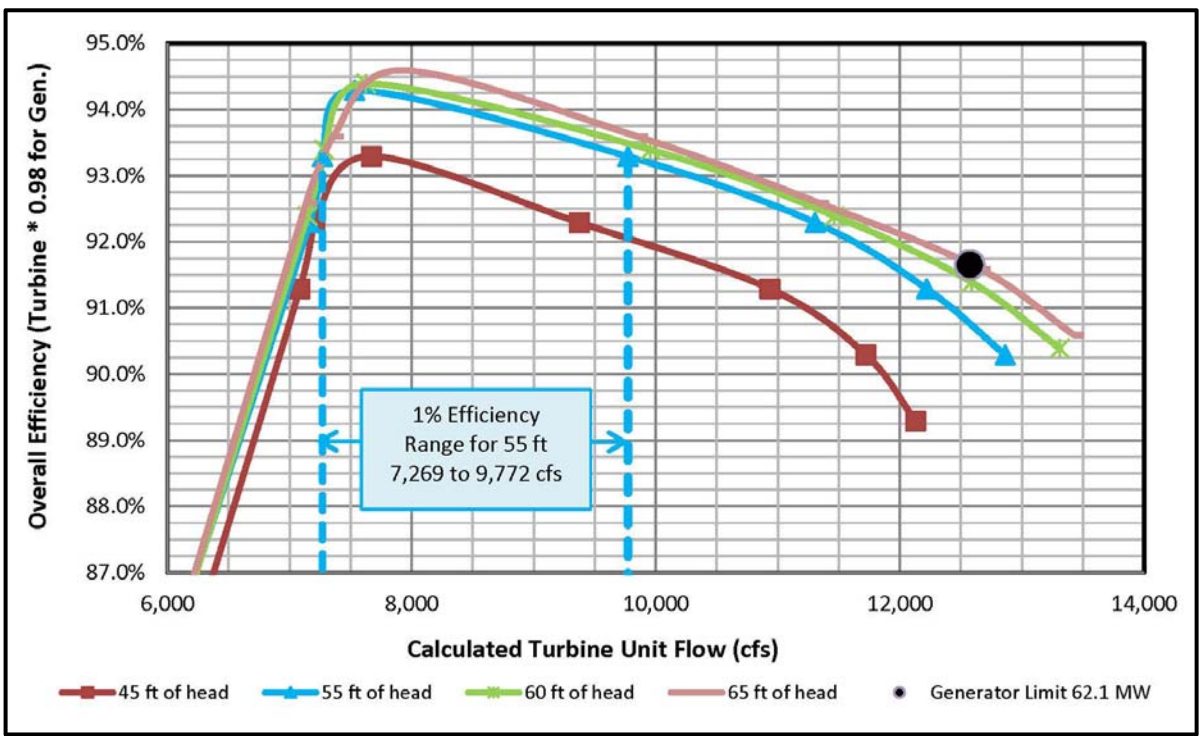


Table 1 shows the operating range and average for multiple turbine operating parameters from 1974 through 2007. Unfortunately, the data to determine where the turbine units are operated on average is not easily available for B1 turbines. Table 1 does shown the large operating head range caused by a tailwater that is influenced significantly by project and powerhouse discharge, as well as some influence of tidal variation. With such a large potential head range, it is important to determine the range of head over which the project normally operates. Based on an assessment of the period April 1 to August 31 for the years 2009 to 2011, 50% of the time the project operated between 50 and 60 feet of head and 80% of the time operated between 45 and 65 feet of head. In general, the fish season average is between 55 and 60 feet of head with high project discharge (spring and summer of high water years) causing closer to 55 feet and low project discharge (summer and spring of low water years) causing closer to 60 feet over slightly higher. The cross section of a B1 turbine unit is shown in Figure 5.

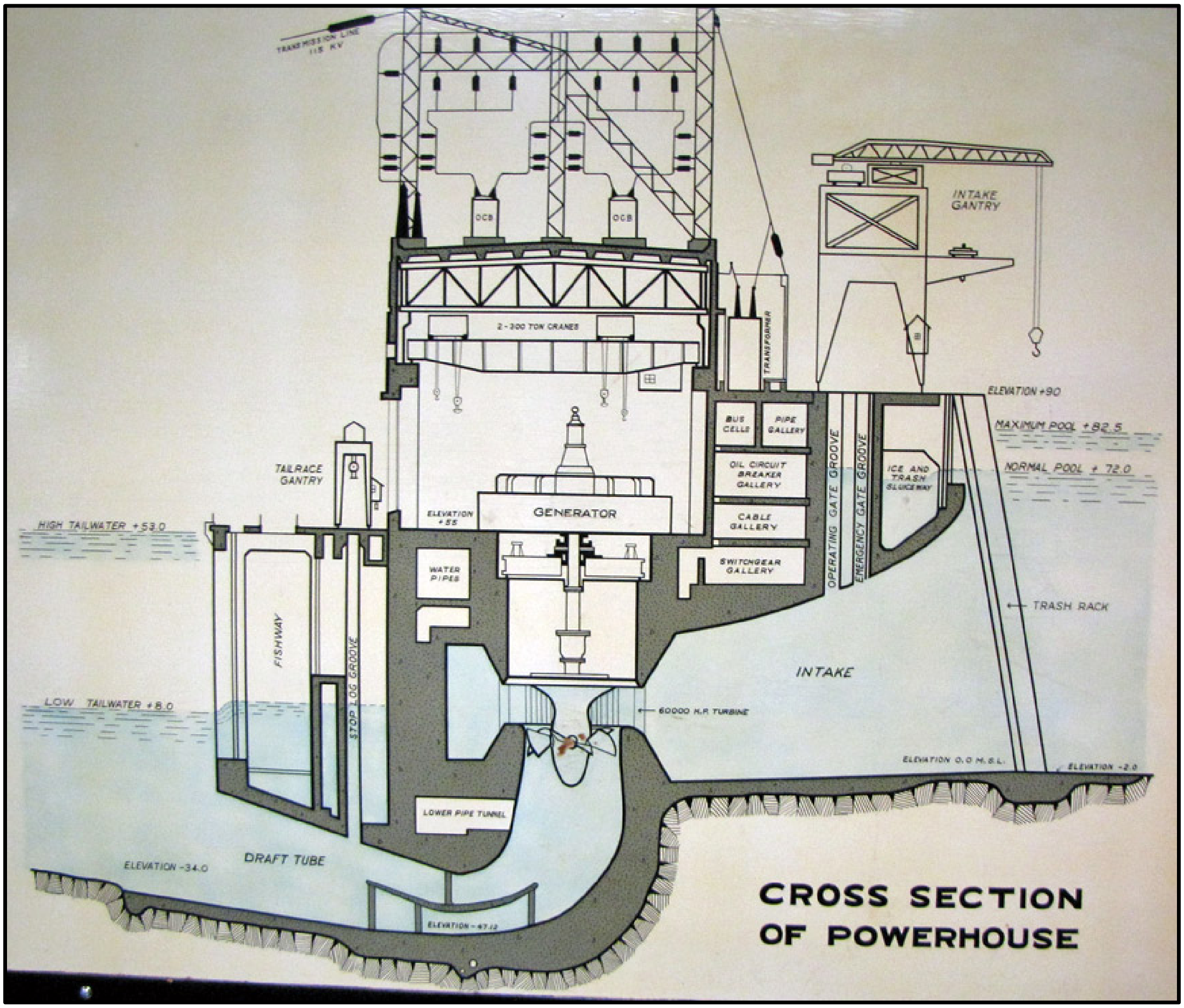
Table 1. Fish Season Operations for B1 (April 1 through October 31)

Parameter	Average 1974-2007	Operating Range	
		Low	High
Forebay Elevation (feet msl)	74.2	71.5 [b]	76.5 [b]
Tailwater Elevation (feet msl)	15.1	7 [b]	36.9 [b]
Head (feet)	59.1	34.6	69.5
Total PH Flow (B1 & B2) (kcfs)	107.7	35	250
Turbine Unit Flow (kcfs)	Not Avail.	7.2 [a]	10 [a]
Turbine Unit Power (MW)	Not Avail.	18 [a]	50.6 [a]
Turbine Units Operating	8 [c]	3 [c]	18 [c]

[a] Based on 1% efficiency range over the head range with no screens installed.
[b] Based on project operating range defined in Water Control Manual.
[c] Based on when the powerhouse is operating. Certain times of the year only B2 operates.
msl = mean sea level; kcfs = thousand cubic feet per second

The FPP specifies turbine unit operating priority in the following order: 1, 10, 3, 6, 2, 4, 5, 8, 7, and 9. The high unit priority of the edge units (1 and 10) is intended to improve adult fish attraction to the Bradford Island and south shore fish ladders. The remainder of the unit priority is intended to reduce recirculation in the tailrace and provide good egress for B1 passed juvenile fish. The FPP also requires spill during much of the fish passage season. However, due to the separation by islands, there is minimal influence of the spill on powerhouse tailrace egress conditions other than some influence on tailwater elevation. Details of the operational requirements can be found in the current FPP (USACE 2012), which is updated annually.

Figure 5. B1 Turbine Cross Section



2. DEFINE TARGET OPERATING RANGE FOR TURBINES

There are many different pieces of information that help to estimate the TOR for fish passage survival through B1 turbines. First, the physical geometry of different operating conditions will be considered. Second, physical modeling data of different operating conditions guided by the physical geometry of the wicket gate and blade angles will be discussed. Pressure information for B1 turbines is limited to a small number of sensor fish releases. However, this in conjunction with laboratory studies can give an initial indication of the potential for pressure injuries at different operating conditions. Additionally, the turbine specific biological field studies performed to date will be discussed. Finally, this information will be tied together to provide an estimate of a TOR for B1 turbines.

2.1. PHYSICAL GEOMETRY CONSIDERATIONS

As discussed in Section 3.2 of the Phase II Main Report, there is potential to reduce injury and direct mortality of migrating salmon passing through turbines by operating at a more open geometry. Wittinger and others (2010) suggested that a good geometric relationship is often not found within the existing 1% operating limits. The alignment of wicket gates and stay vanes were analyzed for "on-cam" operation at 60 feet of head, which is close to average head shown in Table 1.

At the lower 1% of the efficiency range, a significant misalignment and gap exists that would likely cause increased injury for fish passing through turbines (Figure 6). At the upper 1% operating condition, the alignment of the wicket gates and stay vanes are improved over the lower 1% operating condition, but are still not in alignment (Figure 7). At the generator limit at 60 feet of head (Figure 8), the wicket gates go slightly past the best geometrical alignment with stay vanes. The best alignment of wicket gates and stay vanes occurs at a wicket gate angle (WGA) between the upper 1% and generator limit operating conditions at approximately 40.5 degrees.

While best alignment is ideal, the goal of minimizing the gap between the wicket gates and stay vanes while keeping the wicket gate within the hydraulic shadow of the stay vane is expected to occur within the broader range of WGA at 37 to 43 degrees. At 60 feet of head, this is from a point between peak and upper 1% up to generator limit. While this incorporates some of the 1% operating range, it also extends well above the current operating range. Operating conditions at 60 feet of head (for on-cam operation) over the target geometry range and best geometry for wicket gate alignment are presented in Table 2. Due to the relatively large variation in head at B1, it is expected that there could be variation in the turbine unit discharges associated with the best wicket gate geometry range.

Table 2. Best Wicket Gate Geometry for B1 at 60 feet of Head

Parameter	Best Geometry	Best Geometry Range	
		Lower	Upper
Wicket Gate Angle (WGA) – degrees open	40.5	37.0	43.0
Blade Angle – degrees open	28.6	24.0	31.0
Power – horsepower (hp)	69,500	59,500	82,500
Flow – kcfs	11.00	9.30	13.40
Efficiency – %	92.6	93.9	90.4

Note: Peak efficiency at 60 feet of head is 94.4%

Figure 6. B1 Turbine Wicket Gate and Stay Vane Alignment at Lower 1% Efficiency

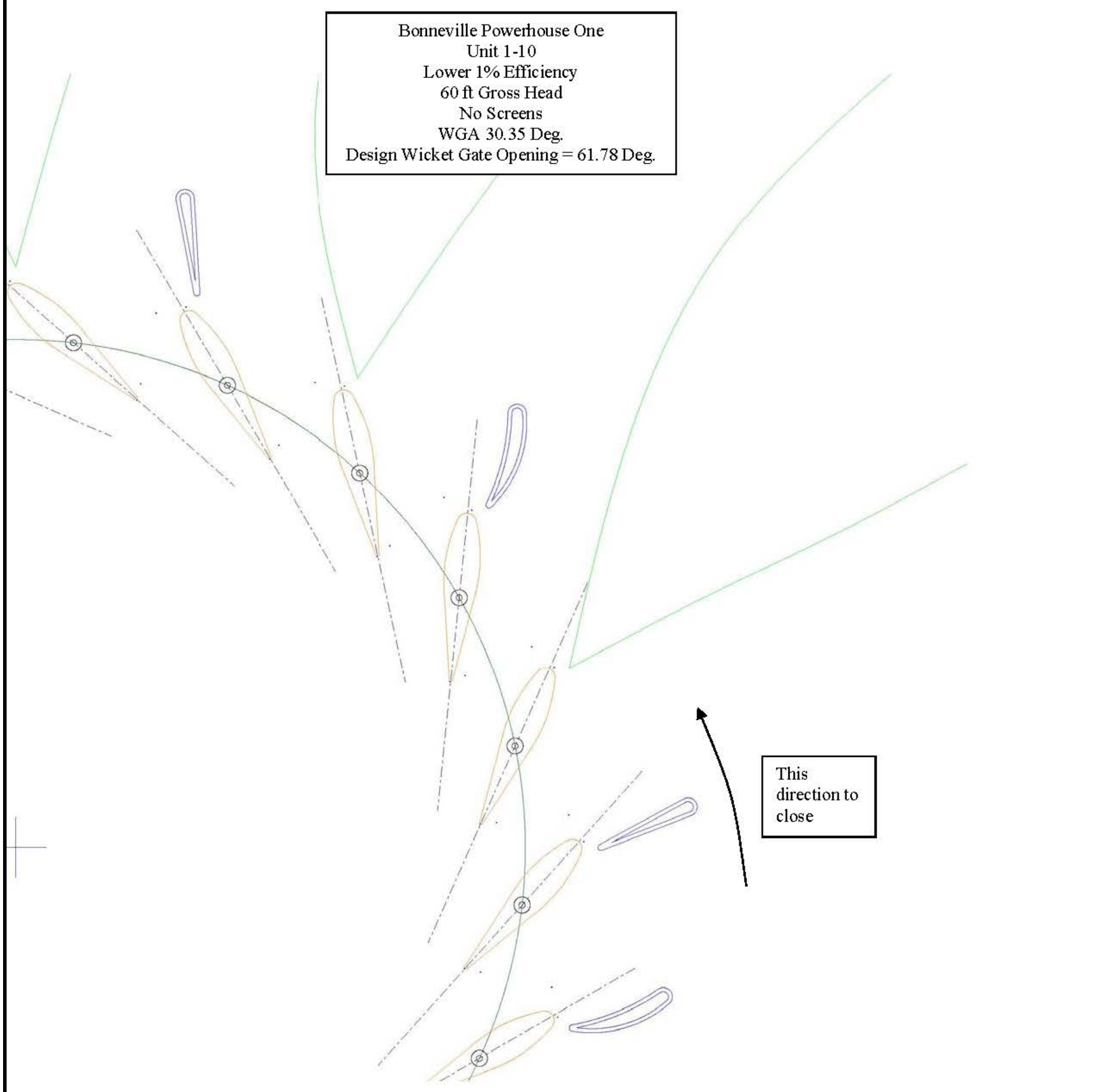


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Figure 7. B1 Turbine Wicket Gate and Stay Vane Alignment at Upper 1% Efficiency

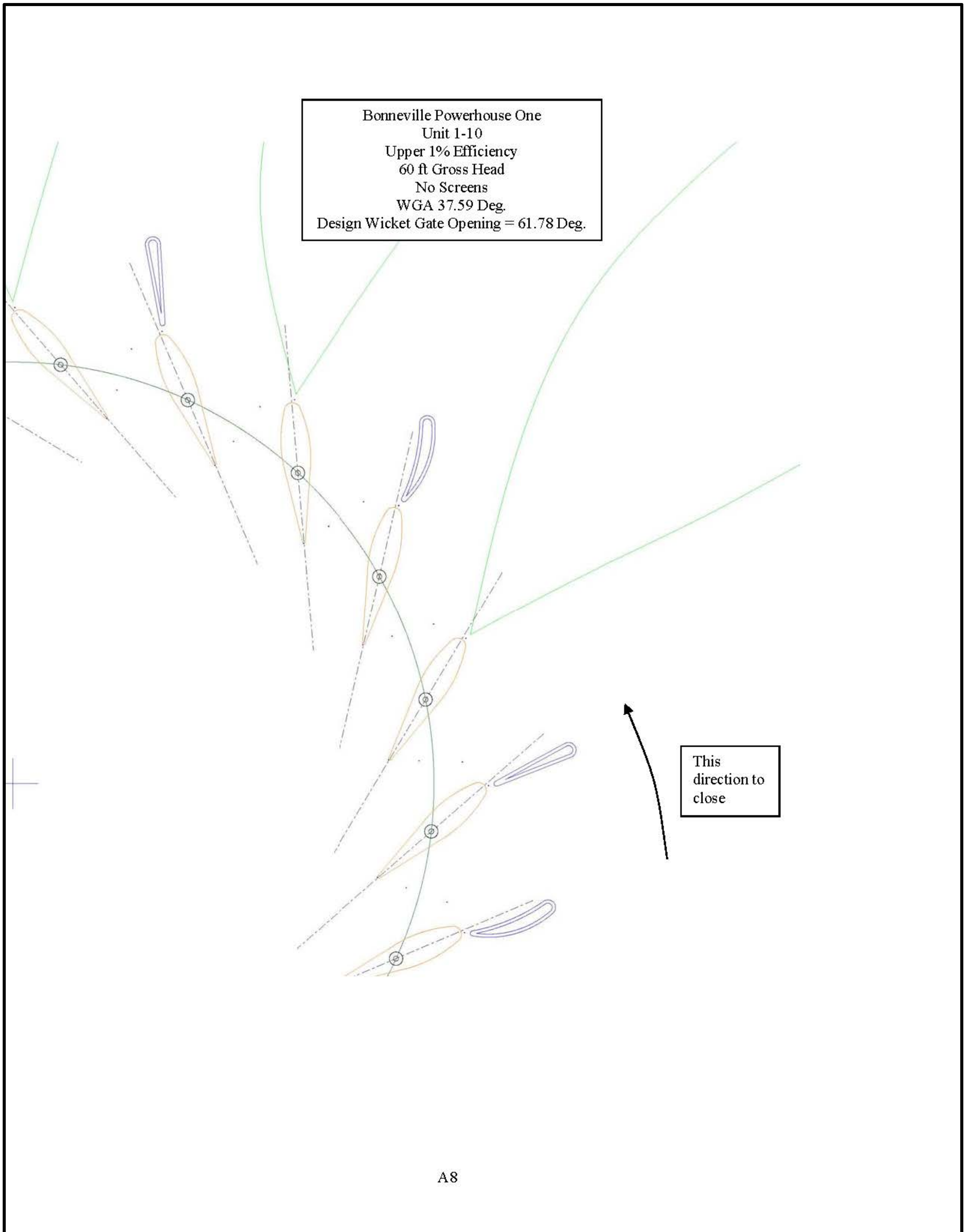
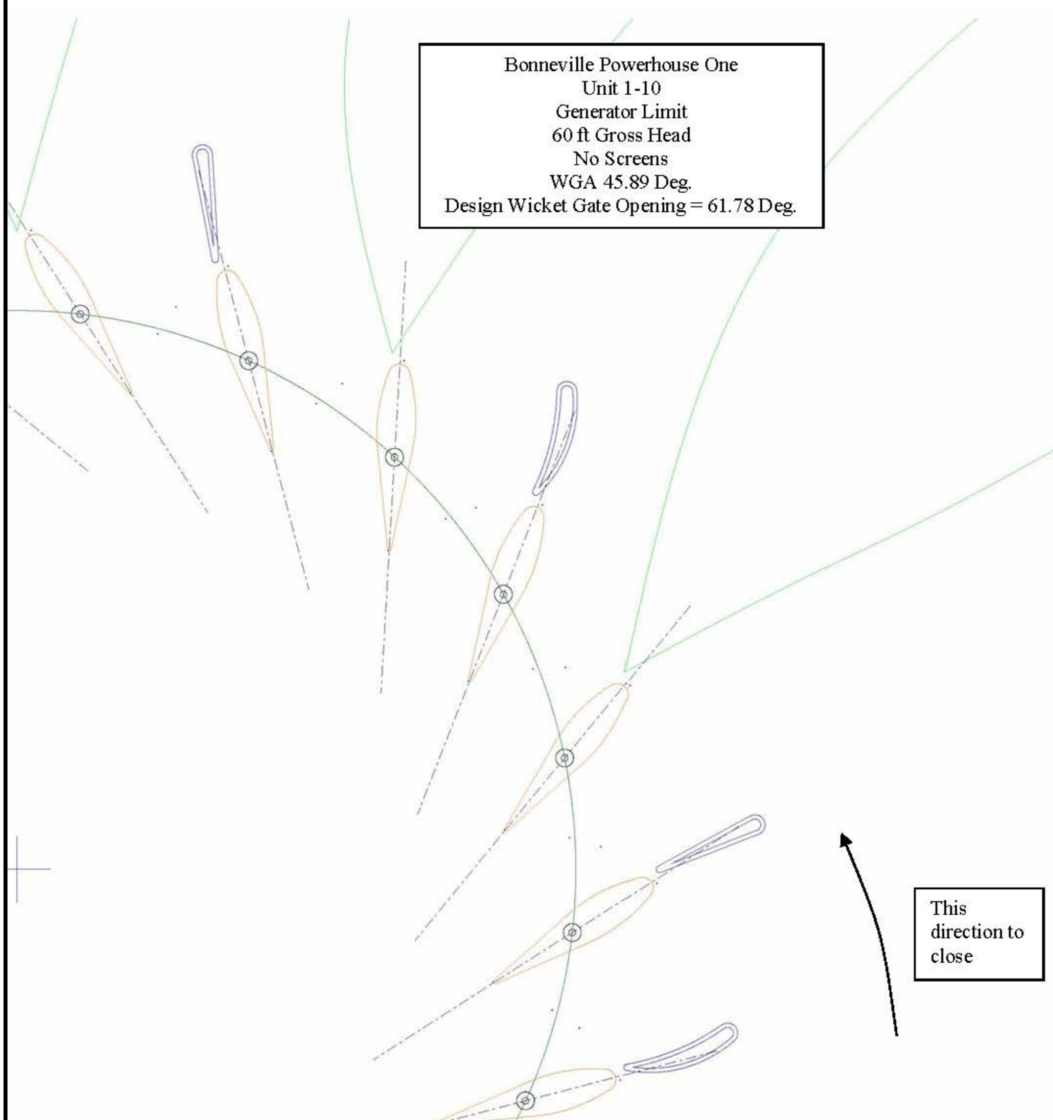


Figure 8. B1 Turbine Wicket Gate and Stay Vane Alignment at Generator Limit



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2.2. PHYSICAL OBSERVATIONAL MODEL INFORMATION

Construction of a physical observational model of forebay through tailrace for a single B1 turbine unit was completed in 2001 at Engineering Research and Development Center (ERDC) in Vicksburg, MS. The 1:25 Froude-based scale model (Figure 9) was used to evaluate the hydraulic condition within the turbine and the potential impact of variable turbine operations on fish. The model was partially funded by the U.S. Department of Energy and was used to determine release points for the balloon-tag study used to assess the fish passage survival through the new MGRs. The model replicates the approach to a single unit, all three intake bays, the scroll case, the distributor including the stay vanes and adjustable wicket gates, the six-bladed Kaplan turbine runner, the draft tube and enough downstream topography to establish uniform flow conditions. The evaluation included the release of dye into the turbine flow path to observe general flow patterns, extensive velocity measurements using a Laser Doppler Velocimeter (LDV) and high-speed imaging of neutrally buoyant beads released into the flow path. Experiments were conducted in 2010 in support of the turbine survival program.

The model flow rate and runner speed were established using Froude similitude equations. The prototype flow rates investigated in detail were 7.53 thousand cubic feet per second (kcfs), 9.77 kcfs, and 11.47 kcfs. These flow rates in relation to the 1% efficiency range are peak, upper 1%, and approximately upper 2% from peak (best geometry; see Figure 4 for 1% efficiency range). These detailed investigations were conducted at 55 feet of head (prototype scale), which is close to an average spring head. Testing was performed without screens since that matches current field conditions. In addition, qualitative observations were made at lower 1% (7.27 kcfs) and generator limit (13.25 kcfs) at 55 feet of head and peak (7.62 kcfs) and generator limit (12.21 kcfs) at 60 feet of head (approximately average summer head conditions).

Neutrally buoyant beads were introduced at various points within the intake. High-speed video was then used to determine potential shear and strike injury by observing indications of bead contacts and change in directions (those that did not follow the general flow direction). While assuming fish act as passive particles (similar to beads) during runner passage may be imperfect, this assumption may be reasonably valid for passage within the runner due to the high velocities. Release points were selected that corresponded to passage at the runner hub, mid-blade, and the runner blade tip. Without adequate information on fish distribution due to a possible fish behavior effect, an equal distribution within the runner was assumed. Therefore, all the bead passage data was averaged together for information presented in this appendix. An ERDC technical report (still in draft) will give more detailed results and methodology for the physical modeling effort.

The first area that presented a chance of strike injury is in the vicinity of the stay vanes and wicket gates. High speed video was used to determine the percentage of beads that contacted the runner, or experienced severe changes in direction while passing either the stay vanes or wicket gates (Figure 10). In this figure severe contacts and direction changes are defined as the beads scoring a 1 or 2 for each metric. The percentage of beads with severe contacts and direction changes are relatively flat across the operating range. The stay vanes at turbines in B1 are one of the few stay vanes that are shaped, which may explain why little change exists across the operating range for contacts and direction changes. While the percentages are higher than desired, the velocities are much lower than runner passage and it is possible fish may be able to avoid some of the contacts.

Figure 9. B1 Turbine Physical Model

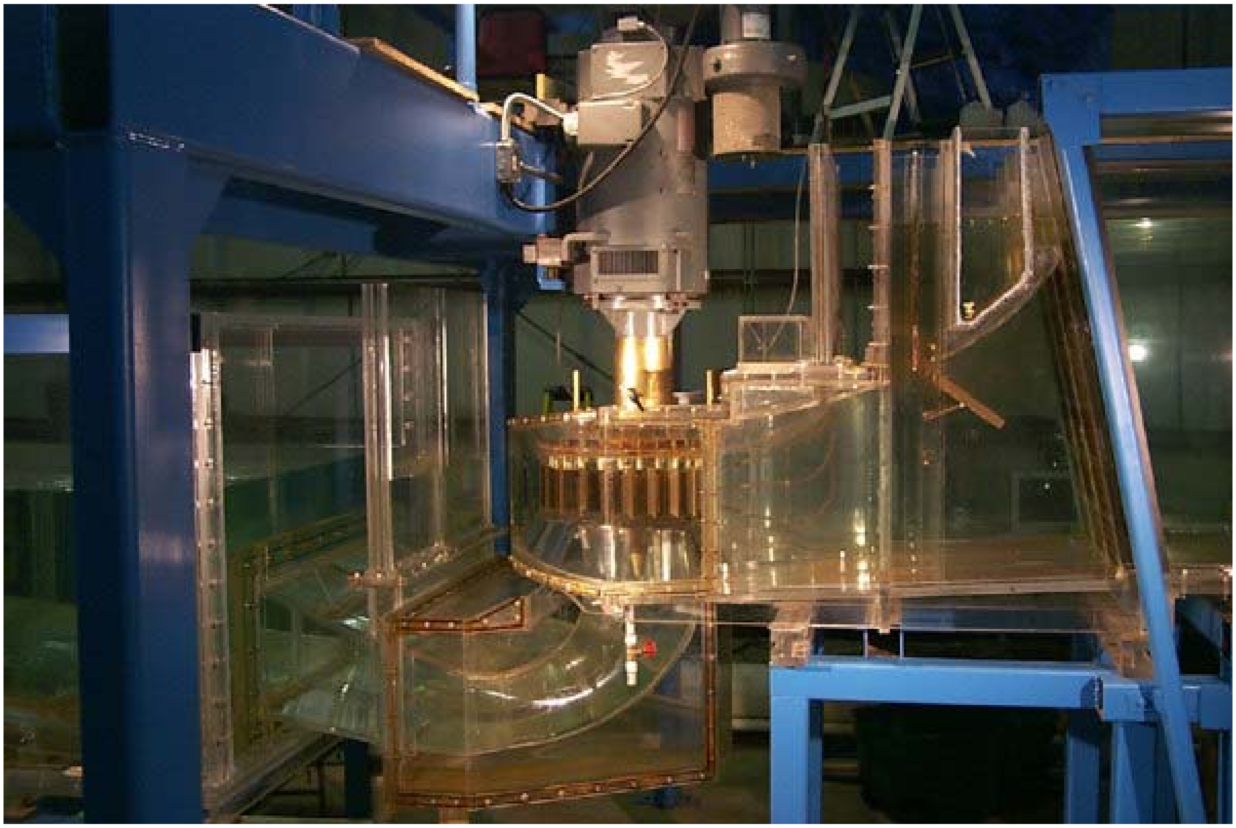
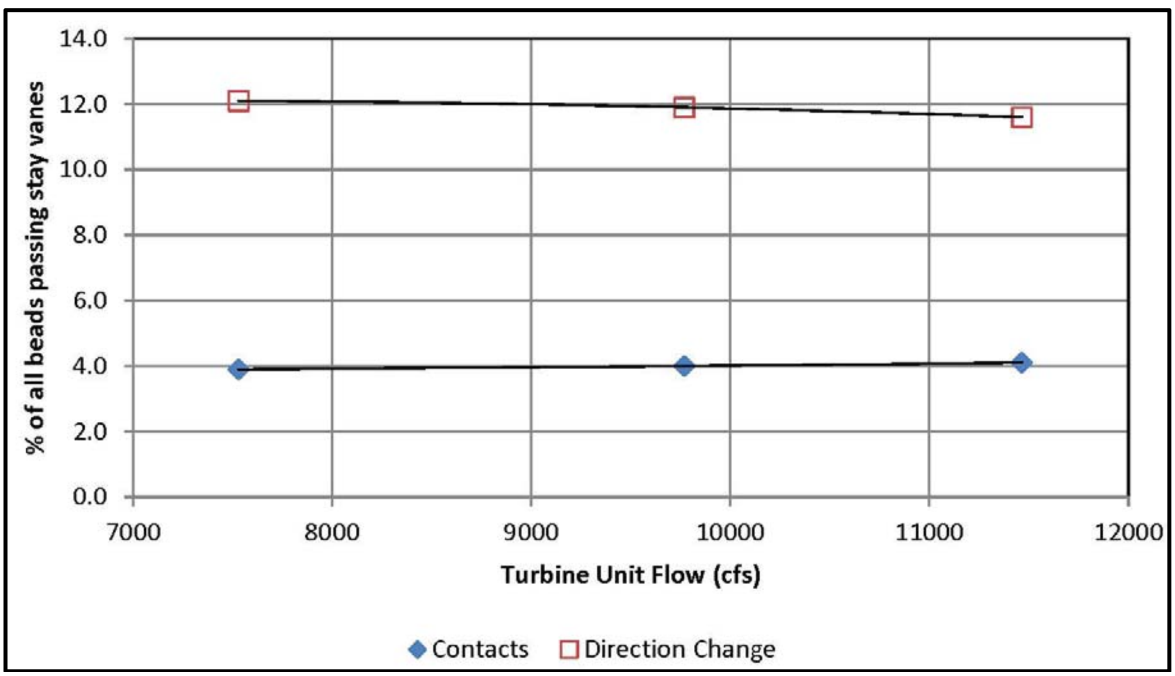
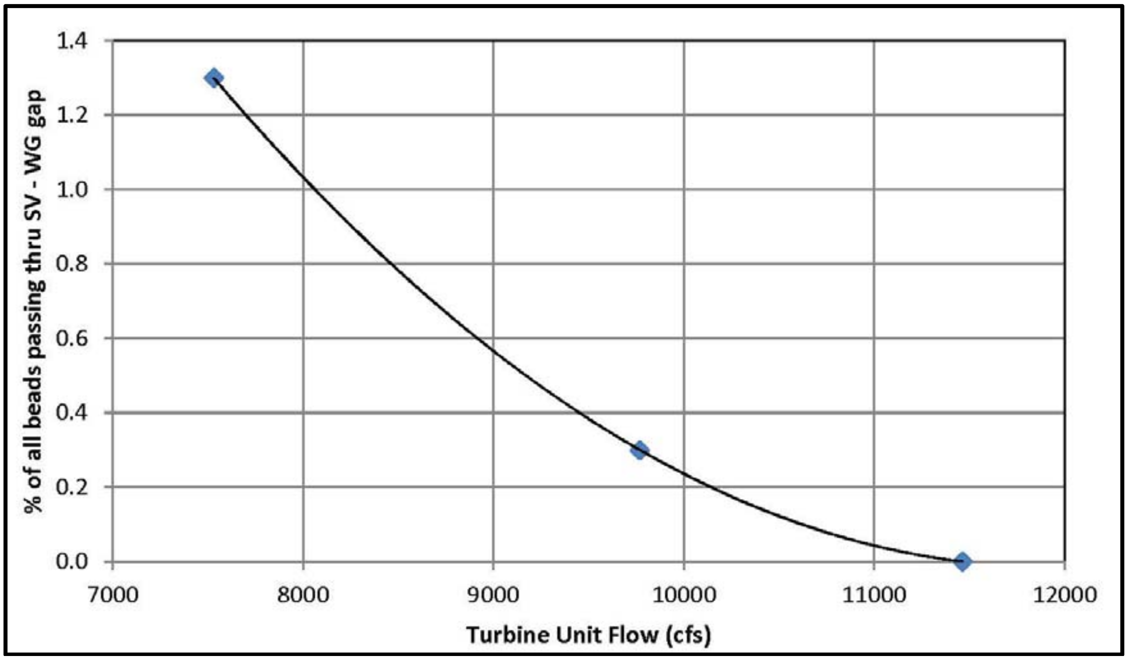


Figure 10. Severe Bead Contacts and Direction Changes at Stay Vane and Wicket Gates



The percentage of beads passing through the gap between the stay vanes and wicket gates was also analyzed using the high-speed video (Figure 11). This percentage does decrease with flow and is well correlated with the improved alignment at the best wicket gate geometry.

Figure 11. Beads Passing through Gap between Stay Vanes and Wicket Gates



The second area for potential mechanical injury to fish is passing the runner blades of the turbine. As with the stay vane region, analysis of beads contacting the runner can give an indication of potential injury. Severe contact with the runner significantly decreased with increasing flow rate through the runner (see Figure 12). Increasing flow rate corresponded to an increase in blade angle and increased open area within the runner environment. This trend was also supported by the percentage of beads that experience severe direction changes within the runner, where an increase in discharge improved passage conditions (see Figure 13). While quantitative investigations were not performed for the generator limit operating condition, based on qualitative observations and the trends in Figure 12 and Figure 13, it would be expected that bead contact and direction changes would be fairly low.

Figure 12. Severe Bead Contacts with Runner Blades

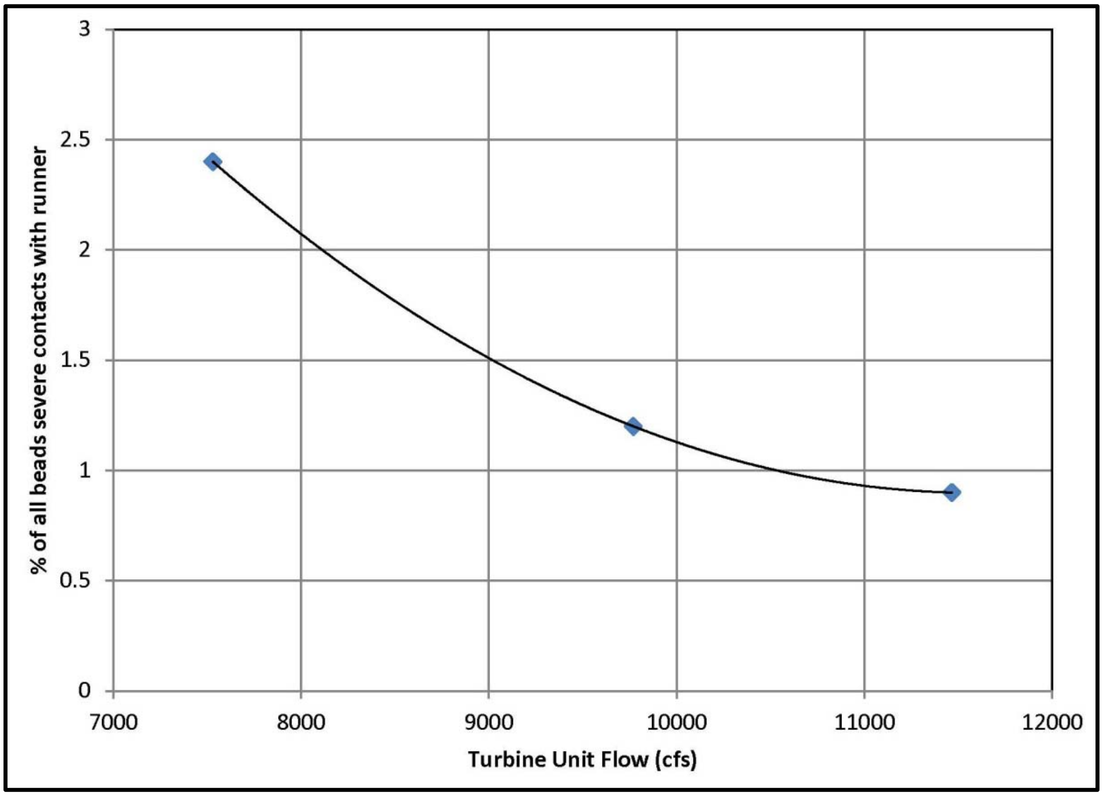
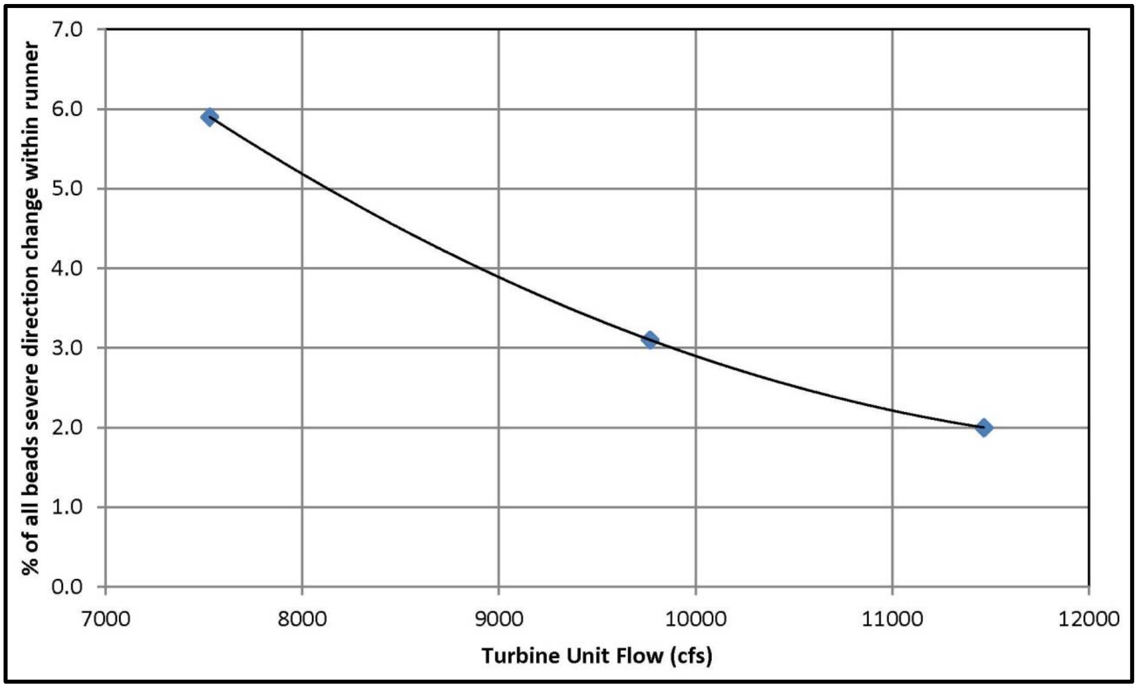
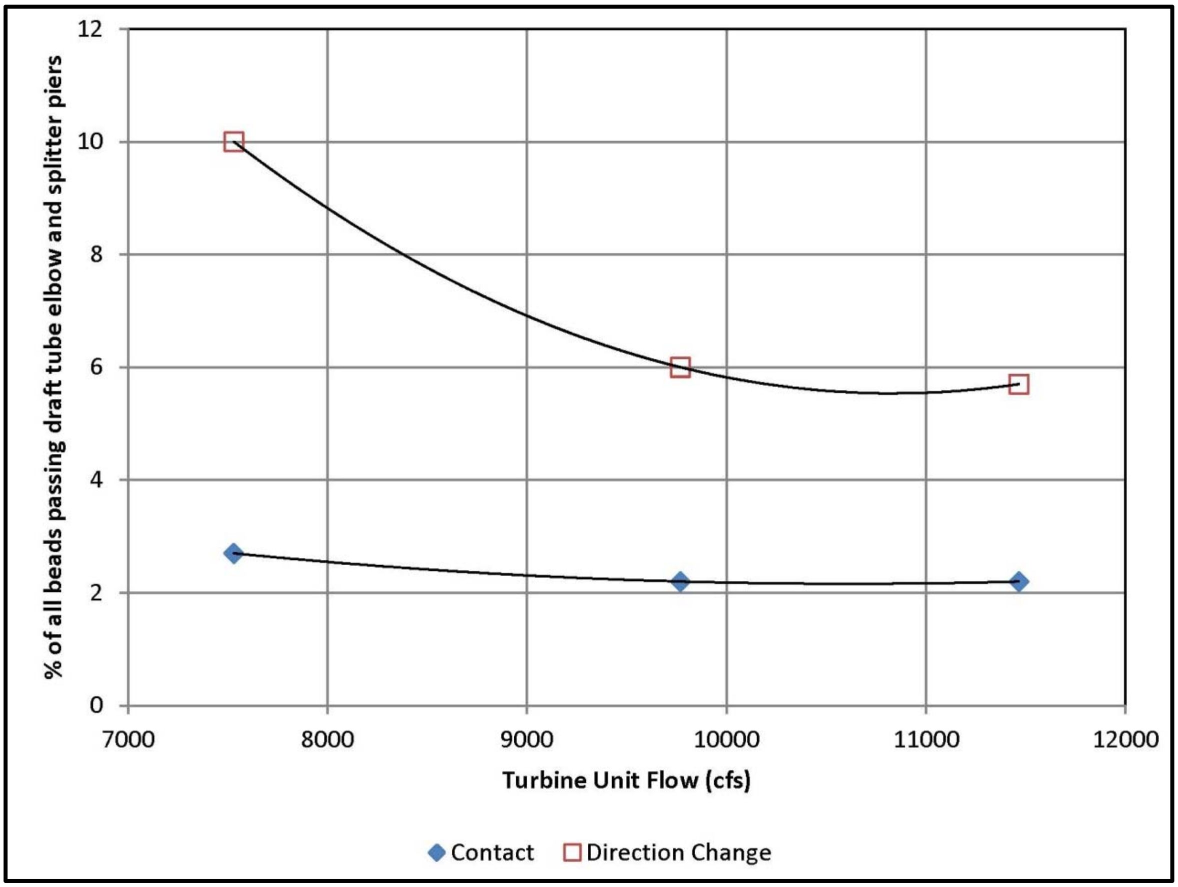


Figure 13. Severe Bead Change in Direction within Runner Blades



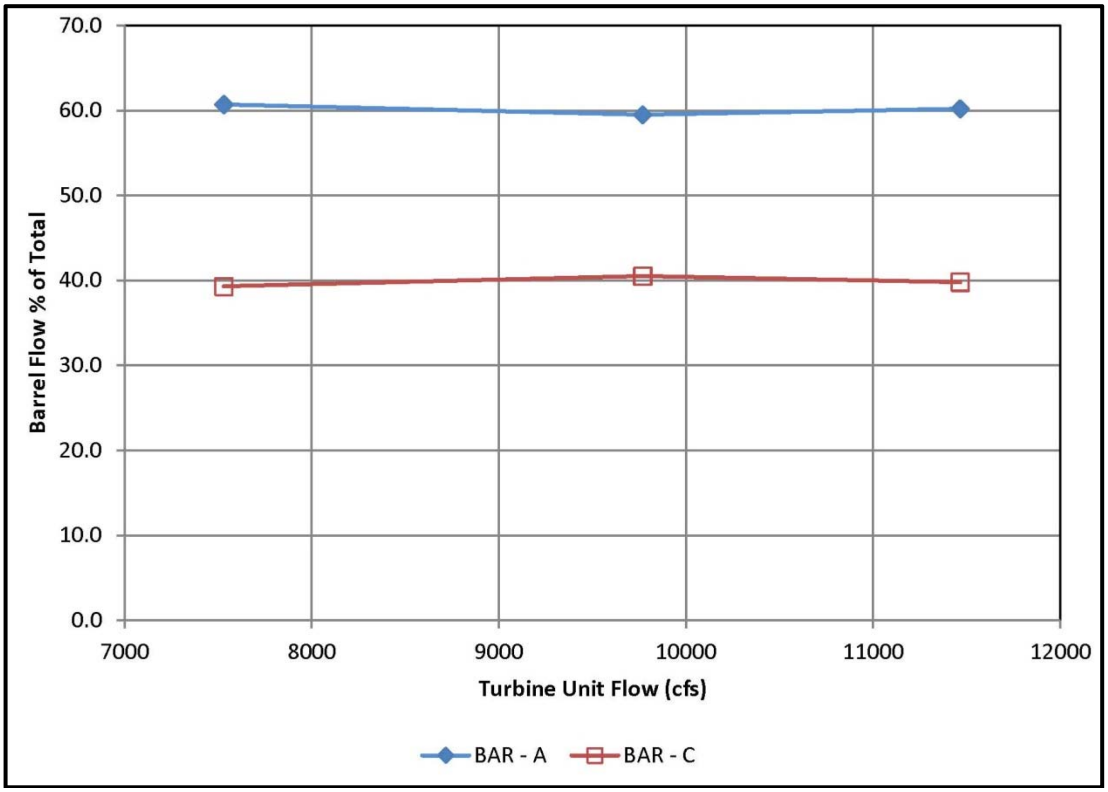
Similar to many other projects, the draft tube for B1 turbines has a vertical splitter pier that splits the draft tube into two barrels (designated A and C) of equal cross-sectional area and length. However, a unique aspect of these draft tubes is that there is also a horizontal splitter pier that splits each of the barrels approximately in half. Due to this, feature bead contacts and direction changes with the horizontal or vertical splitter piers or the draft tube walls were also analyzed. Figure 14 shows that decrease in severe contacts (1's and 2's) and direction changes (1's and 2's) with an increase in discharge. The high percentage of severe direction changes at the peak operating point (7.53 kcfs) qualitatively corresponded to a vortex coming off the runner that was significantly worse at the lower 1% operating condition (approximately 7.27 kcfs). While a quantitative bead assessment was also not performed for the generator limit (approximately 13.25 kcfs), the qualitative assessment was that this operating condition appeared to be as good as or better than the 11.47 kcfs operating condition.

Figure 14. Severe Bead Contacts and Direction Changes within Draft Tube



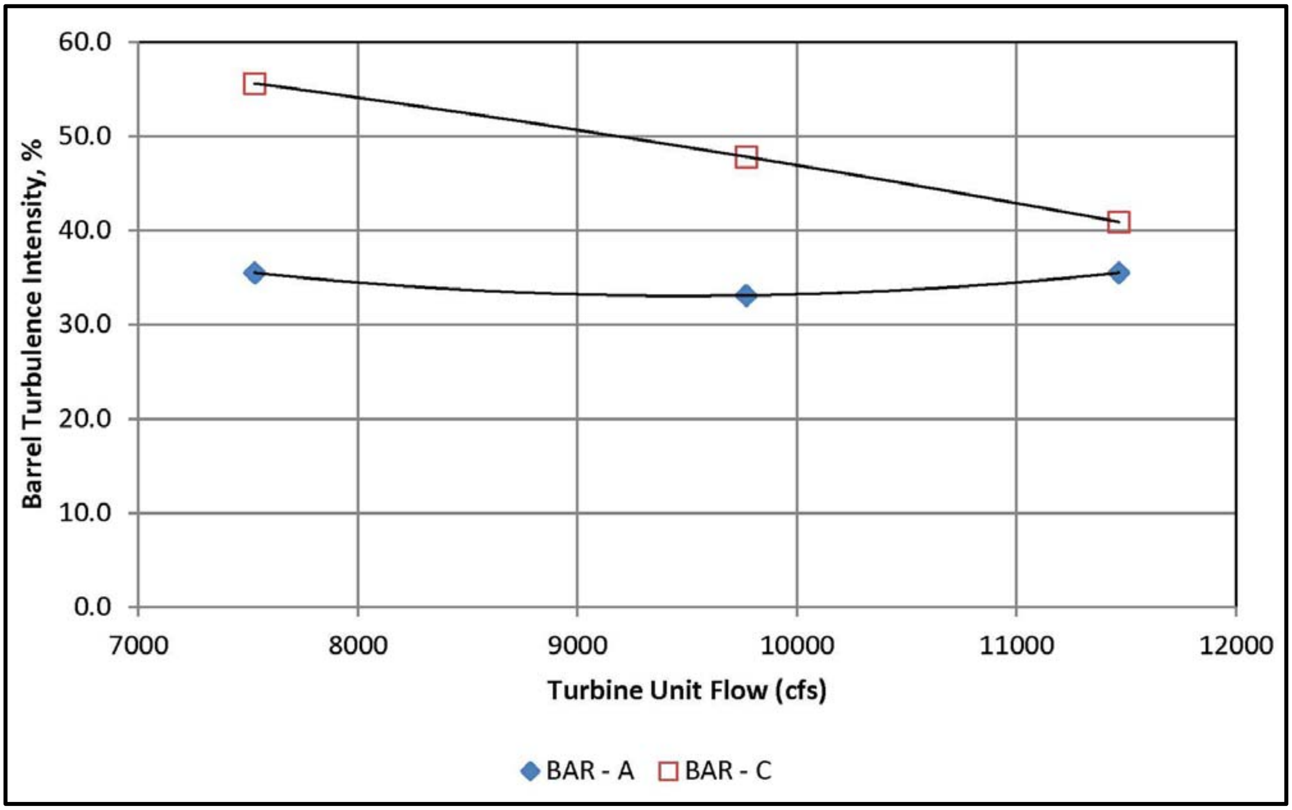
In addition to the bead analysis, velocity measurements were taken at the exit of the draft tube exit using a LDV (measurements could be taken from outside the model due to the clear walls). These velocities taken 5 feet (prototype) from the draft tube exit were used to estimate the flow rate through each barrel. Barrel A has higher flow rate than barrel C across the operating range with approximately 60% of the flow passing through Barrel A (Figure 15).

Figure 15. Flow Percent Passing Through Each Draft Tube



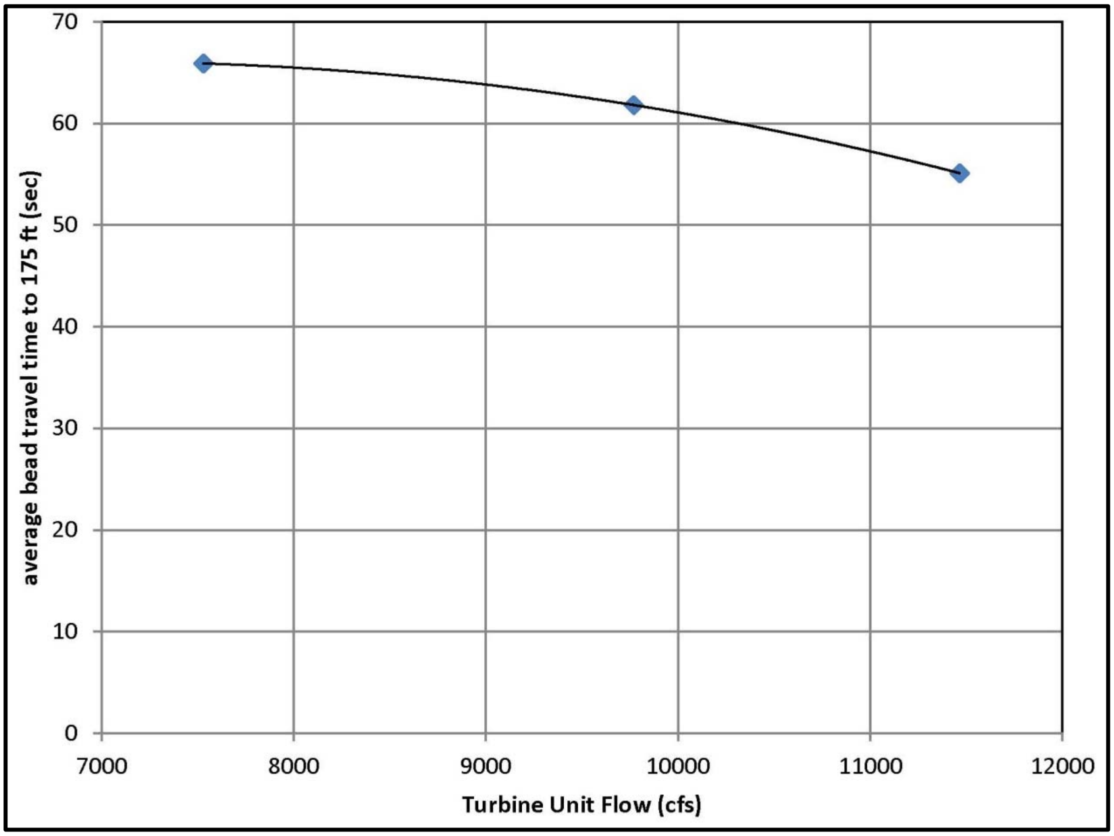
The velocity measurements in the draft tube are also used to a parameter called turbulence intensity. This parameter is calculating by averaging over all the point measurements the ratio of the standard deviations at each point measurement over the average velocity at that point measurement. Figure 16 indicates that turbulence intensity in Barrel A is fairly constant over the operating range but in Barrel C the turbulence intensity decreases over the operating range. Qualitative observations of the model also confirmed this trend. The lower 1% was qualitatively observed to have a significant vortex (or swirl) below the runner which resulted in significant turbulence in the draft tube. This swirl was reduced at the peak operating condition but still present as reflected by the high turbulence intensity in Barrel C. As discharge increased, the draft tube conditions were observed to be less turbulent with generator limit draft tube conditions being generally as good as or better than the best geometry operating condition.

Figure 16. Turbulence Intensity for Draft Tube Barrels



It is believed that significant predation may occur within the tailrace of powerhouses, since fish may not be able to avoid predator immediately after exiting a turbine. Therefore, fish egressing from the immediate powerhouse tailrace rapidly may experience reduce indirect turbine mortality. An attempt to look at differences in operating conditions can be made by analyzing the time it takes for beads to travel to 175 feet downstream into the tailrace. Figure 17 indicates that the travel time for passive particles (beads) to this point will decrease with increasing unit discharge as might be expected. Other egress parameters were also analyzed such as the number of beads that get caught in the backroller behind the turbine boil. This parameter as well as others remained relatively constant over the operating conditions tested. All egress data was taken only at 55 feet of head but qualitatively change at 60 feet of head.

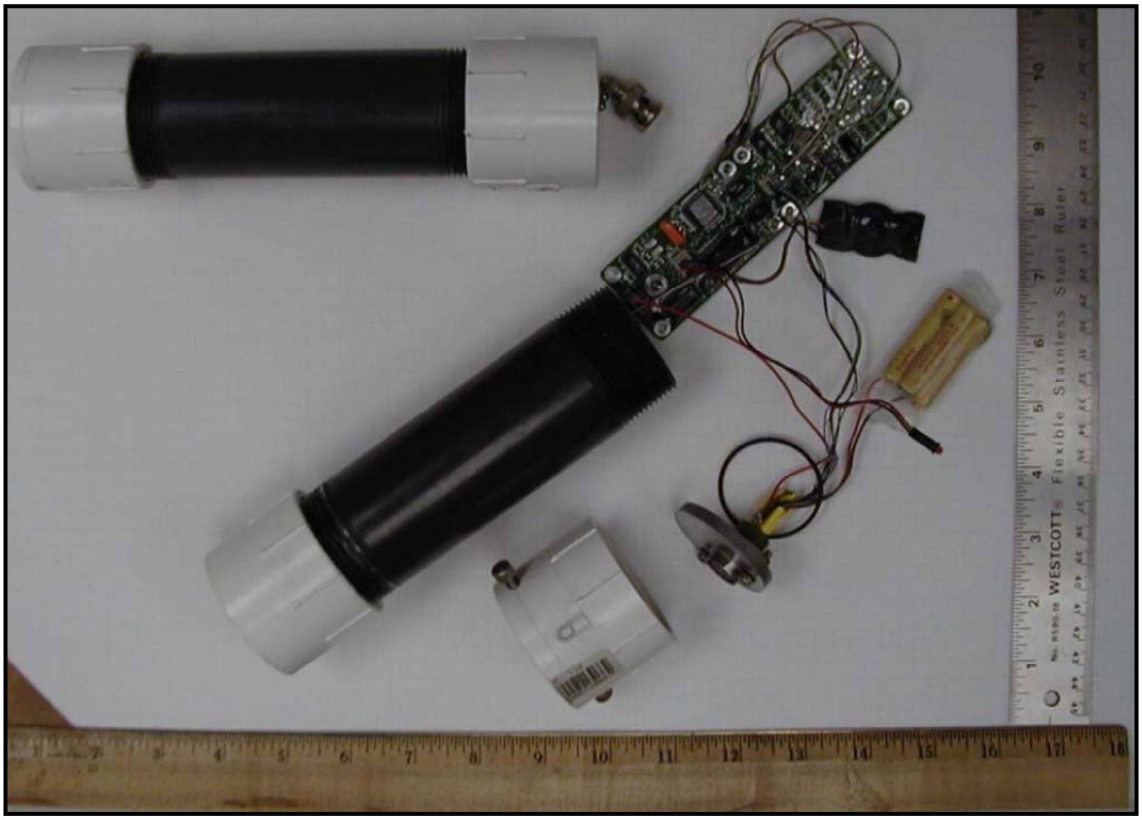
Figure 17. Average Bead Egress Time to 175 Feet Into Tailrace



2.3. PRESSURE INFORMATION FROM LABORATORY AND FIELD DATA

An assessment of barotrauma mortality risk for B1 turbines can be made using relationships established with laboratory testing (see Section 3.4 in the Phase II Main Report) and field pressure data using sensor fish. To apply the data to fish passage at B1 for run-of-river fish, the acclimation pressure and the nadir pressure are needed. There is minimal information for the acclimation pressure for fish entering B1 turbines; however, there is some nadir pressure information for four operational points that have been evaluated in the field study using sensor fish. In December 1999-January 2000, the Pacific Northwest National Laboratory (PNNL) released sensor fish devices into B1 turbine unit 6 with a new MGR and into B1 turbine unit 5 with an older unit (has since been replaced) to obtain the some minimal pressure information for the new and older turbine units. The sensor fish devices were PVC tube that was capped, cylindrical in shape, and nearly neutrally negatively buoyant in fresh water. This model of sensor fish was created quickly to support comparison of the two runners and is described in detail in Carlson and Duncan (2003). The sensor housing was a simple PVC pipe with end caps and was approximately 10.5 inches in length and 2.5 inches in diameter (Figure 18). The device did not have adequate shock protection so little acceleration data was collected, but pressure information was obtained. Digital samples of the sensors' analog output were taken every 0.005 second over a period of 2 minutes as the sensor passed through the turbine environment. Current model sensor fish can achieve an even higher sampling frequency. However, the older model sensor fish were the ones released with balloon tags attached to allow for recovery and retrieval of data following the turbine passage in the 1999/2000 study. The devices were released near the stay vanes to target either hub, mid or tip passage.

Figure 18. Sensor Fish Device Developed by PNNL



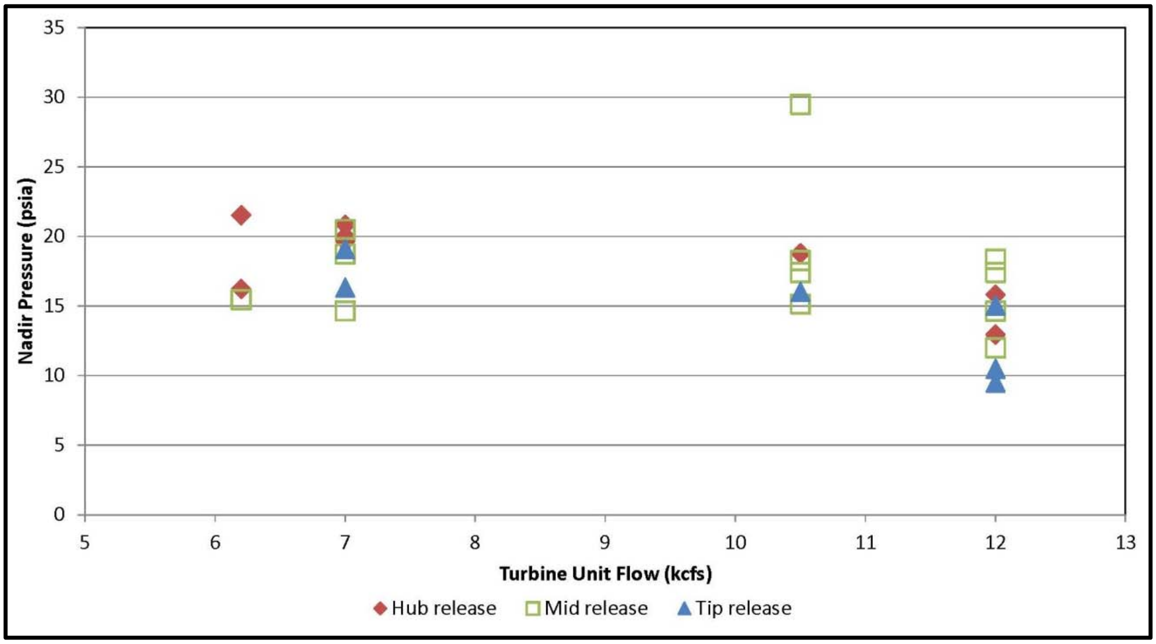
A total of 27 sensor fish devices were released at three different passage locations while operating the turbine at the following four operating points: 6.22 kcfs (below lower 1%), 6.85 kcfs (lower 1%), 10.41 kcfs (between upper 1% and best geometry point) and 11.69 kcfs (between best geometry point and generator limit). These are the same points done for the balloon-tag study and these are the actual average discharges rather than the target discharges for this study (Normandeau 2000). The head during the tests was approximately 57 feet with a range of tailwater elevations of 17 to 19 feet, which is not the worst case head and tailwater but is near average and lower than the majority of the spring fish passage season. The lowest pressures recorded by these devices (nadir pressure; Figure 19) is summarized in Table 3. Due to the slower sampling frequency and the low number of sensor fish used in the study, the mean nadir pressure may not be accurate. However, the mean nadir pressure in a B1 turbine is likely within the range recorded by sensor fish.

Table 3. Sensor Fish Device Nadir Pressure Results at B1 MGR Turbines

Operating Point	Mean Nadir Pressure (psia)	Minimum Nadir Pressure (psia)	Maximum Nadir Pressure (psia)
6.2 kcfs (below lower 1%)	17.74	15.46	21.52
6.9 kcfs (lower 1%)	18.83	14.66	20.83
10.4 kcfs (upper 1% to best geo.)	19.18	15.14	29.49
11.7 kcfs (best geo. to gen. limit)	14.02	9.50	18.38

psia = pounds per square inch absolute. Source: PNNL database.

Figure 19. B1 MGR Turbine Nadir Pressures by Flow Rate and Passage Location



A pressure profile can be created by binning the sensor fish into different 1 psia bins. Due to the limited data, this pressure profile is not that accurate so the average nadir pressure will also be used as well for comparison. In addition to nadir pressure, an acclimation pressure needs to be determined to estimate the mortality rate for untagged juvenile Chinook salmon using Equation 2 (see Section 3.4 in the Phase II Main Report). Little is known about acclimation depth of juvenile salmon approaching turbines but it was suggested that 22 feet is maximum acclimation for juvenile Chinook salmon (Pflugrath et al. 2012). Therefore, an acclimation depths (or pressures) of surface and 22 feet were used to estimate the probability of mortal injury from barotrauma (Table 4).

Surface-acclimated fish probably have very low barotrauma rates but to be conservative, the 22 feet acclimation depth will be assumed. For the 22 feet of acclimation depth, both the mean nadir and the pressure profile indicate that the risk of barotrauma is fairly low for conditions except for the highest turbine unit discharges. Unfortunately, with the use of very few, older model sensor fish and the unknown acclimation depth, there is a significant uncertainty with these calculated mortalities. Collecting additional sensor fish releases and/or pressure information from computational fluid dynamics (CFD) models are being considered. However, based on the available information, it does appear that there may be some increased barotrauma risk at higher discharge through B1 turbines.

Table 4. Calculated Barotrauma Mortality for B1 Turbines

Operating Point	Calculated Fish Mortality using Avg. Nadir		Calculated Fish Mortality using Pressure Profile and Water Acclimation @ 22 feet
	Water Acclimation @ 0 feet	Water Acclimation @ 22 feet	
6.2 kcfs (below lower 1%)	0.2%	1.3%	1.3%
6.9 kcfs (lower 1%)	0.1%	1.0%	1.0%
10.4 kcfs (upper 1% to best geometry point	0.1%	0.9%	1.1%
11.7 kcfs (best geometry point to generator limit)	0.5%	3.1%	4.0%

2.4. BIOLOGICAL FIELD STUDY INFORMATION

While many downstream fish passage survival studies have been performed at Bonneville, there have been only two field studies to specifically evaluate turbine survival at B1 turbines. These included a balloon-tag study (December 1999-January 2000) and a radio-tag study (2004). The balloon-tag study compared mortality of balloon-tagged fish passing through turbine unit 6 with a new MGR (current units) and the original Kaplan turbine unit 5 (has since been replaced; Normandeau 2000). The study was designed as a 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 within ≤±3% 90% of the time, which resulted in 2,593 juvenile Chinook salmon being released through the MGR unit 6 (and approximately the same number for unit 5). These objectives were accomplished by releasing fish through a specially designed induction system for fish to pass them near the blade tip, mid-blade, and hub regions in each turbine at four discrete turbine unit discharges. The study targeted four power levels but the actual average turbine unit discharges tested for the MGR turbine (unit 6) were 6.22 kcfs, below the lower 1% operating limit; 6.85 kcfs, approximately the lower 1% operating limit; 10.41 kcfs, beyond the upper 1% but less than the best geometry point; and 11.69 kcfs, between best geometry point and the generator limit. The head during the test was approximately 57 feet (same as sensor fish study since they were released at the same time). Table 5 shows the 48-hour survival for the MGR turbine unit at each release point and these are averaged to calculate a mortality rate at each operating point.

Table 5. B1 MGR Balloon-Tag Study Results

Operating Point	48-hour Survival % by Target Passage (Standard Error %)			Average Passage Mortality %
	Tip	Mid	Hub	
6.2 kcfs (below lower 1%)	94.8% (1.74%)	97.1% (1.64%)	98.2% (1.46%)	3.3%
6.9 kcfs (lower 1%)	94.3% (1.77%)	95.4% (1.55%)	97.4% (1.44%)	4.3%
10.4 kcfs (upper 1% to best geometry point)	97.6% (1.40%)	96.1% (1.61%)	98.2% (1.47%)	2.7%
11.7 kcfs (best geometry point to generator limit)	93.9% (1.72%)	96.6% (1.55%)	98.0% (1.32%)	3.8%

No statistical correlation existed between fish passage survival and turbine unit discharge in either turbine. Qualitatively, however, the highest point estimate of survival for the MGR unit at all release locations occurred at power level 3 (approximately 10.4 kcfs operating point). The 48 hour survival probabilities for all operating point passage locations are fairly high with all being above 94%. In the comparison of the original unit 5 and the new MGR unit 6, the difference in 48-hour survival rate was also not considered statistically significant; however, the overall injury rate was reduced by approximately 40% changing from the original unit 5 to the new MGR unit 6 (Normandeau, 2000). It should be noted that the fish were surface acclimated, and as indicated in Table 4, barotrauma mortality was expected to be very low. Finally, it was noted that 2.1% of the fish released in the study ended up being entrapped in the tailrace stop log slot. While most of these fish were recovered alive, this indicates that entrapment in the tailrace stop log slot could add to stress during turbine passage at B1.

In addition to the balloon-tag study, a radio-tag study was conducted in 2004 (Counihan et al. 2006). This study produced survival estimates for the release of 399 yearling Chinook and 292 steelhead passing through the B1 turbines (MGR runners). The report indicates that these were direct releases (implying surface acclimation) but does not describe the releases so it is unknown where they passed the turbine. Unfortunately, these releases were all averaged together with no separation by how the turbine was operating. However one interesting component is the comparison of using a control release off the tailrace deck within the turbine boil, and using a control release further downstream near the B2 JBS outfall location (Table 6). This allows comparison of the direct mortality and total mortality (including the indirect mortality). According to this study, the passage survival is fairly high and the indirect mortality is approximately the same as direct turbine mortality. During the spring periods, a mean of 33.3 kcfs was discharged from B1 and during the summer period, an average of 10.5 kcfs was discharged. On average, there were 4 to 5 units operating in spring and 1 to 2 units in summer, which is probably less than the units typically operated; thus, egress conditions would be expected to be worse than average. However, indirect mortality was not overly high during this test despite lower powerhouse flow conditions.

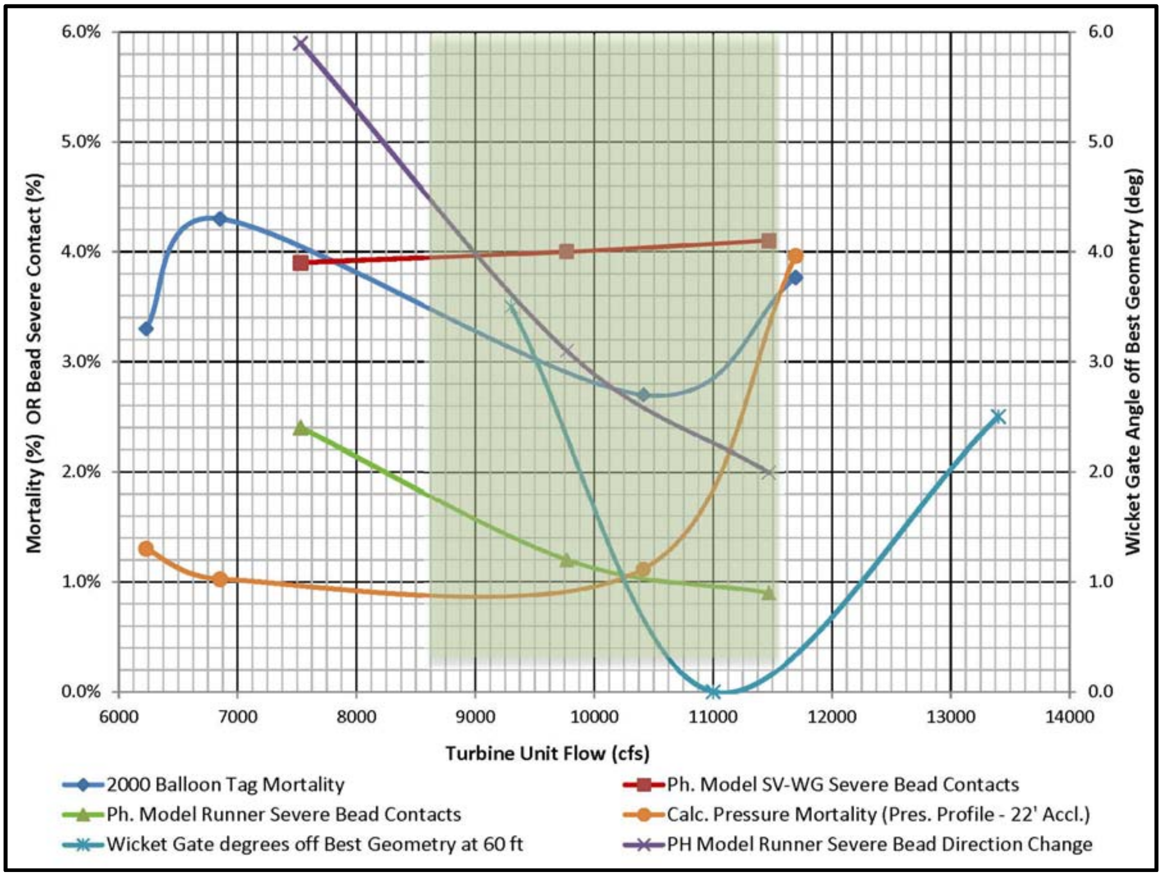
Table 6. Turbine Passage Survival at Bonneville using Radio Tags

Fish Studied	**Juvenile Steelhead**	**Yearling Chinook**
Date Range for Passage	**4/29/04 - 6/7/04**	**4/29/04 - 6/7/04**
Powerhouse 1 - MGR treatment released fish	**292**	**399**
MGR Turbine Survival - Front Roller Control	**0.952**	**0.956**
Lower End of 95% Confidence Interval	0.9	0.83
Upper End of 95% Confidence Interval	1.003	1.042
MGR Turbine Survival - B2 JBS Outfall Control	**0.926**	**0.944**
Lower End of 95% Confidence Interval	0.861	0.913
Upper End of 95% Confidence Interval	0.992	0.976
Average Internal Tag Weight in Air (g)	1.4	1.4
Fish Weight	102.0	34.0
Average Tag Burden (%)	1.4%	4.1%
Average Powerhouse 1 Flow (kcfs)	33.3	33.3
Average Total River Flow (kcfs)	218.4	218.4

2.5. DISCUSSION

The preceding sections presented the available turbine survival information applicable to B1 turbines. This information was derived from geometry considerations, physical model data, laboratory studies, field passage and survival studies, and sensor fish studies. None of the information alone can identify a TOR for survival of fish passing through turbines. Biological studies performed in the field that attempt to directly measure the mortality or survival of fish passing through turbines have limitations, and results are not necessarily representative of the mortality expressed by the run-of-river fish population. The turbine physical model provides valuable information on potential physical injury within the turbine environment, particularly with the bead passage analysis; however; the model data do not indicate the frequency of barotrauma injury or account for fish behavior. The barotrauma injury rate was not accurately estimated by balloon-tag studies (Normandeau Associates 2000) due to the lack of depth acclimation of the fish prior to turbine passage, but barotrauma injury rate can be inferred from sensor fish data (Carlson and Duncan 2004) and laboratory data (Carlson et al. 2010). These various sources of information have been combined in Figure 20. This figure only shows direct turbine mortality information.

Figure 20. Combined Information on Direct Turbine Mortality for B1 Turbines



At 55 feet of head, physical injury information (physical model bead data and geometry considerations) suggests a lower rate of physical injury and mortality above approximately 8.5 kcfs with lower rates of extending up to the generator limit (13.25 kcfs at 55 feet of head) based on the qualitative assessment. This is supported by the balloon-tag study that showed a lower mortality at 10.4 kcfs even though there was not a statistically significant difference between the operating points (Normandeau 2000).

The only information on potential barotrauma mortality is derived by combining the sensor fish nadir pressure information with the laboratory-based barotrauma mortality equation (Equation 2) using assumed acclimation depths. The calculated mortality uses a pressure profile using the sensor fish data with an assumed acclimation depth of 22 feet. Unfortunately this is the weakest data set since so few sensor fish were released. However, the limited data does indicate that there could be an increase in barotrauma mortality at the highest turbine unit discharges.

Therefore, based on available information, the proposed TOR for fish passage survival at B1 is defined by the shaded area on Figure 20, which is approximately 8.5 kcfs to 11.5 kcfs at 55 to 60 feet of head. If additional sensor fish information is collected that indicates less of a barotrauma risk at higher discharges, the proposed TOR could be extended up in discharge based on the physical model data. Based on the physical model study, this proposed TOR should also reduce draft tube turbulence providing a potential reduction in tailrace predation. The lower end of this proposed range is within the 1% efficiency operating range, but the upper end of the range is above the 1% range for B1 turbines. Longer-term operation within this range will require adjustment to the FPP.

3. DEFINE TARGET PROJECT OPERATIONS

The best operating range for direct turbine survival is only one component of total turbine survival. Indirect turbine mortality includes predation and could account for a significant portion of total mortality. Reducing probability of indirect mortality should be considered when defining target operations. Indirect mortality of turbine-passed fish is thought to result primarily from predation by birds and piscivorous fish (USACE 2004). Neitzel and others (2000) found an increase in predation in laboratory studies when fish were exposed to high stress rates. Fish that pass through turbines uninjured are exposed to stress caused by the hydraulic environment and may experience loss of equilibrium making them more susceptible to predation in the tailrace.

As seen in Figure 17, increasing the turbine unit discharge appears to improve the egress in a model of single unit. Therefore, increasing the turbine unit discharge to the TOR is expected to reduce indirect turbine mortality. It is acknowledged that improving full tailrace egress conditions have much more to do with project operations rather than individual units. However, as shown in Figure 2, Bonneville is a unique project where the tailrace of the two powerhouses and the spillway are separated by islands. While the total discharge from B2 and the spillway influence the tailwater elevation at B1, the egress from B1 turbines is almost completely dependent on B1 operations. In general, it is expected that indirect turbine mortality would decrease with increasing powerhouse discharge due to decreasing egress times and less predation habitat. The current unit priorities in the FPP for B1 are optimized to provide adult ladder attraction and improve downstream egress; therefore, no change is recommended to the current unit priority established in the FPP.

4. OTHER CONSIDERATIONS

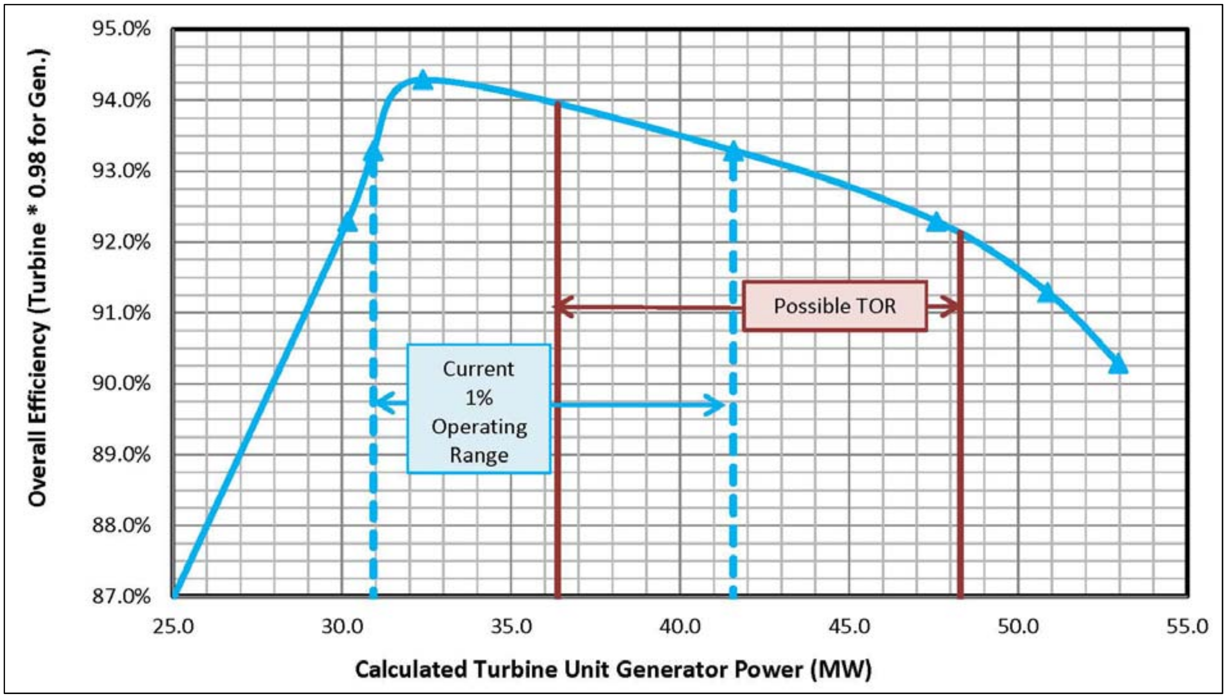
The B1 turbines are currently operated without bypass screens. However, B2 turbines have bypass screens installed where gatewell injury is a concern at higher unit discharges. An additional issue is high total dissolved gas levels that can happen with high spill discharge. Therefore, how the project should split river discharge between B1, B2, and the spillway is currently being debated. Since the focus of this appendix is the B1 turbines, it does not address these larger project issues.

5. RECOMMENDED PATH FORWARD

The information presented in this appendix indicates that turbine unit operation may have a significant effect on direct turbine mortality at the Bonneville first powerhouse. Based on available information, a TOR of 8.5 kcfs to 11.5 kcfs at approximately 55 feet of head is proposed. Figure 21 translates this flow range to generator power and efficiency at 55 feet of head, since flow is a calculated value based on power and efficiency. Without bypass screens, there is not an obvious downside to operating within this proposed TOR.

Although the proposed TOR is supported by some field studies, the TSP team believes that additional pressure information is needed to fine tune the upper end of the operating range. Therefore, either additional sensor fish releases and/or CFD modeling should be conducted to better define the barotrauma risk. If this additional information is collected, it could result in a revision to the proposed TOR.

Figure 21. B1 Turbines Proposed Target Operating Range at 55 feet of Head



The TSP team also suggests that comprehensive turbine survival testing (TST) be conducted within and surrounding the proposed TOR (see Turbine Survival Testing Phase II Appendix). The first step in turbine survival testing would be to conduct direct turbine survival testing while attempting to control conditions that may lead to indirect turbine mortality. Due to the effects of indirect turbine mortality, any biological turbine test of varying turbine unit operations should be performed as similar to appropriate seasonal project operations as possible. Additionally, the test should measure both direct and indirect turbine survival, if possible.

If the TST determines turbine unit operation within the TOR can improve the direct survival of turbine passed fish, the TOR would need to be defined at multiple heads since this flow range may vary slightly with changing head. Since Bonneville can have a more significant head variation than other projects, it is important to define this range at other heads. It is possible to define an operating range based on efficiency, wicket gate angle, blade angle, discharge or some combination of these variables. The difference in survival shown by testing at the edge of the range as well as practical operational considerations will need to be taken into consideration when defining the TOR over a range of heads.

Following the definition of operating conditions for best direct fish passage survival, the next step would be to explore and define methods for improving indirect turbine survival. In general, increasing powerhouse discharge with the current unit priority is expected to improve indirect turbine survival. However, there are many other factors that go into what percentage of river is targeted to pass through each portion of the project.

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US Army Corps of Engineers ®

PHASE II PROJECT APPENDIX

TURBINE OPTIMIZATION FOR PASSAGE OF JUVENILE SALMON AT JOHN DAY DAM

John Day Lock and Dam located on the Columbia River near Rufus, Oregon.

PREPARED BY
U.S. ARMY CORPS OF ENGINEERS
TURBINE SURVIVAL PROGRAM

JUNE 2013

REVISION 0

EXECUTIVE SUMMARY

This report identifies operating conditions for turbine units at John Day Dam on the Columbia River, where turbine fish passage survival is expected to be higher based on using the tools developed by the Turbine Survival Program (TSP). The 2004 TSP Phase I Report indentified that operating conditions of large Kaplan turbine units appear to have a significant effect on the survival of fish passing through them. This TSP Phase II Project Appendix involves identifying target operating range (TOR) and the targets for project operations.

To reduce strike injuries to fish, the physical geometry of John Day's turbine components was examined. As flow increased, the wicket gates open up and the blade angles steepen. The wicket gates achieve the best alignment with the stay vanes over a 7-degree rotational range from 36 to 43 degrees open. However, the maximum wicket gate opening is often restricted by other constraints such as generator limit.

Additional information to reduce strike frequency, exposure to shear, and turbulent environments came from 1:25 Froude scale model constructed at the Engineering Research and Development Center of a John Day turbine unit. High-speed video of neutrally buoyant beads was taken to assess the strike frequency and severity. The physical model showed that the percentage of beads contacting the stay vanes and wicket gates was low. The lowest number of contacts and direction changes seem to occur for flows larger than 16.0 thousand cubic feet per second (kcfs). In addition, the percentage of beads passing through the gap between the stay vanes and wicket gates appears to increase with flow and be relatively unrelated to the best wicket gate geometry. As with the stay vane region, analysis of beads contacting the runner can give an indication of potential fish injury. In general, contact with the runner was found to decrease with increasing flow rate through the runner. Increasing flow rate of course corresponds to an increase in blade angle and increased open area within the runner environment.

Velocity data was taken at transects near the runner and draft tube exit. Velocity measurements taken near the exit of the draft tube displayed a large difference between the different flow rates tested. The draft tube for John Day turbines has a single vertical splitter wall that divides the draft tube into two equal-sized barrels (designated A and C). Barrel A has a much higher flow rate than barrel C at lower turbine flow rates, but the flow distributes more evenly for flow rates of 16.50 kcfs and higher. Turbulence intensity decreased with increasing flow for both barrels and especially for barrel C. The increased turbulence could cause fish disorientation. While a direct injury or mortality may not result, fish disorientation has the potential to increase vulnerability to predation.

Injury and mortality (barotrauma) can also occur to fish passing through turbines due to exposure to low nadir pressures. An assessment of barotrauma mortality risk for John Day turbines was made using relationships established by laboratory testing, computational fluid dynamics, and field pressure data collected from sensor fish. An equation was generated using the log ratio pressure and tag burden to predict fish mortality. Assuming a 22-foot acclimation depth for salmonids in the John Day forebay, and using existing data and the generated equation, a barotrauma mortality rate without internal tags of 0.62% for 11.80 kcfs (lower 1%) and 6.18% for 20.30 kcfs (upper 1%) was calculated.

Although a number of biological tests have estimated turbine fish passage survival at John Day, they were not designed to provide specific survival estimates at specific operating points. The 2009 Juvenile Salmon Acoustic Telemetry System estimate of survival is 72.8% for subyearling fish and 85.5% for

yearling fish. The tag burden for this study was 2.6% for subyearlings and 1.5% for yearlings, which may have resulted in a biased barotrauma injury.

Based on available information, the recommended target operating range for John Day is 15.0 kcfs to 18.80 kcfs at approximately 100 feet of head. This target operating range is consistent with the most open geometry and with bead strike data and draft tube conditions from the physical model, while accounting for the concerns with barotraumas and low nadir pressures at the higher operating discharges.

The TSP team proposes that a thorough turbine survival test be conducted at John Day to establish whether increased survival is seen under the target operating range conditions. Indirect mortality (i.e., predation) is considered to be a large portion of total turbine mortality; therefore, any TST must make the project operating conditions as similar as possible while testing the different unit operating conditions.

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ACRONYMS AND ABBREVIATIONS

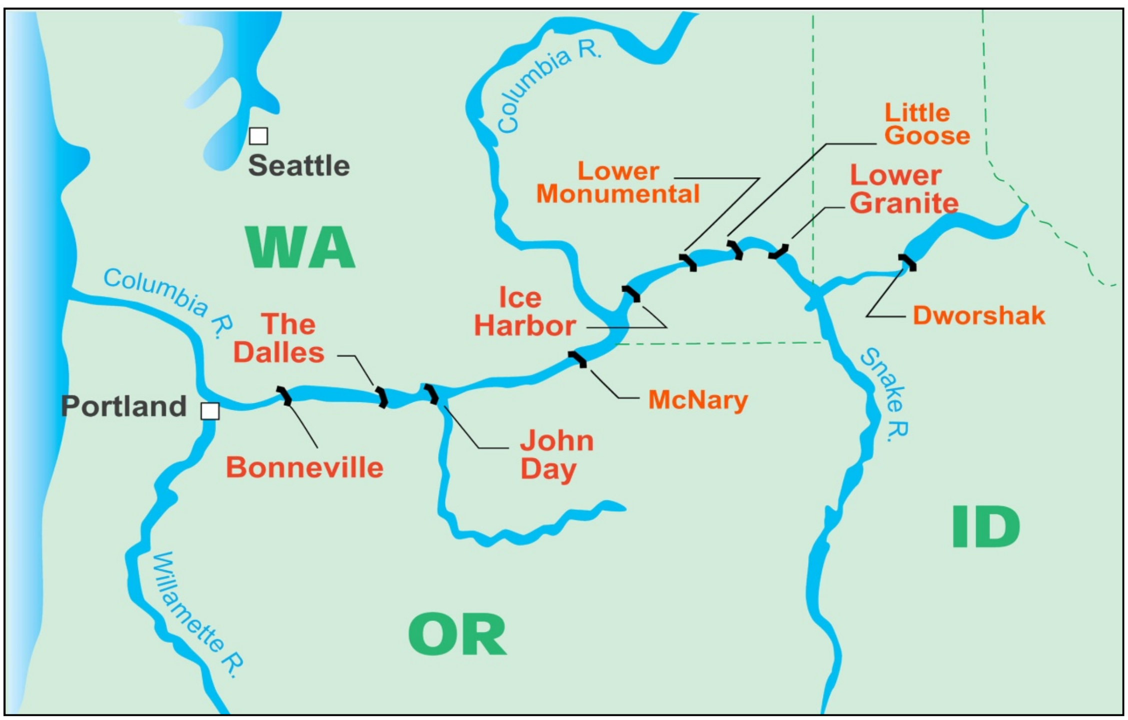
BiOp	Biological Opinion
BLH	Baldwin-Lima-Hamilton (turbine manufacturer)
CFD	computational fluid dynamics
cfs	cubic feet per second
CI	confidence interval
CRFM	Columbia River Fish Mitigation
ERDC	Engineering Research and Development Center
FPE	fish passage efficiency
FPP	Fish Passage Plan
ft	feet (foot)
JBS	juvenile bypass system
kcfs	thousand feet per second
LDV	Laser Doppler Velocimeter
msl	mean sea level
MW	megawatt(s)
NOAA	National Oceanic and Atmospheric Administration
psia	pounds per square inch absolute
RM	river mile
SPE	spill passage efficiency
STS	submerged traveling screen
TOR	target operating range
TSP	Turbine Survival Program
TST	turbine survival testing
TSW	top spillway weir(s)
USACE	U.S. Army Corps of Engineers
VBS	vertical barrier screen

1. INTRODUCTION

The Turbine Survival Program (TSP) is part of the U.S. Army Corps of Engineers' (USACE) multi-faceted Columbia River Fish Mitigation (CRFM) program. The first phase of the TSP involved developing tools to evaluate the physical conditions fish experience as they pass through large Kaplan turbines typical of USACE projects. The TSP Phase I Report (USACE 2004a) indentified that the operating conditions of the large Kaplan turbine units appear to have a significant effect on survival of fish passing through them. Phase II of the TSP involves turbine survival testing (or biological index testing) at USACE facilities. This report identifies operating conditions for John Day turbines where turbine fish passage survival is expected to be higher based on the utilization of the tools developed by the TSP program.

John Day Dam is the third hydroelectric project from the mouth of the Columbia River located at river mile (RM) 216 (Figure 1). The dam crosses the river near Rufus, Oregon, about 25 miles upstream from The Dalles and just below the mouth of the John Day River. Lake Umatilla, impounded by the John Day Dam, extends about 76 miles up to McNary Dam.

Figure 1. Location of John Day Lock and Dam



The John Day powerhouse has 16 turbine units; fish by-pass screens are installed in each of the turbine unit intakes. Although these screens are effective in intercepting the majority of the juvenile steelhead, a significant percentage of juvenile fish continue to pass through the turbines. Survival estimates for radio-tagged fish passing the John Day turbines are among the lowest observed within the Federal Columbia River Power System. Turbine survival estimates (route-specific survival model of Skalski et al. 2002) for yearling and subyearling Chinook salmon ranged from 71.9% to 83.2% in 2002 and 2003 (Counihan et al. 2003a, b). Turbine survival estimates for Columbia and Snake River dams more commonly fall within the 85% to 95% range (USACE 2004b). The need to improve survival through John Day turbines is clear and the possibility for improving survival exists while specifying operations that are realistic.

Results of multiple field and laboratory studies indicate that improved survival through the John Day turbines may be achieved by changing the operating conditions for the existing turbines. These include balloon tag and telemetry tag survival studies, sensor fish pressure and acceleration measurements of the turbine flow path, laboratory pressure investigations, and physical hydraulic model investigations. Results from these studies indicate restricting the operating zone currently defined by within ± 1% of peak efficiency may improve fish passage survival. This report summarizes results from the various studies and presents information to support the recommendation to conduct a field test for verification of an improved operating range for safer fish passage.

1.1. PROJECT DESCRIPTION

Completed in 1971, the John Day Project includes a powerhouse, spillway, navigation lock, and fish passage facilities (Figure 2 and Figure 3). The structure is primarily a concrete gravity dam with a north abutment embankment section.

Figure 2. John Day Powerhouse, South Fish Ladder, and Juvenile Fish Bypass System

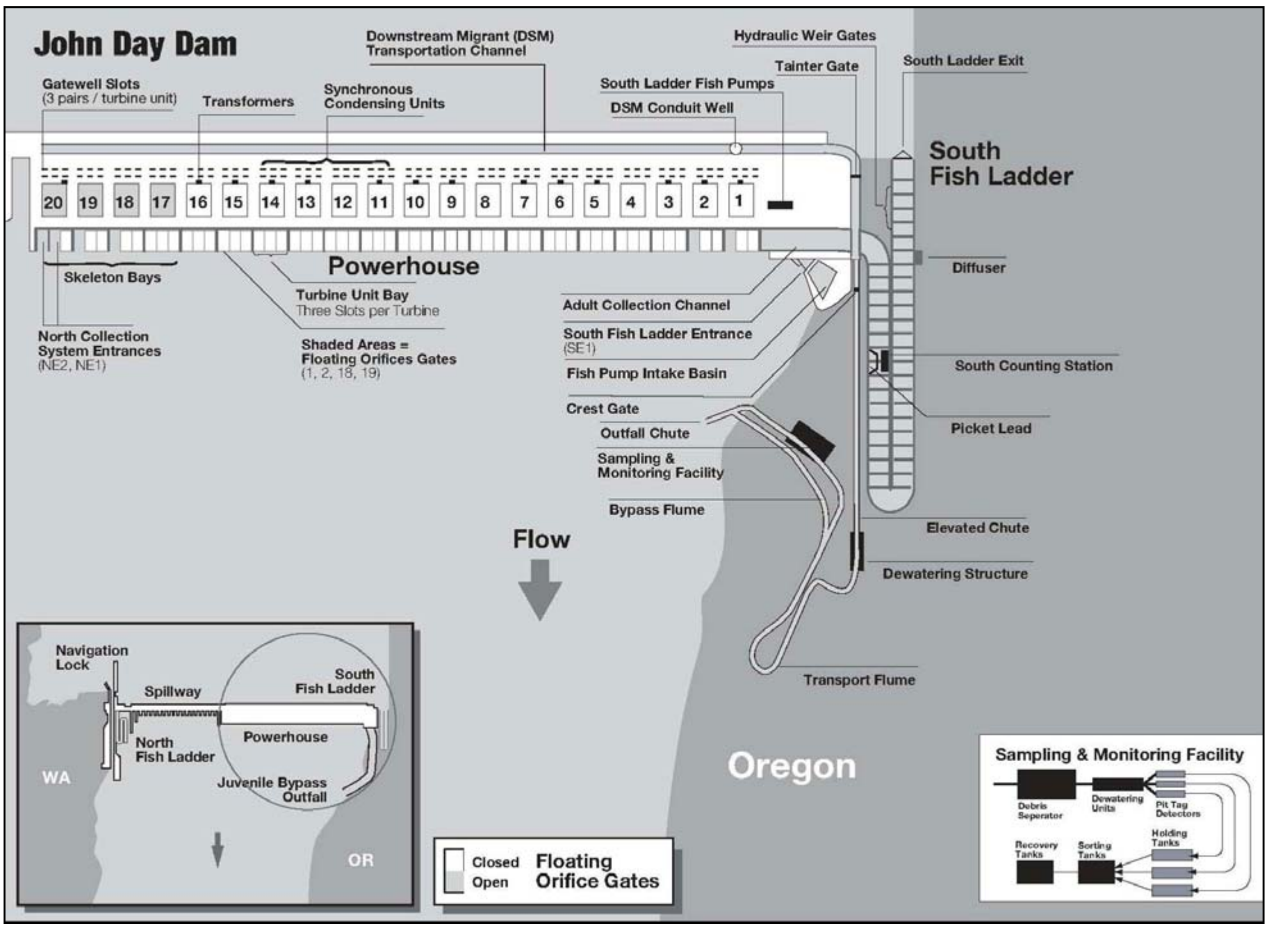
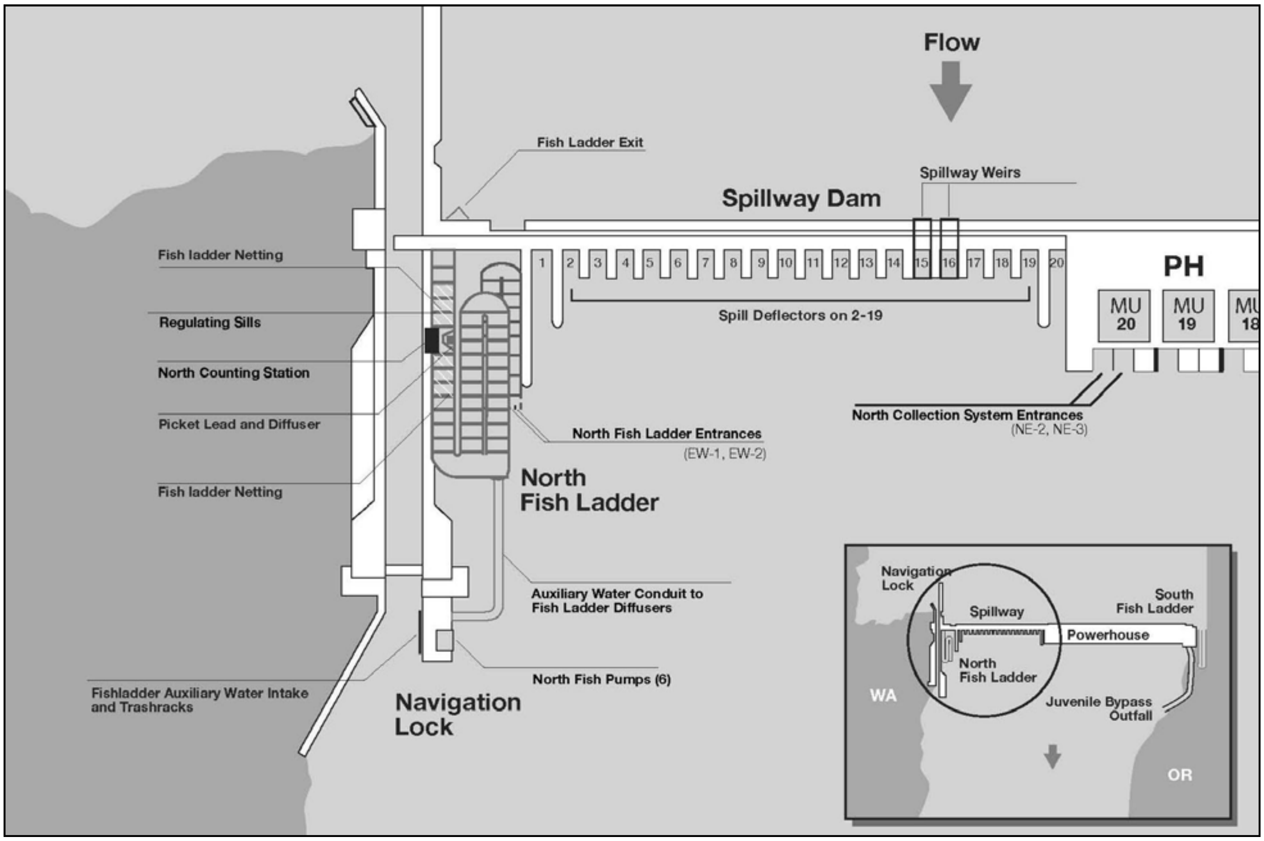


Figure 3. John Day Dam Spillway, Navigation Lock, and North Fish Ladder



The powerhouse is 1,975-feet long and contains 16 Baldwin-Lima-Hamilton (BLH) turbines of 155 megawatts (MW) each, for a total generating capacity of 2,480 MW. All turbines are Kaplan, six-blade units operating at 90 revolutions per minute. The last of the 16 generators went on line in November 1971. The north end of the powerhouse has four skeleton bays providing a potential expansion of four additional turbines. There is a history of linkage problems for the BLH turbines. Several turbine units have blades presently welded in a fixed position.

The spillway is located adjacent to the powerhouse and abuts the navigation lock on the Washington shore. It has twenty 50-foot wide spillway bays each capable of discharging up to 50,000 cubic feet per second (cfs) under normal pool elevations. In a flood event, the total spillway discharge capacity is approximately 2,250,000 cfs.

Fish passage facilities include two adult fish ladders and a screened juvenile bypass system (JBS). The north fish ladder has two main entrances located adjacent to spillway bay 1 and exits upstream along the Washington shore. The south fish ladder has three main entrances, one at the south end of the powerhouse and two smaller entrances at its north end. Ten floating orifice-type entrances also are distributed across the downstream powerhouse face. The south fish ladder exits upstream adjacent to the Oregon shore.

The JBS at John Day has undergone several modifications in the last 25 years. Currently, each main unit intake has a 20-foot submersible traveling screen that diverts approximately 200 cfs of flow up into a dewatering gate slot. A vertical barrier screen (VBS) located between the dewatering gate slot and the operating gate slot removes all but 14 cfs of this flow. The remaining 14 cfs of water and guided fish are discharged through a 14-inch orifice into a collection channel, and eventually released approximately 600 feet downstream of the powerhouse through an outfall adjacent to the Oregon shore. The JBS also includes a juvenile smolt monitoring facility that was put into operation in 2000.

1.2. PROJECT OPERATIONS

1.2.1. General Project Operations

John Day is a storage project and the dam can be manipulated to provide flood risk management for the lower river. The normal operating pool elevation during fish passage season (April 1 through November 30) typically fluctuates from elevation 262 to 265 feet mean sea level (msl). The operating range varies from elevation 257 to 268 feet msl.

A strict operating plan is used for John Day to maintain acceptable tailrace conditions for downstream migrant fish. As the total river flow increases, the amount of discharge released from the powerhouse must increase relative to the spillway discharge. If the powerhouse discharge is too high, a large eddy forms downstream of the spillway, which results in a large percentage of the flow returning into the stilling basin. If the spillway discharge is too high, a large eddy is formed downstream of the powerhouse. As a result of these conditions, spillway and powerhouse operations are coordinated to provide hydraulic conditions deemed optimal for egress of migrating salmonids through the tailrace.

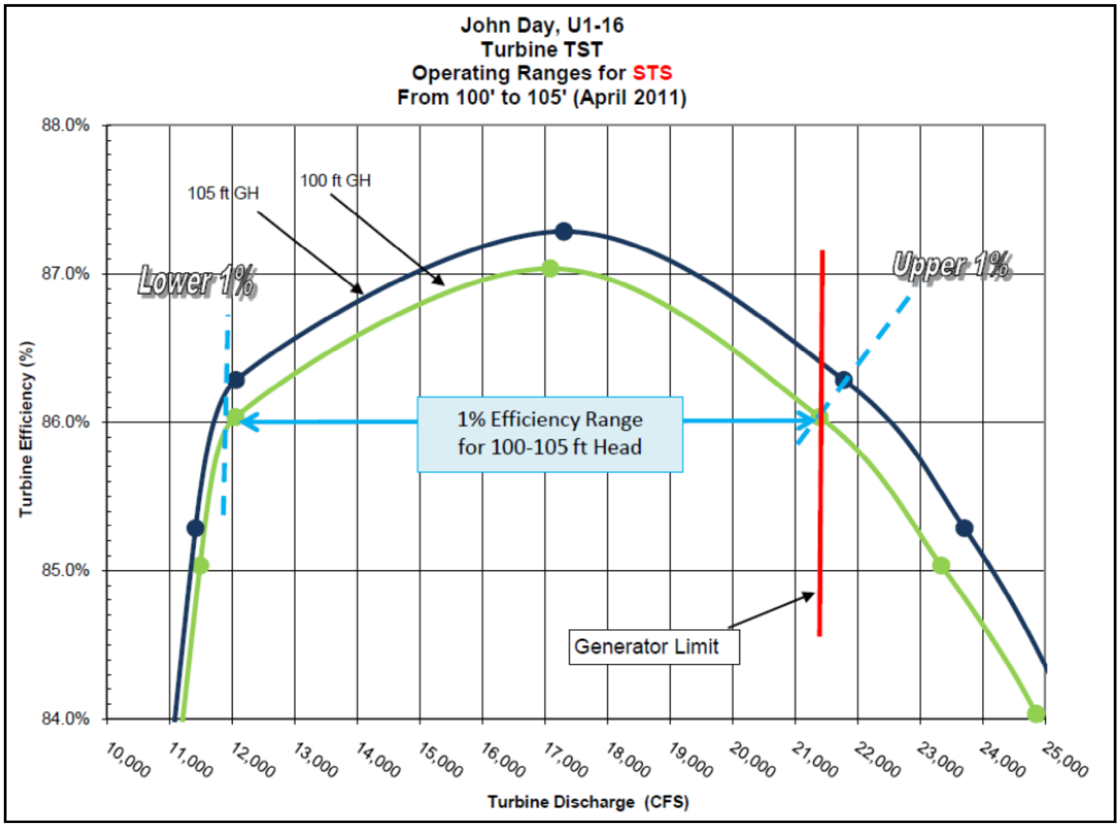
Flow distribution and operational guidelines for John Day, as described in the National Oceanic and Atmospheric Administration (NOAA) Fisheries Biological Opinion (BiOp) and in the annual Fish Passage Plan (FPP) developed by the USACE Northwestern Division, are based upon many different factors that affect juvenile and adult passage at the dam. Requirements include seasonal operation, turbine unit restrictions for tailrace patterns, turbine unit operation priority, turbine operation within 1% of peak efficiency, minimum and maximum turbine operation, Bonneville Power Administration power requirements, spillway gate operation pattern, scheduled maintenance, unplanned outages, and others. All of these factors play a role in the operation of John Day in consideration of juvenile and adult fish migration. These factors are not variables within the context of this study and are assumed to be a part of project operation. The current FPP is the approved method of operating John Day.

1.2.2. Turbine Operations

The John Day turbines are operated within 1% of the best efficiency in accordance with the FPP, which implements requirements of the NOAA Fisheries BiOp (2000, 2004, 2008). The FPP is updated annually. The approach of restricting turbine operations was formalized in the 2000 BiOp, which requires turbine operations be limited to ± 1% of best operating efficiency. The basis for this rule resulted from research reported by Bell (1981) and Eicher Associates (1987).

A review of turbine survival study results and the 1% operating range was completed by Bickford and Skalski (2000). It was found that highest direct survival did not occur at the best operating efficiency and that direct passage survival did tend to exhibit a curvilinear relationship with increasing turbine discharge. Direct turbine passage survival tests were normally limited to turbine operations within ± 1% of best operating range, highest survival was often found to occur within the 1% operating range but not always. It cannot be concluded that highest direct turbine survival occurs within 1% of best operating efficiency. Highest direct turbine survival for some turbine units may well occur at untested turbine operations outside the 1% operating range. The peak efficiency and the 1% operating range are dependent on both the head on the turbine and the flow through the turbine. The John Day turbine efficiency vs. flow curves, with the submerged traveling screen (STS) installed, are shown in Figure 4. The 1% operating range is defined by a ±1% drop from peak efficiency for the head at which the turbine is operated. Compared with a number of projects, John Day has a very wide 1% operating range and for most heads, the upper 1% limit is above or near the generator limit.

Figure 4. John Day Turbine Efficiency Curves with STS Installed



The JDA turbines were designed for a head range of 100 to 105 feet with an optimum design head of 102 feet. The forebay continues to operate at the original design of 260 to 268 feet msl as described in John Day's Water Control Manual.

The FPP specifies turbine unit operating priority as shown below. The FPP also requires spill during much of the fish passage season, which influences the powerhouse tailrace egress conditions. Details of the operational requirements for John Day can be found in the FPP (USACE 2012). The spill requirements are for alternating 30% and 40% spill with the top spillway weirs (TSWs) from early April through July 20. Late summer spill through August 31st the spill requirements are 30% spill with TSWs. It can be seen that for the majority of the time during fish passage season, the TSWs are installed; therefore, this should be consider the current baseline turbine unit priority.

- Fish passage season without TSWs: Units 1-4 in any order, then units 5-16 in any order.
- Fish passage season with TSWs: Units 5, 1, 3, 16, 14, 12, 10, 8, 15, 2, 11, 7, 4, 13, 9, 6.

2. DEFINE TARGET OPERATING RANGE FOR TURBINES

There are many different pieces of information that help to estimate the target operating range (TOR) for fish passage survival through John Day turbines. First, the physical geometry of different operating conditions will be considered. Second, physical modeling data of different operating conditions that was guided by the physical geometry will be discussed. Pressure information for John Day comes from both a computational fluid dynamics (CFD) model and a sensor fish study. This information, in conjunction with laboratory studies, gives an indication of the potential for pressure injuries at different operating conditions. While no turbine-specific biological field studies have been performed to date, the project survival studies and some data correlation will be discussed. Finally, this information will be tied together to provide an estimate of a target operating range for John Day turbines.

2.1. PHYSICAL GEOMETRY CONSIDERATIONS

As discussed in Section 3.2 of the Phase II Main Report, there is a potential to reduce injury and direct mortality of migrating salmon passing through turbines by operating at a more open geometry. Wittinger and others (2010) indicate that a good geometric relationship is often not found within the existing 1% operating limits. For John Day, well-aligned stay vanes and wicket gates occur over a 7-degree rotational range from 36 to 43 degrees open. However, the maximum wicket gate opening is often restricted by other constraints such as generator limit. The runner blade angle can vary from 19 to 36 degrees. Open geometry blade angles would be considered the top of this range, but these are also restricted by other constraints.

The geometry for turbine operation (runner blade position and wicket gate position) is represented in a family of curves called an “on-cam diagram.” For example, Figure 5 illustrates a family of on-cam curves over the head range of 90 to 105 feet at John Day. Some of the units have broken blade mechanisms and have the blade angle fixed at 29 degrees. Superimposed on the curves is a horizontal line drawn at fixed 29-degree blade angle illustrating the effect of a Kaplan turbine runner operating at a single blade position. Over the operating head range, the wicket gate position corresponding to that blade angle varies from about 37 to 41.5 degrees. The best wicket gate geometric alignment is about 41 degrees open.

To better illustrate the best geometric wicket gate opening range, sketches were prepared from a graphical three-dimensional computer model of the John Day design to show the wicket opening in relation to the stay vanes. Figure 6 shows the minimum wicket gate opening beginning to shadow the stay vane at 36 degrees open. Figure 7 shows an interim wicket gate opening of 38 degrees open, and Figure 8 shows the best overall wicket gate opening of 41 degrees considering the entire arrangement of the wicket gate and stay vanes.

Figure 9 shows the best geometric operating range of the wicket gates for heads between 100 to 105 feet. The operating range of the wicket gates is about 5 degrees of rotation. The positions show a very good geometric relationship while maintaining a reasonable total flow capability with limited operational flexibility.

Figure 5. Cam Curves and Wicket Gate Operating Range

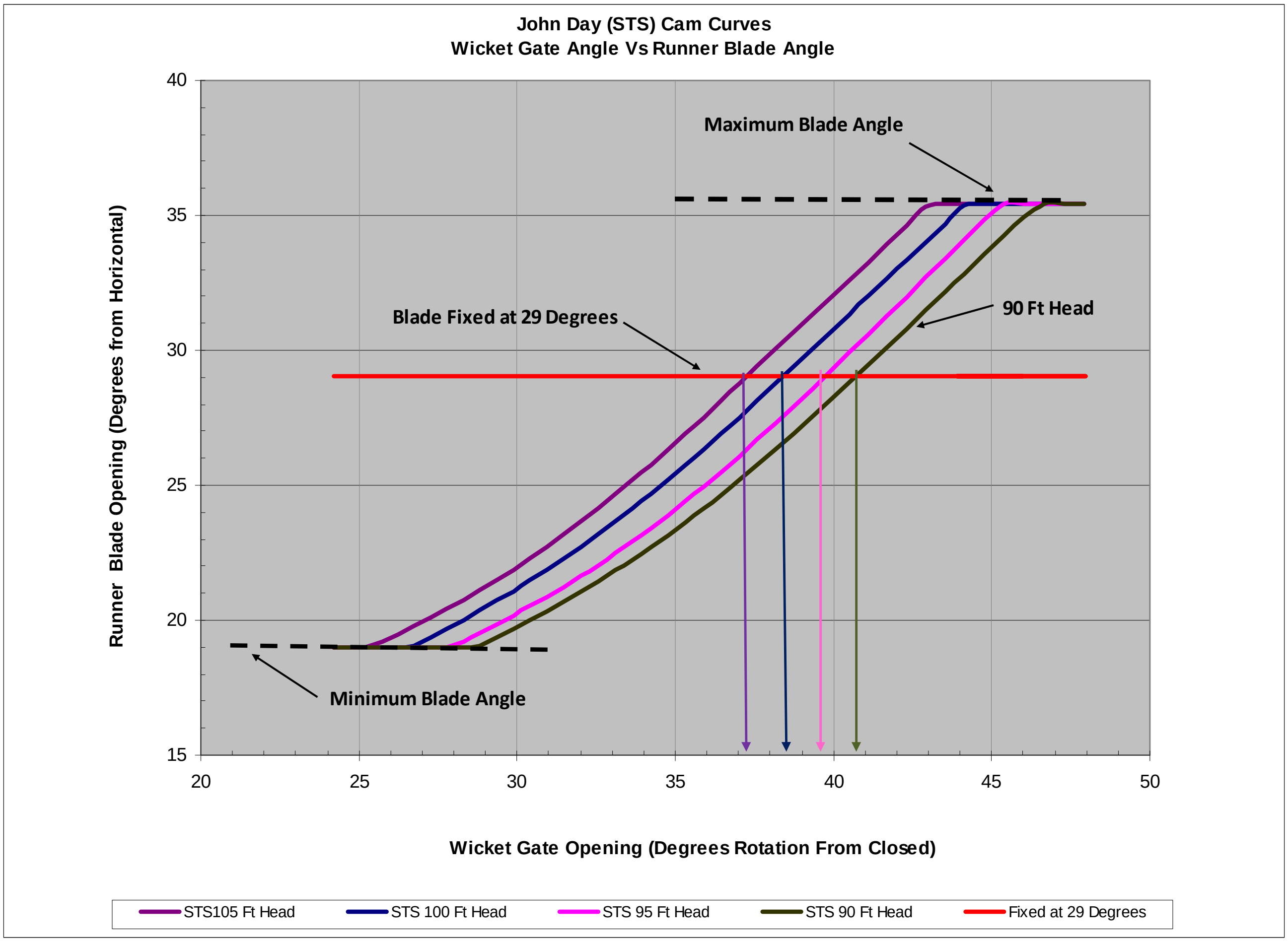


Figure 6. Wicket Gate at 36 Degrees

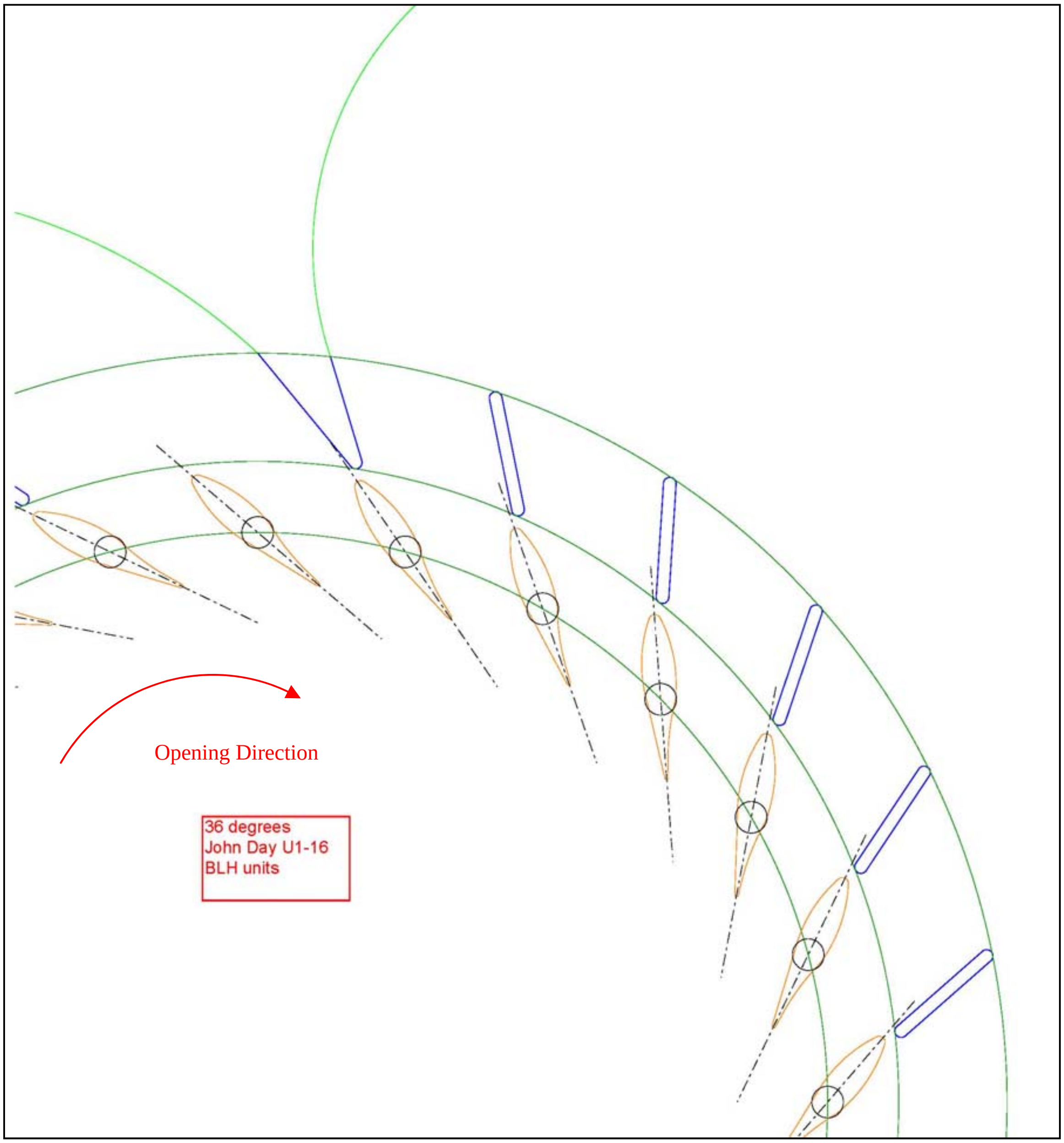


Figure 7. Wicket Gate at 38 Degrees

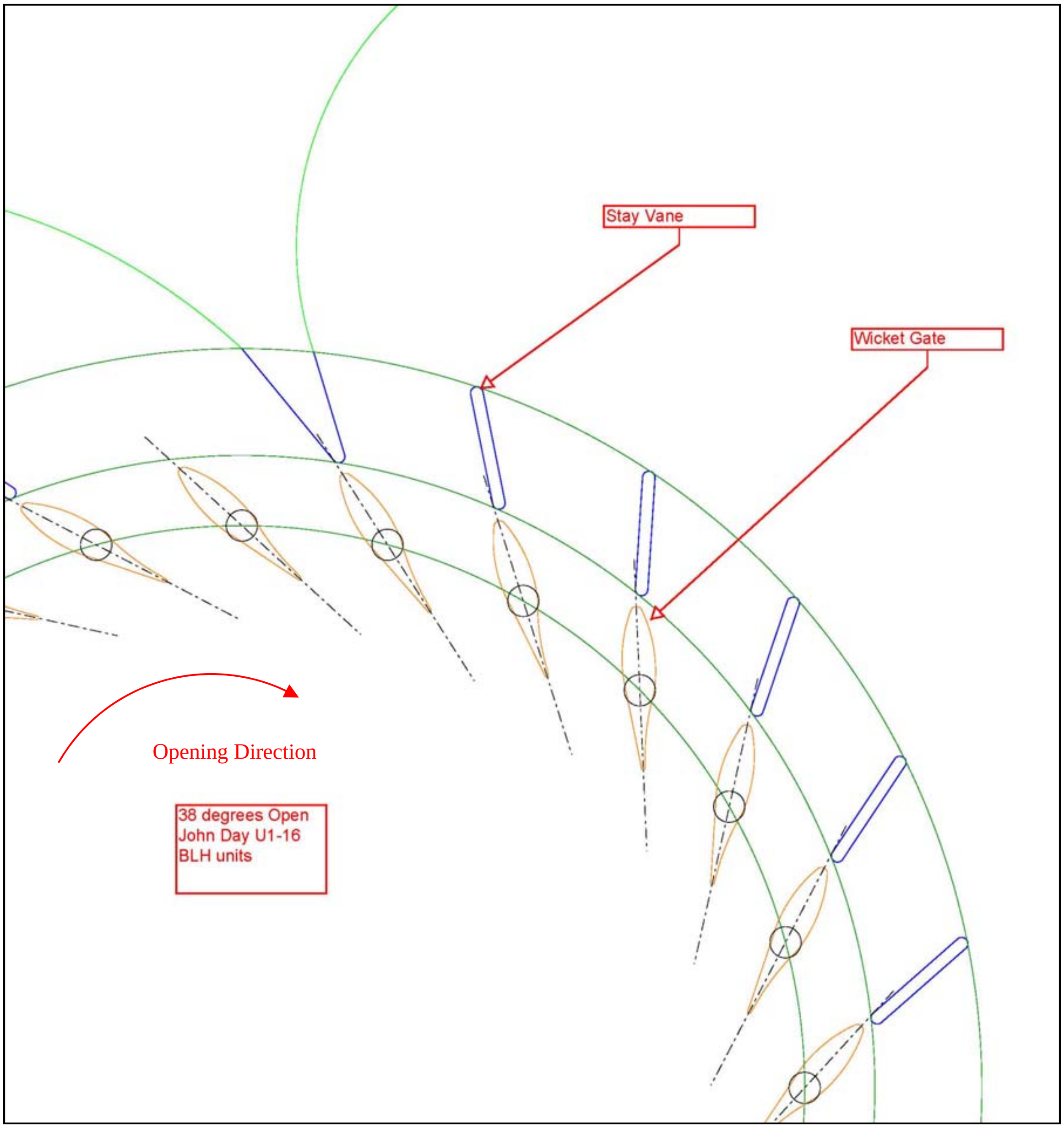


Figure 8. Wicket Gate at Best Geometric Opening of 41 Degrees

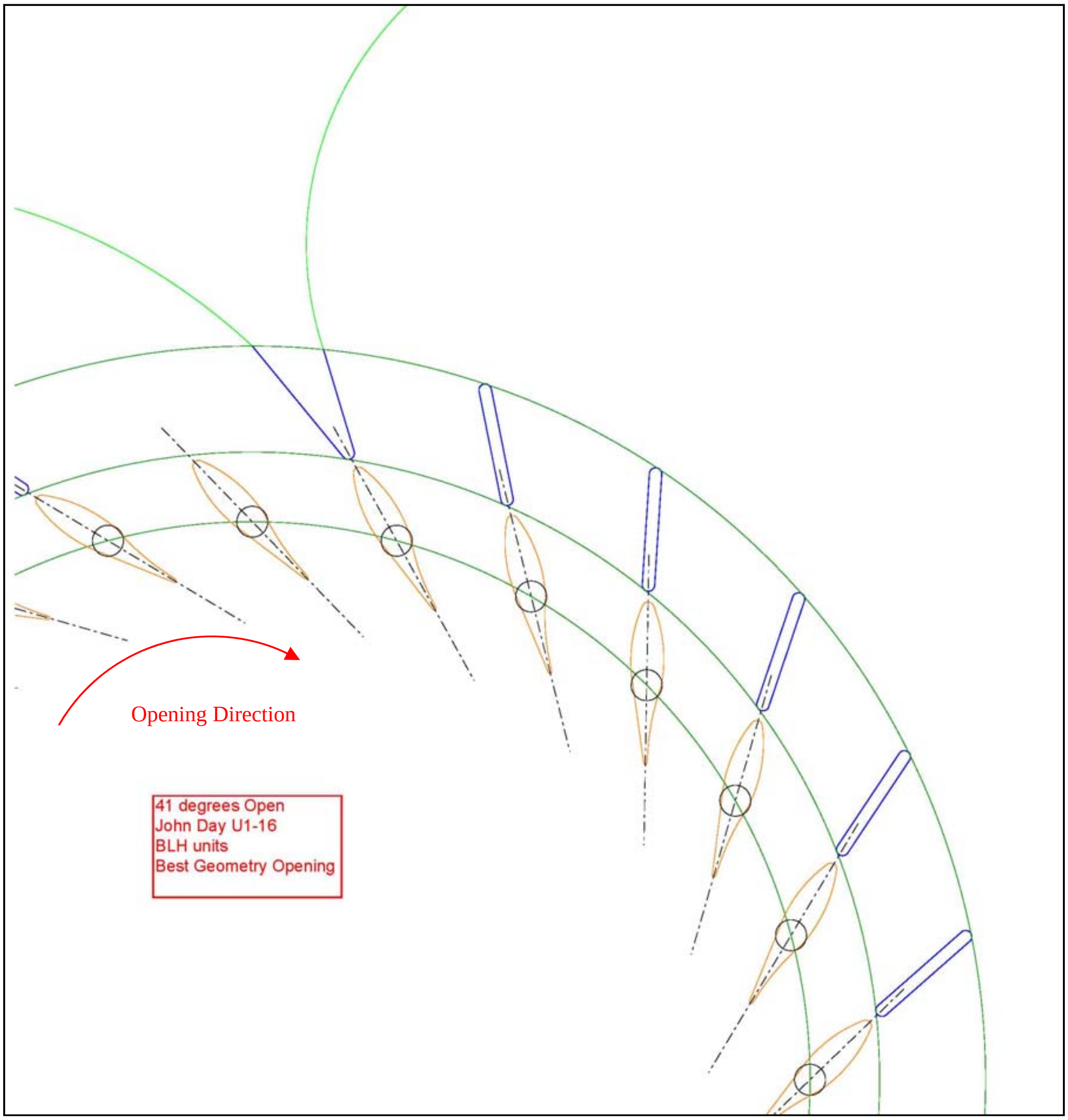
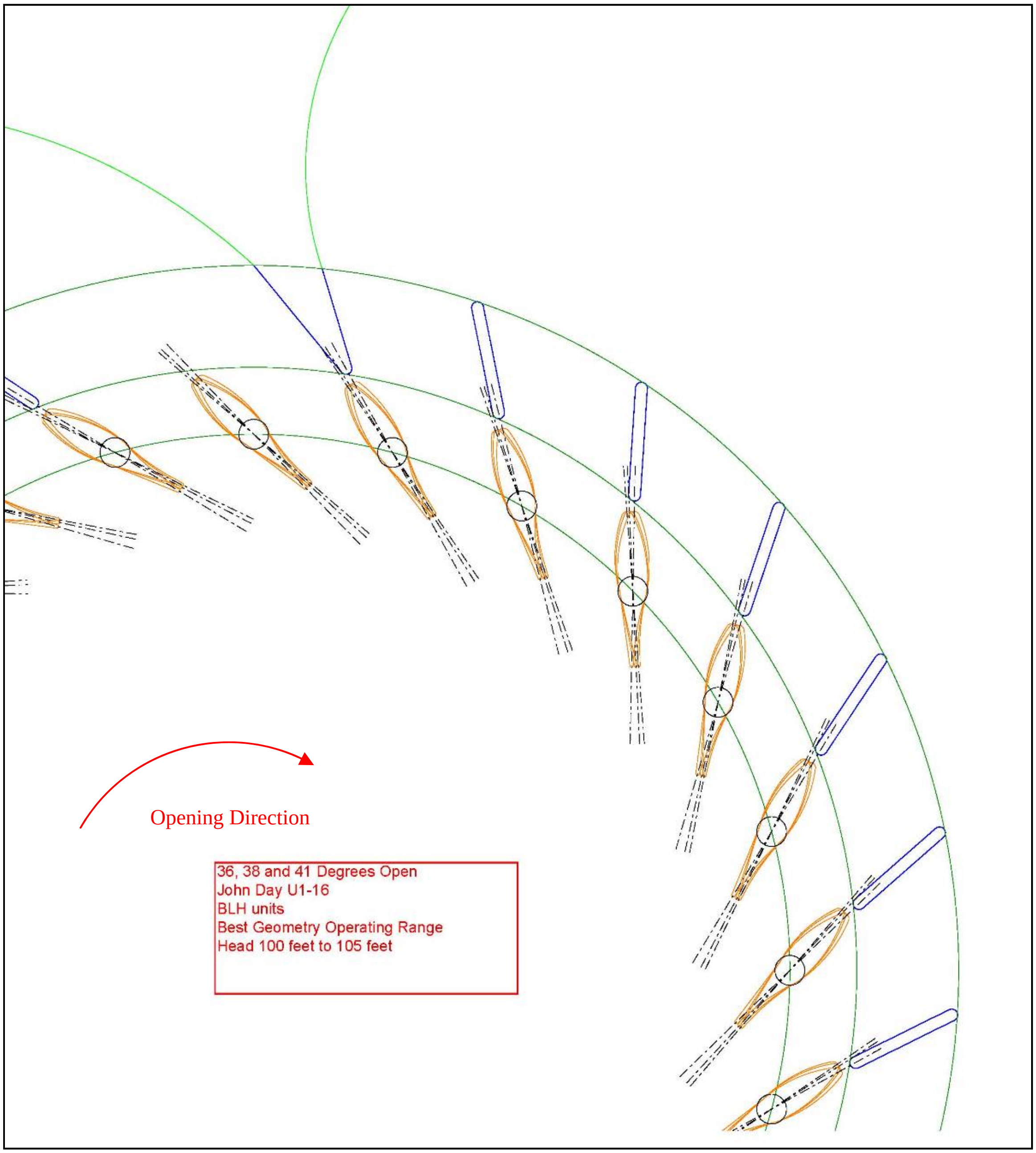


Figure 9. Best Geometry Wicket Gate Operating Range



When operated as a Kaplan, the wicket gate operating range for best geometry is 36 to 43 degrees. However, other constraints such as head, generator power limit, cavitation limit and 1% operating limit restrict operation. Considering these constraints, the normal operating range is 36 to 41 degrees open. A turbine operating zone of best geometry is defined to allow flexibility in turbine and powerhouse operation. The normal operating head range is typically between 100 to 105 feet with 102 feet being the average. The best geometric operating range for turbine survival testing (TST) will be limited to being between these two heads.

To illustrate the effect of wicket gate position on turbine geometric operation, a family of “on-cam” curves was prepared for John Day. Figure 10 represents wicket gate and runner blade geometric relationship for a range of 90 to 105 feet head. Overlaid on this graph are generator limit, 1% limits and best operating point for each head. The shaded area (red) is the zone (100 to 105 feet head) of best geometric operation of a John Day turbine.

Figure 10. Best Geometry Operating Range

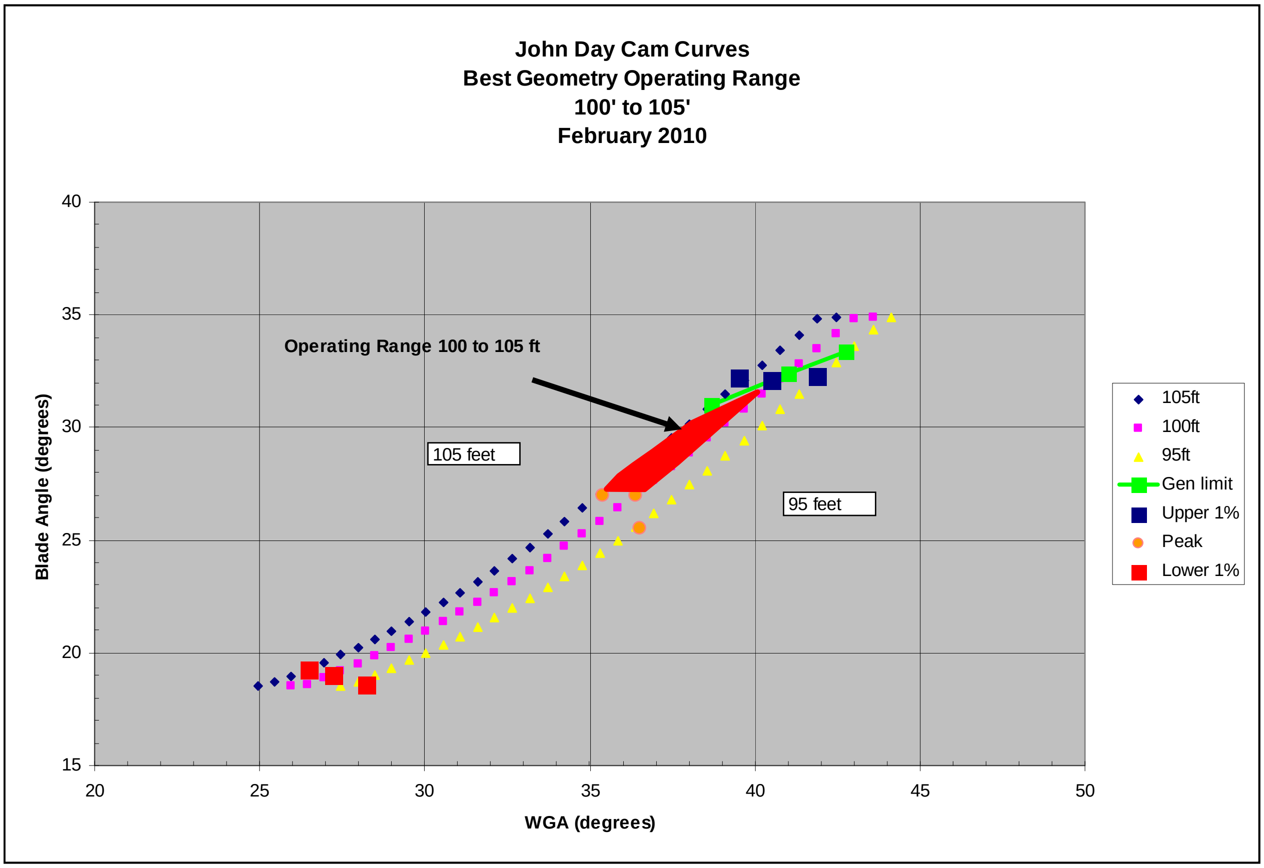


Figure 10 shows the zone of best turbine operating geometry for John Day; however, this information is difficult to relate to existing operating parameters such as power and wicket gate servomotor percent open. To better illustrate the turbine-operating zone based on power, Figure 11 was prepared. This figure overlays the best geometric zone of turbine operation on the turbine performance curves of 100 to 105 feet of head with the various operational constraints identified.

Figure 11. Turbine Best Geometry Operating Power Range

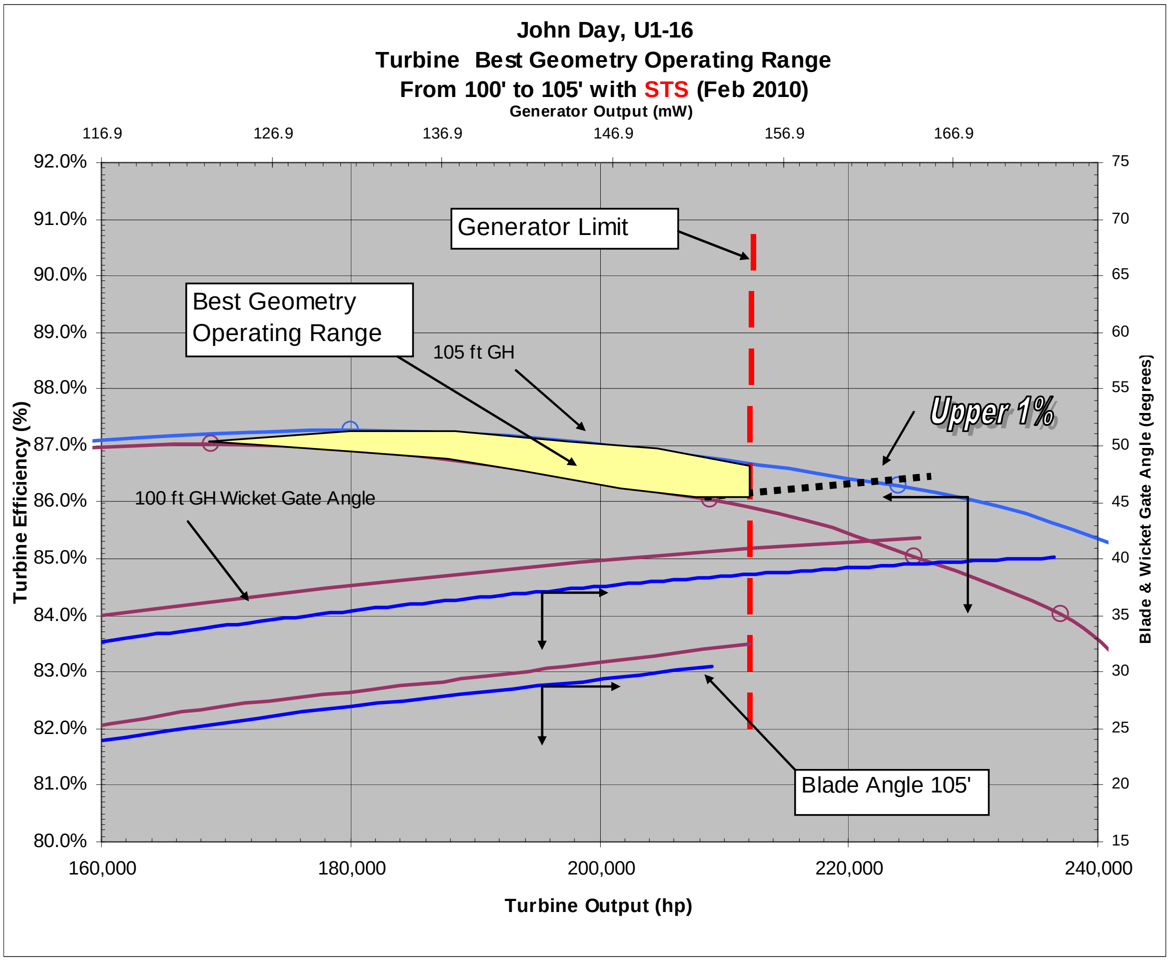


Table 1 shows the operating conditions (for on-cam operation) over the target geometry range and at best geometry for wicket gate alignment.

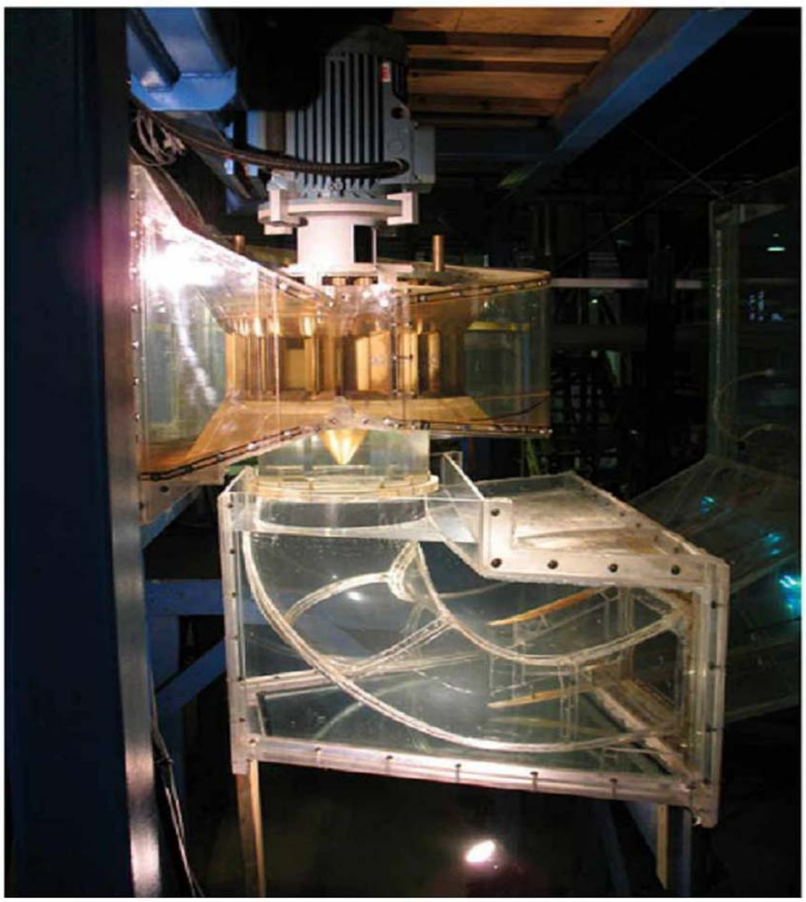
Table 1. Best Wicket Gate Geometry for John Day at 95 feet of head

Parameter	Best Geometry	Best Geometry Range	
		Lower	Upper
Wicket Gate Angle – degrees open	41.0	36	43
Blade Angle – degrees open	31.5	26.2	33.6
Power – horsepower (hp)	200,500	155,800	212,400
Flow – thousand cubic feet per second (kcfs)	21.70	16.70	23.10
Efficiency – %	85.70%	86.4%	85.1%

2.2. Physical Observational Model Information

The John Day physical turbine model is a 1:25 Froude-based scale model of a single turbine unit constructed at the Engineering Research and Development Center (ERDC) in Vicksburg, MS (Figure 12). The model replicates 800 feet of approach, each of the three intake bays, the scroll case, the distributor including all adjustable wicket gates and stay vanes, the six-bladed Kaplan turbine runner, the draft tube, and 400 feet of downstream topography. The model was used to evaluate the hydraulic condition within the turbine and the potential impact of variable turbine operations on fish. The evaluation included the release of dye into the turbine flow path to observe general flow patterns, extensive velocity measurements using a Laser Doppler Velocimeter (LDV) and high-speed imaging of neutrally buoyant beads released into the flow path.

Figure 12. John Day 1:25 Physical Model Turbine and Draft Tube



The prototype flow rates investigated were approximately 11.80 thousand cubic feet per second (kcfs), 16.30 kcfs, 18.60 kcfs, and 19.90 kcfs for the runner operated as Kaplan. These correspond to approximately lower 1%, between peak and lower 1%, and two points between peak and upper 1%. Prior to pinning some blades in the field, additional tests were conducted at the lower 1%, peak and upper 1% for the runner operated as a propeller at a fixed-blade angle of 29 degrees. These tests were performed approximately at the average project head of 102 feet (prototype scale) with the STS installed.

Neutrally buoyant beads were introduced at various points within the intake. High-speed video was then used to determine potential shear and strike injury by observing indications of bead contacts and severe change in directions (those that did not follow the general flow direction). It was proven through a study at McNary Dam that fish do not behave as passive particles within an intake at 7.0 kcfs and 12.0 kcfs through a turbine (Carlson 2002). However, the passive particle hypothesis is an assumption that must be made without solid alternative information, although this assumption may be valid for passage within the runner due to the high velocities. Release points were found that corresponded to passage at the runner hub and the runner blade tip. Without adequate information on fish distribution, an equal distribution within the runner was assumed. Therefore, all the bead passage data was averaged together for information presented in this appendix.

The first major area that presents a chance of strike injury is in the vicinity of the stay vanes and wicket gates. High-speed video was used to analyze the percentage of beads that had a severe contacts and change in direction while passing either the stay vanes or wicket gates (Figure 13). The physical model showed that the percentage of beads contacting these structures was much more constant across the operating range than the change in direction. Additionally, the lowest number of direction changes seemed to occur for flows larger than 16.0 kcfs. The percentage of beads passing through the gap between the stay vanes and wicket gates were also analyzed using the high-speed video (Figure 14). Unlike the contacts and direction changes, this percentage appears to increase with flow and be relatively unrelated to the best wicket gate geometry; however, the percentages at all operating points is still very low.

Figure 13. Severe Bead Contacts and Direction Changes at Stay Vanes and Wicket Gates

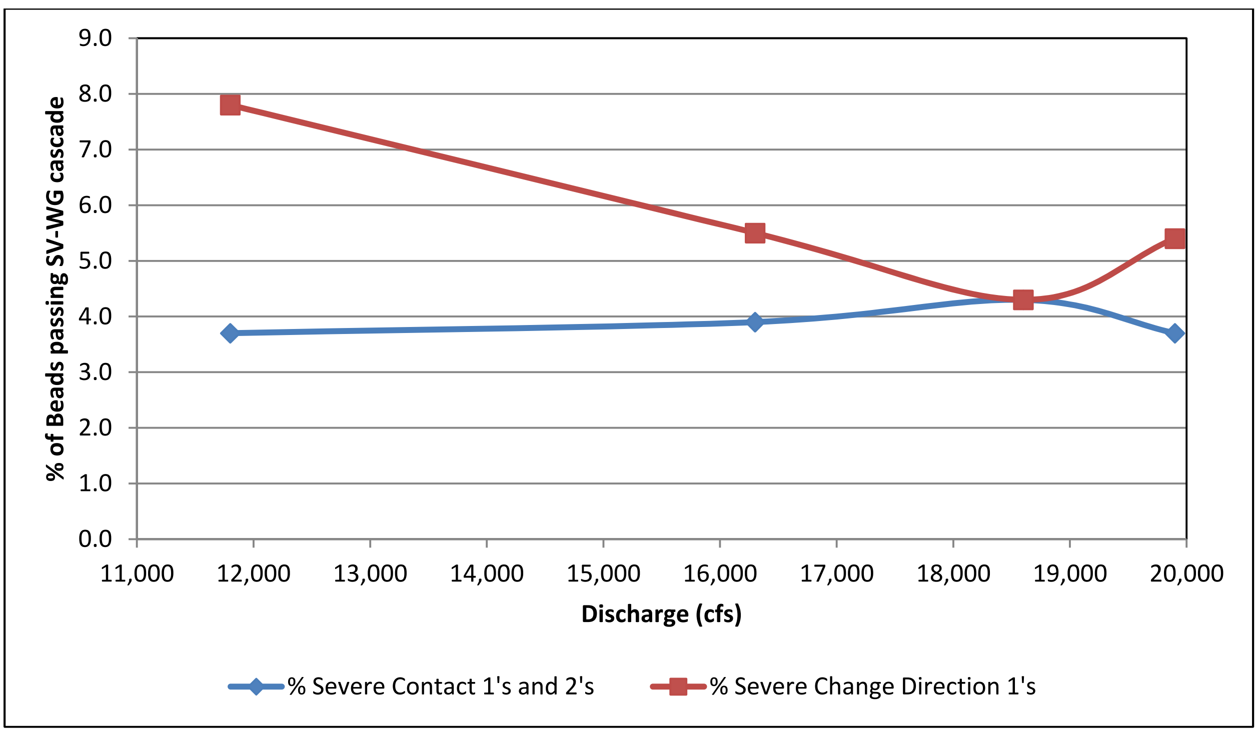
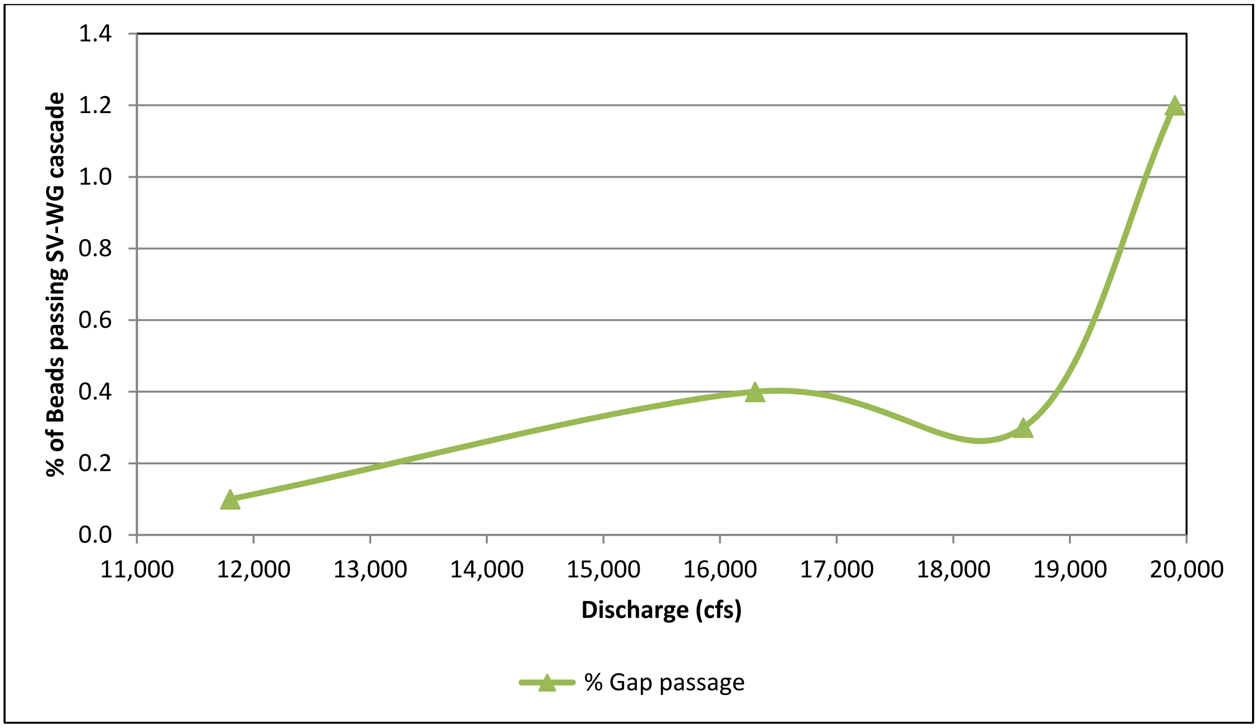
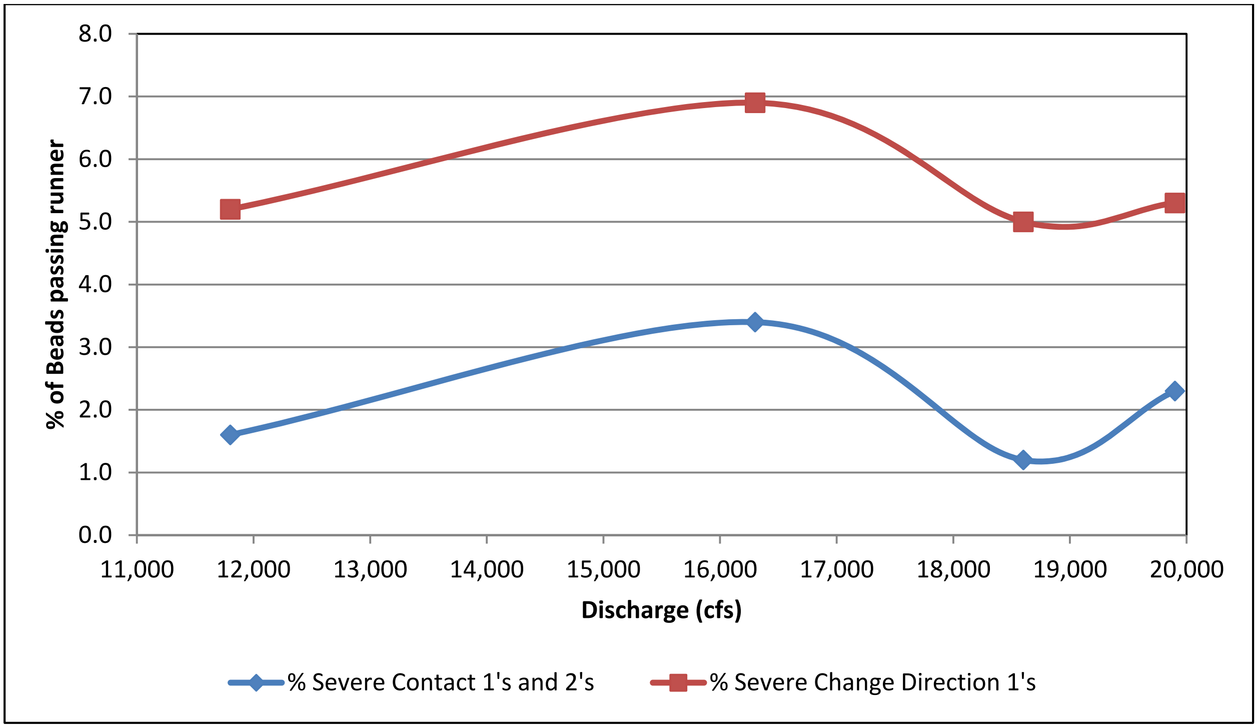


Figure 14. Beads Passing Through Gap between Stay Vanes and Wicket Gates



The next area for potential mechanical injury for fish is passing the runner blades of the turbine. As with the stay vane region, analysis of beads contacting the runner can give us an indication of potential injury. In general, Figure 15 shows that contact and direction change within the runner decreases with increasing flow rate through the runner but surprisingly the lower 1% has low numbers. Increasing flow rate of course corresponds to an increase in blade angle and increased open area within the runner environment.

Figure 15. Severe Bead Contacts and Direction Change within Runner



In addition to the bead analysis, velocity measurements were made at multiple transects using a LDV. The draft tube exit is one area that displayed a large difference between the tested flow rates as determined by velocity measurements. The draft tube for the John Day turbine units has a single vertical splitter wall which divides the draft tube into two barrels (designated A and C) of equal cross-sectional area and length. The velocities at the draft tube exit were used to estimate the flow rate through each of these barrels. Barrel A has a much higher flow rate than barrel C at the lower turbine flows, but the flow distributes more evenly for flow rates of 16.30 kcfs and higher (Figure 16). Relating the average barrel velocity with individual velocity measurements, turbulence intensity is a measure of variability within the draft tube. Data indicates that turbulence intensity decreases with increasing flow for both barrels, but particularly in barrel C (Figure 17). This also corresponds to a qualitative observation of a large vortex existing below the runner at the lower 1% that disappears at higher discharges. Results shown in these two figures relate to the fact that the draft tubes were designed to pass the highest design flows; thus, the full flow area is not fully utilized at lower flow rates resulting in areas of recirculation. The increased turbulence at the lower flow rates could cause fish disorientation. While a direct injury or mortality may not result, the disorientation has the potential to increase vulnerability to predation.

Figure 16. Flow Percent Passing Through Each Draft Tube

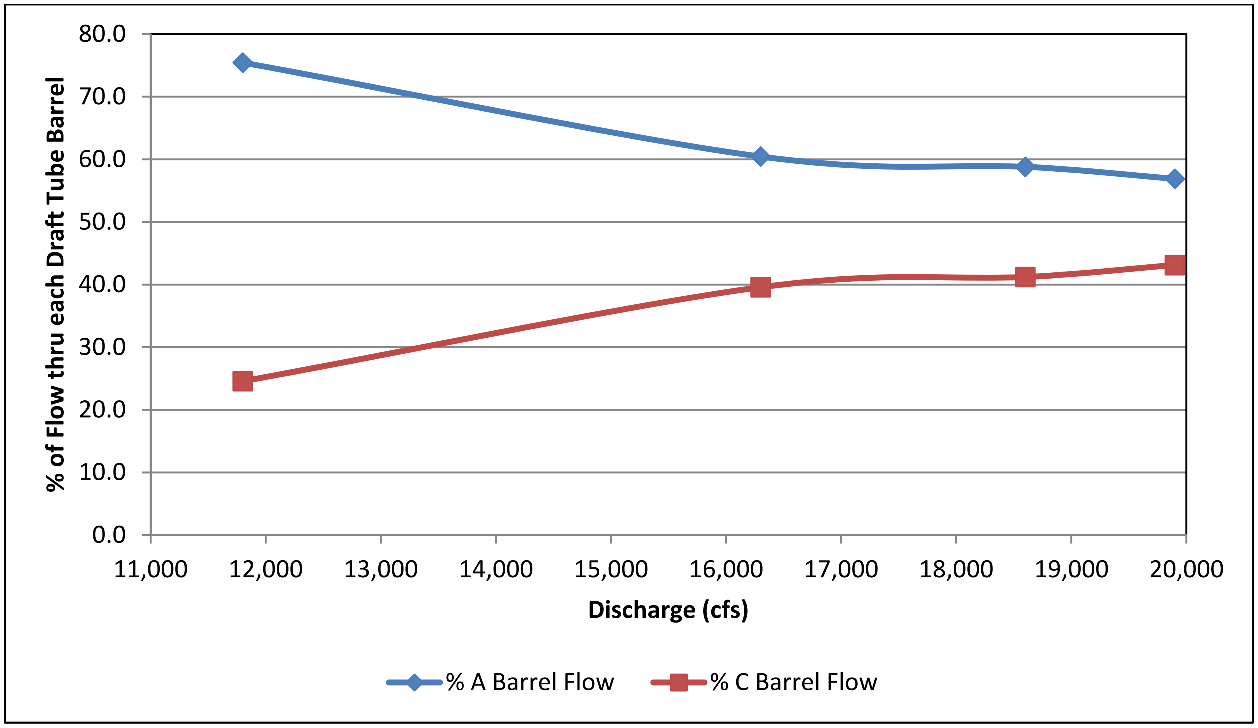
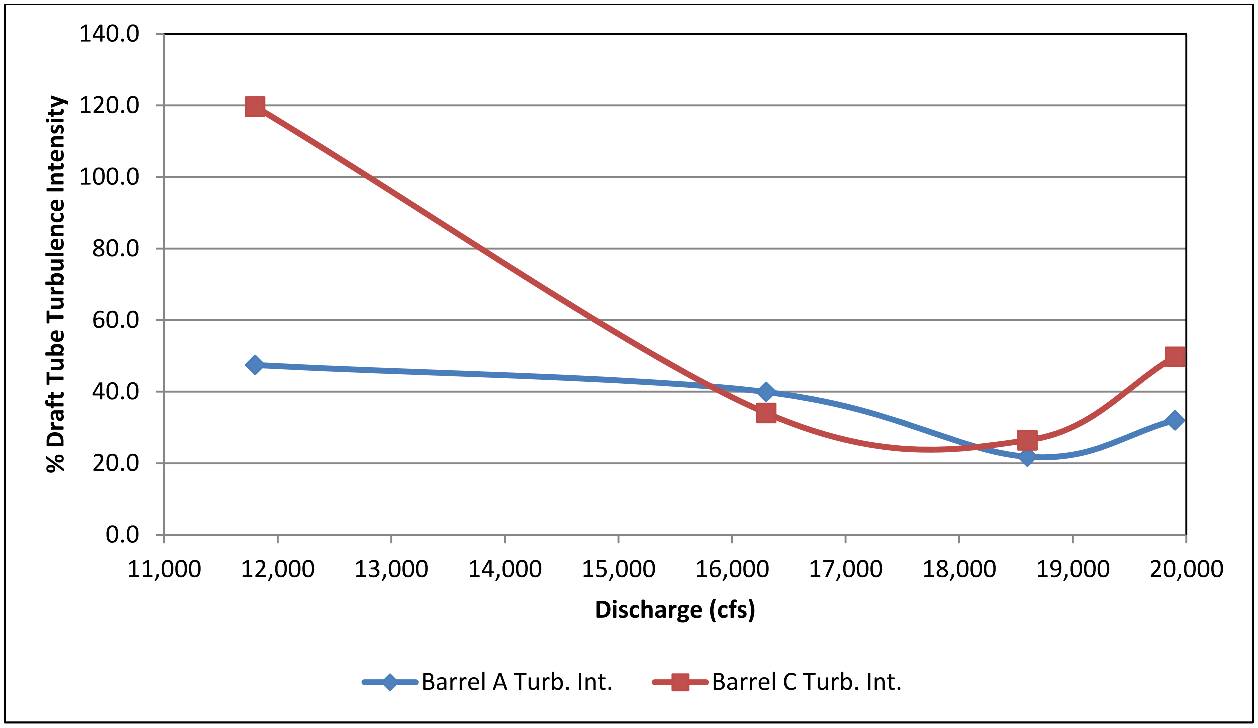


Figure 17. Turbulence Intensity for Draft Tube Barrels



Based on physical model information, flow rates above 16.30 kcfs (slightly above peak efficiency) show improved hydraulic conditions over flow rates below 16.30 kcfs. There is some improvement in draft tube conditions for flow rates higher than 16.30 kcfs and additionally the best operating point for runner passage is the 18.60 kcfs or 29 degree on-cam operating point. It would be expected that mechanical and shear related injuries would reduce between peak efficiency and the 18.60 kcfs operating point (compared to operating at the low end of the operating range). For both the distributor and the runner the collected model information shows an increase in bead contact and direction change above the 18.60 kcfs operating point. While the increase is not significant for the runner passage, this points to little fish passage benefit for increasing discharge significantly above the 18.60 kcfs operating point.

2.3. Pressure Information from Laboratory and Field Data

An assessment of barotrauma mortality risk for John Day turbines were made using relationships established with laboratory testing (see Section 3.4 in the Phase II Main Report), field pressure data collected with sensor fish, and CFD information. To apply this laboratory data to fish passage at John Day for run-of-river fish, the acclimation pressure and the nadir pressure are needed. There is minimal information for the acclimation pressure for fish entering the John Day turbines; however, the nadir pressure for three operating points has been identified using sensor fish (Figure 18). Computational fluid dynamics has also been used to define the nadir pressure for the same three operating points (Figures 18 and 19). The CFD results and descriptions of the methods used for generating a nadir distribution are discussed in the 2011 Electric Power Research Institute-Department of Energy conference proceedings (Kiel and Ebner 2011).

Figure 18. Sensor Fish and CFD Data for John Day

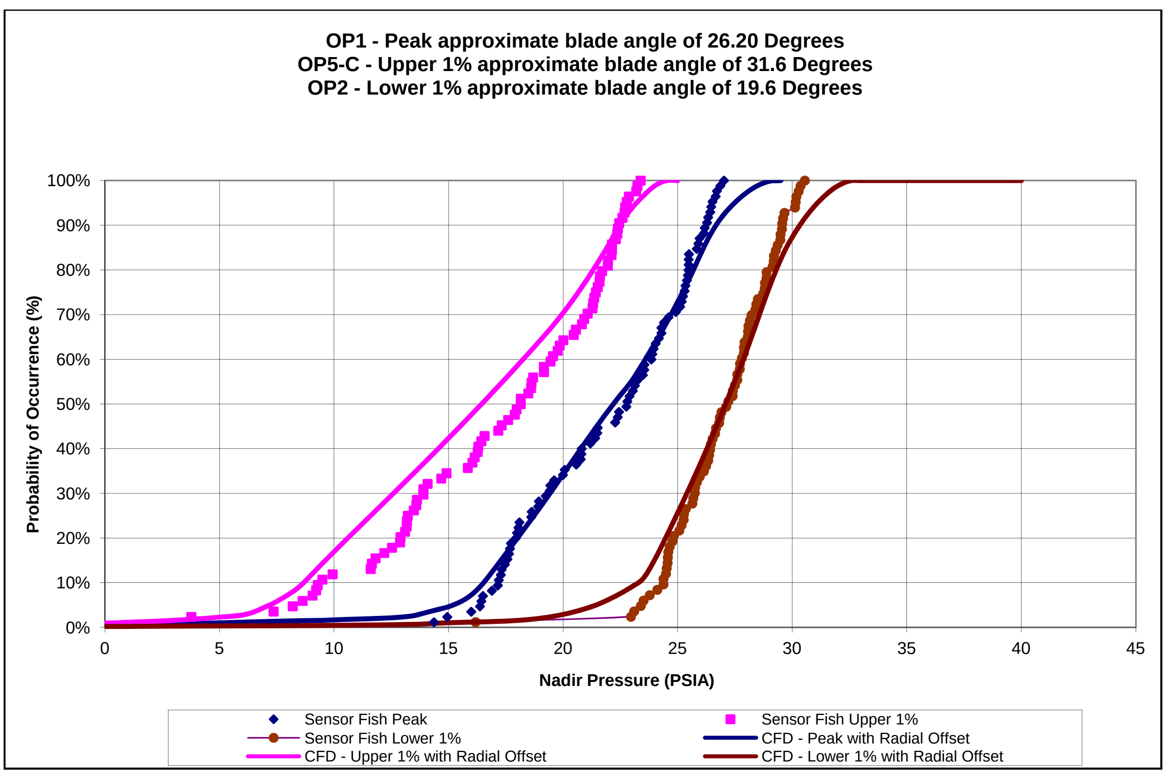
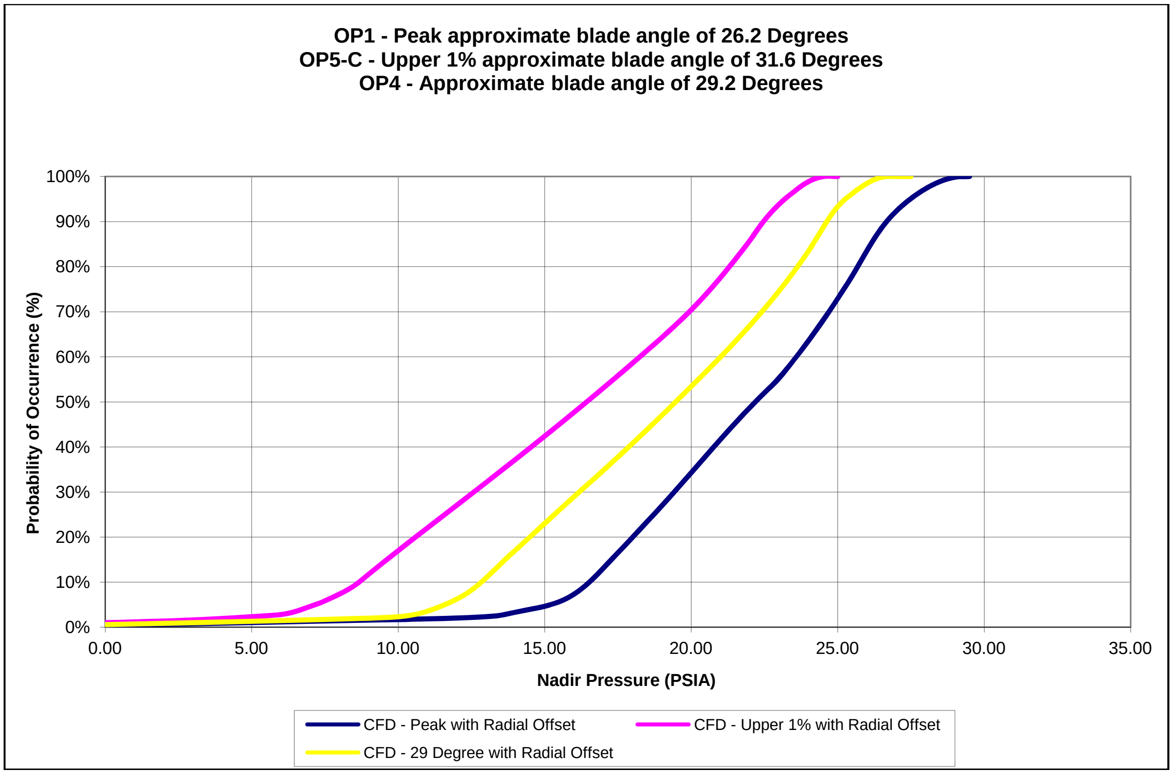


Figure 19. CFD Data for John Day



In addition, nadir and acclimation pressures need to be determined to estimate the mortality rate for untagged juvenile Chinook salmon using Equation 2 (see Section 3.4 in the Phase II Main Report). Since little is known about acclimation depth of juvenile salmon approaching turbines, four acclimation depth (or pressures) are shown in Table 2. For the purposes of this report, a predicted maximum acclimation depth of 22 feet (Pflugrath et al. 2012) will be used to compare predicted barotrauma mortality rates at different operating conditions with those from other sources. The predicted pressure related mortal injury varies significantly across the distribution of nadir pressures that fish acclimated to a distribution of depths may experience. Additional methods are to utilize the full nadir distribution generated by the CFD by determining probabilities for different nadir bins, as well as the acclimation distribution; however, for the purposes of this appendix, the single maximum acclimation depth of 22 feet will be utilized.

Table 2. Calculated Mortality at John Day (using Equation 2)

Parameter	**Nadir Pressures (psia)**	**Calculated Fish Mortality for Lower 1% Operating Condition**			
		0 ft Water Acclimation	**10 ft Water Acclimation**	**22 ft Water Acclimation**	**25 ft Depth Acclimation**
Mean Nadir	22.19	0.08%	0.21%	0.54%	0.66%
Minimum Nadir	0.73	99.75%	99.91%	99.96%	99.97%
Maximum Nadir	30.55	0.02%	0.06%	0.16%	0.19%
		Calculated Fish Mortality for Peak Operating Condition			
Mean Nadir	21.97	0.08%	0.22%	0.56%	0.68%
Minimum Nadir	14.36	0.42%	1.13%	2.81%	3.41%
Maximum Nadir	27.02	0.04%	0.10%	0.25%	0.31%
		Calculated Fish Mortality for Upper 1% Operating Condition			
Mean Nadir	16.08	0.27%	0.73%	1.83%	2.23%
Minimum Nadir	0.125	100.00%	100.00%	100.00%	100.00%
Maximum Nadir	22.87	0.07%	0.19%	0.48%	0.58%

Table 3 shows the results using the risk assessment method. It is interesting to compare the results of the risk assessment method to the single point method in that for the same acclimation depth, the predicted mortality is greater than using the median nadir pressure but certainly less than using the minimum nadir pressure, which appears to indicate that the calculated mortality by this method is heavily influenced by the high mortality rate of the less frequent low nadirs. Due to uncertainties for both the acclimation exposure, the magnitude of the difference between the operating conditions cannot be predicted. However, the direct mortality due to decompression is most likely higher at higher flow rates and the risk assessment mortality estimates at 22 feet of acclimation will be used, which likely slightly overestimates the mortality rate.

Table 3. Calculated Mortality at 22 feet Acclimation Using Risk Assessment Method

Turbine Passage Condition	Turbine Discharge (kcfs)	Calculated Mortality (%)
Lower 1%	11.80	0.62%
Peak	16.50	1.81%
Upper 1%	20.30	6.18%

2.4. BIOLOGICAL FIELD STUDY INFORMATION

The John Day Configuration and Operation Plan (USACE 2007) describes project passage distribution and survival for the various passage routes at John Day. Tables 3-2, 3-3 and 3-4 in the plan are replicated here as Tables 4, 5 and 6. Turbine survival has not been correlated to turbine operating condition.

Table 4. Estimated Passage Distribution and Survival for Yearling Chinook Salmon

Year	Spill Treatment % spill day/night	Spillway		Juvenile Bypass		Turbine		Dam Passage Survival
		Passage	Survival	Passage	Survival	Passage	Survival	
1999	12-hr 0/45	52.6	---	29.9	---	17.5	---	---
	24-hr 30/45	65.6	---	21.9	---	12.5	---	---
2000	12-hr 0/53	75.1	98.6 (92.5, 104.7)[a]	14.6	---	10.3	---	97.6 (90.9, 104.3)[a]
	24-hr 30/53	85.8	93.7 (87.6, 99.8)[a]	6.0	---	8.2	---	93.5 (87.8, 99.2)[a]
2001	12-hr 0/30	---	---	---	93.2 (89.0, 97.4)[a]	---	---	---
2002	12-hr 0/54	48.1	99.3 (95.8, 103.0)	36.0	91.1 (85.7, 95.9)[a]	15.9	77.8 (67.3, 87.0)	92.9 (89.5, 96.3)
	24-hr 30/30	53.1	100.0 (96.5, 104.0)	26.7	99.1 (94.0, 103.0)[a]	20.2	83.2 (74.4, 90.9)	96.3 (93.0, 99.6)
2003	12-hr 0/60	56.7	93.4 (90.0, 96.3)	29.0	101.9 (99.6, 103.6)	14.3	89.1 (82.9, 95.3)[b]	92.2 (87.5, 96.9)
	12-hr 0/45	47.4	93.9 (90.3, 96.7)	36.2	98.8 (95.9, 100.8)	16.4	80.7 (77.2, 84.2)[c]	94.0 (89.9, 98.1)

Passage distribution is the percentage of all study fish passing JDA. The 95% confidence intervals (CI) are in parentheses. Survival estimated using the route-specific survival model, unless otherwise noted.

[a] Survival estimated using the paired release-recapture model.

[b] Estimated turbine survival for fish released directly into turbine intake during the day/no spillway operations.

[c] Estimated turbine survival for fish released directly into the turbine intake at night during 45% spill.

Table 5. Estimated Passage Distribution and Survival for Subyearling Chinook Salmon

Year	Spill Treatment % spill day/night	Spillway		Juvenile Bypass		Turbine		Dam Passage Survival
		Passage	Survival	Passage	Survival	Passage	Survival	
1999	12-hr 0/25	44.0	---	---	---	---	---	---
	12-hr 0/51	50.0	---	---	---	---	---	---
	24-hr 28/51	78.0	---	---	---	---	---	---
	24-hr 21/25	58.0	---	---	---	---	---	---
2000	12-hr 0/59	53.9	---	24.8	---	21.3	---	---
	24-hr 30/59	81.5	---	9.6	---	8.9	---	---
2001	24-hr 0/0	---	---	---	86.8 (78.4, 95.2)[a]	---	---	---
2002	12-hr 0/54	41.7	98.5 (93.4, 102.3)	28.9	---	29.4	86.6 (79.5, 92.8)[b]	92.8 (88.5, 97.1)
	24-hr 30/30	57.1	100.3 (98.3, 107.8)	13.1	---	29.8	96.6 (88.5, 103.1)[b]	99.2 (94.1, 104.3)
2003	12-hr 0/60	48.1	90.1 (87.7, 92.2)	22.6	89.2 (85.5, 92.4)	29.3	71.9 (67.1, 76.4)	84.5 (81.4, 87.6)
	24-hr 30/30	61.7	95.5 (93.8, 97.0)	13.1	92.1 (87.7, 95.5)	25.2	72.2 (67.3, 76.7)	88.6 (85.6, 91.6)

Passage distribution is the percentage of all study fish passing the project. The 95% confidence intervals (CI) are in parentheses. Survival estimated using the route-specific survival model, unless otherwise noted.
[a] Survival estimated using the paired release-recapture model.
[b] Estimate represents total powerhouse passage survival (turbine- and JBS-passed fish combined).

Table 6. Estimated Passage Distribution and Survival for Juvenile Steelhead

Year	Spill Treatment % spill day/night	Spillway		Juvenile Bypass		Turbine		Dam Passage Survival
		Passage	Survival	Passage	Survival	Passage	Survival	
1999	12-hr 0/45	44.9	---	49.3	---	5.8	---	---
	24-hr 30/45	52.6	---	37.8	---	9.6	---	---
2000	12-hr 0/53	68.8	98.8 (96.1, 101.5)[a]	24.2[d]	---	7.0[d]	---	95.7 (91.6, 99.8)[d]
	24-hr 30/53	76.0	90.5 (84.0, 97.0)[a]	15.3[d]	---	8.7[d]	---	90.4 (83.7, 97.1)[d]
2001	12-hr 0/30	---	---	---	91.7 (87.7, 95.7)[a]	---	---	---
2002	12-hr 0/54	57.2	95.8 (89.9, 100.0)	28.0	88.2 (82.2, 94.2)[b]	14.8	93.0 (84.7, 99.5)[c]	94.0 (88.7, 99.3)
	24-hr 30/30	55.3	93.2 (85.7, 98.8)	34.6	92.6 (85.9, 99.3)[b]	10.1	89.9 (80.7, 96.7)[c]	91.5 (86.2, 96.8)

Passage distribution is the percentage of all study fish passing the project. The 95% confidence intervals (CI) are in parentheses. Survival estimated using the route-specific survival model, unless otherwise noted.
[a] Survival estimated using the paired release-recapture model.
[b] Estimated survival for fish released directly into the JBS during night spill operations.
[c] Estimated total powerhouse passage survival (turbine- and JBS-passed fish combined due to lower numbers of fish passing either route).
[d] Estimated passage efficiency through turbines and the JBS were calculated using the spill passage efficiency (SPE) and fish passage efficiency (FPE) estimates (FPE-SPE = JBS passage and 1-FPE = turbine passage).

Normandeau and Skalski (2007) conducted a study of turbine survival of juvenile hatchery Chinook (total length = 117-183 millimeters) at John Day Dam in 2006. Fish were balloon tagged and released directly into the A, B, and C intake bays of unit 9 and turbines were operated at the lower 1%, peak, and upper 1% range (Table 7). Recapture rates were high ranging from 96.1% to 99.4%. The lowest 48-hour survival (93%; 95% CI = 89.3% to 96.7%) was observed in the B intake at peak efficiency, and highest 48-hour survival (98%; 95% CI = 95.9% to 100.1%) was observed in the A intake at the lower 1% (Table 7). Control fish were released in the tailrace with 100% survival.

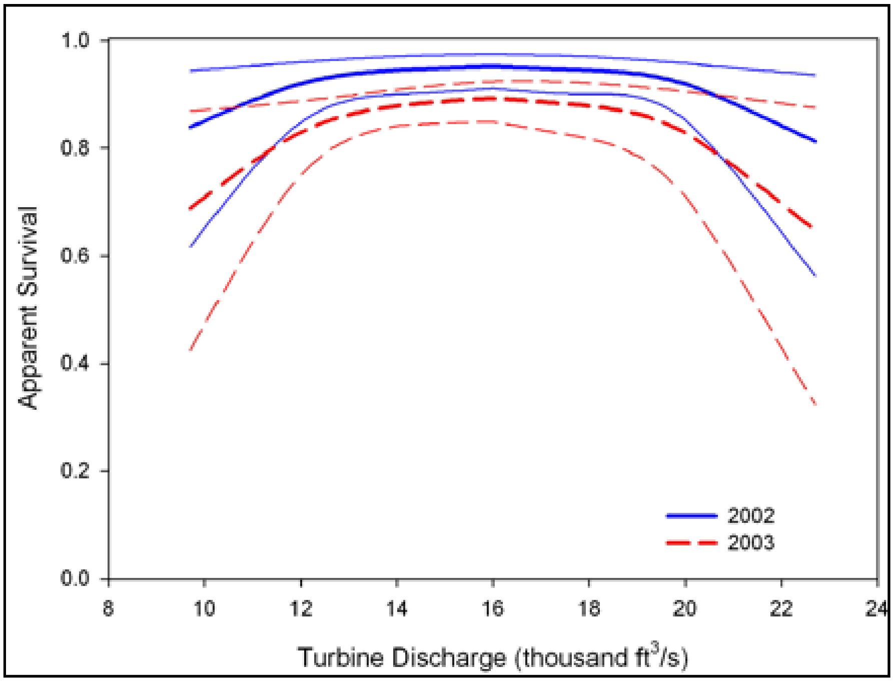
Table 7. Juvenile Chinook Turbine Survival for John Day within 1% Operating Range

Intake Bays	Lower 1% Efficiency (11.8 kcfs)	Peak Efficiency (16.6 kcfs)	Upper 1% Efficiency (best geometry) (19.9 kcfs)
Slot A	0.979 (0.011)	0.939 (0.020)	0.977 (0.013)
Slot B	0.931 (0.019)	0.930 (0.019)	0.940 (0.019)
Slot C	0.935 (0.020)	0.932 (0.020)	0.959 (0.015)

*Survival estimates presented with standard error in parenthesis.
Source: Normandeau and Skalski 2007.

In 2010, the U.S. Geological Survey was contracted by the USACE to conduct an analysis of data from previous radio or acoustic tagged juvenile salmonids passing through John Day turbines (Beeman et al. 2011). Passage survival data at John Day from 2002 and 2003 was pooled and associated with environmental and operating conditions at time of passage. A relationship between turbine passage survival and water temperature was found for both yearling and subyearling Chinook. It is possible that water temperature could affect the acclimation depth of turbine passed fish and therefore, could affect the barotrauma mortality rate. Additionally, a quadratic relationship of subyearling Chinook survival relative to turbine unit discharge was found (Figure 20). No relationship was found for yearling Chinook. It can be noticed that the peak of the survival curve is very broad and difficult to differentiate. The areas of the graphs that do exhibit lower survival are based on very few operating points; therefore, this might not be the correct fit for the data. While this analysis was an important step, the results of the analysis indicate that a targeted turbine survival test might better define the effect of turbine unit discharge on survival.

Figure 20. John Day Turbine Unit Effect for Subyearling Chinook

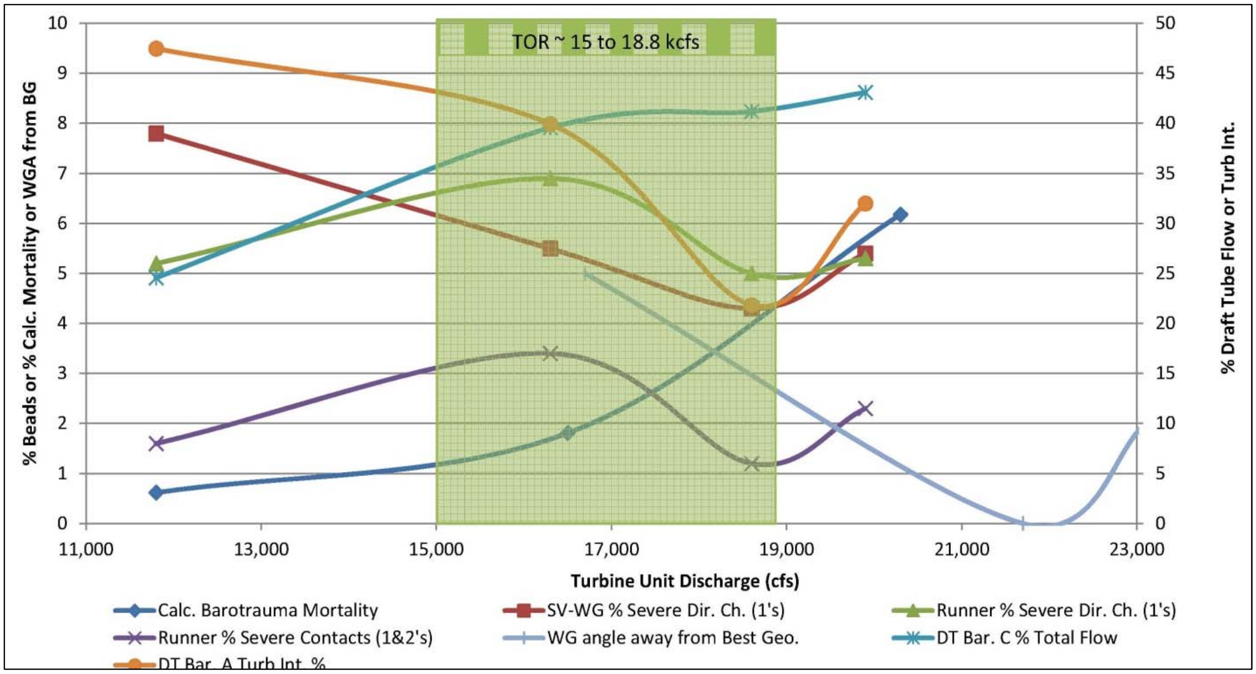


2.5. DISCUSSION

The preceding sections presented the available turbine survival information applicable to John Day turbines. This information comes from geometry considerations, physical model data, laboratory studies, field passage and survival studies, some CFD analysis, and sensor fish studies. None of the information alone can identify a target operating range for survival of fish passing through turbines. While the biological studies performed in the field may attempt to measure the direct mortality of fish passing through the turbines, all studies to date have limitations and may not accurately estimate mortality for run-of- river fish passing through turbines with natural depth acclimation and without tag burden.

The turbine physical model provided valuable information on physical injury inside turbines, especially with the bead passage analysis. However, the model data did not indicate the frequency of barotrauma injury and did not account for fish behavior. The barotrauma injury rate can be inferred from using the sensor fish combined with the CFD data (Carlson et al. 2010; Kiel and Ebner 2011) and the laboratory data (Carlson et al. 2010). These various sources of information have been combined in Figure 21. This figure only shows information that point at direct turbine mortality factors. It is important to remember that all the information is not equal since calculated pressure mortality would likely be mortalities, while direction changes and draft tube turbulence would only factor into injury and possible mortality.

Figure 21. Combined Information on Direct Turbine Mortality



Based on information provided in the various studies and summaries in this appendix, the recommended TOR is 15.0 kcfs to 18.0 kcfs at approximately 100 feet of head (see shaded area on Figure 21). At different heads, this flow range would change slightly. This TOR is consistent with the most open geometry and with bead strike data and draft tube conditions from the physical model. However, due to the concerns with barotraumas and low nadir pressures, the upper part of the range is limited to approximately 18.0 kcfs. The lower part of the range at 15.0 kcfs was selected to avoid the poor hydraulic conditions that appear near the lower 1% operating point, while allowing a large enough operating range to permit operating flexibility.

3. DEFINE TARGET PROJECT OPERATIONS

The John Day tailrace has a number of areas that influence tailrace egress from the project. Downstream of both the powerhouse and spillway, river thalwegs (e.g., channels), are separated by shallows in the near dam tailrace area and islands further downstream. These areas compose bathymetric obstacles to smooth tailrace egress. In addition, the contraction of the south shore in and around the area near the JBS outfall acts to force flow from turbine units 1 to 4 on a northern trajectory. These areas, in concert with spillway and powerhouse operations, act to form a variety of flow patterns and eddies that are not conducive to rapid downstream fish egress. Such flow patterns and eddies move either clockwise or counter-clockwise depending on project operations. As a result, tailrace flow patterns vary considerably, depending upon tailrace water elevations and flow levels from the spillway and powerhouse. For this reason, attaining reasonable tailrace egress conditions depends on maintaining balanced flow levels between the powerhouse and spillway. In addition, the presence of the four skeleton bays provides a gap in water flow where predator species can reside. This gap creates either a localized eddy just downstream of the skeleton bays or a significant stagnant region in the same area, depending on project operations.

With these difficulties in mind, in March 2012 the powerhouse egress at John Day Dam was evaluated in the 1:80 general model at ERDC. The modeling focused on low flow conditions were egress is more challenging. The river discharges investigated were 250 kcfs, 200 kcfs, 150 kcfs and 100 kcfs. Turbine unit discharges of 15.30 kcfs were used as a starting point representing current operations but were adjusted up and down for several model runs. Spill was modeled at 40%, 30%, 20% and 0% with and without TSWs with the existing fish passage plan patterns.

The modeling concluded that the unit priorities identified in the FPP were reasonable. Block loading the powerhouse (north and south ends) does not improve powerhouse egress due to the large area between bulked flows (either powerhouse bulked flow or spillway bulked flow) causing recirculation cells moving flow upstream. Therefore the existing pattern with TSW's installed is still recommended (5, 1, 3, 16, 14, 12, 10, 8, 15, 2, 11, 7, 4, 13, 9, then unit 6). When the spillway is in operation, powerhouse egress is reasonable when seven units are operational (at any unit operating point). Direct survival may increase if operating higher in the 1% operating range, but egress would diminish somewhat if that operation resulted in operating less than seven units. In general, powerhouse egress improves with reduced spill but especially at low river flow (below 150 kcfs). In fact below 150 kcfs, the TSW had very poor egress and project egress was better with 0% spill rather than 20% spill. However due to the significantly higher survival from spill per existing passage and survival studies, spill reduction is not likely.

4. OTHER CONSIDERATIONS

Since the proposed TOR is within the current operating range for John Day, there should be little to no effect on the JBS. No other considerations have been identified for John Day at this time.

5. RECOMMENDED PATH FORWARD

The information presented in this appendix indicates that turbine unit operation may have a significant effect on direct turbine mortality at John Day. Based on information provided, the recommended TOR is 15.0 kcfs to 18.80 kcfs at approximately 100 feet of head. This TOR is consistent with the most open geometry and with bead strike data and draft tube conditions from the physical model, while accounting for the concerns with barotraumas and low nadir pressures at the higher operating discharges.

The exploration of target project operations resulted in no change to the current unit priority. With spill at the current levels, turbine egress looks adequate when at least seven units can be operated. Below this number of units operating, significant recirculation can occur.

The TSP team proposes that a thorough turbine survival test be conducted at John Day to establish whether increased survival is seen under the TOR conditions. Indirect mortality (i.e., predation) is considered to be a large portion of total turbine mortality; therefore, any TST must make the project operating conditions as similar as possible while testing the different unit operating conditions.

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US Army Corps
of Engineers ®

PHASE II PROJECT APPENDIX

TURBINE OPTIMIZATION FOR PASSAGE OF JUVENILE SALMON AT MCNARY DAM

McNary Lock and Dam located on the Columbia River near Umatilla, Oregon.

PREPARED BY
U.S. ARMY CORPS OF ENGINEERS
TURBINE SURVIVAL PROGRAM

JUNE 2013 REVISION 0

EXECUTIVE SUMMARY

This report identifies operating conditions for turbine units at McNary Dam on the Columbia River, where turbine fish passage survival is expected to be higher based on using the tools developed by the Turbine Survival Program (TSP). The 2004 TSP Phase I Report indentified that operating conditions of large Kaplan turbine units appear to have a significant effect on the survival of fish passing through them. This TSP Phase II Project Appendix involves identifying target operating range (TOR) and the targets for project operations.

To reduce strike injuries, the physical geometry of McNary's turbine components was examined. As flow increased, wicket gates opened up and blade angles steepen. The wicket gates achieve the best alignment with the stay vanes at 43 degrees open, which corresponds to about 14.40 thousand cubic feet per second (kcfs) at 75 feet of head. Good alignment of the stay vanes and wicket gates are maintained within a wider range of 38 to 48 degrees open, which corresponds to a range of 12.90 kcfs to 16.40 kcfs at 75 feet of head.

Additional information to reduce strike frequency, exposure to shear, and turbulent environments came from a physical model of a turbine unit. High-speed video of neutrally buoyant beads was taken to assess the strike frequency and severity. The percentage of beads with severe contacts to the wicket gate or stay vanes decreased significantly between best operating efficiency and the upper 1% efficiency. Bead contact was lowest at 12.19 kcfs, 13.41 kcfs, and 16.45 kcfs and increased slightly at the highest flow rate. For the runner, the percentage of beads with severe contacts appeared to have a general decreasing trend with increasing flow rate.

Velocity data was taken at transects near the runner and draft tube exit. As expected, the runner velocity increased as flow rate increased, possibly causing increased contact severity; however, the frequency of contacts decreased. The draft tube for McNary turbines has a single vertical splitter wall that divides the draft tube into two equal sized barrels (designated A and C). Barrel A had a much higher flow rate than barrel C at the lower turbine flow rates, but the flow distributes more evenly for flow rates of 13.41 kcfs and higher. In addition, barrel C had high turbulence at low flows, which dropped significantly for flows of 13.41 kcfs and higher. The increased turbulence could cause fish disorientation. While direct injury or mortality may not result, fish disorientation has the potential to increase vulnerability to predation.

Injury and mortality (barotrauma) can also occur to fish passing through turbines due to exposure to low nadir pressures. An assessment of barotrauma mortality risk for McNary turbines was made using relationships established using laboratory testing and field pressure data using sensor fish. Using existing data and generated equations, a barotrauma mortality rate without internal tags of 0.7% for 7.66 kcfs and 2.4% for 16.56 kcfs was calculated.

Although a number of existing biological studies have estimated fish passage survival at McNary, very few have looked at fish passage survival as related to turbine operations. In 2002, balloon-tagged fish were introduced into the intake of unit 9 at four different operating conditions; the lowest mortality occurred at 13.40 kcfs discharge with survival at 12.0 kcfs being only slightly better than at 7.70 kcfs and at 16.60 kcfs.

A concurrent radio-tag study was conducted at unit 9 to estimate total turbine mortality of yearling Chinook (direct and indirect) at the 12.0 kcfs and 16.60 kcfs operating conditions. This study concluded no significant difference in mortality between the operating conditions but found an increase in mortality

with distance downstream. Both studies used fish acclimated to surface conditions, which may have biased barotrauma injury. In addition, a 2004 study using radio tags attempted to determine a difference in survival for fish passing through turbines operating at high flows outside the 1% operating range, and turbines operating at lower flow inside the 1% operating range. This study allowed natural acclimation of fish by releasing them upstream but had a significant tag burden. This study had very large confidence intervals and could not find a significant difference in high discharge (average 15.90 kcfs) and low discharge (average 11.0 kcfs) treatments.

An analysis of data from tagged juvenile salmonids passing through McNary turbines from 2002 to 2009 was conducted. This analysis found a decrease in survival with increased tag burden for both control and turbine-passed fish, but the effect was more severe for turbine-passed fish. Turbine unit discharge did not have an effect on fish passage survival as found by this analysis, but very few of the fish passed through turbines under operating conditions above the 1% efficiency range.

Based on available information, a TOR of 12.75 kcfs to 15.5 kcfs at 75 feet of head is being proposed for McNary. While the proposed TOR is supported by some field studies, the TSP team recommends that a comprehensive turbine survival test be conducted at McNary to verify that these operating conditions do improve turbine fish passage survival. There is some additional injury risk for juvenile bypass system-passed fish under higher turbine unit flow conditions, which needs to be considered prior to long-term operation within the TOR. However, there also is potential benefit that needs to be fully explored.

Indirect mortality (i.e., predation) is considered to be a large portion of total turbine mortality; therefore, physical model and computational fluid dynamics model information was looked at to see if a change in unit priority was necessary. Based on this information, the current unit priority (unit 1, then units 14 to 2) while operating in the TOR should provide the best powerhouse egress. Operation of the McNary turbines permanently within the proposed TOR will require turbine performance tests to define the TOR or the control systems.

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ACRONYMS AND ABBREVIATIONS

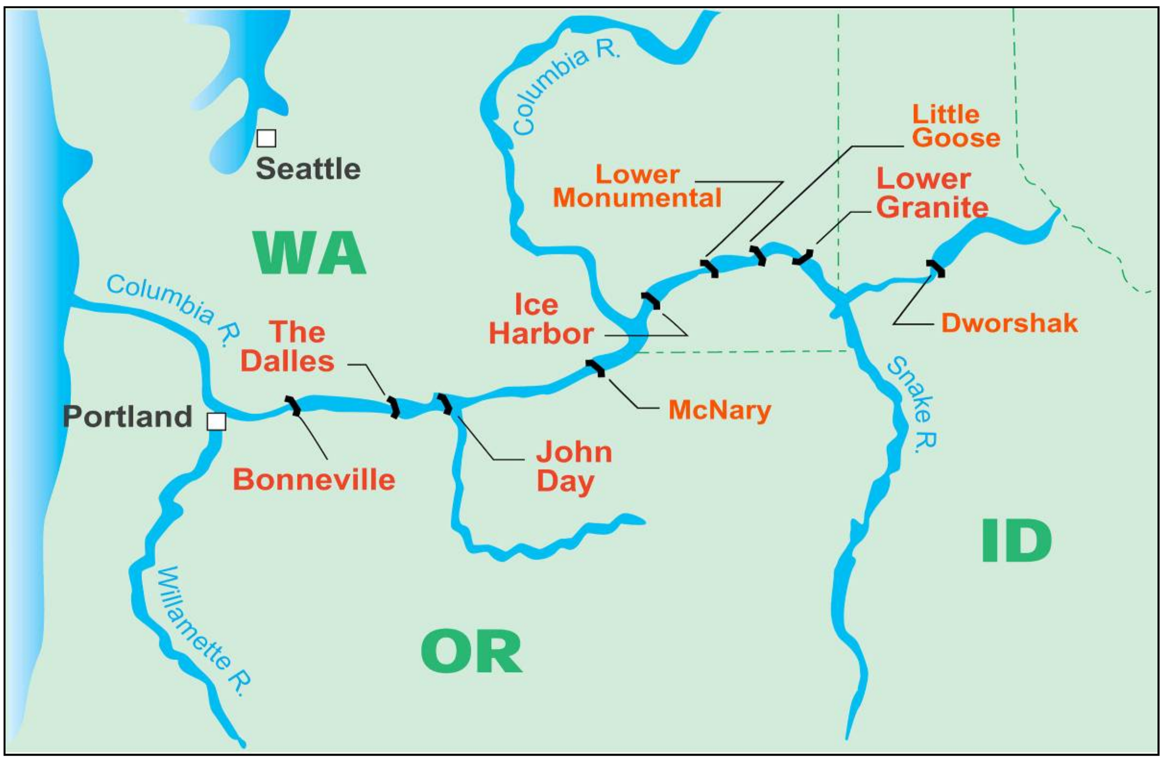
BiOp	Biological Opinion
CFD	computational fluid dynamics
cfs	cubic feet per second
CI	confidence interval
CRFM	Columbia River Fish Mitigation
ERDC	Engineering Research and Development Center
ESBS	extended-length submersible bar screens
FGE	Fish Guidance Efficiency
FPP	Fish Passage Plan
hp	horsepower
kcfs	thousand cubic feet per second
fps	feet (foot) per second
ft	feet (foot)
LDV	Laser Doppler Velocimeter
msl	mean sea level
MW	megawatt(s)
NOAA	National Oceanic and Atmospheric Administration
PIT	passive integrated transponder
PNNL	Pacific Northwest National Laboratory
psia	pounds per square inch absolute
RM	river mile
TDG	total dissolved gas
TOR	target operating range
TSP	Turbine Survival Program
TST	turbine survival testing
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VBS	vertical barrier screen
WGA	wicket gate angle

1. INTRODUCTION

The Turbine Survival Program (TSP) is part of the U.S. Army Corps of Engineers' (USACE) multi-faceted Columbia River Fish Mitigation (CRFM) program. The first phase of the TSP involved developing tools to evaluate the physical conditions fish experience as they pass through large Kaplan turbines typical of USACE projects. The TSP Phase I Report (USACE 2004) indentified that the operating conditions of the large Kaplan turbines appear to have a significant effect on survival of fish passing through them. Phase II of the TSP involves turbine survival testing (or biological index testing) at USACE facilities. This report identifies operating conditions for McNary turbines where fish passage survival is expected to be higher based on the utilization of the tools developed by the TSP program.

McNary Dam is the fourth hydroelectric project from the mouth of the Columbia River located at river mile (RM) 292 (Figure 1). It is the first dam downstream from the confluence of the Columbia and Snake rivers and influences anadromous fish migrations from both river systems.

Figure 1. Location of McNary Lock and Dam

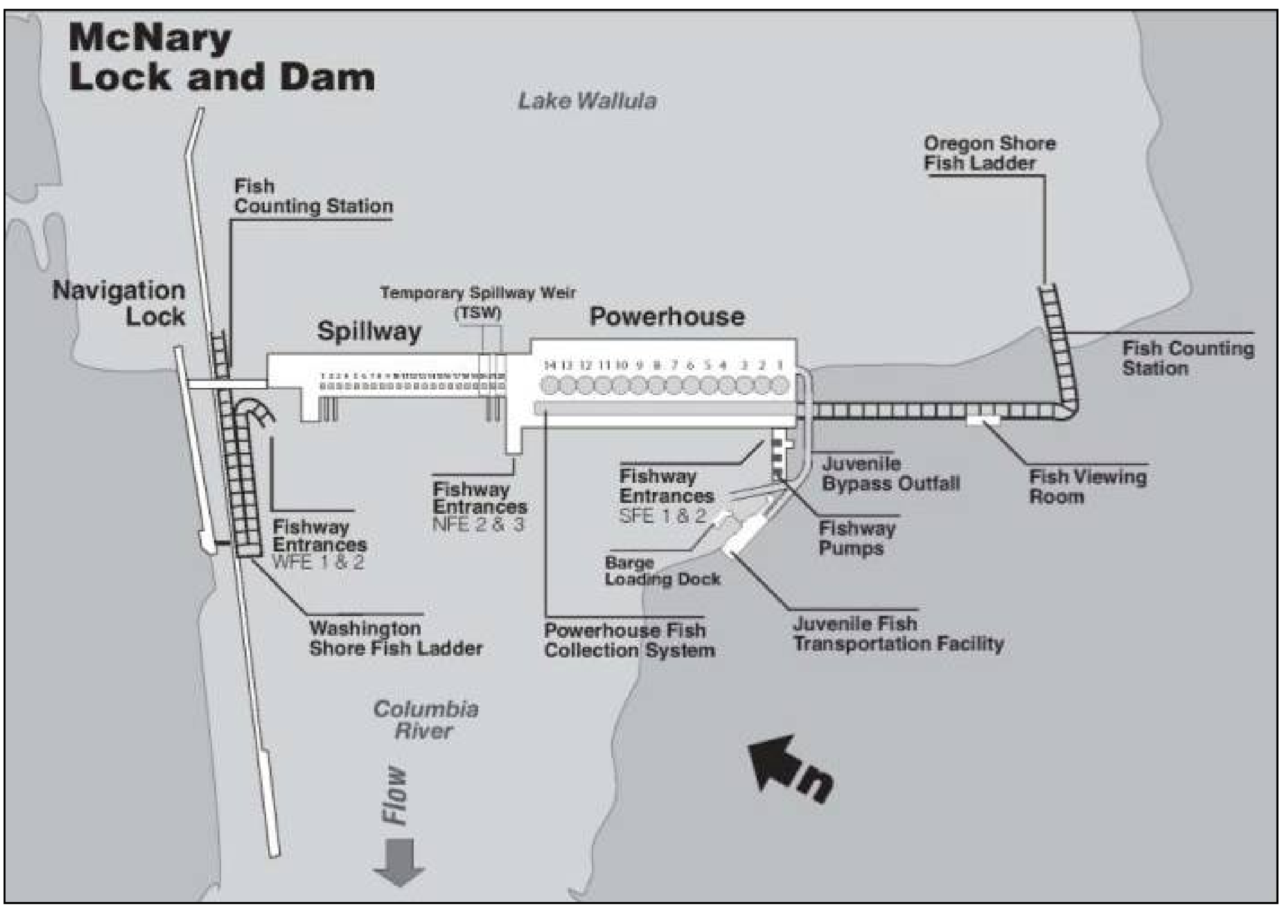


McNary Dam has 14 turbine units with fish by-pass screens installed in each of the turbine unit intakes. Although these screens are effective in intercepting the majority of the juvenile steelhead, a significant percentage of yearling and subyearling Chinook continue to pass through the turbines. Based on acoustic telemetry survival studies conducted from 2006 to 2009, annual total survival probabilities for the McNary turbines and tailrace varied from 82.4% to 90.3% for yearling Chinook, 67.9% to 76.3% for subyearling Chinook, and 66.4% to 88.7% for juvenile steelhead (Adams and Evans 2011). Survival studies conducted at McNary prior to 2006 using radio tags found similar turbine survival probabilities (Ham et al. 2009). Telemetry studies may have a negative bias associated with the surgical implantation of tags (Carlson et al. 2010); however, the survival probabilities continue to indicate a need to improve turbine operations for safer fish passage. Results of multiple field and laboratory studies indicate that improved fish survival through the McNary turbines may be achieved by changing their operating conditions. The studies included balloon tag and telemetry tag survival studies, sensor fish pressure and acceleration measurements of the turbine flow path, laboratory pressure investigations, and physical hydraulic model investigations. Results from the studies indicate modifying the current operating zone, defined as being within the 1% of peak efficiency, may improve fish passage survival. This appendix summarizes results from various studies and presents information to support a recommendation to conduct a field test at McNary for verification of an improved target operating range (TOR) for safer fish passage through turbines.

1.1. PROJECT DESCRIPTION

Completed in 1953, the McNary Project includes a powerhouse, spillway, navigation lock, and fish passage facilities (Figure 2). The dam is 7,365-feet long and rises approximately 183 feet above the streambed. It consists of a concrete structure with an earth embankment 1,620 feet long between the Washington shore and the navigation lock, and an earth embankment 2,465 feet long between the Oregon shore and the powerhouse. McNary Dam impounds the Columbia River at RM 292, creating Lake Wallula, which extends 64 miles upstream, and includes small portions of the Snake and Yakima Rivers. At maximum pool, Lake Wallula has a water surface area of 38,800 acres and 242 miles of shoreline.

Figure 2. Diagram of McNary Lock and Dam



McNary's powerhouse is 1,422 feet in length and contains 14 Kaplan turbine units manufactured by S. Morgan Smith. Total capacity of the turbine units is 980,000 kilowatts. Units 1-12 are 70,000 kilowatts each and each has a generator capacity of 80.5 megawatts (MW). Units 13-14 are 73,700 kilowatts each and each as a generator capacity of 84.7 MW. The turbine units were put into service in 1957 and the 280-inch diameter runners were designed to operate at 85.7 revolutions per minute. Flows into the turbines are regulated by 20 wicket gates that are accompanied by 19 stay vanes.

The spillway is located adjacent to the powerhouse and abuts the navigation lock on the Washington shore. The spillway is a concrete, gravity-type spillway dam that is 1,310 feet long and contains 22 vertical lift gates, each 50 feet by 51 feet. The crest is at elevation 291 feet mean sea level (msl) and is designed to pass a design flood of 2,200,000 cubic feet per second (cfs). The navigation lock is a single lift type with dimensions of 86-feet wide and 683-feet long, and a 15-foot minimum depth over the sills. The vertical lifts average 75 feet. The lock is located on the Washington shore. There are two fish ladders, one on each shore of the dam, and a powerhouse fish collection system.

1.2. PROJECT OPERATIONS

1.2.1. General Project Operations

McNary is a run-of-river project. It has no flood control storage, no irrigation storage, and only limited short-term power-peaking functions. Therefore, the pool level is relatively stable, with small daily fluctuations occurring normally from power peaking. In the upper reaches of the pool, greater fluctuations occur seasonally from the backwater effect of variations in river flows. At the dam, the project is physically capable of drawdown from full pool level (elevation 340 feet msl) to minimum pool level (elevation 335 feet msl), a total of 5 feet. Presently, normal drawdown does not exceed 3 feet.

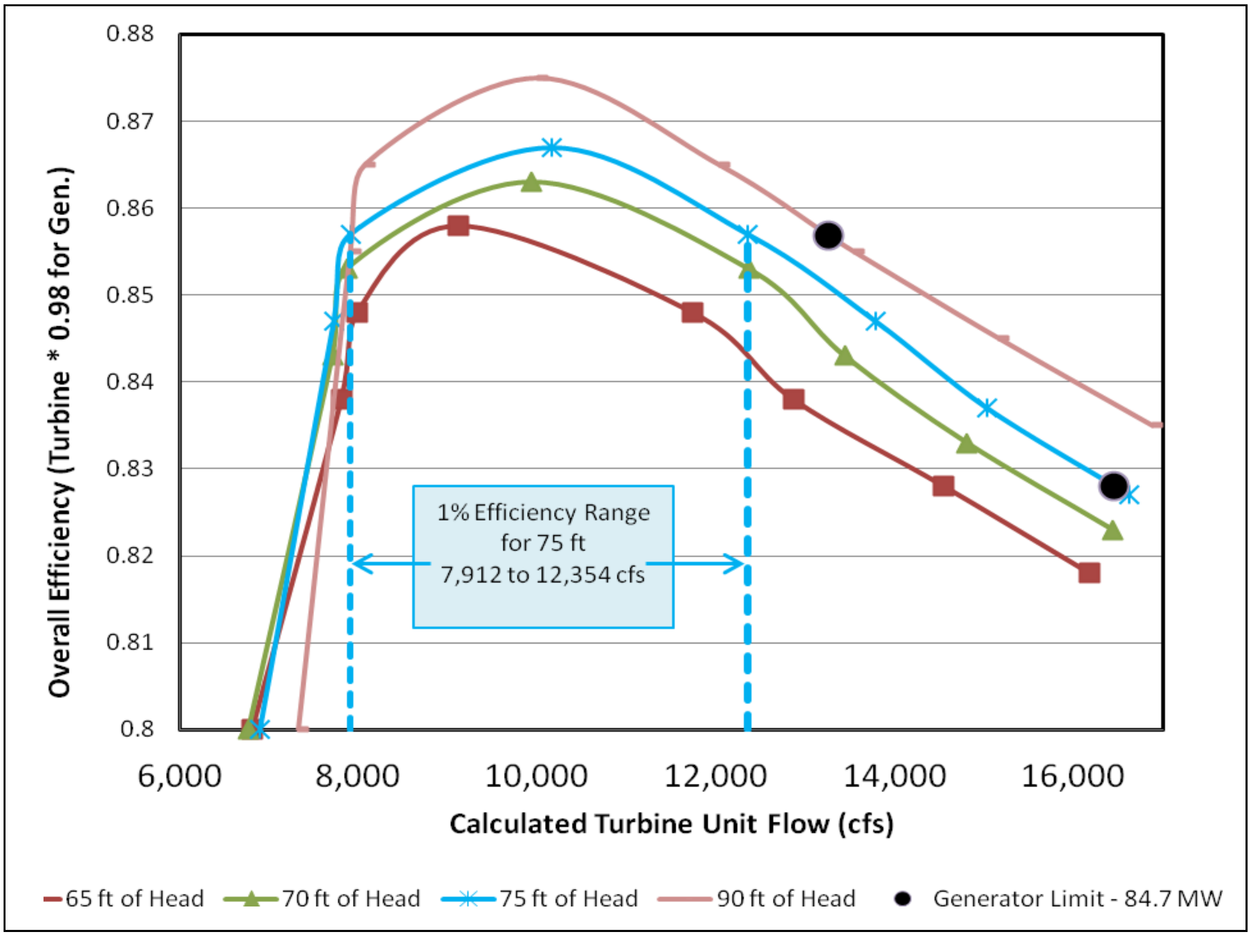
1.2.2. Turbine Operations

The McNary turbines are operated within 1% of the best efficiency in accordance with the USACE's Fish Passage Plan (FPP; USACE 2012), which implements requirements of the National Oceanic and Atmospheric Administration (NOAA) Fisheries Biological Opinion (BiOp; 2000, 2004, 2008). The FPP is updated annually. The approach of restricting turbine operations was formalized in the 2000 BiOp, which requires turbine operations be limited to ± 1% of best operating efficiency. The basis for this rule resulted from research reported by Bell (1981) and Eicher Associates (1987).

A review of turbine survival study results and the 1% operating range was completed by Bickford and Skalski (2000). It was found that highest direct survival did not occur at the best operating efficiency and that direct passage survival did tend to exhibit a curvilinear relationship with increasing turbine discharge. Direct turbine passage survival tests were normally limited to turbine operations within ± 1% of best operating range, highest survival was often found to occur within the 1% operating range, but not always; thus, it cannot be concluded that highest direct turbine survival occurs within 1% of best operating efficiency. Highest direct turbine survival for some turbine units may well occur at untested turbine operations outside the 1% operating range.

The peak efficiency and 1% operating range are dependent on both the head on the turbine and the flow through the turbine. For McNary turbines, the efficiency versus flow curves are shown in Figure 3 with extended-length submersible bar screens (ESBS) installed. The 1% operating range is defined by a ±1% drop from peak efficiency at the head at which the turbine is operated.

Figure 3. McNary Turbine Efficiency Curves with ESBS Installed



Because both the BiOp and the FPP require operation within the 1% range, it is not surprising that the average turbine unit flow in Table 1 is close to peak efficiency. Table 1 also shows the operating range and average for multiple turbine operating parameters from 2004 through 2010.

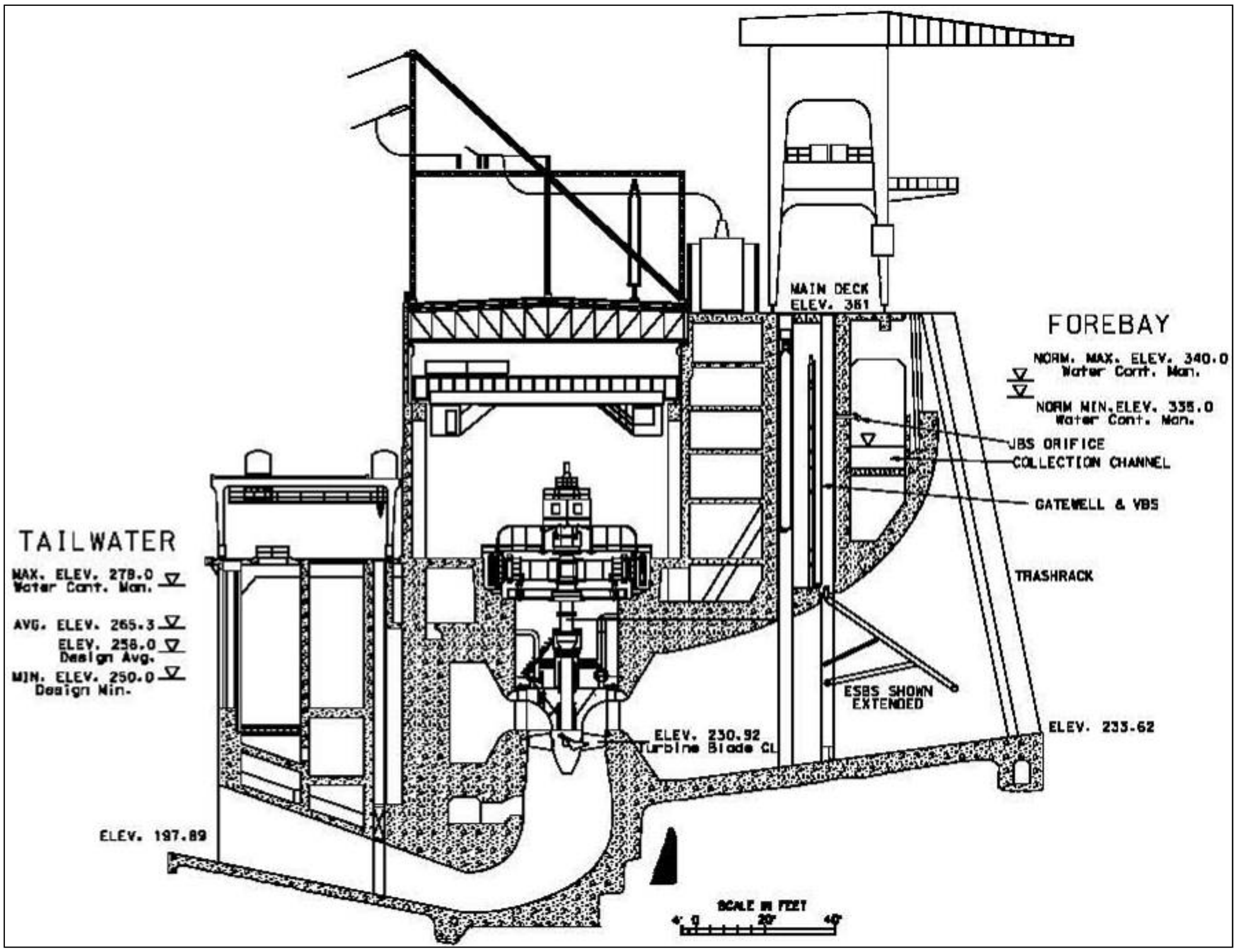
Table 1. Fish Season Operations (April 1 through October 31)

Parameter	Average 2004-2010	Operating Range	
		Low	High
Forebay Elevation (feet msl)	338.8	335 [b]	340 [b]
Tailwater Elevation (feet msl)	265.3	264 [b]	278 [b]
Head (ft)	73.4	67.3	76.6
Powerhouse Flow (kcfs)	105.8	0	174.6
Total Flow (kcfs)	172.7	59.6	426.7
Turbine Unit Flow (kcfs)	10.4	7.9 [a]	12.4 [a]
Turbine Unit Power (MW)	54.6	37.5 [a]	72.2 [a]
Turbine Units Operating	10.1	0	14

[a] Based on 1% efficiency range over the head range with ESBS installed.
[b] Based on project operating range defined in Water Control Manual.
kcfs = thousand cubic feet per second

The McNary turbines were designed for a head range of 62 to 92 feet with an optimum design head of 80 feet (USACE 1949). The forebay continues to operate at the original elevation design of 335 to 340 feet msl (see Figure 3) and described in McNary's Water Control Manual. However, the tailrace now operates over a much more limited elevation range than the design range of 250 to 285 feet msl. The normal expected tailwater elevation of 258 feet in the design is no longer valid after the installation of John Day Dam (USACE 1946). Based on the backwater from John Day, the normal tailwater elevation now varies from 264 to 278 feet msl per the Water Control Manual. Therefore, the project now operates at a lower head than originally designed (Figure 4).

Figure 4. McNary Turbine Cross Section



The FPP specifies turbine unit operating priority from unit 1 and then unit 14 down to unit 2 is intended to improve adult fish attraction to the McNary fish ladders. The FPP also requires spill during much of the fish passage season, which influences the powerhouse tailrace egress conditions. Details of the operational requirements can be found in the FPP (USACE 2012).

2. DEFINE TARGET OPERATING RANGE FOR TURBINES

There are many different pieces of information that help to estimate the TOR for fish passage survival through McNary turbines. First, the physical geometry of different operating conditions will be considered. Second, physical modeling data of different operating conditions guided by the physical geometry of the wicket gate and blade angles will be discussed. Pressure information for McNary Dam is limited to a sensor fish study. However, this in conjunction with laboratory studies can give an indication of the potential for pressure injuries at different operating conditions. Additionally, the turbine specific biological field studies performed to date will be discussed. Finally, this information will be tied together to provide an estimate of a TOR for McNary turbines.

2.1. PHYSICAL GEOMETRY CONSIDERATIONS

As discussed in Section 3.2 of the Phase II Main Report, there is potential to reduce injury and direct mortality of migrating salmon passing through turbines by operating at a more open geometry. Wittinger and others (2010) suggested that a good geometric relationship is often not found within the existing 1% operating limits. The alignment of wicket gates and stay vanes based on the original design of the McNary turbines for different operating conditions are presented in Figures 5 to 8. All alignments are shown for “on-cam” operation at 75 feet of head, which is close to average head shown in Table 1.

At the lower 1% of the efficiency range, a significant misalignment and gap exists that would likely cause increased injury for fish passing through turbines (Figure 5). At the upper 1% operating condition, the alignment of the wicket gates and stay vanes are improved over the lower 1% operating condition, but are still not in alignment (Figure 6). At the generator limit at 75 feet of head (Figure 7), the wicket gates go slightly past the best geometrical alignment with stay vanes. The best alignment of wicket gates and stay vanes occurs at a wicket gate angle (WGA) of approximately 43 degrees (Figure 8).

While best alignment is ideal, the goal of minimizing the gap between the wicket gates and stay vanes while keeping the wicket gate within the hydraulic shadow of the stay vane is expected to occur within the broader range of WGA at 38 to 48 degrees. At 75 feet of head, this is between the upper 1% operating range and the generator limit (as expected based on Figure 6 and Figure 7) and thus, not within the current 1% operating range. Operating conditions at 75 feet of head (for on-cam operation) over the target geometry range and best geometry for wicket gate alignment are presented in Table 2.

Table 2. Best Wicket Gate Geometry at 75 feet of Head

Parameter	Best Geometry	Best Geometry Range	
		Lower	Upper
Wicket Gate Angle (WGA) – degrees open	43.0	38.0	48.0
Blade Angle – degrees open	26.3	24.0	29.8
Power – horsepower (hp)	103,000	94,000	116,000
Flow – kcfs	14.40	12.90	16.40
Efficiency – %	84.3	85.4	83.2

Note: Peak efficiency at 75 feet of head is 86.7%

Figure 5. McNary Wicket Gate and Stay Vane Alignment at Lower 1% Efficiency

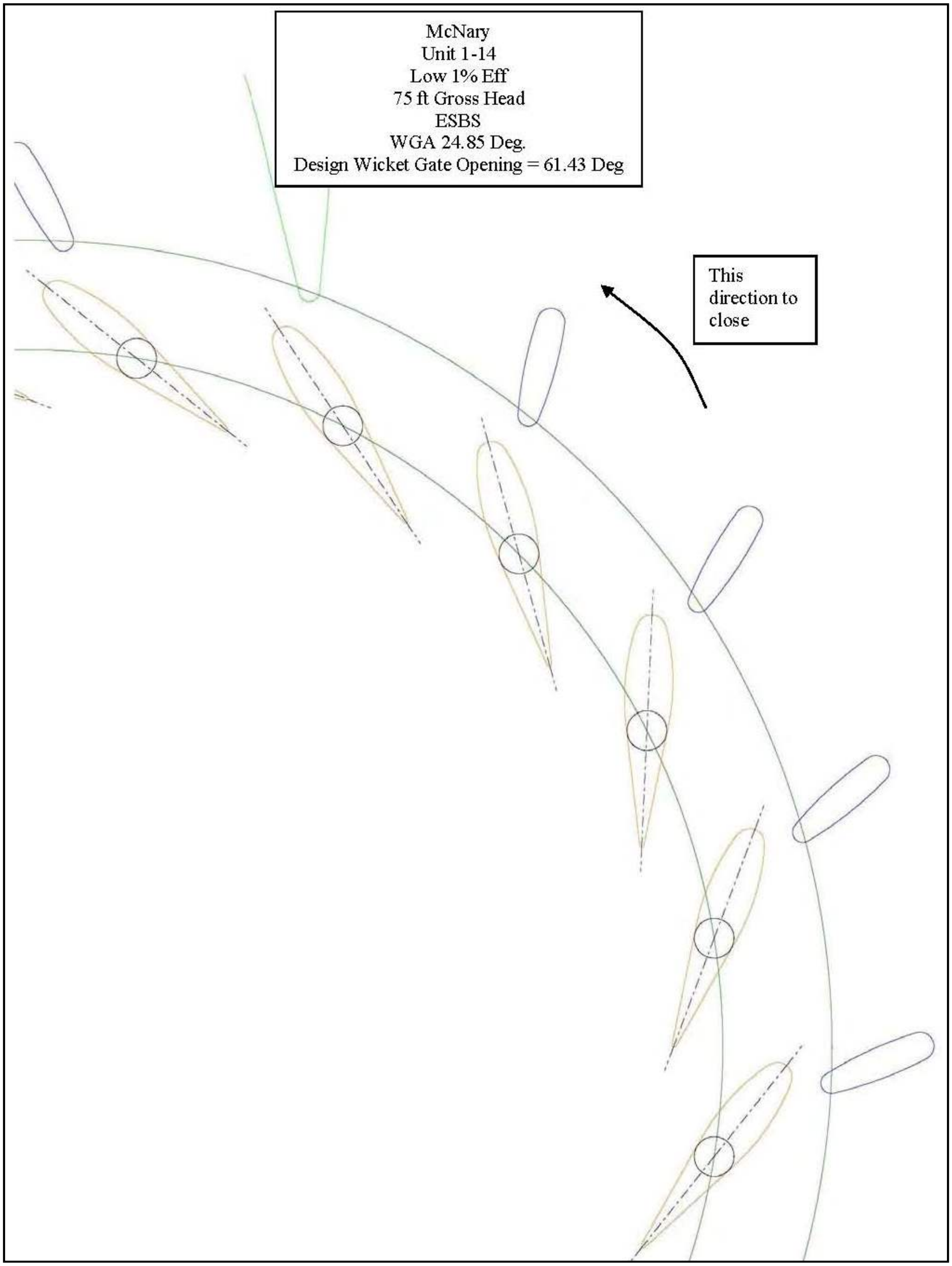


Figure 6. McNary Wicket Gate and Stay Vane Alignment at Upper 1% Efficiency

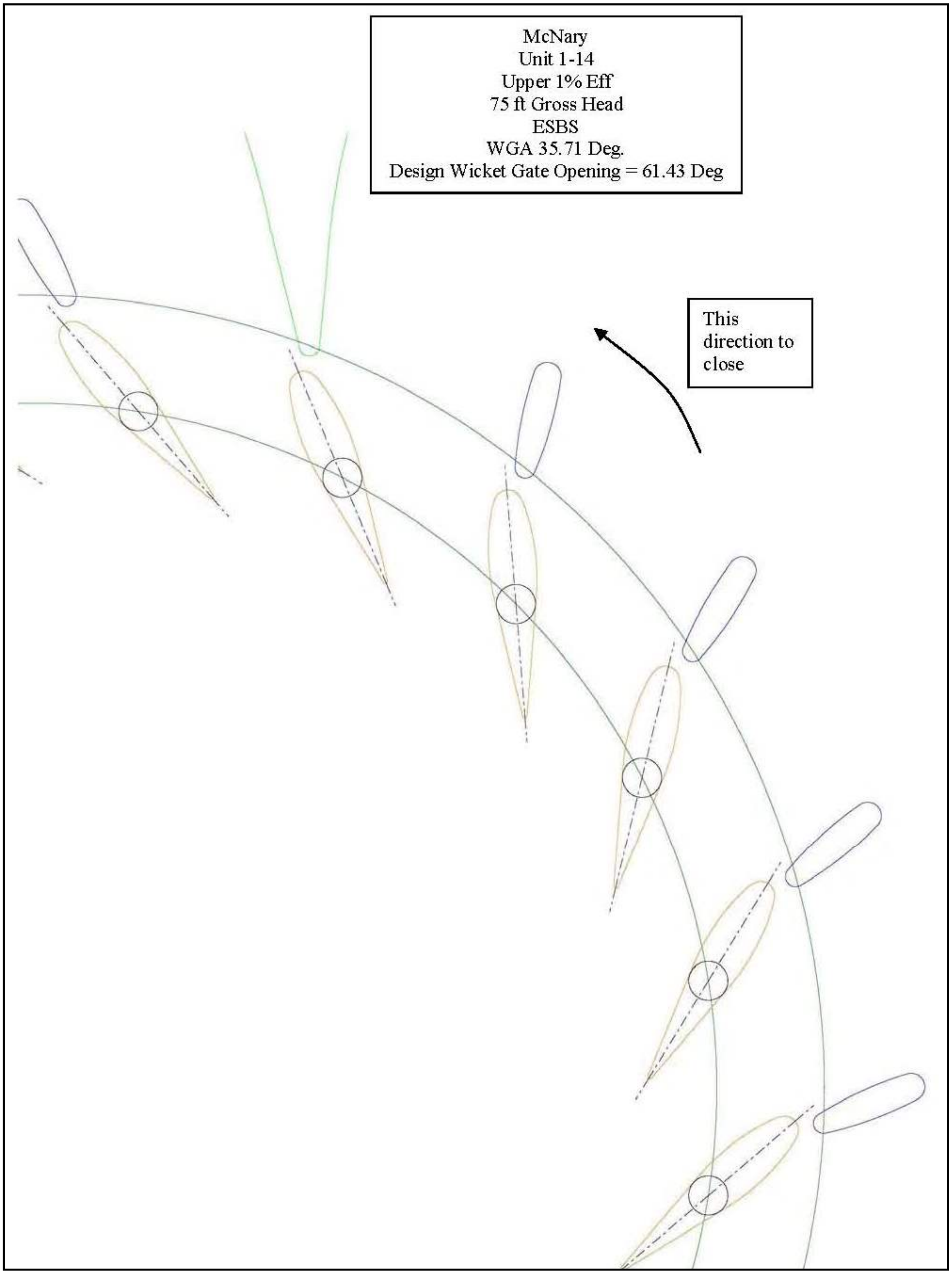


Figure 7. McNary Wicket Gate and Stay Vane Alignment at Generator Limit

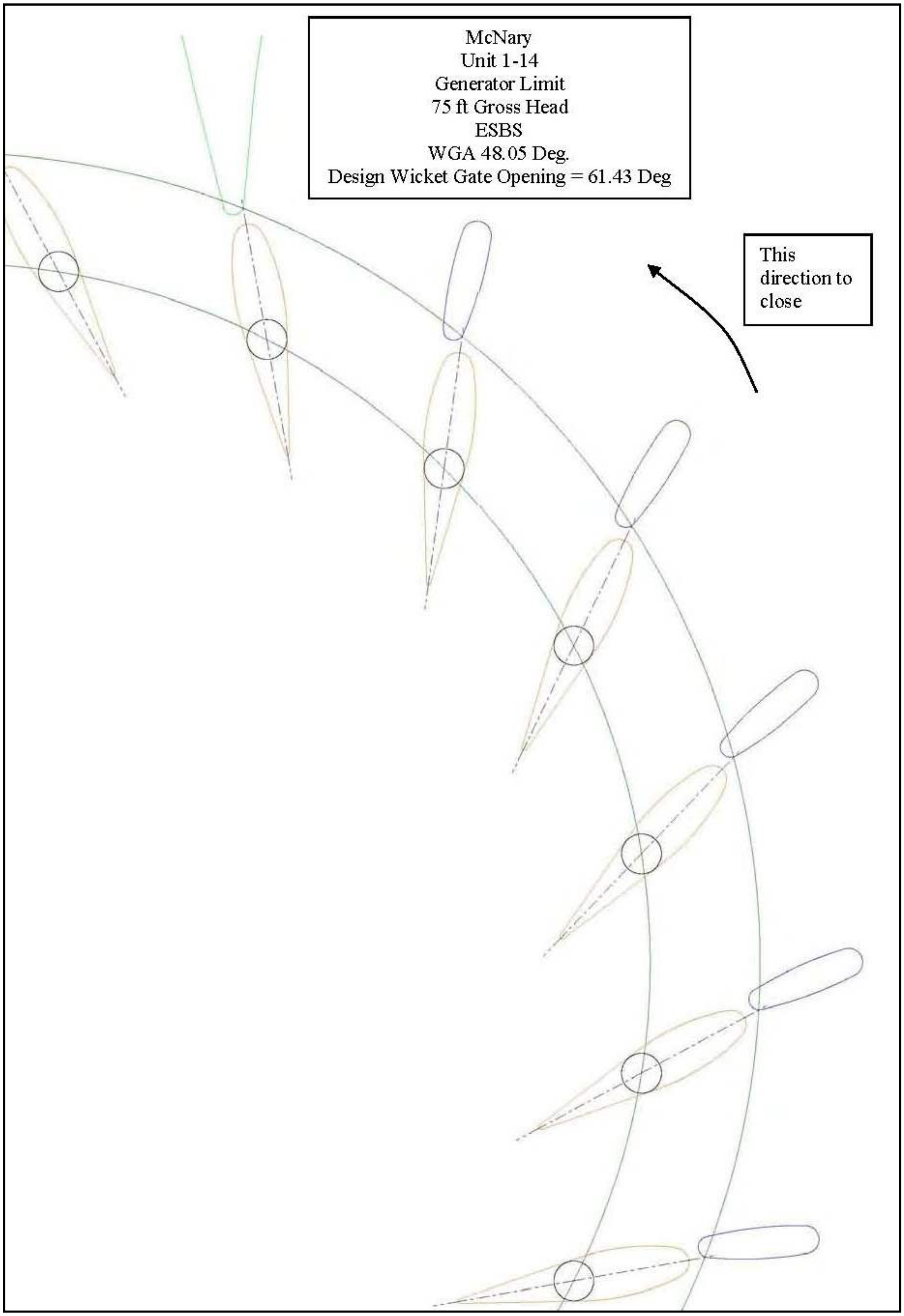
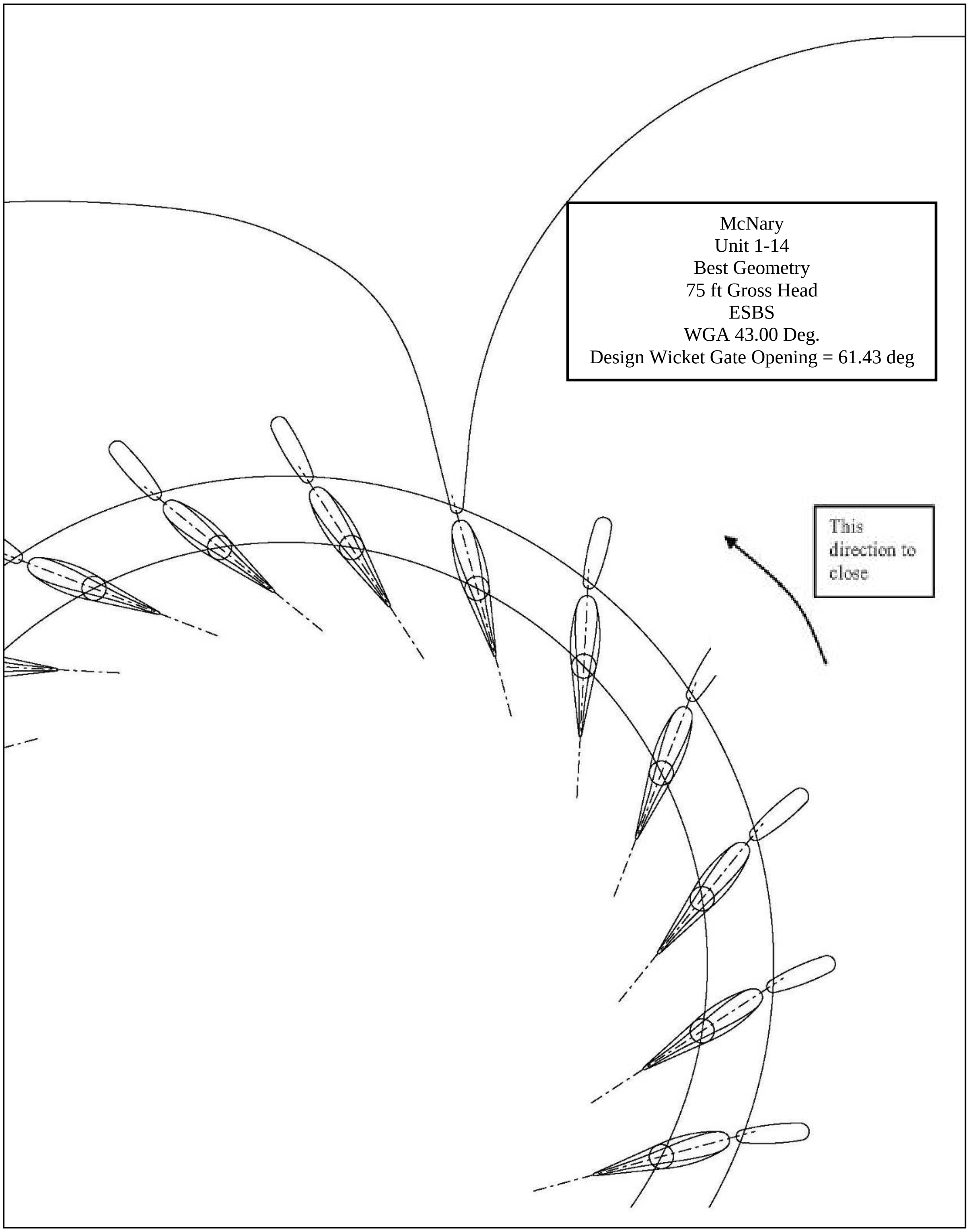


Figure 8. Best Alignment of McNary Wicket Gate and Stay Vane



Another consideration is the range of head over which the project normally operates. While operating in a head range from 67.3 to 76.6 feet for the past 6 years during the fish passage season (Table 1), the project was operating between 70 and 75 feet of head 72% of the time. The variation of the WGA and blade angle for on-cam operation at various operating heads is presented in Figure 9. There is not a large variation in blade angle for on-cam operation between operating heads of 70 and 75 feet. Therefore, it is expected that there would not be a large variation in project operating conditions (Table 2) for the best wicket gate geometry range.

2.2. PHYSICAL OBSERVATIONAL MODEL INFORMATION

Construction of a physical observational model of forebay through tailrace for a single McNary turbine unit was completed in 2000 at the Engineering Research and Development Center (ERDC) in Vicksburg, MS. The 1:25 Froude-based scale model (Figure 10) was used to evaluate the hydraulic condition within the turbine and the potential impact of variable turbine operations on fish. The model replicates the approach to a single unit, all three intake bays, the scroll case, the distributor including the adjustable wicket gates and stay vanes, the six-bladed Kaplan turbine runner, the draft tube and enough downstream topography to establish uniform flow conditions. The evaluation included the release of dye into the turbine flow path to observe general flow patterns, extensive velocity measurements using a Laser Doppler Velocimeter (LDV) and high-speed imaging of neutrally buoyant beads released into the flow path. Experiments were conducted from 2000 to 2002 in support the turbine survival program for the design of new turbines and turbine modifications at the McNary powerhouse.

The model flow rate and runner speed were established using Froude similitude equations. The prototype flow rates investigated were 10.22, 12.19, 13.41, 16.45, and 17.70 thousand cubic feet per second (kcfs). These flow rates in relation to the 1% efficiency range are peak, upper 1%; approximately upper 2% from peak, generator limit, and beyond 100% of generator limit, respectively (see Figure 3 for 1% efficiency range). All tests were conducted between approximately 72.5 and 73.1 feet of head (prototype scale), which is close to the average head shown in Table 1. Testing was performed with and without ESBS within the intake; however, all model data presented in this report is with the ESBS installed since that is the current field condition.

Figure 9. McNary Wicket Gate and Blade Angle at Different Heads

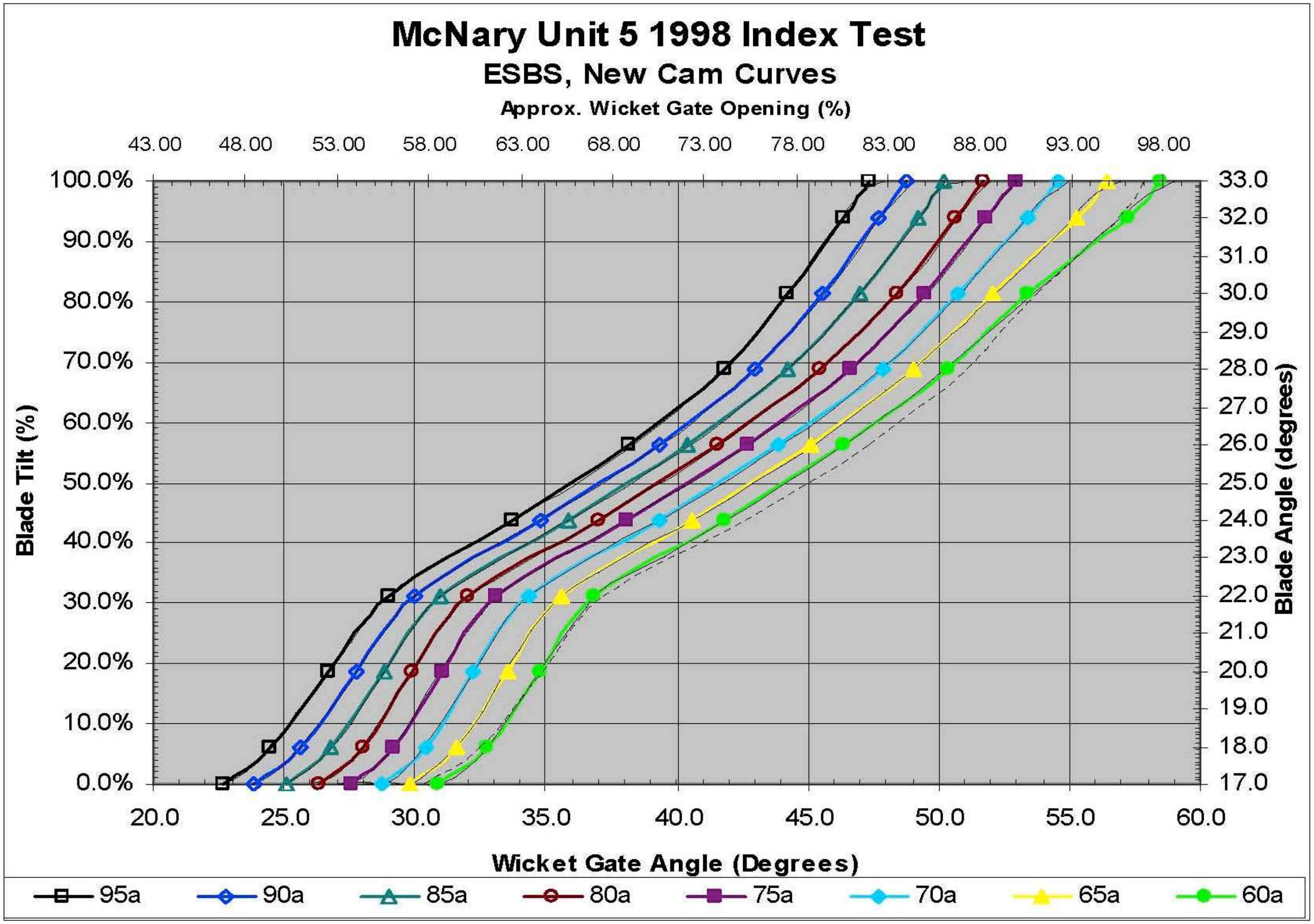
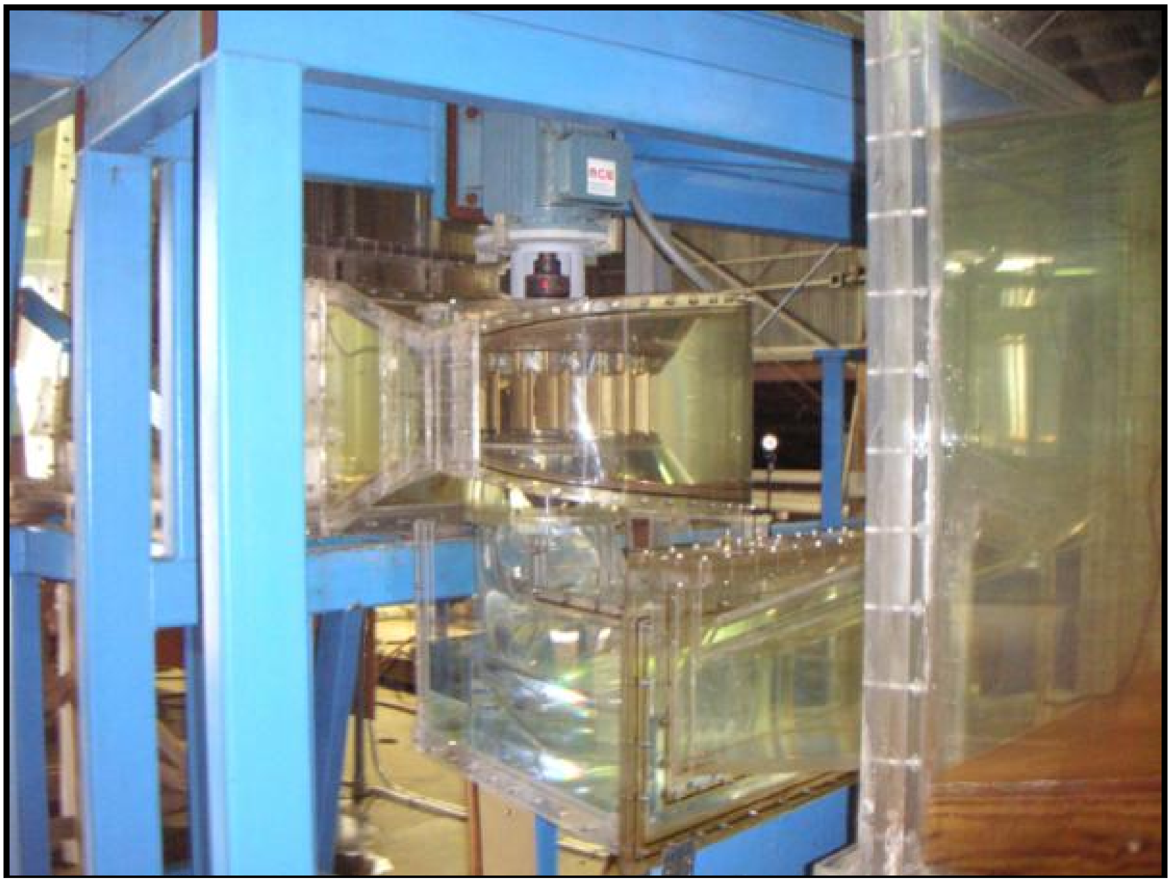


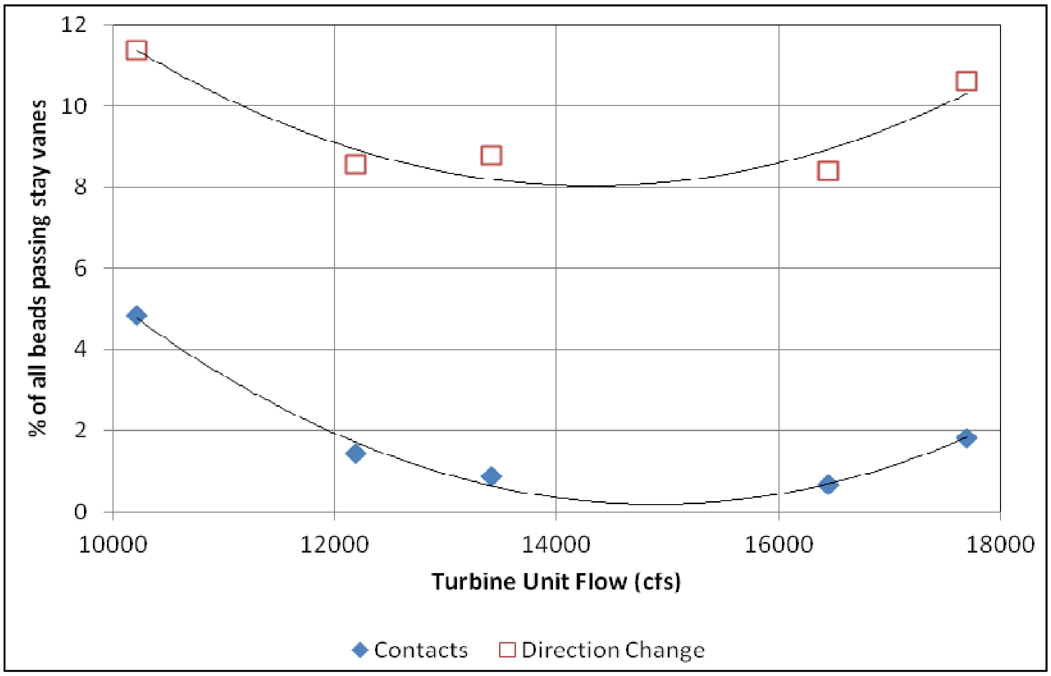
Figure 10. McNary Turbine Physical Model (tailwater in foreground)



Neutrally buoyant beads were introduced at various points within the intake. High-speed video was then used to determine potential shear and strike injury by observing indications of bead contacts and change in directions (those that did not follow the general flow direction). It was proven through a study at McNary Dam that fish do not behave as passive particles within an intake at 7.0 kcfs and 12.0 kcfs through a turbine (Carlson 2002). However, the passive particle hypothesis is an assumption that must be made without solid alternative information, although this assumption may be valid for passage within the runner due to the high velocities. Release points were selected that corresponded to passage at the runner hub, mid-blade, and the runner blade tip. Without adequate information on fish distribution due to a possible fish behavior effect, an equal distribution within the runner was assumed. Therefore, all the bead passage data was averaged together for information presented in this appendix.

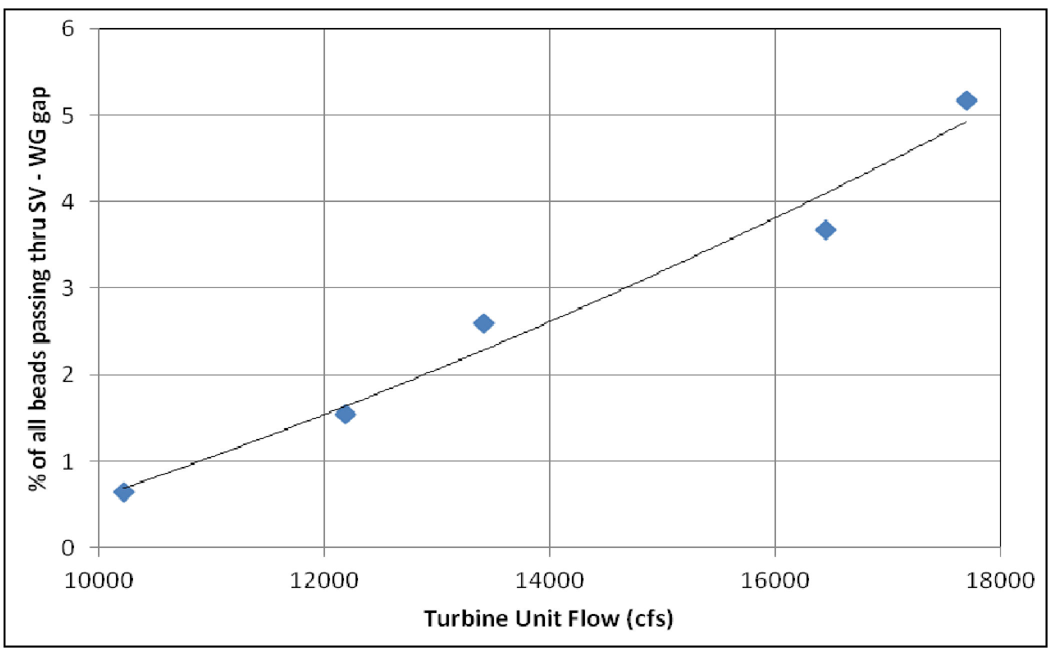
The first area that presented a chance of strike injury is in the vicinity of the stay vanes and wicket gates. High speed video was used to determine the percentage of beads that contacted the runner, or experienced severe changes in direction while passing either the stay vanes or wicket gates (Figure 11). In the physical model, the percentage of beads contacting these structures was low. Additionally, the lowest number of contacts and direction changes seemed to occur between 14.0 kcfs and 16.0 kcfs, which roughly corresponded to the best wicket gate geometry alignment.

Figure 11. Severe Bead Contacts and Direction Changes at Stay Vane and Wicket Gates



The percentage of beads passing through the gap between the stay vanes and wicket gates was also analyzed using the high-speed video (Figure 12). Unlike the contacts and direction changes, this percentage appears to increase with flow and be relatively unrelated to the best wicket gate geometry.

Figure 12. Beads Passing through Gap between Stay Vanes and Wicket Gates



The second area for potential mechanical injury to fish is passing the runner blades of the turbine. As with the stay vane region, analysis of beads contacting the runner can give an indication of potential injury. Contact with the runner generally decreased with increasing flow rate through the runner (Figure 13). Increasing flow rate corresponded to an increase in blade angle and increased open area within the runner environment. Less variation occurred between operating points and the percentage of beads that experience severe direction changes within the runner still generally decreases with increasing flow rate through the runner (Figure 14).

Figure 13. Severe Bead Contacts with Runner Blades

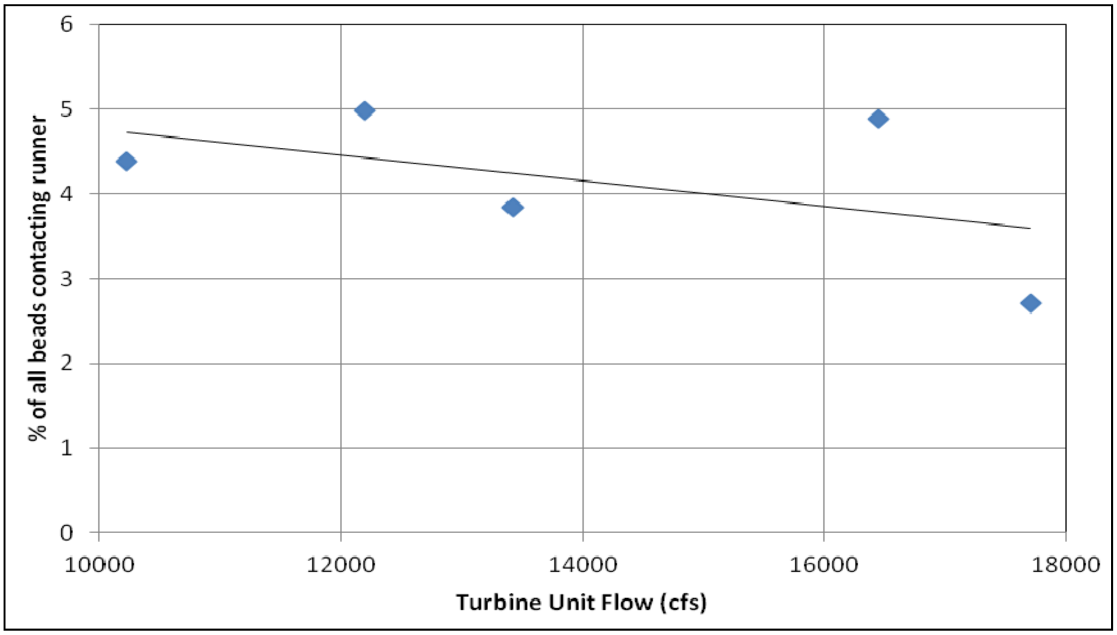
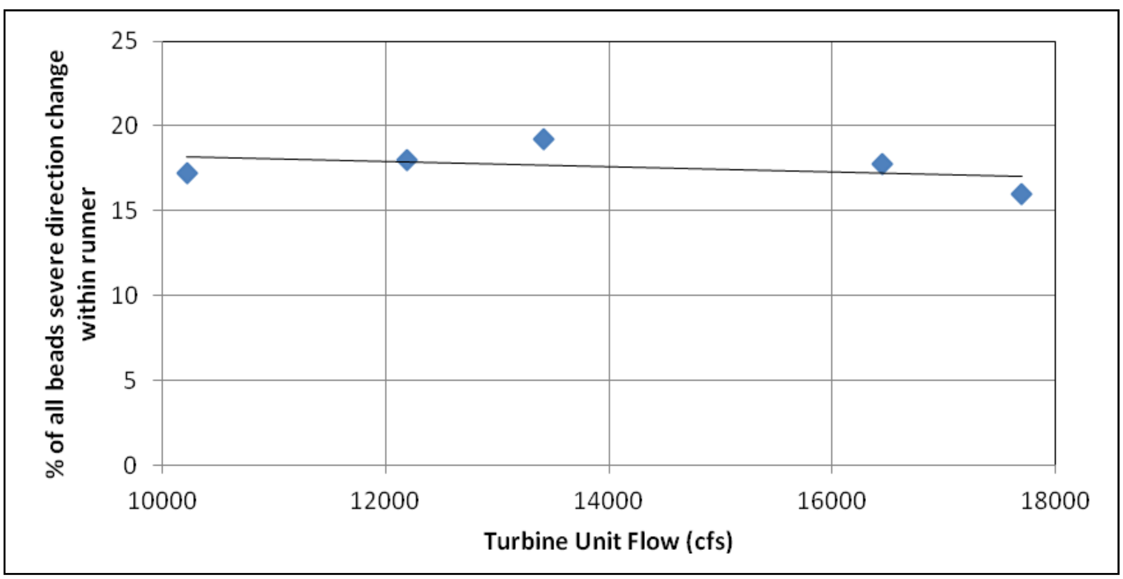


Figure 14. Severe Bead Change in Direction within Runner Blades



In addition to the bead analysis, velocity measurements were taken at multiple transects using a LDV (measurements could be taken from outside the model due to the clear walls). The draft tube exit is one area that displayed a large difference between the tested flow rates as determined by velocity measurements. The draft tube for McNary turbines has a single, vertical splitter wall that divides the draft tube into two barrels (designated A and C) of equal cross-sectional area and length. The velocities at the draft tube exit were used to estimate the flow rate through each barrel. Barrel A had a much higher flow rate than barrel C at the lower turbine flows, but the flow distributes more evenly for flow rates of 13.41 kcfs and higher (Figure 15). Relating the average barrel velocity with individual velocity measurements, turbulence intensity is a measure of variability within the draft tube. Data indicates that turbulence intensity decreases with increasing flow for both barrels, particularly in barrel C (Figure 16).

Results shown in Figure 15 and Figure 16 relate to the fact that the draft tubes were designed to pass the highest design flows and thus, the full flow area is not fully utilized at lower flow rates resulting in areas of recirculation. The increased turbulence at the lower flow rates could cause fish disorientation. While direct injury or mortality may not result, fish disorientation has the potential to increase vulnerability to predation.

Figure 15. Flow Percent Passing Through Each Draft Tube

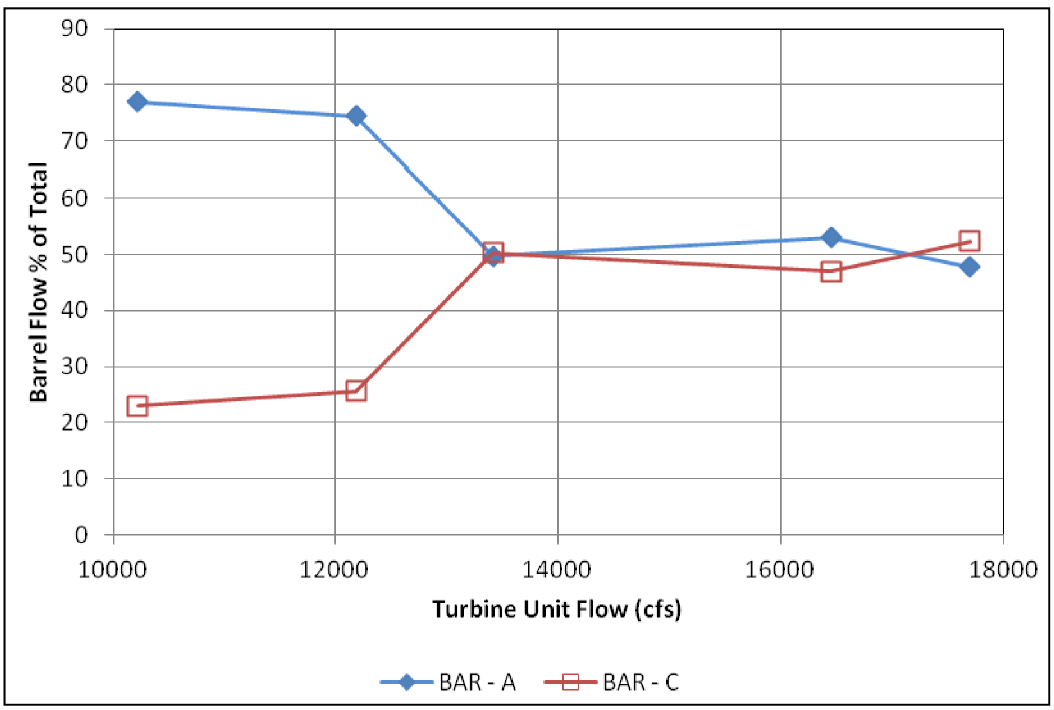
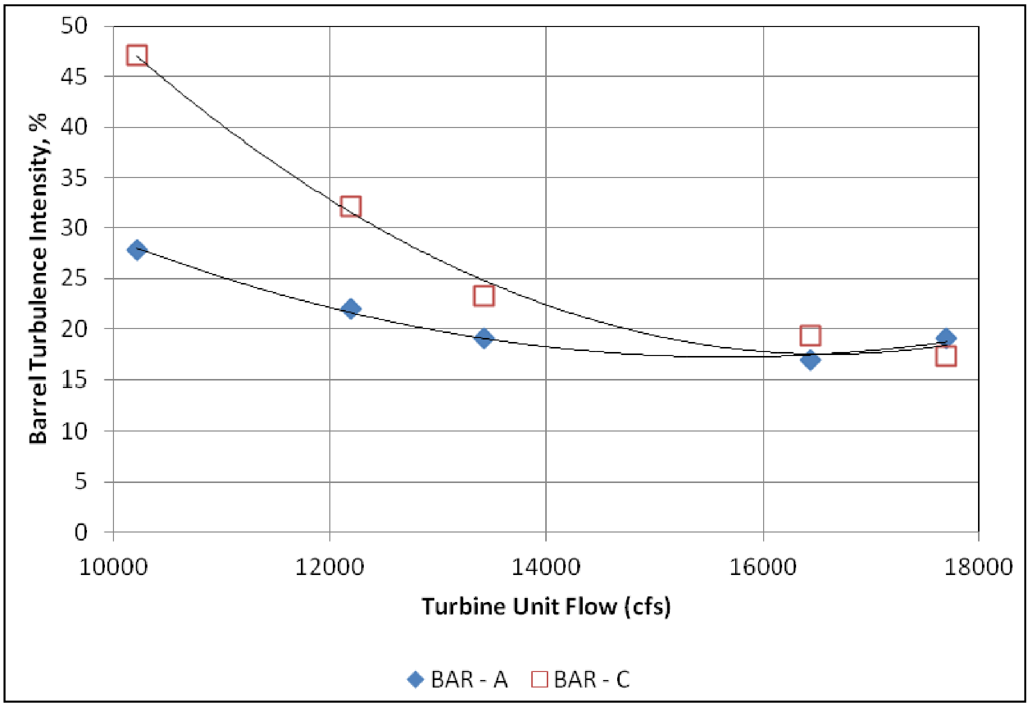
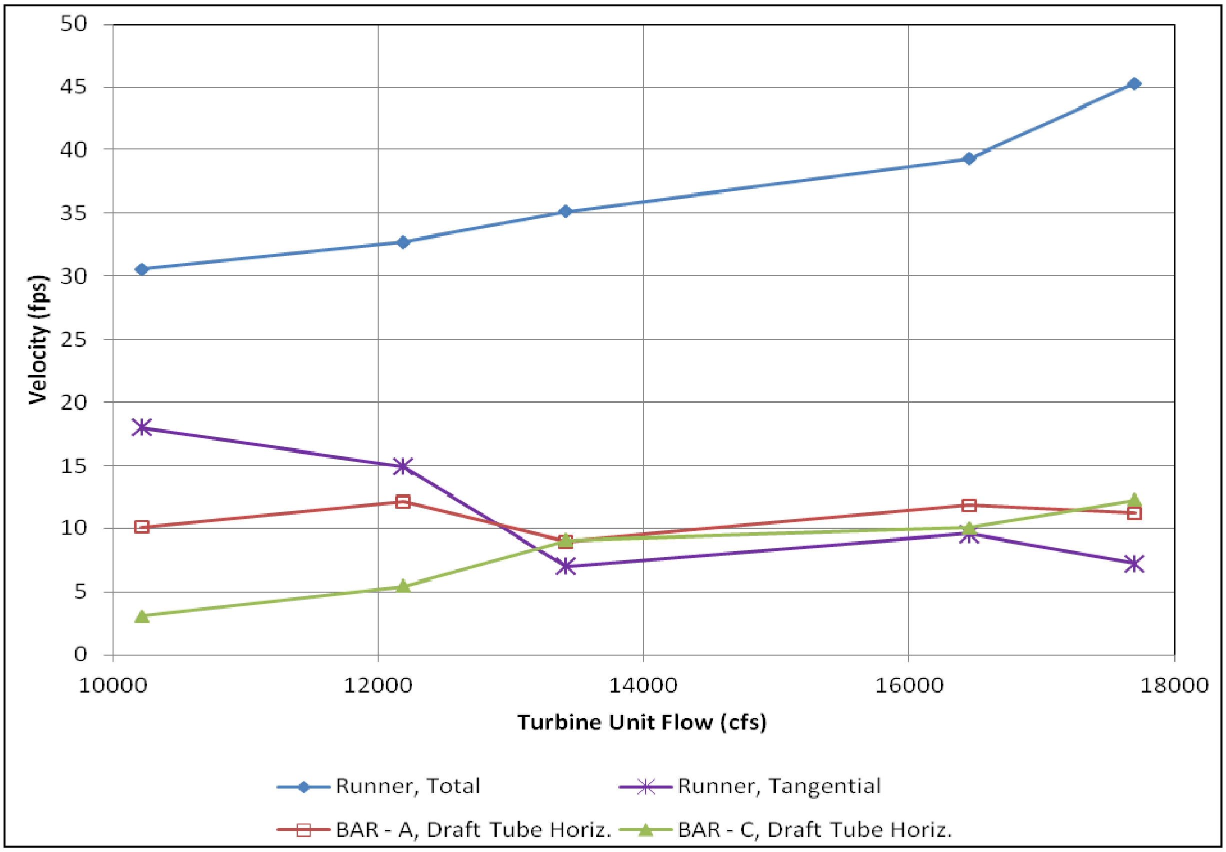


Figure 16. Turbulence Intensity for Draft Tube Barrels



The average horizontal velocity within the draft tube and the average total and tangential velocity magnitude 5 feet above the bottom of the runner hub are displayed in Figure 17. The velocity within the runner is significantly higher, meaning that a fish contacting a runner is much more likely to get injured than one contacting the draft tube wall. Lower turbine flow rates have lower average velocities, especially through the runner inferring that the highest turbine flow rates may not be the best for fish injury and mortality. However, opposed to this are the results in Figure 14 that indicate the frequency of severe contact with runner blades goes down with increasing flow rate through the runner. Meanwhile, the tangential velocity drops significantly with increasing flow rate due to the steeper blade angles and is surprisingly the lowest at 13.41 kcfs. This likely corresponds to the more equal velocities seen in both draft tube barrels and thus the more equal flow seen in Figure 15, and lower turbulence seen in Figure 16.

Figure 17. Velocity within Runner and Draft Tube

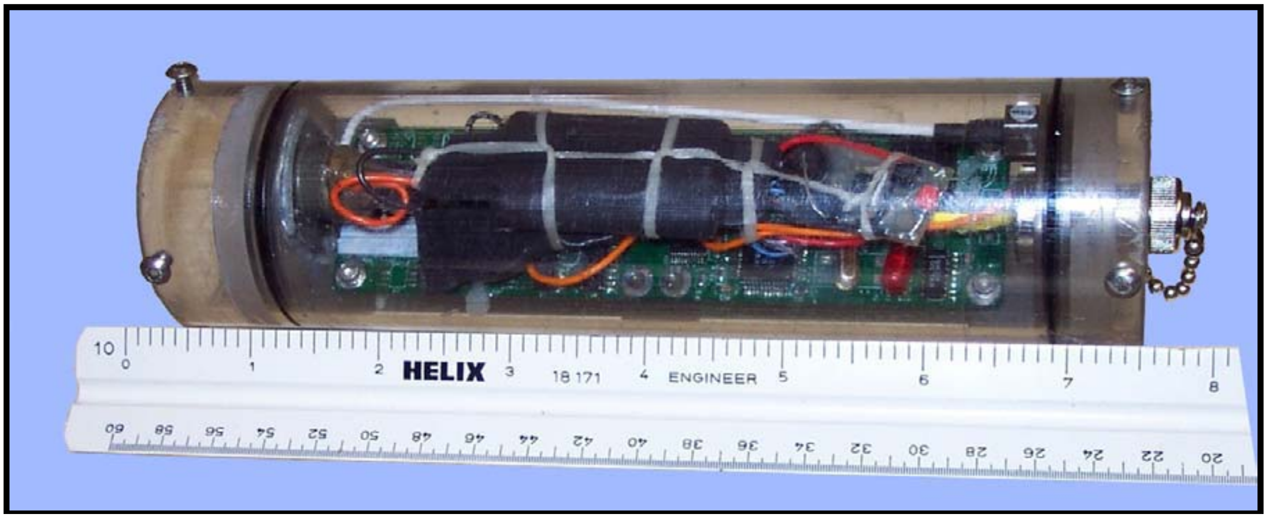


2.3. PRESSURE INFORMATION FROM LABORATORY AND FIELD DATA

An assessment of barotrauma mortality risk for McNary turbines can be made using relationships established with laboratory testing (see Section 3.4 in Main Report) and field pressure data using sensor fish. To apply the data to fish passage at McNary for run-of-river fish, the acclimation pressure and the nadir pressure are needed. There is minimal information for the acclimation pressure for fish entering McNary turbines; however, the nadir pressure for two operational points has been evaluated in the field study using sensor fish. In April 2002, the Pacific Northwest National Laboratory (PNNL) released sensor fish devices into McNary turbine unit 9 to obtain the pressure profile at two turbine operating conditions (Carlson and Duncan 2003, 2004).

The sensor fish devices used in this field study were cylindrical in shape and nearly neutrally buoyant in fresh water – redesigned sensor fish II (Carlson and Duncan 2003). The sensor housing is constructed of clear polycarbonate plastic and is 7.5 inches in length and 2 inches in diameter (Figure 18). Digital samples of the sensors' analog output are taken every 0.005 second over a period of 2 minutes as the sensor passes through the turbine passage environment. Current sensor fish have been able to achieve an even higher sampling frequency. However, these older model sensor fish devices were the ones released with balloon tags attached to allow for recovery and retrieval of the data following the turbine passage in the 2002 study. The devices were released in all three intake bays of McNary turbine unit 9 at a location behind the ESBS, where the physical model indicated the devices would be dispersed over the full range of turbine passage routes.

Figure 18. Sensor Fish Device Developed by PNNL



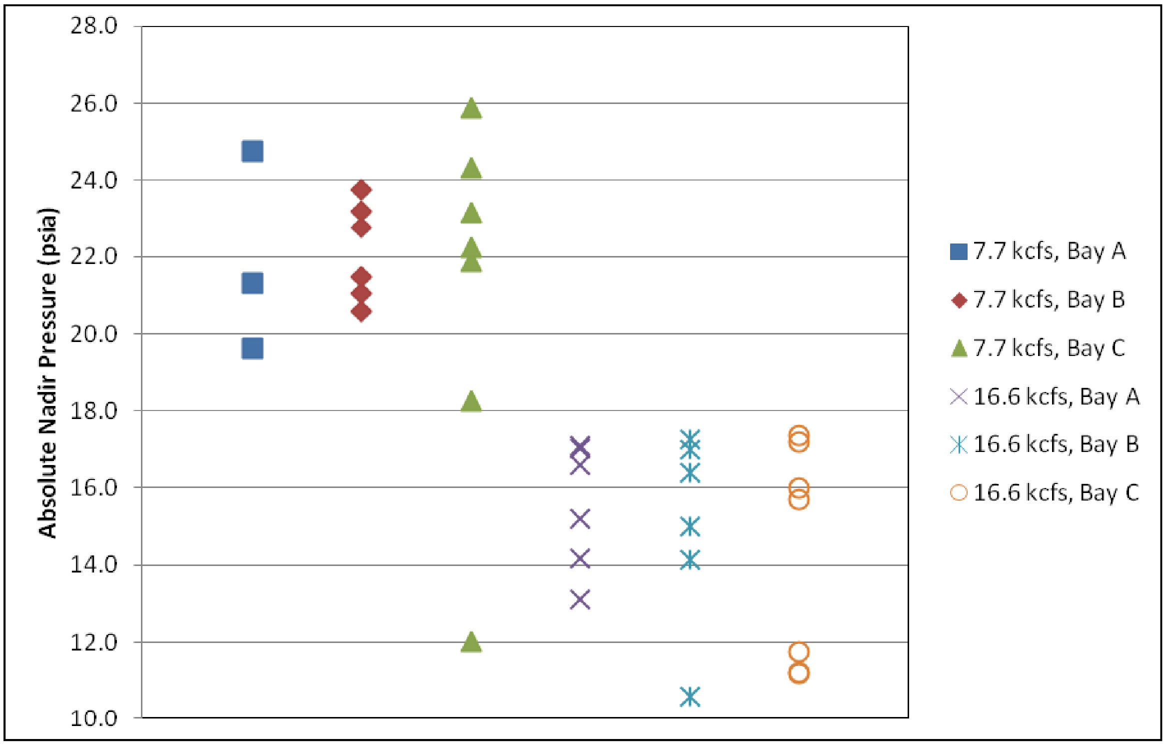
A total of 16 sensor fish devices were released while operating the turbine at approximately 7.66 kcfs at a head of 75 feet (Carlson and Duncan 2004). A total of 19 sensor fish devices were released while operating the turbine at approximately 16.56 kcfs at a head of 72.5 feet (Carlson and Duncan 2004). These operating conditions roughly correspond to the low end of the 1% efficiency range and generator limit at McNary (Figure 3). The lowest pressures recorded by these devices (the nadir pressure; Figure 19) is summarized in Table 3. Due to the slower sampling frequency and the low number of sensor fish used in the study, the mean nadir pressure may not be accurate. However, the mean nadir pressure in a McNary turbine is likely within the range recorded by sensor fish (Table 3).

Table 3. Sensor Fish Device Nadir Pressure Results at McNary

Parameter	7.70 kcfs Operating Condition	16.60 kcfs Operating Condition
Mean nadir pressure (psia)	21.64	14.95
Minimum nadir pressure (psia)	12.03	10.60
Maximum nadir pressure (psia)	25.89	17.36

psia = pounds per square inch absolute. Source: Carlson and Duncan 2004.

Figure 19. McNary Nadir Pressures by Flow Rate and Intake Bay



In addition to nadir pressure, an acclimation pressure needs to be determined to estimate the mortality rate for untagged juvenile Chinook salmon using Equation 2 (see Section 3.4 in Main Report). Since little is known about acclimation depth of juvenile salmon approaching turbines, four acclimation depths (or pressures) were used to estimate the probability of mortal injury from barotrauma (Table 4). The predicted pressure related mortal injury varies significantly from the combination of the minimum acclimation and maximum nadir pressures to the maximum acclimation and the minimum nadir pressures. Due to uncertainties for both the acclimation and the true mean nadir exposure, the magnitude of the difference between the operating conditions cannot be predicted. However, the direct mortality due to decompression is most likely higher at 16.60 kcfs operating condition than the 7.70 kcfs operating condition. Unfortunately, operating conditions between these flow rates were not tested with sensor fish. Due to the physical environment and the hydraulics, it is reasonable to predict that intermediate flow rates would result in exposures to nadir pressures that fall between the values in Table 3. This would imply that mortal injury due to decompression at different operating conditions would also fall between the values in Table 4. Therefore, it is expected that higher flow rates would result in marginally higher mortal injury due to decompression., For the purposes of this report, a predicted maximum acclimation depth of 22 feet (Pflugrath et al. 2012) and a mean nadir pressure will be used to compare predicted barotrauma mortality rates at different operating conditions with those from other sources.

Table 4. Calculated Barotrauma Mortality for McNary Turbines

Parameter	Calculated Fish Mortality for 7.70 kcfs Operating Condition			
	0 ft Water Acclimation	10 ft Water Acclimation	22 ft Water Acclimation	25 ft Depth Acclimation
Mean Nadir	0.09%	0.23%	**0.59%**	0.72%
Minimum Nadir	0.83%	2.20%	5.40%	6.53%
Maximum Nadir	0.04%	0.12%	0.30%	0.36%
	Calculated Fish Mortality for 16.60 kcfs Operating Condition			
Mean Nadir	0.36%	0.97%	**2.41%**	2.94%
Minimum Nadir	1.34%	2.25%	8.50%	10.20%
Maximum Nadir	0.20%	0.34%	1.37%	1.67%

In addition to pressure data, the sensor fish devices were able to give some information based on the accelerometers (Carlson and Duncan 2004). High acceleration values were seen as either a physical strike event or entrainment into an area of high shear and turbulence, both of which have the ability to injure fish. No strike events were determined to occur during passage through the runner, which agrees with the low rate of contacts seen in the physical model (Figure 13). However, at low discharge at a time believed to coincide with passage through the stay vane-wicket gate cascade, acceleration impulses indicated a high probability of either strike or scraping of the sensor, or response of the sensor to flow conditions (turbulence and/or shear).

2.4. BIOLOGICAL FIELD STUDY INFORMATION

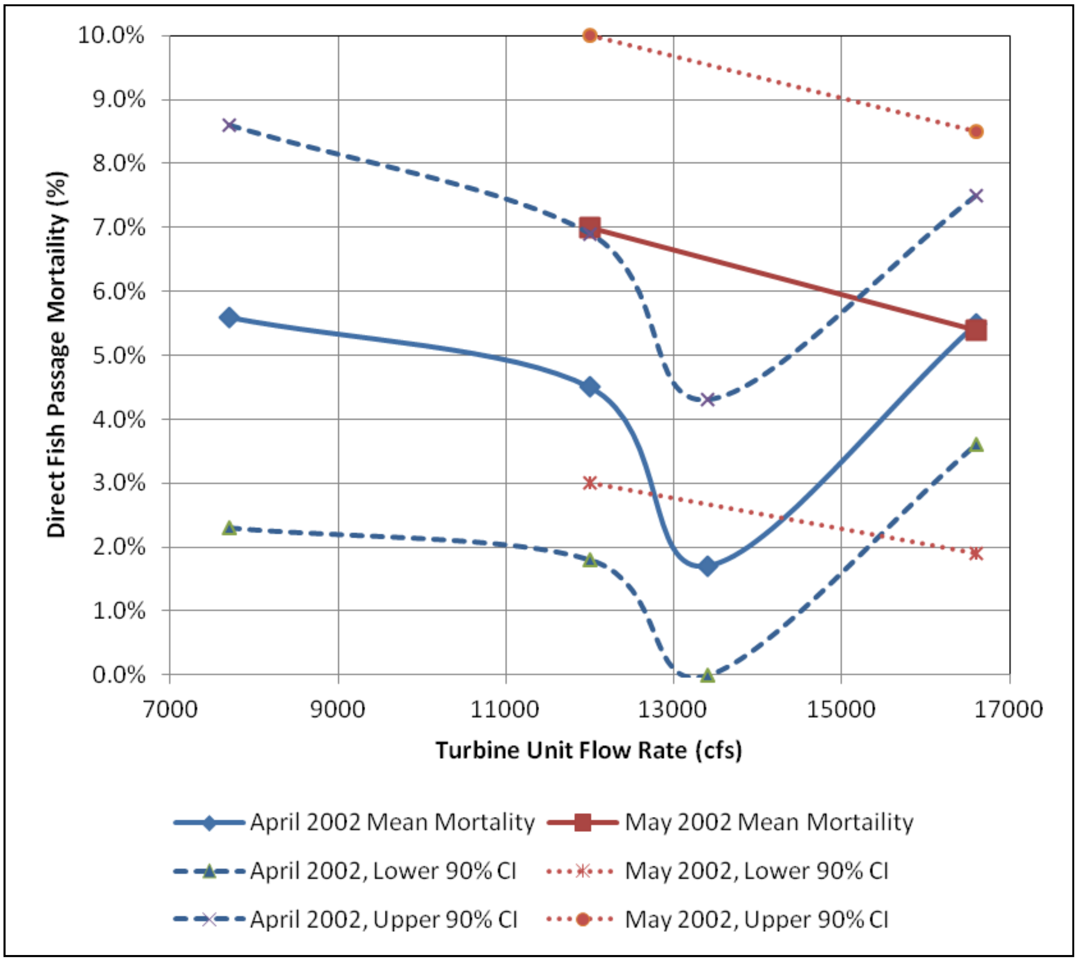
While there have been many downstream fish passage survival studies completed at McNary, only three field studies have specifically evaluated turbine survival. In 2002, a study introduced balloon-tagged fish into the intake of McNary turbine unit 9 at four different operating conditions: approximately 7.70 kcfs, 12.0 kcfs, 13.40 kcfs, and 16.60 kcfs (Normandeau Associates 2003). The 7.70 kcfs and 16.60 kcfs corresponded to the same release times as the sensor fish (but at a much higher release quantity) and represented approximately the lower end of the 1% range and generator limit at the test head, respectively. The additional operating conditions of 12.0 kcfs and 13.40 kcfs represented approximately the upper end of the 1% range and the upper 2% drop from peak efficiency at the test head, respectively. The HI-Z tag recapture method was used with hatchery yearling Chinook salmon in April 2002 with a total release of 1,340 treatment fish over the four operating conditions. An additional 781 treatment fish were released in May 2002 over the 12.0 kcfs and 16.60 kcfs operating conditions. Control fish were released at the exit of the draft tube so that direct turbine survival could be estimated. The mean direct fish passage mortality and 90% confidence interval (CI) for each operating condition are listed in Table 5 and illustrated in Figure 20.

Table 5. Direct Passage Turbine Mortality at Different Operating Conditions

Parameter	April 2002 Testing				May 2002 Testing	
Operating Condition (kcfs)	7.70	12.0	13.40	16.60	12.0	16.60
Mean Mortality (%)	5.6	4.5	1.7	5.5	7.0	5.4
90% CI	2.3 - 8.6	1.8 - 6.9	0.0 - 4.3	3.6 - 7.5	3.0 - 10.0	1.9 - 8.5

Source: Normandeau Associates 2003

Figure 20. Direct Passage Turbine Mortality at Different Operating Conditions



Source: Normandeau Associates 2003

The April releases indicate that the highest survival (lowest mortality) occurred at 13.40 kcfs discharge with survival at 12.0 kcfs discharge being only slightly better than at the 7.70 kcfs and 16.60 kcfs discharges. The May release results at 16.60 kcfs are almost identical to the April release results at this flow rate; however, the results at 12.0 kcfs do differ between the two months. Although the 90% CIs at 12.0 kcfs discharge overlap, predation in the tailrace could explain some of the difference. There was an indication of predation for some of the retrieved fish that increased with longer recovery times. High spill volumes during May releases were associated with longer recovery times due to entrainment of powerhouse flow and unsafe recovery conditions in the immediate powerhouse tailrace (Normandeau Associates 2003). While this study had a large number of fish released and a number of operating conditions, all fish were acclimated to surface or atmospheric pressures. Unfortunately, the surface acclimation is a consequence of using the balloon tags and could not be avoided with the tagging method. As noted in the PNNL laboratory studies, acclimation at deeper depths (higher pressures) would likely have resulted in higher mortality due to decompression-related injuries.

Ferguson and others (2006) performed a turbine survival study in 2002 at McNary turbine unit 9. The study was intended to measure both direct and indirect turbine mortality. Yearling Chinook salmon tagged with implanted radio tags and passive integrated transponder (PIT) tags were released to estimate turbine mortality under varying operations. Control fish were released 1.2 miles downstream of McNary

Dam. Releases were performed in May 2002 at the 12.0 kcfs and 16.60 kcfs operating conditions, which correspond to the same treatment release times and locations as the May releases by Normandeau and Associates (2003) for the balloon-tag study. The yearling Chinook used in this study had a median length of 145 millimeters and were surgically implanted with a radio tag weighing 1.4 grams in air and a PIT tag (typically 0.1 grams in air) for both treatment and reference fish. A total of 573 fish were released at 12.0 kcfs, 570 fish were released at 16.60 kcfs, and 565 reference fish were released (Absolon et al. 2003). Multiple detection arrays were used to fully assess the mortality using the single release model where fish that are not detected are assumed dead and reference releases are used to determine a "relative mortality." Generally, mortality increased with distance traveled from McNary (Table 6).

Table 6. Total Passage Turbine Mortality at Different Operating Conditions

Detection Site (Method)	Distance Downstream	Mortality (Standard Error)	
		12.0 kcfs Operation	16.60 kcfs Operation
Irrigon (radio tag)	9 miles	12.9% (1.6%)	14.4% (1.1%)
East Crow Butte (radio tag)	25 miles	16.8% (2.3%)	17.7% (2.1%)
West Crow Butte (radio tag)	29 miles	14.2% (3.8%)	18.6% (3.7%)
John Day Dam (PIT tag)	123 miles	27.6% (19.7%)	20.4% (22.7%)

Source: Ferguson 2006

Standard errors reported for the John Day detection site are so high that the mortality estimate is meaningless; however, it can be seen that the mortality increases with increasing distance downstream for the other three detection sites. Since these detection sites are relative to reference fish, this finding does indicate some sort of delayed turbine passage mortality (i.e., indirect mortality). It was concluded that there was no significant difference in mortality between the two operating conditions.

While the finding of increased turbine passage mortality with distance downstream is significant, this study has some associated weaknesses. Since the same release methods were used as the balloon-tag study, all fish were acclimated to surface or atmospheric pressures. In addition, since tags (1.5 grams) were surgically implanted in each fish, a high tag burden was likely associated with this study. A median weight of fish used in testing was not reported but a 30-gram fish would have a tag burden of 5.0% in this study. While the acclimation of test fish to surface conditions would tend to decrease mortality, the large tag burdens would most likely more than offset this and cause an overall increase in mortality. The increased mortality due to tag burden would also agree with the study conclusion of "a trend of higher mortality in smaller fish than larger fish" at the 12.0 kcfs discharge. Ferguson and others (2006) attributed higher mortality to turbulence affecting smaller fish more; however, it may have been the higher tag burden borne by smaller fish given the results of the PNNL study (Carlson et al. 2010).

In 2004, a project survival study was conducted with radio tags (Perry et al. 2006). While this study was not specific to turbines, efforts were made to determine mortality differences in fish passing through turbines operating at high flows outside the 1% operating range and lower flow inside the 1% operating range. Turbine units 2-6 and 9 were intermittently operated above a 13.0 kcfs threshold (chosen to represent unit flow rates above 1% operating range; average 15.90 kcfs). Low flow turbine passage (or turbine flow rate within the 1% operating range) averaged around 11.0 kcfs. Fish tagged with surgically implanted radio and PIT tags were released 6 miles upstream of the dam. Three different sizes of radio tags were used to ensure that each run (yearling and subyearling Chinook and juvenile steelhead) all experienced a maximum tag burden of 6.5%. While subyearling Chinook were part of the study, mortality estimates during high flow operations were only available for spring run yearling Chinook and juvenile steelhead. Mortality estimates and the 95% CI for these two species under high and low turbine unit flows are presented in Table 7, including average fish weight, tag weight and tag burden.

Table 7. Turbine Mortality at Different Operating Conditions/Species (Perry et al. 2006)

Fish Type	Turbine Passed Fish	Avg. Fish Weight	Tag Weight*	Avg. Tag Burden	Turbine Flow Rate	Fish Passage Mortality	95% CI
Yearling Chinook	28	37.6 g	1.68 g	4.47%	High	18.7%	±17.7%
	38				Low	11.0%	±12.4%
Juvenile Steelhead	9	98.6 g	2.08 g	2.11%	High	-7.4% **	±44.2%
	7				Low	9.0%	±27.5%

* A PIT tag weight of 0.1 grams was added to reported radio tag weights.
** A survival of 1.074 was reported.

Although mortality estimates differed between the high and low turbine flows (Table 7), the mixed results and wide CIs between species suggests no significant difference in mortality at high and low turbine discharge. There are likely multiple reasons for the large CIs: (1) the ESBS guides fish out of the turbines so that only a smaller proportion of yearling Chinook (28 at high flow and 38 at low flow) and juvenile steelhead (9 at high flow and 7 at low flow) passed through the turbines; and (2) the study was not targeted at turbine unit operation; therefore, the "high" and "low" flow categories had significant flow rate variability, as well as large variability in other conditions (powerhouse tailrace egress, etc). Furthermore, high tag burden may have caused fish to hold a greater gas volume in the swim bladder during depth acclimation. This may have caused increased mortality during turbine passage, particularly in yearling Chinook salmon as mortality estimates suggest (Table 7).

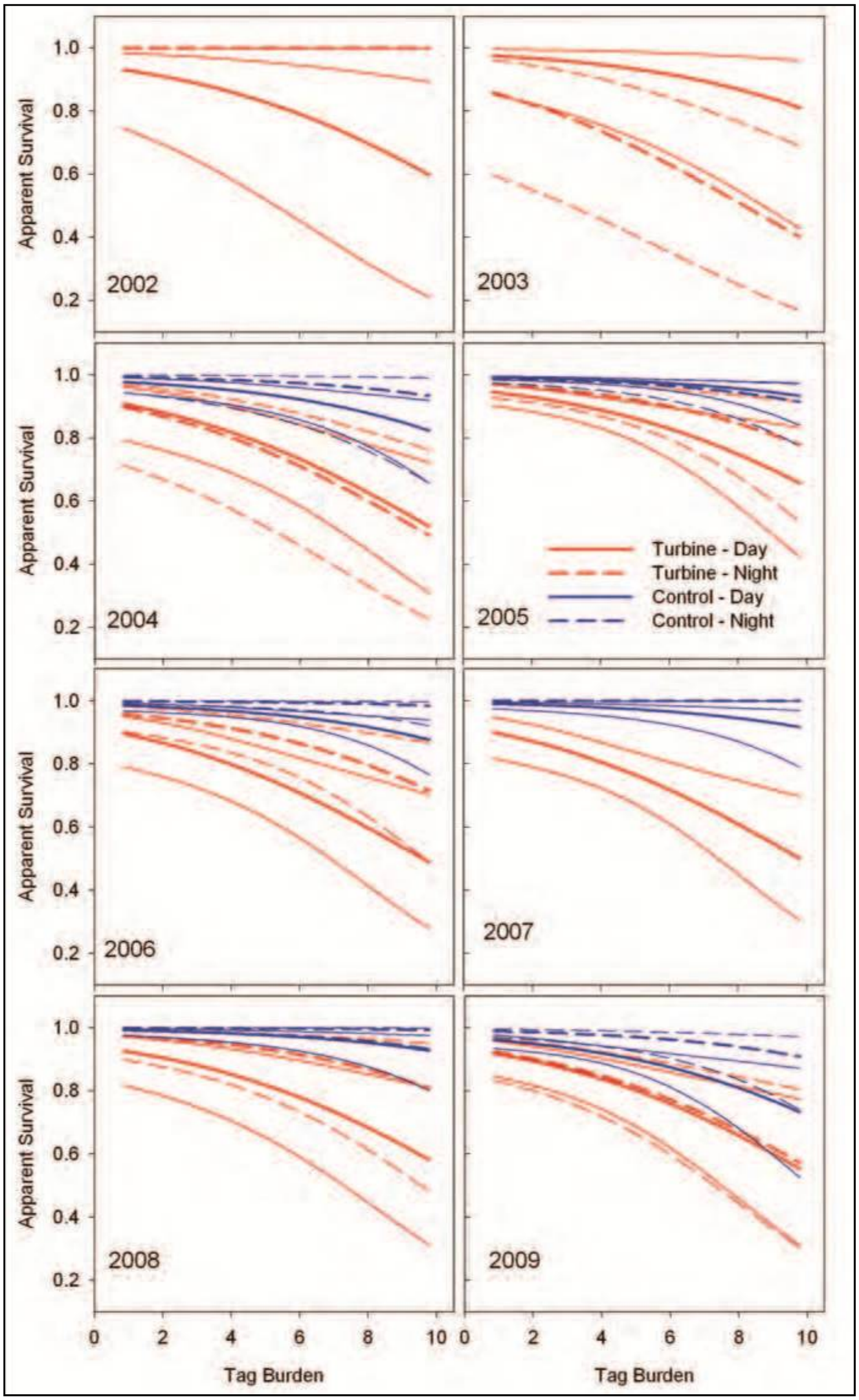
In 2010, the U.S. Geological Survey (USGS) was contracted by the USACE to conduct an analysis of data collected for McNary turbines from previous radio and acoustic tag studies (Beeman et al. 2011). Passage survival data for McNary from 2002 through 2009 were pooled and associated with environmental and operating conditions at time of passage. The data showed decreased survival with increased tag burden for both control and turbine passed fish, although the affect was more severe for turbine passed fish (Figure 21).

Along with tag burden, a quadratic relationship between turbine passage survival and head was found for both yearling Chinook and juvenile steelhead. Head and total discharge were highly correlated among the data and nadir pressures may be influenced by head. Total discharge is expected to have a significant influence on egress and predation; therefore, a relationship between turbine passage survival and total discharge is more likely than a relationship with head. For subyearling Chinook and juvenile steelhead, survival was found to decrease with increasing spill.

A relationship between turbine passage survival and water temperature was found for both yearling and subyearling Chinook. It is possible that water temperature could affect the acclimation depth of turbine-passed fish and thus, affect the probability of barotrauma related mortality. Both linear and quadratic relationships with turbine unit discharge and survival were explored, but unit discharge had no effect on survival. This may be explained by so few fish passed through turbines under operating conditions above the 1% efficiency range.

While the analysis was an important step, the results indicated that a targeted turbine survival test is needed to truly test the affect of turbine unit discharge on survival, particularly for a TOR outside of the existing operating range.

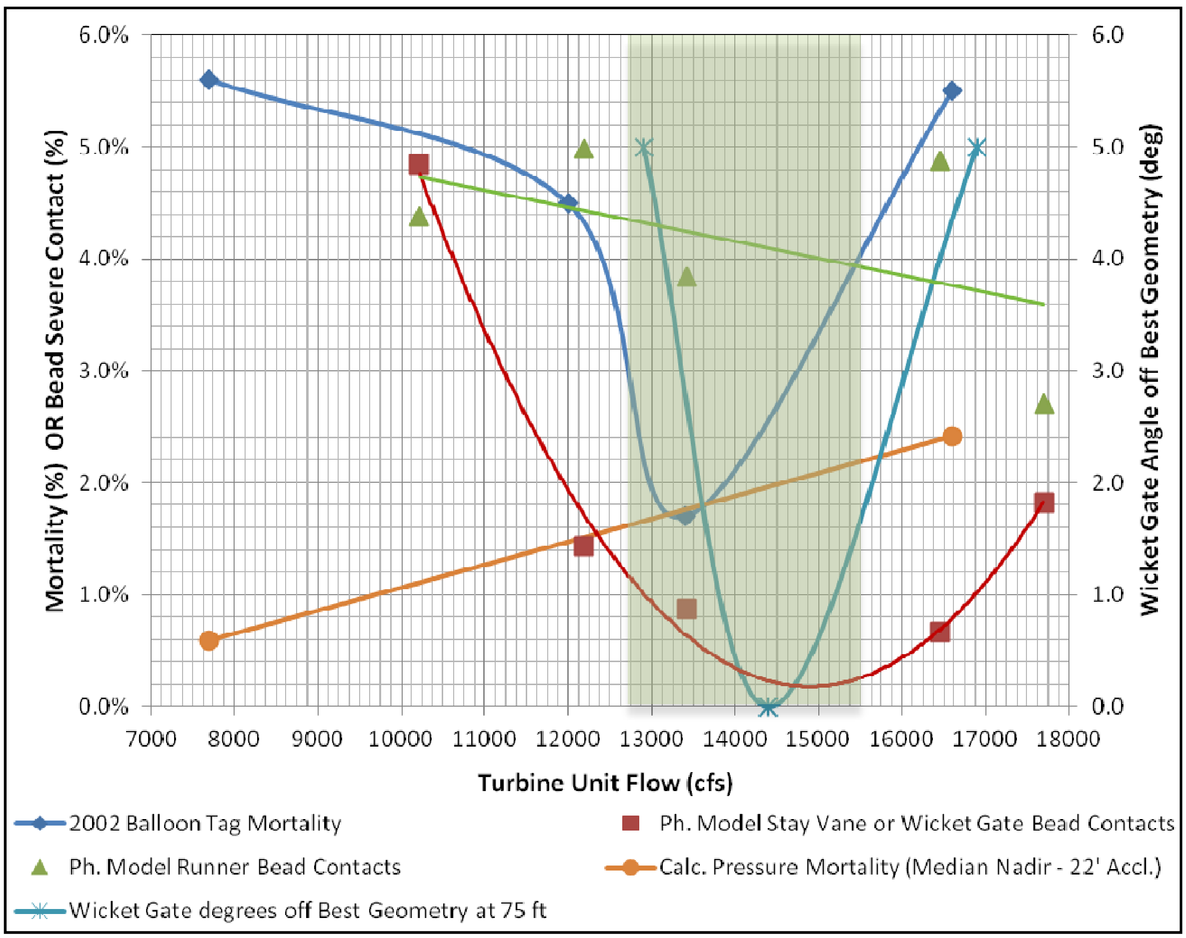
Figure 21. McNary Tag Burden Effect for Yearling Chinook Salmon



2.5. Discussion

The preceding sections presented the available turbine survival information applicable to McNary turbines. This information was derived from geometry considerations, physical model data, laboratory studies, field passage and survival studies, computational fluid dynamics (CFD) analysis, and sensor fish studies. None of the information alone can identify a TOR for survival of fish passing through turbines. All biological studies performed in the field that have attempted to measure the mortality or survival of fish passing directly through turbines have limitations with results that are not necessarily representative of the mortality expressed by the run-of-river population. The turbine physical model provides valuable information on potential physical injury within the turbine environment, particularly with the bead passage analysis; however; the model data do not indicate the frequency of barotrauma injury or account for fish behavior. The barotrauma injury rate was not accurately estimated by balloon-tag studies (Normandeau Associates 2003) due to the lack of depth acclimation of the fish prior to turbine passage, but barotrauma injury rate can be inferred from sensor fish data (Carlson and Duncan 2004) and laboratory data (Carlson et al. 2010). These various sources of information have been combined in Figure 22. This figure only shows direct turbine mortality information.

Figure 22. Combined Information on Direct Turbine Mortality (McNary units 1-14)



At approximately 75 feet of head, physical injury information (physical model bead data and geometry considerations) suggests a lower rate of physical injury and mortality between approximately 12.50 kcfs and 16.60 kcfs (Figure 22). This is supported by the balloon-tag study, which indicated a lower mortality at 13.40 kcfs (Normandeau Associates 2003). The only information on potential barotrauma mortality is derived by combining the sensor fish nadir pressure information with the laboratory-based barotrauma mortality equation (Equation 2) using assumed acclimation depths (Table 5). The calculated mortality (Figure 22) uses the median nadir pressure found by the sensor fish with an assumed acclimation depth of 22 feet. While only 7.70 kcfs and 16.60 kcfs were measured using sensor fish, this does indicate there could be a slight increase in barotrauma mortality with increasing flow. Therefore, based on available information, the proposed TOR for fish passage survival is defined by the shaded area of Figure 22, which is approximately 12.75 kcfs to 15.50 kcfs with 75 feet of head. Based on the physical model study, this proposed TOR should also reduce draft tube turbulence providing a potential reduction in tailrace predation. While this flow range may vary slightly with changing head, it will not vary significantly within the normal operating range for the McNary Project. This proposed range is above the 1% efficiency operating range for McNary turbines (Figure 22) and longer-term operation within this range will require adjustment to the FPP.

The initial planning stage has begun for a project to replace the turbine runners at McNary. It is likely that these runners will improve turbine passage survival above the existing runners even while operating at the identified TOR. However, the current project schedule for the new turbine runners does not have the final unit being installed until 2028. Because the existing runners will still be in service for a number of years, biological testing and implementation of the TOR for the existing units is still considered important until all of the existing units are replaced.

3. DEFINE TARGET PROJECT OPERATIONS

The best operating range for direct turbine survival is only one component of total turbine survival. Indirect turbine mortality includes predation and could account for a significant portion of total mortality. Reducing probability of indirect mortality should be considered when defining target operations. Indirect mortality of turbine-passed fish is thought to result primarily from predation by birds and piscivorous fish (USACE 2004). Neitzel and others (2000) found an increase in predation in laboratory studies when fish were exposed to high stress rates. Fish that pass through turbines uninjured are exposed to stress caused by the hydraulic environment and may experience loss of equilibrium making them more susceptible to predation in the tailrace.

High mortality rates estimated from the 2002 radio-tag study were hypothesized to be a result of predation (Ferguson et al. 2006). While a portion of the mortality could have been due to the large tag burden, it is possible that indirect turbine mortality from predation contributed largely to the overall mortality. While the effects of indirect mortality are difficult to quantify, significant evidence suggests that indirect mortality rates are as high or higher than direct mortality rates.

There is still a great deal of uncertainty on the best methods to reduce indirect turbine mortality. The primary ideas are to improve the condition of fish (reduce injury rate not just mortality) entering the tailrace and to improve tailrace egress conditions. Operating individual turbine units within the TOR applies to the first objective by improving the draft tube conditions. Additionally, a higher rate of flow within the TOR would provide higher and more evenly distributed velocities exiting a draft tube, potentially providing better egress directly downstream of a turbine unit. Conversely, the individual turbine unit operation is unlikely to provide better egress relative to the entire powerhouse region of the tailrace. Improving full tailrace egress conditions has much more to do with project operations rather than individual units.

Therefore, the TSP conducted hydraulic modeling using a 1:55 physical model of McNary at ERDC. Physical models include all of the major dam components including the powerhouse, spillway and navigation lock, as well as upstream and downstream bathymetry. The effective size of the flume containing the physical model is 200-feet long by 125-feet wide, providing potential prototype dimensions of more than 11,000-feet long by nearly 6,900-feet wide. The purpose of the March 13-15, 2012, modeling trip was to determine project operations that may improve powerhouse tailrace egress without impacting full project egress. Figure 23 is a picture taken of the project and tailrace during this modeling effort.

To limit the possible test conditions, only three different total river discharges were modeled: 125.0 kcfs, 200.0 kcfs, and 300.0 kcfs representing low summer, middle (low spring/high summer), and high spring river discharge conditions, respectively. A total of 20 conditions were tested at these three flows comparing existing unit discharge vs. TOR, several different unit priorities, and existing spill vs. reduced spill. No attempts were made to adjust spill pattern, and either the spring or summer spill pattern in the 2011 FPP was utilized for the selected volume. Existing spill is 40% in spring with temporary spillway weirs in 19 and 20 and 50% in summer with no temporary spillway weirs.

Figure 23. McNary General ERDC Model During Testing in March 2012

The primary evaluation methods were the use of dye and confetti to observe flow patterns associated with each test condition. In addition, velocity measurements were taken in the model at five different consistent locations. The measurement was attempted to be made at approximately the 60% depth (from bottom) to approximate a depth averaged velocity. It was hypothesized that powerhouse egress conditions would improve with higher unit discharge and blocked loading, and be concentrated to the north near the spillway flow. This was observed in the modeling for the most part. In general, the velocity downstream of the north end of the powerhouse increased for conditions using the higher unit discharge of the TOR. In most cases, the increase in unit discharge also increased the velocity to over 4 feet per second (fps), which is the generally accepted threshold for eliminating predator habitat.

The higher unit loading with the same powerhouse flow also decreases the number of units operating, and in some cases allows for recirculation to develop in front of the powerhouse. Therefore, the alternating gap powerhouse priority was also tested. While the alternating or "saw tooth" pattern did reduce the larger scale recirculation in front of the powerhouse in most cases, the velocities were decreased as compared to the north loaded unit priority. In general, a higher percentage of the juvenile salmon approach the project near the center of the river. Considering this, an emphasis on improved turbine egress conditions at the north end of the powerhouse could improve overall project survival. In the 2012 FPP, the existing turbine unit priority is unit 1 followed by units 14 through 2. Since turbine unit 1 is still required for attraction flow to the south fish ladder, there is no recommended change to unit priority.

In general, there were no test conditions that degraded generally good egress conditions at the new outfall location. Higher unit discharge for units 12 to 14 and operating the ice trash sluiceway exit did seem to increase velocities past the outfall, although no measurements were made. The addition of the ice trash sluiceway also reduced or eliminated the stagnation zone between the powerhouse and the spillway.

As expected, reducing the spill flow improved the powerhouse egress by allowing higher powerhouse discharge. The spring spill pattern resulted in better spill egress than the summer spill pattern and none of the conditions resulted in major recirculation of spillway flow. Additionally, there did not appear to be a break point on spill flow either by percentage or discharge where conditions became significantly worse. Of the conditions tested, it appeared that the best project egress for 200.0 kcfs total river flow occurred with 20% spill (spring pattern), the 2012 FPP unit priority with turbine units operating within the TOR, and 4.0 kcfs in an ice trash sluiceway exit between the powerhouse and spillway.

While the general model is a good tool, there are some portions of the model that do not accurately reflect field conditions. The most obvious inaccuracy is entrainment of the powerhouse flow into the spillway, which is significantly less in the model relative to field conditions. Therefore, another piece of information that can be used is the recent CFD modeling of the McNary tailrace by the University of Iowa (with oversight by CH2M Hill).

The focus of the CFD modeling was to investigate a change in powerhouse unit priority between the FPP for 2011 and 2012 to determine the conditions at the new juvenile bypass outfall (Politano 2012). The goal was to accurately model entrainment flow by modeling two-phase flow with gas exchange and calibrating these parameters using dissolved gas field measurements. Simulations were performed of current and proposed operations at a variety of river discharges while using both spring and summer spill patterns and percentages. The “current” powerhouse operation (odd numbered simulations) had a priority of units 1 to 4, then units 14 to 5 and looked at unit operations closer to the lower 1% (i.e., more units, less flow per unit). The “proposed” powerhouse operation(even numbered simulations) had a priority of unit 1, then units 14 to 2 and looked at unit operations as many units at the upper 1 % as possible (i.e., less units, more flow per unit). While the CFD modeling did not look at operations beyond the 1% range, the trend based on the increase in flow and the north loading provided useful information.

It was observed that proposed operations provided a higher velocity in the north part of the powerhouse due to higher unit discharge and the increased number of northern units operating. This caused the total dissolved gas (TDG) flow to entrain in the spillway region further downstream from the aerated zone, thereby reducing TDG production and increasing dilution. The increased velocity can be seen in Figure 24, where the powerhouse flows (>4 fps) coming out of the north units for the proposed operation are entrained in the higher spillway velocities. Higher velocities can also push the entrainment further downstream (Figure 25). Current operations have larger areas of higher TDG concentrations than the proposed operation and higher velocities may decrease overall TDG concentrations (Figure 26). The trend of higher TDG for the current operations may be even more accentuated at other river discharges (Figure 27). Current operations also create an area in front of the entire powerhouse that is below the predation velocity criteria.

It could be assumed that both of these trends would continue with increased unit loading of the TOR, while still operating at the same unit priority as the even numbered CFD simulations. The CFD modeling suggests that increasing unit flow may provide benefits of decreased predator habitat and possibly decreased TDG concentration for some river discharges. Compared to the physical modeling, the CFD also supports the north loaded unit priority as it appears to improve overall powerhouse egress, even with increased entrainment.

Figure 24. Increased Velocities for Simulations 11 and 12

Note: Velocities over 4 fps for 201.70 kcfs river discharge with spring spill for simulation 11 (near lower 1% for all powerhouse) and simulation 12 (upper 1% for most units with units 1 and 5-14).

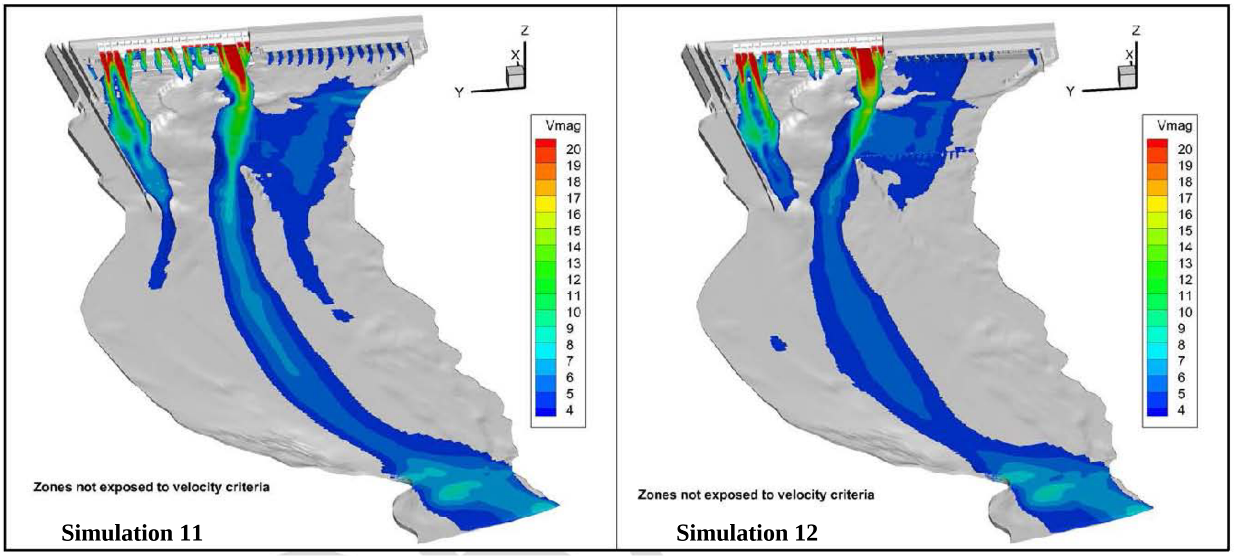


Figure 25. Increased Velocities on Entrainment, Simulations 11 and 12

Note: Streamlines for 201.70 kcfs river discharge with spring spill for simulation 11 (near lower 1% for all powerhouse) and simulation 12 (upper 1% for most units with units 1 and 5-14).

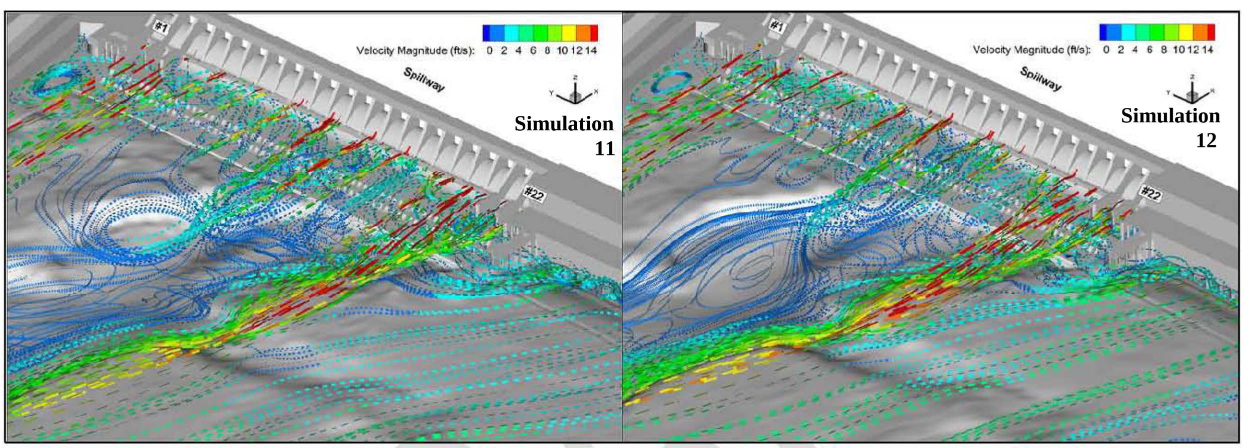


Figure 26. Increased Velocities on TDG Concentrations, Simulations 11 and 12

Note: TDG concentrations for 201.70 kcfs river discharge with spring spill for simulation 11 (near lower 1% for all powerhouse) and simulation 12 (upper 1% for most units with units 1 and 5-14).

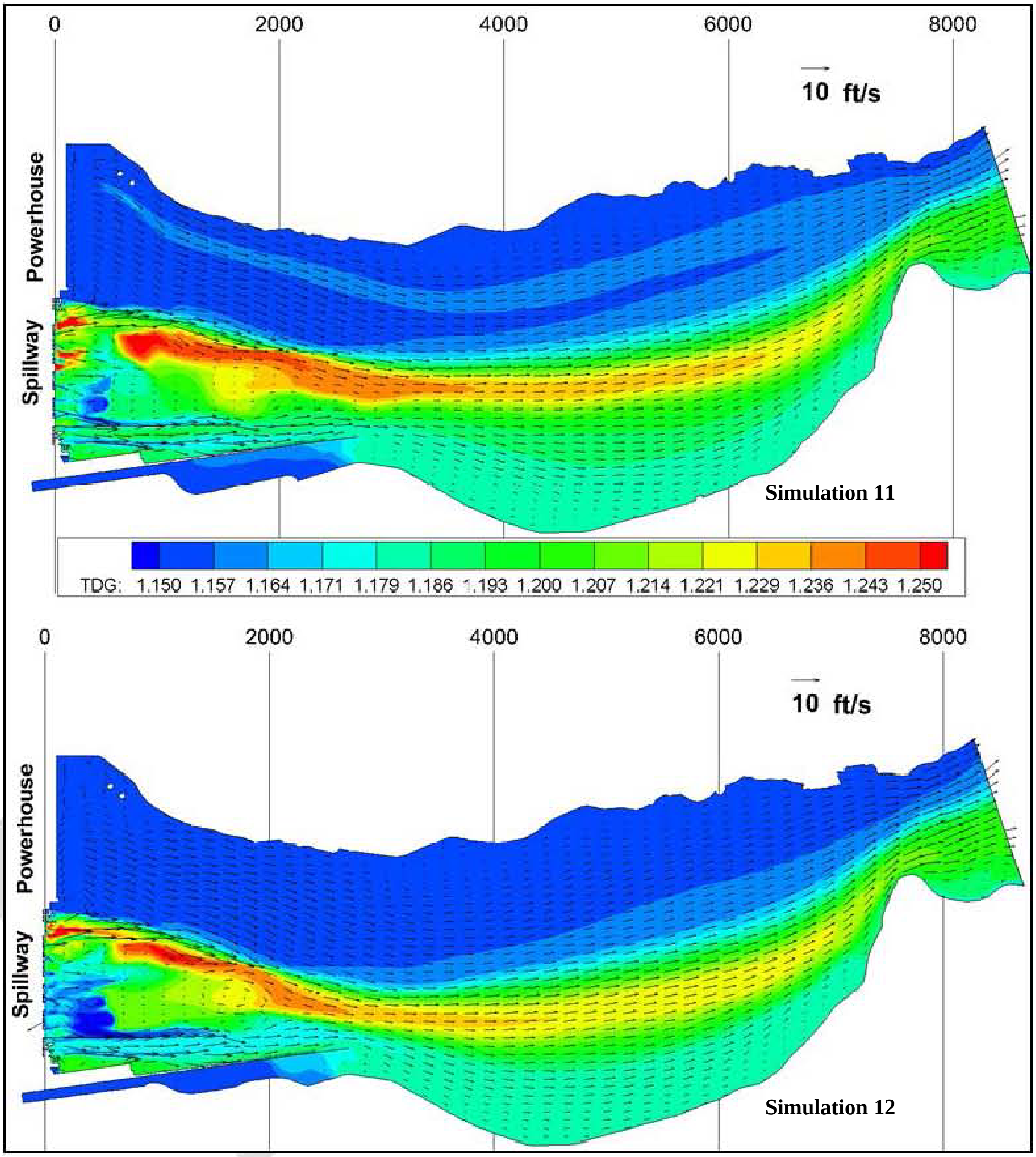
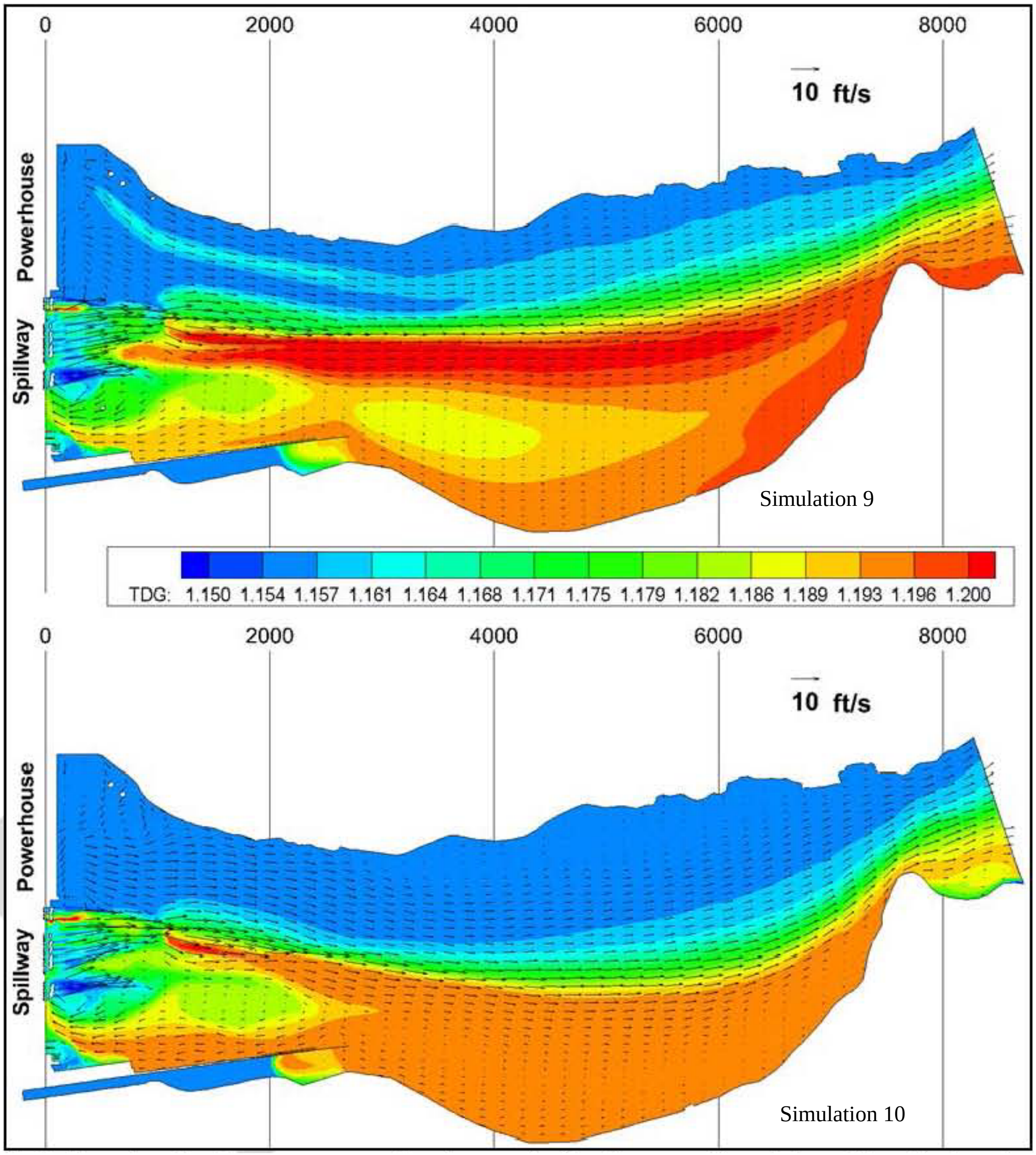


Figure 27. Increased Velocities on TDG Concentrations, Simulations 9 and 10

Note: TDG concentrations for 152.50 kcfs river discharge with spring spill for simulation 9 (at lower 1% for units 1-4 and 8-14) and simulation 10 (upper 1% for most units with units 1 and 8-14).



Field measurements and biological tests are needed to completely verify current unit priority with units operating at the TOR for improved powerhouse egress. Based on the physical modeling, spill could be reduced without harming project egress. The feasibility of meeting project survival goals with reduced spill should be considered as part of the McNary Configuration Operation Plan.

4. OTHER CONSIDERATIONS

The McNary turbines are currently operated with an ESBS installed in front of the turbines which route fish up the bulkhead gatewell slot and into the collection channel through orifices. As long as the ESBS are installed, the effect that the TOR has on the gatewell environment should be considered in the context of achieving the highest overall project survival and lowest fish injury rates.

There has been concern that increased flow rate through the turbines at McNary may result in decreased fish condition and survival in the juvenile bypass system. It is known that fish can spend a significant amount of time in the gatewell prior to locating and passing through the orifices. This is of concern because with ESBS installed, increased flow through the turbine will increase flow up the gatewell. This increase in turbine unit flow results in increased velocities and turbulence in the gatewell, and may consequently increase fish injury and mortality. Since McNary has significant capacity beyond the 1% operating range, multiple studies have focused on fish delay, injury and mortality at different turbine unit operating flows with mixed conclusions.

A 1997 study compared descaling (at least 20% of scales removed – a fish injury that may or may not result in mortality) and orifice passage efficiency (percent of fish passed through the orifices in 24 hours) at 12.0 kcfs and 16.0 kcfs through turbine units 4 and 5 (Brege et al. 1998). Fish were recovered in this study by the use of a dip net in the gatewell. Results suggested that higher turbine loading resulted in increased orifice passage efficiency for both yearling and subyearling fish (63% at low load and 94% at high load). However, high turbine loading also resulted in increased descaling for yearling fish (6.7% at low load and 17.1% at high load).

In 2002, a study was conducted using PIT tags and separation by code equipment at the juvenile fish facility to compare descaling and passage time for unit 8 operating at 11.20 kcfs and unit 9 operating at 16.40 kcfs (Absolon et al. 2003). A total of 1,202 yearling Chinook were placed in gatewell slot 9B and 1,108 yearling Chinook were placed in gatewell slot 8B. Very low descaling rates were observed among fish placed in either gatewell and no significant difference was found for high or low turbine loading (0.3% at low load and 0.2% at high load). Significantly shorter passage times were measured for the gatewell with high turbine loading (0.58 hours) relative to the gatewell with low turbine loading (18.7 hours).

In 2004, a study was initiated at McNary to look at prototype vertical barrier screens (VBS) at turbine loadings of 60 MW and 80 MW (Absolon et al. 2005). Observations of increased descaling at 80 MW at the start of the study resulted in modification of the study design to determine the cause of the descaling. However, at the conclusion of the study when the data were analyzed, it was determined that little difference in descaling rates between 60 MW and 80 MW turbine operations (approximately 12.0 kcfs and 16.0 kcfs, respectively) were found for fish released directly into the gatewell.

Due to the inconclusive and incomplete 2004 study, a 2005 study was conducted to estimate descaling differences for a prototype VBS and different turbine unit loading (Gessel et al. 2006). Fish were released into the gatewell and in front of the trashrack, where fish would then be guided by the ESBS into the gatewell. For fish released in the gatewell, there was no significant difference in descaling at 62 MW (7.7% at approximately 12.20 kcfs) and 80 MW (8.7% at approximately 16.0 kcfs). Significant differences in descaling were found relative to release location with 6.4% in the gatewell and 8.6% at the trashrack.

In 2006, a study was performed with a flow control device and a prototype VBS in unit 4 and a standard VBS without a flow control device in unit 5 (Gessel et al. 2007). During the initial phase of this study, the flow control device was not working. Ultimately, modifications were made to allow proper operation. Descaling and mortality were evaluated in turbine unit 4 gatewell at high load (80 MW, ~16.0 kcfs) and low load (62 MW, ~12.20 kcfs). Descaling was not significantly different between the high (2.8%) and low loading (2.5%) but mortality was significantly different between high (1.9%) and low loading (0.6%).

In 2009, PNNL compiled a synthesis report of McNary biological studies performed from 1990-2006 (Ham et al. 2009). This report was inconclusive on whether high turbine unit flows resulted in increased injury or mortality in the gatewell, and determined more study was needed to reach a firm conclusion. Furthermore, in 2009, regional stakeholders held a discussion about operating McNary turbines beyond the upper 1%. It was determined that an additional descaling study would be needed to assure that descaling would not be a factor when operating McNary turbines above the 1% range.

Therefore, in 2010 a study was conducted to evaluate descaling at average test flows of 12.10 and 13.80 kcfs through turbine units 4 and 5 (Axel et al. 2011). Both flow rates were tested to estimate descaling rates in the “A” slots of both turbines (“A” slots were used since these slots receive the highest gatewell slot flow and thus, the highest turbulence). The study had difficulties with debris loading on the trashracks and the VBS of the test units. Attempts were made to incorporate VBS head differential into the analysis, but it was not possible to incorporate trashrack head differential. While the analysis showed significant unit and time effects, head differential was not a significant factor in descaling. For yearling Chinook, a 2.1% (95% CI = 0.14% to 4.06%) to 3.4% (95% CI = 0.85% to 5.78%) increase in descaling occurred at turbines operated at 13.80 kcfs as compared to 12.10 kcfs. For subyearling Chinook a 3.8% (95%CI = 1.64% to 5.95%) increase in descaling occurred at turbines operated at 13.80 kcfs as compared to 12.10 kcfs. Descaling was the highest for sockeye salmon, but declined sharply after the trashracks were raked. No significant difference in descaling between operating conditions were found for sockeye or steelhead and results for coho salmon were inconclusive due to small sample size. No gatewell mortality data were collected during this study.

Table 8 summarizes all the gatewell studies done to date that looked at high turbine unit loading. Since yearling Chinook was a common thread to the studies, the findings on these fish are reported in the table, with some subyearling data included as well. A summary of results from studies testing gatewell fish condition at high turbine unit loading is presented in the table. Data collected for yearling Chinook salmon was common among the studies and is presented with some subyearling data as well in Table 8.

A large degree of variation in the descaling estimates resulted from the various studies. The most likely cause of this is the variation on debris loading on the trashrack, ESBS and the VBS. Despite the variation, the overall body of data suggests an increase in descaling with increased flow through the turbine unit. The magnitude of increase overall is difficult to determine from the studies completed to date, but it is potentially less than 5%. It should be noted that a large proportion of descaled fish will not suffer mortality; however, the proportion descaled relative to proportion of mortality is unknown and speculation of these proportions should be strictly limited.

All studies suggest trashrack debris loading as a major contributor to descaling, although none of the studies were able to quantify it. Overall, these studies point to an increased risk in fish passed through the juvenile bypass system when turbines are operated at the predicted TOR of 12.75 kcfs to 15.50 kcfs at 75 feet of head. However, if debris on the trashracks, ESBS and VBS are managed appropriately, this increase may be kept to a minimum.

Table 8. McNary Gatewell Fish Condition at Different Operating Conditons

Study Year	1997	2002	2004	2005	2006	2010	2010
Reference	(Brege 1998)	(NOAA Fisheries 2002)	(Absolon 2005)	(Gessel 2006)	(Gessel 2007)	(Axel 2011)	(Axel 2011)
Test Fish	Yearling Chinook	Yearling Chinook	Yearling Chinook	Yearling Chinook	Subyearling Chinook	Yearling Chinook	Subyearling Chinook
High Turbine Unit Flow Results							
High Test Q (kcfs)	16.0	16.40	16.0	16.0	16.0	13.80	13.80
Descaling (%)	17.1	0.2	Incomplete	8.7	2.8	7 to 11	11% for U4 4% for U5
Mortality (%)	---	----	Incomplete	---	1.8	---	---
Orifice Passage	94% OPE in 24 hrs	0.58 hr avg. GW residence time	0.38 days avg. GW residence	---	---	---	---
Low Turbine Unit Flow Results							
Low Test Q (kcfs)	12.0	11.20	12.0	12.20	12.20	12.10	12.10
Descaling (%)	6.7	0.3	Incomplete	7.7	2.5	4 to 7	4.5% for U4 2.5% for U5
Mortality (%)	----	----	Incomplete	----	0.6%	----	----
Orifice Passage	63% OPE in 24 hr	18.7 hr avg. GW residence time	0.51 days avg. GW residence	----	----	----	----

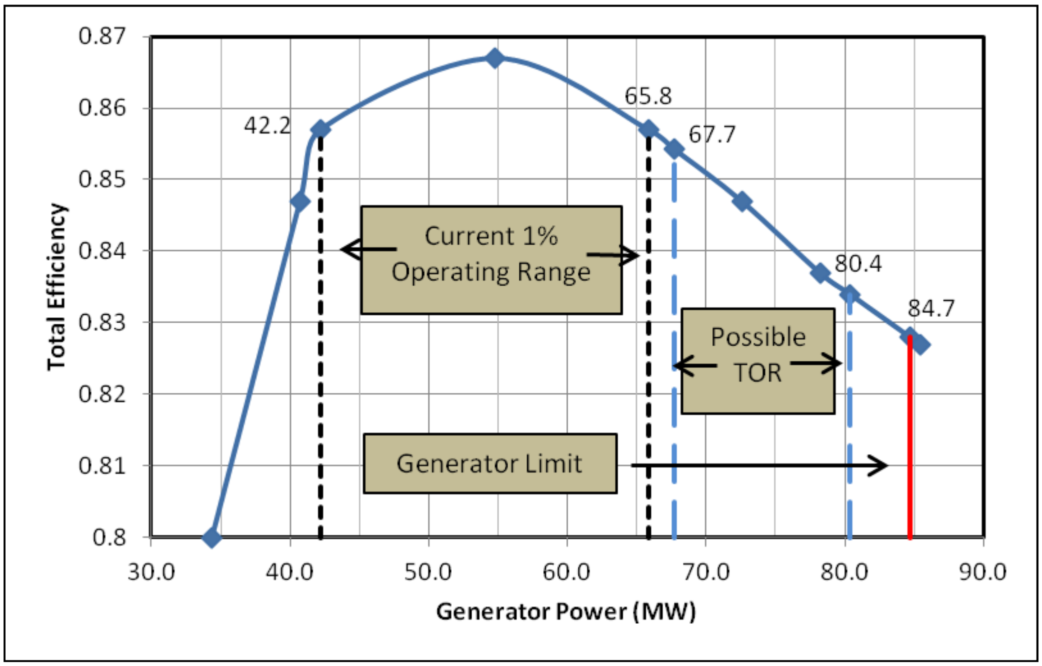
Currently, plans are underway to bevel the bottom edge of the head gate in one unit to allow for more flow between the ledger beam and head gate. This is being considered as an alternative to major structural changes that will allow head gates to be lowered to the standard operating gate position to satisfy a ten minute emergency gate closure requirement. This modification has the potential to change hydraulic conditions in the gatewell. Plans to test fish guidance efficiency (FGE) and subsequent fish condition and gatewell retention time are also underway for 2013 relative to head gate position (partially raised operating gate position and standard operating gate position). If no significant impact on FGE is realized by lowering the head gates to the standard operating gate position, head gates may subsequently be lowered across the full powerhouse.

Another consideration of the affect head gate position on fish guidance screens and subsequent turbine passage survival is gap loss. While gap loss is not typically measured behind the guidance screen, fish that may be injured due to gap loss may bias turbine survival estimates. If fish experience injury from gap loss and subsequent tailrace predation it is considered turbine mortality. If head gates are lowered at McNary, velocities will increase through the ESBS gap and may increase gap loss. While it is unknown whether this phenomenon may or may not provide a detectable decrease in turbine survival, a TST is recommended to test for significant differences in turbine survival with and without screens installed.

5. RECOMMENDED PATH FORWARD

The information presented in this appendix indicates that turbine unit operation may have a significant effect on direct turbine mortality at McNary Dam. Based on the available information, a TOR of 12.75 kcfs to 15.50 kcfs at approximately 75 feet of head is proposed. Figure 28 translates this flow range to generator power and efficiency at 75 feet of head since flow is a calculated value based on power and efficiency. The proposed TOR may increase the descaling rate of fish diverted by the ESBS into the juvenile bypass system; however, with diligent debris management descaling may be kept at a minimum. While increased juvenile bypass system injury is a concern, descaling does not necessarily result in mortality; therefore, the potential benefit in total turbine survival using the TOR is worth exploring.

Figure 28. McNary Turbines Proposed Target Operating Range at 75 feet of Head



Although the proposed TOR is supported by some field studies, the TSP team believes that additional field verification is needed. Therefore, this appendix suggests that a comprehensive turbine survival test (TST) be conducted within and surrounding the proposed TOR (see Turbine Survival Testing Phase II Appendix). The first step in turbine survival testing would be to conduct direct turbine survival testing while attempting to control conditions that may lead to indirect turbine mortality. Due to the effects of indirect turbine mortality, any biological turbine test of varying turbine unit operations should be performed as similar to appropriate seasonal project operations as possible. Additionally, the test should measure both direct and indirect turbine survival, if possible.

If the TST determines turbine unit operation within the TOR can improve the direct survival of turbine passed fish, the TOR would need to be defined at multiple heads. It is possible to define an operating range at the full range of heads based on efficiency, wicket gate angle, blade angle, discharge or some combination of these variables. The difference in survival shown by testing at the edge of the range as well as practical operational considerations will need to be taken into consideration when defining the TOR over a range of heads.

Following the definition of operating conditions for best direct fish passage survival, the next step would be to explore and define methods for improving indirect turbine survival. Based on the use of the physical model and CFD modeling of McNary, the current unit priority (unit 1, then units 14 to 2) with units operating at the TOR would improve powerhouse egress and reduce total river TDG levels. Reductions in required spill would benefit powerhouse egress without impact to project egress. Spill reductions are considered unlikely at this time but could be considered as part of the McNary Configuration Operation Plan. Field velocity measurements and/or biological studies could verify whether further improvements to powerhouse egress and indirect turbine mortality could be made. Finally, field biological studies could be undertaken to evaluate total turbine survival, which would encompass the benefits of operating at the TOR and improved egress conditions.

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US Army Corps
of Engineers ®

PHASE II PROJECT APPENDIX

TURBINE OPTIMIZATION FOR PASSAGE OF JUVENILE SALMON AT LOWER MONUMENTAL DAM

PREPARED BY
U.S. ARMY CORPS OF ENGINEERS
TURBINE SURVIVAL PROGRAM

JUNE 2013 REVISION 0

EXECUTIVE SUMMARY

This report identifies operating conditions for turbine units at Lower Monumental Dam on the Columbia River, where turbine fish passage survival is expected to be higher based on using the tools developed by the Turbine Survival Program (TSP). The 2004 TSP Phase I Report indentified that operating conditions of large Kaplan turbine units appear to have a significant effect on the survival of fish passing through them. This TSP Phase II Project Appendix involves identifying target operating range (TOR) and the targets for project operations. Lower Monumental uses two different turbine manufacturers, Baldwin-Lima-Hamilton (BLH) turbine units 1-3 and Allis-Chalmers (AC) turbine units 4-6; due to their design differences, they are expected to have different TORs.

To reduce strike injuries, the physical geometry of Lower Monumental turbine components was examined. For BLH units 1-3, the wicket gates achieve the best alignment with the stay vanes at 41 degrees open (range 36-45 degrees), which corresponds to about 19.75 thousand cubic feet per second (kcfs) at 100 feet of head. For AC units 4-6, the wicket gates achieve the best alignment with the stay vanes at 42 degrees open (range 36-44 degrees), which corresponds to about 18.70 kcfs at 100 feet of head.

Additional information to reduce strike frequency, exposure to shear, and turbulent environments came from a physical model of a John Day turbine unit, which is expected to apply to Lower Monumental BLH units 1-3. High-speed video of neutrally buoyant beads was taken to assess the strike frequency and severity. The physical model showed that the percentage of beads contacting the stay vanes and wicket gates was low. The lowest number of contacts and direction changes seem to occur for flows larger than 16.0 kcfs. In addition, the percentage of beads passing through the gap between the stay vanes and wicket gates appears to increase with flow and be relatively unrelated to the best wicket gate geometry. As with the stay vane region, analysis of beads contacting the runner can give an indication of potential fish injury. In general, contact with the runner was found to decrease with increasing flow rate through the runner. Increasing flow rate of course corresponds to an increase in blade angle and increased open area within the runner environment.

Lower Monumental turbine units 4-6 and Lower Granite turbine units 4-6 are of the same design and operate at approximately the same head. While a physical model was constructed for unit 4 at Lower Granite and operated in 1998, the primary purpose of this modeling was to look at bead release points and potential draft tube modifications. Although some information was collected about the existing turbines, there are no comparisons across operating range for the existing unmodified turbine passageway, and detailed bead analysis was not performed at the time this model was investigated. The bead analysis that did occur indicated that flow conditions downstream of the turbine intake screens (submersible traveling screen at Lower Monumental and extended length submersible bar screen at Lower Granite) are very turbulent and can potentially impact the distribution of flow as it approaches and enters the scroll case. The head loss and non-uniform flow distribution created by the screens reduces turbine efficiency.

Injury and mortality (barotrauma) can also occur to fish passing through turbines due to exposure to low nadir pressures. Because no pressure studies have been done at Lower Monumental, it is necessary to use surrogates such as John Day BLH turbine units 1-3. No data exists that would represent Lower Monumental AC units 4-6. For the John Day BLH units, sensor fish were used along with computational fluid dynamics model to generate a nadir distribution. Assuming a worst case acclimation depth of 22 feet, a barotrauma mortality rate of 0.62% for 11.80 kcfs (lower 1% operating range) and 6.18% for 20.30 kcfs (upper 1% operating range) was calculated.

Passage behavior and survival studies for radio-tagged juvenile Chinook and steelhead were conducted from 2006 through 2009 at Lower Monumental. Yearling Chinook survival rates ranged from 90.9% in 2007 to 100% in 2009; juvenile steelhead ranged from 83.8% in 2006 to 100% in 2009. The turbine passage survival estimates were not operation or geometry specific, nor were the numbers of fish passing through the turbines during these studies sufficient enough to provide strong survival estimates. These studies focused on spillway survival and spill patterns. Because a small percentage of fish released passed through turbines during the study, turbine passage survival may not be representative of actual survival. Therefore, using John Day information is likely the best surrogate for Lower Monumental BLH turbine units 1-3. The selected TOR for John Day is 15.0 kcfs to 18.80 kcfs. While it is a different dam, there is no additional information for Lower Monumental that would cause a change to this proposed range.

There is limited information for the Lower Monumental AC turbine units 4-6. Based on physical geometry considerations and some 2009 data correlation, the best operating range for these units is likely between peak and upper 1% or slightly higher. Pressure information for these turbine units is lacking and could restrict the range if lower pressures are found at the higher operating points.

Modeling done as recently as 2011 for the relocated juvenile bypass system outfall looked at tailrace conditions at river flows from 60.0 kcfs to 90.0 kcfs and two different spill patterns (28.0 kcfs and 25.0 kcfs for each pattern). The 60.0 kcfs and 70.0 kcfs flows had a large eddy downstream of the powerhouse. In addition, data correlation was performed for turbine passage data from 2004-2009 fish survival studies. The number of units operating at Lower Monumental correlated with increased detection of fish downstream. In general, this indicates that the more units that are operating, the better the egress and the better the turbine passage survival. The turbine unit of passage at Lower Monumental Dam also correlated with increased detection of fish downstream. Turbine unit 1 is the unit close to shore and unit 6 is closer to the center of the dam. In general, this indicates that the closer the unit is to the center of the river, the better the egress and the better the turbine passage survival.

The powerhouse unit priority at Lower Monumental should be adjusted to pass fish through units near the spillway to leverage on the egress conditions created by spill. Unit 1 and possibly unit 2 will continue to be prioritized for adult fish attraction water, but may not be the best for juvenile salmon moving downstream due to the strong reverse eddy associated with that region at the dam. Therefore, a single unit could be used for adult attraction, while subsequent units are prioritized toward the center of the dam. Physical model operation could be used to further justify this change in unit priority.

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ACRONYMS AND ABBREVIATIONS

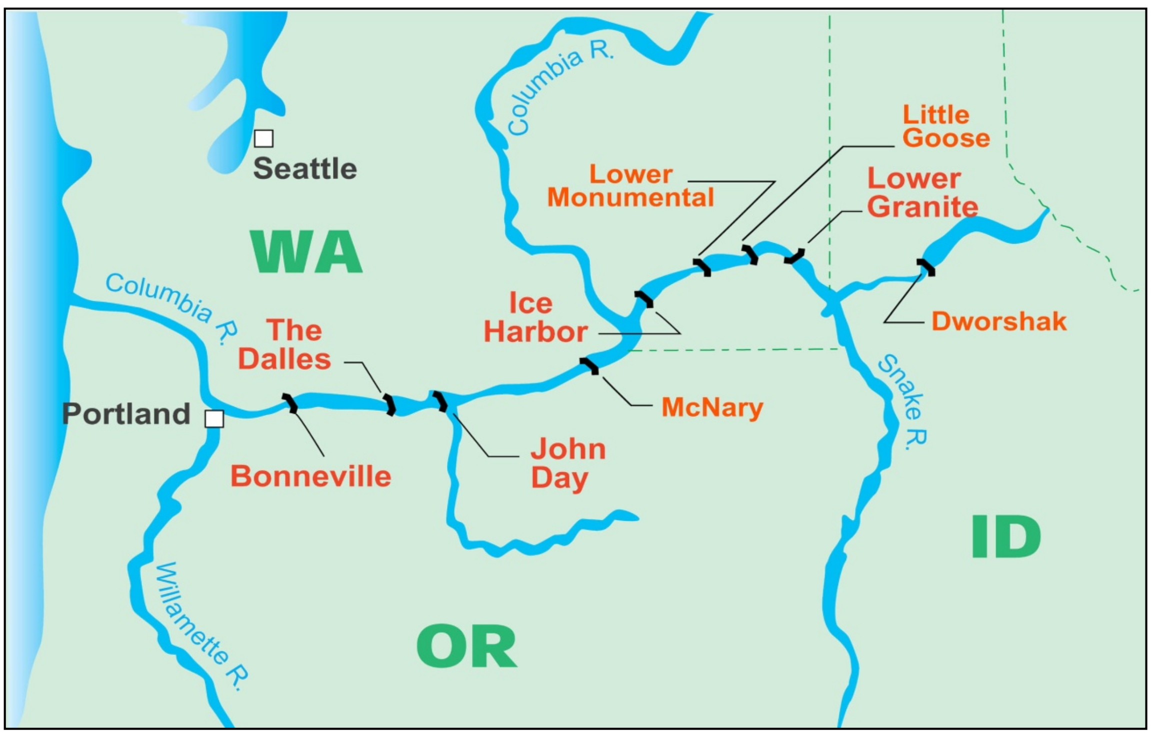
AC	Allis-Chalmers (turbine manufacturer)
BLH	Baldwin-Lima-Hamilton (turbine manufacturer)
BiOp	Biological Opinion
CFD	computational fluid dynamics
cfs	cubic feet per second
CRFM	Columbia River Fish Mitigation
ERDC	Engineering Research and Development Center
ESBS	Extended length submersible bar screen
FPP	Fish Passage Plan
hp	horsepower
JFF	juvenile fish facility
kcfs	thousand cubic feet per second
km	kilometer(s)
LDV	Laser Doppler Velocimeter
msl	mean sea level
MW	megawatt(s)
NOAA	National Oceanic and Atmospheric Administration
PIT	passive integrated transponder
RM	river mile
RSW	removable spillway weir
STS	submersible traveling screen
TOR	target operating range
TSP	Turbine Survival Program
USACE	U.S. Army Corps of Engineers
WGA	wicket gate angle

1. INTRODUCTION

The Turbine Survival Program (TSP) is part of the U.S. Army Corps of Engineers' (USACE) multi-faceted Columbia River Fish Mitigation (CRFM) program. The first phase of the TSP involved developing tools to evaluate the physical conditions fish experience as they pass through large Kaplan turbines typical of USACE projects. The TSP Phase I Report (USACE 2004) indentified that the operating conditions of large Kaplan turbine units appear to have a significant effect on survival of fish passing through them. Phase II of the TSP involves turbine survival testing (or biological index testing) at USACE facilities. This report identifies operating conditions for Lower Monumental turbines where turbine fish passage survival is expected to be higher based on the utilization of the tools developed by the TSP program.

Lower Monumental Dam is the second dam upstream from the confluence of the Snake River with the Columbia River, and is located on the Snake River at river mile (RM) 41.66 (Figure 1). The reservoir formed by the dam (Lake Herbert G. West) extends approximately 28.1 miles upstream to the tailrace of Little Goose Dam.

Figure 1. Location of Lower Monumental Lock and Dam



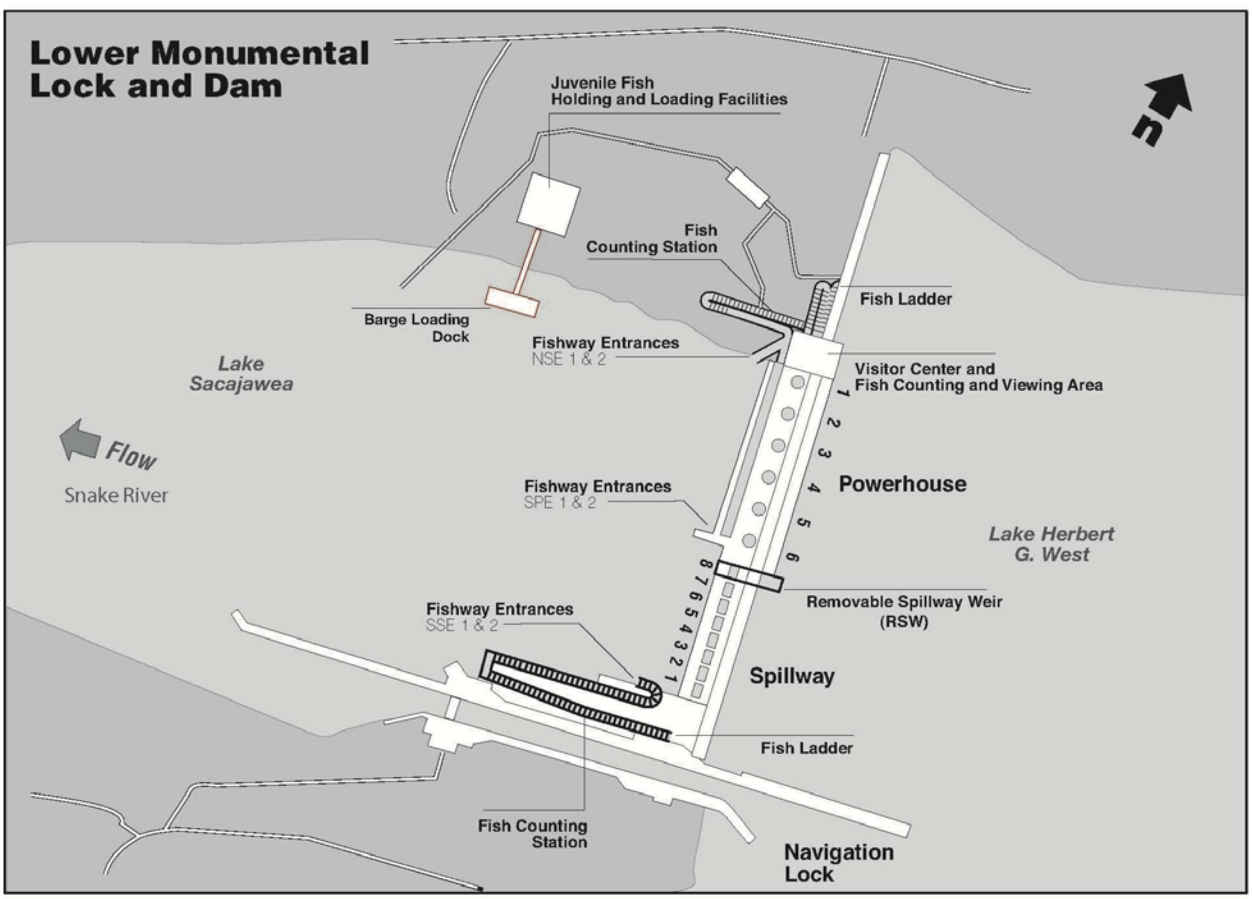
The Lower Monumental powerhouse has six turbine units; the intakes for all turbine units are screened with a submersible traveling screen (STS). These screens are effective in intercepting the majority of the juvenile fish, although a significant percentage of juveniles continue to pass through the turbines. Based on acoustic telemetry survival studies conducted from 2006 to 2009, relative turbine survival ranged from 91% (Hockersmith et al. 2008a) to 102% (Absolon et al. 2010) for yearling Chinook salmon, 89% (Dumdei et al. 2010) to 96% (Hockersmith et al. 2010a) for subyearling Chinook salmon, and 100% for juvenile steelhead (Hockersmith et al. 2008a, 2010b). Similar survival was noted for studies using radio-tagged fish prior to 2006 (Ham et al. 2009).

The potential to achieve high turbine passage survival has been proven; however, the need to maintain high survival through Lower Monumental turbines is clear and may be achieved by specifying operations that are realistic and possibly include higher powerhouse discharge. This appendix summarizes results from the various passage and survival studies, as well as physical model studies, and presents information supporting the need to conduct field testing at Lower Monumental for verification of an improved target operating range for safer fish passage through turbines.

1.1. PROJECT DESCRIPTION

Completed in 1969, the Lower Monumental project includes a powerhouse, eight-bay spillway, navigation lock, fish passage facilities, and an earth-filled section (Figure 2). The dam is 3,791-feet long and has an effective height of 100 feet. The dam is a concrete gravity-type dam, with short earthen abutment embankments. Lake Herbert G. West behind the dam has a surface area of about 6,600 acres. The eight-bay spillway is 572-feet long with an overflow crest at elevation 483 feet mean sea level (msl); it has eight tainter gates, 50-feet wide and 60-feet high, that provide capacity to pass a design flood of 850 thousand cubic feet per second (kcfs).

Figure 2. Diagram of Lower Monumental Lock and Dam



The navigation lock at lower Monumental is a single-lift type with dimensions of 86 feet by 666 feet and a 15-foot minimum depth of the sills. A navigation channel (250-feet wide, 14-feet deep, and 28.1-miles long) is provided from the dam to Little Goose.

The concrete powerhouse at Lower Monumental is 656 feet in length and contains six 135-megawatt (MW) turbine units, three Baldwin-Lima-Hamilton (BLH) units and three Allis-Chalmers (AC) units. All turbine units are Kaplan, six-blade units operating at 90 revolutions per minute. Total capacity of the turbine units is 810 MW. Turbine units 1-3, from north to south, have BLH turbines and were installed in 1969 as part of original dam construction. Turbine units 4-6 have AC turbines and were installed in 1979 under the powerhouse expansion contract. There is a history of linkage problems for the three BLH turbines. Turbine unit 1 is presently welded in a fixed-bladed position. The remaining five turbines have full Kaplan configuration. The intakes for all six turbine units are screened with STSs and are required to operate within 1% of best efficiency during the fish passage season from April 1 through October 31.

1.2. PROJECT OPERATIONS

1.2.1. General Project Operations

Lower Monumental provides for navigation, hydropower generation, recreation, and incidental irrigation. Lower Monumental is a run-of-river project with no reservoir storage capacity. The reservoir has a normal operating range between elevations 540 and 537 feet mean sea level (msl). Baseline operations include the juvenile fish facility (JFF), the spillway with a removable spillway weir (RSW) installed in bay 8, the powerhouse, and two adult fish ladders. The JFF operates from 1 April through 15 December and consists of a bypass system and juvenile transportation facilities. The bypass system contains standard length traveling screens with flow vanes, improved modified balanced flow vertical barrier screens, gatewell orifices, a bypass channel running the length of the powerhouse, and a bypass pipe to send fish to the transportation facilities or return to the river. The transportation facilities include an upwell and separator structure to separate the juveniles from the excess water and adult fish. Other features include raceways for holding fish, a distribution system for distributing the fish among the raceways or to the barge or back to the river, a sampling and marking building, truck and barge loading facilities, and passive integrated transponder (PIT) tag detection and deflection systems. The transport system typically operates from 1 May through 30 September. The project operation is spill to the 115% to 120% total dissolved gas spill cap using the bulk spill pattern as described in Section 7 of the USACE's Fish Passage Plan (FPP; USACE 2012) during the spring and 17.0 kcfs spill during the summer.

1.2.2. Turbine Operations

The Lower Monumental turbines are operated within 1% of the best efficiency in accordance with the FPP, which implements requirements of the 2000 Biological Opinion (BiOp; NOAA Fisheries 2000, 2004, 2008). Restricting turbine operations was formalized in the 2000 BiOp, which requires turbine operations be limited to ±1% of best operating efficiency. The basis for this rule resulted from research reported by Bell (1981) and Eicher Associates (1987).

The current FPP prescribes that Lower Monumental turbine units be operated to enhance adult and juvenile fish passage from 1 March through 30 November. Turbine unit operating priorities under various river flow and spill level scenarios are shown in Table 1. Turbine unit 1 was the fish priority unit prior to its blade linkage failure.

Table 1. Turbine Unit Operating Priority for Lower Monumental

Season	River Flow	Spill Level	Unit Priority
Mar 1 – Nov 30	Less than 70.0kcfs	Bulk spill gas cap	2, 3, 4, 5, 6 then 1
	Over 70.0kcfs	Bulk spill gas cap	1*, 2, 3, 4, 5, then 6
	Any river flow	No spill	2, 3, 4, 5, 6 then 1**
Dec 1 – Feb 28	Any river flow	Any spill level including no spill	Any order

*If U1 is OOS, run U2. **If no spill is occurring, U1 may be operated at any priority level at the discretion of project personnel. Note: U1 has fixed-pitch blades and can operate only at about 130 MW.

Temporary repairs were made to turbine unit 1 including welding the blades in a fixed position with a blade angle of approximately 29 degrees. With the blades fixed, the unit can only operate at about 130 MW, or 18.80 kcfs. Continued operation of unit 1 as a priority unit improves juvenile fish passage by mitigating the reverse flow eddy created by spill at the fish loading dock. Unit 1 also serves to create attraction flow for adult salmon approaching toward the north fish ladder. The following operating guidance is provided for unit 1 while it is in temporary repair:

> Since this turbine unit has fixed blades and a narrow operation window, starts and stops can cause excessive wear and tear. Turbine unit 1 should be turned on and left on for extended periods to minimize starting and stopping the unit. The operation of turbine unit 1 in first priority position should be initiated when flows are in an increasing trend and flows are over 70.0 kcfs. Turbine unit 1 may be turned off at the power plant operator's discretion, when the flows are between 55.0 and 70.0 kcfs.

The actual operating characteristics during the fish passage season should be well understood prior to determining the target operating range (TOR) for safe fish passage. Figures 3 and 4 illustrate the overall operating efficiency and 1% efficiency range of BLH turbine units 1-3 (11.12 to 19.79 kcfs) and AC turbine units 4-6 (14.09 to 19.04 kcfs) at Lower Monumental. Turbine units 1-3 have a broader 1% operating range (10.57 kcfs) than turbine units 4-6 (5.56 kcfs). These operating ranges were developed using data with STSs installed. (Table 2; Figures 3 and 4)

Table 2. Fish Season Operations (March 1 through November 30)

Parameter	Average 2004-2010	Operating Range	
		Low	High
Forebay Elevation (feet msl)	538.0	536.8	540.2
Tailwater Elevation (feet msl)	439.3	436.4	447.9
Head (feet)	98.7	89.7	102.4
Powerhouse Flow (kcfs)	37.20	0.0	122.0
Total River Flow (kcfs)	50.40	5.0	215.30
Turbine Units Operating	2.3	0	6
Turbine Units 1-3 Flow (kcfs)[a]	15.19	11.05	21.62
Turbine Units 1-3 Power (MW)[a]	110.0	71.7	149.7
Turbine Units 4-6 Flow (kcfs)[a]	16.58	14.06	19.62
Turbine Units 4-6 Power (MW)[a]	122.6	94.6	146.8

[a] Operating range based on 1% efficiency range over head range with STSs installed.

Figure 3. Lower Monumental Turbine Units 1-3 Efficiency Curves with STS Installed

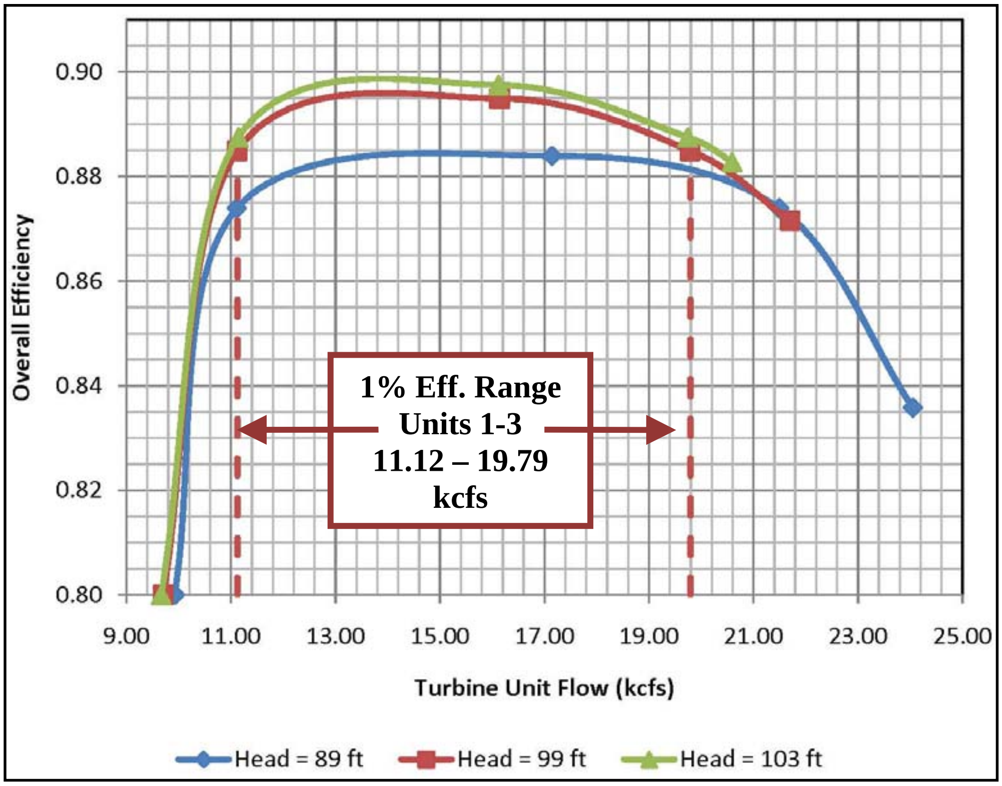
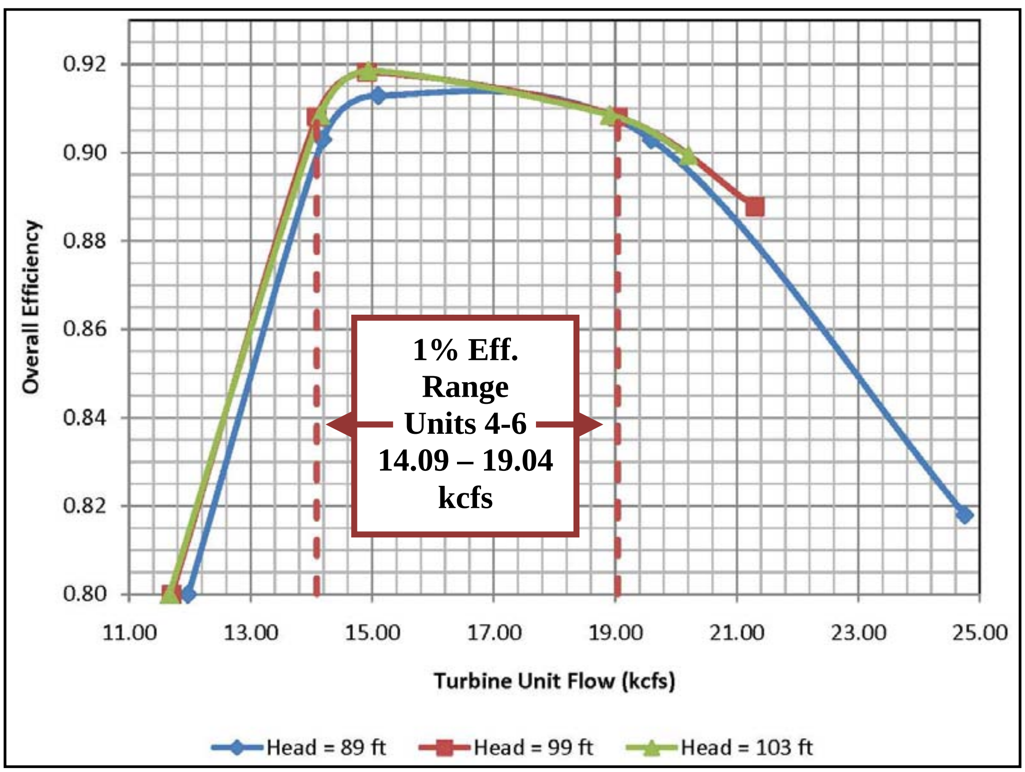


Figure 4. Lower Monumental Turbine Units 4-6 Efficiency Curves with STS Installed



2. DEFINE TARGET OPERATING RANGE FOR TURBINES

There are many different pieces of information that help to estimate the target operating range for fish passage survival through Lower Monumental turbines. Lower Monumental has two different turbine families (BLH turbine units 1-3 and AC turbine units 4-6); hence, two different TORs must be identified and most information is exclusive to the particular family. First, the physical geometry of different operating conditions for both sets of turbines will be considered. Second, physical modeling data of different operating conditions that was guided by the physical geometry for both sets of turbines will be discussed. Pressure information is limited to a sensor fish study for John Day which can be correlated to the BLH units (1-3); however, no pressure data exists for the AC units (4-6). The pressure data in conjunction with laboratory studies can give an indication of the potential for pressure injuries at different operating conditions. While there has been no turbine-specific biological field studies performed to date, project survival data and some data correlation information will be discussed. Finally, this information will be tied together to provide an estimate of TOR for the two different turbine units.

2.1. PHYSICAL GEOMETRY CONSIDERATIONS

As discussed in Section 3.2 of the Phase II Main Report, there is a potential to reduce injury and direct mortality of migrating salmon passing through turbines by operating at a more open geometry. Wittinger and others (2010) indicate that a good geometric relationship is often not found within the existing 1% operating limits. Stay vane and wicket gate alignment for different operating conditions for BLH units 1-3 and AC units 4-6 are detailed in Figures 5 to 14 (plan view followed by one enlarged section for each of the lower 1% efficiency limit, best operating efficiency, upper 1% efficiency limit, and the generator limit). For Lower Monumental, the best physical alignment of stay vanes and wicket gates occurs at a wicket gate angle (WGA) of approximately 41 degrees for BLH units 1-3 and 42 degrees for AC units 4-6. However, the goal of minimizing the gap between wicket gate and stay vanes, and maintaining the wicket gate within the hydraulic shadow of the stay vane, is expected to occur within the broader range of a WGA (Wittinger et al. 2010). Lower Monumental is expected to have good wicket gate to stay vane alignment down to a 36 degree WGA for both sets of units, but the upper end of this range is limited by the generator limit (at approximate average head, Lower Monumental - 44 degrees WGA). Best geometry information at a nominal project head of 100 feet is 41 degrees for BLH units 1-3 and 42 degrees for AC units 4-6 (Table 3). The best geometry point would not be expected to vary significantly over the head range; however, since the generator limit factors into the upper range, the upper range would be compressed for larger than average project heads.

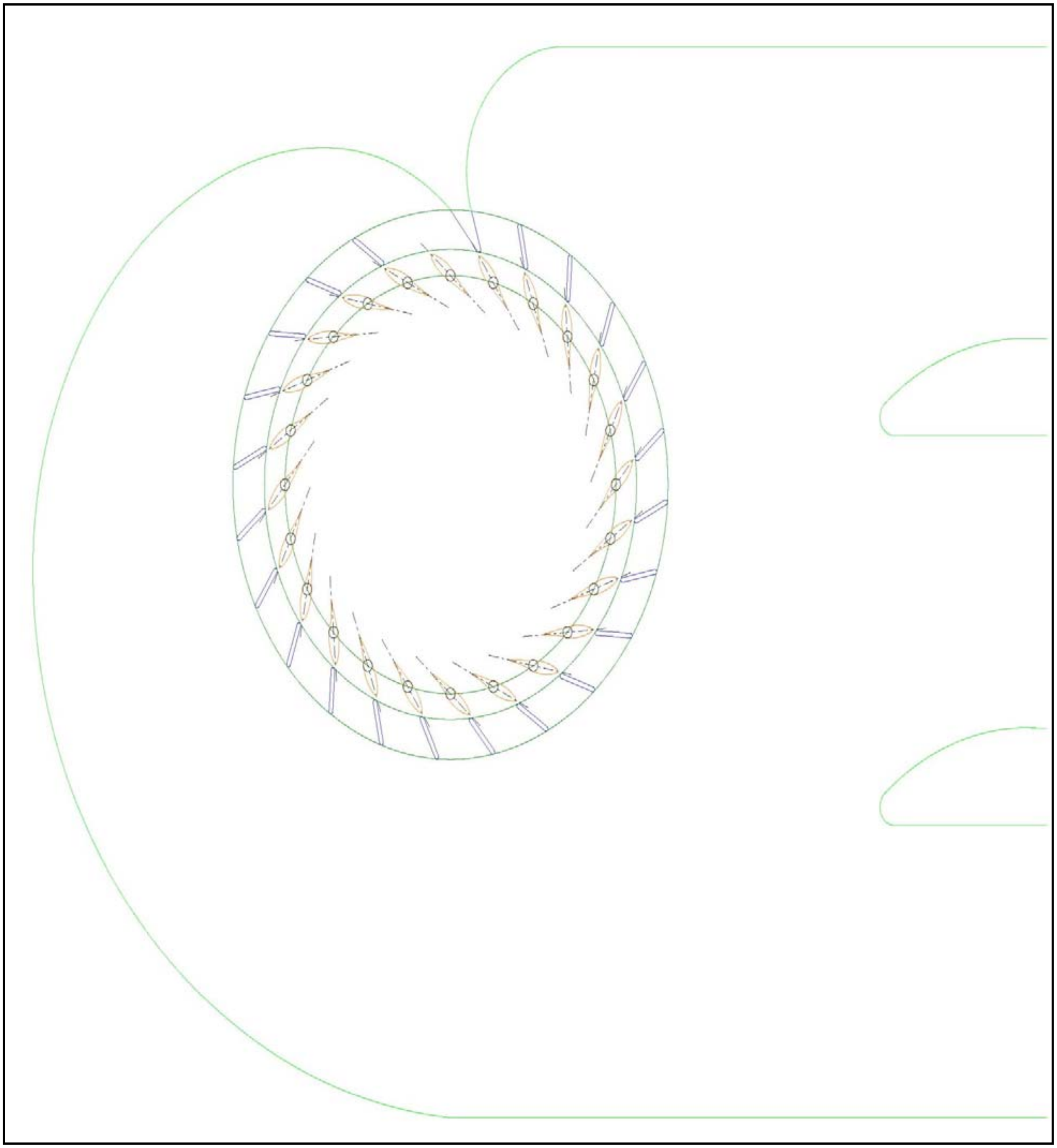
Table 3. Lower Monumental Best Wicket Gate Geometry (100 feet of head)

Units	Parameter	Best Geometry	Best Geometry Range	
			Lower	Upper
BLH Units 1-3	Wicket Gate Angle – Degrees Open	41.0	36.0	45.0
	Blade Angle – Degrees Open	32.4	27.5	35.0
	Power – hp	199,000	162,500	212,400
	Flow – kcfs	19.75	16.0	21.40
	Efficiency – %	88.7%	89.6%	87.4%
AC Units 4-6	Wicket Gate Angle – Degrees Open	42.0	36.0	44.0
	Blade Angle – Degrees Open	26.5	20.25	29.0
	Power – hp	193,000	155,500	212,400
	Flow – kcfs	18.70	14.90	20.90
	Efficiency – %	90.9%	91.8%	89.3%

Source: Wittinger et al. 2010

Figure 5. Lower Monumental BLH Units 1-3 Peak Efficiency (Plan View)

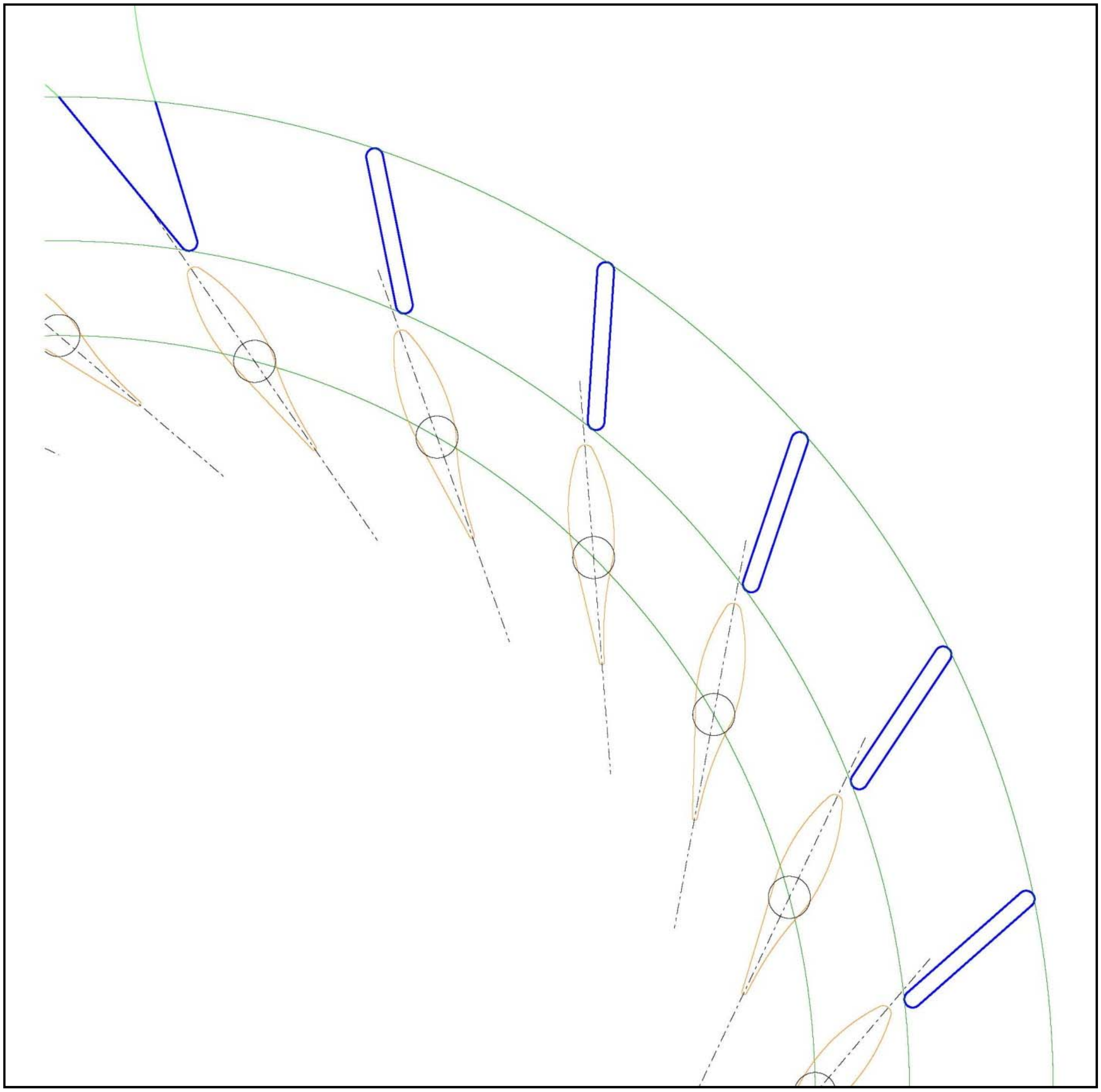
At 100 feet gross head with STS, WGA 35.49 degrees, design wicket gate opening at 50.0 degrees.



Source: Wittinger et al. 2010

Figure 6. Lower Monumental BLH Units 1-3 Peak Efficiency

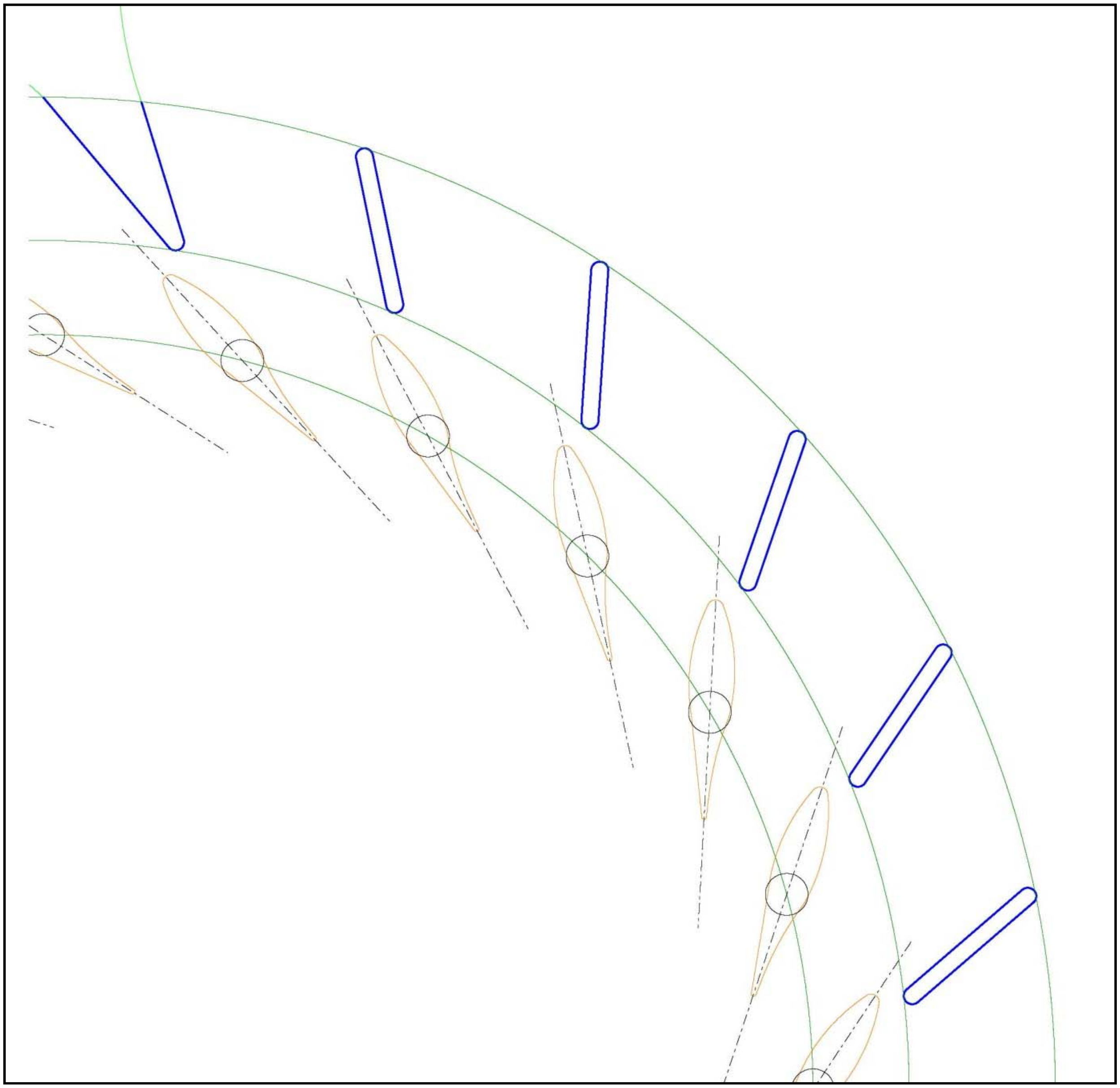
At 100 feet gross head with STS, WGA 35.49 degrees, design wicket gate opening at 50.0 degrees.



Source: Wittinger et al. 2010

Figure 7. Lower Monumental BLH Units 1-3 Lower 1% Efficiency

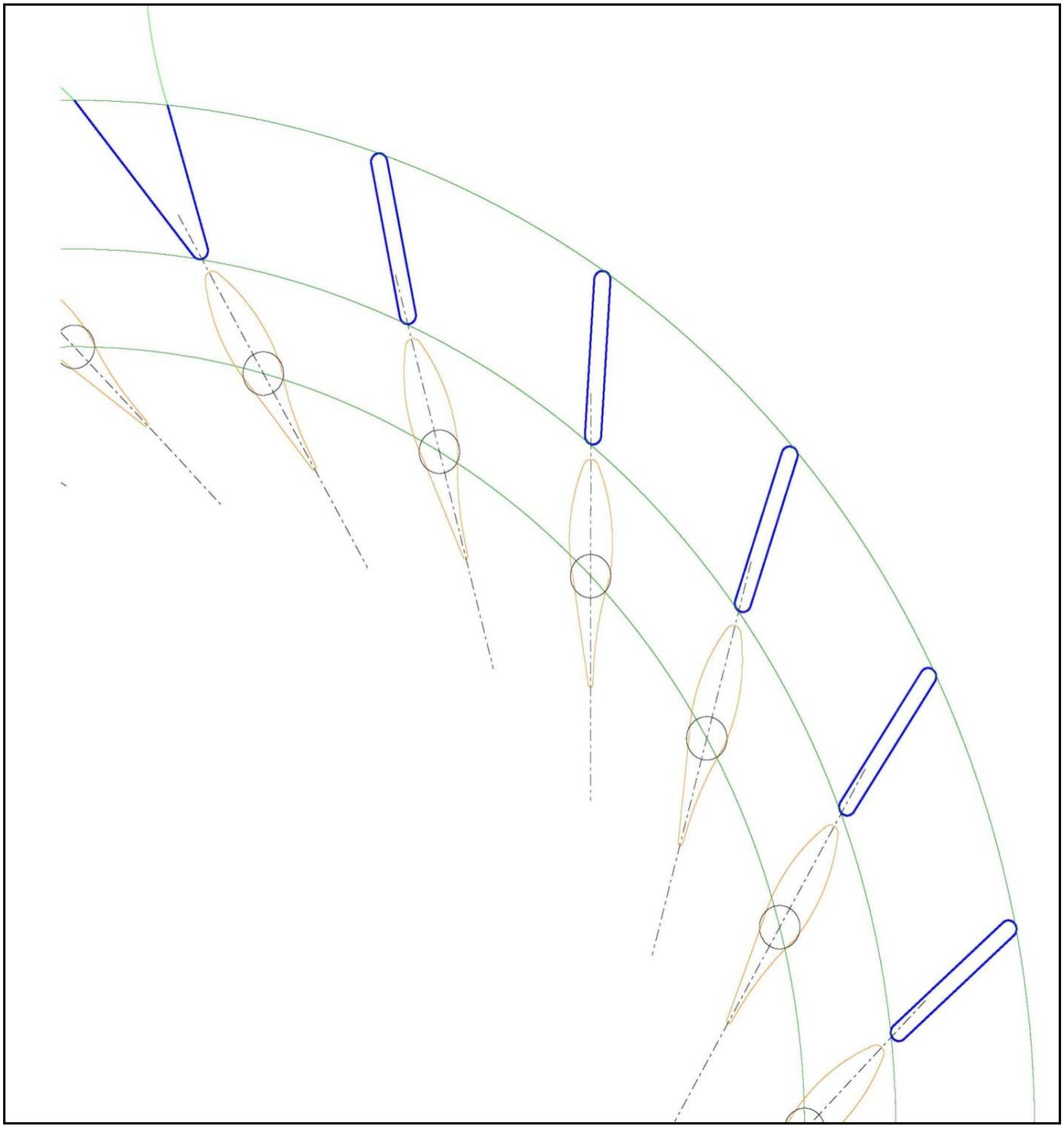
At 100 feet gross head with STS, WGA 26.05 degrees, design wicket gate opening at 50.0 degrees.



Source: Wittinger et al. 2010

Figure 8. Lower Monumental BLH Units 1-3 Upper 1% Efficiency

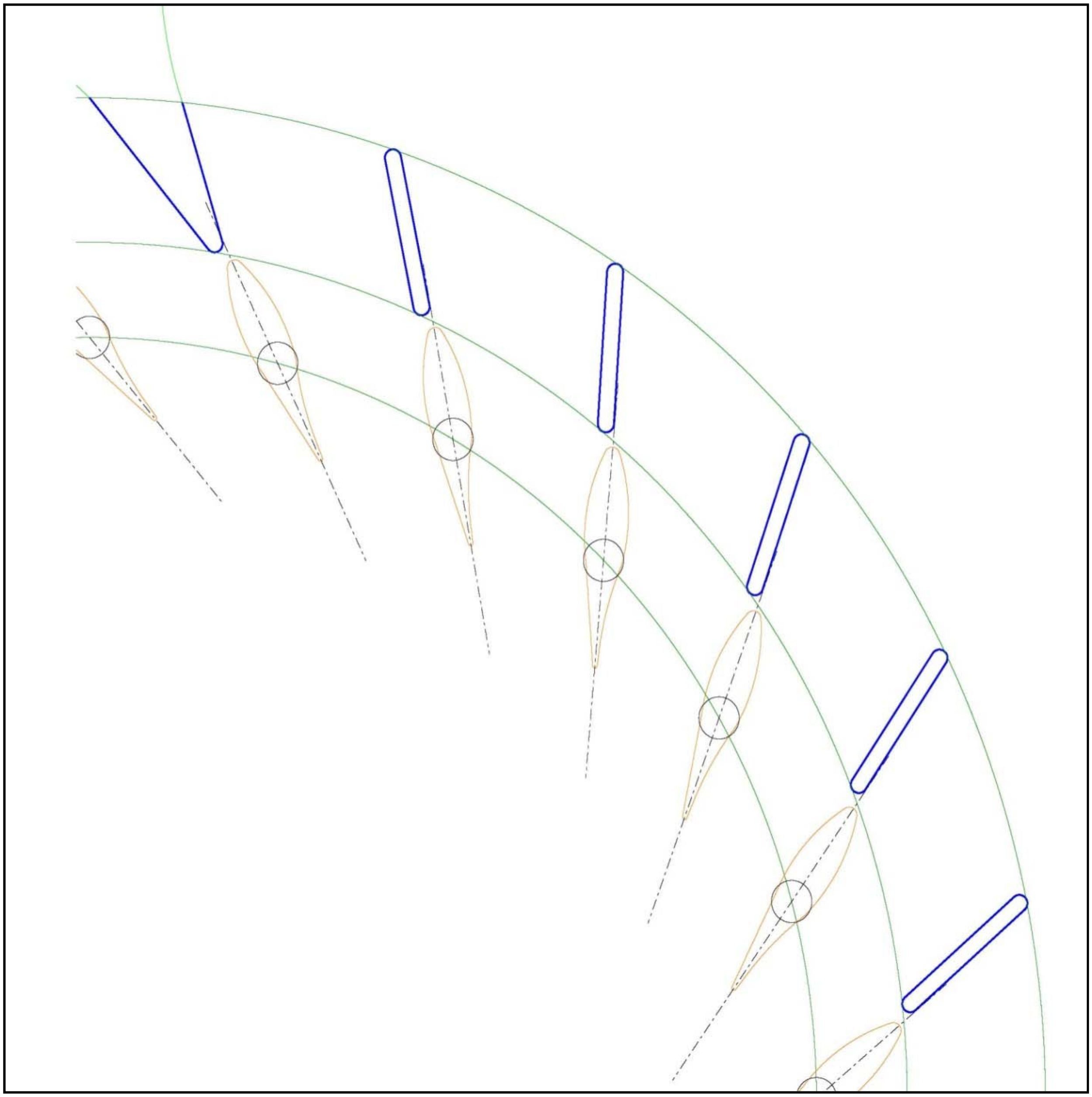
At 100 feet gross head with STS, WGA 40.08 degrees, design wicket gate opening at 50.0 degrees.



Source: Wittinger et al. 2010

Figure 9. Lower Monumental BLH Units 1-3 Generator Limit Efficiency

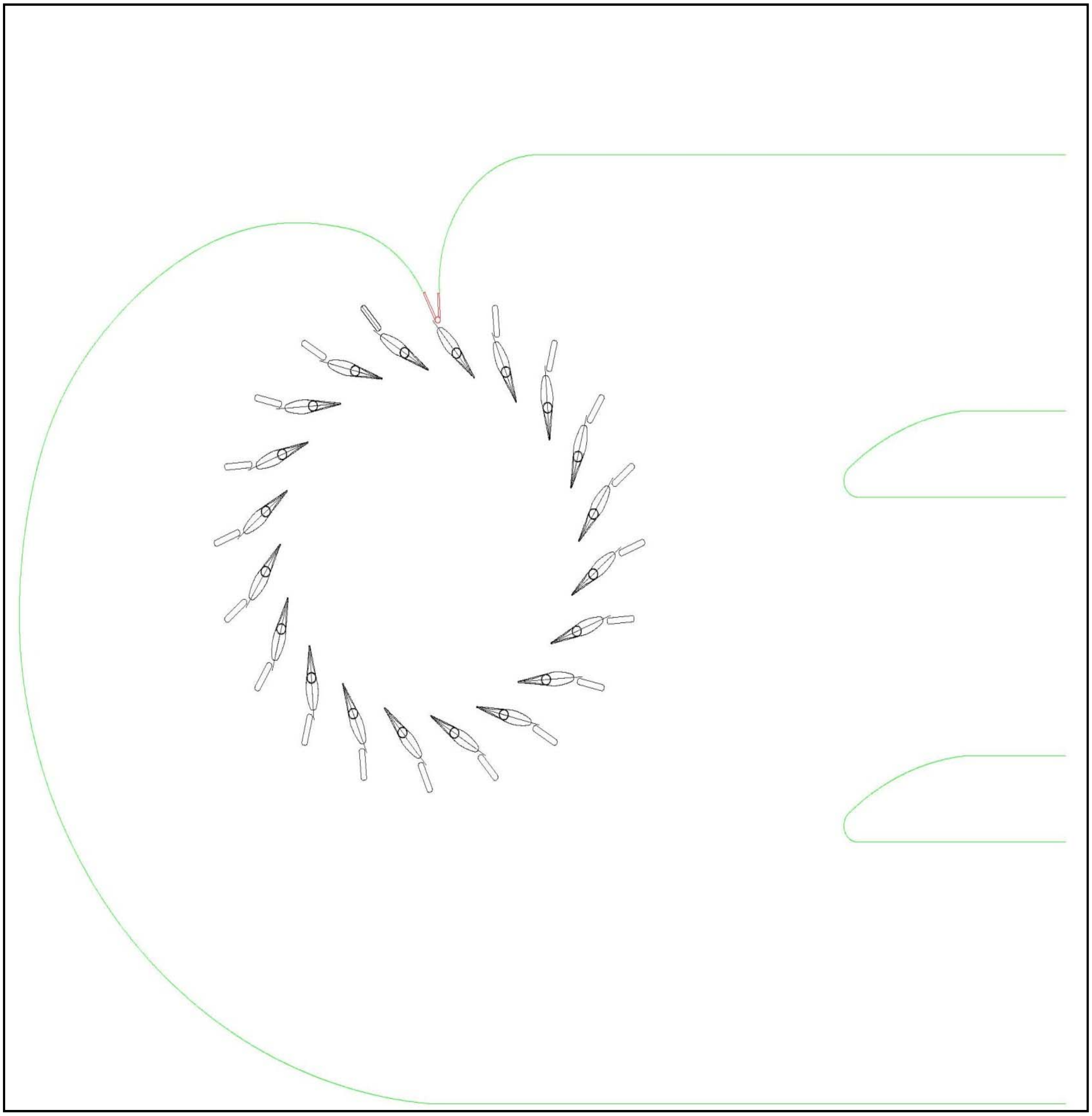
At 100 feet gross head with STS, WGA 44.91 degrees, design wicket gate opening at 50.0 degrees.



Source: Wittinger et al. 2010

Figure 10. Lower Monumental AC Units 4-6 Peak Efficiency (Plan View)

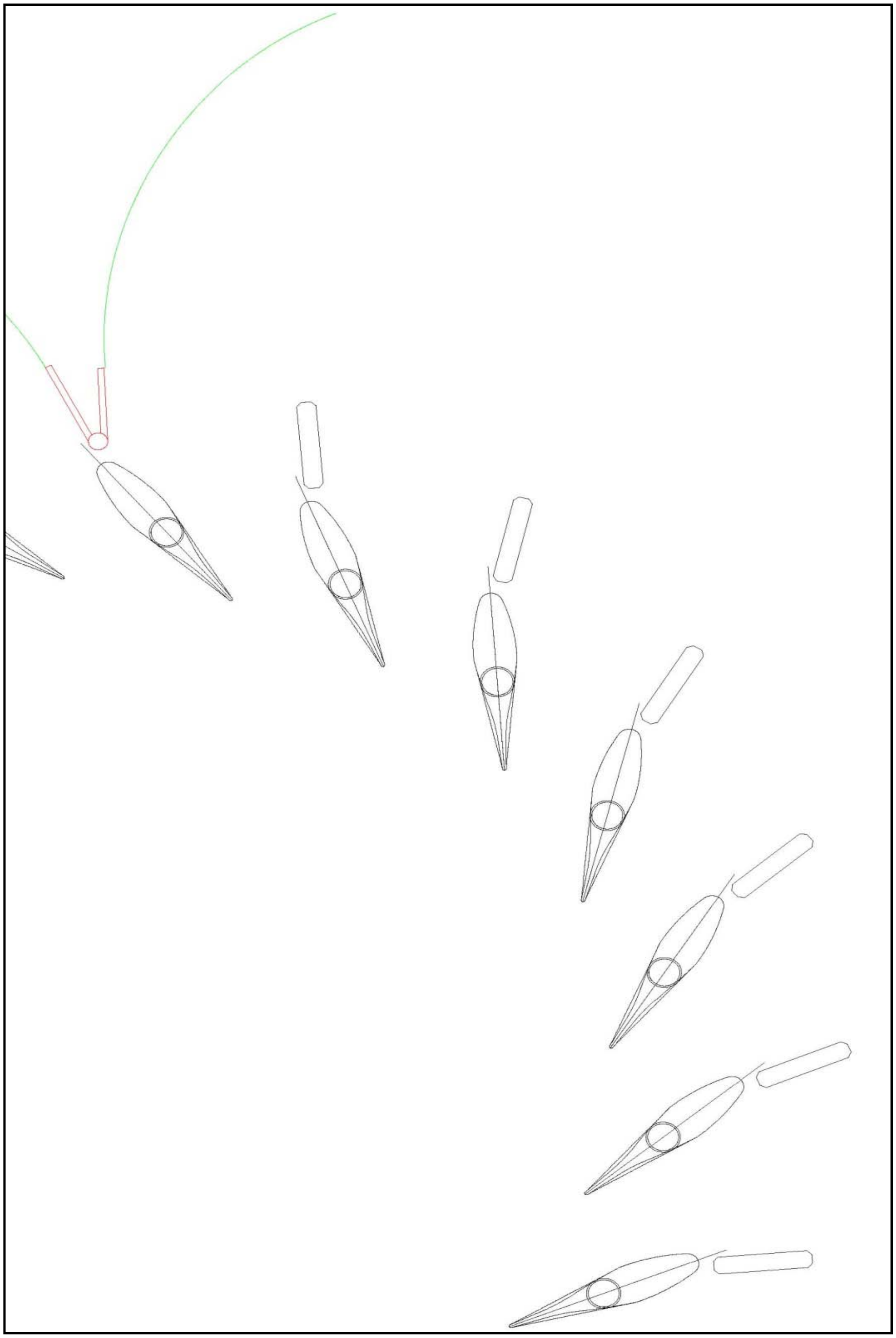
At 100 feet gross head with STS, WGA 35.61 degrees, design wicket gate opening at 51.25 degrees.



Source: Wittinger et al. 2010

Figure 11. Lower Monumental AC Units 4-6 Peak Efficiency

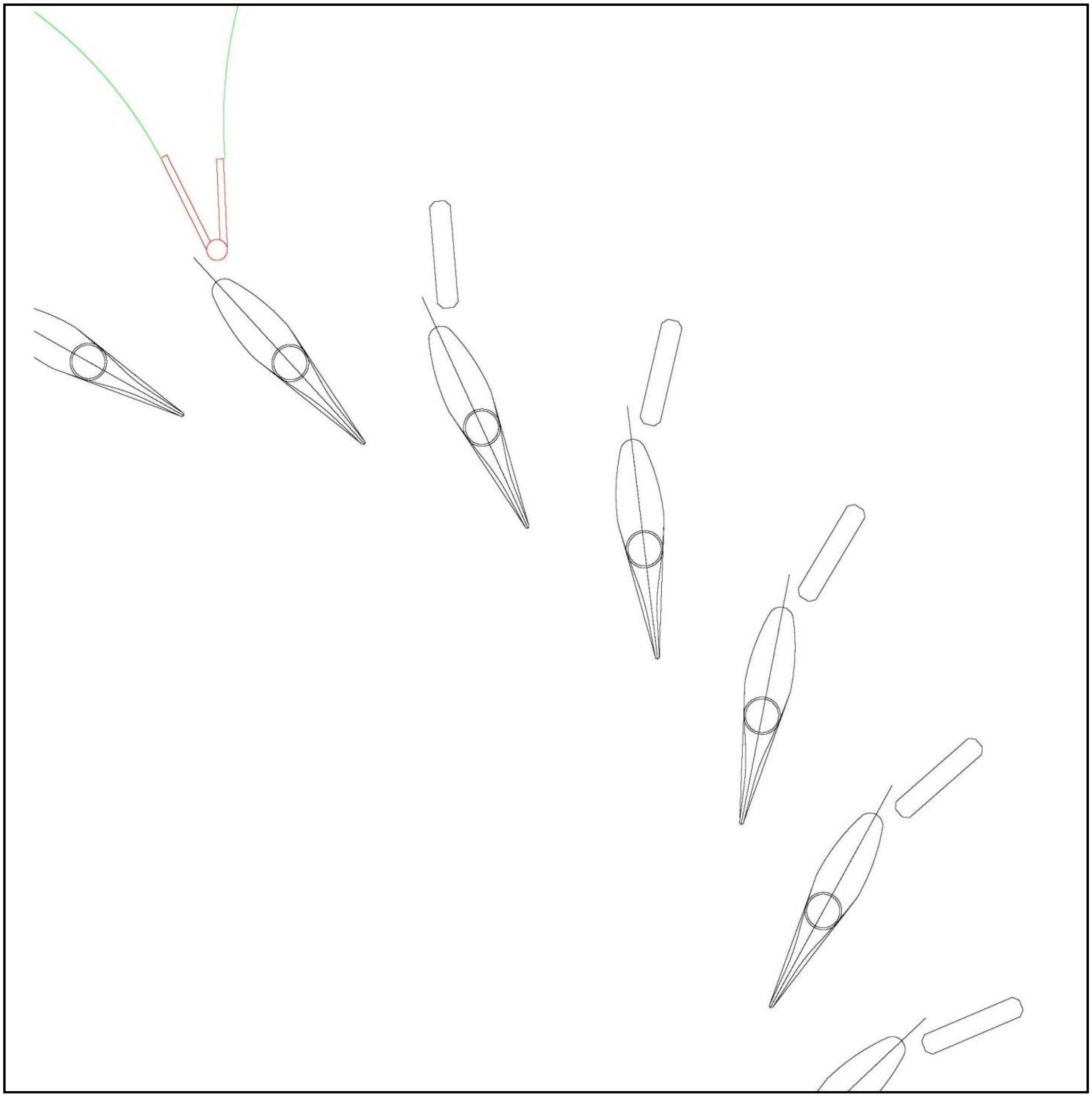
At 100 feet gross head with STS, WGA 35.61 degrees, design wicket gate opening at 51.25 degrees.



Source: Wittinger et al. 2010

Figure 12. Lower Monumental AC Units 4-6 Lower 1% Efficiency

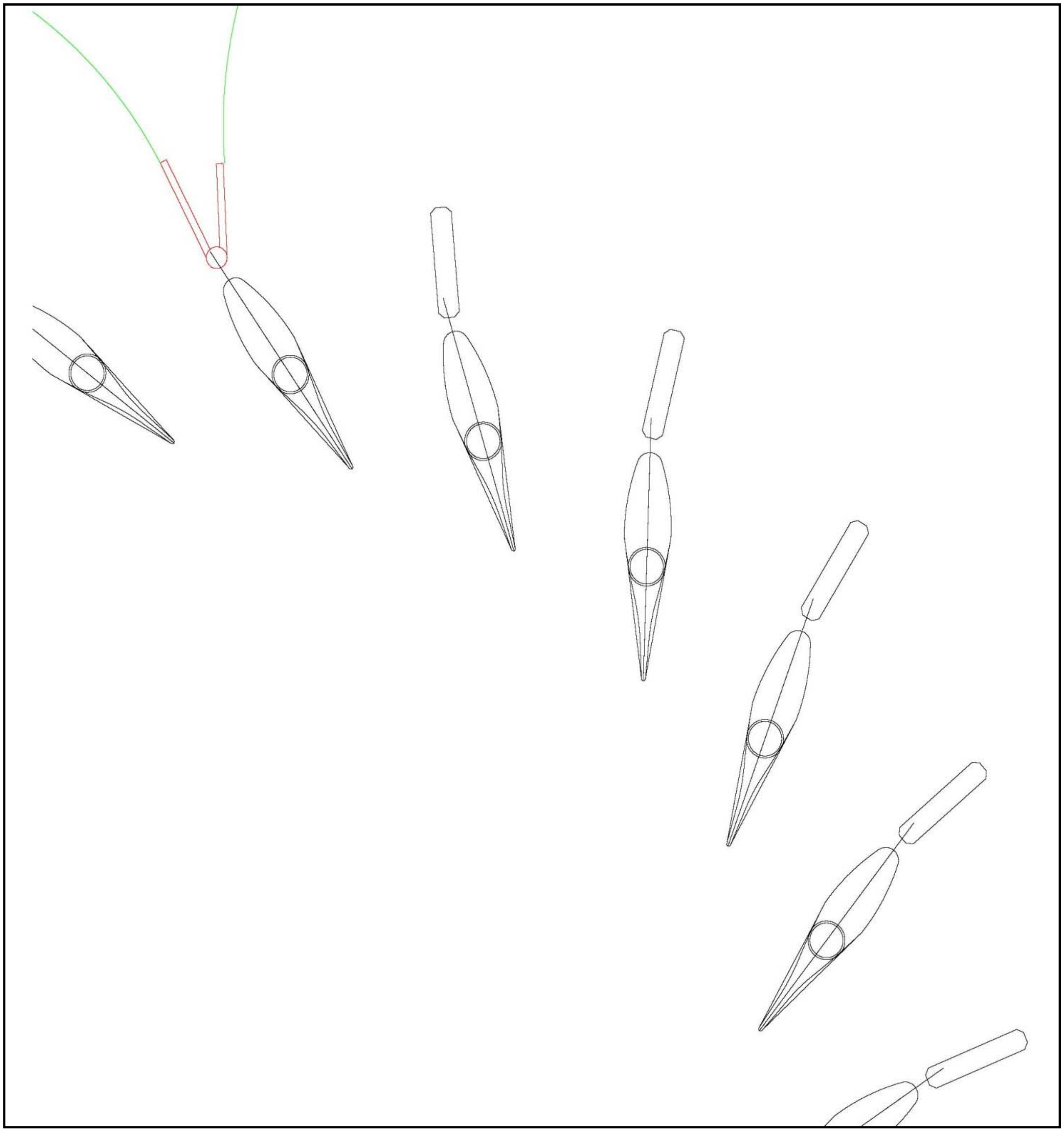
At 100 feet gross head with STS, WGA 32.72 degrees, design wicket gate opening at 51.25 degrees.



Source: Wittinger et al. 2010

Figure 13. Lower Monumental AC Units 4-6 Upper 1% Efficiency

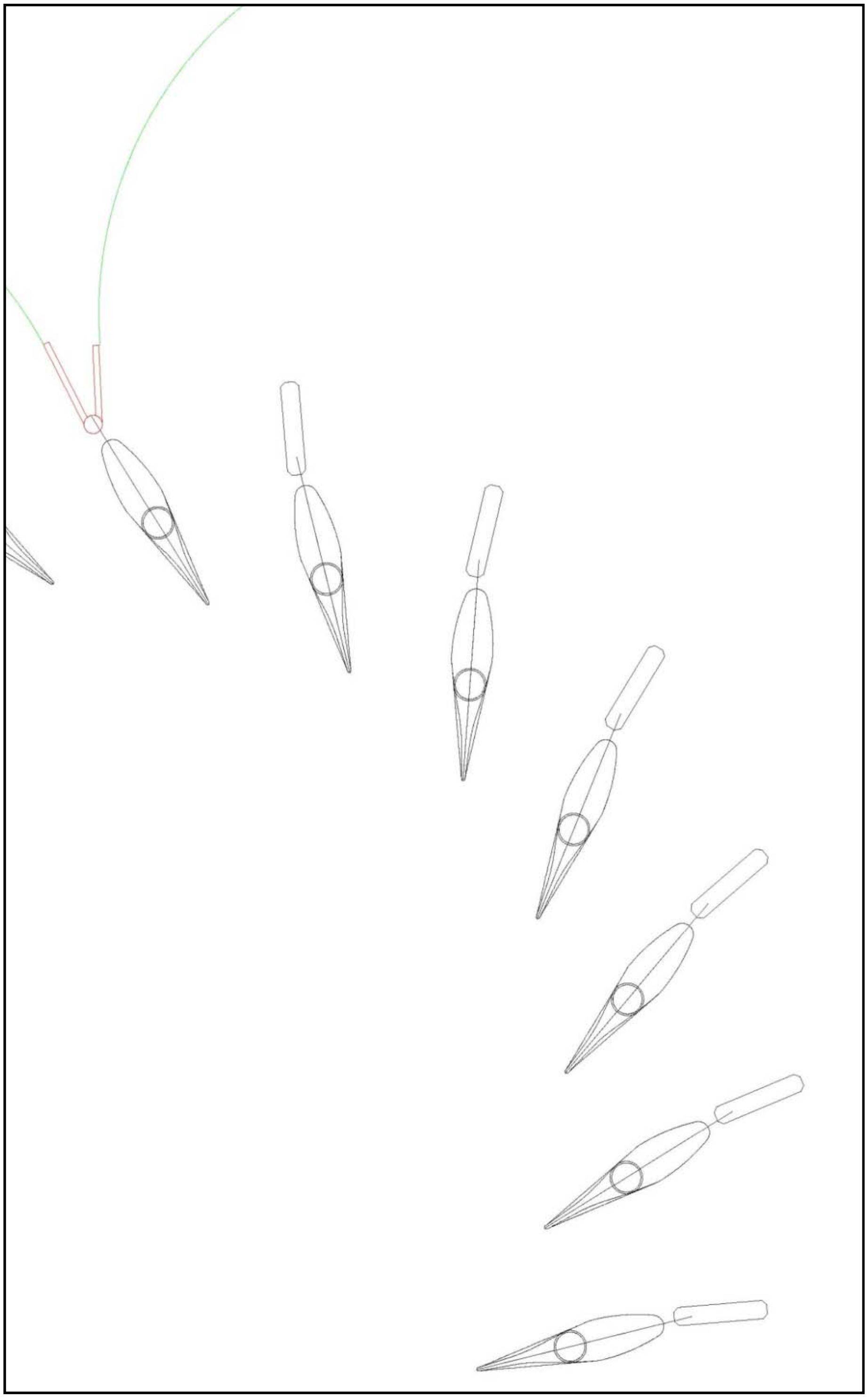
At 100 feet gross head with STS, WGA 41.39 degrees, design wicket gate opening at 51.25 degrees.



Source: Wittinger et al. 2010

Figure 14. Lower Monumental AC Units 4-6 Generator Limit Efficiency

At 100 feet gross head with STS, WGA 43.77 degrees, design wicket gate opening at 51.25 degrees.



Source: Wittinger et al. 2010

Good geometric relationships at Lower Monumental were found to fall outside the existing 1% operating limits used in current turbine operations. The wicket gate/stay vane alignment illustrated above suggests that the best geometry (alignment) occurs at the upper 1% of operating efficiency for both BLH units 1-3 and AC units 4-6. However, it is not clear that this alignment will provide the best survival based on bead evaluations (Robert Davidson, USACE Engineer Research and Development Center, personal communication). While the ideal alignment of the wicket gates and stay vanes suggest a geometry that would present the least probability of contact with the structures, bead data suggests that a slight misalignment can aid in buffering (by turbulence or vortices) fish away from areas of high shear, such as the gap between the stay vanes and the wicket gates. It could be that the ideal biological alignment is somewhere between the peak and upper 1% operating efficiency; however, modeling and subsequent field testing to identify such a narrow window of operation within the already BiOp-specified operation may not be feasible.

2.2. Physical Observational Model Information

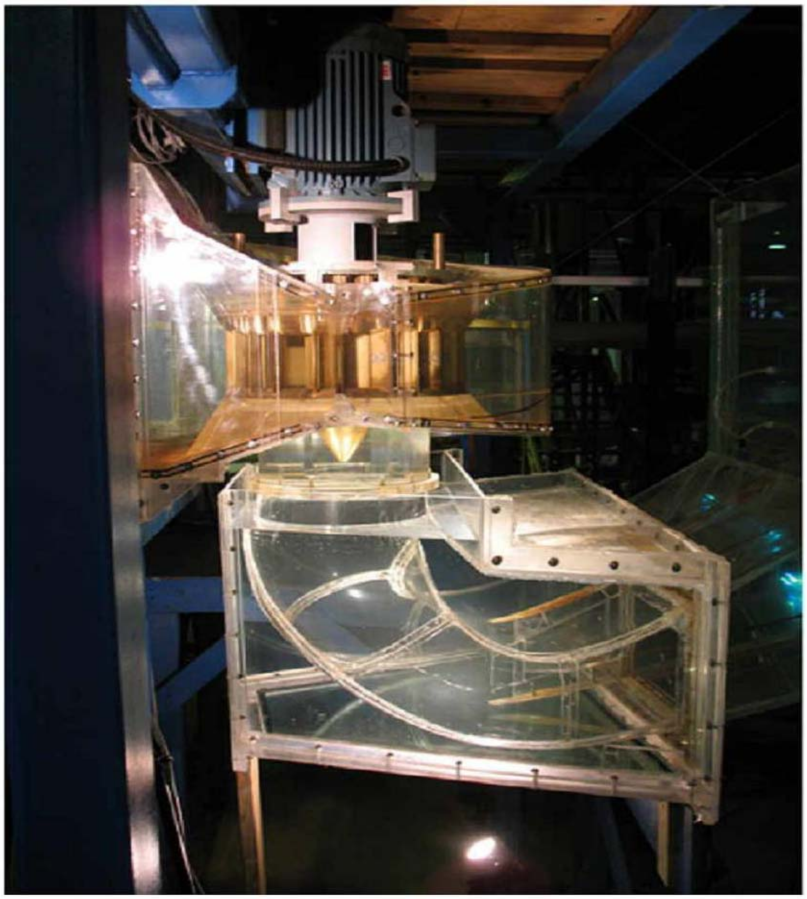
2.2.1. Lower Monumental BLH Turbine Units 1-3

The John Day physical observation model was used to investigate the performance of a Kaplan BLH unit and a BLH unit with fixed blade set with a 29-degree blade. The head for these tests was not significantly different and thus, the information from the John Day model is expected to apply to Lower Monumental BLH units 1-3. The John Day 1:25 Froude-based scale model is a replica of a single turbine unit constructed at the Engineering Research and Development Center (ERDC) in Vicksburg, MS (Figure 15). The model replicates 800 feet of approach, each of the three intake bays, the scroll case, the distributor including all adjustable wicket gates and stay vanes, the six-bladed Kaplan turbine runner, the draft tube, and 400 feet of downstream topography. The model was used to evaluate the hydraulic condition within the turbine and the potential impact of variable turbine operations on fish. The evaluation included the release of dye into the turbine flow path to observe general flow patterns, extensive velocity measurements using a Laser Doppler Velocimeter (LDV), and high-speed imaging of neutrally buoyant beads released into the flow path.

The prototype flow rates investigated were approximately 11,800 kcfs, 16,300 kcfs, 18,600 kcfs and 19,900 cfs for the runner operated as Kaplan. These correspond to approximately lower 1%, between peak and lower 1%, and two points between peak and upper 1%. Prior to pinning some blades in the field, additional test were conducted at lower 1%, peak and upper 1% for the runner operated as a propeller at a fixed-blade angle of 29 degrees. These tests were performed approximately at the average project head of 102 feet (prototype scale) with the STS installed.

Neutrally buoyant beads were introduced at various points within the intake. High-speed video was then used to determine potential shear and strike injury by observing indications of bead contacts and severe change in directions (those that did not follow the general flow direction). It was proven through a study at McNary Dam that fish do not behave as passive particles within an intake at 7.0 kcfs and 12.0 kcfs through a turbine (Carlson 2002); however, the passive particle hypothesis is an assumption that must be made without solid alternative information, although this assumption may be valid for passage within the runner due to the high velocities. Release points were found that corresponded to passage at the runner hub and the runner blade tip. Without adequate information on fish distribution, an equal distribution within the runner was assumed. Therefore, all the bead passage data was averaged together for information presented in this appendix.

Figure 15. John Day 1:25 Physical Model



The first area with high potential for strike injury is the stay vanes and wicket gates. Analysis of the high-speed video provided the percentage of beads that experienced severe contacts and change in direction while passing either the stay vanes or wicket gates (Figure 16). The percentage of bead contacts with these structures was much more constant across the operating range than the change in direction. The lowest percentage of direction changes seemed to occur at flows greater than 16,000 cfs. The percentage of beads passing through the gap between the stay vanes and wicket gates appears to increase with flow (Figure 17) and is relatively unrelated to the best wicket gate geometry; however, the percentages at all operating points is still very low.

Figure 16. Severe Bead Contacts and Direction Changes at Stay Vanes and Wicket Gates

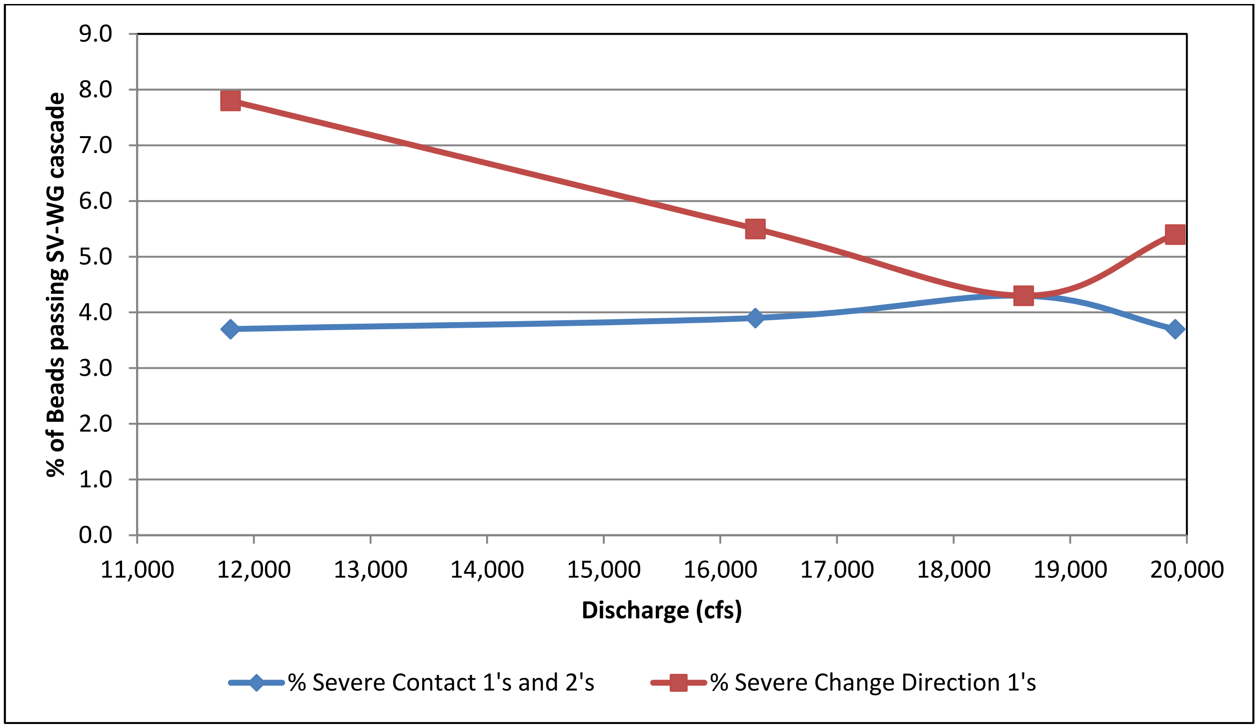
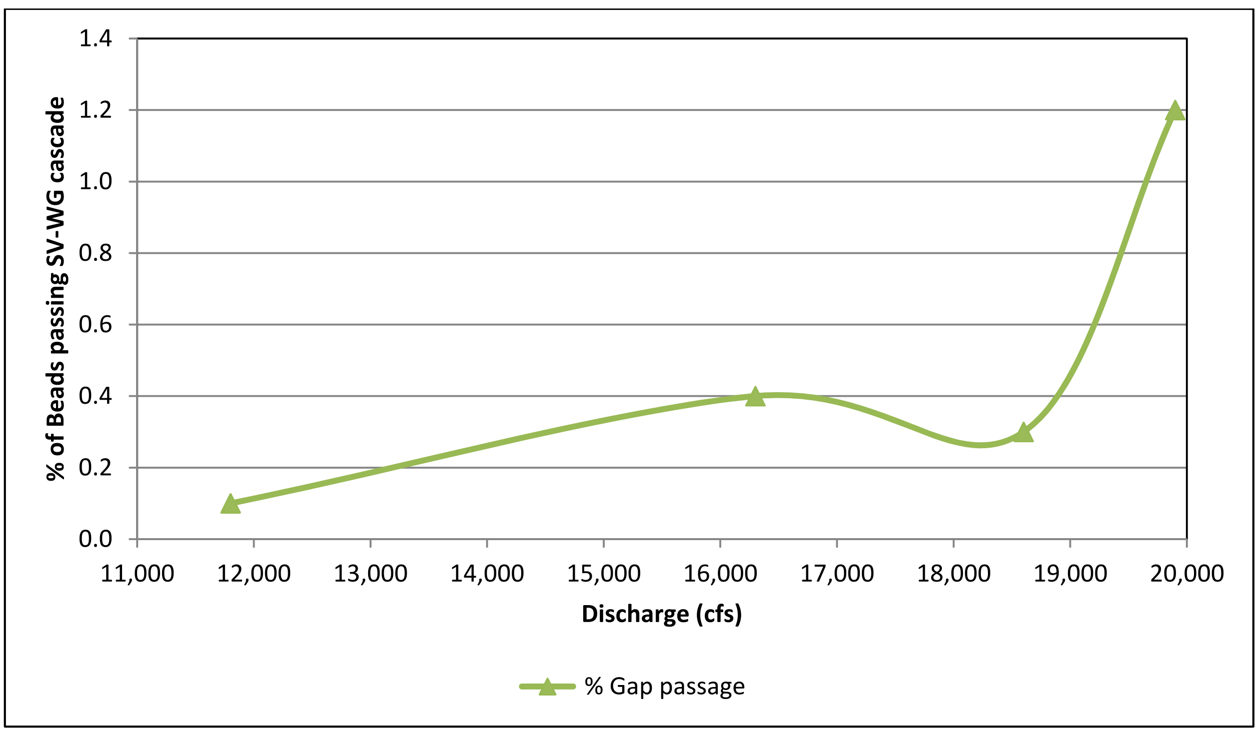
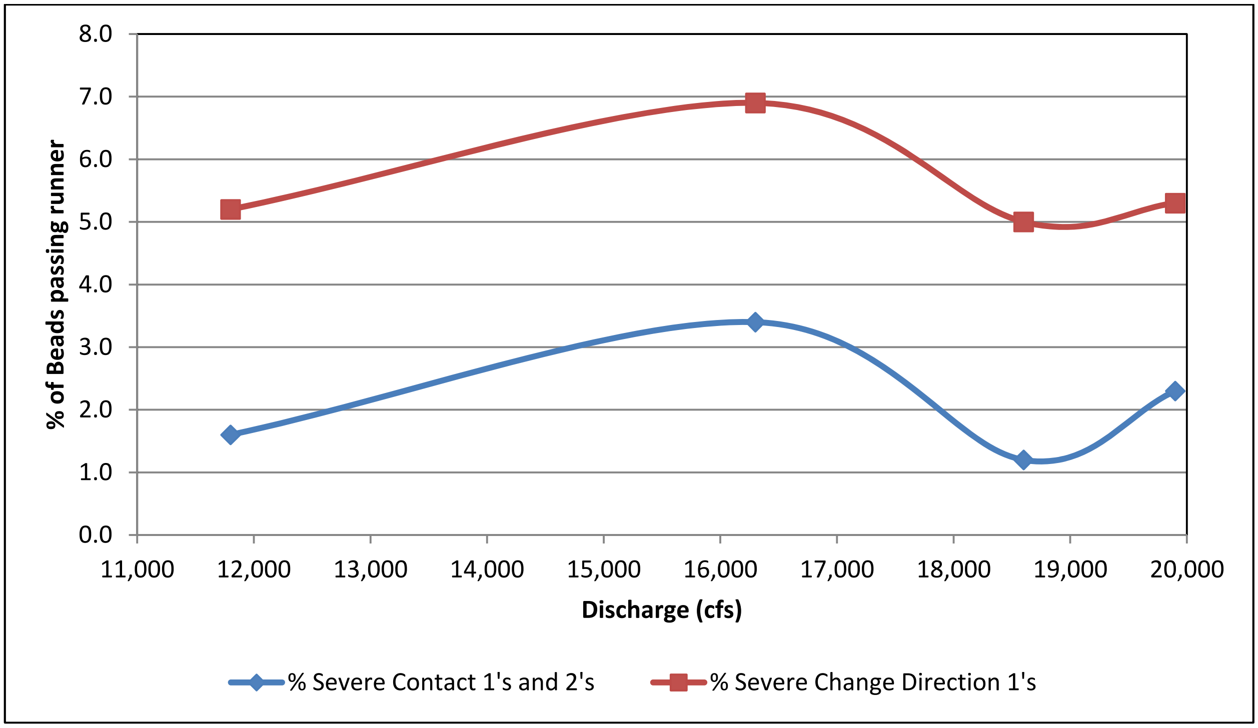


Figure 17. Beads Passing Through Gap between Stay Vanes and Wicket Gates



The next area for potential mechanical injury for fish is passing the runner blades of the turbine. As with the stay vane region, analysis of beads contacting the runner can give us an indication of potential injury. In general, bead contact and direction change within the runner decreases with increasing flow rate through the runner but surprisingly the lower 1% has low numbers (Figure 18). Increasing flow rate corresponds to an increase in blade angle and subsequent increased open area within the runner environment.

Figure 18. Severe Bead Contacts and Direction Change within Runner



In addition to the bead analysis, velocity measurements were made at multiple transects using a LDV. One area that displayed a large difference between the different flow rates tested was near the draft tube exit. The draft tube for John Day units (and Lower Monumental) has a single vertical splitter wall which divides the draft tube into two barrels (designated A and C) of equal cross-sectional area and length. The velocities at the draft tube exit were used to estimate the flow rate through each of these barrels. Barrel A had a much higher flow rate than barrel C at the lower turbine flow, but flow distribution is more even 16.30 kcfs and higher (Figure 19). Relating the average barrel velocity with individual velocity measurements, turbulence intensity is a measure of variability within the draft tube. The turbulence intensity decreased with increasing flow for both barrels but particularly barrel C (Figure 20). This also corresponds to a qualitative observation of a large vortex existing below the runner at the lower 1% that disappears at higher discharges. Results shown in these two figures relate to the fact that the draft tubes were designed to pass the highest design flows and therefore, the full flow area was not utilized at lower flow rates resulting in areas of recirculation. Increased turbulence at the lower flow rates could cause fish disorientation. While direct injury or mortality may not result, the disorientation has the potential to increase vulnerability to predation.

Figure 19. Flow Percent Passing Through Each Draft Tube

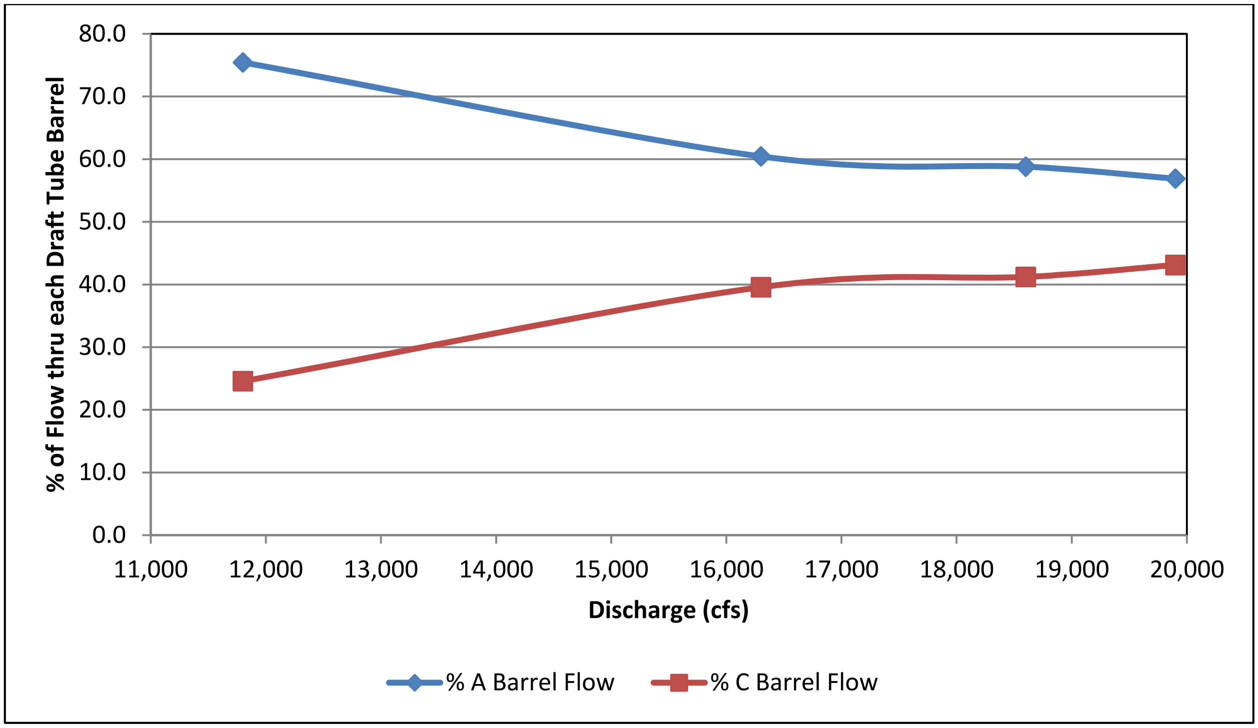
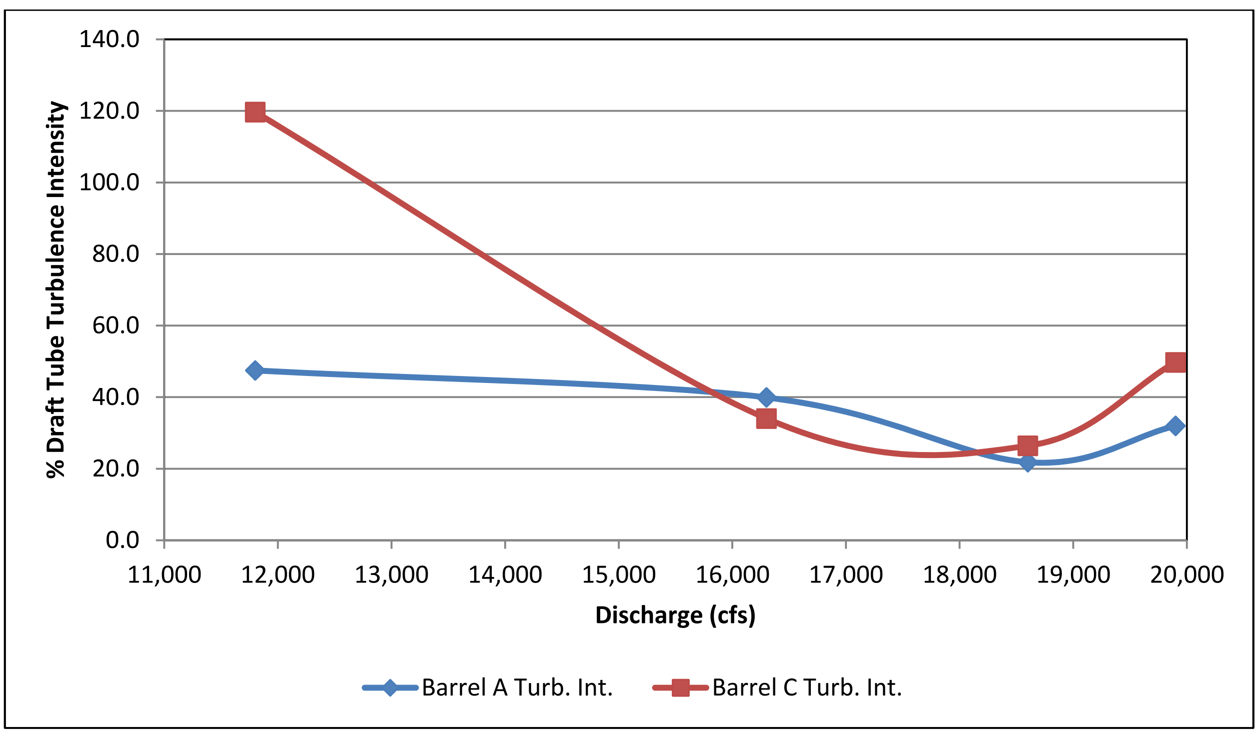


Figure 20. Turbulence Intensity for Draft Tube Barrels



Based on physical model information, flow rates above 16,300 cfs (approximately above peak efficiency) show improved hydraulic conditions over flow rates below 16,300 cfs. There is some improvement in draft tube conditions for flow rates higher than 16,300 cfs and additionally the best operating point for runner passage is the 18,600 cfs or 29 degree on-cam operating point. It would be expected that mechanical and shear related injuries would reduce between peak efficiency and the 18,600 cfs operating point (compared to operating at the low end of the operating range). For both the distributor and the runner the collected model information shows an increase in bead contact and direction change above the 18,600 cfs operating point. While the increase is not significant for the runner passage, this points to little fish passage benefit for increasing discharge significantly above the 18,600 cfs operating point.

2.2.2. Lower Monumental AC Turbine Units 4-6

Turbine units 4-6 at Lower Monumental and Lower Granite are of the same design and operate at approximately the same head. In 1998, a physical model was constructed for unit 4 at Lower Granite. The primary purpose of the modeling was to evaluate bead release points and potential draft tube modifications. Although some information was collected about the existing turbines, there was no data for comparisons across the operating range for the existing unmodified turbine passageway, and detailed bead analysis was not performed at the time this model was investigated. The bead analysis that did occur indicated that flow conditions downstream of the turbine intake screens (STS at Lower Monumental and extended length submersible bar screens (ESBS) at Lower Granite) are very turbulent and can potentially impact the distribution of flow as it approaches and enters the scroll case. Furthermore, the head loss and non-uniform flow distribution created by the screens reduces turbine efficiency.

2.3. PRESSURE INFORMATION FROM LABORATORY AND FIELD DATA

Exposure to severe pressure changes during turbine passage has potential to be a source of injury to juvenile salmonids. An assessment of barotrauma mortality risk has been conducted for several lower Columbia and Snake River dams with data collected in laboratory and field studies using sensor fish (see Section 3.4 in Phase II Main Report). Relationships were established among variables such as tag burden, nadir pressure, and acclimation depth; however, no pressure studies have been conducted at Lower Monumental. Consequently, it is necessary to use surrogates such as John Day BLH units 1-3 (see John Day Phase II Project Appendix and Appendix C.4.3.3 in Wittinger et al. 2010). No data exists that would represent Lower Monumental AC units 4-6. For John Day units 1-3, sensor fish were used along with computational fluid dynamics (CFD) model to generate a nadir distribution. Assuming a worst case acclimation depth of 22 feet (Pflugrath et al. 2012), a pressure mortality risk was calculated for John Day that can be used as a surrogate for Lower Monumental (Table 4).

Table 4. Barotrauma Risk Assessment Calculated for John Day Dam (22 feet acclimation depth)

Turbine Passage Condition	Turbine Discharge (kcfs)	Calculated Mortality (%)
Lower 1%	11.80	0.62
Peak	16.50	1.81
Upper 1%	20.30	6.18

2.4. BIOLOGICAL FIELD STUDY INFORMATION

The main avenues to estimate turbine survival at Lower Monumental is to conduct biological testing on site or through data extrapolation. Data may be used from more current acoustic telemetry route specific survival estimates from Lower Monumental or other turbine survival studies where turbines tested are identical to those at Lower Monumental. Data from other projects, such as lower Granite units 4-6, are applicable to Lower Monumental because these turbine units at both dams are the same family with the same configuration and operating range; however, Lower Granite is configured with ESBSs and Lower Monumental with STSs. The release elevation for Lower Granite for fish in field studies and beads in the physical models are aligned with the bottom of the longer ESBS, so the results may not align perfectly with the Lower Monumental configuration. The two different screen types may produce very different hydraulic conditions downstream from the screens, and the ESBSs force fish deeper to bypass the screen, which may result in differing passage locations through the runner.

Initial turbine survival tests were conducted at Lower Granite turbine unit 4 in 1994-1995 (Normandeau et al. 1995). Balloon-tagged salmon were released to determine direct survival rates through turbines. Fish were released in each intake bay at the emergency closure bulkhead slot for three different turbine operating points of 13.50 kcfs, 18.0 kcfs, and 19.0 kcfs (Normandeau et al. 1995). Study results were acceptable for both 1- and 120-hour survival probability (Table 5); however, the hypothesis that survival would be greater for fish at ±1% of turbine peak efficiency was not supported by this study.

Table 5. Survival Probabilities of Balloon-tagged Juvenile Chinook at Lower Granite, 1995

Test Scenario	Intake Bay Vertical Release Point	Turbine Operation	Survival Probability (CI)	
			1 hour	120 hours
1	A-upper	±1% normal eff. range: 18.0 kcfs	0.949(0.925-0.970)	*0.959(0.919-1.000)
4	A-mid	±1% normal eff. range: 18.0 kcfs	0.953(0.928-0.973)	0.936(0.893-0.978)
5	A-mid	±1% normal eff. range: 13.50 kcfs	0.972(0.949-0.989)	**0.987(0.944-1.000)
6	A-mid	Cavitation mode: 19.0 kcfs	0.946(0.922-0.965)	0.941(0.909-0.972)
2	B-mid	±1% normal eff. range: 18.0 kcfs	0.975(0.955-0.992)	0.940(0.901-0.979)
3	C-mid	±1% normal eff. range: 18.0 kcfs	0.975(0.955-0.992)	0.954(0.916-0.992)
Pooled (all 6 test scenarios)			0.961(0.951-0.969)	0.948(0.931-0.965)

*Survival established at 0.949 because 120 hour survival estimate exceeded 1 hour estimate.
**Survival established at 0.972 because 120 hour survival estimate exceeded 1 hour estimate.
Source: Normandeau et al. 1995.

The highest survival occurred during test scenario 5 at 13.50 kcfs discharge with a middle release point in intake bay A. However, the 90% confidence intervals are overlapping among the operation treatments making it difficult to draw conclusions from the study. While data suggest relatively high survival, they do not include tailrace effects (i.e., predation pressures on disoriented fish after passing through turbines) and barotrauma injury rate (due to surface acclimation). Despite this, the data from the 1994 tests did comport well with 1995 data adding credence to results less tailrace effects and barotrauma injury rate.

One of the earliest studies resulting in an estimate of juvenile salmon survival at Lower Monumental turbines was conducted in 1994 by Muir and others (1995). The data was based on a paired release survival model using PIT tags (12 millimeters; 0.077 grams) injected into yearling Chinook salmon. The treatment fish were released at a point within the turbine intake structure and the reference fish were released mid-river downstream of the juvenile bypass outfall pipe. The turbine release location was at unit 6B under normal load response (135 MW). The resulting relative survival for the turbine route was 86.5% (95% CI = 83.0% to 90.0%). Later, Muir and others (2001) published a compendium of research (1993-1997) on the relative passage survival of juvenile salmonids through bypass systems, turbines, and spillways with and without spill deflectors at Snake River dams. More recently, a synthesis report by Ham and others (2009) compiled survival data from 1990-2006 at Lower Monumental.

Contemporary studies were conducted from 2006 through 2009 at Lower Monumental. During these studies there were sufficient numbers of fish passing through turbines to allow for route specific turbine survival estimates (Table 6). A post-study analysis was undertaken to see if the geometry that juvenile salmon were exposed to had any particular consistency that would suggest a preferential operation for successful fish passage. Wicket gate positions and blade angles were isolated for each fish at the time they passed through the turbines. For BLH units 2-3 (unit 1 was fixed at 29 degrees and not considered in the analysis), the wicket gate/blade angle positions for all three species of interest ranged from the lower 1% operating point to the upper 1% operating point with head varying from around 95 to 100 feet during the study (Figure 21). For AC units 4-6, the data ranged from just above peak operation to the upper 1%. The latter units have a strongly skewed operating range encompassing the peak operation to generator limit with less than a degree of blade angle adjustment below the peak (Figure 22).

Table 6. Turbine Passage Survival at Lower Monumental (2006-2009)

Year	Tag Type	Survival Model	Treatment Release (type/location)	Reference Release (type/location)	Test Fish	Relative Survival	Standard Error	References
2006	RT	Paired	Boat/7 km u/s, mid-channel	Boat/1 km d/s, mid-channel	YCS SYCS SHT	0.910 Insuff. #s 0.838	0.017 Insuff. #s 0.017	Hockersmith et al. 2008a Absolon et al. 2008a
2007	RT	Paired	Boat/7 km u/s, mid-channel	Flume/1250 meters d/s, 7.6 meters from north shoreline	YCS SYCS SHT	0.909 Insuff. #s Insuff. #s	0.051 Insuff. #s Insuff. #s	Hockersmith et al. 2008b Absolon et al. 2008b
2008	RT	Paired	Boat/7 km u/s, mid-channel	Flume/1250 meters d/s, 7.6 meters from north shoreline	YCS SYCS SHT	Insuff. #s 0.960 Insuff. #s	Insuff. #s 0.057 Insuff. #s	Hockersmith et al. 2010 Absolon et al. 2010
2009	RT	Paired	Boat/7 km u/s, mid-channel	Flume/1250 meters d/s, 7.6 meters from north shoreline	YCS SYCS SHT	1.021 0.891 1.009	0.007 0.025 0.004	Hockersmith et al. 2010 Dumdei et al. 2010

Key: RT = radio tag; km = kilometers; YCS = yearling Chinook salmon; SYCS = subyearling Chinook salmon; SHT = steelhead.

Figure 21. Wicket Gate vs. Blade Angle for Fish Surviving Turbine Passage through Units 2-3

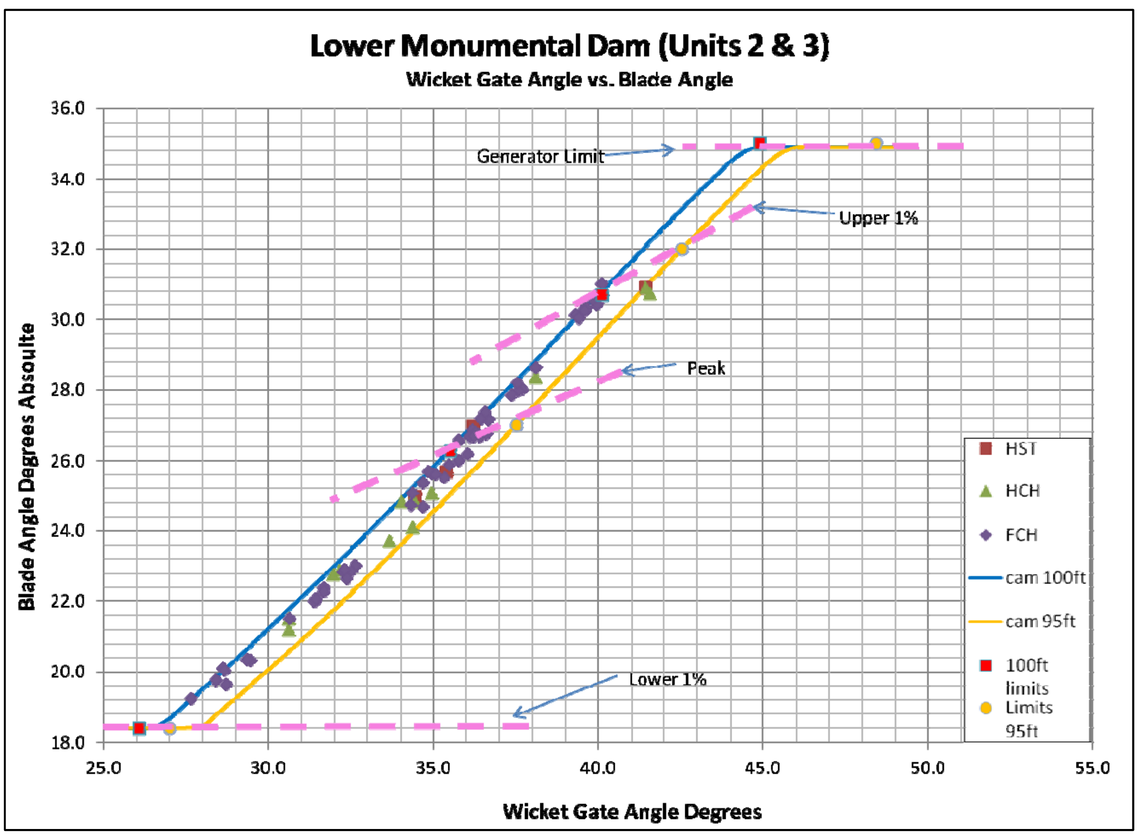
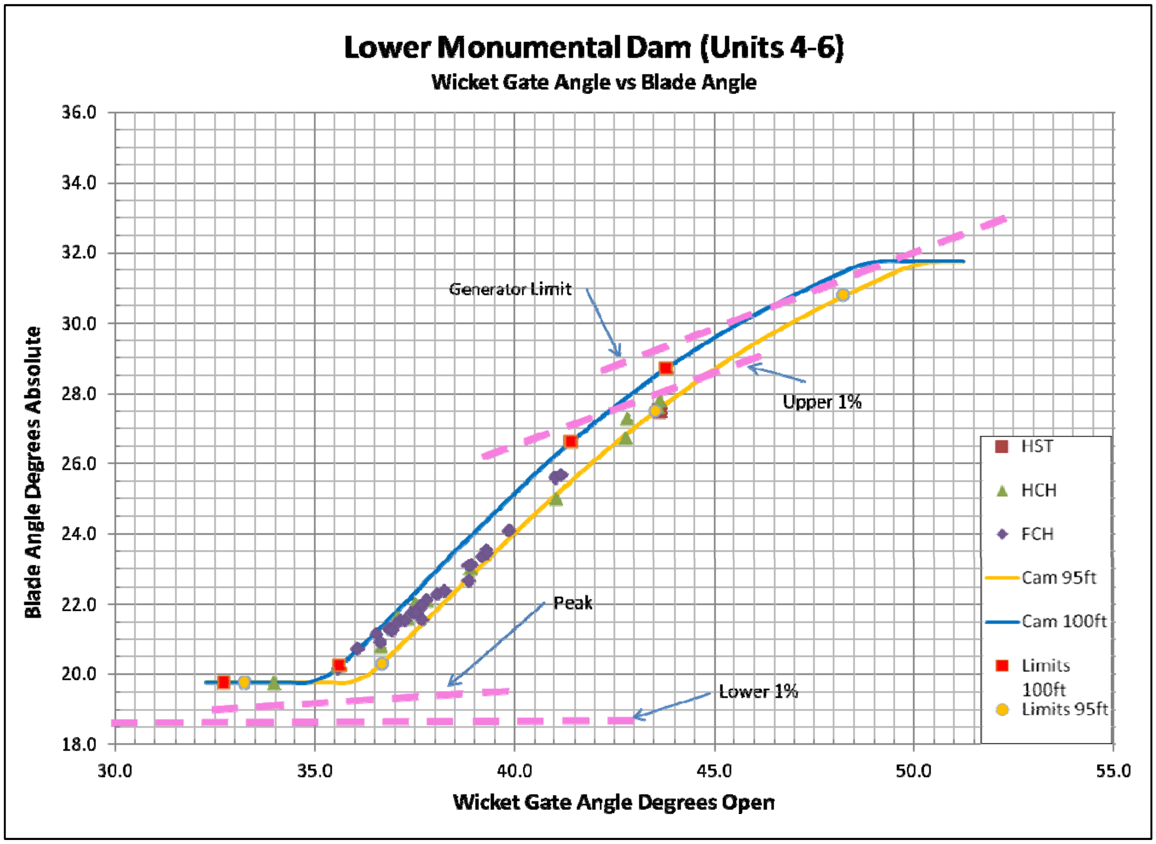


Figure 22. Wicket Gate vs. Blade Angle for Fish Surviving Turbine Passage through Units 4-6



In 2008 and 2009, a RSW post-construction passage and survival study was conducted using two spill treatments to evaluate the RSW efficiency and effectiveness, as well as all the other metrics associated with dam survival including route-specific survival (Absolon et al. 2010; Hockersmith et al. 2010a, 2010b). Turbine survival was found to be exceptional for subyearlings in 2008 (Absolon et al. 2010), acceptable for yearlings in 2009 depending on spill treatment (Hockersmith et al. 2010b), and exceptional for steelhead in 2009 (Hockersmith et al. 2010b). Virtually all of the yearling Chinook salmon and juvenile steelhead survived (100% based on a single release estimate), not only through the two downstream survival gates, but all the way to the next dam (Ice Harbor). The subyearling Chinook had a survival rate of 96.0% based on a single release estimate.

The operations aligning with fish passage through units 2-3 showed a wide range of passage conditions for the surviving fish from the lower 1% to the upper 1%. Operationally, units 2-3 were operated over the entire 1% range. There was a tendency for the data to be concentrated around the peak operation. Conversely, the operations aligning with fish passage through units 4-6 were mostly between peak and upper 1%. Operationally, this is where most of the operations fell during the fish passage season.

None of the Lower Monumental turbine survival estimates were derived from special operations that would test the benefit of operating conditions other than normal load response. For this reason, it is necessary to look at surrogate dams for information that might lead us to preferred operations at Lower Monumental. John Day, Lower Granite, and Little Goose all have similar BLH turbines in units 1-3.

Lower Granite and Little Goose also have the larger AC turbines in units 4-6. An important difference between Lower Monumental and other similar dams on the Snake River is that Lower Monumental uses STS screens instead of the longer ESBS screens. Past studies conducted at these dams may provide insight into alternate operations that may yield higher fish passage survival through the Lower Monumental turbines.

2.5. DISCUSSION

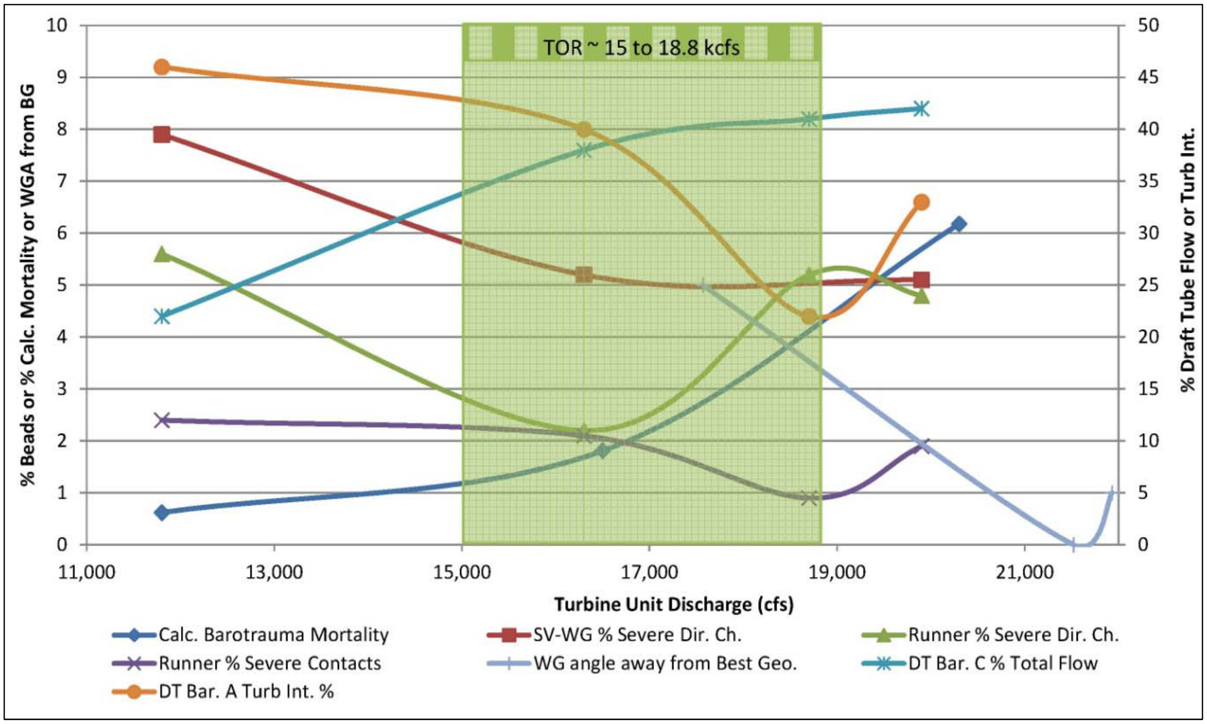
The 1% efficiency operating range specifies that turbines are to be operated within 1% of the best efficiency from April 1 through October 31. This operating range is in place to provide optimum fish passage conditions while maintaining turbine efficiency and benefit from the hydropower generated. Studies by Bell (1981) and Eicher Associates (1987) have shown that fish passage survival was greater within this operating range and the results have shaped turbine operation guidelines since. The 1% operating range is currently mandated by the 2008 BiOp (NOAA Fisheries 2008) and implemented by the 2012 FPP (USACE 2012). While the 1% operating range appears to provide fairly good conditions for fish passage, advancements in turbine runner design and passage survival studies justifies the need to improve the precision and accuracy of turbine survival estimates and further refine operating conditions based on additional information.

It is hypothesized that more open geometries provide the least probability of strike on stay vanes, wicket gates, and runner blades during passage leading to higher turbine discharge and power output. Hypotheses such as this may be tested presently with greater accuracy and precision than was ever possible in previous studies such as those of Bell (1981) and Eicher Associates (1987). Best geometry at Lower Monumental has been found to be a 42 degree WGA with a range of 36-44 degrees; but in 2011, a simple analysis of geometry showed that turbine operations to maintain the 1% efficiency of a turbine generator may provide adjustment of wicket gates outside of the best geometry range dependant on flow, possibly affected by environmental phenomena such as trash rack conditions. Subsequently, survival was estimated to be 100% for Lower Monumental making a case for more extensive studies to explore operations and geometries both within and outside of the 1% range, particularly in AC turbine units 4-6 where data is lacking.

Turbine passage survival estimates at Lower Monumental between 2006 and 2009 were not operation or geometry specific, nor were the numbers of fish passing through the turbines during these studies sufficient enough to provide reportable survival estimates. The survival estimates varied greatly with standard errors ranging from 8% to 50% in some cases (Absolon et al. 2010). Confidence intervals (CI) ranged widely as well, from 66% (Hockersmith et al. 2008a) to 108% (Hockersmith et al. 2010a). These studies focused on spillway survival and spill patterns, some RSW specific. For this reason, a small percentage of fish released passed through turbines during the study; hence, turbine passage survival may not be representative of actual survival (Ham et al. 2009; Absolon et al. 2010; Hockersmith et al. 2010a, 2010b).

Therefore, using John Day information is likely the best surrogate for Lower Monumental BLH turbine units 1-3. The selected TOR for John Day is 15.0 kcfs to 18.80 kcfs (Figure 23). Although John Day is a different dam, there is no additional information for Lower Monumental that contradicts this proposed range.

Figure 23. Combined Information on Direct Turbine Mortality at John Day Dam



There is limited information for the Lower Monumental AC turbine units 4-6. Based on physical geometry considerations and some 2009 data correlation, the best operating range for these units is likely between peak and upper 1% or slightly higher. Pressure information for these turbine units is lacking and could restrict the range if lower pressures are found at the higher operating points.

3. DEFINE TARGET PROJECT OPERATIONS

Past biological evaluations of turbine survival have suggested that the majority of turbine mortality occurs as a result of indirect mortality. The Phase I report (USACE 2004) suggested that, "Total turbine passage survival cannot be optimized without improving conditions that influence indirect survival." The TSP recommended that further research be conducted to better understand the dynamics of indirect mortality associated with turbine passage and particularly the influence of tailrace hydraulic conditions on indirect mortality. It is commonly thought that the main loss of turbine-passed fish occurs in the powerhouse tailrace. Fish passing through turbines are undoubtedly stressed and disoriented. Under this condition, they are more susceptible to predation from piscivorous predators, both avian and fish. Again, both CFD and physical models should be used to understand the effects of powerhouse operations and configurations on tailrace hydraulics. Modeling efforts to optimize the tailrace environment for speedy egress and to afford turbine-passed fish the opportunity for recovery with minimum exposure to predators will provide a potential path forward for future dam operations.

While no physical modeling has been completed that specifically explores improving turbine passage at Lower Monumental, modeling has been completed as recently as 2011 to evaluate egress of the relocated JBS outfall. The Lower Monumental general model at ERDC evaluated at tailrace conditions at river flows from 60.0 kcfs to 90.0 kcfs and two different spill patterns (with approximately 28.0 kcfs and 25.0 kcfs for each pattern). The powerhouse unit priority was not varied in this modeling and the 60.0 kcfs and 70.0 kcfs flows created a large eddy downstream of the powerhouse (Figure 24). Although most powerhouse flow was entrained in the spill flow and move downstream, some of the powerhouse flow was entrained in this relatively high velocity eddy. Higher powerhouse flows allowed this eddy to be pushed out.

In addition, data correlation was performed with turbine passage data from 2004-2009 from fish survival studies at Lower Monumental. This data was pooled and the number of fish detected downstream (an indication of survival) was correlated with multiple different variables. Note that these detections have not been compared against detection of control fish; therefore, the detection percentage is likely lower and not representative of survival percentage. Nevertheless, these data may still be used for comparing the relative effect of turbine operations on downstream detection of tagged fish. Two project operation variables indicated trends in the number of fish detected downstream. The number of units operating (Figure 25) and the unit of passage (Figure 26) at Lower Monumental correlated with increased detection downstream. In general, the greater the number of units operating suggests better egress and better potential turbine passage survival. It is interesting to note the relatively large jump in detection percent that occurred between operating two and three units (Figure 25). Unfortunately, this variable also would correlate fairly closely with total river discharge and total powerhouse discharge, which could have a similar effect on detection percentage.

Figure 24. Example of Flow Patterns from Lower Monumental Physical Modeling

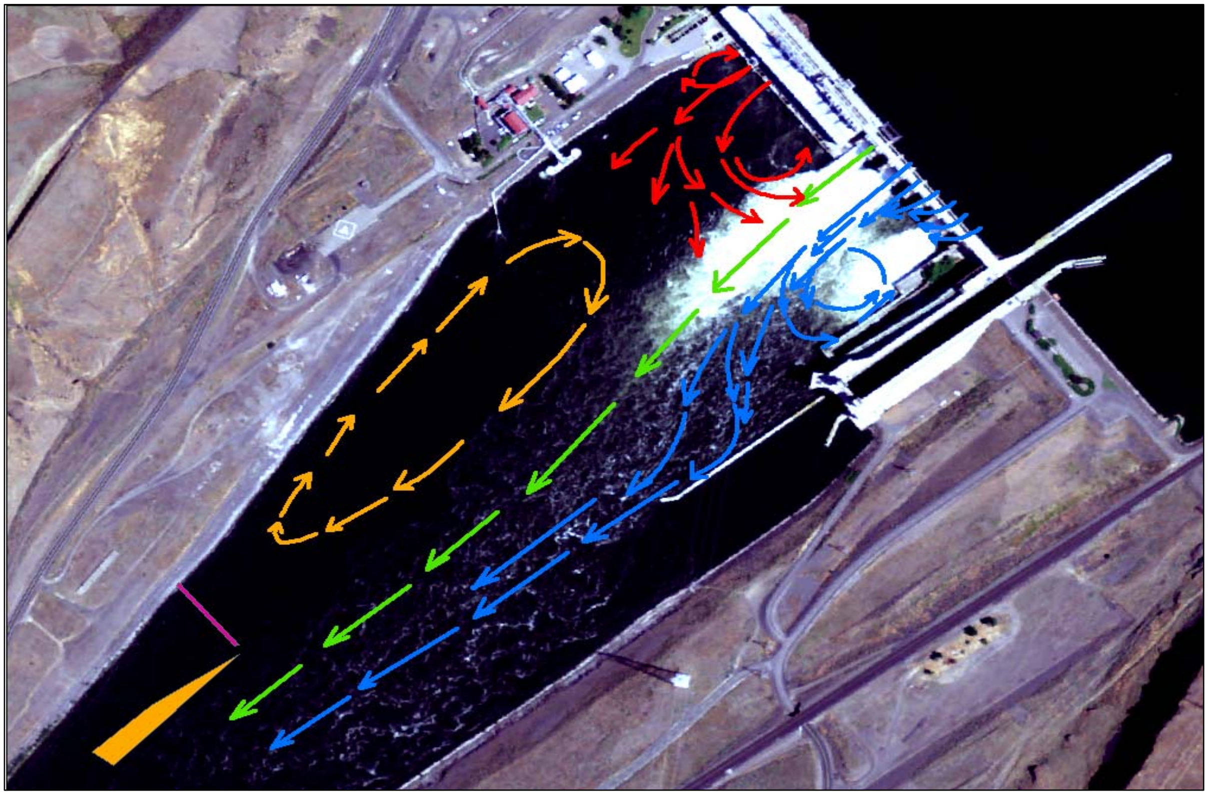


Figure 25. Correlation of Downstream Detection with Number of Units Operating (2004-2009)

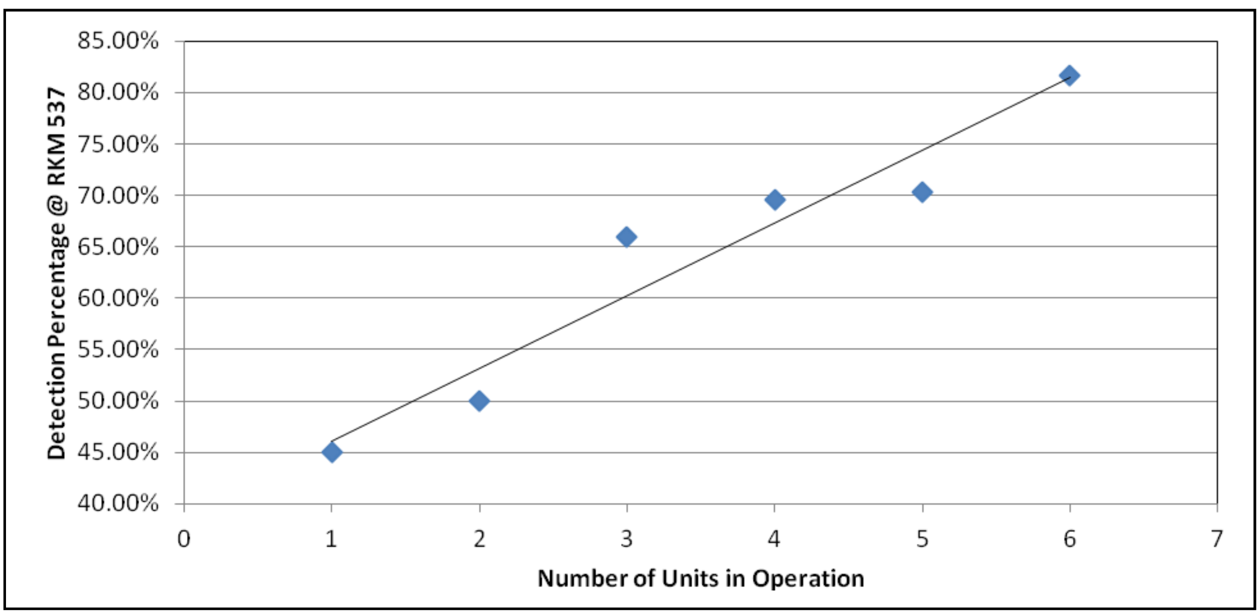
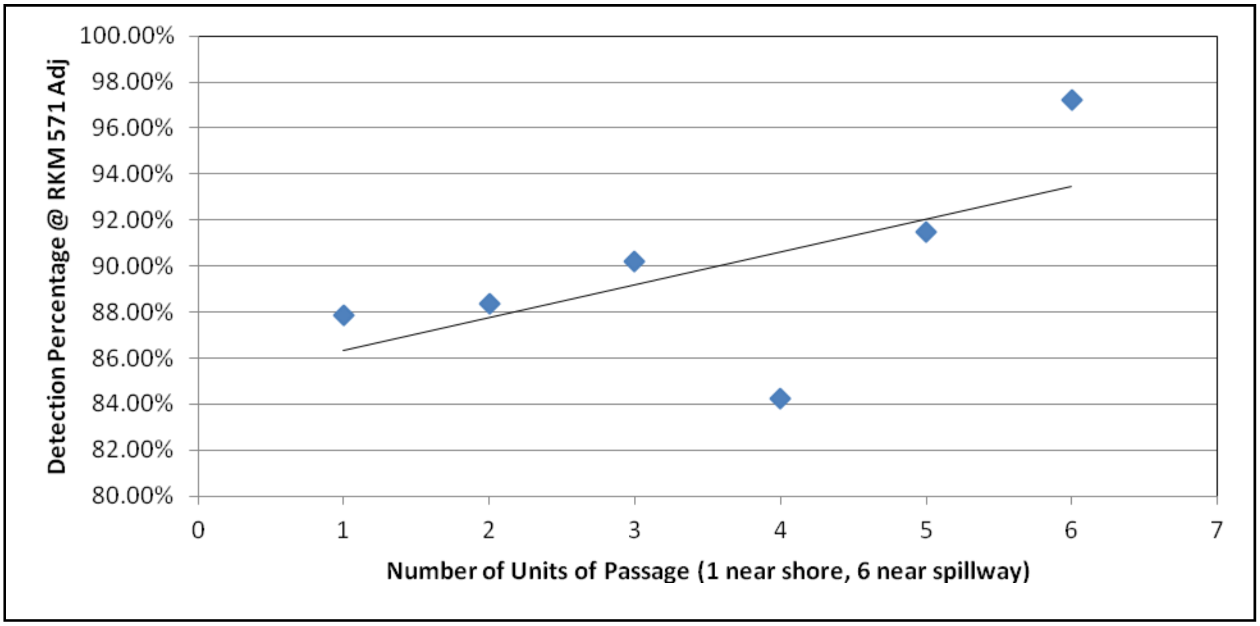


Figure 26. Correlation of Downstream Detection with Number of Units of Passage (2004-2009)



Turbine unit 1 is the unit close to shore and unit 6 is closer to the center of the dam. In general, the closer the unit is to the center of the river, the better the egress and the better the potential turbine passage survival (Figure 26). Since Lower Monumental had a fairly fixed unit priority over the 2004-2009 time frame, the unit of passage could also cross-correlate with the number of units operating. However, the general trend does make sense that passage closer to shore may decrease survival due to predation. Based on the physical modeling done to date in support of spill and outfall egress, changing the unit priority would not remove the eddy on the north shore at lower river discharges. However, changing unit priority by using units closer to the center of the dam has the potential to reduce some of the entrainment of powerhouse flow into this eddy and instead entrain into the spill flow. Additionally, the physical modeling at ERDC could be utilized to test if egress hydraulics support this theory.

4. OTHER CONSIDERATIONS

The standard length traveling screens used at Lower Monumental have several potentially detrimental effects on fish passing beneath them and eventually passing through the turbine. The screens cause turbulence, loss of turbine efficiency, and sometimes reverse flows near the ceiling of the intake that can delay and disorient juvenile salmon. It is not clear that the bypass routes are necessarily better for survival of juvenile salmonids relative to turbines. In spring 2009, juvenile salmon survivals through the bypass system were lower (0.965 for yearling Chinook and 0.939 for juvenile steelhead) than for fish passing through the turbines (1.021 for yearling Chinook and 1.009 for juvenile steelhead; Hockersmith et al. 2010b). While it should be noted that turbine passage sample size was extremely small, these study results are interesting and may suggest that the removal of screens during non-transport periods may provide better powerhouse survival and fish passage benefit relative to the bypass system. However, the JBS outfall has since been relocated downstream where the egress conditions are more favorable and continued monitoring will be necessary to determine if bypass survival will increase.

5. RECOMMENDED PATH FORWARD

Lower Monumental Dam uses two different turbine manufacturers (BLH turbine units 1-3 and AC turbine units 4-6); due to their design differences, they are expected to have different TORs. Turbine units 1-3 are the same design as John Day and since they are operated a fairly similar heads, the information from John Day is considered applicable to Lower Monumental. Based on this, the recommended TOR for Lower Monumental turbine units 1-3 is 15.0 kcfs to 18.80 kcfs.

Meanwhile, there is very little information for AC turbine units 4-6 for improved fish passage survival; therefore, it is more difficult to select a defined TOR. Based on geometry information, a discharge between peak and upper 1% to even higher is recommended; based on unknown pressure mortality, this range should be limited to the upper 1%. As seen in Figure 22, the majority of the operations within the ±1% of peak efficiency criteria for units 4-6 occur between peak efficiency and the upper 1%. Thus, turbine units 4-6, by default, operate in a preferred manner.

Understanding that mandated spill is an operational requirement into the foreseeable future, increasing the number of units operating is not likely to occur. However, powerhouse unit priority at Lower Monumental should be adjusted to pass fish through units near the spillway to leverage on the egress conditions created by spill (Figure 24). Unit 1 and possibly unit 2 will continue to be prioritized for adult fish attraction water, but may not be the best for juvenile salmon moving downstream due to the strong reverse eddy associated with that region at the dam. Therefore, a single unit could be used for adult attraction, while subsequent units are prioritized toward the center of the dam. Physical model operation could be used to further justify this change in unit priority.

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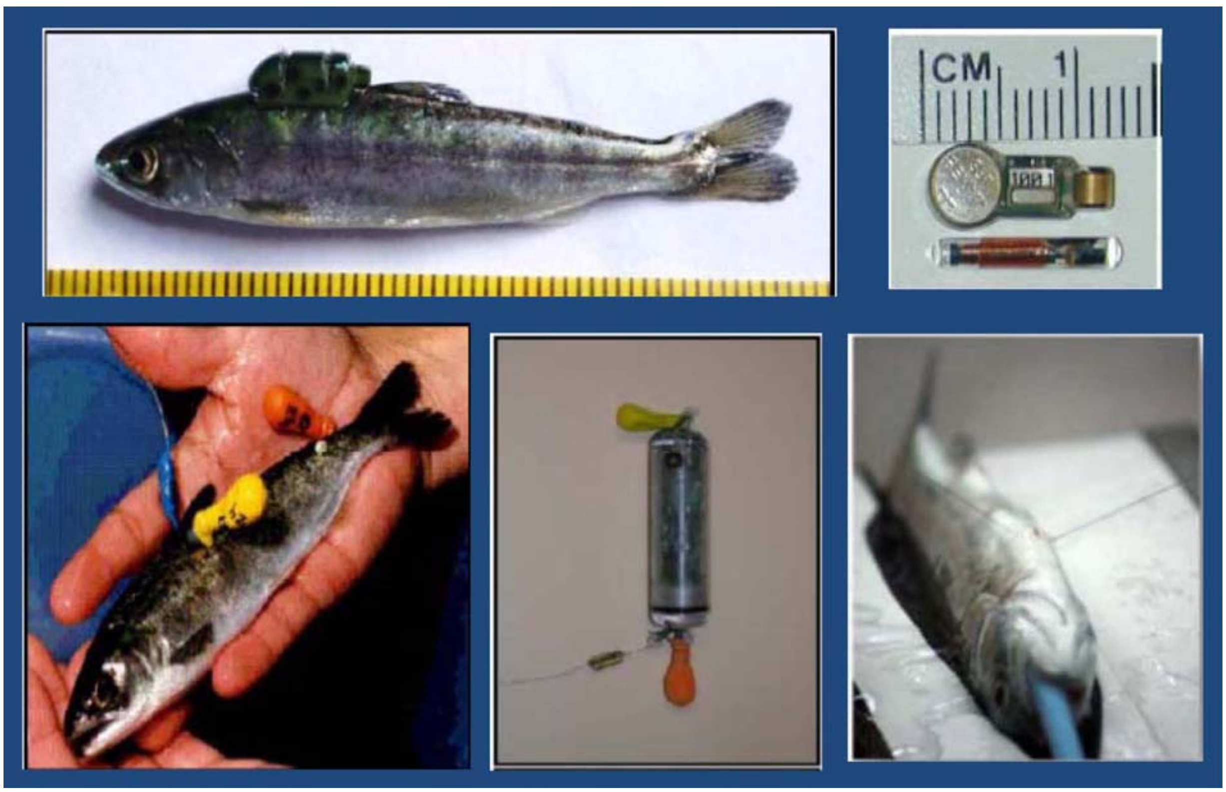
PHASE II APPENDIX

COMPREHENSIVE TURBINE SURVIVAL TESTING CONSIDERATIONS



PREPARED BY
U.S. ARMY CORPS OF ENGINEERS
TURBINE SURVIVAL PROGRAM

JUNE 2013

REVISION 0

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ACRONYMS AND ABBREVIATIONS

BiOp	Biological Opinion
ERDC	Engineering Research and Development Center
FCRPS	Federal Columbia River Power System
fmsl	feet mean sea level
ft	feet (foot)
JSATS	Juvenile Salmon Acoustic Telemetry System
PNNL	Pacific Northwest National Laboratory
NMFS	National Marine Fisheries Service
SE	standard error
STS	submerged traveling screen
TOR	target operating range
TSP	Turbine Survival Program
TST	turbine survival testing

1. TURBINE SURVIVAL TESTING CONSIDERATIONS

1.1. INTRODUCTION

While the proposed target operating range (TOR) at some lower Columbia and Snake River projects is supported by field studies, the TOR at other projects may fall outside the 1% operating range generally established as the preferred operating range for salmonid passage. Although the TORs at these projects are supported by some field studies, the Turbine Survival Program (TSP) team believes additional field verification is needed. Therefore, it is recommended that a comprehensive turbine survival test be conducted to validate the proposed TOR for these projects.

Turbine survival testing (TST) may be conducted with a variety of methods to achieve various degrees of precision. The TSP must evaluate the available data for a given project to determine what specific questions are to be answered in order to develop an appropriate study design. This appendix provides brief discussion of the requirements and considerations for performing a general TST. A more comprehensive investigation of TST methodology is available in the Ice Harbor biological study design (Trumbo et al. 2013). While the study design was developed specifically for Ice Harbor, the methodology and considerations presented are applicable to any hydropower project.

1.2. GOALS

For the purpose of biological index testing, the goal of TST may generally involve estimating turbine passage survival at different operations to identify the operating range providing the highest survival. It may also be important to determine if a significant difference in survival exists between operations (e.g., survival at peak efficiency compared to a point beyond the upper 1%). The study goals must be clear as the study objectives will be defined appropriately to achieve the goals.

1.3. FORMULATING OBJECTIVES

There are several questions that must be taken into consideration when formulating objectives for conducting TST. These questions are listed below.

- What are the operational scenarios that need to be tested?
- What statistical model should be used to evaluate the survival tests?
    - What type of tracking technology should be used to evaluate passage and survival?
    - How do the juvenile salmonids approach the powerhouse and at what depth do they acclimate immediately prior to entrainment into a turbine intake?
    - Where should fish be released and with what methodology?

1.4. TEST OPERATIONS

There are a number of possible operational scenarios that may be tested to accomplish the main goal of determining the best TOR for fish passage, as discussed below.

- Effort may be concentrated within the TOR to determine the range of survivals associated with various levels of generator power. The idea here would be to select a high operation and a low operation within the TOR and conduct a survival test for two or more operations.
- A survival test could also be performed using an operation within the normal 1% operating range as compared to an operation within the TOR.
- A survival test could be conducted at one operation within the TOR to test if survival is improved over historical turbine survivals.

All of these test cases require compromise on the part of power production since the normal operating flexibility would be constrained for test purposes. A recommended test scenario would be to block load the powerhouse to assure that there is a high likelihood of the fish being exposed to one of the designated treatments. The exact block loading design needs further investigation, particularly in the relation to the tailrace egress conditions that may result from the altered configuration. This may best be evaluated using the general models located at the Engineering Research and Development Center (ERDC).

1.5. Statistical Models and Methodology

Acoustic telemetry study designs are implemented at Federal Columbia River Power System (FCRPS) projects for many reasons including the following: (1) estimate dam survival ("performance standard") of juvenile salmonids; (2) evaluate fish passage through or over newly constructed or modified structures that may directly influence fish passage and survival; and (3) evaluate specific passage routes for survival and potential for improvement.

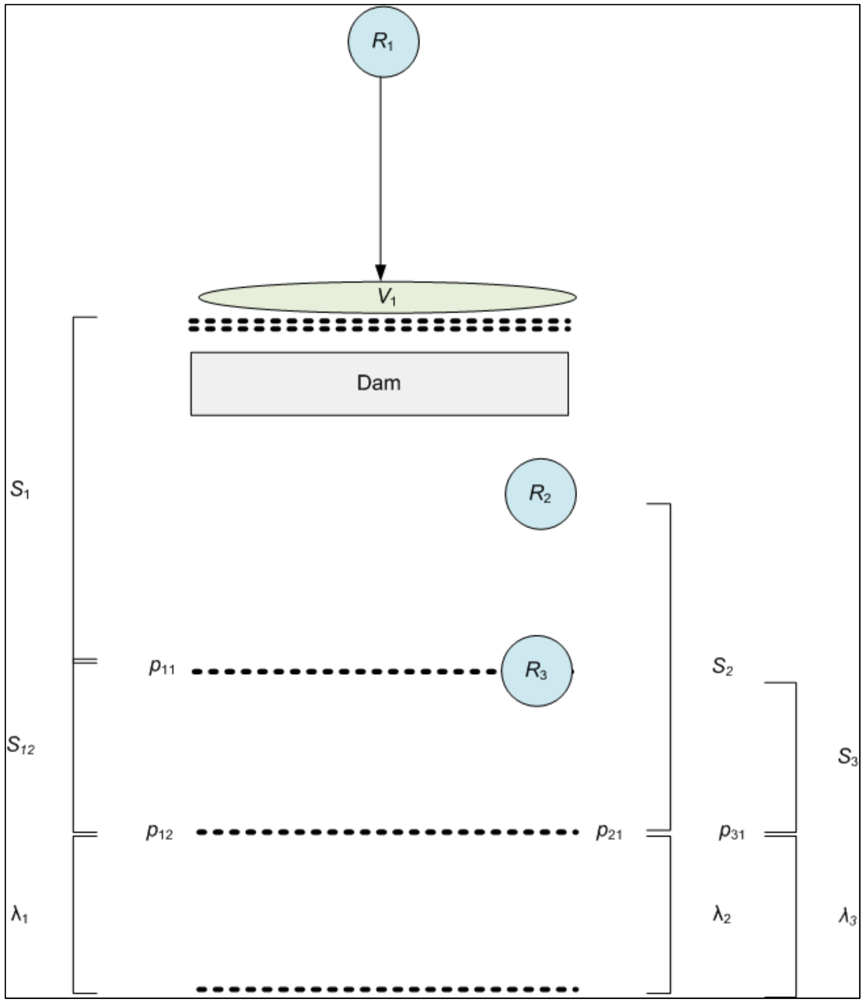
Dam passage survival (defined as survival from the upstream face of the dam to a downstream location outside of project operation effects on hydraulic conditions) is required to meet values ≥ 96% for spring stocks (yearling Chinook salmon and steelhead) and ≥ 93% for summer stocks (subyearling Chinook salmon) and should be estimated with a standard error (SE) of ≤ 1.5% (0.015) (NMFS 2008, Skalski 2011). These parameters are used with detection probabilities to achieve a precision ±0.03, 95% of the time (Normandeau et al. 2007, 2008; NMFS 2008; Skalski 2009; Skalski et al. 2009; Skalski 2011). In the case of Biological Opinion (BiOp) specifications, precision should be calculated as follows.

$$0.03 = 1.96 * SE(\hat{S}) \rightarrow SE(\hat{S}) = 0.0153 \text{ or } 0.015 \qquad \text{(Skalski 2011)}$$

The preferred model used for statistical evaluation of passage and survival at both lower Columbia and Snake River dams is the virtual/paired-release model developed by Dr. John Skalski at the University of Washington (Skalski 2009; Figure 1). Paired release analysis can be used to estimate survival for tailrace release groups. A joint likelihood model can be used to estimate dam survival and the estimate of variance. Akaike's information criterion and likelihood ratio tests can be used to determine the best model(s) for describing capture data and parameter estimates.

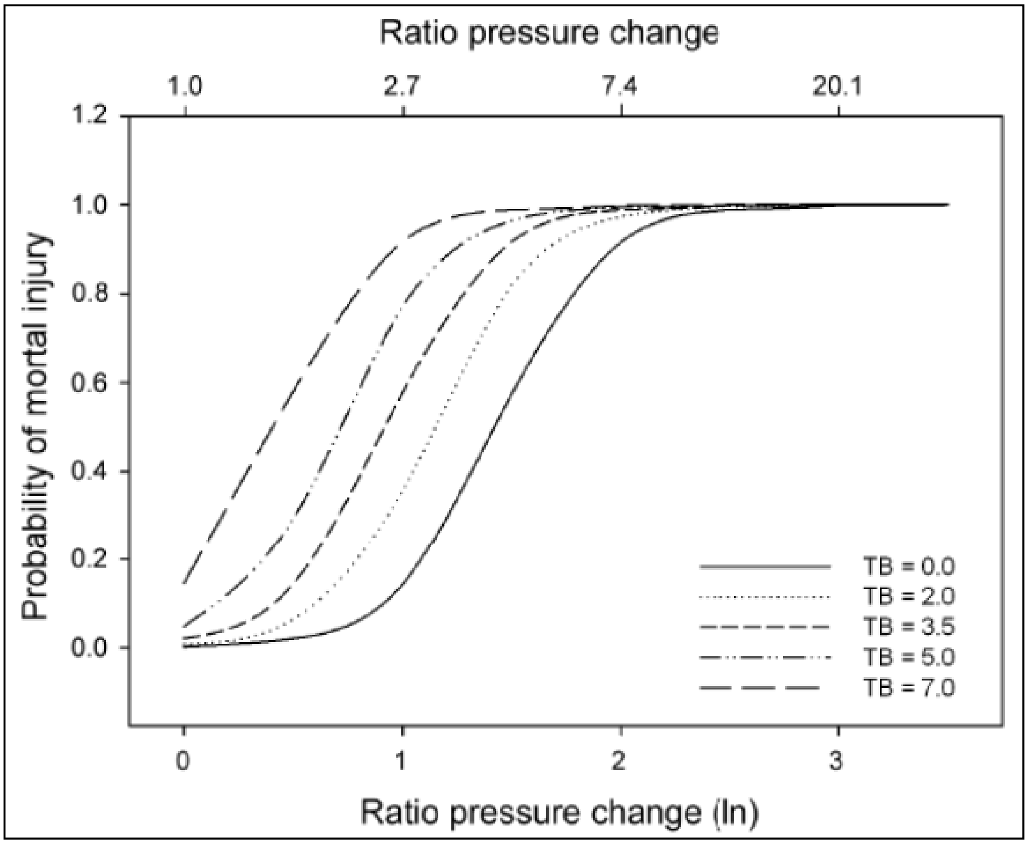
The virtual/paired-release study design has been employed at lower Columbia and Snake River dams for performance standard testing (NMFS 2008) and typically does not account for particular operations such as a specific turbine load. Performance standard testing evaluates overall dam survival during spring and summer smolt outmigration under typical BiOp-mandated (NMFS 2008) powerhouse and spillway discharges. This study design may also include multiple dam passages where the upstream release groups combine to create a large virtual release group at subsequent dams (Skalski 2009).

Figure 1. Schematic of the Virtual/Paired-Release Model from Skalski (2011)



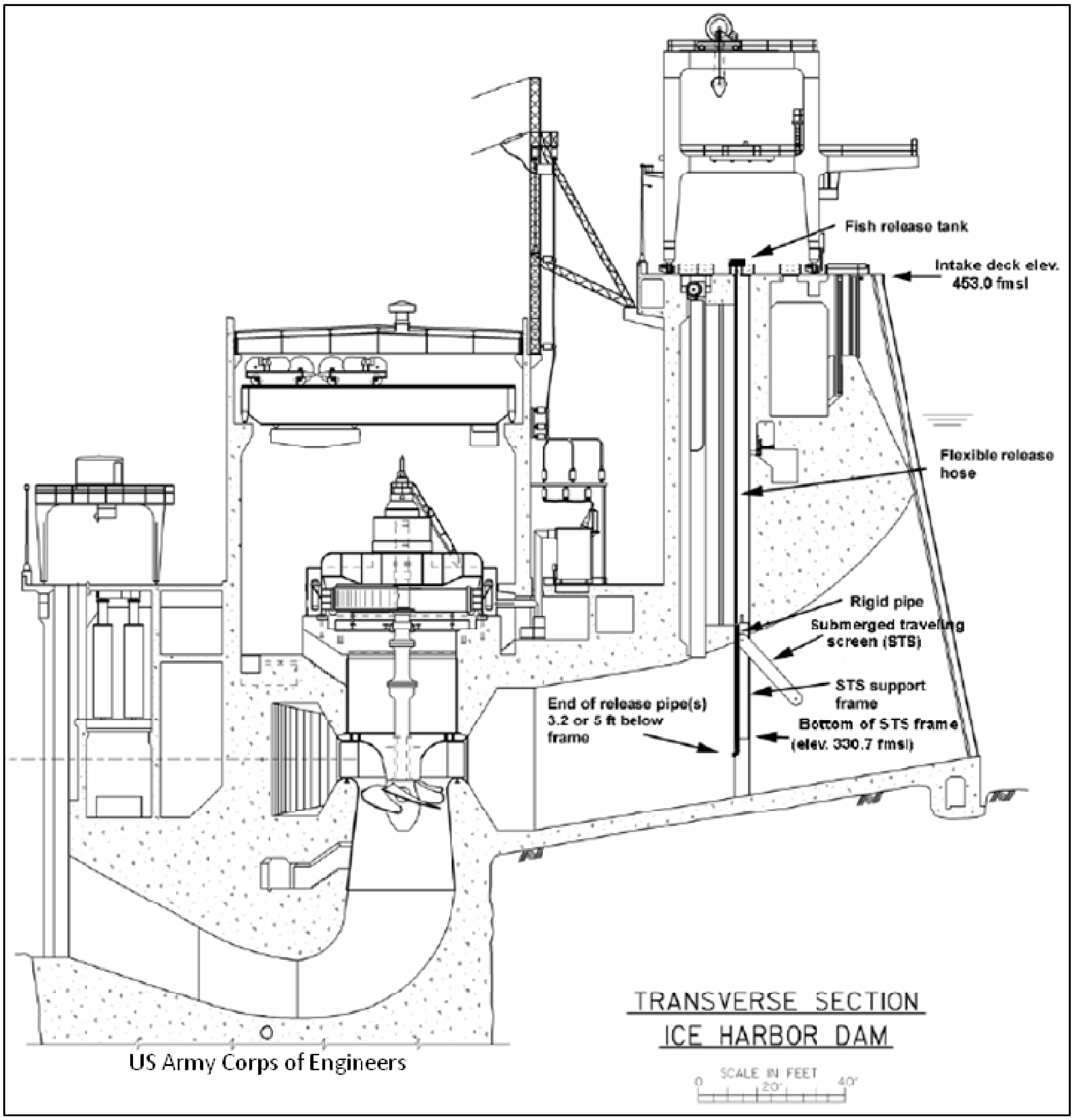
The technology being used for performance standard measures is the Juvenile Salmon Acoustic Telemetry System (JSATS). This technology employs small transmitters (12L x 5.3W x 3.7H millimeters, 0.425 grams), acoustic receiver arrays on the dam, and autonomous nodes for the downstream array lines. Recent laboratory assessment of barotrauma in both tagged and untagged juvenile Chinook salmon suggests that even these very small tags have a significant effect on their mortality rates when exposed to nadir pressures typical of those encountered when passing through a turbine runner (Figure 2). While it may be possible to back calculate the effect of tag burden if the sensor fish are used during the same study, the uncertainty that would be associated with this back calculation would suggest that tag burden should be minimized or eliminated.

Figure 2. Predicted Barotrauma Mortality with Tag Burden (Carlson et al. 2010)



Since the mid-1990s, another methodology that has been used to evaluate turbine passage involves directly releasing fish carrying balloon tags into the turbine intakes and recapturing them in the tailrace for observation. Direct release models typically estimate injury and survival probabilities using joint likelihood models (Normandeau et al. 2008), which are similar to maximum likelihood that is used for virtual with paired release study designs. Direct release studies allow for reduced sample size relative to studies such as the virtual with pared release as one assumption of the study is that all sample fish will pass through the specific turbine and experience the desired treatment (operation). One critical piece of information for a direct release study is where to release fish. The release locations for the most recent Ice Harbor Dam study (Normandeau et al. 2008) determined and/or verified through physical hydraulic model investigations using the ERDC 1:25 scale model Ice Harbor turbine (Trumbo et al. 2013; Figure 3). This is recommended for any TST implementing direct releases.

Figure 3. Cross-section of Ice Harbor Dam Powerhouse and Turbine Unit 3 Showing Release Locations for a Balloon Tag Study (Normandeau et al. 2008)



While direct release and virtual/paired-release study designs are quite different, the effects of tag burden are also quite different between tagging methodologies and releases. While acoustic telemetry studies employ tags that are surgically implanted in smolts, direct release studies attach balloon and radio tags externally, which eliminate the internal damage potential associated surgically implanted tags. Conversely, directly released fish do not experience depth acclimation as with upstream releases typically associated with acoustic telemetry studies. In either case, a correction must be made to appropriately address barotrauma potential.

For this reason, additional research has been performed to determine if acoustic transmitters could be packaged and made neutral buoyant for external attachment. Laboratory results indicate that the mortality rate for fish with the external transmitter is not different from an untagged fish (Deng et al. 2012). Additional tests were conducted to evaluate the efficacy of external transmitters in relation to shear environments, susceptibility to predators, and effects on swimming ability. Of these tests, swimming ability was the only one that did not compare favorably to an untagged fish (Janak et al. 2012).

Tag loss was moderate in laboratory studies at 5% (N = 21; loss = 1), and field studies at 10% (N = 30, loss = 3; Brown et al. 2013). No mortality was experienced during laboratory pressure and shear testing of fish carrying the external tag, and field testing resulted in no significant differences in survival between internal and external tagged fish up to approximately 7 days in-river (Brown et al. 2013). Further, no significant difference in detection efficiency was found between internal and external tags (Brown et al. 2013).

The external tag appears to be a useful tool for short-term turbine survival studies; however, there are inefficiencies in tag production. It is likely that internal acoustic tags may be employed given a new smaller version of the JSATS tag is available for future studies.

1.6. Other Considerations

Sample season, dam operations and particular fish run or species (i.e., subyearling and yearling Chinook salmon and juvenile steelhead) affect survival estimates, route-specific passage proportions, and sample sizes. Sample sizes generated for biological studies may differ depending upon a particular calculation method and the population of inference and associated parameters. Further, dam operations with or without screens and spill level will influence sample size and survival estimates. While release groups upstream of a dam may be the most appropriate for estimating dam passage survival, this may not be the most feasible approach in terms of sample size for estimating specific turbine passage survival.

Spring and summer study periods will provide different tailrace scenarios regarding predation for juvenile salmonids passing the project. There is evidence of predation being greater during summer outmigration rather than spring; however, this may not be clear among all projects, between the lower Columbia and Snake rivers, or between aquatic and avian predators. Predation effects on smolt survival should be considered when conducting survival studies with telemetry methods. However, telemetry methods do not allow for differentiating among factors of mortality when estimating survival. Trumbo and others (2013) provides a detailed discussion of how operations, fish species, and seasons affect sample size and subsequent costs in choosing a study design, as well as justifying operations required to achieve meaningful results.

It will be necessary to discuss potential dam configurations and operations with the regional fishery agencies to determine what is acceptable while conducting a TST during fish passage season. Consulting the general models may suggest particular dam operations that will improve egress and subsequent survival estimates.

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