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Bonneville Second Powerhouse ERDC Turbine Model Operating Range Investigation

Robert A. Davidson

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Abstract

The Bonneville Second Powerhouse (B2) turbine model investigations were performed in support of the joint U.S. Army Corps of Engineers, Portland and Walla Walla Districts, Turbine Survival Program (TSP). The TSP was developed to evaluate juvenile fish passage through turbines, with emphasis on identifying turbine structures and operations responsible for fish injury. The purpose of this B2 turbine model study was to investigate potential risk of injury to juvenile fish passing through all regions of the B2 turbines water passageway, using the existing 1:25 scale physical hydraulic model of the B2 turbines. The model investigations were divided into five study areas. These include the stay vane and wicket gate cascade, the runner, the region immediately below the runner, the exit of each of the two draft tube barrels, and the immediate tailrace region. Results from this model investigation indicate operations with steeper blade angles, resulting in higher unit discharge, create better passage conditions for fish. Fewer severe contacts with the turbine runner and less severe change in direction occur at steeper blade angles. The draft tube performs better at steeper blade angles, and the quality of flow exiting the draft tube is better at steeper blade angles. In addition, model experiments indicate egress conditions may be better at steeper blade angles.

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Preface

This study was conducted for the U.S. Army Corps of Engineers under Turbine Survival Program, Work Unit 157101, “CRFM SYS-S Turbine Bio Index Test.” The technical monitor was Mr. Martin L. Ahmann U.S. Army Engineer District, Walla Walla (NWW).

The work was performed by the Navigation Branch, Fish Passage Group of the Navigation Division (CEERD-HNN-F), U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication, Mr. Timothy W. Shelton was Chief, CEERD- HNN; Dr. Jacqueline S. Pettway was Chief, CEERD- HN; and Mr. W. Jeff Lillycrop, CEERD- HZT, was the Technical Director for Civil Works. The Acting Director of CHL was Mr. Jeffrey R. Eckstein, and the Acting Deputy Director was Mr. John T. Tucker III.

The experimental program was led by Ms. D. M. Guimbellot-Polk. Mr. Jon Renholds and Mr. Martin Ahmann U.S Army Engineer District, Walla Walla (NWW), and Ms. Laurie Ebner, U.S Army Engineer District, Portland (NWP), performed technical peer review of the report.

NWP performed technical peer review of the report.

During the course of the model study, Messrs. M. Ahmann and J. Renholds, NWW; J. Rerecich, NWP; D. Patla, NWP Hydroelectric Design Center; G. Fredricks and E. Myers, National Marine Fisheries Service; and J. Duombia and S. Bettin, Bonneville Power Administration, visited ERDC to observe model operation, review experimental results, and discuss model results.

The Commander of ERDC was COL Ivan P. Beckman, and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters

Executive Summary

The Bonneville Second Powerhouse (B2) turbine model investigations were performed in support of the joint U.S Army Corps of Engineers (USACE), Portland and Walla Walla Districts, Turbine Survival Program (TSP). The TSP was developed to evaluate juvenile fish passage through turbines, with emphasis on identifying turbine structures and operations responsible for fish injury. The first phase (Phase I) of TSP included four main objectives: (1) evaluate and recommend operational criteria to improve the survival of fish passing through Kaplan turbine units, (2) identify the biological design criteria for design of new modifications to the existing turbines, (3) investigate modifications to existing designs that have a potential to increase survival of fish passing through Kaplan turbine units, and (4) recommend a course of action for turbine rehabilitation or replacement that incorporates improvements for safer fish passage.

The USACE 2004 Turbine Survival Program Phase I Report (USACE 2004) identifies turbine passage conditions that may improve juvenile fish survival and suggests the best turbine operating range may not coincide with peak efficiency as previously assumed but may better correlate to an *open-turbine geometry*. The study report recommended additional model investigations be conducted to evaluate the best operating range for juvenile salmonids passing through those turbines within the powerhouses of the eight lower Snake and Columbia Rivers hydropower dams.

The purpose of this B2 turbine model study was to investigate potential risk of injury to juvenile fish passing through all regions of the B2 turbines water passageway, using the existing 1:25 scale physical hydraulic model of the B2 turbines. Results will be used to help establish a target operating range (TOR) for safer passage of juvenile fish. The study evaluated passage through the stay vane and wicket gate cascade (distributor), the turbine runner, and the draft tube. The study also evaluated retention time within the immediate tailrace region as influenced by draft tube exit conditions.

This report presents results of the B2 turbine model investigations, recommends the best operating range for juvenile fish passage, and provides a discussion as to why the B2 turbines have a higher survival rate than other turbines within the Lower Snake and Columbia Rivers hydropower projects.

Model investigations

The model investigations were divided into five study areas. These include the stay vane and wicket gate cascade, the runner, the region immediately below the runner, the exit of each of the two draft tube barrels, and the immediate tailrace region. Model investigations were performed for each of three operating points, at a prototype head of 55 ft (average project head at Bonneville during the juvenile fish outmigration season). The three operating points correspond to (1) a 1% drop from peak turbine efficiency on the low discharge side (blade angle [BA] of 16.5°), (2) peak efficiency (20.3° BA), and (3) generator limit (26.5° BA). The upper 1% limit, which is generally the upper operating limit for turbine operations during the fish passage season (USACE 2011), was not evaluated for B2 as operation at this point would be beyond the B2 generator limit.

Neutrally buoyant plastic beads were released within the model turbine intake at various locations; their path was documented through the stay vane and wicket gate cascade, runner, draft tube elbow, and tailrace region using highspeed digital cameras. The digital imaging frame rates used ranged from 120 to 1000 frames per second (frames/s) depending on the region being studied. Individual beads were imaged and evaluated for contact with both stationary and rotating surfaces, sudden changes in direction resulting from hydraulic shear and turbulence, and resident time durations in the immediate tailrace region. Laser Doppler velocimeter (LDV) measurements were taken within the draft tube near the exit to evaluate flow distribution and uniformity of flow.

Three regions of the turbine runner were separately evaluated for each of the three operating conditions. These include the near hub region, the mid-blade region, and blade tip region. The percentages of severe blade contacts observed for beads passing near the hub were significantly higher at the flatter BA of 16.5° compared to those observed at 20.3° and 26.5° . The same trend was observed for beads exhibiting a severe change in direction while passing through this region. The flatter blade angle of 16.5° had significantly higher percentages of beads with sudden changes in direction compared to the two steeper blade angles. In addition, hub-to-blade gap passage was very high at the 16.5° compared to the two steeper blade angles with the least occurring at 26.5° .

Overall severe bead contact and sudden changes in direction for the mid-blade passage were observed to be the least when compared to hub and

blade tip passage. The number of beads observed to have a severe contact was low for both 20.3° and 26.5° BAs but was significantly higher at the 16.5° BA.

The percentage of beads having severe contact within the blade tip region was highest at the flattest BA (16.5°) when compared to the 20.3° and 26.5°; contact for the two steeper blade angles was approximately the same. The beads observed to exhibit severe changes in direction had a trend of reduction as the blade angle was increased. Observations of bead contact (strike) and sudden changes in direction (shear) were the lowest for turbine operations at generator limit followed by peak efficiency. The highest rates of contact and sudden changes in direction occurred at the lower 1% operating point.

Distribution of flow between the two draft tube barrels was uneven throughout the turbine operating range. The largest disparity between the draft tube barrels occurred at 16.5° BA. Quality of flow within each draft tube barrel was worst at the 16.5° BA and improved with the steeper BAs.

Retention of the beads within the tailrace, or the rate at which beads pass through the tailrace, provide an indication of juvenile fish egress. Higher egress rates would indicate a lower risk of predation. Operating at a 26.5° BA resulted in lowest passage times indicating improved egress conditions compared to 16.5° BA. The number of beads entrained into the backroll area was significantly less for the 26.5° BA compared to the 16.5° BA. These results are similar to and consistent with results for other turbine model studies indicating improved egress conditions with higher turbine unit flows (i.e., steeper blade angles).

An analysis of the distribution of beads as they pass through the runner was performed for three operating points to determine where fish are most likely to pass through the stay vane/wicket gate cascade and subsequently the runner. Beads were released at multiple locations within each of the three intake bays. The release locations were within a vertical plane below the tip of the submerged traveling screens (STS) and are assumed to represent passage of fish not intercepted by the STSs. Individual beads were imaged using high-speed digital cameras as they passed through the stay vane and wicket gates and as they exited the turbine runner. The STSs cause large scale turbulence and instability of flow as flow enters the turbine distributor. This resulted in a random and broad distribution of beads entering the stay vane cascade. Beads exiting the runner also

exhibited a large radial as well as circular distribution for all three operating points.

The highest percentage of beads passed through the mid-blade region, but significant numbers of beads passed through the hub and tip regions. Both hub passage and tip passage routes likely have a significant contribution to the overall mortality of turbine-passed fish.

If screens are removed, the distribution of beads passing through the turbine would shift. A larger proportion of fish would likely pass in the mid-blade and hub region with fewer fish passing through the tip region. It may therefore be even more beneficial to operate turbine runners at a steeper blade angle when operating without screens, as the gap near the hub becomes smaller with steeper blade angles and the risk of injury to juvenile fish passing near the hub is reduced.

B2 comparison to other USACE projects

A secondary purpose of this study was to compare ERDC B2 model results with other ERDC turbine model study results to determine why juvenile fish passing through the B2 turbines generally have a higher survival rate than fish passing through other turbines within the other Lower Snake and Columbia Rivers Projects.

In comparing the physical attributes of the projects, there are several desirable features of the B2 turbines: large runner diameter, five-bladed runner, low runner speed, shaped stay vane leading edges, flat draft tube invert exit angle, flat draft tube roof exit angle, deep tailrace, and confined tailrace channel.

Bead interaction with the B2 model turbine stay vane and wicket gates was not significantly different than that of other model turbines evaluated. Bead interaction near the B2 runner hub is generally worse than that observed of other models, but in general there is no specific aspect of the B2 turbine runner design that performs marginally better than the other model turbine runners evaluated; these include Bonneville First Powerhouse, John Day, McNary, Ice Harbor, and Lower Granite turbines.

Metrics used for the draft tube evaluations for B2 such as draft tube barrel split, draft tube barrel flow intensities, and uniformity of flow were compared to the five other USACE projects (listed above). The B2 runner

and draft tube configuration did not exhibit an improvement in draft tube flow conditions when compared to the other projects.

Overall egress conditions for B2 appear to be somewhat improved when compared to other projects, and B2 egress performs much better at generator limit.

Key features of the B2 runner that most likely attribute to higher survival include lower flow velocity through the distributor, lower axial flow velocity through the runner, lower tangential velocity of the runner blade (i.e., lower runner speed), and lower velocities through the draft tube. Although the rate of bead strike and bead direction changes may be similar to the other turbines modeled, the turbulence intensity magnitude of force of strike and shear would be less. Based on sensor fish field data collected from the B2, John Day, McNary, and Ice Harbor Turbine runners, B2 generally exhibits a lower pressure rate of change with higher nadir pressures than other turbine units; this would also attribute to higher fish survival (USACE 2013).

Recommendations

Results from this model investigation indicate operations with steeper blade angles, resulting in higher unit discharge, create better passage conditions for fish. Fewer severe contacts with the turbine runner and less severe change in direction occur at steeper blade angles. The draft tube performs better at steeper blade angles, and the quality of flow exiting the draft tube is better at steeper blade angles. In addition, model experiments indicate egress conditions may be better at steeper blade angles.

The flattest blade angle of 16.5° should be avoided during juvenile fish passage season if possible. From this model evaluation, the TOR for fish would be from 20.3° to 26.5° BA with the best operating point being at 26.5°. This is within the current B2 operational range. Additional turbine pressure information developed through computational fluid dynamics (CFD) or possibly additional field tests may be needed to fine tune the TOR.

Turbine passage pressure effects and project operations are important factors for a full determination of TOR for fish passage but could not be directly addressed in this study. To fully refine the TOR, these two factors should be explored and combined with the results of this model study.

1 Introduction

In 1995, the U.S. Army Corps of Engineers (USACE), Portland and Walla Walla Districts of the Northwest Division, implemented the joint district Turbine Survival Program (TSP). The TSP was established to assess the survival of juvenile salmonids passed through the hydro turbines of the Lower Snake and Columbia Rivers and to evaluate the operations and potential modifications to the turbine units for improved fish passage survival (USACE 2004, 2013).

Eight USACE hydropower projects are being studied by TSP. These include Bonneville (first and second powerhouse), The Dalles, John Day and McNary on the lower Columbia River and Ice Harbor, Lower Monumental, Little Goose, and Lower Granite on the Snake River. These studies include biological field studies, hydraulic observational models, performance models, and computational fluid dynamic models. The TSP recommends the best target operating range (TOR) for the turbines based on results and outcomes from these studies.

Project description

Bonneville Dam (Figure 1) is located on the Columbia River at river mile 146.1, approximately 40 miles east of Portland, OR (Figure 2).

Figure 1. Bonneville project.

Figure 2. Project location map.

The dam is a multipurpose project that consists of the first and second powerhouses, the old and new navigation locks, and a spillway with a design capacity of 1.6 million cubic feet per second (ft³/s). Construction of the first powerhouse, the old navigation lock, and the spillway began in 1933. President Franklin D. Roosevelt dedicated the lock and dam on 28 September 1937.

The construction of the first powerhouse was completed in 1943. The first powerhouse has 10 units and a flow capacity of approximately 128,000 ft³/s and a rated power output of 526,700 kilowatts (kW). The original B1 runners were designed and manufactured by S. Morgan Smith. All 10 units at B1 were replaced from 1998 to 2010 by Voith Hydro with minimum gap runners (MGR).

Construction of the second powerhouse began in 1974 and was completed in 1981. The second powerhouse consists of eight units and has a flow capacity of approximately 160,000 ft³/s and a rated power output of 558,200 kW. These units were designed and installed by Allis-Chalmers. The turbine units are five-bladed Kaplans and rotate at 69.2 rotations per minute (rpm).

Turbine unit operations

The prototype turbines on the Lower Columbia River USACE projects are presently operated within 1% of the overall peak efficiency for any head while juvenile salmon are migrating. This is a requirement of National Oceanic and Atmospheric Administration (NOAA) Fisheries Biological Opinion (BiOp) (NOAA 2000, 2004, 2008). This requirement was set in the 2000 BiOp based on research conducted by Bell and Eicher Associates (Bell et al. 1967; Bell 1981, 1986).

Background

Presently, all turbines are required to operate within 1% of peak efficiency at any operating head. Based on direct survival tests conducted at the project and model observations, this may not be the best operating range to minimize the effect of turbines on fish at all projects. Each project should be studied to determine a TOR for minimizing turbine effects on fish and thereby maximizing fish survival. In addition, operating points that should be avoided should be identified as well. There are several things to consider in determining the TOR. Turbine survival is largely dependent on the passage conditions through the powerhouse, overall project operations, and predator abundance downstream of the powerhouse. For turbine passage, direct severe contact with the turbine runner, passing through gaps, passing through high shear zones, and low pressures contribute to direct mortality. Indirect mortality is influenced by the same mechanisms, but in addition, fish experience reduced levels of exposure that result in fish entering the tailrace in a more stressed and disoriented condition. Disoriented and stressed fish in the tailrace may be more susceptible to higher levels of predation as the fish may have greater difficulty in avoiding predators.

A physical model with an operational runner is an excellent tool to investigate the conditions a fish might experience passing through the powerhouse into the tailrace region. This can be conducted in a controlled environment without disruption to project operations or expensive invasive biological evaluations requiring numerous fish. The investigations can be performed throughout the entire operational range of the runner. This includes operational zones outside the current 1% operating range. These investigations are used to give a relative comparison of different operating points, hydraulic conditions, and their potential impact on direct and indirect mortality. Every path that a fish may take through the

intake, wicket gates, turbine runner, draft tube, and the influence of the passage environment on egress can be evaluated.

Objective

The purpose of this study was to thoroughly investigate all potential passage routes through the powerhouse main units to assist in determining the TOR for improving fish passage conditions at the B2. Relative effects of blade contact, shear, stay vane and wicket passage, draft tube conditions, and effects on egress were determined across the entire turbine operational range at 55 ft head. Turbine passage pressure effects and project operations are important factors for a full determination of TOR for fish passage but cannot be directly addressed in this study. A secondary purpose was to compare B2 results with other ERDC turbine study results to assess why B2 appears to have higher survival than other turbine units.

Approach

A physical model was used to fully investigate passage routes through the areas of the powerhouse intake structure where direct fish injury or mortality might occur. This included the stay vane and wicket gate cascade, the turbine runner, and draft tube elbow and draft tube passageway. In addition, the effect of turbine passage on egress conditions in the tailrace was also investigated.

These investigations were conducted throughout the turbine operating range utilizing turbine investigation techniques and methods developed at the U.S. Army Engineer Research and Development Center (ERDC). Analysis of results from these investigations allowed for a recommendation of a TOR based on mechanisms contributing to direct injury as well as indirect injury and mortality occurring downstream of powerhouse related to turbine passage. There are other factors that could affect TOR that have to be considered that cannot be addressed or determined from this model study, such as pressures through the turbine, depth acclimation of migrating smolts, predator loading at the B2 powerhouse, and distribution of smolts entering the powerhouse intake structure.

2 Physical Model

Turbine model description

The Portland District supplied as-built drawings of the B2 structure and screens. Pertinent information needed for model design and construction was taken from these drawings and transferred into a computer-aided design program.

A new 1:25 scale model of a B2 turbine was constructed at ERDC in 2006 and 2007. This model is a geometric replicate of a single powerhouse unit including three intake flow bays, scroll case, stay vane and wicket gate cascade, draft tube, trashracks, screening devices, and vertical barrier screens. The model also replicates approximately 650 ft of approach topography and 325 ft of downstream tailrace topography. The bathymetry upstream and downstream of the prototype powerhouse varies across the powerhouse, so the model topography is an average of expected topographies and is representative of what exists at the prototype. The model was constructed of acrylic to allow visual observations, turbine evaluation for fish, and hydraulic investigations through the entire structure. Photographs of the new model are provided in Figures 3–5.

Figure 3. Overall view of model, looking upstream.

Figure 4. Overall view of model, looking downstream.

Figure 5. View of model structure and motor.

A five-bladed turbine runner was constructed by Voith Siemens in 2007 and delivered to ERDC. The ERDC model was constructed to accommodate this turbine runner. Figure 6 shows the model runner.

Figure 6. Model runner.

The hydraulic design, the operating performance including power, efficiency, cavitation limits, and operating curves were developed using a high-head turbine performance model. Performance models have very limited visual access to the intake structure, turbine runner area, draft tube, and the tailrace area. In addition, the experiments in the performance model are conducted at high heads, normally 50% to 70% of prototype head. This is done to increase the model Reynolds number to allow more accurate head, discharge, and torque measurements. These measurements are required to accurately determine model turbine efficiency. Because of the high-head model test requirements, the performance models are generally constructed of steel, with the exception of an acrylic discharge ring. This steel construction limits the ability to observe and investigate the entire hydraulic passage.

The experiments in the ERDC turbine model were conducted at Froude head (1 to 25). This allows for the entire model to be constructed from acrylic (except for trashracks, fish screens, stay vanes, wicket gates, and runner). Accurate hydraulic investigations can be performed anywhere in the flow field. This includes the forebay, intake structure (approach to turbine), stay vane cascade, turbine environment, draft tube, and downstream of the draft exit. Torque is not measured in ERDC turbine models due to the high friction between the runner shaft and runner seals. Therefore, efficiency cannot be determined from this model. The operational parameters utilized for the ERDC cam curves are developed in

the performance model combined with information obtained from the prototype turbine during field index testing. Cam curves define the runner blade setting and wicket gate setting at a given project head for a desired power or discharge output.

Froude modeling more accurately scales screening devices that are used for fish diversion within the intake structure as well as conditions in the draft tube into the tailrace.

Model calibration

Calibration of the B2 turbine model requires calibration of the water supply system and the turbine runner control system including control of the wicket gate angle, the runner blade angle, and runner speed. Operation and setting of the model blade angle, gate position, and runner speed are most critical. They are the most well-defined and primary operating parameters of the prototype. Because discharge is the least accurate prototype measurement, once the model blade angle, gate position, and runner speed are set, the model discharge can be adjusted as needed to maintain any given project head. An accurate measurement of model discharge can be helpful in assuring that the model turbine runner is operating properly and that the proper prototype cam curves are used in establishing the model test conditions. Cam curves are plots of efficiency versus power or discharge and define the most efficient turbine operating point for a given head for a desired power or discharge output. Discharge information supplied to ERDC for model operation is a calculated value from other measured prototype values such as power and head. Once the model blade angle and wicket gate are set according to the prototype cam curves and the desired project head is reached, the model discharge (which is accurately measured and controlled in the model) should agree with the prototype predicted discharge within 4%. Historically, they normally are within 3% of each other. Prototype turbine discharge is the least accurate operating parameter supplied to ERDC for model operation. Often the prototype calculated discharge does not match the model discharge determined values for the supplied CAM. This results in extended periods of investigations by ERDC and Hydroelectric Design Center (HDC) to determine more accurate prototype target discharges.

Inflow meter calibration

Water is supplied to the model by three pumps. Each pump is capable of supplying 9,375 ft³/s prototype or 3 ft³/s model scale. This provides a total inflow capacity of approximately 28,125 ft³/s (prototype), which exceeds the maximum discharge expected at B2 of 20,000 ft³/s. A Data Industrial flow meter was placed in each inflow supply line to measure the inflow rate. Each flow meter was calibrated in the Coastal and Hydraulics Laboratory Volumetric Calibration Flume before it was installed.

Calibration is accomplished by introducing a desired flow into the calibration flume and recording the amount of time needed to fill a known volume. The flow rate is calculated by dividing the flume volume by the time required to fill the flume. This procedure is repeated, and the two values are averaged. The resulting value becomes the established flow rate. During the above procedure, the flow is measured by a Data Industrial flow meter, and this value is recorded. This procedure is repeated for several different inflows. The established flow rates are then plotted against the corresponding Data Industrial-measured values, and a correction factor is applied to the Data Industrial flow meter to give the correct discharge value. Flow calibration curves for the two flow meters are provided in Plates 1–3.

The final calibration curves allow for setting the desired model discharge with an accuracy of 1.0%. The R-squared values for each calibration curve varied between 0.9998 and 0.9989, which proves a very good fit for the calibration data. Calibrations are checked yearly or before a new testing program begins.

Wicket gate calibration

A regulating ring with graduated marks controls the wicket gate opening. The regulating ring setting-to-wicket gate opening is calibrated by setting the regulating ring to a specified mark and then measuring the channel opening between each pair of wicket gates. The wicket gate channel openings for all channels are averaged and plotted against the regulating ring mark number. This process is repeated incrementally until the full operating range is covered. This information is used to develop a calibration curve for wicket openings vs. regulating mark numbers. This calibration curve is provided in Plate 4.

The final calibration allows for setting the wicket gate opening within 1.1% of the desired opening. The R-squared value for the calibration curve was 0.999, which proves a very good correlation for the calibration data. The sensitivity of the model regulating ring allows for setting the wicket gate opening to within 0.33 inch (in.) prototype or 0.013 in. model scale. The wicket gate angle range for the B2 model is 0° to 57.0°. The accuracy permitted by the regulating ring is $\pm 0.5^\circ$, which is a maximum error of 1.5% over the expected operating range.

Runner speed calibration

The rotational speed of the turbine runner is controlled by a direct current motor/generator. The speed of the model runner was 346 rpm. The speed of the runner is verified by a strobe light to ensure the motor speed output is correct. The strobe light emits a pulse of light at a wide range of frequencies, which encompasses the runner speed, with a precision of 0.1%.

Blade angle calibration

Voith Siemens supplied the model runner. The B2 model runner can vary between BAs of 16.5° and 30°. Changing the displacement rod connected to lever arms within the model hub of each runner sets the blade angle. The method Voith Siemens uses for setting the blade angle in its performance model is based on measurements made on the pressure side of the blade in a calibration cradle. Since the runner would have to be removed to perform this calibration, it is not a usable method for the runners in the ERDC model.

Voith Siemens scribed two marks on the runner hub and runner blade trunnions. The marks corresponded to two known BAs. The rod displacement was measured for each of the BAs. To check calibration of the blades in the ERDC model, the marks on the trunnion and the runner hub are matched, and the rod displacement is measured and compared to the Voith Siemens-calibrated measurements. If the marks match, then the runner blades are still calibrated. They have matched each time they have been checked. Voith Siemens calibrated each runner and supplied ERDC with the curves.

ERDC added additional scribe marks to the hub to allow for calibration points between marks provided by Voith Siemens. The final calibration allows for setting the blade angle to within 0.3% of the desired angle. The

R-squared value for the calibration curve was 0.999, which is a very good fit for the calibration data. The calibration curve used during ERDC model experiments is provided in Plate 5.

Model similitude

Equations of hydraulic similitude, based on the Froudian relations, are used to express mathematical relations between the dimensions and hydraulic quantities of the model and the prototype. General relations for the transfer of model data to prototype equivalents, or vice versa, are presented in Table 1.

Table 1. Equations of hydraulic similitude.

Dimension	Ratio	Model:Prototype Scale Relations
Head	$L_r=L$	1:25
Length	$L_r=L$	1:25
Area	$A_r=L_r^2$	1:625
Velocity	$V_r=L_r^{1/2}$	1:5
Time	$T_r=L_r^{1/2}$	1:5
Discharge	$Q_r=L_r^{2.5}$	1:3125
Runner speed	$N_r=1/L_r^{1/2}$	1:0.2

Even though the ERDC model is operated according to Froude similitude, Reynolds number similitude is also maintained in the ERDC model within the intake structure, turbine environment, and draft tube. The difference between performance models (Reynolds similitude) and ERDC turbine models is that the Reynolds number is higher in the performance model to minimize frictional resistance. This allows for more accurate determination of model efficiency. Since friction resistance is a very small component for turbine passage hydraulics (with the exception of the power produced), operating the ERDC model at lower Reynolds numbers (still fully turbulent flow) has little effect on the accuracy of the modeling.

Model operation procedure

The ERDC B2 turbine model is set up by the following procedure. A desired blade angle and wicket gate angle are set, and the inflow discharge is controlled to a desired value. The water elevation in the flume downstream of the draft tube is controlled by a number of vertical wicket gates operated in parallel. When the desired tailrace water elevation is set, the discharge is

adjusted until the upstream water surface reaches its desired elevation. The discharge, blade angle, headwater elevation, and tailwater elevation will match prototype values. The model discharge is the only variable that does not exactly match the prototype. Note that measurement of discharge through the prototype unit is very difficult. The discharge provided to ERDC for setting the model is a calculated value and thus is not a highly accurate value but is based on both performance model and field-test data. This value has the most uncertainty of any input variable. During the testing of the B2 model, all measured discharges were within 5%, and most were within 3% of predicted prototype discharge. Also, it is not possible to match every variable because of differences in Reynolds number and roughness between the model and the prototype structures. The blade-to-wicket gate relationship is the same for a given head for the ERDC model and prototype turbines. Therefore, the difference in discharge for an on-CAM point should not affect ERDC model results.

This should be true as long as the turbines are operated using a correct CAM.

Operational information such as the blade angle, discharge, and wicket opening for 55 and 60 ft of head was supplied by HDC and is based on prototype index tests and high-head model tests (Figure 7).

Figure 7. B2 operational CAM graph.

3 Model Experiments Approach

Model test conditions and investigations

The model investigations were performed for three operating points. These operating points corresponded to the lower 1%, peak efficiency, and generator limit at 55 ft of head. At 55 ft of head, the upper 1% occurs above generator limit. Operating conditions at 55 ft of head were chosen since it is approximately the average head during the bulk of the fish passage season in spring and early summer. At the time of this study, the units were required to operate within 1% efficiency (off of peak efficiency). STS (20 ft long) were installed for all experiments. For 55 ft of head, the forebay was at 72.5 ft mean sea level fmsl, and tailwater was at 17.5 fmsl (prototype). The operating parameters supplied by HDC for the model tests are provided in Table 2.

Table 2. Operational test points.

Operating Point	Blade Angle (deg)	Wicket Gate Rotation (deg)	Head (ft)	Target Discharge (ft ³ /s)
Lower 1% (L1%)	16.5	33.1	55	11,280
Peak	20.3	39.1	55	14,925
Generator Limit (GenL)	26.5	45.9	55	19,115
Upper 1% (U1%)	27.9	47	55	19,758

All physical hydraulic model investigations were conducted with the 20 ft STS installed. At the time of this study, the STSs are installed during fish passage season. The investigations included bead analysis and draft tube velocity measurements. The model was also qualitatively examined with dye. The bead analysis consisted of analyzing high-speed digital imaging of small, neutrally buoyant plastic beads released into the flow path. The digital video was evaluated to determine the exposure of those beads to high shears zones, the potential for those beads to impact structure, and defining egress metrics downstream of the draft tube exit. LDV measurements were obtained to define the characteristics of flow within the turbine draft tube barrels.

Study areas

The model experiments were divided into four parts or study areas identified by region in Plate 6. Part I was to release beads into each intake bay at the screen slot and to capture their passage path through the stay vane and wicket gate cascade with high-speed video and then document and analyze each bead for surface contact and sudden changes in direction. Part II was to release beads between stay vane pairs to pass beads through the three zones of the runner (near hub, mid-blade, and near blade tip) for each operating point. The beads paths were imaged with high-speed digital cameras to determine the rate at which beads impact structure and/or experience sudden changes in direction. Part III was to assess turbine operation effect on egress by releasing beads into the intake and imaging them as they exited the draft tube. Part IV was to obtain velocities in the draft tube (near its exit) to determine the quality of draft tube flow.

Stay vane cascade evaluation

Beads were released in each of the intake bays at various elevations and lateral locations (Plate 7). Their passage through the stay vane cascade was imaged with three high-speed digital cameras at a frame rate of 500 frames/s. A schematic of the stay vane cascade arrangement is shown in Plate 8. Numerous release locations within each intake bay were required to pass beads through the entire stay vane cascade. Each bead was graded for surface contact, sudden change in direction, and for stay vane-to-wicket gate gap passage (Figure 8). This analysis was performed for three operating points. Stay vane testing was completed before the scope of the ERDC evaluation was changed to include two additional operating points.

Figure 8. Wicket gate to stay-vane gap definition.

Turbine runner evaluation

Beads were released at the stay vanes to evaluate the impact of the runner. Specific release locations were chosen such that groups of beads would pass through three defined runner zones: near the runner hub, the mid-blade region, and near the blade tip. Release tubes were secured to the stay vanes (e.g., near top of the stay vane for hub passage) to ensure consistent release point during bead analysis. Between 450 and 650 beads were released for each of the three runner zones. Beads passing through the runner were imaged using three high-speed cameras at frame rate of 1,000 frames/s. One camera was set to image the leading edge of the blade, a second camera to image the pressure and suction side of the blade profile, and the third camera to image the bottom of the blades. All three cameras were time sequenced to each other to ensure that during analysis each bead could be identified and evaluated from each camera.

The distribution of fish passing through the prototype runner is unknown and most likely varies with differences in seasonal and diel patterns.

Therefore, each passage zone is analyzed independently so that the risk in each passage route can be defined. Then all passage routes are combined

into one data set (at each operating point), and an analysis of all passage routes together is performed.

This treats all areas of the turbine equally as potential passage routes.

Assumptions could be made that for fish that pass under the screens, more fish would pass near mid-blade zones compared to the tip passage zone. This is because fish that pass through the top of the intake would be screened out, and the majority of the remaining fish would pass middle to bottom of the distributor (if they followed flow lines). However, since fish behavior within the intake and the distribution of fish entering the intake are unknown, no passage zones can be excluded from the potential fish passage route. In addition, turbulence that is caused by the STS results in a vertical redistribution of beads (fish) approaching the stay vane cascade.

Egress bead evaluation

Neutrally buoyant beads were released into each turbine intake bay at three lateral positions per intake bay (Plate 8); multiple release locations were used to give a broad distribution of beads and would be representative of fish having a wide vertical and lateral distribution as they pass through the intake structure. The beads were imaged with three cameras (120 frames/s rate) as they exited the draft tube barrels and traveled to a location downstream of the influence of the turbine boil (175 prototype ft). The general flow path and time of passage was documented. Other parameters, such as entrainment within the backroll and exposure to near surface elevations, were also documented.

4 Model Evaluation Techniques

Data acquisition with laser Doppler velocity (LDV) meter

A four-beam, two-color LDV was used to measure draft tube velocities. This system consisted of a 4-watt Argon laser, optics to split and color separate the laser beam according to precise frequencies of light, fiber optics to carry the light to the model, a fiber probe with a 23.6 in. focal length, and signal processors for analyzing the signal from the fiber probe. A computer-controlled traversing system precisely controlled the position of the fiber probe for each velocity measurement. This system measured two components of the flow field within a plane perpendicular to the light beam. The LDV system is a critical non-invasive tool for defining flow distributions, velocity magnitudes and direction, turbulence, and investigations of hydraulic shear.

Velocities were measured at two cross sections in each draft tube barrel. Only the most downstream section is reported. The upstream cross section is used as a quality control for the reported cross section. The calculated discharge between the upstream and downstream sections should agree within 2%. The reported cross section is 12 prototype ft upstream of the draft tube exit. Plate 10 details the measurement locations. This cross section is in the draft tube as physically close to the draft tube exit where a complete cross section of velocities can be obtained. This is so that the effects of the draft tube exit flow characteristics on egress conditions can be determined.

The velocity data were used to document the flow split between the two draft tube barrels as well as provide a barrel turbulence intensity value for each barrel and the uniformity of flow within and exiting each draft tube barrel. They are defined as

$$\text{Draft Tube Turbulence Intensity} = \frac{\text{Average Section Standard Deviation of Velocities}}{\text{Average Section Mean Velocity}} = *100$$

$$\text{Draft Uniformity} = \frac{\text{Standard Deviation of Section Velocities}}{\text{Average Section Mean Velocity}} = *100$$

This information is used to indicate where it would better to operate the turbine to provide better quality of flow within the draft tube. A higher level of turbulence and shear in the draft tube increases the potential for fish to become disoriented and is likely to increase stress levels in the fish. Both of these metrics potentially have a negative effect on indirect survival rates. In addition, the more uniform the flow exiting the draft tube, the more turbulence is reduced and the better the chance the fish will be released into the tailrace with an overall positive downstream movement. In addition, reverse flow (upstream direction) in the draft tube is undesirable and not optimal for the most benign passage experience.

Data acquisition and analysis with neutrally buoyant beads

A high-speed digital camera system was used to image neutrally buoyant beads as they passed through the stay vanes, wicket gate cascade, runner region, and draft tube elbow. This system consists of four monochrome cameras set up to capture images of bead passage at a frame rate of up to 1000 frames/s with a resolution of 1024 pixels. Because of file size, the maximum film duration is limited to 6 s. Each 6 s segment will capture the passage of 25 to 50 beads depending on passage route, visible access, and the analysis to be conducted. The image segments are stored in an audio-video interleaved (AVI) format.

Beads passing through the stay vane, wicket gates, runner, and draft tube elbow were individually evaluated to identify rate and severity of contacts with surfaces in the flow field. A surface contact grading system was established as follows:

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

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

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

After grading each bead, the contact scores and change-in-direction scores were averaged to obtain an overall score. The percentages of severe contacts (those with a score of 1 and 2) and severe direction changes (those with a score of 1 and 2) were also calculated. The grading of the beads was performed manually by the same technician.

In addition to the contact and change-in-direction score, a product score is also calculated for each bead. The product score is obtained by multiplying the contact score by the change-in-direction score. The product score gives an overall grade for comparing different passage routes as well as different turbine operation points. Once the product score has been obtained for each test bead, all the product scores are summed, and the average of the sum is the overall product score for a particular release.

Beads are not fish and do not behave or react to a stimulus in the flow field. However, fish passing through the stay vane cascade entrance would experience velocities that exceed sustained swim speeds of juvenile salmon (Bell 1986). They would have little control to no control when passing into the runner region where velocities are so high that fish would have no choice but to go with the flow. Beads are excellent tools to indicate and predict contact and/or shear impacts fish might experience passing through these areas. Also, beads are excellent tools to compare one turbine operation to another (relative comparison). The beads are approximately cylindrical in shape, which allows bead rotation to be observed. The length of the beads is 4 in. (prototype scale), which is close to the length of a juvenile salmon. Figure 9 show beads used in the analysis.

Figure 9. Beads used for analysis.

Fish mortality for turbine-passed fish is comprised of two parts: direct mortality and indirect mortality. Direct mortality is attributed to several mechanisms.

Direct mortality is mainly the result of fish contact with the turbine runner, passing through gaps in the stay vane cascade, runner blade gap passage, high area of shear, and low-pressure areas within the turbine environment.

Indirect mortality results mainly from predation downstream of the powerhouse. It is directly influenced by passage through the stay vane cascade, runner passage, draft tube conditions, and where and how the fish are introduced into the tailrace area. It is also influenced by predator abundance, environmental conditions, and project operations.

Bead experiments that evaluate stay vane passage, runner passage, draft quality of flow, and egress investigations allow for the comparison of all passage areas across the entire turbine operational zone. It relatively compares severe contacts and severe changes in direction (high shear), which indicates where it should be better to operate the turbine to minimize risk of direct mortality. However, it also indicates where it is better to operate the turbine to reduce potential stress, disorientation of fish, non-lethal impacts, and changes in direction so that the fish are delivered into the tailrace with a better ability to avoid predation. This is not to say that this will eliminate downstream predation, but it should be possible to reduce the downstream predation by operating the turbines as described above. These physical model results should help identify the optimal operation range and hydraulic conditions to minimize the

potential for strike, shear, and downstream predation applicable to both direct and indirect mortality.

Test bead sample size

The initial bead sample size determination was based upon the methods used by Normandeau Associates Inc. (2000) for its direct survival tests.

A report entitled *Characterization of Sampling Precision and Sample Size Requirements for Bead Strike Trials* was prepared for ERDC by Dr. John R. Skalski in 2006 (Skalski 2006). This report is documented in ERDC report “Bonneville First Powerhouse Operating Range Investigations” (Davidson 2017) and details the methods used by ERDC to determine sample sizes for all bead evaluations. This method is similar to the methods used in direct-survival balloon tag studies for determining sample size.

Control releases of beads are not required for ERDC experiments, as all beads released are accounted for. The target precision level is between precision level (ϵ) of $\leq +0.03\%$ and $\leq +0.02\%$, 95% of the time. For the runner evaluation, ERDC uses an expected probability of 12% of encountering a strike or shear event (based on previous bead studies). A precision level of 2.5% would require approximately 650 beads.

For stay vane passage evaluation, an expected event (strike or shear) of 12% was used to determine a bead sample size of 317 beads to obtain ϵ of $\leq +0.03\%$, 95% of the time. The stay vane evaluation requires beads to be released into each of the three intake bays. ERDC targeted releasing 450 beads into each of the intake bays for a total sample size of 1350 beads.

5 Model Experiment Results

Stay vane cascade results

Approximately 450 beads were released into each intake bay at various elevations and lateral locations. They were filmed as they passed through the stay vane and wicket gate region. The high-speed video was then reviewed, and the individual beads analyzed as discussed above. Percentages of beads experiencing a severe contact or severe change direction and the standard error (SE) associated with the data was calculated. Results for beads released into all bays were combined into one data set for each of the three operating test points. These operating points corresponded to the L1%, Peak, and GenL (all at 55 ft head). Results for these experiments are provided in tabular format in Plate 11. These three operating points cover the entire operation range of the turbine at 55 ft head during fish passage season.

Average bead contact score for the three operating points (Plate 12) was highest at GenL (5.78) and was lowest at L1% (5.61) with a score of 5.68 at Peak. Higher scores indicate a better passage condition, with 6.0 being a perfect score. The percentage of beads experiencing a severe contact (1s and 2s) with a surface was 2.3% (SE 0.52) at GenL compared to 2.8% (SE 0.44) at Peak and 3.8 at L1% (SE 0.52) (Plate 13). This indicates fewer severe contacts with the stay vane and wicket gate cascade occur with increasing wicket gate openings.

There was a higher trend in the change-in-direction scores for the three operating points for more open wicket gates (3.69 at L1%, 3.76 at Peak, 3.83 at GenL). The percentage of beads observed to exhibit a severe change-in-direction score of 1 was nearly the same at Peak (1.3%, SE 0.31) and GenL (1.2%, SE 0.30), with a higher percentage at L1% (1.8%, SE 0.36). The percentage of beads observed to have a sudden change-in-direction scores of 1 and 2 was lowest at GenL operating point (6.2%, SE 0.65) compared to stay vane passage at Peak (9.0 %, SE 0.76). The percentage of beads observed to have a change-in-direction of scores of 1 and 2 was significantly highest at L1% (13.1%, SE 0.91). Graphical representations of change-in-direction scores and beads exhibiting a severe change in direction, during stay vane cascade passage, are shown in Plates 14 and 15.

A slightly increasing (although not significant) product score trend occurs with increasing wicket gate opening for stay vane wicket gate passage. The product score is obtained by multiplying the contact score by the change-in-direction score and is an indication of the overall impact of passage through the stay vane and wicket gate cascade (the higher the score the better the passage route). The product scores (Plate 16) varied very little across the evaluated operational range (21.01 to 21.14).

The rate of bead passage through the stay vane and wicket gate gap was also determined for each of the three test conditions identified above. Results are reported as a percentage of the overall number of beads in the data set. The highest gap passage rate occurred at the operating point corresponding to the L1% (6.6%) compared to 2.9% at Peak and was lowest GenL (1.9%). All of the 6.6% gap passage occurring at L1% does not result in poor passage conditions but a significant number pass without significant contact or severe changes in directions. A graphical representation of stay vane-to-wicket gate passage is shown in Plate 17. For minimizing gap passage, it would be better to operate at operating points with larger wicket gate openings.

All results obtained for the stay vane passage investigations indicate that better conditions for fish passage occur at higher or more open wicket gates. The best condition investigated occurred at GenL, and the worst condition occurred at L1%.

Runner results

Beads were released between the stay vanes, and their paths through the runner were imaged with high-speed cameras. Analysis and evaluation of the impacts of bead strike and change in direction were completed per the procedure described previously in this report for each of the three runner regions.

Runner hub region

A total of 650 beads were released at the stay vanes such that they passed near the hub area of the runner for each of the three operating points at 55 ft of head. The distribution of beads exiting the runner for all hub releases is provided in Plates 18–20. Bead evaluation results for the hub region in tabular format are shown in Plate 21.

The bead passage contact scores for passage through the runner hub region were lowest (5.38) for the operating point corresponding to the L1% and nearly the same for Peak and GenL (5.62 and 5.65). The higher the number the better the operating point is for reducing surface contact. Based on ERDC experience, the difference between L1% and the other two operating points is significant. The contact score includes all surface contacts through the runner including minor contacts as well as severe contacts. This shows a trend for fewer overall contacts at higher blade angles. To reduce overall contacts in the hub region, it would be better to operate the turbine at higher BAs. A plot of contact scores across the operating range is provided in Plate 22.

The percentage of beads exhibiting a severe contact (1s and 2s) with a surface in the hub area was lowest at GenL (3.2%, SE 0.69) and then Peak (3.7%, SE 0.74%) and significantly higher at L1% efficiency (6.0%, SE 0.93). To minimize severe contacts in the near hub region, it is best to operate with steeper blade angles and avoid the flattest BA (Plate 23).

The change-in-direction score was lower for operating points corresponding to the L1% compared to the other evaluated operating points (Plate 24). The L1% score was 3.24 compared to 3.40 at Peak and 3.37 at GenL. Higher change-in-direction scores are better than lower scores indicating smoother hydraulics with less potential for shear.

The percentage of beads observed to make a severe change in direction (1s) passing through the hub region was higher at operating point corresponding to the L1% (4.8%, SE 0.84) compared to the two other evaluated operating points at steeper BAs. The percentage of beads exhibiting a severe change-in-direction score was best at the operating point corresponding to the GenL% operating point (2.0%, SE 0.55%) followed by Peak (2.5%, SE 0.61). Plate 25 shows the differences across the evaluated operating points. Operating at steeper BAs would be best to minimize undesirable hydraulic shear zones for juvenile salmon passing through the hub region. Operating at L1% should be avoided to minimize exposure to poor hydraulic conditions fish would encounter in the hub region. Although the distribution of fish entering the turbine is uncertain, a significant number of fish may pass through this region, even with screens in place. A larger percentage of fish would be expected to pass through the hub zone if screens are removed.

The hub bead passage product score for the upper two evaluated operating points was significantly higher (19.52 and 19.68) compared to L1% operating point (18.33). Higher scores are better and indicate better operating points to operate for fish. Plate 26 graphically shows the difference across the evaluated operational points. These product scores indicate that a much better operational zone for fish passing near the hub would be at and above the peak operating point (steeper BAs), and operating at flatter BAs should be avoided.

The number of beads passing through the runner hub to blade gap was recorded for each operating point. Significantly more beads passed through the gap at the operating point corresponding to L1% (5.1%) compared to Peak (2.0%). The gap passage was (0.5%) lowest at GenL. Fish passage through this gap would be subjected to high rates of shear and severe contacts. This indicates that operating at the flat BA of 16.5° should be avoided. Operating at steeper blade angles reduces fish exposure to this gap area. A plot of percentage of beads passing through the gap vs. BA is provided in Plate 27. The TOR for improved hub passage would be from Peak to GenL. Additional tests points between Peak and L1% would have to be conducted to further refine this operational zone.

With screens installed, passage through the hub should be reduced compared to a screened intake, as the fish that pass through the top of intake are screened out.

However, the screens impart a significant amount of turbulence to flow in the intake downstream of the screens resulting in the potential for fish to pass through the hub area.

Runner mid-blade region

Beads were released at the entrance to the stay vane cascade resulting in runner mid-blade region passage. The release was positioned at a mid-stay vane height between the stay vanes and positioned to ensure that there was no bead contact with any stay vanes or wicket gates. The distribution on beads exiting the runner for each operating point is shown in Plates 28–30. Fewer beads were released for the mid-blade evaluation than for the hub or tip regions of the runner. This is because the mid-blade region is expected to be a better passage route than the blade tip or hub region (based on ERDC experience on other runner evaluations) resulting in lower blade surface contact and lower incidences of severe changes in

direction. This allows for releasing fewer beads to obtain the same precision as other passage routes with higher expected runner interactions. An amount of 450 beads was the targeted sample size. This sample size was used for all three operating points. Plate 31 shows the results for the mid-blade region including sample size and precision obtained at each operating point.

The bead passage contact scores for passage through the mid-hub region were lowest (5.79) for operating point corresponding to the L1% nearly the same for Peak and GenL (5.87 and 5.88). The higher the number is, the better the operating point is for reducing surface contact. The contact score includes all surface contacts through the runner including minor contacts as well as severe contacts. These scores indicate a trend for fewer overall contacts at higher BAs. To reduce overall contacts of juvenile salmon in the mid-blade region, it would be better to operate the turbine at higher BAs. A plot of contact scores across the operating range is provided in Plate 32.

Percentage of severe bead contacts (1s and 2s) with the runner in the mid-blade region was highest at the operating points corresponding to the L1% (3.1%, SE 0.82) compared to peak efficiency and Gen (both = 1.1%, SE 0.49). The difference in severe contacts between L1% and the two steeper BAs is significant. These data indicate that it is better to operate at steeper BAs to reduce the potential for fish encountering a severe contact with the runner blade at the mid-blade region. Operation at flatter BAs increases the potential for severe contact with the runner blade in the mid-blade region. Although the distribution of fish passing through the runner is unknown, a significant percentage of fish passing through the runner would be expected to pass through the mid-blade region. This would be expected with or without screens in place. A plot of the percentage of severe contacts vs. blade angle is shown in Plate 33.

Change-in-direction scores for the mid-blade region (Plate 34) were highest at the operating point corresponding to the GenL (3.70) followed by Peak (3.65). The change-in-direction score was lowest at L1% (3.39). These data indicate that operating at steeper blade angles decreases turbulence in the mid-blade region compared to flatter blade angles.

The percentage of beads experiencing a severe change in direction (1s) was significantly higher for L1% operating point (3.1%, SE 0.82%) compared to both Peak (0.7%, SE 3.8) and GenL (0.8%, SE 0.41%). These data indicate

that it is better to operate at steeper BAs to reduce the percentage of beads (fish) experiencing a severe change in direction in the mid-blade region. Operating at flatter blades angles increases the potential for fish to experience a severe change in direction (higher shear) in the mid-blade region. A graphical representation of percentage of beads with severe changes in direction for beads passing through the mid-blade region is provided in Plate 35.

Product scores for the mid-blade region did not differ significantly between Peak and GenL (21.65 compared to 21.95). It was lower for L1% (20.95). A graphical representation of the product scores for beads passing through the mid-blade region is provided in Plate 36.

Runner blade tip region

A total of 650 beads were released at the stay vanes (bottom of stay vanes) such that they passed through the runner blade tip region of the MGR for each of the five operating points at 55 ft of head. The release points were positioned between pairs of stay vanes to ensure that there was no contact with stay vanes or wicket gates and as close to the invert of the stay ring as possible. The distribution on beads exiting the runner for each operating point in the tip region is shown in Plates 37–39. Also, the bead evaluation results for the tip region are shown in Plate 40.

For beads passing through the blade tip region, contact scores were highest for BAs of 20.3° (5.67 at Peak) and the steepest blade angle of 26.5° (5.65 GenL). The lowest contact scores for the tip region occurred at the flattest blade angle of 16.5° (5.53 at L1%). These data indicate that when considering all contacts in the blade tip region, it is better to avoid operating the units at the flat BA of 16.5° and would be better to operate at steeper BAs. A graphical representation of the contact scores for the blade tip passage region is provided in Plate 41.

The percentage of beads observed encountering a severe contact with the blade in the tip region was highest at the flatter BAs of 16.5° (4.3%, SE 0.8%). Passage through this region was better at the two steeper BAs with the percentage of severe contacts varying between 2.6% (Peak - SE 0.63%) and 2.8% (GenL - SE 0.64%). A graphical presentation of the percentage of beads having a severe surface contact through the blade tip region is provided in Plate 42. The bead passage evaluation indicates that steeper BAs provide fewer opportunities for fish to make severe contacts with the

runner blade in the blade tip region. It also indicates that flatter BAs should be avoided to reduce risk of fish injury due to direct contact with the runner blades in this region.

Change-in-direction scores for the tip region (Plate 43) were low but virtually the same for all evaluated blade angles varying between 3.06 and 3.07. Change-in-directions scores include all changes-in-direction scoring, severe, moderate to severe and small changes in directions.

Percentage of beads observed to make a sudden change in direction (1s) decreased when the blade angle was increased (Plate 44). This was true throughout the operational zone investigated. At the flattest BA (16.5°), the percentage of beads encountering a sudden change in direction was 9.2% (SE 1.1), 7.1 % (SE 1.0) at Peak and 6.5% (SE 1.0) at the steepest blade angle (26.5°). This evaluation indicates that to improve fish passage conditions at the tip region, the turbine should be operated at steeper BAs, and the flat BA of 16.5° should be avoided.

Product scores calculated for the tip passage region (Plate 45) were lowest for the 16.5° (17.62) blade angle compared to 17.88 at 20.3° blade angle and 17.75 for the steepest blade angle of 26.5° (GenL). The product scores reflect all contacts and all changes in direction including all minor contacts and minor changes in direction. Based on ERDC experience with other Kaplan runners, product scores of 17 to 18 are not abnormally low for the tip passage region.

The lateral and depth distribution of fish approaching the B2 powerhouse is uncertain. Seasonal and diel changes affect fish distribution as well project operations. In addition, fish redistribution within the intake structure probably occurs as fish react to hydraulic conditions in the intake before entering the runner. Thus, the distribution of fish passing through the runner region is unknown. However, fewer fish would be expected to pass through the blade tip region compared to the hub and mid-blade region. Also, deep eddies along the front face of the powerhouse cause fish to sound or approach the intake at deeper depths. This adds to the uncertainty of fish distribution passing through the intake.

Runner all regions combined

Bead data for hub, mid-blade, and blade tip passage routes were combined into one data set per operating point. Performing a data analysis on all the beads from all three passage routes together provides a good indication of passage conditions through the runner, assuming all passage zones are weighted equally. This allows for comparison of the operating points throughout the potential operation of the B2 runner and will indicate where the turbine should be operated as well as operating points to avoid, minimizing the impacts of the turbine on migrating juvenile salmon. Results for all releases combined are shown in tabular format in Plate 46.

The bead contact score was lowest for 16.5° blade BA (5.57) compared to 20.3° BA (5.72) and 26.5° BA (5.73). This indicates that when considering all severities of bead contacts with the runner, it is better to operate at steeper BAs. A plot of contact score vs. blade angle for all releases combined is shown in Plate 47.

The percentage of severe bead contacts was significantly higher at 16.5° BA (4.5%, SE 0.49) compared to 20.3° BA (2.5%, SE 0.37) and 26.5° BA (2.4%, SE 0.36) (Plate 48).

This indicates that the runner should be operated at steeper BAs to decrease the potential for fish to make a severe contact with the runner blade. An angle of 16.5° BA should be avoided during fish season if possible.

The bead change-in-direction score was lowest at 16.5° BA (3.29). The score was the same for 20.3° and 26.5° BAs (3.38). This indicates a better overall passage condition for steeper BAs (reduced changing in direction) compared to flattest BA. A graphical representation of change-in-direction scores vs. blade for all regions combined is provided in Plate 49.

Percentage of beads experiencing a severe change in direction was highest for the flattest BA (Plate 50). At a 16.5° BA, 5.7% (SE 0.55) beads were observed to experience a higher rate of severe change-in-direction events in the runner region compared to 3.4% (SE 0.43) at 20.3° BA and 3.1% (SE 0.41) at 26.5° BA. This comparison indicates that the runner should be operated at steeper BAs to reduce impacts of shear on fish passing through the runner region. Flatter BA of 16.5° should be avoided.

Product score was lowest at 16.5° (18.97) blade angle product score compared to 20.3° and 26.5° BAs (both 19.74). This indicates a better overall passage conditions at steeper BAs. A plot of the product score for all releases combined is shown in Plate 51.

Runner passage distribution

The front face of B2 is angled at 8.1° (off the vertical). In addition, a berm exists approximately 260 ft upstream of the powerhouse at elevation 30. This causes deep lateral eddies along the upstream face of the powerhouse. Fish approaching the powerhouse become entrained into these lateral eddies and in most cases do not immediately enter the powerhouse units. The fish eventually enter the intakes at deeper depths. B2 powerhouse units also have 20 ft long STSs installed in the intake bulkhead slots. A significant percentage of fish pass unguided into the powerhouse turbines. The screens intercept between 20% and 60% of fish entering the powerhouse units. The interception rate (fish guidance efficiency) varies between night and day, spring and summer, powerhouse loadings, between different units, and from year to year. The screens also impart a great deal of turbulence into the flow that redistributes fish downstream of the screens. Because of effects of the STSs and the upstream flow patterns, the distribution of fish entering the stay vane cascade (and runner) is unknown.

Runner bead distribution experiments were conducted to address or investigate potential distributions of fish entering the stay vane cascade and therefore the runner.

An amount of 100 beads were released at three lateral positions in each of the three bays at three elevations for three operating points. These beads were imaged as they exited the runner, using high-speed digital cameras with a frame rate of 1000 frames/s. The release elevations corresponded to tip of the STS, 5 vertical ft below the tip of the STS and 10 ft lower than this elevation (Plate 52).

Screen tip release

Beads were released at the tip of the STS. From this release location, beads exiting the runner had a large radial as well as circular distribution for all three operating points (Plates 53–55). This highly scattered pattern was somewhat unexpected as the beads were released from nine distinct points but from one consistent elevation. A tabular formatted summary of the

runner bead distribution data for this release elevation is provided in Plate 56. For 26.5° BA, 28.7% of the beads passed within 24 in. of the hub, but only 7.1% of the beads passed within 24 in. of the runner blade tip. Similar results were observed for the two other blade angles. An amount of 30.7% of the beads passed within 24 in. of the hub at 20.3° BA compared to 31.1% at the flat BA of 16.5°. An amount of 6.6% of the beads passed within 24 in. of the tip of the blade for both 20.3° and 16.5° BAs.

The percentage of beads passing within 24 in. of the runner hub was higher than expected considering that the STSs screen approximately 22.4% of the total intake flow (all top of intake flow).

In addition to bead distribution, the number of beads passing through runner gaps was also determined. An amount of 1.6% of the beads passed through the runner hub gap for both the 16.5° and 20.3° BAs. The runner hub gap passage was reduced to 0.3% at the steepest BA (26.5°). No beads were observed to pass through the blade tip gaps.

Note that the distribution of beads passing through runner for each intake bay at this release elevation was different at each operating point. Bay A had a significantly lower percentage of beads passing through the hub region and more passing through the mid-blade region compared to Bays B and C. Plots of runner passage bead distributions from each bay at all three operating points are provided in Plates 57–59.

5 ft below screen tip release

The release location was lowered 5 ft, and the beads exiting the runner (as documented for the screen tip release) had a large radial as well as circular distribution at all three operating points (Plates 60–62). A tabular formatted summary of the runner bead distribution data for this release elevation is provided in Plate 63. Slightly fewer beads passed within 24 in. of the runner hub when compared to the screen tip release (for all three operating points). The hub to blade gap passage varied from 0.3% at 26.5° BA to 2.3% at 20.3° BA. The passage rate was 1.8% at 16.5°. These gap passage results are very similar to what occurred for the screen tip releases. The percentage of beads passing the tip region for the 5 ft lowered releases was low and was also nearly the same rate occurring for the screen tip release (at all three operating points). The highest percentages of beads passed through the mid-blade region. An amount of

63% of the beads passed the mid-blade region at 20.3° BA compared to 65.7 % at 16.5° BA and 66.2% at 26.5° BA.

The runner passage distribution varied between the three intake bays at this release elevation (Plates 64–66). A significantly lower percentage of beads passed within 24 in. of the runner hub for the Bay A releases compared to Bays B and C releases. Bay C releases had the greatest percentage of beads passing near the hub.

15 ft below screen tip release

A wide distribution of beads exiting the runner was documented (both radial and lateral) for the 15 ft below screen tip release points. This can be seen in Plates 67–69. The percentage of beads passing within 24 in. of the hub was significantly reduced compared to the other two release elevations. The percentage of beads passing within 24 in. of the at hub at this release elevation was 8.8% at 26.5°, 10.5% at 16.5° BA, and was lowest at 20.3° BA (6.8 %). But even with these low hub passage rates, between 0.8% and 1.0% of the total beads was observed to pass through the hub-to-runner blade gap. The amount of tip passage significantly increased for this release elevation when compared to the other two higher release elevations. The largest percentage of beads passed through the mid-blade area. At this release elevation, between 54.7% (16.5° BA) and 59.6% (20.3° BA) of the beads passed through the mid-blade region. A tabular formatted summary of the bead distribution data for this release elevation can be seen in Plate 70.

As documented for the two previous release elevations, there was a significant difference in runner passage distributions between the intake bays. More beads passed within 24 in. on the hub and fewer beads passed within 24 in. of the runner tip for Bay A releases compared to releases from Bays B and C (Plates 71–73).

Combining screen tip and 5 ft lowered releases

Runner distribution results for the tip of STS and 5 ft lowered release elevations were combined into one data set at each operating point (Plate 74). Discounting fish behavior, this would predict a runner passage distribution for the majority of unguided fish passing within 5 ft of the screen tip. A high number of beads passed though the hub region. An amount of 30.8% of the beads passed within 24 in. of the runner hub at

20.3° BA compared to 29.2% at 16.5° BA and 27.4 % at 26.5 BA°. The hub passage rates were higher than expected considering the STS intercepts the top 22.4% of the intake flow. Runner-to-hub gap passage rates were lowest at 26.5° BA (0.3%) compared to 20.3° BA (1.9%) and 16.5° BA (1.7%).

Low passage rates through the tip passage region occurred for these releases. The passage rates were lowest at 20.3° BA (6.3%) followed by 16.5° BA (6.8%) and then by 26.5 BA (7.4%).

The highest percentage of beads passed through the mid-blade region for these releases and were similar for all three operating points. The mid-blade passage rate was highest at 26.5° BA (65.2%) and lowest at 20.3° BA (62.5%). These rates are more than double the rates occurring through the hub passage region and therefore would be weighted higher for better fish passage zone.

For this intake passage distribution (within 5 ft of screen tip), the most prominent passage route is the mid-blade region followed by a significant percentage through the hub region. While the tip passage region cannot be totally discounted, it would not contribute much to the mortality rates for turbine passage.

Combining all release elevations

All runner passage distribution data for all three release elevations were combined for each operating point (Plate 74). The percentage of beads passing the hub region was fairly uniform for the three operating points but lower than the previous evaluation with the top two release elevations combined. The hub region passage percentages ranged from 21.2% to 22.9%. The percentage of beads passing through this region is significant.

The percentage of beads passing the tip region increased for each operating point compared to the previous evaluation and ranged from 15.4% (20.3° BA) to 16.4% (26.5° BA). Tip passage is still a lower percentage than the hub region and much lower than mid-blade region but is not insignificant.

The mid-blade region passage rates were much higher compared to hub and tip passage and varied little (62.4% to 60.9%) throughout the evaluated operation range. These passage percentages are a little lower

compared to the previous evaluation with the top two release elevations combined.

Combining all three release elevations into one data set to represent fish distribution passing through the intake is not unreasonable to get a feel for percentages of fish passing different areas of the turbine. From this evaluation, the highest percentage of fish would pass through the mid-blade region, but both hub passage and tip passage will significantly contribute to overall mortality rates for turbine passage. This is because the passage conditions through the hub and tip regions are significantly worse than the mid-blade region. If fish are entering the intake significantly distributed deeper than the 15 ft lowered model release, then the percentage passing the tip area will increase and the percentage passing the hub region will decrease. The distribution would have to be very different to significantly affect the percentage passing the mid-blade region. For assessing different regions for the B2 turbines for fish passage, the mid-blade region should be weighted higher than the hub or tip regions.

If screens are removed, the distributions of beads passing through the turbine would be significantly different. Many more beads (fish) would pass through the hub region when compared to a screened condition. Also, how fish redistribute downstream of the screens due to their behavior may significantly affect turbine passage distributions.

Draft tube exit region

The horizontal velocity components (upstream to downstream) of flow through each draft tube barrel were measured with an LDV system for three operating points at 55 ft. Plots of the velocities obtained at the test cross section for all three operating points are provided in Plates 75–77. The velocity from these cross sections was used to determine the flow split between the two draft tube barrels, determine the uniformity of flow, and determine the draft tube barrel turbulence intensity. Results from the evaluation are provided in tabular form in Plate 78.

The flow split determined from the measured velocities was non-balanced for all the operational points tested but was the most non-balanced at the flattest blade angle. At a 16.5° BA, Barrel C (right barrel looking downstream) carried approximately 18.9% of the flow compared to 81.1% for Barrel A. The percentage of flow in Barrel C increased to 38.4% at 20.3° BA and to 34.5% at a 26.5° BA. Based on other studies conducted by

ERDC on other Kaplan turbines, Barrel A normally carries more flow than Barrel C throughout the operation zone. Normally, the lower the turbine loading is, the more unbalanced the flow will be between the draft tube barrel. But the disparity in flow between the barrels for B2 at 16.5° BA is unusual when compared to other Kaplan turbines that ERDC has investigated. This is an indication that the draft tube does not perform well with the B2 runner design. The 16.5° BA should be avoided, and the turbine should be operated at steeper BAs to improve flow in the draft tube. A graphical presentation of the data is provided in Plate 79.

Barrel A turbulence intensity was highest at L1% (27.6%) and was lowest for GenL (17.2%). These intensity levels values are low, indicating low turbulence levels exiting Barrel A. For Barrel C, the turbulence intensity was significantly higher compared to Barrel A. The turbulence intensity improved with increasing turbine discharge. The turbulence intensity at L1% for Barrel C was 72.4% and 48.7% at GenL. This indicates the unit should be operated at higher turbine loadings to minimize the effects of turbulence near the draft tube exit on fish disorientation and stress. A graphical presentation of the results is provided in Plate 80.

Barrel A draft uniformity varied from 47.5% at L1%, 21.1% at Peak, to 19.2% at GenL. While a value of 47.5% is an indicator of fairly non-uniform exit flow, 19.2% is an indicator of good exit flow uniformity. Barrel C flow was less uniform than Barrel A for all three operating points evaluated. The L1% Barrel C had the worst uniformity of flow (63.9%) compared to GenL (53.5%) and Peak (46.0%). Even though the uniformity of flow was poor near the draft tube exit, very little reverse flow was documented at the downstream measurement section. A graphical presentation of the results is provided in Plate 81. This evaluation shows that to provide the most uniform flow exiting the draft tube, it is best to operate between peak and generator limit. It also indicates that at the L1% operating point, uniformity of flow is very poor, and operating at this BA should be avoided during fish passage season.

Egress evaluation

The draft tube exiting flow is turbulent, unsteady, and changes throughout the operational points of the turbine. All of this is reproduced and can be evaluated with a physical turbine model. This model is the best tool available for evaluating local effects of turbine operations on downstream egress. In the model, the flow downstream of the draft tube is in a confined

flume. This is not representative of conditions at the prototype. However, since B2 has a tailrace that is isolated from the spillway, it is a reasonable approximation for a unit that has the adjacent units running. Additionally, the model bathymetry is representative of the prototype, therefore minor changes in individual unit bathymetry would have minor effects on egress conditions. This model egress evaluation does give a relative comparison of the affect that varying turbine operating points will locally have on fish exiting the draft tube (e.g., potential for backroll entrainment, average depth of tailrace passage, average time it takes to pass the turbine boil). Project operations will affect predator horizontal and vertical distributions as well as overall tailrace conditions. An amount of 810 beads were released into the intake for two operating points at 55 ft head (Plate 9). These operating points were Peak and GenL. The beads were imaged as they exited the draft tube to a point 200 prototype ft downstream of the draft tube exit. Results from the egress evaluation are provided in tabular format in Plate 82.

The percentage of beads entrained into the backroll was very low at GenL (3.7%). The rate of entrainment at L1% was higher (19.4%). Lower backroll entrainment rates are considered to be better. The backroll area has the potential to have higher rates of avian and fish predation. A graphical representation of the backroll entrainment rates is provided in Plate 83.

As beads passed through the tailrace area, the number of beads that were observed to come into contact with the water surface or within 5 ft of the water surface was documented. The percentage of beads coming into contact with the water surface was lowest for GenL (17.8%) and increased to 24.6% at L1%. The trend was the same for the beads passing within 5 ft of the water surface. It was lowest at GenL% (19.5%) and highest at L1% (34.0%). The lower in the water column, the more likely the fish would pass downstream with reduced exposure to avian predation. A graphical representation of the results is provided in Plates 84–85.

The time it took the bead to exit the draft tube and pass 200 ft downstream was recorded for each bead. The average time was the shortest for GenL% (59.7 s) and much longer for L1% (119.3 s). Shorter time would indicate a shorter exposure time to predation in the turbine boil area. A graphical representation of the results is provided in Plate 86.

Overall the egress evaluation provided consistent results. Lower turbine loadings caused a larger percentage of beads to become entrained into the backroll and had more beads coming into contact with water surface (to a distance of 200 ft downstream). Higher turbine loadings had fewer percentages of beads exposed to the top 5 ft of the water surface, and the average bead took much less time to move beyond the turbine boil. Taking all the evaluated metrics into consideration, the steeper BA should provide better egress conditions. Noted, this evaluation is comparative for only a single unit operation and does not take into account effects of multiple unit operations.

6 Model Target Operating Range (TOR) Conclusions and Recommendations

Experiments were conducted to compare entire turbine passage routes that affect direct and indirect fish survival throughout the operating range of the B2. The results will assist in determining the TOR to minimize impacts on juvenile salmon passing through the B2 powerhouse. Operation within the TOR should reduce fish mortality, injury, stress, and fish disorientation, thereby increasing fish survival for fish passing through the B2 turbines. The modeling results are not direct predictors of survival but are a relative comparison of operating points throughout the complete operation zone at 55 ft of head.

Stay vane passage

Experiments for stay vane and wicket passage indicate that when considering surface contact and shear, operating point GenL provided the best passage followed by Peak. Operating at L1% provided the least favorable passage and is dramatically worse than the other two operating points. B2 stay vanes have beveled leading and trailing edges and are fairly well aligned with flow entering the stay vane cascade. This allows for little flow separation at the leading edge, but this beveled leading edge also provides a more pointed edge that may not be the best design for fish. Stay vane-to-wicket gate gap passage decreased with increasing wicket gate angle. This gap passage is considered to be negative and is a potential injury point for juvenile salmon. Stay vane passage optimization is important for minimizing fish injury, disorientation, and stress.

Runner hub region passage

Observed severe blade contact was significantly higher at the flatter BA of 16.5° compared to what was observed at 20.3° and 26.5° BAs. Also, the same trend was observed for the percentage of beads exhibiting a severe change in direction while passing through this region. The flatter blade angle of 16.5° had a significantly higher percentage of beads with sudden changes in direction compared to the other two steeper blade angles. In addition, hub-to-blade gap passage was very high at 16.5° compared to the two steeper blade angles with the least occurring at 26.5°. With screens in place, it is unknown what percentage of the total fish population would be expected to pass through the hub region. This region cannot be discounted

because of the redistribution of beads (or fish) occurring due to turbulence caused by the screens and without knowing how fish behavior would affect fish distribution downstream of the screen. Distribution bead tests indicate that a significant number of beads (fish) could still pass through this region.

Runner mid-blade region passage

Overall mid-blade passage was observed to be the best passage route through the turbine when compared to hub and near blade tip passage. The number of beads observed to have a severe contact event with the blade was low for both 20.3° and 26.5° BAs but was significantly higher at the 16.5° BA.

Beads observed to exhibit severe changes in direction had a similar rate of occurrence as severe contacts. This indicates that the majority of severe change-in-direction events occurred as the result of severe contact. When the moderate change-in-direction events are added to the severe events, the rate of event occurrence is highest at flattest BA.

A significant percentage of the total fish population would be expected to pass through the mid-blade region. This is especially true with screens in place. Based on this bead evaluation, the TOR for the mid-blade region would be from Peak to GenL. Flatter blade angles should be avoided during fish passage season.

Runner tip region passage

The percentage of beads making severe contact with the runner blade was highest at the flattest BA (16.5°) when compared to the two steepest BAs, with the percentage at 20.3° BA and 26.5° BA being approximately the same. Also, the rate of beads observed to exhibit a severe change in direction had a trend of reduction as the blade angle was increased. Fewer fish would be expected to pass through the tip region when compared to the mid-blade passage region. However, some fish would be expected to pass through this region. In addition, the fish distribution approaching the turbine is unknown, so this region cannot be excluded. To provide for the best conditions for fish passage, the unit should be operated at steeper blade angles, and minimum blade angles should be avoided during fish passage season.

All turbine region combined passage

Since the distribution of fish entering the intake and the runner is unknown, data from the three passage routes were combined into one data set. The data indicate a trend of decreasing severe contact with the turbine blade with increasing blade angles. The same trend can be seen in the data when looking at the rates of severe change-in-direction events during turbine passage. Steeper BAs should provide better fish passage conditions compared to flatter BAs. Flatter blade angles should be avoided if possible during fish passage season.

Draft tube exit region

The flow split between the two draft tube barrels was uneven throughout the operational range of the turbine. The largest disparity between the draft tube barrels occurred at 16.5° BA where 81.1% of the flow passed through Barrel A. Even draft tube loading is thought to be desirable for improved egress conditions. Quality of flow (turbulence intensity and draft tube uniformity) within each draft tube barrel was worst at the 16.5° BA and improved at other BAs. This indicates that to achieve better draft exit flow, it is better to operate the turbine at steeper BAs.

Egress region

Egress results and outcomes were consistent for all egress evaluation metrics. Operating at a 26.5° BA resulted in improved egress conditions compared to 16.5° BA. The number of beads entrained into the backroll area was significantly less for the 26.5° BA compared to the 16.5° BA. The other metrics of passage time, distance downstream to achieve minimum depth, and beads within 5 ft of water surface were also better for the steepest BA (26.5°) evaluated.

Overall turbine passage conclusion

While the model data are not a direct predictor of fish mortality, the model data are a good method for defining and comparing hydraulic and passage conditions between turbine operating points. It is clear from the model evaluation that steeper BAs (if operated at peak efficiency for each subject blade angle) provide for better passage conditions for fish. Fewer severe contacts with the turbine runner and less severe change in direction occur at steeper BAs. The quality of flow exiting the draft tube and egress conditions are better at steeper BAs.

In fact, the flat BA of 16.5° should be avoided during juvenile fish passage season, if possible. From this model evaluation, it is recommended to operate the turbine between 20.3° to 26.5° BAs to improve fish passage conditions related to turbulence, shear, and blade contact. This does not constrain the operation of the turbine to BA operating range but only recommends operation of the turbine within these BA when possible and avoidance of operating at the flattest BAs. Note that operating between 20.3° to 26.5° BAs falls within the current 1% operating range constraints.

From the bead distribution evaluation, the highest percentage of fish should pass through the mid-blade region, but both hub passage and tip passage will significantly contribute to overall mortality rates for turbine passage. This is because the passage conditions through the hub and tip regions are significantly worse than the mid-blade region. If fish are entering the intake distributed significantly deeper than the 15 ft lowered modeled release, then the percentage passing the blade tip area will increase and the percentage passing the hub region will decrease. The distribution would have to be very different to significantly affect the percentage passing the mid-blade region. For assessing different regions for the B2 turbines for fish passage, the mid-blade region should be weighted higher than the hub or tip regions.

If screens are removed, the distributions of beads passing through the turbine would be significantly different. Many more beads (fish) would pass through the hub region when compared to a screened condition. Also, how fish redistribute downstream of the screens due to their behavior may significantly affect turbine passage distributions.

Turbine passage pressure effects and project operations are important factors for a full determination of TOR for fish passage but could not be directly addressed in this study. Pressures tend to be lower with increasing turbine discharges. To fully refine the TOR, these two factors should be explored and combined with the results of this model study.

7 Bonneville Second Powerhouse (B2) Comparison to other U.S. Army Corps of Engineers (USACE) Projects

Survival rates of juvenile salmon passing through the B2 turbines appear to be higher compared to other USACE projects on the Snake and Lower Columbia Rivers. One of the goals of this B2 model study is to compare B2 model results to model results obtained for other ERDC USACE turbine models. This is to determine if some part of the B2 turbine design, configuration, or operation may provide for better fish passage conditions compared to other turbines or projects. If a superior B2 metric can be identified, then it may be possible to incorporate this metric or finding at other USACE projects or at least be incorporated during future rehabilitation of USACE turbines.

ERDC has previously conducted observational model turbine studies for five other USACE powerhouses. These powerhouses include McNary, Lower Granite (Units 4–6), John Day, Ice Harbor (Units 1–3) and Bonneville First Powerhouse (B1). The primary purposes of these studies were to assist in determining TOR and support turbine rehabilitation. However, these models have also been used for Kaplan blade studies, stay vane shaping, and support of performance models. All ERDC turbine models are constructed at a 1:25-scale and constructed in the similar manner as B2 described previously in this report.

Prototype operational and geometric comparison

The existing USACE turbines on the Lower Snake and Lower Columbia Rivers were designed primarily for their power output requirements. Fish survival was not a primary design goal or requirement of their design process. During their design process, stay vane and wicket gate arrangements, turbine blade design, draft tube design, and the effect of turbine design on fish egress conditions were not really considered. The partial exception to this is B1 rehab, where the runner was designed to include minimum gap features to the runner, but no considerations were given to other attributes or other important structures such as stay vanes, wicket gates, draft tube, and effects of turbine passage on egress. Also new B1 runner design did not consider turbine pressure effect on fish survival.

At the time of B1 rehabilitation design, only considered pressure as it relates to cavitation was addressed.

There are numerous geometric and operational parameters that can be used to compare the projects. Some are head, turbine discharge, runner configuration, draft tube configuration, tailrace configuration, and runner speed.

The turbine and intake geometry for B2 was overlaid with the five other USACE powerhouses. The centerline of the runner was chosen as the control point for the overlay. These overlays are provided in Plates 87–91. In addition, project metrics for B2 and the other five USACE projects, such as runner speed, runner diameter, number of runner blades, project head tested, are provided in Plate 92. Operational and geometric information for each project was used to calculate tangential blade runner speeds and axial water velocity through the runner. This information can be seen in Plate 93. Detailed project descriptions and discussions of each of these projects can be found in Turbine Survival Program Phase 1 and 2 Reports (USACE 2004, 2013). Results from biological field studies, detailing survival rates through the turbines for each of these projects, is documented in TSP Phase II Main Report (USACE 2013).

Prototype sensors fish pressure tests

The Pacific Northwest National Laboratory performed sensor fish tests at Ice Harbor in 2005, John Day in 2006, and B2 in 2007. A limited number of sensor fish were released through the McNary Turbines in 2002. In addition, sensor fish were used to compare the original B1 turbines with the newly installed turbines in 1999–2000. Sensor fish are released into the flow to document pressure profiles through the turbine at various passage routes. The mean, maximum, and minimum nadir pressures as well as a time history of the pressures experienced from just upstream of the turbine, through the turbine, and through draft tube are recorded.

Compared to other projects, the B2-recorded nadir pressures are fairly high resulting in fairly low pressure related mortality probability (USACE 2013).

B2 and B1 comparisons

B1 and B2 powerhouses are located at the Bonneville project, so they operate at the same heads. The B1 powerhouse has 10 units, and the B2 powerhouse has 8 units. B1 has recently had all its runners replaced with minimum gap runners. The tailwater for these two powerhouses varies significantly throughout the year and has the greatest tailwater variability compared to the other three USACE dams on the Lower Columbia and four USACE projects on the Lower Snake River. B2 discharge ring diameter (331.2 in.) is much larger than the discharge ring at B1 (280 in.) and operates at lower rotational speed (69.2 rpm vs. 75 rpm). However, the tangential speed of the runner at the tip is higher for B2 (99.9 ft/s) compared to B1 (91.5 ft/s) while the tangential speed of the blade at the runner hub to blade interface is nearly the same. Higher tangential speeds will potentially result in more significant fish impacts with the blade leading and trailing edges. The tangential blade speed varies along the length of the blade for all turbines. Both B1 and B2 turbines have five blades.

The velocity through stay vane and wicket gate cascade and runner varies throughout each of the project powerhouse turbine operating ranges (Plate 94). B2 1% discharge operating range varies from 11,280 ft³/s to 19,700 ft³/s at 55 ft head. This is much higher compared to B1 1% operating range of 7,266 ft³/s to 9,800 ft³/s. This results in a significantly higher average axial turbine water velocity at the upper 1% operating point through B2 turbines (39.1 ft/s) compared to B1 (28.3 ft/s). Higher axial velocities do increase the potential for injuring fish with blade contact but do have a positive tradeoff of shortening the exposure time of fish to the blade leading and trailing edges.

B1 draft tubes are unique among the USACE projects in that they have horizontal and vertical splitter piers located in the draft tube. More structure and leading edges result in higher potentials for fish contact. However, the amount of structure within B1 draft tube results in better quality of flow within the draft tube. B2 draft tube elbow is very large compared to B1 (as well as all other projects in this report). The larger elbow allows for lower average velocities but also results in some flow separation in the draft tube elbow that does not occur at other projects. While the flow separations potentially do not injure fish, they may result in increased fish disorientation exiting the draft tube.

The topography in the tailrace downstream of the powerhouse is deeper (at comparable tailrace elevations) for B2 and provides for a significantly larger flow depth. This may allow for better egress conditions when combined with higher turbine discharges. The tailrace channel for both B2 and B1 are isolated from each other and from the spillway and are not directly influenced by spillway flow.

The topography upstream of B2 differs greatly from B1 (as well as the other four subject powerhouses). A shelf left over from the dam construction exists at B2. This shelf results in a significantly shallower approach flow upstream of the powerhouse topography coupled with the blunt shape of the intake entrance causes a deep, two-directional lateral eddy along the front face of the powerhouse. This affects fish distribution and possibly fish depth acclimation entering the powerhouse differently compared to B1 (and the other four subject powerhouses).

Most of the powerhouses on the Lower Snake and Lower Columbia Rivers have diversion screens installed in the intake upstream of the turbines for diverting fish away from the turbines. B2 has 20 ft long STSs installed while B1 had its diversion screens removed because of problems with its bypass system. The diversion screens intercept and bypass a significant percentage of fish passing into the intake structure. In addition, the screens impart a significant amount of turbulence into the flow approaching the turbine. This turbulence affects the distribution of fish downstream of the screens. In other words, the fish would be expected to be more widely distributed due to screen effects. The flow approaching the B1 turbine is unaffected by screens, and the distribution of fish approaching the turbine would be expected to be higher in the intake and therefore pass more near the hub to mid-blade region. Of course, fish distribution in the vicinity of the stay vane cascade is not known for any project, and the effects of behavior of the fish in this region are also unknown. Fish injury and mortality of fish passing through the turbine are passage distribution dependent.

Pressure effects on fish passing through the turbine is an important factor for fish mortality and injury. It would be expected that these two projects would have somewhat different pressure impacts through their operation ranges (compared to each other). This would have to be determined through prototype pressure tests, performance models, and CFD modeling along with fish distribution studies. Acclimation depth of

fish approaching the powerhouse as well as distribution of fish passing through the turbine will influence the injury and mortality rates if turbine pressures are at undesirable levels where the fish are passing through the turbine. Actual fish acclimation depth, as it relates to turbine passage, is essentially an unknown.

B2 and John Day comparison

John Day intake structure is significantly taller than B2 (Plate 88) and is a higher head project. The discharge through the 1% operating range for the two turbines is somewhat similar with the L1% nearly the same and the upper 1% being 1,000 ft³/s greater for John Day (compared at B2 Head 55 ft and John Day at 102 ft). However, since the B2 discharge ring is larger, the average axial velocity for B2 (39.1 ft/s) is significantly lower compared to John Day (48.6 ft/s) at U1%. Also, the rotational speed of John Day (90 rpm) is faster compared to B2 (69.2 rpm). This results in a much higher tangential runner blade tip velocity for the John Day runner (122.4 ft/s vs 99.9 ft/s). The same is true for the tangential speed of the blade at the runner blade to hub junction. The number of runner blades is another positive attribute of the B2 runner. The B2 runner has five blades compared to six for John Day.

Both B2 and John Day have 20 ft submerged traveling screens installed in the intake. The screen affects fish distributions through the intake for unguided fish, but the B2 distributor is higher in the intake compared to the John Day distributor.

The diversion screen potentially affects distribution of unguided fish approaching the stay vane cascade at B2 to a greater extent when compared to John Day. A larger effect of turbulence on distribution of beads entering the stay vane cascade exists for B2 compared to John Day. This was observed during comparable or similar experiments performed for both models.

The invert and roof of the draft tube exit of B2 are significantly flatter compared to John Day. This allows for exiting flow to enter the tailrace in a manner that should reduce fish entrainment into the back roll. The depth of water at the draft tube exits are similar for these two projects. However, the topography downstream of B2 is significantly deeper and potentially allows for fish to have a larger distribution, which may help reduce predation rates in the tailrace. In addition, the tailrace channel for B2 is isolated from the

spillway and therefore is not directly influenced by spillway flow. The powerhouse at John Day is not isolated from the spillway, and therefore flow exiting the powerhouse is affected by spillway flow.

B2 and McNary comparison

McNary is a higher head project with a large, smooth intake roof shape (Plate 89). Flow is straight into the McNary powerhouse compared to the deep lateral eddies at B2. The McNary fish diversions screens are 40 ft long screens compared to the 20 ft length for B2. The McNary screens impart a great deal of turbulence to the flow downstream of the screens and affect the distribution of unguided fish into the turbine. The effect of the 40 ft screens causes much more turbulence in flow approaching the turbine compared to 20 ft screens. However, the 40 ft screens intercept more fish at McNary compared to 20 ft screens at B2. The bottom line is that the different length screens affect distribution of unguided fish to different extents and thus influence the distribution of unguided fish through the turbine to different extents. Also, screens greatly affect flow distributions approaching the turbine and add more turbulent flow into the runner, which affects the way the turbine operates. Longer screens have a greater effect on turbine operations CAM.

The upper 1% operating point discharge for McNary is significantly lower compared to B2. McNary has significantly more operational capacity beyond its upper 1% operational fish limit while B2 does not. The runner speed for McNary is greater (85.7 rpm) compared to B2, and the diameter of the runner for B2 is significantly larger. The tangential speed of the runner tip is lower for B2 (99.9 ft/s) compared to McNary (104.6 ft/s). Additionally, the tangential speed of the blade at the runner blade to hub junction is significantly higher for McNary compared to B2 (50.4 ft/s vs. 39.7 ft/s). The average axial turbine velocity at the upper 1% is a little higher for B2 (39.1 ft/s vs. 37.2 ft/s), but at comparable discharges the axial velocity for the B2 runner would be significantly slower.

The exit draft tube invert exit slope is flatter for B2, and the depth of water at the draft tube exit is significantly deeper for B2. The depth of flow 150 ft downstream of the draft tube exit is significantly deeper at B2. Also, the tailrace channel for B2 is isolated from the spillway flow. The McNary powerhouse tailrace flow is not isolated from the spillway, and tailrace conditions are greatly influenced by spillway flow.

B2 and Ice Harbor comparison

Ice Harbor is the most downstream powerhouse on the Snake River and is a higher head project compared to B2 (Plate 90). The powerhouse is configured with two different diameter Kaplan units. ERDC investigations were performed for Units 1–3. The Ice Harbor runner is a six-blade runner. The Ice Harbor turbine unit intake structure is larger, but Units 1–3 runner diameters (280 in.) are smaller than B2. The speed of the B2 runner is much lower compared to Ice Harbor (69.2 rpm vs. 90 rpm). The result is a higher runner blade tip tangential velocity for Ice Harbor compared to B2 (109.8 ft/s vs. 99.9 ft/s). In addition, the angular velocity of the blade at the hub to blade conjunction is significantly lower for B2 (39.7 ft/s vs. 48.2 ft/s).

The discharge range within the 1% operating zone is larger for B2 (compared at 96 ft head for Ice Harbor and 55 ft at B2). The upper and lower 1% discharges for B2 are significantly higher than Ice Harbor. Even though the discharges are significantly higher at B2, the average water velocity through the runner is slightly lower. This is due to the much larger discharge ring at B2, which results in significantly larger flow area.

The draft tube elbow is much larger at B2 compared to Ice Harbor and the B2. The draft tube exit geometry is much flatter at B2, and the downstream topography is much deeper at B2. Also, depth of water at the draft tube exit is deeper at B2 (B2 tail water elevation 19.5 ft). All of these metrics may provide for better egress conditions for fish to recover and better avoid predators in the tailrace environment. In addition, the tailrace channel at B2 is confined and separated from direct effects of spillway flow. The tailrace channel at Ice Harbor is not physically separate from the spillway, and therefore the powerhouse tailrace flow can be directly affected by flow from the spillway.

The approach topography is different for the two projects and will affect fish distributions entering the intake structure differently. This effect is the same that has been discussed for previous project comparisons. Both projects have 20 ft STSs installed in the intake. The STSs do affect the flow distribution into the stay vane cascade as well as the distribution of unguided fish. Because of the relative relationship of the stay vane cascade to the intake ceiling, this effect would be expected to be greater at B2. Fish distributions entering the stay vane cascade, and thus the runner, are

unknown at these two projects. Survival and injury rates through turbines are dependent on the distribution of fish passing through the runner.

B2 and Lower Granite comparison

The Lower Granite powerhouse is a six-unit powerhouse with one runner design for Units 1–3 and another one for Units 4–6 (two different runner manufacturers). ERDC investigations were conducted for Units 4–6. The Lower Granite Units 4–6 have a narrower operation range compared to B2 (Plate 91) with the upper 1% discharge being greater at B2 (19,700 ft³/s vs. 18,000 ft³/s). Since the discharge ring is significantly larger at B2, the average water velocity through the runner is lower at B2 at comparable discharges. The runner speed at Lower Granite is 90 rpm, which results in a tangential runner blade tip speed of 122.4 ft/s which is significantly greater compared to B2 (99.9 ft/s).

Also, the tangential speed of the runner blade near the hub (at the blade to hub conjunction) is significantly lower for the B2 runner (69.8 ft/s vs. 86.9 ft/s).

The Lower Granite project is a higher head project, and the intake structure is much taller (Plate 91). The approach topography is much different between the two projects. As discussed during the other project comparisons, B2 has a relatively shallow depth of approach flow over an upstream berm. Both B2 and Lower Granite have fairly vertical front faces at the powerhouse entrance. Due to the approach topography and the front face configuration, deep eddies occur and run laterally along the B2 powerhouse face. This affects the acclimation depth and distribution of fish entering the intake. This compares to Lower Granite where flow enters the intake straight (no significant lateral flow). Because of the nearly vertical shape of the face of the intake structure, the Lower Granite intake draws water deep in the water column, which also affects the distribution of fish entering the intake.

The John Day draft tube exit and downstream topography are very similar to Lower Granite. The comparison between the John Day and B2 of the draft tube exit and tailrace configurations is the same as for comparing Lower Granite to B2.

Lower Granite has 40 ft extended submerged bar screen in the intake compared to 20 ft STSs for B2. The 40 ft screens cause a significant

amount of turbulence to be imparted into the flow downstream of the screens. This turbulence and skewed flow distribution would also cause a large distribution of unguided fish entering the stay vane cascade. This effect would be greater than what occurs with 20 ft screens. Also, 40 ft screens have a greater effect on the operational cam of the turbine and a decrease in turbine efficiency compared to 20 ft screens. Screens at different projects and different times of the fish passage season have varying fish interception efficiencies and therefore would affect turbine passage fish distributions differently. It is unknown if screen directly affects fish survival rates through turbines, but bypass screens definitely affect the turbines operational cam as well as the performance of draft tubes. As discussed for each of the project comparisons, fish distributions entering the turbine are unknown.

Overall unknowns

As can be seen from the above comparisons, there are many geometric and operational metrics that can be compared between projects. Some are head, runner speed, runner diameter, number of runner blades, turbine discharge, turbine water velocity, draft tube exit configuration, tailrace geometry, tailrace water depth, intake screens, length of screens, etc. Some would logically seem to be better for fish, some would be trade-offs, and for some, it is just not known what would be better for fish. In addition, other metrics are unknown and are very important for comparing the projects. Some of these are condition of fish entering the turbine (could be different at different projects), turbine pressure characteristics throughout the operating ranges, fish depth acclimation as they enter the turbine, distribution of fish entering the turbine, effects of project operations on egress conditions, and tailrace predator loading throughout the fish passage season.

U.S. Army Engineer Research and Development Center (ERDC) data project comparisons

The first testing of an ERDC turbine model to evaluate turbines was for the McNary project in support of TSP and then in support of the McNary Modernization Program. The turbine model techniques and methods for evaluating turbines were developed in this model between 1997 and 2002. The type of information obtained for the McNary study was mainly to support stay vane and wicket gate passage bead evaluations, runner passage bead evaluations, and draft tube quality of flow experiments. This

information was obtained with 40 ft screens in place. In 2015, it was discovered that the CAM information provided to ERDC for these model evaluations was incorrect. In addition, the bead sample size for the runner evaluations is one-half the size that ERDC currently uses for evaluations. Stay vane, runner, and draft tube evaluations were obtained between 2000 and 2002 and will be used to compare to B2 ERDC model evaluations.

ERDC model evaluations for other projects were conducted between 1998 and 2010. Table 3 lists the available ERDC turbine model evaluations from McNary, Lower Granite Units 4–6, B1, John Day, and Ice Harbor Units 1–3 to be used to compare to evaluations conducted for B2.

Table 3. ERDC turbine models evaluations by project.

Project	Evaluation Performed Time frame	Stay Vane Evaluation	Runner Evaluation	Draft Tube Evaluation	Egress Evaluation
B1	2009-2011	Yes	Yes	Yes	Yes
B2	2015-2016	Yes	Yes	Yes	Yes
McNary	1998-2002	Yes	Yes	Yes	No
John Day	2006-2008	Yes	Yes	Yes	No
Ice Harbor 1-3	2005-2009	Yes	Yes	Yes	Yes
Lower Granite 4-6	1999-2005	Yes	Yes	Yes	No

Stay vane evaluation comparisons

Stay vane and wicket gate ERDC bead evaluations were conducted for the projects listed in Table 3 utilizing the same methods as described previously in this report for the B2 project. For the stay vane and wicket gate comparison of B2 to the other projects, the percentages of beads exhibiting a severe change in direction, experiencing a severe contact with the stay vanes or wicket gates, and gap passage will be used.

A plot of the percentage of beads observed to exhibit a sudden change in direction vs. turbine discharge for B2 and the other projects can be seen in Plate 95. Compared to all other projects and operating points, the B2 GenL has the lowest incidence of beads exhibiting a severe change in direction. At the B2 peak point, the incidence rate is equally low to any other projects operating points. At the B2 L1%, the incidence rate is a little higher than B1 and John Day trend lines but lower than the other projects. Overall, B2 stay vanes cascade causes less shear and thus provides for smoother flow in this region compared to the other projects.

B2 stay vane and wicket severe contacts rates are nearly the same compared to rates for McNary, Ice Harbor, and B1 when compared at similar discharges or the trend of the data. B2 does perform better for severe contacts compared to John Day and Lower Granite through most of their operating ranges. This can be seen by observing Plate 96. However, there does not appear to be anything (when comparing these project stay vane evaluations) that indicates that B2 design is a significantly superior design for reducing severe contact with structure in this region.

The final comparable metric for comparisons in this region is the stay to wicket gap. This gap has previously been described in this report. A plot of the passage rate vs. turbine discharge for all projects (listed in Table 3) is provided in Plate 97. At the B2 L1%, the gap passage rates are significantly higher compared to all other projects, but as mentioned earlier in this report that for B2, at the L1%, all gap passage is not all bad because the gap is very large and does not result in overly poor passage conditions. The gap passage rate at the B2 peak operating point is equal to McNary but significantly greater than the other projects. Finally, at the B2 GenL operating point, the rate is nearly the same as what occurs for the Lower Granite but higher than John Day (when compared at comparable turbine discharges). Compared to the other projects, the B2 stay vane and wicket cascade do not provide for lower rates of gap passage throughout its operating range.

Runner regions evaluation comparisons

A comparison of ERDC B2 evaluated beads (passing through three different regions of the turbine) to ERDC bead evaluations of B1, John Day, McNary, Ice Harbor Units 1–3 and Lower Granite Units 4–6 follows (see Table 3). The three turbine regions are hub region, mid-blade region, and near blade tip region. In addition, all three regions are combined into one data set at each project operating point and then compared between projects. Runner evaluations for the five projects were performed in similar methods to B2 as discussed earlier in this report.

It is a complicated endeavor (not straight forward) to compare ERDC bead runner results from one project to another. As discussed earlier, B2 has the slowest runner rotational speed but largest runner diameter. This results in different average turbine water velocities for comparable discharges; in addition, the tangential velocity of the B2 runner is high compared to other projects. These two factors vary between most of the

other projects as well. ERDC bead evaluations are not a one-to-one predictor of direct fish mortality but are more a relative comparison between operation points of a project or for comparing the design of an existing turbine to a newly designed turbine for that project. For this report, B2 runner evaluations are compared to the other projects at comparable turbine discharges.

The comparison between the projects in the turbine region will consist of comparing the percentage of beads exhibiting a severe direction change and the percentage of beads making a severe contact with some structure in the runner region during turbine passage. This comparison will be made throughout the turbine 1% operating range (and outside for available data).

Runner hub region evaluation comparison

Plot of turbine discharge vs. percentage of beads with a severe change in direction for B2 and the other five projects is provided in Plate 98. At L1%, the B2 hub region has the highest rate of beads exhibiting a severe change in direction compared to the other five projects (at comparable discharge). At the B2 peak, its severe direction performance is in the middle compared to the other five projects while at B2 GenL, it performs somewhat better (at comparable discharges).

When comparing the B2 hub severe contact performance to the other five projects, it can be seen that B2 has the highest severe contact rate at L1% and performs in the middle for its Peak and GenL operating points (Plate 99).

Runner mid-blade region evaluation comparison

When comparing the percentage of beads having a sudden change in direction while passing through the mid-blade region (Plate 100), B2 L1% performs the same as McNary and John Day but worse than B1 and Ice Harbor (at similar turbine discharges). For the B2 Peak operating point, it performs better than McNary and Lower Granite but the same as Ice Harbor and John Day. B2 had significantly fewer beads exhibiting a sudden change in direction at its GenL compared to the other projects (at similar turbine discharges).

A plot of percentage of beads of having made a severe contact with the runner blade (in the mid-blade region) vs. turbine discharge for all ERDC evaluated projects can be seen in Plate 101. B2 had the highest percentage of beads with a severe blade contact at L1% compared to all the other projects. However, at the B2 Peak, it had the lowest rates but nearly the same percentage as John Day and McNary. At the B2 GenL, the rate was slightly lower than John Day and significantly lower than Lower Granite.

Runner near tip region evaluation comparison

A plot of percentage of beads making a severe direction vs. turbine discharge while passing through the runner tip region for B2 and the other projects for all evaluated operating points is provided in Plate 102. The B2 percentage rate was lower than McNary but significantly higher than Ice Harbor, B1, and John Day (at similar turbine discharges). The B2 severe direction change percentage was lowest at its peak operational point compared to the other projects. However, at the B2 GenL, the percentage rate was higher than Lower Granite but lower than John Day (at comparable turbine discharge).

The percentage of beads making a severe contact with some structure in the tip region was nearly the same for B2 GenL compared to John Day and Lower Granite at (at comparable discharge). A plot of percentage of beads making a severe contact with structure in the tip region at all operating points for B2 and the other projects vs. discharge is provided in Plate 103. At the B2 Peak operating point, B2 had the lowest rate of severe surface contact compared to the other projects at comparable discharges. B2 had the second highest severe contact rate at the L1% operating points compared to the other projects at similar turbine discharges.

Runner all region combined evaluation comparison

All the beads (for the three turbine passage regions) at each operating point for each project were combined into data sets with each turbine passage region weighted equally. The percentage of beads making a severe contact with a surface in the runner region and the percentage of beads exhibiting a severe change in direction during their passage through the turbine was calculated as described previously in this report.

Plots of the percentage of beads exhibiting a severe change in direction vs. turbine discharge at each operating point for each project are provided in

Plate 104. B2 had one of the highest percentages of beads with severe bead changes in directions at L1% (at comparable turbine discharges), but at the peak, the percentage rate was lower compared to McNary and Lower Granite and nearly the same as Ice Harbor and John Day. At GenL, B2 had the lowest severe direction change percentage (at comparable turbine discharges).

The B2 L1% operating point severe contact percentage rate was the highest of all projects at comparable discharge rates (Plate 105). However, the percentage of beads making severe contact through the runner region was lower at the B2 Peak and GenL operating points compared to all the other projects (at comparable turbine discharges).

If all runner passage routes are weighted equally and combined, the comparative project runner bead analysis indicates that B2 seems to perform as well or a little better for operating points above the L1% compared to the other projects, but this would not be true of all regions of the turbine. The B2 hub region is probably a worse passage route compared to the other projects and with mid-blade and tip regions being slightly better than most of the other projects. Fish distribution through the turbine will affect the survival rates of turbine-passed fish. From this comparative analysis, B2 bead passage runner performance is not substantially better (or worse) than the other projects. There are not any attributes that could be identified that could be transferred to other projects to improve fish passage conditions. Some of the B2 runner metrics or attributes are negative, such as operating at flattest blade angle and hub gap passage.

Draft tube comparisons

Draft tube LDV measurements were obtained for the projects listed in Table 3. The LDV measurements for each project were taken within each draft tube barrel as close to the draft tube exit as physically possible. The analysis methods performed with the LDV measurements (for each project as listed in Table 3) were the same as defined for the B2 project earlier in this report. The only exception is that the draft uniformity was not calculated for the McNary and Lower Granite Projects.

Plate 106 shows the flow split between each draft tube barrel plotted against turbine discharge for all projects in Table 3. As described earlier in the report, the flow split between the two B2 draft tube barrels is uneven throughout the operating range. This also occurs for all projects except

McNary where the draft tube flow split is nearly even above 12,400 ft³/s. When compared to the other projects, the B2 draft tube barrels flow disparities are nearly the largest throughout its operating ranges (at comparable discharges). More balanced flow between the draft tube barrels is thought to be beneficial for introducing fish into the tailrace. There is no indication from these data that the B2 draft design tube would perform better for providing balanced loading between the draft tube barrels than most of the other projects. Therefore, there is nothing in the B2 runner and draft tube design that would provide for balanced loading between the draft tube barrels.

The method for calculating the uniformity of flow within each draft tube barrel is defined earlier in this report. In addition to B2, the uniformity of flow for each draft tube barrel through its operating range was calculated for the B1, Ice Harbor, and John Day projects. The uniformity of flow for each draft tube barrel was weighted by its barrel flow. The weighted uniformity of flow for the two barrels was then combined into one overall draft tube uniformity of flow metric. This was done at each operating point tested for each of the four projects. The overall draft tube uniformity of flow was plotted against the turbine loading at each operating for the four projects (Plate 107). B2 draft tube uniformity of flow through its operating range is very similar to the other three projects (at comparable discharges) with the exception at the B2 Peak operating where B2 is a little better, but the B2 draft tube uniformity of flow is not better than the other projects at all comparable points.

The method for calculating the draft tube barrel turbulence intensity has been defined previously in this report. The turbulence intensity was calculated for both draft tube barrels at several operating points for each of the projects listed in Table 3. The turbulence intensity calculated for each draft tube barrel for each operating point was weighted for its respective draft tube barrel flow. The two weighted draft tube barrel turbulence intensities were combined into one overall draft tube turbulence intensity value. This was done for each operating point for all projects. The overall draft tube turbulence intensity vs. turbine loading for all projects is provided in Plate 108. In examining this plot, it can be seen that B2 turbulence intensity values are in the middle of the other five projects throughout the B2 operating range (at comparable turbine loadings). B2 runner and draft tube designs do not provide draft tube exit turbulence intensity values that would be desirable to transfer to other projects.

Egress comparisons

Egress evaluations were conducted for the B2, B1, and Ice Harbor Projects. Egress experiments for these three projects were conducted utilizing the methods and techniques outlined previously in this report. The only exception to this is the distance downstream of the draft tube exit used for egress evaluations. An amount of 175 prototype ft was used for B1 compared to 200 ft for B2 and Ice Harbor.

A plot of percentage of beads entrained into the back roll vs. turbine loading evaluated for the three projects can be seen in Plate 109. At B2 L1% discharge level, the number of beads entrained into the backroll was lowest for B1 and highest for Ice Harbor with B2 backroll performance between the two projects. The percentage of beads entrained into the backroll at GenL for B2 was very low (performed well). The egress upper discharge evaluated for B1 and Ice Harbor were substantially lower than B2 GenL, and therefore the B2 GenL performance cannot be directly compared to the B1 and Ice Harbor projects at this operating point.

Beads passage time from the draft tube exit to a point 200 ft downstream of the draft tube exit obtained for the B2 egress evaluation was compared to egress evaluation results for Ice Harbor and B1 projects (Plate 110). Longer passage times indicate potentially more exposure to predation in the tailrace immediately downstream of the draft exit. B2 had significantly longer passage times compared to both B1 and Ice Projects at its L1%. Bead passage time for B2 was low at the B2 GenL.

The minimum depth was recorded for each test bead in the egress evaluation zone at the B2 L1% and GenL operating points. The minimum depths for all beads were averaged for each operating point. The same procedure was performed for operating points for the B1 and Ice Harbor projects. A graphical comparison of the three projects is shown in Plate 111. Deeper average tailrace depths for turbine-passed fish may allow for better avoidance of predators in the tailrace region. Average bead passage depths were slightly higher at the B2 L1% compared to B1 and significantly higher compared to Ice Harbor (at comparable turbine loadings). The B2 GenL operating point turbine loading is significantly higher than the other two projects and therefore cannot be directly compared to other projects, but B2 average minimum bead passage depth was slightly higher (worse) at the B2 GenL compared to the B2 L1% operating point.

In addition to the average minimum depth of beads passing through the evaluation zone, the percentage of beads passing within 5 ft of water surface is also a metric that may be important when comparing the three projects. The graphical comparison of the three projects for this metric is provided in Plate 112. At the Ice Harbor Project, a very significant percentage of beads came within 5 prototype ft of the water surface throughout its operating range. B2 performed much better than Ice Harbor at its L1% operating point but had somewhat higher percentage than B1 (at similar turbine loadings). The B2 GenL operating point turbine loading is significantly higher than the other two projects and therefore cannot be used to compare minimum depth passage metric. The percentage of beads passing within 5 ft of the water surface in the evaluation zone was lower at the B2 GenL operating point compared to the B2 L1% percentage.

Project comparisons conclusions

There are many geometric and operational metrics that can be compared between projects. Some are head, runner speed, runner diameter, number of runner blades, turbine discharge, turbine water velocity, draft tube exit configuration, tailrace geometry, tailrace water depth, intake screens, length of screens, etc. Some would logically seem to be better for fish, some would be trade-offs, and for some it is just not known what would be better for fish. In addition, other metrics are very important for comparing the projects, but project data for these metrics are incomplete (pressure, depth acclimation, fish distribution through the runner, etc.).

In comparing the physical attributes of the projects, there are several desirable features of the B2 Project. Some of these features are large runner diameter, five-bladed runner, low runner speed, shaped stay vane leading edges, flat draft tube invert exit angle, flat draft tube roof exit angle, deep tailrace, and confined tailrace channel.

Overall, the stay vane bead data project evaluation comparisons do not show significant differences in performance between B2 and the other projects throughout its operating range. It did perform a little better for shear at higher turbine loadings, which does indicate a shaped stay vane design should provide for smoother flow through the stay vane cascade.

The runner performance of B2 (comparisons to the other five projects) indicates that B2 comparable performance depends on the region of passage and operating points being compared. The hub area is much

worse for bead passage regarding blade contact for B2. However, overall from the project comparisons, there is not any aspect of the B2 turbine design that performs marginally better than all of the other projects turbine designs. As discussed earlier, the turbines have different rotational speeds, different diameter runners, different turbine water velocities for similar discharges, and varying tangential blade speeds. Thus, it is difficult to make direct comparisons between ERDC bead evaluations of different projects. Different projects have different screening devices, and B2 intake geometry and approach topography are significantly different compared to the other projects, which will affect distribution of fish entering the turbine. The distribution of fish entering the turbine will dictate the level of injury to fish passing through the turbine. For example, if all fish pass through the mid-blade region, then the blade-to-fish interaction should be at its minimum value compared to other turbine region passage.

Comparisons of metrics of draft tube evaluations for B2 such as draft tube barrel split, draft tube barrel flow intensities, and uniformity of flow were compared to the five other USACE projects. B2 draft tube and runner did not provide better draft tube flow attributes compared to the other projects. Therefore, there were not any B2 design features of the runner or draft tube that could be transferred to other USACE projects to improve flow within the draft tube.

Only limited data could be compared from B2 egress evaluations to the other USACE projects. Results for B2 indicate that the egress should be better as discharge is increased. Comparing B2 to two other USACE projects at B2 L1% indicated that B2 provides for average rates of bead entrainment into the backroll, but backroll rates were very low for B2 at GenL. Also, time passage of the beads from the draft tube exit to 200 or 150 ft downstream was highest for B2 at L1% compared to the other two USACE projects but was much lower at the B2 GenL. Other metrics compared indicate the B2 egress performs nearly as well and in some cases better than the other two projects. Overall egress conditions for B2 appear to be somewhat better for B2 compared to the other two projects and performs well at GenL. The better overall performance can probably be attributed to the flat invert and roof of the B2 draft tube at its exit with high discharges and a relatively deep tailrace (at 55 ft head). As pointed out earlier in this report, projects operations will affect tailrace conditions, and the ERDC evaluations cannot address this.

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Bonneville 2nd Powerhouse ERDC Turbine Model Model Inflow Meter 1 Calibration

Bonneville 2nd Powerhouse ERDC Turbine Model Model Inflow Meter 2 Calibration

Bonneville 2nd Powerhouse ERDC Turbine Model Model Inflow Meter 3 Calibration

Bonneville 2nd Powerhouse ERDC Turbine Model Model Wicket Gate Calibration

**Bonneville Second Powerhouse ERDC Turbine Model
Model Minimum Gap Runner Blade Calibration**

**Bonneville Second Powerhouse ERDC Turbine Model
Regions of Study**

Lateral Release Locations

Release Locations Elevations

Bonneville Second Powerhouse ERDC Turbine Model
Stay Vane Bead
Release Locations

**Bonneville 2nd Powerhouse
Stay Vane and Wicket Gate Arrangement
Wicket Gates in Full Open Position**

Bonneville 2nd Powerhouse ERDC Turbine Model
Draft LDV Measurement Locations

Bonneville 2nd Powerhouse
ERDC Turbine Model
Stay Vane Contact Bead Passage Results
55 FT Head

Operation Point	Target Discharge, Cfs	Blade Angle, deg	Wicket Gate Angle, Deg	Contact Score	Contact Stdev	% Severe contact 1's and 2's	Standard error	95% Confidence interval	# of Beads
L1%	11,280	16.5	33.1	5.61	1.03	3.8	0.52	1.01	1371
Peak	14,925	20.3	39.1	5.68	0.92	2.8	0.44	0.86	1409
GenL	19,115	26.5	45.9	5.78	0.79	2.3	0.40	0.79	1372

Bonneville 2nd Powerhouse
ERDC Turbine Model
Stay Vane Contact Bead Passage Results
55 FT Head

Operation Point	Target Discharge, Cfs	Blade Angle, deg	Wicket Gate Angle, Deg	Change Direction Score	Change Direction Stdev	% Severe Change Direction 1's	Standard error	95% Confidence interval	% Change Direction 1's and 2's	Standard error	95% Confidence interval	# of Beads
L1%	11,280	16.5	33.1	3.69	0.74	1.8	0.36	0.71	13.1	0.91	1.78	1371
Peak	14,925	20.3	39.1	3.76	0.65	1.3	0.31	0.60	9.0	0.76	1.50	1409
GenL	19,115	26.5	45.9	3.83	0.56	1.2	0.30	0.59	6.2	0.65	1.28	1372

Bonneville 2nd Powerhouse
ERDC Turbine Model
Stay Vane Passage Bead Product Score Results
55 FT Head

Operation Point	Target Discharge, Cfs	Blade Angle, deg	Wicket Gate Angle, Deg	Product Score	Product Std Dev	Product Variance	Gap Passage, %	# of Beads
L1%	11,280	16.5	33.1	21.38	6.14	37.72	6.6	1371
Peak	14,925	20.3	39.1	21.93	5.46	29.83	2.9	1409
GenL	19,115	26.5	45.9	22.56	4.64	21.56	1.9	1372

**Bonneville 2nd Powerhouse
ERDC Turbine Model
55 ft Head
Stay Passsage Bead Results
Bead Contact Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
55 ft Head
Stay Passage Bead Results
Percent Stay Vane Bead Severe Contact (1's and 2's)**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
55 ft Head
Stay Passage Bead Results
Bead Change in Direction Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
55 ft Head
Stay Passage Bead Results
Percent Stay Vane Bead Severe Direction Change (1's)**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
55 ft Head
Stay Passsage Bead Results
Bead Product Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
55 ft Head
Stay Passage Bead Results
Model Set-up Based on HDC August 8, 2014
CAM Stay Vane to Wicket Gate Gap Passage**

Bonneville 2nd Powerhouse
 ERDC Turbine Model
 HDC August 8, 2014 Cam
 Bead Distribution Exiting Runner
 Near Hub Passage
 16.5 Deg Blade Angle

Bonneville 2nd Powerhouse
ERDC Turbine Model
HDC August 8, 2014 CAM
Bead Distribution Exiting Runner
Near Hub Passage
20.3 Deg Blade Angle

Bonneville 2nd Powerhouse ERDC Turbine Model
HDC August 8, 2014 CAM
Bead Distribution Exiting Runner
Near Hub Passage
Blade Angle = 26.5 Deg

Bonneville 2nd Powherhouse
ERDC Turbine Model
Runner Contact Bead Passage Results
55 ft Head
Hub Region (Top Of Stay Vane Release)

Blade Angle, Deg	Target Discharge, cfs	Contact score	Contact Stdev	% Severe contact 1's and 2's	Standard error	95% Confidence interval	% Contact 1's, 2's and 3's	Standard error %	95% Confidence interval	# of beads
16.5	11280	5.38	1.25	6.0	0.93	1.83	9.8	1.17	2.29	650
20.3	14925	5.62	0.98	3.7	0.74	1.45	5.5	0.90	1.76	650
26.5	19115	5.65	0.92	3.2	0.69	1.36	4.6	0.82	1.61	650

Bonneville 2nd Powherhouse ERDC Turbine Model
ERDC Turbine Model
Runner Change in Direction Bead Passage Results
55 ft Head
Hub Region (Top Of Stay Vane Release)

Blade Angle, Deg	Target Discharge, cfs	Direction change score	Direction Change Stdev	% Severe Direction Change 1's	Standard error	95% Confidence interval	% Severe to Moderate Direction Change 1's and 2's	Standard error %	95% Confidence interval	# of beads
16.5	11280	3.24	0.86	4.8	0.84	1.64	18.5	1.52	2.98	650
20.3	14925	3.40	0.76	2.5	0.61	1.19	12.0	1.27	2.50	650
26.5	19115	3.37	0.74	2.0	0.55	1.08	11.4	1.25	2.44	650

Bonneville 2nd Powherhouse ERDC Turbine Model
ERDC Turbine Model
Runner Bead Product Results
55 ft Head
Hub Region (Top Of Stay Vane Release)

Blade Angle, Deg	Target Discharge, cfs	Procdut Score	Procdut Std Dev	Hub Gap Passage, %	# beads
16.5	11280	18.33	6.77	5.1	650
20.3	14925	19.68	4.56	2.0	650
26.5	19115	19.52	5.60	0.5	650

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Hub Region
Runner Contact Bead Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Hub Region**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Hub Region
Runner Bead Direction Change Bead Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Hub Region
Percent of Runner Beads with Severe Direction Change (1's)**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Hub Region
Bead Product Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Percent Runner Hub Gap Passage**

Bonneville 2nd Powerhouse
ERDC Turbine Model
HDC August 8, 2014 Cam
Bead Distribution Exiting Runner
Mid Blade Passage
Q = 11,280 cfs
16.5 Deg Blade Angle

Bonneville 2nd Powerhouse
ERDC Turbine Model
HDC August 8, 2014 CAM
Bead Distribution Exiting Runner
Mid Blade Passage
20.3 Deg Blade Angle

**Bonneville 2nd Powerhouse
ERDC Turbine Model
HDC August 8, 2014 CAM
Bead Distribution Exiting Runner
Near Blade Tip Passage
20.3 Deg Blade Angle**

Bonneville 2nd Powherhouse
ERDC Turbine Model
Runner Contact Bead Passage Results
55 ft Head
Mid-blade Region (Middle Of Stay Vane Release)

Blade Angle, Deg	Target Discharge, cfs	Contact score	Contact Stdev	% Severe contact 1's and 2's	Standard error	95% Confidence interval	% Contact 1's , 2's and 3's	Standard error %	95% Confidence interval	# of beads
16.5	11280	5.79	0.82	3.1	0.82	1.60	3.6	0.87	1.71	450
20.3	14925	5.87	0.54	1.1	0.49	0.97	1.3	0.54	1.06	450
26.5	19115	5.88	0.57	1.1	0.49	0.97	1.6	0.58	1.14	450

Bonneville 2nd Powherhouse ERDC Turbine Model
ERDC Turbine Model
Runner Change in Direction Bead Passage Results
55 ft Head
Mid-blade Region (Middle Of Stay Vane Release)

Blade Angle, Deg	Target Discharge, cfs	Direction change score	Direction Change Stdev	% Severe Direction Change 1's	Standard error	95% Confidence interval	% Severe to Moderate Direction Change 1's and 2's	Standard error %	95% Confidence interval	# of beads
16.5	11280	3.55	0.69	3.1	0.82	1.60	5.3	1.06	2.08	450
20.3	14925	3.65	0.57	0.7	0.38	0.75	3.6	0.87	1.71	450
26.5	19115	3.70	0.56	0.8	0.41	0.81	1.7	0.61	1.19	450

Bonneville 2nd Powherhouse ERDC Turbine Model
ERDC Turbine Model
Runner Bead Product Results
55 ft Head
Mid-blade Region (Middle Of Stay Vane Release)

Blade Angle, Deg	Target Discharge, cfs	Procdut Score	Procdut Std Dev	# beads
16.5	11280	20.95	4.99	450
20.3	14925	21.65	4.00	450
26.5	19115	21.95	3.98	450

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Mid Blade Region Runner
Contact Bead Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Mid Blade Region**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Mid Blade Region
Runner Bead Direction Change Bead Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Mid Blade Region
Percent of Runner Beads with Severe Direction Change (1's)**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Mid Blade Region
Bead Product Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
HDC August 8, 2014 Cam
Bead Distribution Exiting Runner
Near Blade Tip Passage
16.5 Deg Blade Angle**

Bonneville 2nd Powerhouse
ERDC Turbine Model
HDC August 8, 2014 CAM
Bead Distribution Exiting Runner
Near Blade Tip Passage
20.3 Deg Blade Angle

Bonneville 2nd Powerhouse
ERDC Turbine Model
HDC August 8, 2014 CAM
Bead Distribution Exiting Runner
Near Blade Tip Passage
26.5 Deg Blade Angle

Bonneville 2nd Powherhouse
ERDC Turbine Model
Runner Contact Bead Passage Results 55
55 ft Head
Tip Region (Bottom Of Stay Vane Release)

Blade Angle, Deg	Target Discharge, cfs	Contact score	Contact Stdev	% Severe contact 1's and 2's	Standard error	95% Confidence interval	% Contact 1's , 2's and 3's	Standard error %	95% Confidence interval	# of beads
16.5	11280	5.53	1.05	4.3	0.80	1.56	6.5	0.96	1.89	650
20.3	14925	5.67	0.91	2.6	0.63	1.23	4.3	0.80	1.56	650
26.5	19115	5.65	0.89	2.8	0.64	1.26	4.2	0.78	1.53	650

Bonneville 2nd Powherhouse ERDC Turbine Model
ERDC Turbine Model
Runner Change in Direction Bead Passage Results
55 ft Head
Tip Region (Bottom Of Stay Vane Release)

Blade Angle, Deg	Target Discharge, cfs	Direction change score	Direction Change Stdev	% Severe Direction Change 1's	Standard error	95% Confidence interval	% Severe to Moderate Direction Change 1's and 2's	Standard error %	95% Confidence interval	# of beads
16.5	11280	3.06	0.95	9.2	1.14	2.23	23.2	1.66	3.25	650
20.3	14925	3.07	0.85	7.1	1.01	1.97	18.8	1.53	3.00	650
26.5	19115	3.06	0.85	6.5	0.96	1.89	20.5	1.58	3.10	650

Bonneville 2nd Powherhouse ERDC Turbine Model
ERDC Turbine Model
Runner Bead Product Results
55 ft Head
Tip Region (Bottom Of Stay Vane Release)

Blade Angle, Deg	Target Discharge, cfs	Procdut Score	Procdut Std Dev	# beads
16.5	11280	17.62	6.67	650
20.3	14925	17.88	5.93	650
26.5	19115	17.75	5.91	650

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Blade Tip Region
Runner Contact Bead Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Blade Tip Region
Percent of Runner Beads with Severe Contact (1's and 2's)**

**Bonneville2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Blade Tip Region
Runner Bead Direction Change Bead Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Blade Tip Region
Percent of Runner Beads with Severe Direction Change (1's)**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
Near Blade Tip Region
Bead Product Score**

Bonneville 2nd Powherhouse
ERDC Turbine Model
Runner Contact Bead Passage Results
55 ft Head
All Regions Combined

Blade Angle, Deg	Target Discharge, cfs	Contact score	Contact Stdev	% Severe contact 1's and 2's	Standard error	95% Confidence interval	% Contact 1's , 2's and 3's	Standard error %	95% Confidence interval	# of beads
16.5	11280	5.57	1.04	4.5	0.49	0.97	6.6	0.59	1.17	1750
20.3	14925	5.72	0.81	2.5	0.37	0.73	3.7	0.45	0.89	1750
26.5	19115	5.73	0.79	2.4	0.36	0.71	3.4	0.44	0.85	1750

Bonneville 2nd Powherhouse ERDC Turbine Model
ERDC Turbine Model
Runner Change in Direction Bead Passage Results
55 ft Head
All Regions Combined

Blade Angle, Deg	Target Discharge, cfs	Direction change score	Direction Change Stdev	% Severe Direction Change 1's	Standard error	95% Confidence interval	% Severe to Moderate Direction Change 1's and 2's	Standard error %	95% Confidence interval	# of beads
16.5	11280	3.29	0.83	5.7	0.55	1.09	15.7	0.87	1.70	1750
20.3	14925	3.38	0.73	3.4	0.43	0.85	11.4	0.76	1.49	1750
26.5	19115	3.38	0.72	3.1	0.41	0.81	11.2	0.75	1.48	1750

Bonneville 2nd Powherhouse ERDC Turbine Model
ERDC Turbine Model
Runner Bead Product Results
55 ft Head
All Regions Combined

Blade Angle, Deg	Target Discharge, cfs	Procdut Score	Procdut Std Dev	# beads
16.5	11280	18.97	6.15	1750
20.3	14925	19.74	4.83	1750
26.5	19115	19.74	5.16	1750

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Bead Results
All Regions Combined
Runner Contact Bead Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
All Regions Combined
Percent of Runner Beads with Severe Contact (1's and 2's)**

**Bonneville2nd Powerhouse
ERDC Turbine Model
Runner Results
All Regions Combined
Runner Bead Direction Change Bead Score**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
All Regions Combined
Percent of Runner Beads with Severe Direction Change (1's)**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Runner Results
All Regions Combined**

Percent of Runner Beads with Severe to Moderate Direction Change (1's and 2's)

**Bonneville Second Powerhouse ERDC Turbine Model
Runner Distribution Experiment Release Locations**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Beads Released in all Bays at Screen Tip
Bead Distribution Exiting Runner
26.5 Deg Blade Angle**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Beads Released in all Bays at Screen Tip
Bead Distribution Exiting Runner
20.3 Deg Blade Angle**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Beads Released in all Bays at Screen Tip
Bead Distribution Exiting Runner
16.5 Deg Blade Angle**

Bonneville 2nd Powherhouse ERDC Turbine Model
 Runner Passage Location Results
 55 ft Head
 Position 1 - Tip of STS

	Blade Angle, Deg	Target Discharge, cfs	Average Radial Location	Mean Radial Location	Standard Deviation	Percentage of Gap Passage	Percentage of beads within 18 inches of hub	Percentage of beads within 24 inches of hub	Percentage of beads Passing Mid Blade (24")	Percentage of beads within 18 inches of Tip	Percentage of beads within 24 inches of Tip	# Beads
Bay A	26.5	19,115	9.44	9.52	1.99	0.3	18.0	19.3	72.0	4.7	8.7	300
Bay B	26.5	19,115	8.85	8.83	2.04	0.3	25.0	32.3	60.3	5.0	7.3	300
Bay C	26.5	19,115	8.52	8.83	1.99	0.3	29.7	34.3	60.3	3.0	5.3	300
Combined	26.5	19,115	8.94	9.19	2.03	0.3	24.2	28.7	64.2	4.2	7.1	900
Bay A	20.3	14,925	9.16	9.19	1.85	1.0	17.3	20.7	72.7	5.3	6.7	300
Bay B	20.3	14,925	8.67	8.83	2.01	1.7	27.7	33.3	60.7	4.0	6.0	300
Bay C	20.3	14,925	8.37	8.04	2.07	2.0	33.0	38.0	55.0	3.0	7.0	300
Combined	20.3	14,925	8.73	8.83	2.00	1.6	26.0	30.7	62.8	4.1	6.6	900
Bay A	16.5	11,280	9.31	9.19	1.89	1.0	14.3	19.3	71.7	5.7	9.0	300
Bay B	16.5	11,280	8.79	8.83	1.88	0.7	27.7	35.0	60.3	2.3	4.7	300
Bay C	16.5	11,280	8.47	8.62	2.03	3.0	30.7	39.0	55.0	4.0	6.0	300
Combined	16.5	11,280	8.86	8.83	1.96	1.6	24.2	31.1	62.3	4.0	6.6	900

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Screen Tip Release Points
Blade Angle vs Percent Beads Passing Within 24" of Hub**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Screen Tip Release Points
Blade Angle vs Percent Beads Passing Mid Blade Region**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Screen Tip Release Points
Blade Angle vs Percent Beads Passing Within 24" of Blade Tip**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Beads Released in all Bays 5 ft Below Screen Tip
Bead Distribution Exiting Runner
26.5 Deg Blade Angle**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Beads Released in all Bays 5 ft Below Screen Tip
Bead Distribution Exiting Runner
20.3 Deg Blade Angle**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Beads Released in all Bays 5 ft Below Screen Tip
Bead Distribution Exiting Runner
16.5 Deg Blade Angle**

Bonneville 2nd Powerhouse ERDC Turbine Model
 Runner Passage Location Results
 55 FT Head
 Position 2 - 5 ft Below Tip of STS

Release Bay	Blade Angle, Deg	Target Discharge, cfs	Average Radial Location	Mean Radial Location	Std dev	Percentage of Gap Passage	Percentage of beads within 18 inches of hub	Percentage of beads within 24 inches of hub	Percentage of beads Passing Mid Blade (24")	Percentage of beads within 18 inches of Tip	Percentage of beads within 24 inches of Tip	# Beads
Bay A	26.5	19,115	9.64	9.77	1.89	0.7	12.0	15.0	76.0	5.3	9.0	300
Bay B	26.5	19,115	9.01	9.19	1.91	0.0	23.0	26.7	67.3	2.7	6.0	300
Bay C	26.5	19,115	8.53	8.83	2.05	0.3	30.3	36.7	55.3	3.3	8.0	300
Combined	26.5	19,115	9.06	9.19	2.04	0.3	21.8	26.1	66.2	3.8	7.7	900
Bay A	20.3	14,925	9.53	9.77	1.94	2.3	13.3	17.3	73.0	6.3	9.7	300
Bay B	20.3	14,925	8.80	9.19	1.93	2.0	24.0	32.7	63.3	2.0	4.0	300
Bay C	20.3	14,925	8.09	8.04	1.93	2.7	36.7	42.7	52.7	2.7	4.7	300
Combined	20.3	14,925	8.81	9.19	2.02	2.3	24.7	30.9	63.0	3.7	6.1	900
Bay A	16.5	11,280	9.70	9.77	1.87	1.0	9.3	16.0	71.7	10.3	12.3	300
Bay B	16.5	11,280	9.06	9.19	1.83	1.0	20.3	28.7	67.0	0.7	4.3	300
Bay C	16.5	11,280	8.34	8.27	1.89	3.3	32.7	37.0	58.3	1.7	4.7	300
Combined	16.5	11,280	9.03	9.19	1.94	1.8	20.8	27.2	65.7	4.2	7.1	900

**Bonneville 2nd Powerhouse
ERDC Turbine Model
5 ft Below Screen Tip Release Points
Blade Angle vs Percent Beads Passing Within 24" of Hub**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
5 ft Below Screen Tip Release Points
Blade Angle vs Percent Beads Passing Mid Blade Region**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
5 ft Below Screen Tip Release Points
Blade Angle vs Percent Beads Passing Within 24" of Blade Tip**

Bonneville 2nd Powerhouse
ERDC Turbine Model
Beads Released in all Bays 15 ft Below Screen Tip
Bead Distribution Exiting Runner
26.5 Deg Blade Angle

**Bonneville 2nd Powerhouse
ERDC Turbine Model
Beads Released in all Bays 15 ft Below Screen Tip
Bead Distribution Exiting Runner
20.3 Deg Blade Angle**

Bonneville 2nd Powerhouse ERDC Turbine Model
Beads Released in all Bays 15 ft Below Screen Tip
Bead Distribution Exiting Runner
16.5 Deg Blade Angle

Bonneville 2nd Powerhouse ERDC Turbine Model
 Runner Passage Location Results
 55 ft Head
 Position 3 - Tip of screen minus 15 ft

Release Bay	Blade Angle, Deg	Target Discharge, cfs	Average Radial Location	Mean Radial Location	Standard Deviation	Percentage of Gap Passage	Percentage of beads within 18 inches of hub	Percentage of beads within 24 inches of hub	Percentage of beads passing mid Blade	Percentage of beads within 18 inches of Tip	Percentage of beads within 24 inches of Tip	# Beads
Bay A	26.5	19,115	9.87	10.07	1.86	1.7	16.3	18.7	62.0	15.0	19.3	300
Bay B	26.5	19,115	11.47	11.49	1.54	0.3	2.0	3.0	53.3	29.0	43.7	300
Bay C	26.5	19,115	11.16	11.31	1.62	0.3	4.7	4.7	54.7	19.7	40.7	300
Combined	26.5	19,115	10.83	11.31	1.94	0.8	7.7	8.8	56.7	21.2	34.6	900
Bay A	20.3	14,925	10.19	10.27	1.99	0.0	7.3	9.3	70.0	17.7	20.7	300
Bay B	20.3	14,925	11.43	11.58	1.60	0.7	1.0	2.0	54.3	30.0	43.7	300
Bay C	20.3	14,925	10.71	11.03	2.10	1.7	7.7	9.0	54.3	21.0	36.7	300
Combined	20.3	14,925	10.78	11.03	1.97	0.8	5.3	6.8	59.6	22.9	33.7	900
Bay A	16.5	11,280	10.26	10.48	2.13	1.7	9.7	14.0	61.3	19.3	24.7	300
Bay B	16.5	11,280	11.26	11.49	1.69	0.3	3.0	5.3	53.3	26.7	41.3	300
Bay C	16.5	11,280	10.72	11.31	2.22	1.0	12.0	12.3	49.4	27.3	38.3	300
Combined	16.5	11,280	10.75	11.31	2.07	1.0	8.2	10.5	54.7	24.4	34.8	900

**Bonneville 2nd Powerhouse
ERDC Turbine Model
15 ft Below Screen Tip Release Points
Blade Angle vs Percent Beads Passing Within 24" of Hub**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
15 ft Below Screen Tip Release Points
Blade Angle vs Percent Beads Passing Mid Blade Region**

**Bonneville 2nd Powerhouse
ERDC Turbine Model
15 ft Below Screen Tip Release Points
Blade Angle vs Percent Beads Passing Within 24" of Blade Tip**

Bonneville 2nd Powerhouse ERDC Turbine Model
 Runner Passage Location Results
 55 ft Head
 Average of Top 2 Release Elevations

Release Bay	Blade Angle, Deg	Target Discharge, cfs	Average Radial Location	Mean Radial Location	Standard Deviation	Percentage of Gap Passage	Percentage of beads within 18 inches of hub	Percentage of beads within 24 inches of hub	Percentage of beads passing mid Blade	Percentage of beads within 18 inches of Tip	Percentage of beads within 24 inches of Tip	# Beads
All	26.5	19,115	9.0	9.2	2.04	0.3	23.0	27.4	65.2	4.0	7.4	1800
All	20.3	14,925	8.8	9.0	2.01	1.9	25.3	30.8	62.9	3.9	6.3	1800
All	16.5	11,280	8.9	9.0	1.95	1.7	22.5	29.2	64.0	4.1	6.8	1800

Bonneville 2nd Powerhouse ERDC Turbine Model
 Runner Passage Location Results
 55 ft Head
 Average of Top 3 Release Elevations

Release Bay	Blade Angle, Deg	Target Discharge, cfs	Average Radial Location	Mean Radial Location	Standard Deviation	Percentage of Gap Passage	Percentage of beads within 18 inches of hub	Percentage of beads within 24 inches of hub	Percentage of beads passing mid Blade	Percentage of beads within 18 inches of Tip	Percentage of beads within 24 inches of Tip	# Beads
All	26.5	19,115	9.6	9.9	2.01	0.5	17.9	21.2	62.4	9.7	16.4	2700
All	20.3	14,925	9.4	9.7	2.00	1.6	18.7	22.8	61.8	10.2	15.4	2700
All	16.5	11,280	9.5	9.8	1.99	1.4	17.7	22.9	60.9	10.9	16.1	2700

Draft Tube Barrel A

13.1	13.8	12.8	11.7	10.4	8.4	6.8	5.4	3.5	2.2	0.4	0.9	-0.8	-0.8	-1.3	-0.3
13.6	13.7	13.1	12.5	11.0	9.4	7.6	6.2	4.7	3.7	3.1	1.1	0.4	0.5	-0.6	-1.1
13.5	13.5	13.0	12.3	11.5	10.2	8.5	6.5	5.5	4.3	3.8	3.4	1.3	1.0	0.2	-0.3
13.3	13.8	13.0	12.1	11.3	10.5	9.4	8.0	7.1	6.1	4.7	5.0	3.3	2.5	1.2	0.3
13.8	13.5	12.7	12.2	11.3	10.4	8.5	6.6	7.2	6.8	6.4	5.4	3.5	2.4	2.2	0.3
13.2	13.4	12.9	12.0	11.4	10.5	10.0	8.5	8.8	7.8	6.8	5.8	5.3	3.9	2.5	1.1
13.3	13.4	13.1	12.2	11.3	10.3	10.8	9.8	9.3	9.0	8.0	6.7	5.1	4.4	3.8	1.5
13.2	13.5	13.1	12.4	11.8	11.0	10.7	10.2	9.7	9.3	8.5	7.4	6.7	3.7	4.1	2.3
13.2	13.5	13.2	12.5	11.8	11.3	10.5	10.4	-10.3	9.5	8.9	8.3	6.8	5.1	3.9	2.2
13.4	13.5	13.4	12.9	12.0	11.3	11.1	10.7	-10.3	9.3	8.3	7.2	5.7	4.4	2.5	
13.2	13.3	13.2	12.7	12.2	11.7	11.2	11.0	-10.8	10.1	8.4	7.8	5.5	4.3	2.2	
13.0	13.2	13.4	12.8	12.3	11.8	11.4	11.3	10.8	10.1	8.5	8.7	8.2	5.9	4.8	2.5
12.9	12.9	13.1	12.7	12.3	11.8	11.5	11.2	11.1	10.4	8.8	9.0	7.5	5.1	4.8	3.0
12.8	12.7	12.8	12.8	12.4	12.0	11.8	11.5	11.1	10.3	9.7	9.2	7.3	5.8	4.0	3.0
12.6	12.4	12.4	12.4	12.3	12.1	11.8	11.5	-10.3	9.8	8.8	8.2	6.3	5.6	3.5	2.3
12.4	11.8	11.8	12.3	12.1	12.0	11.4	11.2	10.9	9.7	8.4	7.6	5.3	5.2	3.4	0.2
12.5	11.8	11.3	11.4	11.4	11.3	10.5	9.5	8.3	7.9	7.4	5.6	4.4	4.1	2.1	1.3

Draft Tube Barrel C

2.5	2.4	2.4	2.3	2.7	2.7	2.5	2.4	2.3	2.3	1.9	2.1	1.8	1.3	1.2	1.0
2.2	2.2	2.3	2.1	2.4	2.1	2.0	2.1	1.9	1.8	2.2	1.9	2.0	1.7	1.3	0.9
1.7	2.3	2.1	1.8	1.5	1.3	1.5	1.3	1.4	1.4	1.8	1.7	1.9	1.7	1.5	1.1
1.8	1.8	1.8	1.5	1.2	0.8	0.9	1.1	1.0	1.0	1.3	1.2	1.3	1.6	1.5	1.2
1.7	1.5	1.5	1.2	1.1	0.8	0.8	0.8	0.8	1.1	1.0	1.3	1.6	1.2	1.5	1.1
2.2	1.8	1.4	0.9	1.1	0.5	0.8	0.7	0.4	0.7	1.0	1.3	1.4	1.3	1.5	1.2
2.0	1.8	1.5	1.2	0.8	0.3	0.5	0.3	0.6	0.3	0.8	1.0	1.2	1.4	1.5	1.1
2.0	1.7	1.5	1.2	0.5	0.5	0.5	0.7	0.3	0.7	0.9	1.3	1.2	1.4	1.8	1.4
2.0	1.3	1.6	1.4	0.9	0.8	0.7	0.8	0.9	0.8	0.9	1.1	1.5	1.7	1.5	1.4
2.0	2.1	1.8	1.5	1.3	1.2	0.8	1.0	0.8	1.1	1.4	1.8	1.8	2.4	1.9	1.8
2.5	2.1	2.0	1.7	1.3	1.2	1.2	1.2	1.3	1.5	1.7	2.2	2.3	2.8	2.3	1.8
2.3	2.4	2.2	2.1	1.8	1.4	1.7	1.3	1.8	1.8	2.4	2.6	3.2	3.8	3.5	1.2
2.4	2.1	1.9	2.4	2.1	2.2	1.7	2.0	2.3	2.8	3.4	3.8	4.3	4.9	4.5	4.1
2.0	2.2	2.1	2.3	2.1	2.6	2.6	2.6	3.2	3.6	3.7	4.5	4.8	5.8	5.9	7.0
2.5	2.1	2.4	2.5	2.7	3.1	3.3	3.8	3.8	4.8	5.0	5.8	6.4	6.4	6.4	5.5
2.3	2.9	2.9	3.0	3.2	3.7	4.0	4.4	5.0	5.4	5.3	6.4	7.1	6.9		

Note: Velocities units are prototype ft/sec.

Bonneville 2nd Powerhouse ERDC Turbine Model
Draft Tube Cross Section 11.95 Ft Upstream of Draft Tube Exit
Horizontal Velocity Component (Upstream/Downstream Direction)

55 ft Head
Operating Point = L1%
Q = 11,280 cfs
Blade Angle = 16.5 Deg
Wicket Angle = 33.1 Deg

Draft Tube Barrel A

7.6	8.9	9.2	9.0	8.7	8.5	8.2	8.0	7.8	7.6	7.4	7.3	7.0	6.4	2.8
7.7	9.0	9.8	8.7	8.0	7.9	7.6	7.8	7.7	7.9	8.0	8.1	8.1	7.9	3.9
8.6	9.1	8.4	8.2	7.6	7.7	7.6	7.8	8.8	8.8	8.5	8.8	8.6	8.7	5.4
8.6	8.8	8.2	8.2	7.8	7.7	8.0	8.3	8.8	9.0	9.5	9.4	9.2	9.0	8.6
8.6	8.6	8.1	8.1	7.9	8.2	8.7	9.2	9.6	9.6	8.8	8.6	8.3	8.9	7.8
9.2	8.7	8.1	8.0	8.1	8.5	9.0	9.6	9.9	9.9	9.9	9.8	9.3	8.8	8.2
9.1	8.1	7.8	8.0	8.3	8.7	8.9	9.7	10.0	10.1	10.1	9.9	9.2	8.2	7.0
9.2	8.0	7.8	7.8	8.3	8.8	9.4	9.7	10.6	10.1	9.9	9.7	9.2	7.8	5.8
9.1	7.7	7.3	7.6	8.3	8.8	9.3	9.8	9.9	9.9	9.7	9.4	8.9	7.9	6.2
9.2	7.2	6.3	6.5	7.7	8.7	9.8	10.2	10.3	10.3	9.7	9.2	9.0	7.3	5.8
9.1	6.7	5.8	8.1	7.1	8.9	9.7	10.1	10.3	9.8	9.8	8.7	7.9	7.5	4.8
9.1	6.3	5.4	6.0	7.0	8.5	9.5	10.6	9.6	9.1	8.3	7.7	6.5	5.6	3.6
8.9	6.0	5.4	5.9	7.3	8.5	9.4	9.7	8.8	7.8	7.3	6.2	5.7	4.7	3.8
8.9	6.3	5.5	8.2	7.1	8.5	9.3	9.1	8.3	6.7	5.8	4.7	4.2	3.8	4.2
9.2	7.2	6.4	6.1	7.5	8.5	9.2	8.7	7.5	6.8	6.2	4.2	3.4	2.8	2.5
9.4	8.1	7.3	8.2	7.7	8.3	8.8	8.5	7.3	6.7	5.3	4.7	4.1	3.0	
9.6	9.0	8.1	8.7	7.1	7.5	7.5	8.0	7.7	7.3	6.5	6.4	5.2	4.6	4.5

Draft Tube Barrel C

3.4	3.9	6.0	4.7	5.7	4.8	4.4	2.6	2.5	3.8	4.8	5.5	5.9	6.2	6.4
3.1	4.8	4.7	5.1	5.1	4.2	3.8	2.3	2.6	3.7	4.6	5.5	5.8	6.3	5.8
5.4	4.8	4.3	4.5	4.8	3.2	3.8	1.7	2.4	3.8	4.4	4.8	5.6	6.4	6.7
5.3	4.5	3.5	3.5	3.2	3.0	3.0	2.0	1.9	2.8	3.4	4.1	4.7	5.4	6.7
5.6	5.4	3.5	3.1	2.8	2.8	2.4	2.1	1.8	2.4	3.1	3.9	4.7	5.5	6.7
6.3	4.3	3.0	2.1	2.0	1.6	2.0	2.0	1.8	2.2	2.7	3.5	4.4	4.9	6.7
6.4	4.6	2.8	2.5	1.8	1.7	1.4	1.8	1.3	2.0	2.5	3.3	4.2	5.8	7.2
6.3	4.9	3.0	2.8	1.8	1.2	1.2	1.4	1.4	2.2	2.8	3.8	4.4	5.8	7.8
6.6	4.7	2.8	1.7	0.8	1.3	1.7	1.7	2.4	2.6	3.1	4.2	5.6	6.5	7.9
7.3	5.3	3.1	1.8	1.4	1.5	1.8	2.1	2.5	3.5	4.3	4.8	6.0	7.1	8.3
7.5	5.7	3.3	2.5	2.1	1.9	2.8	3.2	3.1	4.1	5.0	5.6	6.6	7.7	9.0
7.5	6.4	4.2	3.8	3.0	2.7	3.6	4.1	4.3	5.2	5.6	6.8	7.4	8.3	9.5
8.8	7.3	5.2	4.4	4.2	4.1	4.9	4.8	5.8	6.1	6.7	7.5	9.0	8.7	9.3
8.1	7.8	6.6	6.4	5.8	5.9	8.8	8.2	8.6	7.1	7.7	8.1	9.9	9.3	9.0
8.0	7.8	7.1	7.2	7.2	7.2	7.2	7.3	7.5	7.8	8.4	8.8	9.0	9.4	9.8
7.6	7.5	7.5	7.8	7.7	7.8	8.0	7.7	7.8	8.3	8.2	9.0	9.1	9.4	9.8

Note: Velocities units are prototype ft/sec.

Bonneville 2nd Powerhouse ERDC Turbine Model
 Draft Tube Cross Section 11.95 Ft Upstream of Draft Tube Exit
 Horizontal Velocity Component (Upstream/Downstream Direction)

55 ft Head
 Operating Point = Peak
 Q = 14,925 CFS
 Blade Angle = 20.3 Deg
 Wicket Gate Angle = 39.1 Deg

Draft Tube Barrel A

7.8	10.0	11.0	11.8	11.8	11.8	11.4	11.2	11.0	10.8	10.2	8.4	7.2	4.9	4.1
9.0	10.9	11.4	11.7	12.0	12.0	11.7	11.4	11.4	11.2	11.2	11.0	10.6	7.1	4.8
10.1	11.1	11.5	11.7	11.7	11.7	11.5	11.4	11.5	11.6	11.7	11.7	11.8	10.3	7.0
10.6	11.2	11.5	11.7	11.8	11.8	11.8	12.0	12.0	12.2	12.2	12.1	12.1	11.8	9.0
11.0	11.3	11.7	11.8	12.0	12.1	12.2	12.2	12.4	12.4	12.6	12.8	12.7	12.2	10.8
11.2	11.4	11.9	12.0	12.1	12.3	12.3	12.4	12.5	12.9	13.1	13.4	13.3	12.8	11.3
11.5	11.6	12.0	12.1	12.2	12.2	12.1	12.1	12.2	12.6	13.1	13.5	13.7	13.6	12.2
11.7	11.7	11.8	12.0	11.8	11.8	11.8	11.8	11.9	12.6	13.1	13.5	13.8	14.0	12.2
11.9	11.9	11.7	11.6	11.4	11.2	11.2	11.5	12.3	12.9	13.1	13.4	13.9	14.2	12.7
12.1	11.8	11.8	11.5	11.2	10.8	10.8	10.8	11.9	12.4	12.2	12.1	12.3	13.4	13.8
12.3	11.8	11.7	11.3	10.8	10.0	9.7	10.3	11.8	11.8	10.8	10.2	10.6	11.8	13.4
12.5	12.0	11.5	10.8	10.1	9.1	9.1	10.2	11.0	10.7	9.3	8.0	8.0	9.9	12.4
12.5	12.0	11.8	10.4	9.1	8.6	8.9	10.1	10.7	9.7	7.7	6.5	5.6	8.1	10.9
12.5	11.9	11.4	9.6	8.5	8.2	9.1	10.3	10.4	9.0	8.7	5.7	5.5	7.3	9.4
12.6	11.7	10.8	9.0	7.7	6.4	9.6	10.4	9.8	8.3	6.5	5.6	5.8	9.8	10.2
12.3	11.3	10.5	8.8	7.3	6.5	10.0	10.4	9.9	8.1	6.3	5.4	5.8	7.1	8.4
11.8	11.0	10.7	8.9	6.8	6.1	9.6	10.0	9.6	7.8	5.1	4.5	5.1	6.1	7.1

Draft Tube Barrel C

0.2	0.8	0.6	1.3	1.7	3.0	1.8	1.0	1.9	2.8	2.8	3.6	5.3	5.8	5.8
0.4	3.1	3.3	3.3	2.6	2.1	1.8	1.8	1.9	2.4	3.4	4.5	6.1	8.0	6.8
2.0	4.1	3.4	2.9	2.8	2.0	1.8	1.3	1.8	2.1	3.2	4.1	4.6	5.6	6.4
2.7	4.1	4.3	4.2	3.2	2.8	1.3	1.6	1.6	1.7	2.7	3.4	4.3	4.9	5.5
2.4	5.7	5.4	4.3	3.1	2.7	1.9	1.4	1.4	1.7	2.2	2.5	3.8	4.8	6.0
3.0	5.8	6.4	4.8	4.3	2.5	1.8	1.6	0.9	1.8	1.8	2.2	2.9	4.3	6.4
5.2	6.4	6.1	6.1	4.4	2.8	2.2	2.1	1.8	1.3	1.6	1.8	2.3	4.1	6.1
4.6	7.8	7.1	6.2	6.4	3.6	2.7	2.1	2.0	1.4	1.7	2.6	2.6	4.1	5.8
7.3	8.1	7.5	7.0	5.8	4.5	3.5	3.3	2.1	1.8	1.8	2.3	2.3	4.2	5.9
8.1	8.7	8.4	7.5	5.8	5.0	3.8	3.2	2.9	2.6	2.8	3.1	3.8	4.6	6.5
8.8	9.4	8.9	8.0	7.3	6.7	5.0	4.6	4.0	3.6	3.8	4.2	4.8	5.2	7.2
9.3	9.8	8.8	8.3	7.4	6.2	6.7	5.0	5.1	4.5	5.0	5.2	6.7	6.3	7.4
9.8	9.8	9.8	9.0	8.5	8.8	8.8	8.4	6.3	5.6	6.3	6.3	7.3	7.5	8.7
8.8	10.4	10.3	9.4	9.3	7.9	7.5	7.4	7.2	7.1	7.2	7.8	8.3	8.9	10.0
8.5	9.8	10.3	9.8	9.4	9.6	9.2	9.1	8.7	8.7	8.8	9.3	9.6	10.3	11.0
8.8	9.1	9.7	9.8	10.2	9.6	8.7	9.8	9.8	10.3	10.7	10.8	11.2	11.8	11.5
2.7	8.1	8.0	9.3	9.7	10.2	8.8	10.6	10.5	11.0	11.4	11.8	12.1	12.2	12.4

Note: Velocities units are prototype ft/sec.

Bonneville 2nd Powerhouse ERDC Turbine Model
 Draft Tube Cross Section 11.95 Ft Upstream of Draft Tube Exit
 Horizontal Velocity Component (Upstream/Downstream Direction)
 55 ft Head
 Operating Point - Generator Limit
 Q = 19,115 cfs
 Blade Angle = 26.5 Deg
 Wicket Gate Angle = 45.9 Deg

Bonneville 2nd Powerhouse
ERDC Turbine Model
Draft Tube Investigation
Based on LDV Measurements
55 ft Head
Downstream Section Barrel A

Screens	Blade Angle, deg	Discharge, cfs	Average Hor Vel Comp, ft/sec	STD Dev of all Hor Vel Comp, ft/sec	Average of STD of Hor Vel Measurements, ft/sec	STD dev of all Hor vel Measurements/Ave vel, %	Ave STD dev of Hor Vel Measurement/Ave Vel %	Max Hor Measured Velocity, ft/sec	Min Hor Measured Velocity, ft/sec	% Barrel Flow
installed	16.5	11,280	8.6	4.1	2.4	47.5	27.6	13.8	-1.3	81.1
installed	20.3	14,295	7.8	1.6	1.6	21.1	21.1	10.3	2.8	61.6
installed	26.5	19,120	10.8	2.1	1.9	19.2	17.2	14.2	4.1	65.5

Bonneville 2nd Powerhouse
ERDC Turbine Model
Draft Tube Investigation
Based on LDV Measurements
55 ft Head
Downstream Section Barrel C

Screens	Blade Angle, deg	Discharge, cfs	Average Hor Vel Comp, ft/sec	STD Dev of all Hor Vel Comp, ft/sec	Average of STD of Hor vel Measurements, ft/sec	STD dev of all Hor vel Measurements/Ave vel,%	Ave STD dev of Hor Vel Measurement/Ave Vel%	Max Hor Measured Velocity, ft/sec	Min Hor Measured Velocity, ft/sec	% Barrel Flow
installed	16.5	11,280	2.0	1.3	1.5	63.9	72.4	7.1	0.3	18.9
installed	20.3	14,295	5.0	2.3	2.3	46.0	46.3	9.6	0.8	38.4
installed	26.5	19,120	5.8	3.1	2.8	53.5	48.7	12.4	0.2	34.5

**Bonneville 2nd Powerhouse ERDC Turbine Model
Flow Split between Draft tube Barrels
Based on LDV Model Measurements**

Bonneville 2nd Powerhouse ERDC Turbine Model
Measure of Draft tube Uniformity
STD of Hor Vels/Ave Vel
Based on LDV Model Measurements

Bonneville 2nd Powerhouse ERDC Turbine Model
Draft Tube Comparisons
Measure of Draft Tube Turbulence Intensity
Ave STDI/Ave Vel
Based on LDV Model Measurements

Bonneville 2nd Powerhouse ERDC Turbine Model
 Bead Egress Data
 55 ft Head
 Screens installed

Discharge, cfs	Intake Bay Release	Average Travel Time, sec	Average Minimum Depth, ft	Average Distance to Minimum Depth, ft	Percent Beads Passing Near Surface	Percent Beads Passing Between Surface and 5 ft	Percent beads Entrained into Backroll	Number of Beads
11278	All Combined	119.3	19.3	140.1	24.6	34.0	19.4	810
14924	All Combined	N/A	N/A	N/A	N/A	N/A	N/A	N/A
19115	All Combined	59.7	24.3	179.5	17.8	19.5	3.7	810

Bonneville 2nd Powerhouse ERDC Turbine Model

55 ft Head

Egress Evaluation (To 200 ft DS)

Beads Entrained into Back Roll

Bonneville 2nd Powerhouse ERDC Turbine Model
55 ft Head
Egress Evaluation (To 200 ft DS)
Percentage of Beads Passing Near Surface

Bonneville 2nd Powerhouse ERDC Turbine Model
55 ft Head
Egress Evaluation (To 200 ft DS)
Percentage of Beads Passing Within 5 ft of Surface

Bonneville 2nd Powerhouse ERDC Turbine Model
55 ft Head
Egress Evaluation (To 200 ft DS)
Passage Time

**Bonneville 2nd Powerhouse vs Bonneville First Powerhouse
Configuration Overlay (Referenced to Runner Centerlines)**

— Bonn 2nd — Bonn 1st

**Bonneville 2nd Powerhouse vs John Day Powerhouse
Configuration Overlay (Referenced to Runner Centerlines)**

— Bonn 2 — John Day

**Bonneville 2nd Powerhouse vs McNary Powerhouse
Configuration Overlay (Referenced to Runner Centerlines)**

— Bonn 2nd — McNary

Bonnewille 2nd Powerhouse vs Ice Harbor Powerhouse
Configuration Overlay (Referenced to Runner Centerlines)

— Bonn 2nd — Ice Harbor

Bonneville 2nd Powerhouse vs Lower Granite Powerhouse (Units 4-6)
 Configuration Overlay (Referenced to Runner Centerlines)
 Bonn 2nd — Lower Granite —

Project	In Service	Runner Diameter, inches	Prototype Runner Speed, rpm	Number of Runner Blades	Number of Wicket Gates	Number of Stay Vanes	Head Tested	Screen Type	ERDC Model Runner Speed, RPM
B1	1938 (MGR 2010)	280	75	5	20	17	55 and 60	None	375
B2	1982	331.2	69.2	5	24	23	55	20 Ft STS	346
McNary	1957	280	85.7	6	20	19	73	40 Ft ESBS	428.5
John Day	191	312	90	6	23	22	102	20 Ft STS	450
Ice Harbor 1-3	1962	280	90	6	20	19	96	20 Ft STS	450
Lower Granite 4-6	1978	312	90	6	20	19	100 to 105	40 Ft ESBS	450

Positive attributes for B2:

Largest Runner Diameter - more flow area
Least number of blades - 5
Lowest Runner speed
Only runner with cavitations fins
Leading edge of Stay Vane Shaped
Draft Tube Elbow Very Large (Oversized)

Project	Head Tested	Lower 1% Percent	Axial Average Water Velocity, ft/sec	Upper 1 % or Gen Limit Discharge, cfs	Axial Average Water Velocity, ft/sec	Tangential Blade Speed at Blade Tip,ft/sec	Tangential Blade Speed at Blade Tip, miles/hour	Tangential Blade Speed at Mid Blade, ft/sec	Tangential Blade Speed at Mid Blade, miles/hr	Tangential Blade Speed at Hub, ft/sec	Tangential Blade Speed at Hub, miles/hr
B1	55 and 60	7,266	21.0	9,800	28.3	91.5	62.4	65.7	44.8	39.9	27.2
B2	55	11,280	22.4	19,700	39.1	99.9	68.1	69.8	47.6	39.7	27.1
McNary	73	7,699	23.5	12,190	37.2	104.6	71.3	77.5	52.8	50.4	34.4
John Day	102	11,800	27.7	20,700	48.6	122.4	83.4	88.3	60.2	54.2	37.0
Ice Harbor 1-3	96	8,800	25.5	13,352	42.6	109.8	74.9	79.0	53.9	48.2	32.8
Lower Granite 4-6	100 and 105	13,500	31.4	18,000	41.9	122.4	83.4	87.9	59.9	53.3	36.4

Positive attributes for B2:

Second lowest blade tangential speed at mid blade and tip
Lowest blade tangential speed at hub
Low Project head
Broad operating range

USACE Project Average Stay Vane entrance Velocities

Project	Head Tested	Lower 1% Percent	Average Water Velocity at Stay Vane Leading Edge, ft/sec	Upper 1 % or Gen Limit Discharge, cfs	Average Water Velocity at Stay Vane Leading Edge, ft/sec
B1	55 and 60	7,266	5.3	9,800	7.1
B2	55	11,280	8.7	19,700	15.2
McNary	73	7,699	5.6	12,190	8.9
John Day	102	11,800	7.3	20,700	12.8
Ice Harbor 1-3	96	8,800	6.4	13,352	9.8
Lower Granite 4-6	100 and 105	13,500	8.4	18,000	11.2

USACE ERDC Turbine Models Comparison
Stay Vane Bead Results
Comparison of ERDC Tested Projects
Stay Vane % Severe to Moderate Change in Direction

USACE ERDC Turbine Models Comparison
 Stay Vane Bead Results
 Comparison of ERDC Tested Projects
 Stay Vane % Severe Contacts

USACE ERDC Turbine Models Comparison
Stay Vane Bead Results
Comparison of ERDC Tested Projects
Stay Vane % Gap Passage

**USACE ERDC Turbine Models Comparison
Runner Bead Results
Comparison of ERDC Tested Projects
Near Hub Passage % Severe Direction Change**

USACE ERDC Turbine Models Comparison
Runner Bead Results
Comparison of ERDC Tested Projects
Near Hub Passage % Severe Contacts

**USACE ERDC Turbine Models Comparison
Runner Bead Results
Comparison of ERDC Tested Projects
Mid Blade Passage % Severe Direction Change**

USACE ERDC Turbine Models Comparison
Runner Bead Results
Comparison of ERDC Tested Projects
Mid Blade Passage % Severe Contacts

USACE ERDC Turbine Models Comparison
 Runner Bead Results
 Comparison of ERDC Tested Projects
 Blade Tip Passage % Severe Direction Change

USACE ERDC Turbine Models Comparison
Runner Bead Results
Comparison of ERDC Tested Projects
Blade Tip Passage % Severe Contacts

USACE ERDC Turbine Models Comparison
Runner Bead Results
Comparison of ERDC Tested Projects
All Runner Passage % Severe Direction Change

USACE ERDC Turbine Models Comparison
Runner Bead Results
Comparison of ERDC Tested Projects
All Runner Passage % Severe Contacts

**USACE ERDC Turbine Models Comparison
Flow Split between Draft tube Barrels
Based on LDV Model Measurements
B2 Model Set-up Based on HDC August 8, 2014 Cam**

USACE ERDC Turbine Models Comparison
Measure of Draft tube Uniformity
STD of Hor Vels/Ave Vel
Based on LDV Model Measurements
B2 Model Set-up Based on HDC August 8, 2014 Cam
Combining Both Draft Tube Barrels

**USACE ERDC Turbine Models Comparison
Measure of Draft Tube Turbulence Intensity
Ave STDI/Ave Vel
Based on LDV Model Measurements
B2 Model Set-up Based on HDC August 8, 2014 Cam
Combining Both Draft Tube Barrels**

USACE ERDC Turbine Models Egress Metric Comparison
B2 Data Obtained with HDC Aug 8, 2014 Cam
Egress Evaluation (To 200 ft DS)
Beads Entrained into Back Roll

USACE ERDC Turbine Models Egress Metric Comparison
B2 Data Obtained with HDC Aug 8, 2014 Cam
Egress Evaluation (To 200 ft DS)
Passage Time

USACE ERDC Turbine Models Egress Metric Comparison
B2 Data Obtained with HDC Aug 8, 2014 Cam
Egress Evaluation (To 200 ft DS)
Average Minimum Depth

USACE ERDC Turbine Models Egress Metric Comparison
B2 Data Obtained with HDC Aug 8, 2014 Cam
Egress Evaluation (To 200 ft DS)
Percentage of Beads Passing Within 5 ft of Surface

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14. ABSTRACT <p>The Bonneville Second Powerhouse (B2) turbine model investigations were performed in support of the joint U.S Army Corps of Engineers, Portland and Walla Walla Districts, Turbine Survival Program (TSP). The TSP was developed to evaluate juvenile fish passage through turbines, with emphasis on identifying turbine structures and operations responsible for fish injury. The purpose of this B2 turbine model study was to investigate potential risk of injury to juvenile fish passing through all regions of the B2 turbines water passageway, using the existing 1:25 scale physical hydraulic model of the B2 turbines. The model investigations were divided into five study areas. These include the stay vane and wicket gate cascade, the runner, the region immediately below the runner, the exit of each of the two draft tube barrels, and the immediate tailrace region. Results from this model investigation indicate operations with steeper blade angles, resulting in higher unit discharge, create better passage conditions for fish. Fewer severe contacts with the turbine runner and less severe change in direction occur at steeper blade angles. The draft tube performs better at steeper blade angles, and the quality of flow exiting the draft tube is better at steeper blade angles. In addition, model experiments indicate egress conditions may be better at steeper blade angles.</p>						
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