Options for Reducing Total Dissolved Gas at the Long Lake Hydroelectric Facility

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Abstract

The Long Lake Hydroelectric Development (FERC Project 2545) is owned by Avista Utilities and is located 34 miles downstream of Spokane Washington. It consists of a concrete gravity spillway section and a concrete gravity powerhouse dam section arranged at right angles to each other. The project was built during 1910-1915 and the powerhouse contains four 17.9 MW double runner horizontal Francis units with a combined hydraulic capacity of 6800 cfs. Eight spillway bays have a capacity of 115,000 cfs in total. The center bays (Bays 3-6) discharge into a deep plunge pool, while Bays 1 and 2 fall onto a high bedrock shelf on the right bank and Bays 7 and 8 discharge directly into a narrow gap between the left bank spillway toe and a large bedrock outcrop downstream.

The deeply plunging spillway flow carries entrained air deep into the water column, where it is held for sufficient time for the atmospheric gases (primarily nitrogen) to absorb into the water under pressure, well above the ambient saturation levels. These absorbed gases can cause Gas Bubble Trauma (GBT) in fish inhabiting downstream reaches, and the entrained gases can persist for many miles downstream of the spillway. Total Dissolved Gas (TDG) values at Long Lake Dam can reach 140% at moderate to high spill discharges. A new FERC license in 2009 and Washington State 401 water quality certification require reduction in TDG values at the project. Avista Utilities has partnered with Northwest Hydraulic Consultants to conduct preliminary computational fluid dynamics (CFD) analyses and subsequent physical hydraulic scale modeling of several structural alternatives to reduce TDG. The following paper will summarize the findings of these studies.

Introduction & Project Description

As a part of Avista Utilities' (Avista) relicensing effort, water quality studies were conducted for the Spokane River Project (FERC 10/2545), and the new license requires water quality monitoring and attainment plans. One component of the water quality studies completed during the relicensing process included a Total Dissolved Gas (TDG) evaluation at the Long Lake Hydroelectric Development (HED). Due to the physical characteristics of Long Lake Dam spillway and the potential for high TDG levels, a TDG Water Quality Attainment Plan (WQAP) is required to fulfill the terms of the FERC license issued in 2009.

The Long Lake Hydroelectric Development (Long Lake HED) forms part of the Spokane River Project (FERC 10/2545) and is located at river mile 34, approximately 5 miles upstream of Little

Falls Hydroelectric Project (Little Falls HED). Long Lake dam and associated features were designed and constructed between 1910 and 1915 and include an L-shaped concrete gravity dam with a gated spillway section and a non-overflow powerhouse intake section, a horizontal curving non-overflow gravity arch dam, referred to as the ‘cut-off’ dam (Figure 1). The ogee shaped spillway crest is 353 ft long and set at El. 1508 ft. There are eight spillway bays, numbered sequentially from bay 1 at the east (right) end of the spillway to bay 8 at the west (left) end of the spillway (adjacent to the powerhouse intakes). Each spillway bay is controlled by a 29 ft high by 25 ft wide vertical lift gate.

Spill bays 3 through 6 discharge into a deep plunge pool downstream of the spillway, while the spillway apron below bays 1 and 2 is elevated above the rest of the spillway apron and discharges onto a large rock outcrop roughly 20 feet above the typical tailwater surface. Spill bays 7 and 8 also discharge onto a rock outcrop on the west side of the spillway, but the apron is not elevated, and it simply terminates below bay 8 several feet above the tailwater where it meets existing rock. The hydraulic capacity of each spillway bay is approximately 14,000 cfs at the normal pool elevation of 1536.0 ft with gates wide open. Maximum spillway capacity with all 8 bays open and a reservoir elevation of 1537.0 is about 120,000 cfs. The tailwater level below the dam varies with flow, ranging between El. 1361.0 ft and El. 1378.0 ft. Approximately 300 ft downstream from the spillway plunge pool, flow from the spillway passes through two sharp bends before meeting with powerhouse flows in the downstream river channel. The cut-off dam is located in a saddle along the left bank of the reservoir, approximately 600 ft upstream of the intake dam. The crest of the cut-off dam is at El. 1537.0 ft, and the total crest length is approximately 247 ft with a constant radius of 170 ft.

The non-overflow powerhouse intake section has a length of 148 ft as measured along the face of the headgate section. There is an additional 100 ft of crest length that connects the intake dam to the spillway and to the west abutment through a nearly 90 degree corner. The intake to the powerhouse is comprised of four steel penstocks that penetrate through the intake dam at El. 1499.0 ft. Vertical slide gates, 18 ft square, are located on the upstream face of the dam at the inlet to the penstocks. The penstocks extend along the downstream face of the dam and an exposed rock surface to the powerhouse, which contains four 17.9 MW double-runner horizontal Francis turbines and has a hydraulic capacity of 6,800 cfs.

Figure 1 Aerial view of Long Lake Dam

Long Lake HED is a high head facility, and TDG levels downstream of the project can range from 120% to 140% during spill operation. Current state standards mandate that the TDG downstream of projects must not exceed 110% for flows up to the 7Q10 discharge at the project (where “7Q10” is the highest average seven consecutive day discharge with an average recurrence probability of 10 percent in any given year, commonly referred to as a 10 year frequency). The 7Q10 discharge for the Long Lake project corresponds to a total river discharge of 32,000 cfs, according to the Washington State Department of Ecology estimate. With the powerhouse operating at 6,800 cfs, the resulting 7Q10 for the spillway is 25,200 cfs.

In 2006, Avista managed the Phase I TDG studies (EES Consulting, 2006) for Long Lake HED which included preliminary recommendations for TDG mitigation alternatives. In 2010, Northwest Hydraulic Consultants, Inc. (NHC) was selected by Avista to conduct the Phase II studies to provide a more detailed review of the Phase I alternatives and carry the most promising alternatives forward to the next phase of the design using Computational Fluid Dynamics (CFD) modeling. The findings of the Phase II evaluation were presented in a final report dated December 9, 2010 (NHC, 2010) and included recommendations to evaluate the performance of selected alternatives in the Phase III physical model studies described herein.

The Phase III studies included detailed physical scale modeling at 1:30 scale of one of the original alternatives (Alternative 1) and two additional alternatives (Alternatives 6 and 8), with a summary investigation of a third new alternative (Alternative 7) without modeling. The Phase III studies included developing estimates of TDG production for the three alternatives tested in the physical model.

Atmospheric Gas Entrainment Processes

The atmospheric gas entrainment issue has been acknowledged in the literature and in practice as particularly problematic for aquatic life in altered river systems where dams have been constructed for various purposes. In the simplest terms, atmospheric gas entrainment within the water column of lakes, rivers, and reservoirs occurs when aerated flow is driven to depth and remains there for a long enough period of time that the atmospheric gases, most particularly nitrogen, trapped in the small bubbles comprising the aeration absorbs into the surrounding water volume due to the elevated potential for saturation pressures of those same gases. The higher saturation pressures found within the air bubble allows rebalancing of the interior and exterior gas concentration to ambient pressures. The absorption process is not immediate but rather is a non-linear process as a function of time at ambient pressure. The outgassing process permitting release of the highly saturated gases is similar, but again it requires time to reach equilibrium to the lower ambient pressure.

For aquatic organisms that extract oxygen from the water they inhabit through gill tissues, these supersaturated atmospheric gases are transferred to the bloodstream, where they transfuse into body tissues. Some aquatic organisms, such as fish, cannot readily rebalance the body tissue gas pressure quickly in response to lower or higher ambient pressures. As a result, with high Total Dissolved Gas (TDG) pressures above a nominal value, these fish may suffer the debilitating effects of Gas Bubble Trauma (GBT), which can be lethal if sustained and unmitigated. This impairment is also observed in human deep sea divers when returning to the surface or normal atmospheric pressure too quickly after sustained periods at depth, a condition commonly known as ‘the bends.’

Atmospheric gases, primarily nitrogen, oxygen, and other elemental gases diffuse into water at a rate dependent upon the relative gas concentration and the diffusion coefficient of the particular gas. Hence, the rate of gas transfer varies with time at depth, and is not linear to equilibrium saturation concentration. When highly aerated flow, such as that discharging down a spillway chute into a deep stilling basin, exposes air bubbles to higher ambient pressures at depth, gases diffuse through the air-water interface into the water column. Highly turbulent flows with small scale turbulence structure tend to produce very small bubbles, which do not rise as quickly as larger bubbles and as a result these small bubbles persist deep in the water column for some time and are effective in raising the TDG pressure significantly. The rate of degassing once the supersaturated water reaches the surface is similar to the gassing process, where the rate of gas transfer is again non-linearly dependent on the relative gas pressures across the air-water interface and the diffusion coefficient of the particular gas in question. Though a mathematical representation of the gassing and degassing process has been understood for some time, effective simulation of this process either computationally or physically has not yet produced consistently correct results. There are now several effective methods of modeling the dissolved gas process in spillway flows, but they rely on both empirical results and the mathematical representation of the gas transfer process (Urban, et. al, 2008). Computational efforts have produced better results but still have been able to consistently simulate the process in highly turbulent flow fields such as those found below stilling basins (Politano, et. al., 2007). However, despite these modeling limitations, these methods have produced fairly accurate estimations of the effectiveness of various mitigation measures designed to reduce TDG pressures below hydropower dams (Urban, 2008).

TDG Abatement Description

TDG abatement refers to the reduction of TDG levels downstream from hydroelectric projects. The main goal of TDG abatement design at spillways is usually to reduce the depth of plunging that occurs during spillway operation. If the depth of plunging and the amount of time that entrained air bubbles reside at depth can be reduced, the total amount of gas absorbed into the water will also be reduced. Therefore, preventing plunging flow is a key design element when considering TDG abatement alternatives. Operational changes can include changing the sequence of spillway bay operation to avoid discharging flow into deep areas downstream of the spillway, or spreading the flow across a larger portion of the spillway to reduce the unit discharges, which typically reduces the magnitude of plunging flow. However, operational solutions are often limited to large spillways with a high design capacity where there is the opportunity to reduce the unit discharge by operating additional bays up to the 7Q10 design flow.

The U.S. Army Corps of Engineers (USACE) has evaluated TDG abatement alternatives since the 1970's; and, in the 1990's, the USACE investigated numerous structural gas abatement alternatives (NHC, 1998), including stepped spillways, baffled chute spillways, and spillway chute toe deflectors. In the case of stepped spillways, it was determined that the energy dissipation on the chute reach some uniform rate within the first few steps and then maintain that energy dissipation rate to the toe, where the residual energy was insufficient to drive aerated flow to depths at which TDG pressures could reach troublesome levels. In the case of baffled chute spillway, the effective technique of developing a uniform rate of energy dissipation on the chute was produced by baffles instead of steps, a concept which increased the unit discharge capacity of the spillway structure for the same estimated TDG reduction. In the case of spillway chute toe deflectors, the model evaluation determined spillway chute exit flow patterns that significantly reduced plunging flow downstream of the spillway.

Subsequent TDG testing at prototype projects where spillway deflectors have been installed confirmed that the deflectors are effective at reducing downstream TDG concentrations. To date, the USACE has implemented flow deflectors at numerous dams to deflect flow in a "skimming" or "undular" flow pattern to reduce plunging flow. As projects operated by public and private utilities have undergone the re-licensing process in the Northwest, additional TDG abatement evaluations have been undertaken. These evaluations have resulted in recommendations for both structural abatement alternatives (eg. flow deflectors) and operational changes.

In evaluating alternative deflector designs (typically with the aid of physical model studies), the USACE Engineering Research and Development Center (ERDC) has developed TDG flow classifications as shown in Figure 2, which are associated with increased or reduced chances of elevated TDG levels.

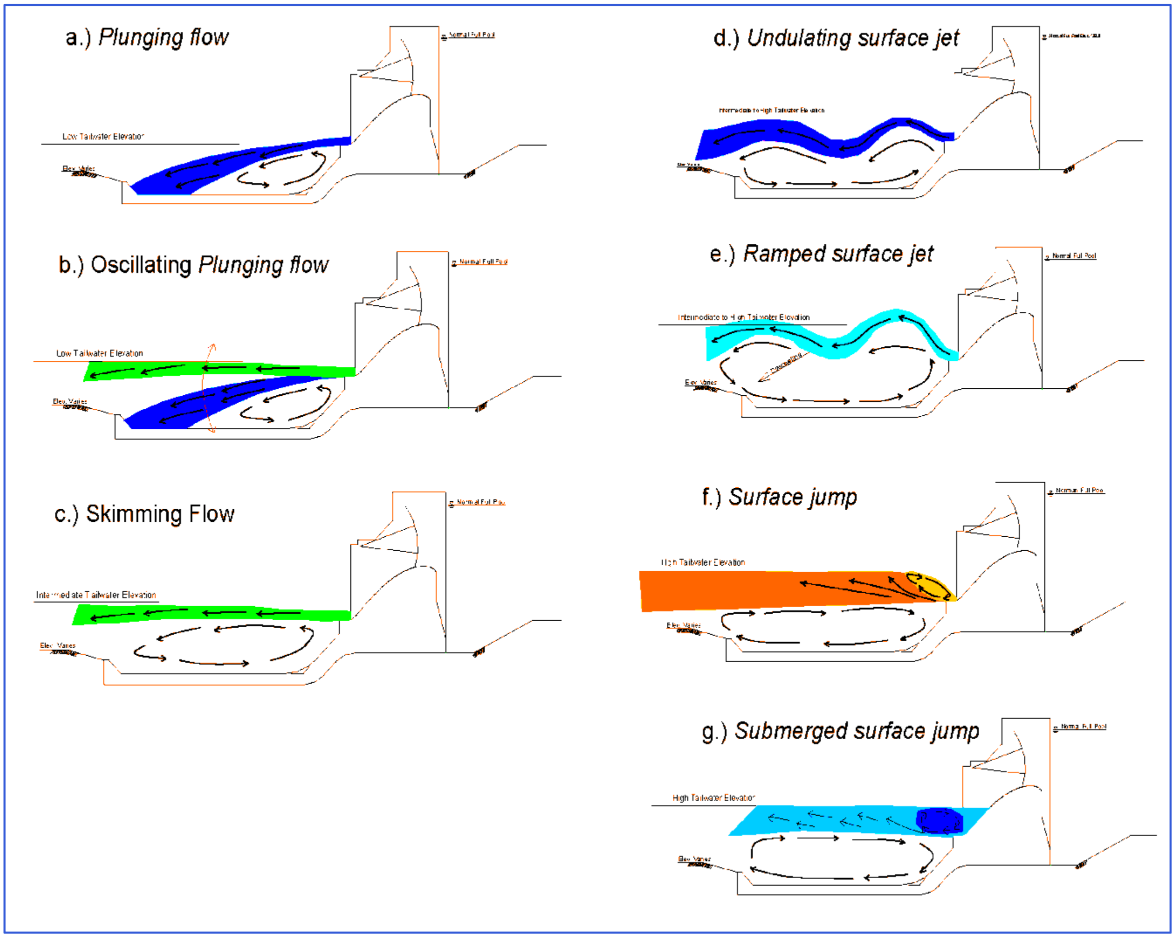

Figure 2 - ERDC Flow Classifications

The “skimming” flow regime is the optimal flow regime for TDG reduction, and deflectors are typically designed to provide skimming flow at the 7Q10 flow. However, since the performance of the deflectors is sensitive to tailwater elevation and unit discharge, it is difficult, if not impossible, to design a stationary deflector that will produce a skimming flow regime over the full range of discharges up to the 7Q10 discharge. At lower discharges, other flow regimes, such as an undulating surface jet, are often considered acceptable.

Although deflectors have been successful in lowering TDG levels at numerous facilities, it should be noted that at several projects on the Lower Snake and Columbia Rivers, deflectors were unable to reduce TDG to 110 percent as mandated by State and Federal agencies. Furthermore, there are unique spillway configurations, such as Oxbow Dam on the Snake River, where the standard deflector design was not feasible. Long Lake HED is another example of a unique spillway and plunge pool configuration that requires a site specific design for an effective TDG abatement alternative.

Long Lake HED TDG Abatement Alternatives

Eight different alternatives were developed and evaluated for application to the Long Lake HED project. As described above, the objective of each alternative was to limit the amount of highly turbulent and highly aerated spillway and/or project outflow allowed to plunge deep into the ambient water column where gas transfer from captured air bubbles could elevate gas pressure to supersaturated levels. In summary, these alternatives were:

- Alternative 1 – Spillway Toe Deflector below Spill Bays 7 and 8 (revised to include deflectors below bays 3 – 6 and below bays 7 – 8)
- Alternative 2 – Spillway Chute Superelevated Extension below Spill Bays 7 and 8
- Alternative 3 – Spillway Chute Deflector below Spill Bays 1 and 2
- Alternative 4 – New High Velocity Spillway Chute below Existing Cut-off Dam
- Alternative 5 – New Additional Powerhouse
- Alternative 6 – New Stepped Spillway below Existing Spillway Tailrace
- Alternative 7 – Noxon Rapids type Dentated Stilling Basin Baffle Blocks
- Alternative 8 – 'Roberts' Crest Splitters' with Spillway Toe Deflectors below Spill Bays 3 – 6 and 7 – 8

Computational Fluid Dynamics Modeling

Computational fluid dynamics modeling was selected to evaluate several of the eight alternatives recommended for mitigating TDG at Long Lake. Generally, the alternatives selected for CFD modeling were those with complicated hydraulic flow fields that could not be readily evaluated with more conventional computational tools or empirical design guidance. In summary, Alternatives 1, 2, and 3 were evaluated using CFD, Alternative 4 was evaluated using HEC-RAS, and Alternative 5 required no computational hydraulic analysis. Alternatives 6, 7, and 8 were evaluated in the physical scale model.

Baseline (Existing Dam Configuration) CFD Modeling

A baseline CFD model of the existing Long Lake spillway and downstream river channel was developed in the commercially available Flow-3D (Version 9.4) CFD software. The base model encompassed a portion of the forebay, the spillway, the plunge pool area, the confluence with the powerhouse tailrace, and approximately 2400 ft of the river channel downstream of the powerhouse. The downstream model limit was selected to include the tailrace TDG monitoring station (LLTR) used during Golder Associates' 2008 TDG field monitoring study (Golder, 2009), which included continuous TDG monitoring in the project forebay and tailrace from May 23 to July 10, 2008. These data included river discharges ranging from 6,500 cfs (July 10, 2008) to 40,000 cfs (May 23, 2008) and were used in selecting the discharges evaluated in the CFD model.

Figure 3 illustrates the approximate limits of the CFD model and the approximate location of the LLTR monitoring station.

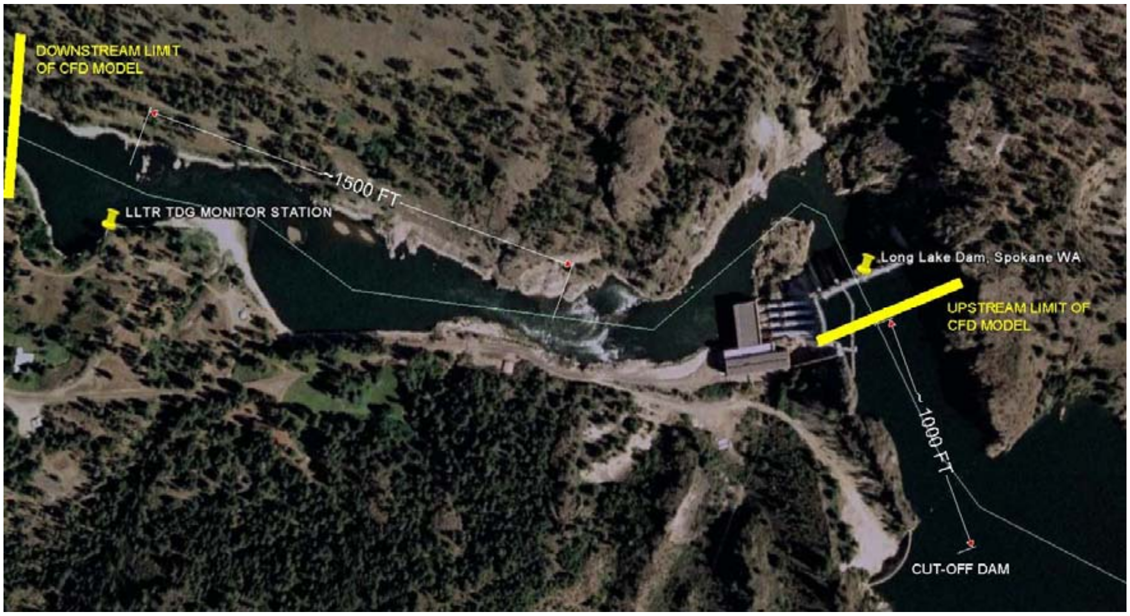

Figure 3 - CFD Model Extents for Baseline Testing

The topography and bathymetry used in the model were developed using LiDAR and bathymetric data (July 2009) supplied by Northwest Hydro Inc. Dimensions for the structures, including the spillway, cut-off dam, and powerhouse, were based on information provided by Avista.

Due to the large area encompassed by the model, a coarse grid of approximately 10 ft x 10 ft in plan and 4 ft in elevation was used to model the dam, the plunge pool, the powerhouse tailrace and the downstream river channel. A finer nested grid (2 ft x 2 ft x 1 ft) was used to model flow through the spillway gates to the base of the spillway to increase the resolution around the gate and capture the flow patterns in better detail.

The types of data generated from the CFD model included water surface elevations, three-dimensional velocities, and simulated "air" particle tracking, which was used as a method of representing the behavior of entrained air in the plunge pool and downstream river channel. The diameter of every particle seeded into the model was set at 0.001 ft (0.012 inches) with a density of 0.00233 slugs/ft^3. These particle characteristics provided a rise velocity of 0.8 ft/s (0.25 m/s) in the CFD model, which has been empirically determined as the terminal velocity for air bubble radii between 0.001 and 0.03 ft (USDI, 1980). No adjustments were made to the density and viscosity parameters of the model fluid (water at 20 degrees Celsius) to simulate the exact temperature measured during the TDG field monitoring study, since the particle size in the CFD model was determined by the rise velocity in water at 20 degrees Celsius. The particles were released in multiple lines across the main flow stream upstream from the gates and at the base of the spillway where air is likely to be entrained into the flow. Particles were deleted by the model when they reached a void region such as the water surface or the model boundary limits.

At the completion of each test flow patterns, water levels and spillway flow trajectory characteristics were extracted from the model and used to compare the hydraulic characteristics of the modified spillway bays. The time history of the position of the "air" particles (x, y, z position), the particle velocity (three velocity components and resulting velocity magnitude) and water levels throughout the length of the model were also extracted from the model results. Figure 4 illustrates the existing spillway configuration as utilized in the CFD model.

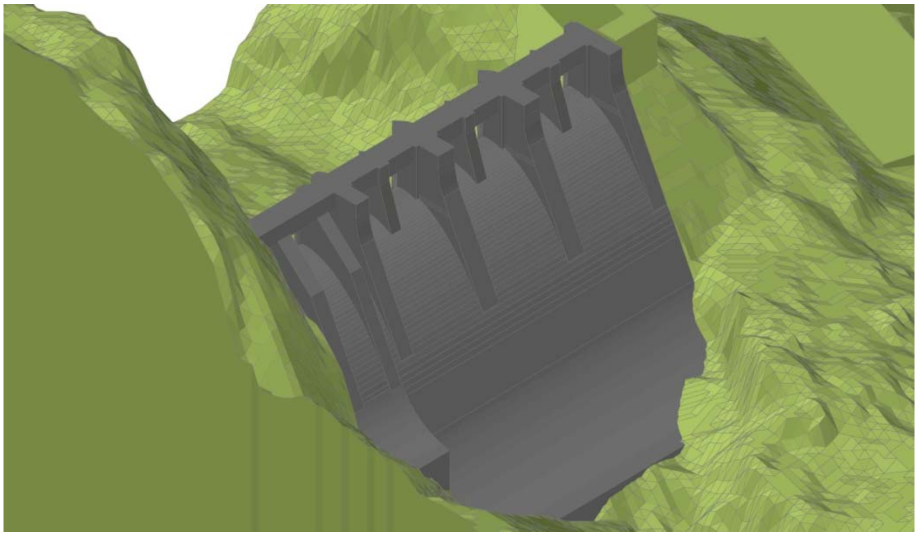

Figure 4 - Schematic of existing spillway CFD mesh (baseline)

The CFD modeling results for the existing spillway configuration exhibited plunging flow at the base of the spillway for both operating conditions tested. Baseline Test 1 was conducted with four spillway gates operating, while Baseline Test 2 had only two gates operating (in accordance with operating conditions followed for the project).

The spillway flow plunges to depths of more than 50 ft and the maximum flow velocities at the base of the spillway were approximately 85 ft/s for both operating conditions. The resulting unit discharge at each spill bay gate was approximately 260 cfs/ft for Baseline Test 1 and 180 cfs/ft for Baseline Test 2.

For Baseline Test 1, the four center gates (Gates 3 to 6) were operated with approximately equal gate openings (10 – 11 ft), which resulted in reasonably uniform flow across the width of the tailrace. For Baseline Test 2, the flow was concentrated through two gates (Gates 5 and 6), which resulted in areas of flow recirculation along both sides of the spillway plunge pool.

Baseline Condition TDG Performance Estimates

The CFD model results were provided to Dr. Gulliver of the University of Minnesota for use in his Bubble Swarm Gas Transfer (BSGT) model (Gulliver et al. 2009), which was developed to predict TDG levels downstream of hydroelectric projects. The ability of the two models (CFD and BSGT) to predict the TDG level in the downstream river channel was assessed for spillway operation at two discharges (Baseline Tests 1 and 2). If the model TDG levels compared well to the TDG values measured in the field, the models would be considered as verified and could be used as one of the tools to estimate the TDG levels for the design alternatives. However, the combination of flow and bubble path prediction by the CFD software and the water-bubble mass transfer calculations of the BSGT model did not compare well to the field measurements for the Long Lake project. It is noted that these types of predictions are relatively innovative, and many factors could have contributed to the inconsistencies with the field data including model effects, the complexities of the Long Lake site layout, and even the location of the field measurements.

The memorandum (Gulliver, July 2010) summarizing this work provides background on the TDG predictive model,

Efforts were made to investigate potential model effects on the predicted TDG levels such as the number of particles used in the simulations, the location where the particles were seeded, and the impact of activating the air modules within the CFD model. Sensitivity checks on the number of tracked particles between 48 and 100 particles showed no significant differences in the predicted TDG levels. Several tests were conducted with changes made to the particle initiation locations. Various combinations were investigated including: the headpond upstream from the spillway gates, an array of particles at base of the spillway, and particles placed at the junction where the spillway flow impacts the spillway plunge pool; however, the results were inconclusive. The CFD model was run with and without the air modules activated for simulation of air bulking and air entrainment, but again the results were inconclusive. As a result of the verification issues, the BSGT model was not pursued further for this site.

Particle Tracking Results

History particles were seeded in the CFD model upstream of the dam at locations 10, 20 and 30 ft upstream from the operating gates at El. 1510 ft and El. 1512 ft (spillway crest at El. 1508 ft) for all geometries tested. There were a total of 24 particles initiated upstream from the spillway gates. An additional 63 particles were seeded into the CFD model downstream from the spillway. For baseline testing, particles were initiated at the base of the spillway in the pool below the operating gates at El. 1340, 1350 and 1360 ft. The particles were driven to depths of 60 ft or more for both tests with a significant quantity of the particles held at depths of greater than 17 ft for extended periods of time. Baseline Test 1 resulted in particles being driven approximately 10 ft deeper (70 ft depth) than Baseline Test 2, while Baseline Test 2 resulted in particles that remained at depth for a longer period of time. The particle tracking information provides information on the depth of the particles and the length of time the particles remained at depth. Since high TDG values are associated with particles being driven to depth for extended periods of time, the baseline particle tracks may be compared to the particle tracks associated with TDG abatement alternatives to provide additional information on how the alternatives modify the flow patterns and TDG levels.

Alternative 1 CFD Modeling

Alternative 1 consists of the addition of a continuous deflector on the downstream face of the spillway ogee below Spill Bays 7-8, combined with excavation of the bedrock knob downstream of those bays to form a shallow submerged shelf, as illustrated in Figure 5.

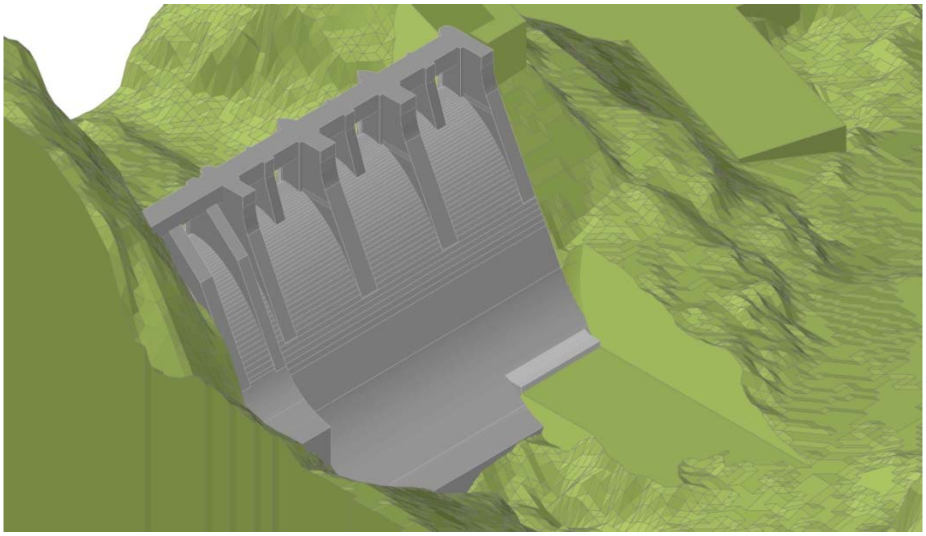

Figure 5 - Schematic of Alternative 1

Alternative 1 was evaluated at the same two operating conditions that were examined for the existing (baseline) geometry; however, since the proposed modifications are restricted to two bays, Tests 1 and 2 were conducted with only spillway gates 7 and 8 operating. Test 3, which is above the 7Q10 discharge, had two additional gates (4 and 5) operating. The resulting unit discharge at each spill bay was approximately:

- 480 cfs/ft for Test 1;
- 180 cfs/ft for Test 2; and,
- 480 cfs/ft through gates 7 and 8 plus 220 cfs/ft through gates 4 and 5 for Test 3.

The CFD modeling results showed that the deflectors designed for spill bays 7 and 8 reduced the depth of the plunging flow by approximately 15 to 20 ft from that observed for the baseline conditions. The pool below spill bays 7 and 8 on the excavated rock shelf is relatively shallow – in the order of 15 to 25 ft. Maximum flow velocities at the base of the spillway were approximately 85 ft/s for Tests 1 and 2, and reached 88 ft/s for Test 3.

For Tests 1 and 2, the flow was concentrated through gates 7 and 8, resulting in a large area of flow recirculation on the right side of the pool. This area of flow recirculation remained for Test 3, but was reduced in size and strength as a result of operating gates 4 and 5.

Similar to baseline testing, history particles were initiated upstream from the operating gates and at the base of the spillway below the operating gates. These particles simulate bubble travel paths and give an indication of the potential resulting TDG levels for the design

Alternative 1 TDG Performance Estimates

Alternative 1 is similar in concept to the spillway deflectors located on the Lower Snake, Mid-Columbia River, and Lower Columbia River projects. However, with the two-bay design concept, the design unit discharge for Alternative 1 at Long Lake is significantly greater than that at which the Lower Snake and Columbia River projects have proven to be successful; and, the receiving pool at Long Lake is significantly shallower. The actual TDG reduction at any project depends on site specific factors. The TDG reduction benefits with deflectors are highly influenced by the unit discharge, stilling basin or receiving pool depth, and hydraulic conditions and flow depth between the spillway and the measurement location downstream. The deflectors installed at the Lower Snake and Columbia River projects have been shown through field testing to reduce TDG levels to the 120% to 125% range just downstream of their stilling basins. The higher unit discharge at the TDG design discharge condition with the 2-bay concept at Long Lake will likely produce less reduction than the Snake / Columbia River projects; however, the shallower receiving pool depth will likely tend to increase the reduction potential as compared to the Snake and Columbia River projects. Thus, it is expected that Alternative 1 has a very reasonable potential of reducing TDG levels at Long Lake to the 120% to 125% range, similar to that at the Snake and Columbia River projects. Furthermore, it may be possible to generate an even higher reduction if deflectors were installed on more than 2 bays in order to reduce the unit discharge.

Alternative 2 CFD Modeling

Alternative 2 is comprised of a super-elevated extension to the spillway chute below Bays 7 and 8, as illustrated in Figure 6. The extension is designed to redirect and spread the spillway flow onto the rock outcropping located downstream of these bays. The rock outcropping would help dissipate energy and prevent flow from plunging into the deep plunge pool. At the terminus of the super-elevated extension, a flip bucket will be incorporated into the design to help redirect and expand the jet in an upward direction to spread the jet onto the rock outcropping.

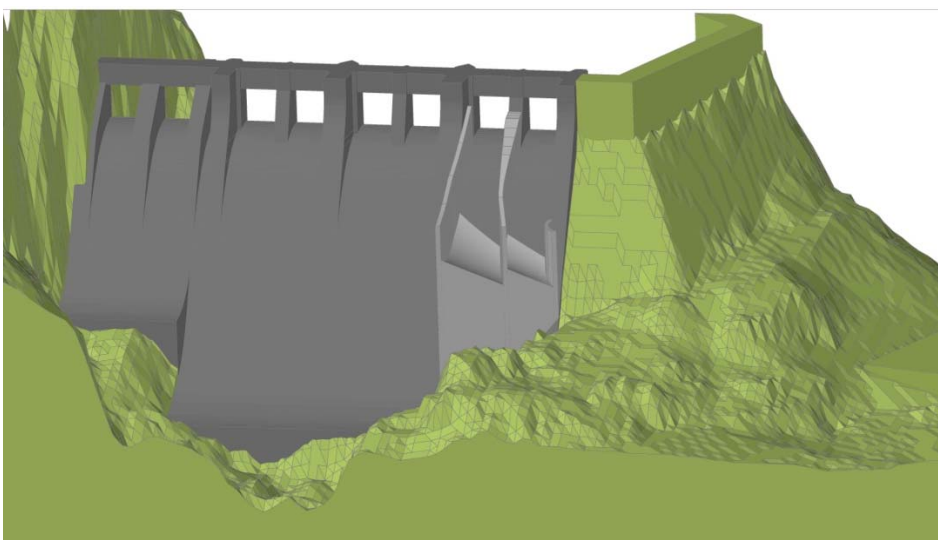

Figure 6 - Schematic of Alternative 2

Alternative 2 was evaluated for the same operating conditions as Alternative 1. Tests 1 and 2 were conducted with spillway gates 7 and 8 operating, while Test 3 had two additional gates (4 and 5) operating. The resulting unit discharge at each spill bay was approximately:

- 480 cfs/ft for Test 1;
- 180 cfs/ft for Test 2; and,
- 480 cfs/ft through gates 7 and 8 plus 290 cfs/ft through gates 4 and 5 for Test 3.

The CFD modeling results showed that the spillway flow trajectory from the super-elevated spillway extension reached the rock outcrop for all three operating conditions. These images show that most of the flow travelled downstream over the rock outcrop and entered the river on the downstream side of the bend, away from the plunge pool at the base of the spillway. These images show that the rock outcrop dissipates the high velocity jet prior to the flow re-entering the river channel and reduce the depth of plunge to approximately 30 ft.

For Alternative 2, the particles were initiated upstream from the operating gates and at the base of the rock outcrop, both upstream in the spillway pool and downstream in the river channel.

Alternative 2 TDG Performance Estimates

Alternative 2 is similar to a flip bucket where the flow trajectory is spread into the air and the unit discharge at impact becomes quite low as a result of the flow spreading. These types of directional flip buckets have a high potential to significantly reduce TDG levels. With the Alternative 2 design at Long Lake the intent of the design is to create a condition where the jet trajectory impacts on the existing rock outcrop, where the receiving depth would be very shallow. By the time the flow re-enters the river channel downstream of the rock outcrop, the energy is largely dissipated and plunging will be largely eliminated, thereby eliminating the production of high levels of TDG. There are some design details that would require further investigation to confirm that this alternative performs as desired from a hydraulic perspective. Specifically, it will be essential to ensure that the jet trajectory spreads and impacts the rock outcrop before it enters the downstream river at all discharges up to the 7Q10 discharge. This will present a very challenging design process. Although the CFD results indicate that this will occur for spillway flows ranging from 8,400 to 33,800 cfs, a physical model is the only reliable method to attempt to develop a design that produces the desired hydraulic characteristics. If the hydraulic design aspect of this alternative proves to be feasible, there is a reasonable potential that it could reduce TDG levels to perhaps as low as 115%.

Alternative 3 CFD Modeling

Alternative 3 is comprised of extending the toe of the spillway chute and incorporating a flow deflector downstream of Spill Bays 1 and 2, as shown in Figure 7. The rock outcropping located downstream of these bays would be reshaped to form a shelf at El. 1370 ft, followed by a 35 ft long deflector set at El. 1363 ft. Due to the configuration of the existing spillway chute and rock surface downstream of the spillway, the construction of a standard deflector was not feasible.

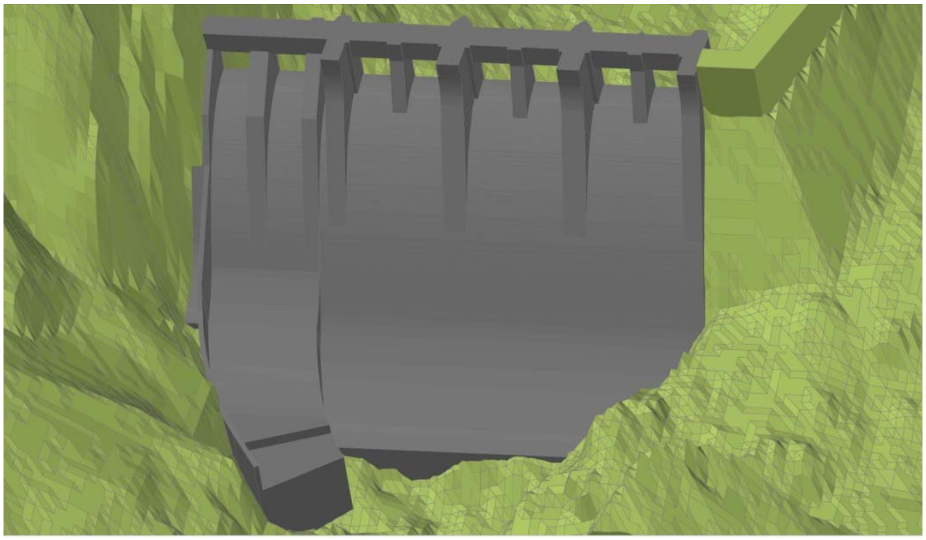

Figure 7 - Schematic of Alternative 3

Alternative 3 was evaluated at the same discharges as the previous alternatives; however, flow was passed through spillway bays 1 and 2 rather than 7 and 8. Due to instabilities with the CFD model, it was necessary to reconfigure the apron and toe modification slightly from that described in the previous section. In the CFD model, void regions formed immediately downstream of the 7 ft vertical drop from the apron, set at El. 1370 ft, to the deflector, which was set at El.1363 ft. These void regions caused the CFD simulations to run extremely slowly and eventually become unstable and fail. As a result, in order to evaluate the design in the CFD model, the apron was removed from the design and the spillway chute transitioned directly to the deflector at El. 1363 ft. The model simulations were run successfully once the 7 ft vertical drop at the base of the spillway was eliminated.

Alternative 3 Tests 1 and 2 were conducted with spillway gates 1 and 2 operating, while Test 3 had two additional gates (4 and 5) operating. The resulting unit discharge at each spill bay gate was approximately:

- 405 cfs/ft for Test 1;
- 190 cfs/ft for Test 2; and,
- 450 cfs/ft through gates 1 and 2 plus 305 cfs/ft through gates 4 and 5 for Test 3.

The CFD modeling results showed that the toe modification and downstream deflector reduced the depth of the plunging flow by approximately 10 ft from that observed for the baseline (existing) conditions.

For Tests 1 and 2, the flow was concentrated through gates 1 and 2, resulting in a large area of flow recirculation on the left (west) side of the pool. This area of flow recirculation remained for Test 3, but was reduced in size and strength as a result of operating gates 4 and 5.

For Alternative 3, history particles were initiated upstream from the operating gates and at the base of the spillway at the downstream end of the spillway toe modification at depths of El. 1365, 1366 and 1367 ft.

Alternative 3 TDG Performance Estimates

Although Alternative 3 includes a deflector design, the topography in area of Bays 1 and 2 requires the flow to be discharged in the existing deep plunge pool which will likely limit the TDG reduction potential. In addition, the deflector is located downstream of a rock apron so it is in a slightly different location in relation to the spillway face compared to the Alternative 1 design. As a result of these site constraints, the reduction potential is considered to be less with this alternative when compared to Alternative 1. The TDG will likely be reduced to the order of 125% to 130% at the 7Q10 discharge.

Empirical and Analytical Evaluation of Alternatives 4 and 5

Alternative 4

Alternative 4 is comprised of a new high-velocity chute spillway constructed downstream of the existing cut-off dam. There were two options under consideration for the location of the spillway crest. For Option 1, the spillway crest would be located at the spillway cut-off dam location; and, for Option 2, the spillway crest would be located approximately 300 ft downstream of the cut-off dam. Option 1 was used for the hydraulic and civil design calculations (Figure 8). For either alternative the crest elevation was set at El. 1513.5 ft and flow to the spillway chute would be controlled using two 24 ft high tainter gates. The spillway chute would be 60 ft wide for the first 725 ft before expanding to 100 ft wide at the chute terminus where there would be an 80 ft long deflector set at El. 1365 ft.

CFD modeling had initially been considered for Alternative 4, but 1 dimensional numerical modeling was selected instead for efficiency, due to the apparent simplicity of the flow down the spillway chute and wide availability of empirical comparative data and standard analysis methods.

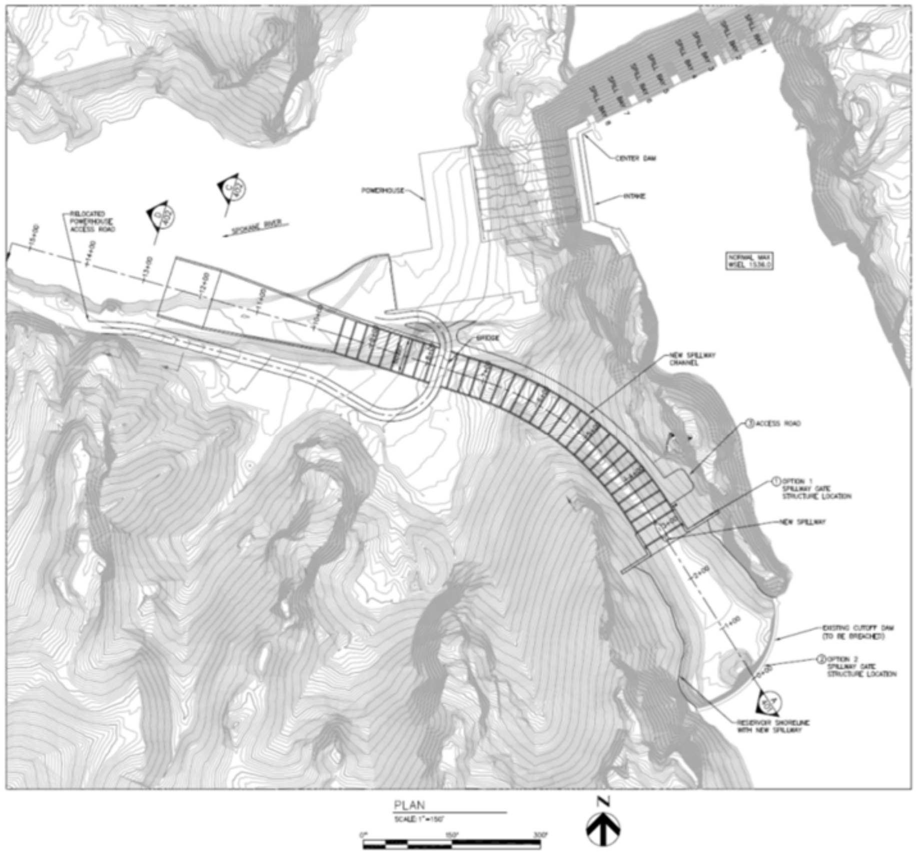

Figure 8 – Alternative 4 - Additional High Velocity Chute Spillway through Cut-off Dam

Alternative 4 TDG Performance

The spillway and chute width for Alternative 4 is limited to approximately 100 ft at its downstream end by the site topography. This results in a unit discharge considerably higher than that encountered at other spillway projects where deflectors have been shown to be effective at reducing TDG. While the general concept of this alternative is considered to have a high potential for TDG reduction, the restricted spillway chute width and resulting high unit discharge at Long Lake may limit the potential effectiveness of this alternative. When compared to the alternatives at the existing spillway, the TDG reduction potential with this alternative would likely be greater than that of Alternative 3, but not any greater than the 120 – 125% range associated with Alternative 1.

Alternative 5

Alternative 5 consists of a new intake structure, two new steel penstocks (17 feet in diameter, 658 and 682 feet in length), and a new powerhouse containing two vertical Francis turbine generator units, each rated at 50 to 60 MW (Figure 9). The existing powerhouse would be refurbished and maintained to operate during very high and very low flows on the Spokane River. During very dry periods, such as the months of August and September, inflows to Long Lake may fall so low that regulated outflows during the 6-hour daily peak generating period will fall below 2,500 cfs. This would happen when daily inflows fall below about 625 cfs, or when the generating schedule does not permit an 18-hour shutdown each day. In those circumstances, one of the new Francis turbines would operate below about 60 percent of rated load. This would result in turbine efficiency below that of the old units operating at or near best gate. When Long Lake inflow exceeded the 9,600 cfs hydraulic capacity of the new plant, the old plant would be operated up to its hydraulic capacity (6,800 cfs) to utilize additional flow.

The recommended improvements included modernization of the generating units and rehabilitation or replacement of the spillway gates and power intake gates. The generating units were modernized during the 1990s and all the dam gates and gate hoists were replaced with new equipment in the same time frame.

As discussed above, the alternatives considered in the 1990 modernization study included new powerhouse arrangements with one, two, or three generating units and total installed capacities of 40, 50, 60, 80, 100, and 120 MW. These power ratings correspond to hydraulic capacities ranging from 3,200 cfs for the 40 MW alternative to approximately 9,600 cfs for the 120 MW alternative.

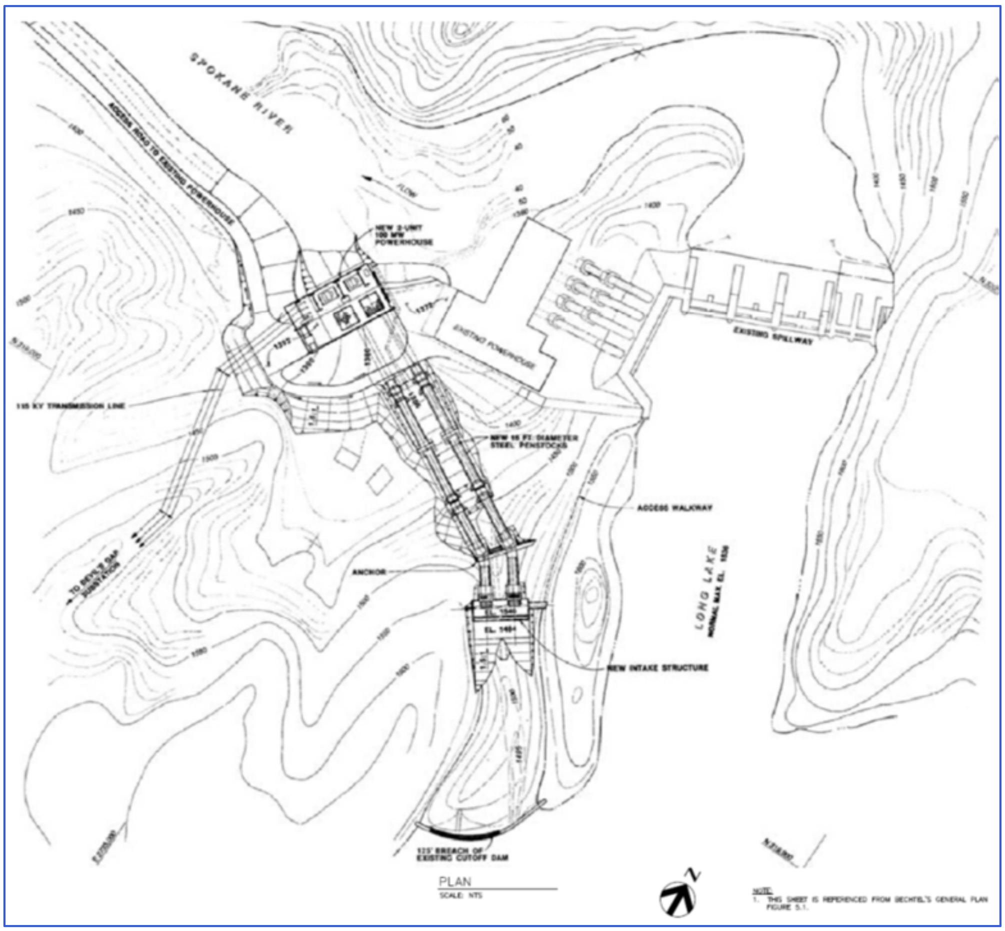

Figure 9 – Alternative 5 – New Powerhouse

Alternative 5 TDG Performance Estimate

The additional powerhouse capacity proposed for Long Lake as part of Alternative 5 would permit passing more flow through turbines than presently possible, limiting necessary spill though not eliminating it entirely. Turbine discharge only passes forebay gas levels through to the tailrace and does not add to TDG levels or reduce it, thereby effecting TDG abatement, provided that forebay TDG levels do not exceed the reset and regassing of spillway flows at the necessary discharge volumes.

Physical Hydraulic Laboratory Study Experiments

Similitude and Scale

Scale hydraulic modeling requires that the force relationships in the model and prototype are dynamically similar. To achieve this similarity, the ratios of the inertial to the gravity, pressure, viscous, and surface tension forces must be the same between model and prototype. Only a 1:1 scale model can achieve these criteria simultaneously. Modeling at reduced scale in any dimension involves identifying the primary force relationship to accurately simulate prototype conditions, then selecting a model scale to minimize any scale effects. For free-surface flow conditions of the type being examined in the current study, the inertial and gravitational forces are the dominant forces that define the hydrodynamic flow conditions. As a result, the Froude number, as defined below, is the key force ratio that must be equal in the model and prototype.

$$F_r = \frac{F_M}{F_P} = 1$$

where,

$$F_M = Froude\ number\ in\ the\ model = \frac{U_M}{\sqrt{g\,L_M}} = \frac{Inertial\ Force}{Gravitational\ Force}$$

and,

$$F_P = Froude\ number\ in\ the\ prototype = \frac{U_P}{\sqrt{g\,L_P}}$$

U = characteristic flow velocity	P = prototype values
M = model values	M = model values
g = gravitational acceleration	L = characteristic length

Based on the study objectives, the dimensions of the structures and the project discharges, a geometric scale of 1:30 was selected for the Long Lake model. At this scale, adherence to Froude criterion for similitude resulted in the scale relationships shown in Table 1.

Table 1 Model Scale Relationships

Parameter	Relationship	Value
Length	L	1:30
Velocity	$L^{1/2}$	1:5.47
Discharge	$L^{5/2}$	1:4930

The 1:30 scale physical hydraulic model encompassed the existing spillway and powerhouse facilities and an 1800 ft long reach of the river downstream of the spillway in which to test these three alternatives (Figure 10). The model was calibrated to qualitatively match the flow patterns observed at the project site at a river discharge of approximately 25,600 cfs (6,700 cfs passing through the powerhouse and 18,900 cfs passing over the spillway). Baseline testing was then

conducted to document the performance of the existing spillway for total river flows ranging from 15,300 cfs to 50,000 cfs (corresponding to spillway flows ranging from 8,500 cfs to 43,100 cfs, with powerhouse flows of 6,800 to 6,900 cfs). Following the baseline testing, the model was used to evaluate and refine the design of the Alternative 1 Spillway Deflectors and the Alternative 6 Stepped Spillway concept, as developed in the Phase II studies; as well as a new concept referred to as Alternative 8 Roberts' Splitters concept.

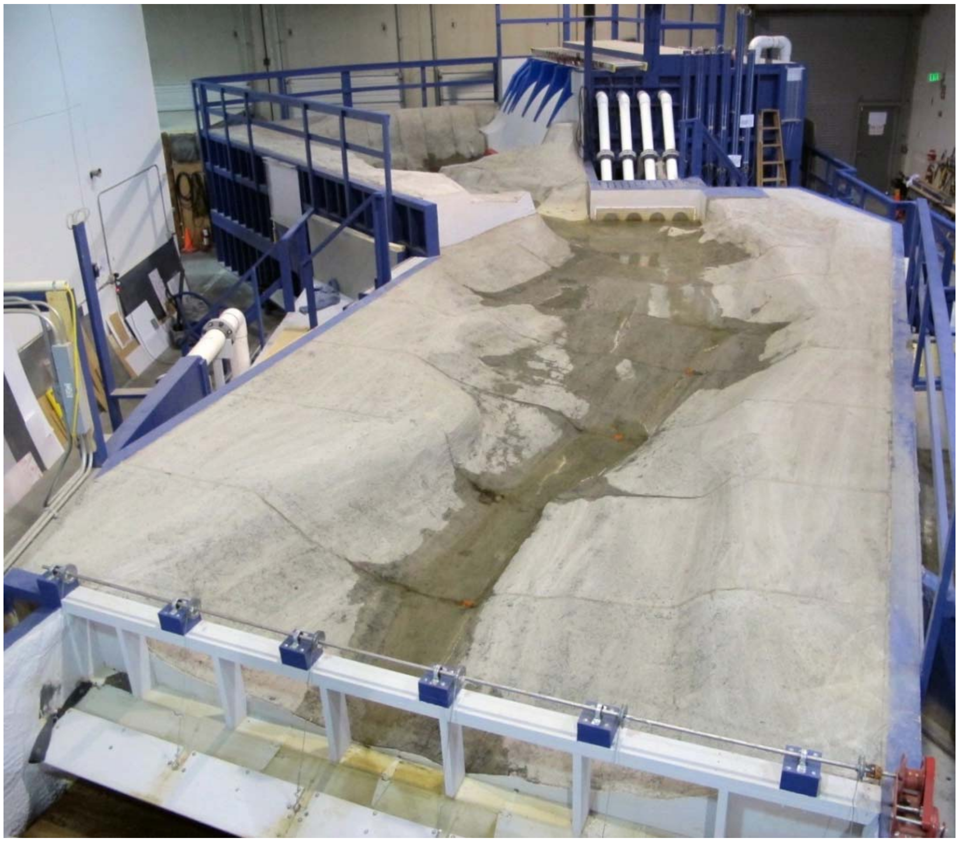

Figure 10 – 1:30 Scale Physical Model of Long Lake HED

Alternative 1 – Spillway Toe Deflectors

Model testing indicated that the original design of the Alternative 1 deflectors, which were initially installed downstream of only spill bays 7 and 8 and subjected to unit discharges of up to 500 cfs/ft (equivalent to the 7Q10 flow passing through those two bays only), did not generate downstream flow patterns conducive to minimizing TDG levels. Based on these results, the deflectors were extended across additional spill bays (bays 3 – 6) and the elevation of the deflectors was refined until the desired skimming flow and slightly ramped surface jet flow regimes were generated for flows up to and including the 7Q10 discharge. In addition, further testing indicated that a 15 foot radius at the joint between the deflector and the spillway improved flow characteristics. The final resulting design (referred to as Alternative 1 Configuration 4) was comprised of a two-step deflector installed downstream of bays 3 – 6 approximately 16.8 ft long at El. 1370 ft and downstream of bays 7 and 8 approximately 15.0 ft long at El. 1368 ft (Figure 11). Both the higher and lower deflector steps shared a common downstream vertical face. The selected design also included excavation of the existing rock outcropping downstream of bays 7 and 8 to form a bench at El. 1353 ft. Based on theoretical degassing predictions for spillways with deflectors, the estimated TDG performance for this design is 119– 122 percent.

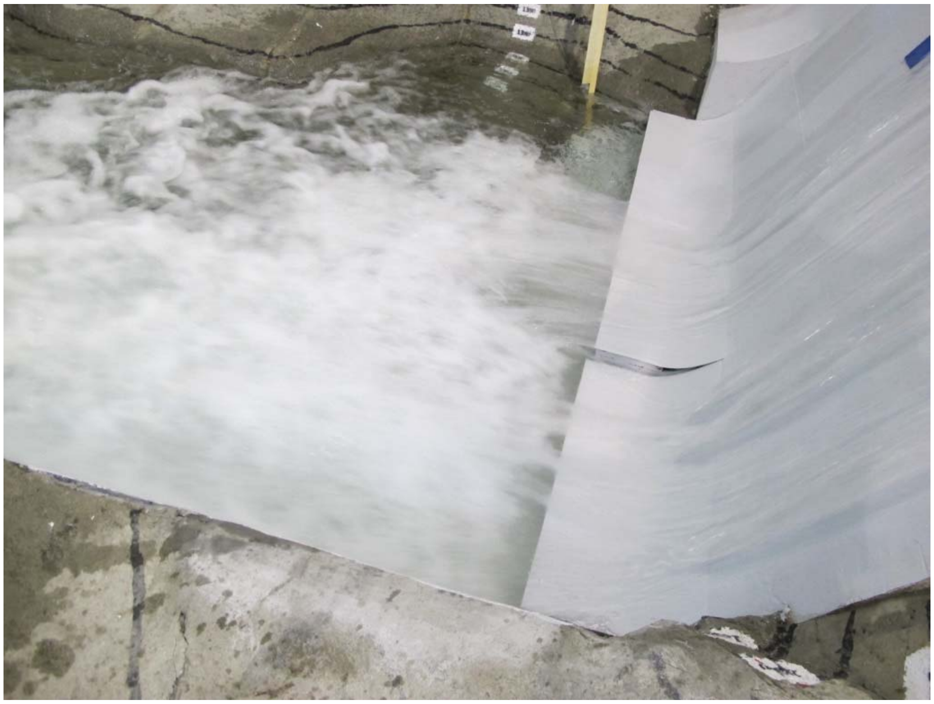

Figure 11 Alternative 1 – Refined Spillway Toe Deflector & Left Bank Bench Excavation

Alternative 6 – Stepped Spillway

The model spillway and plunge pool area were then returned to their original configurations and the Alternative 6 Stepped Spillway concept was installed in the model in the channel reach downstream of the plunge pool (Figure 12). The original stepped spillway concept had a 200 ft wide spillway with a crest at El. 1400 ft followed by eight 5-ft high by 10-ft long steps leading to a final 2-ft high step into a 70 ft long stilling basin set at El. 1358 ft. Development testing conducted in the model indicated that the 5-ft high steps were ineffective and the overall slope of the spillway was too steep to provide satisfactory energy dissipation and degassing for the unit discharges at Long Lake.

Based on these results, the stepped spillway crest was raised to El. 1415 ft, the upstream steps were revised to 10-ft high by 30-ft long and baffles were added to the second step (at El. 1405 ft). This design was shown to be fairly effective at mitigating TDG levels for all flows up to the 7Q10 discharge. However, project safety concerns existed with flows in excess of the 7Q10 discharge when the energy dissipation characteristics of the stepped spillway were inadequate, leading to the hydraulic jump being swept downstream of the stilling basin and high velocities and turbulence generated in the vicinity of the powerhouse structure. Based on theoretical degassing predictions for stepped spillways, the estimated TDG performance for this design is 125 – 128 percent.

Figure 12 – Alternative 6 Stepped Spillway (upper left of photo)

Alternative 7 – Noxon Rapids Dam type Dentated Stilling Basin Baffle Blocks

As mentioned previously, a new alternative was considered during the Phase III model study evaluations. Alternative 7, 'Noxon Spillway Concept', would include the application of the spillway design at Noxon Rapids Hydroelectric Development (Noxon) to the spillway at Long Lake Dam. Noxon is located on the Clark Fork River in Montana and is owned and operated by Avista. The spillway includes a stilling basin with baffles for energy dissipation and nappe deflectors on the interior five spillway bays. Figure 13 shows the top of the baffles, which are above the water surface elevation in this photo, and the nappe deflector for one of the bays. The outer bays of the spillway include three flip bucket type spillways for passing high discharges.

The application of this design to Long Lake would focus on the interior bay nappe deflectors, stilling basin, and baffles. Each of the interior bays includes a dentated sill structure consisting of baffles designed to dissipate energy and minimize erosion downstream. The nappe deflectors were added to reduce the negative pressures on the baffles that resulted in severe cavitation after the first year of operation. Based on TDG data collected by Avista, the TDG levels at the compliance point downstream of the project are typically within the 110% TDG limit.

Figure 13 – Alternative 7 – Noxon Rapids Dam type Dentated Stillng Basin Baffle Blocks

Alternative 8 – 'Robert's Splitter' Concept

Alternative 8 consists of a spillway crest and chute modification which included a concept based on the "Roberts' Splitters" design that has been used as a method to dissipate energy on high head spillways, primarily in Africa and the Middle East, coupled with a toe deflector to produce skimming flow for the reduced residual-energy spillway chute flow (Figure 14). This concept was revised and adapted to the Long Lake spillway and testing was used to evaluate and further refine the design for satisfactory TDG performance. Preliminary testing demonstrated that the solid shelf that is used in the traditional Roberts Splitter design was not appropriate for the Long Lake project as it cast all of the spillway flow into the deep plunge pool downstream of the spillway where it subsequently plunged to depth and negated any TDG reduction potential. The design was modified to use two staggered rows of splitter blocks to aerate the spillway flow and create energy dissipation while bulking the nappe depth and casting the flow only slightly off the face of the spillway chute. The splitter block concept required the installation of an extended flow deflector at the toe of the spillway, similar to the Alternative 1 flow deflector concept, to redirect the aerated jet across the spillway tailrace in a skimming flow regime thereby minimizing TDG levels in the downstream channel.

Model testing demonstrated that the selected Alternative 8 Type B11 design, which combines two rows of 3.75 ft wide by 8 ft high splitter blocks on the upper spillway chute and a 42.5-ft long flow deflector at the toe of the spillway, was effective at dissipating a portion of the energy in the flow at the base of the spillway while also producing skimming flow in the tailrace channel. The velocities recorded downstream of the plunge pool were relatively low compared to the deflector of Alternative 1 (Configuration 4), and the plunging flow downstream of the spillway which currently generates high levels of TDG was eliminated. The theoretically estimated TDG performance for this design is 118 – 123 percent.

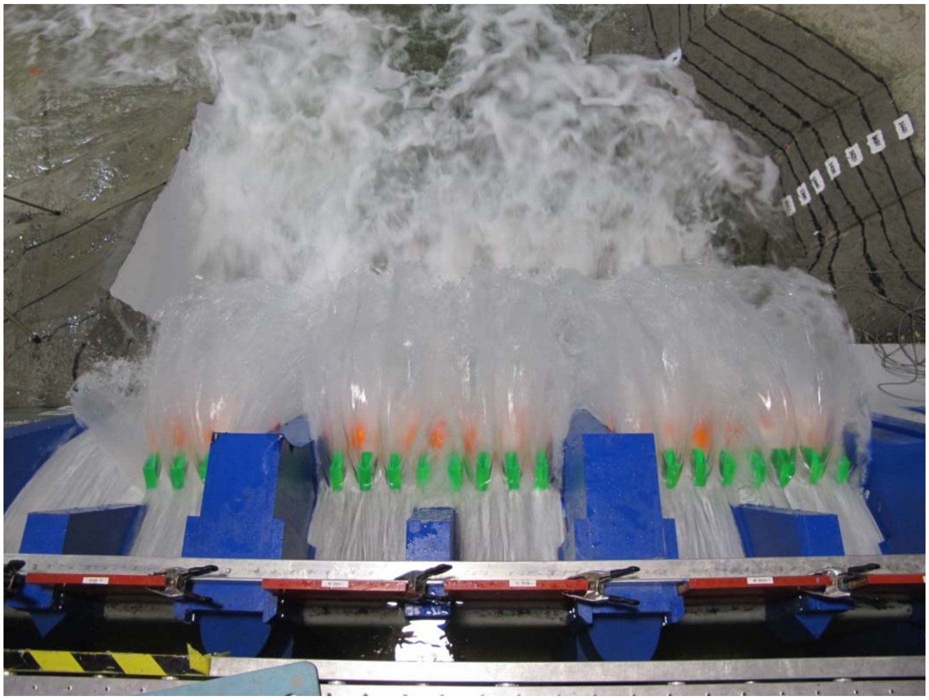

Figure 14 – Alternative 8 'Robert's Splitter' Concept

Results and Discussion

The preferred alternative for Long Lake HED selected following the various technical analyses discussed above was the Alternative 1 Spillway Toe Deflector. This alternative was judged to provide the greatest TDG reduction benefit for the least constructed cost and the greatest chance for successfully meeting the environmental water quality objectives of the full study. The Alternative 1 deflector configuration as initially proposed was refined following the CFD modeling results and the accompanying TDG modeling analysis, then refined again once the full battery of physical scale model testing was completed. The final design consisted of a 16.8 ft long toe deflector with a 15 ft radius transition from the existing spillway chute below spill bays 3 through 6 at elevation 1370 ft, and a 15 ft long toe deflector with a 15 ft radius transition below spill bays 7 and 8. In addition, the existing bedrock knob immediately downstream of bays 7 and 8 was excavated to form a bench at elevation 1353 ft extending entirely through the knob and to the 90 degree bend in the tailrace channel. Rock excavation debris would be used to fill the void below the bays 7 and 8 deflector and the bedrock excavation. Rock debris may also be used to partially infill the deep plunge pool below bays 3 through 6.

The physical characteristics of the spillway exit jet departing the toe deflector most closely resembled the empirically-derived optimal jet trajectory, shape, and skimming behavior identified by the US Army Corps of Engineers as the most successful deflector TDG performance. The two-step deflector permits smaller to moderate spillway flows to be passed through bays 7 and 8 only up to river flows of about 12,000 cfs while producing the optimal skimming flow pattern. Larger flows would be passed through bays 7 and 8 and also bays 3 through 6, which with the slightly higher elevation deflector was able to produce the optimal skimming flow jet for river flows up to the 7Q10 flow of about 32,000 cfs. Figure 15 below shows the typical near-optimal skimming flow produced by spill bays 7 and 8 only in operation at a prototype discharge of about 12,000 cfs total river flow (6,900 cfs through powerhouse +

5,000 cfs spillway flow). Figure 16 below shows the typical near-optimal skimming flow produced by spill bays 3 through 6 and bays 7 and 8 in operation at a prototype discharge of 32,000 cfs total river flow (6,900 cfs through powerhouse + 25,000 cfs spillway flow).

Figure 15 – Alternative 1 (Final Configuration) Skimming Flow at 11,900 cfs total river flow (5,000 cfs through spill bays 7 and 8 only + powerhouse flow of 6,900 cfs)

Figure 16 – Alternative 1 (Final Configuration) Skimming Flow at 32,000 cfs total river flow (25,000 cfs through spill bays 3 through 8 + powerhouse flow of 6,900 cfs)

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