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Cabinet Gorge Dam Spillway Modifications for TDG Abatement - Design Evolution and Field Performance

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ABSTRACT

Avista is implementing spillway modifications to reduce Total Dissolved Gas (TDG) supersaturation downstream of Cabinet Gorge Dam. The key feature of the modifications is the addition of roughness elements, similar to supercavitating baffle blocks, to break up the spillway jet, thereby reducing the depth of plunge and TDG supersaturation. The work is progressing in a step-wise manner. A single bay was modified in 2012 and field tested in 2013. Following the initial field tests, a CFD model was developed to aid in design refinements for the prototype and to improve the design prior to modification of subsequent spillway bays. The prototype demonstrated that spillway modifications are an effective method to reduce TDG downstream of a spillway discharging freely into a deep plunge pool. The CFD model has allowed the design to be simplified while both maintaining the plunge depth improvements of the initial prototype and reducing the effect of the modifications on spillway capacity. This paper presents the prototype design and the design that will be implemented for the next two bays, summarizes the results from the prototype field tests, and describes the CFD model and results.

Keywords: *Spillways, Total Dissolved Gas, Computational Fluid Dynamics, Jets, Plunge Pools, Cavitation*

1. INTRODUCTION

Elevated levels of Total Dissolved Gas (TDG) in spillway discharge is a significant water quality concern at many dams due to the potential for TDG supersaturated water to induce Gas Bubble Trauma (GBT) in endangered fish species. Water quality standards typically limit TDG to 110% of saturation. At Cabinet Gorge Dam, TDG often exceeds 130% during spill.

Avista Utilities owns and operates Cabinet Gorge Dam and is actively implementing modifications to reduce TDG generated by spill releases. Cabinet Gorge Dam is located on the Clark Fork River in Idaho, approximately 16 kilometers (10 miles) upstream of Lake Pend Oreille. The dam was constructed in 1952. It has eight gated spillways that release water over very short chutes before the jets fall freely into a deep plunge pool. The spillway configuration allows the jets to entrain air and plunge to depth, where increased pressure forces the air into solution, resulting in the potential to elevate TDG concentrations in the river downstream. Avista is pursuing structural spillway modifications that will break up the jet to reduce the depth of plunge and the length of time that the aerated water is held at depth, thereby reducing TDG levels downstream. The scientific literature includes considerable research about TDG and GBT. The focus of this paper is to document a new method to reduce TDG downstream of spillways with freely plunging spillway jets. For general information about TDG and GBT, the reader is referred to other sources such as Maynard (2008), Weitkamp (2008), Johnson (1975).

Avista's approach to the spillway modification design, construction, and monitoring has been incremental, with a goal to learn from each installation and to use site-specific performance data to guide the design for a full build-out of the concept. In 2012, Avista modified a single bay, the design of which was based upon extrapolation of studies conducted for other facilities and applications. In 2015, two additional bays are being modified; the design for these bays was developed with the benefit of site-specific Computational Fluid Dynamics (CFD) modeling to estimate plunge depth and the effect of the modifications on spillway capacity. This paper presents the two designs, the numerical modeling used for design development, and the field performance of the spillway modifications, which are the first full-scale application of this TDG abatement measure.

2. LAYOUT OF THE SPILLWAY MODIFICATIONS

Cabinet Gorge Dam has eight spillway bays and a four-unit powerplant with a hydraulic capacity of 1,100 m^3/s (38,800 cfs). Flow release from the spillway bays is controlled by 12.2-meter wide by 10.7-meter high (40-foot by 35-foot) vertical-lift roller gates, which are numbered sequentially from the right bank to the left bank (looking downstream). The drop from the end of the spillway to the downstream water surface varies with tailwater depth but is on the order of 12 meters (40 feet). The plunge pool is lined with a 1.5 meter (5 foot) thick concrete apron that generally follows the natural bathymetry at the time of construction, which varied substantially in elevation. The apron below Bays 5-8 has its invert at elevation 626 meters (2055 feet) and drops up to 4.6 meters (15 feet) at its end. The plunge pool invert is up to 20 meters (65 feet) lower below spillway bays 1-4, and there is a splitter wall dividing the two sides of the plunge pool. The shallow-side apron provides a physical constraint to the depth that a jet from Bays 5-8 may plunge. The plunge pool geometry, coupled with the interaction between spillway and powerplant discharge, creates complex flow patterns that likely affects the degree of TDG supersaturation in the plunge pool and river downstream. See Figure 1 for the general layout of the spillway and plunge pool.

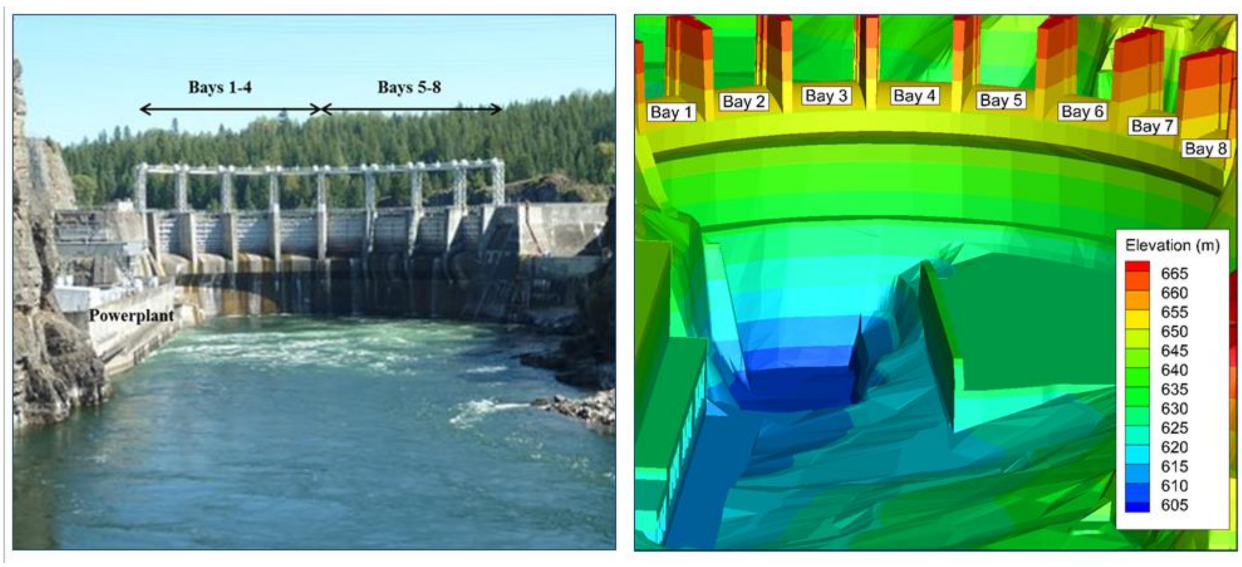
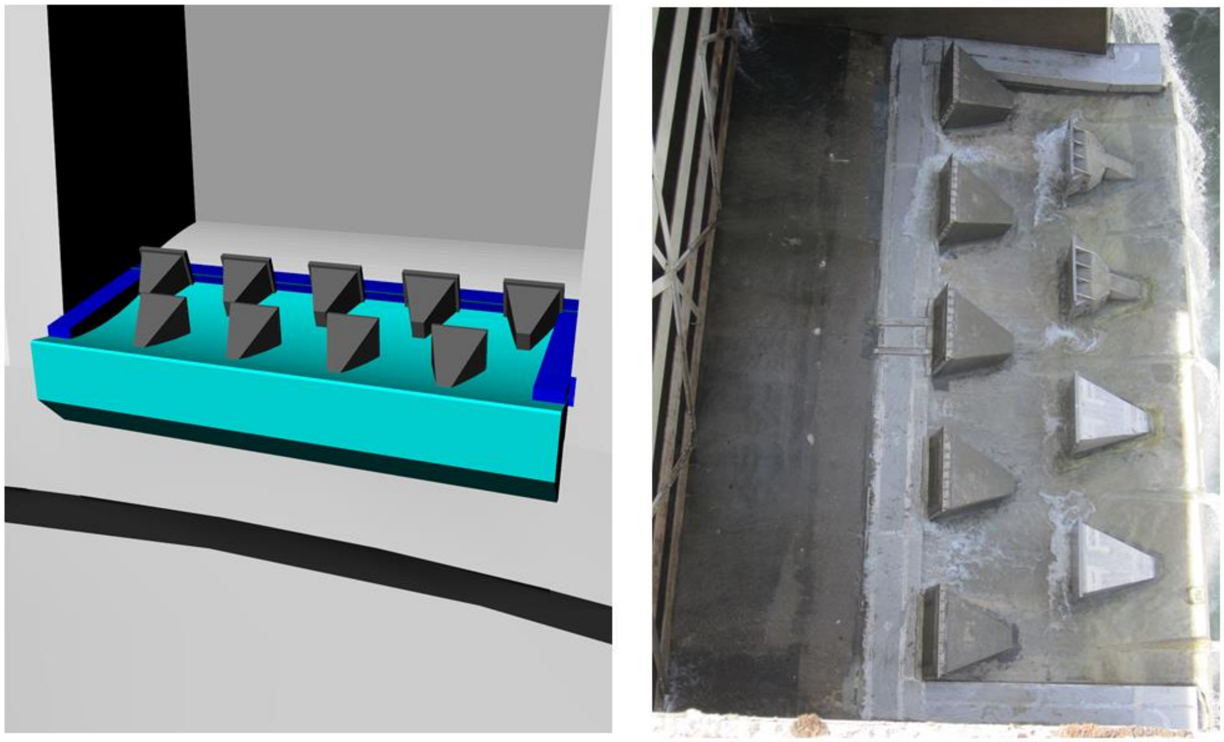


Figure 1. Cabinet Gorge Dam Layout and Plunge Pool Bathymetry

2.1. Spillway Bay 2 Prototype Modifications

The first spillway bay to be modified (Bay 2) features two rows of roughness elements and a flip bucket addition at the spillway terminus. The shape of the roughness elements is intended to mimic the supercavitating blocks studied by the United States Bureau of Reclamation (USBR) (Frizell 2009); however, the function and location of the roughness elements is different for the Cabinet Gorge application. The USBR sought to develop baffle blocks to dissipate energy in a stilling basin, whereas the roughness elements implemented at Cabinet Gorge seek to break up the spillway jet, thereby reducing the depth to which it will penetrate within the plunge pool. A ramp, 25.4 centimeters (10 inches) in height, is located immediately upstream of the first row of roughness elements. The Bay 2 ramp serves two purposes: to lift the tails of horseshoe vortices that form upstream of the roughness elements and to provide a conduit for air, which is supplied to reduce the potential for cavitation damage on the downstream row of roughness elements. Figure 2 shows the layout of the Bay 2 spillway modifications. As illustrated in the photo, the Bay 2 roughness elements have different designs; this was done to evaluate constructability and physical performance in anticipation of future construction on additional bays, but because the differences are all downstream of the roughness elements' faces, these variations do not affect TDG performance.



CFD Isometric   As-Constructed

Figure 2. Bay 2 Final Design

TDG supersaturation was measured in controlled field tests before and after Bay 2 was modified. In addition, field tests were run using Bay 7 to allow comparison between spillway discharges into the shallow and deep sides of the plunge pool. The controlled field tests produced the peak TDG measurements shown in Table 1.

Table 1. Bay 2 Modification TDG Performance, Spillway Only Operation

	Peak TDG (% Saturation)		
	Q = 156 m^3/s (5,500 cfs)	Q = 217 m^3/s (7,660 cfs)	Q = 302 m^3/s (10,660 cfs)
Bay 2 Before Modification	116.7	123.0	127.9
Bay 2 After Modification	110.5	115.2	120.3
Bay 7 Unmodified	110.7	112.6	114.5

Similar controlled tests were conducted with the powerplant operating. These tests were conducted with a total facility discharge of 434 m^3/s (15,320 cfs) evenly split between the spillway and the powerplant, i.e., 217 m^3/s from the spillway and 217 m^3/s from the powerplant. This set of tests attempted to determine if there was any effect of flow interaction between the spillway and powerplant discharges and whether the location of the powerplant discharge affected TDG supersaturation. The results are presented in Table 2.

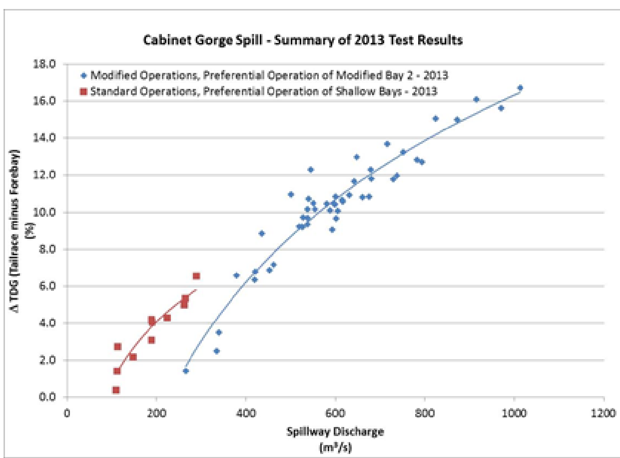
Table 2. Bay 2 Modification TDG Performance, Combined Spillway and Powerplant Operation

	TDG (% Saturation)					
	Average Forebay TDG		Peak Downstream TDG		TDG Increase	
Powerplant Unit and Spillway Bay Operating	Powerplant Unit 1	Powerplant Unit 4	Powerplant Unit 1	Powerplant Unit 4	Powerplant Unit 1	Powerplant Unit 4
Bay 2 After Modification	99.9	101.2	107.7	111.5	7.8	10.3
Bay 7 Unmodified	101.3	100.1	108.2	109.5	6.9	9.4
Bay 3 Unmodified	100.7	101	123.1	135.7	22.4	34.7

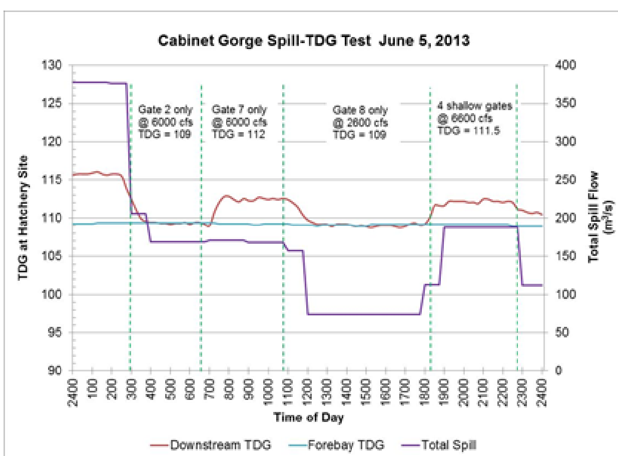
Comparing the results of the modified Bay 2 versus unmodified Bay 3 tests clearly demonstrates that the modifications are effective at reducing TDG generated by a spillway bay discharging into the deep side of the plunge pool. Comparing the results for modified Bay 2 and unmodified Bay 7 indicates that the modifications applied to a deep bay may approach, or even exceed, the performance associated with spillway releases from a shallow bay, depending on operations. Finally, the results indicate that the interaction between flow released from the powerplant draft tubes, flow released from the spillway, and the resulting plunge pool circulation patterns affect TDG supersaturation measured at the downstream TDG monitoring gauge.

Prior to implementing spillway modifications, spillway discharge was released preferentially through Bays 5-8 to minimize TDG supersaturation downstream. After completion of the Bay 2 prototype modifications, Avista changed the operating sequence as follows: the powerplant discharge was maximized, then the first 170 m^3/s (6,000 cfs) of spillway flow was released via modified Bay 2, and any remaining spillway discharge was evenly distributed between the four shallow spillway bays (Bays 5-8). Late in the season, the historic preferential operation in which flow was released only through Bays 5-8 was resumed; this allowed "opportunistic" testing of both operational regimes, which is summarized in Figure 3. Figure 3a indicates that the use of modified Bay 2 discharging up to 170 m^3/s (6,000 cfs) produces lower TDG supersaturation for a given spillway discharge than the historic preferential operation. Figure 3b directly compares the TDG measured upstream and downstream of Cabinet Gorge Dam for different spillway operations on a given day.

The foregoing tests validated the theory that breaking up the spillway jet through the use of roughness elements resulted in a measureable reduction in TDG.



a. Summary of Difference Between Forebay and Tailrace TDG
2013 Spill Season

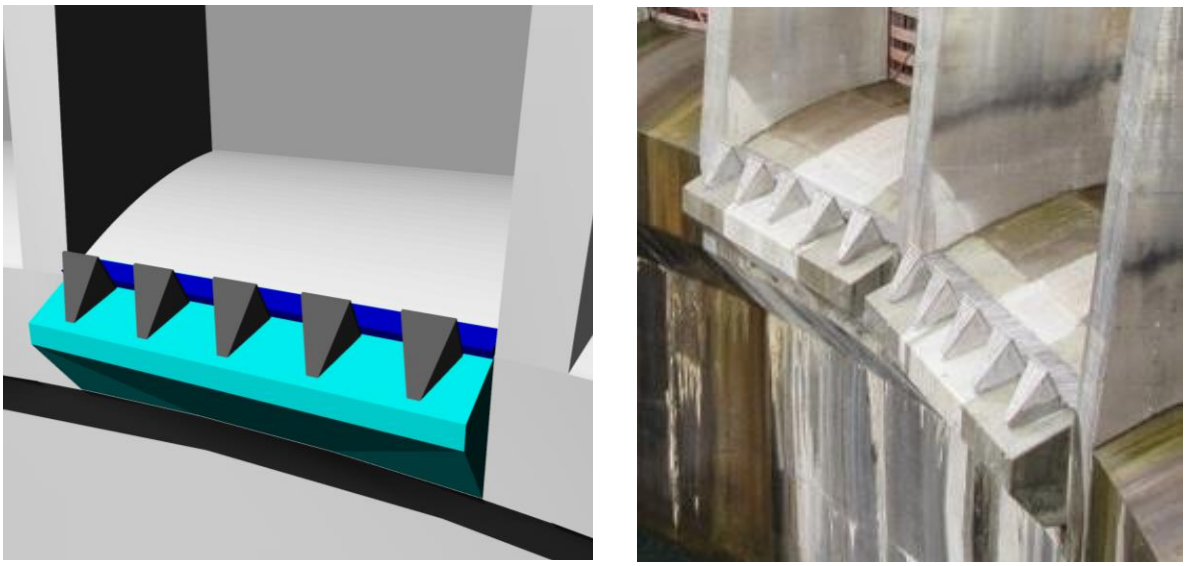


b. Comparison of Forebay and TDG for Varied Spillway Operations
June 5, 2013

Figure 3. Operations Testing, 2013 Spill Season

2.2. Spillway Bays 4 and 5 Modifications

The next two spillway bays to be modified (Bays 4 and 5) feature a single row of roughness elements, a ramp without air supply, and a straight tangential spillway end extension. Figure 4 shows the layouts of Bays 4 and 5. CFD modeling (as described below) was used to develop the design and to evaluate a range of constructible alternatives with the goal of minimizing the effect of the roughness elements on spillway capacity while still reducing TDG levels downstream of the dam. The new design is comparatively straightforward and is expected to treat a higher volume of spill flow per bay than the Bay 2 modifications. Bay 4 (deep plunge pool) and Bay 5 (shallow plunge pool) will be field tested in early 2016, and the results of those tests will guide the selection of which spillway bays to modify for the full TDG abatement project build-out.



CFD Isometric As-Constructed

Figure 4. Bays 4 and 5 Final Design

3. SPILLWAY BAY MODIFICATIONS - DESIGN DEVELOPMENT

The hydraulic design of the Bay 2 modifications was guided by physical and computational modeling that were in progress for a similar approach to TDG abatement being analyzed for Seattle City Light's Boundary Dam (Dunlop *et. al.* 2014), and on work performed by the USBR to develop the stilling basin for Folsom Dam (Frizell 2009). The layout of the Bay 2 roughness elements was established to fit the geometry of the Cabinet Gorge spillway but was not verified using site-specific modeling. The Bay 2 modifications were evaluated for TDG performance during controlled field tests, then Bay 2 was operated continuously for 26 days during the first spill season after construction. The field data validated the theory that roughening the spillway surface to break up the jet is an effective TDG abatement measure; however, cavitation damage to the spillway surface and roughness elements was observed. In response, a CFD model of a single spillway bay was developed to aid the refinement of the Bay 2 configuration. The final Bay 2 modifications (as seen in Figure 2) were field tested for 26 days in 2014. An inspection conducted by Avista after spillway operation confirmed that the revised design successfully mitigated cavitation damage.

Avista subsequently proceeded with implementing spillway modifications for two additional bays. The design for the additional bays was developed with the benefit of the single-bay CFD model. The model was used to the following purposes:

- Quantify any effect of the roughness elements on spillway capacity during passage of the Probable Maximum Flood (PMF)

- Refine the spillway modifications' design to minimize capacity effects while maintaining the reduction in jet plunge depth
- Reduce design and construction complexity, to the extent possible

The design development considered these goals in parallel, *i.e.* for a given layout, input on constructability was obtained prior to modeling, and modeling of the effect on discharge capacity and plunge depth were each considered. In addition, the design development process used the results of each run and the knowledge gained to guide the configuration of the subsequent runs.

3.1. CFD Model Description

The numerical modeling design tool selected for this study was the FLOW-3D software, developed by Flow Science Inc. The software solves the Reynolds-averaged Navier-Stokes equations to predict steady-state and transient flow fields in the model domain. In FLOW-3D, free surfaces are modeled with the volume of fluid (VOF) technique (Hirt and Nichols, 1981). The VOF method consists of three components: a scheme to locate the surface, an algorithm to track the surface as a sharp interface moving through a computational grid, and a means of applying boundary conditions at the surface. The software is also able to model air entrainment by turbulence at the free surface (Hirt, 2012). This capability was used to compare relative air entrainment depth in the plunge pool across the alternatives investigated for this study.

Two discrete computational domains were used for this study. The model domain used for the PMF investigations consisted of a single bay and a limited portion of the forebay. The mesh extended almost a full bay width on either side of the operational bay and included the full pier geometry. The model domain used for the assessment of plunge depth consisted of a single bay, a limited portion of the forebay, and approximately 150 meters (500 feet) of the plunge pool. The exact bathymetry of the forebay and plunge pool were not included in either model; instead, a flat surface at the approximate elevation of the invert at the dam was used. The upstream and lateral forebay boundary conditions were modeled as pressure boundaries. The downstream boundary in the PMF model was simulated as an outlet, allowing free discharge. The downstream boundary in the plunge depth model was simulated as a pressure boundary set to the tailwater elevation. Bay 2 was used as the representative bay for the study, and the corresponding tailrace invert elevation was set to 606.6 meters (1990 feet). This approach allowed the design development for Bays 4 and 5 to build on the modeling work completed for the Bay 2 final design and provided a representative bay for assessing plunge depth into a deep bay.

The computational mesh for the PMF model domain consisted of approximately 2.2 million cells with cell size ranging from 1 meter in the forebay to 8 centimeters in the vicinity of the roughness elements. The computational mesh for the plunge depth model domain was made up of roughly 2.6 million cells with cell size spanning from 1.5 meters in the tailrace to 15 centimeters in the vicinity of the roughness elements.

The air entrainment model estimates the rate at which gas is entrained into the flow by balancing the stabilizing forces (gravity and surface tension) and destabilizing forces (turbulence) (Flow Science, 2014). The air entrainment model setup used the default settings as no field data were available for refinement of the coefficients. Bulking and buoyancy were both included in the air entrainment model, and the renormalized group (RNG) k-ε turbulence model was used based on its robustness and on the advice of Flow Science.

Ten configurations were simulated using the CFD model. These included the baseline (no modifications), the existing Bay 2 geometry, a flip bucket without any roughness elements, and seven different layouts of roughness elements and end treatments. The seven alternative layouts considered changes to the following parameters:

- Roughness element height
- Position of the upstream row of roughness elements
- Spillway end extension configurations
- Roughness element number, orientation, and relative positioning
- Number of rows of roughness elements
- Number of roughness elements per row

3.2. Spillway Capacity during Passage of the PMF

The Bay 2 roughness elements are located in a zone of supercritical flow downstream from the critical flow control at the spillway crest, but they are located high on the spillway, and the flip bucket changes the trajectory of the flow downstream of the roughness elements; therefore, the effect of the roughness elements on spillway capacity could not be conclusively determined using hydraulic theory alone. The CFD model was used to evaluate what effect, if any, the spillway modifications would have on spillway capacity during passage of the PMF.

The following conditions were imposed in the CFD model for the simulation of the PMF discharge capacity: the spillway gate was removed completely from the computational domain, the forebay water surface elevation was set to the PMF peak static reservoir level, and the model was run to simulate 60 seconds of operation in order to capture the range of turbulent flow variation. The discharge through the spillway bay was estimated by monitoring the flow rate at six vertical planes (computational baffles) placed along the spillway. The six baffles were used to improve the accuracy of the computed discharge and to provide accurate comparison across the different spillway geometries.

The discharge during passage of the PMF was determined using the CFD model for each of the spillway modification layouts presented in Table 3. The results were compared to the discharge computed by the CFD model for an unmodified bay. The CFD results for the baseline condition at the design flow rate showed good agreement with the spillway rating curves (within 1%).

Table 3. Effect of Spillway Modifications on Spillway Capacity during Passage of the PMF

Layout	PMF Capacity Reduction from Baseline (%)	Details
Baseline (Unmodified)	N/A	Pre-Modification Baseline
Layout 1	8.1	Max. Block Height (2 rows *h*=1.22 meters (48 inches))
Existing (Bay 2 Prototype)	6.7	Bay 2 Prototype (2 rows – U/S *h*=1.02 meters (40 inches), D/S *h*=0.94 meters (37 inches))
Flip Bucket Only	5.4	Flip Bucket Only
Layout 2	2.5	Single Row *h*=0.94 meters (37 inches), Tangential End Ext.
Layout 3	3.2	Single Row *h*=1.22 meters (48 inches), Tangential End Ext.
Layout 4	4.0	Single Row *h*=1.52 meters (60 inches), Tangential End Ext.
Layout 6	3.0	Single Row *h*=0.94 meters (37 inches), 5 Blocks Rotated, Tangential End Ext.
Layout 7	3.0	Single row *h*=1.14 meters (45 inches), Tangential End Ext.

Layout 1 resulted in a decrease of 8.1 percent in the capacity of a single bay, as compared to the baseline (unmodified) spillway bay capacity. The geometry of Layout 1 represents the largest roughness element that could be physically constructed given the available space.

The next run documented the performance of the Bay 2 prototype and concluded that the as-constructed geometry reduced the discharge of that bay during passage of the PMF by 6.7 percent.

The third run isolated the primary factors causing the reduction in capacity. The geometry of the Bay 2 prototype was simulated with the roughness elements removed, *i.e.*, the only change from the baseline condition was the addition of the flip bucket end extension. The capacity reduction associated with the Bay 2 prototype geometry (6.7 percent) compared with the flip bucket only geometry (5.4 percent) demonstrates that the flip bucket end extension is a primary variable affecting spillway capacity. Based on this finding, the flip bucket end extension was removed from further consideration, and subsequent alternatives were developed using a tangential end extension.

The purpose of the next simulation (Layout 2) was to determine the PMF effect of roughness elements placed as far downstream on the tangential end extension as possible. The maximum length of the end extension and the location of the roughness elements were dictated by structural design and constructability requirements. The roughness element height was set equal to the height of the downstream row of roughness elements in the Bay 2 prototype (0.94 meters). This produced a reduction in discharge capacity during the PMF of 2.5 percent. Simulation of the effect of the change in geometry on plunge depth was conducted in parallel with the PMF analysis and indicated that a single row of roughness elements on a tangential end extension could provide satisfactory TDG performance.

The next four simulations (Layouts 3-6) investigated a range of roughness element heights and arrangements.

The final simulation (Layout 7) was performed in response to a change in the design discharge from 170 m^3/s (6,000 cfs) to 204 m^3/s (7,200 cfs), which was implemented to maintain the desired total TDG abatement design flow while reducing the number of bays that would be modified for full build-out from seven to six.

Layout 7, the preferred alternative, was subsequently analyzed using HEC-HMS to determine the change in peak reservoir elevation that would result from the reduction in spillway capacity. This analysis confirmed that although the amount of freeboard would be reduced, the peak water surface would remain below the critical reservoir elevation for dam safety during passage of the PMF.

3.3. TDG Performance

A primary variable driving TDG production is the depth that entrained air bubbles are carried into the tailwater by the plunging spillway jet(s). Other factors include the duration at which the air bubbles are held at depth and potential mixing of air with powerhouse discharge due to plunge pool circulation patterns. Plunge depth was used as a surrogate for TDG performance to develop the Bay 4 and 5 design. The single-bay model and its simplified tailrace did not allow consideration of the effects of time for gas transfer and plunge pool circulation patterns on TDG; however, for a comparative analysis, plunge depth was considered an acceptable method to estimate relative TDG performance.

The CFD model was run for a range of alternatives, and the results were post-processed to analyze air entrainment at depth. The post-processing procedure provides a simplified representation of the transient and three-dimensional aspects of the plunging spillway jet and TDG generation process. The maximum plunge depth associated with the different spillway modification geometries may occur in different locations and will change for each computational time step. The post-processing procedure addresses this by accounting for both the areal and temporal variation in air concentration by including both area and time in the analysis. The plunge pool region was “sliced” horizontally at a constant elevation from the invert (elevation 606.6 meters) to above the water surface elevation (elevation 633.8 meters) at 1.5 meter increments, and the air concentration for each elevation (or slice) was averaged. This was completed for each time step; then, the air concentration was averaged over 30 seconds of data (31 time steps) to develop an air concentration profile spanning the water column. The region to which the post-processing analysis was applied encompassed the jet impact area in the tailrace, as shown in Figure 5.

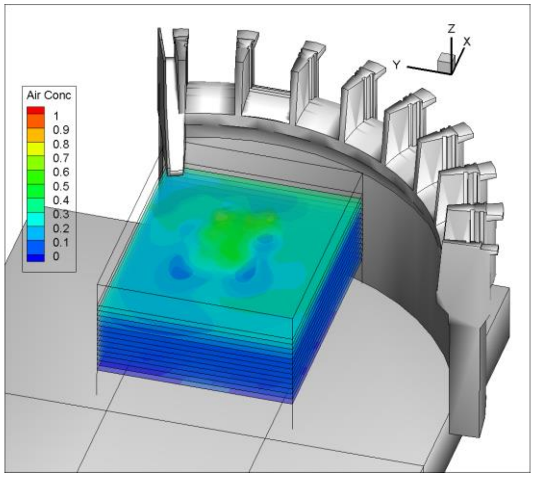


Figure 5. Area used in Plunge Depth Analysis with Slices (Baseline)

For the purposes of comparison, the maximum depth of plunge was assumed to be represented by the depth at which the air concentration was equal to 1 percent. The elevation at which the air concentration would diminish to 1 percent was calculated by linearly interpolating between the two elevations at which the air concentration data went from more than 1 percent to less than 1 percent. The resulting values are presented in Table 4.

Table 4. Plunge Depth Results for 1 Percent Air Concentration

Layout	**1% Air Concentration**		**Details**
	Difference Compared to Baseline (m)	**Percent of Baseline Plunge Depth (%)**	
Baseline (Unmodified)	NA	NA	Pre-Modification Baseline
Layout 1	-4.4	62.3	Max. Block Height (2 rows @ 1.22 meters)
Existing (Bay 2 Prototype)	-4.7	59.7	Bay 2 Prototype Geometry
Layout 2	-5.9	49.7	Single Row @ 0.94 meters, Tangential End Ext.
Layout 3	-5.8	50.5	Single Row @ 1.22 meters, Tangential End Ext.
Layout 4	-5.5	52.6	Single Row @ 1.52 meters, Tangential End Ext.
Layout 5	-4.9	57.9	Single Row @ 0.94 meters, 4 Blocks Rotated, Tangential End Ext.
Layout 6	-5.8	50.0	Single Row @ 0.94 meters, 5 Blocks Rotated, Tangential End Ext.
Layout 7[1]	-5.9	49.2	Single Row @ 1.14 meters, Tangential End Ext.

1. All runs were completed for a discharge of 170 m^3/s except Layout 7, which was run for 204 m^3/s.

Layout 7 produces the shallowest depth of plunge despite having been run for a higher design discharge; however, given the assumptions and limitations of the plunge depth modeling approach, the observed variations for the all of the alternatives except baseline are within the accuracy of the estimate. Importantly, Layout 7 has less effect on discharge capacity while achieving plunge depths that are comparable to Bay 2, which has been proven effective for TDG reduction through field testing.

4. CONCLUSIONS AND APPLICATION OF RESULTS

Avista is implementing modifications to reduce TDG downstream of Cabinet Gorge Dam using an incremental approach of analysis and field study. The initial prototype installation has demonstrated, through field operation and monitoring, that modifying a spillway through addition of roughness elements to break up the jet is an effective means to reduce plunge depth and the associated TDG production. CFD modeling was an effective method to improve upon the prototype design and achieve performance and constructability improvements for the modification of subsequent bays.

The purpose of the CFD modeling for design development was to provide a basis upon which to choose how to modify two additional spillway bays and to select which bays to modify. The Bay 2 modifications with two rows of roughness elements have been field tested and shown to reduce TDG downstream of Cabinet Gorge Dam. However, the two-row design requires a mechanism to introduce air in order to limit the potential for cavitation damage to the downstream row. In addition, CFD modeling indicates that the Bay 2 design reduces the spillway discharge capacity by 6.7 percent. For these reasons, Avista sought an alternative design that would provide a measureable reduction in plunge depth with a limited effect on discharge capacity during passage of the PMF. The finding that the two-row configurations had adverse effects on spillway capacity led to the development of a tangential end extension that would permit construction of a single row of roughness elements as far downstream from and below the spillway crest as possible. Several variations of a single row configuration were evaluated in the CFD model, and a layout was developed that would balance TDG reduction, effect on spillway capacity, and ease of construction.

Keeping with the step-wise design development philosophy, Avista will implement the recommended design on two spillway bays, then field monitor the performance before deciding which bays to modify for the full build-out condition. This intent was known when the simplified, single-bay modeling approach was adopted. A notable unknown is how the jet interaction with the shallow concrete apron will affect TDG after modification. In addition, the interaction of jets from adjacent bays has not yet been evaluated. For these reasons, the modifications will be implemented on Bays 4 and 5, which are located to either side of the training wall that separates the shallow and deep sides of the plunge pool, thereby allowing the aforementioned variables to be examined through field testing.

5. FUTURE WORK

Construction of the modifications to Bays 4 and 5 began during the Fall of 2015 and are scheduled to be complete in early 2016 prior to spill season. Avista intends to execute controlled testing to measure the TDG performance of Bays 4 and 5 singly and in combination prior to the spring freshet. During the spill season, Avista will continuously collect TDG data upstream and downstream of Cabinet Gorge Dam and will record all facility operations. These data will be analyzed during the summer of 2016, and based on the results of the field tests, Avista will decide whether to further refine the design of the spillway modifications or implement the present design on additional bays.

6. ACKNOWLEDGMENTS

The authors would like to recognize Seattle City Light, whose willingness to share the results from their earlier studies on TDG abatement enabled the expedited implementation of prototype designs at Cabinet Gorge Dam.

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