Hydraulic Design of Total Dissolved Gas Mitigation Measures for Boundary Dam

by

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ABSTRACT

Boundary Dam, located on the Pend Orielle River in northeastern Washington is Seattle City Light’s (SCL’s) major hydroelectric power generating resource. The facilities include a 340-foot high variable radius concrete arch dam, with two service spillways, one located adjacent to either abutment, seven low-level sluices through the dam, and a power house with six turbines, having a total installed generating capacity of 1,070 Mw.

SCL is in the process of applying for renewal of their FERC license to operate the project. One of the studies that are being performed in support of the application is investigation of the generation of total dissolved gas (TDG) in the project tailrace by flow passage through the project facilities. Sweeney, et. al. (2008) reported on studies aimed at developing project operational changes that will result in compliance with the state water quality standards during flood passage. These studies showed that operational changes alone will not ensure compliance.

Additional studies are presently underway to assess physical modifications to the existing spillways and sluices and to further optimize their operations to improve TDG performance. Modifications considered include adding deflectors to the spillways and sluices to spread the jets and reduce penetration into the tail water and or adding turbulence inducing elements to the spillway chutes to enhance breakup of the jets.

A 1:25 scale physical hydraulic model of the sluices, spillways, and immediate project tailrace and a three-dimensional computational fluid dynamics (CFD) numerical model of the same region have been constructed as tools to aid in the design development. The physical model is being used to qualitatively assess the relative jet penetration and air entrainment characteristics of various alternative operations and structural modifications. The CFD model will be verified against physical model results for simulations at scale and then used to predict outcomes in the field.

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Introduction

Seattle City Light (SCL) is in the process of applying for renewal of their FERC license to operate their major hydroelectric project, Boundary Dam. As part of the relicensing process, SCL will need to obtain water quality certification from the Washington Department of Ecology (Ecology). Developing a plan for abatement of total dissolved gas (TDG) above the 110 percent TDG saturation standard is part of this certification process. The statutory requirement is “Identification of all reasonable and feasible improvements that could be used to meet standards, or if meeting the standards is not attainable, then to achieve the highest attainable level of improvement” (Ecology 2005).

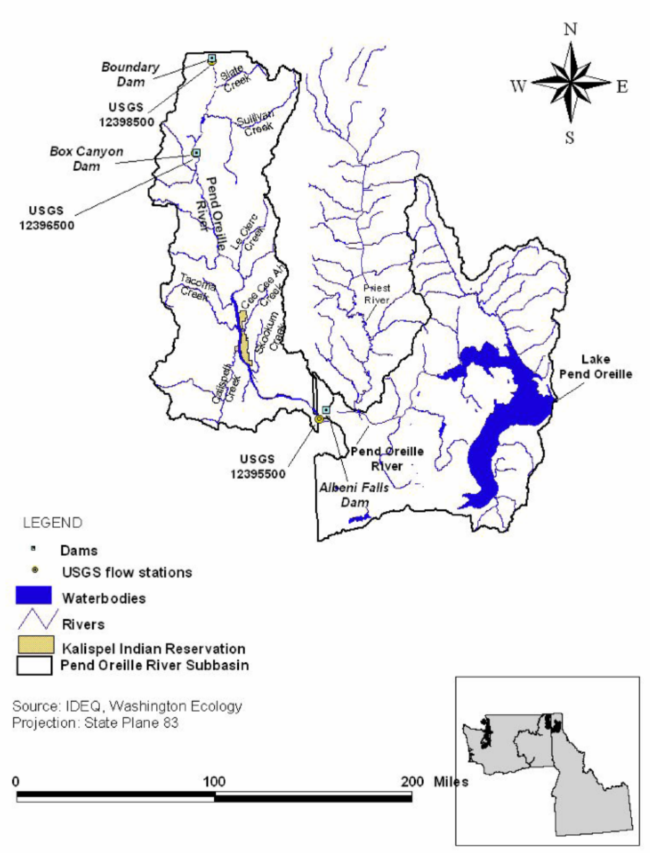
TDG is the amount of air held in saturation in the water and is quantified in the standards in terms of percent of saturation pressure relative to ambient barometric pressure. The generation of TDG in the project tailrace by flow passage through the project facilities is being investigated. SCL is trying to determine if the TDG of the releases will meet the state water quality standard and, if not, to develop facility and/or operational changes that will result in compliance.

Washington Department of Ecology (WDOE) recognizes that incoming flow conditions and flood flows may result in elevated gas conditions that dam operators are not able to ameliorate. The standard is waived for conditions where incoming TDG is greater than that leaving the Project and for flow exceeding the 7Q10 flow event. The 7Q10 flow is the highest flow of a running seven consecutive day average using the daily average flows that may occur in a 10-year period., which is 108,300 cubic feet per second (cfs) for the Project (SCL 2006).

Project Description

The Boundary Hydroelectric Project (Boundary Project) is located on the Pend Oreille River in northeastern Washington, 1 mile south of the Canadian border, 16 miles west of the Idaho border, and 107 miles north of Spokane, as shown in Figure 1. The Boundary Project is the third of five dams on the Pend Oreille River. Seven Mile and Waneta dams are located downstream in Canada. Box Canyon Dam is immediately upstream of the Boundary Reservoir, and Albeni Falls Dam is 50 miles farther upstream.

The Boundary Project, shown in Figure 2, consists of an arch dam, reservoir, and underground powerhouse. Boundary Dam is a variable-radius concrete arch dam with a structural height of 340 feet, a crest length of 508 feet and a total length of 740 feet with both spillways. The gross head of the project for power generation purposes is 261 feet. On each abutment there is a 50-foot-wide spillway with a 45-foot-high radial gate. The two spillways have a combined total maximum discharge capacity of 108,000 cubic feet per second (cfs). In addition, there are seven low-level sluices through the dam under a head of 190 feet that provide 252,000 cfs of capacity. Boundary Project powerhouse flow capacity is approximately 55,000 cfs, through six generating units, Units 51 through 56 (two equipped with 268,000-hp Francis turbines and four equipped with 208,000-hp Francis turbines). Flows through the Boundary Project powerhouse discharge into the tailrace immediately below the dam. The Boundary Project operates in a load-following mode, generating power during peak-load hours and curtailing generation during off-peak hours.



Source: IDEQ, Washington Ecology
Projection: State Plane 83

Figure 1. Boundary Project Site Map

Current Boundary Project operations and forebay TDG are influenced by upstream project operations at Albeni Falls and Box Canyon dams. Albeni Falls Dam has a powerhouse hydraulic capacity of 29,000 cfs and Box Canyon Dam currently has a powerhouse hydraulic capacity of 27,000 cfs. Above these river flows, both dams increase the TDG in the river and in the Boundary Project forebay as flow is passed through spill gates and plunges into the tailwater. As river flow increases, both upstream projects gradually pull their gates out of the water, until at flood levels they are all completely out of the water to pass flood flows unimpeded (Albeni Falls Dam at 74,000 cfs and Box Canyon Dam at 90,000 cfs), removing the plunge and effectively eliminating their TDG contributions to the river and reducing the Boundary Project forebay TDG. Figure 3 shows the 2002 river flows, forebay and tailrace TDG, and project operations and illustrates this process.

The 7Q10 flow for the Boundary Projects is 108,300 cfs and the powerhouse capacity is 55,000 cfs, leaving a target flow for TDG abatement of 53,300 cfs.

Figure 2. Boundary Project Overview

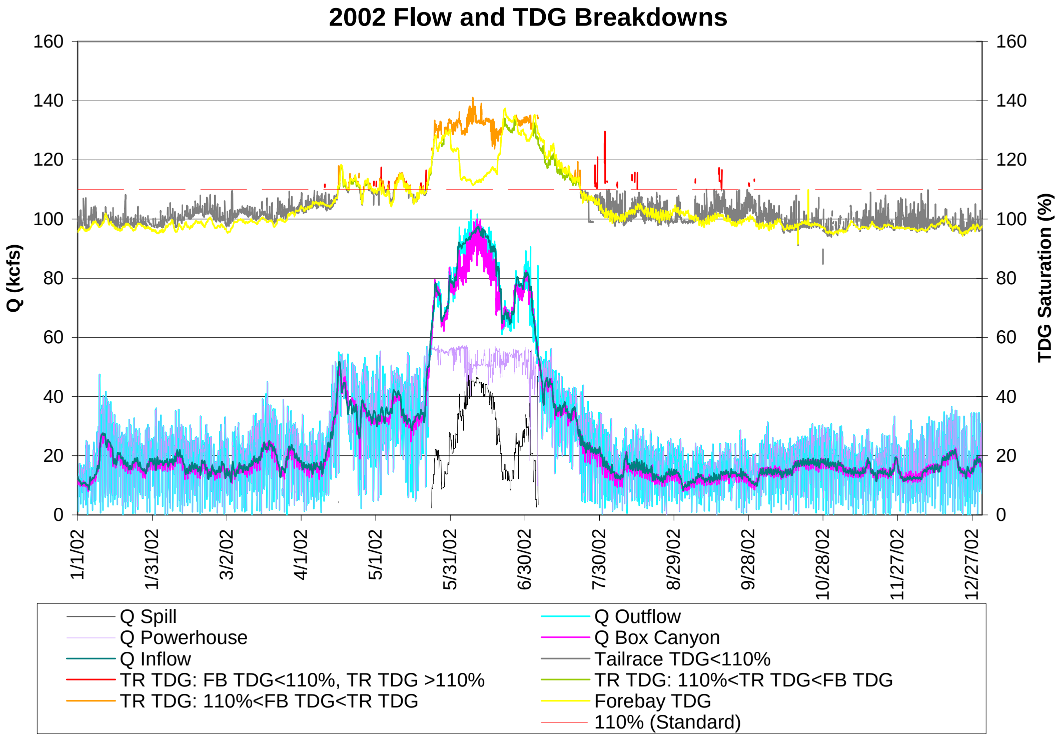


Figure 3. 2002 Boundary Project Flow and TDG

TDG Generation Mechanism

High TDG concentrations at the Project during spill are caused by the spillway configuration: After a short spillway, the flow is released into the air as a falling jet; this jet falls to the plunge pool, gaining energy as it falls. At the intersection between the plunge pool and the falling jet, a high velocity gradient entrains a substantial quantity of air into the flow, which continues as a vertically oriented jet in the water. This air is carried to the bottom of the plunge pool by the vertically oriented jet. The hydrostatic pressure on the bubbles of entrained air increases by one atmosphere for each 34 feet of depth. The bubbles are smaller under pressure, so the concentration of oxygen and nitrogen per unit volume is correspondingly higher. The local equilibrium that the water can eventually reach is based upon this higher concentration, which can be 200 percent of atmospheric saturation at 34 feet of depth, or higher at deeper depths. The local equilibrium of 110 percent occurs at 3.4 feet of depth. The rate of gas transfer from the bubbles under pressure to the water depends upon the turbulent energy of the water (i.e. the time the bubble is at depth), the bubble surface area present, and the difference between local equilibrium and the water concentration.

There are therefore three conditions necessary to result in the high TDG concentrations of the tailwater of a spillway:

1. An energetic flow with a substantial amount of turbulent energy. This condition exists below most spillways and at most dam outlets. One of the best ways to reduce the energy in a flow is to extract it through hydroturbines. The other mechanism is to reduce the energy through head loss as it moves down the channel or conduit. This is the approach used by baffled and stepped spillways.
2. Air entrainment that occurs due to the jet falling through the air and plunging into the pool. In a high velocity, free surface flow, air entrainment is probably the most difficult of the three conditions to avoid. The devices proposed to eliminate air entrainment have all proven to be expensive and often not effective.
3. Air bubbles that are carried to depth. TDG supersaturation requires the bubbles be at depth. If most of the bubbles are kept near the surface, the dissolved gas concentration will be close to 100 percent. This is the approach used by spillway deflectors, which deflect the flow at the bottom of the spillway across the surface of the plunge pool. This is a cost-effective solution which has limitations at higher discharges, because the surface jet that is deflected will expand and carry the bubbles with it. The ~0.7 fps rise velocity of the bubbles and the high turbulent velocities in the jet results in a large portion of the bubbles being pulled to depth with the expansion of the surface jet.

The plunging jet immediately downstream of Boundary Dam has all three of these conditions. Reduction of any of the three, without increasing any of the others, will likely result in lower TDG concentrations.

Effects of Boundary Project Operations on Tailrace TDG

As reported by Sweeney et. al. (2008), historic TDG data and data acquired during tests specifically designed for the purpose were analyzed to determine if changes in project operations might improve TDG performance by spreading the jet impact on the receiving pool water surface and reducing the depth to which air bubbles are driven.

For flow through spill Gate 1 only, the Boundary Project appears to strip TDG at spill flows from 0 to approximately 8,000 cfs under the combined action of spill gate and powerhouse operations. This effect decreases with increasing spill flow, with 1% to 1.5% stripping of TDG typical for spill flow between 2,500 and 7,000 cfs for combined powerhouse and spill flows. The powerhouse and spill flows combine with a neutral effect at spill flows of approximately 8,000 cfs. Above 8,000 cfs, TDG production due to total outflow increases with spill to about 7% at 19,000 cfs and 16% at 37,000 cfs, which was the maximum test spill flow. The neutral point for spill effects alone after discounting powerhouse effects through the mass balance equation is 4,500 cfs.

A similar analysis was conducted for instances when Gate 2 operated alone and instances when Gate 1 and Gate 2 operated simultaneously. The general conclusions from the spill analysis are as follows:

- For spill through Gate 1 alone in combination with powerhouse flows, the Boundary Project appears to strip TDG for spill flows up to about 8,000 cfs.
- For spill through Gate 2 alone in combination with powerhouse flows, the Boundary Project appears to strip TDG for spill flows up to about 9,500 cfs. However, this conclusion is based on a limited number of tests and the resulting regression is highly leveraged by two high spill flow tests (≈45,000 cfs) with no intermediate flow data (10,000-45,000 cfs).
- For spill through both gates in combination with powerhouse flows, the Boundary Project appears to strip or have neutral impact on TDG for spill flows up to about 13,000 cfs, when forebay TDG is less than 120%. When forebay TDG is greater than 120%, the range of stripping action increases up to a spill flow of 15,000 cfs.
- Additional data is required to determine any difference in TDG production as a result of varying the ratio of spill flow from gates 1 and 2.

SCL conducted a series of sluice gate tests in 2006 for flows between 1,500 cfs and 17,100 cfs and incoming TDG between 112 and 127%. Overall TDG production for all tests was fairly neutral and increased uniformly with sluice flow regardless of forebay TDG, with maximum stripping of 1.8% and maximum TDG generation of 1.1% for combined powerhouse and sluice flow. Sluice flows ranged up to 5,600 cfs for a 5-foot gate opening. The sluice tests showed promise for stripping TDG for gate openings up to 4 feet, and up to 5 feet at times.

While these analyses showed that some incremental improvements in TDG performance can be achieved with project operations, additional structural measures may be required to achieve the desired TDG mitigation.

Structural Mitigation Alternatives Under Consideration

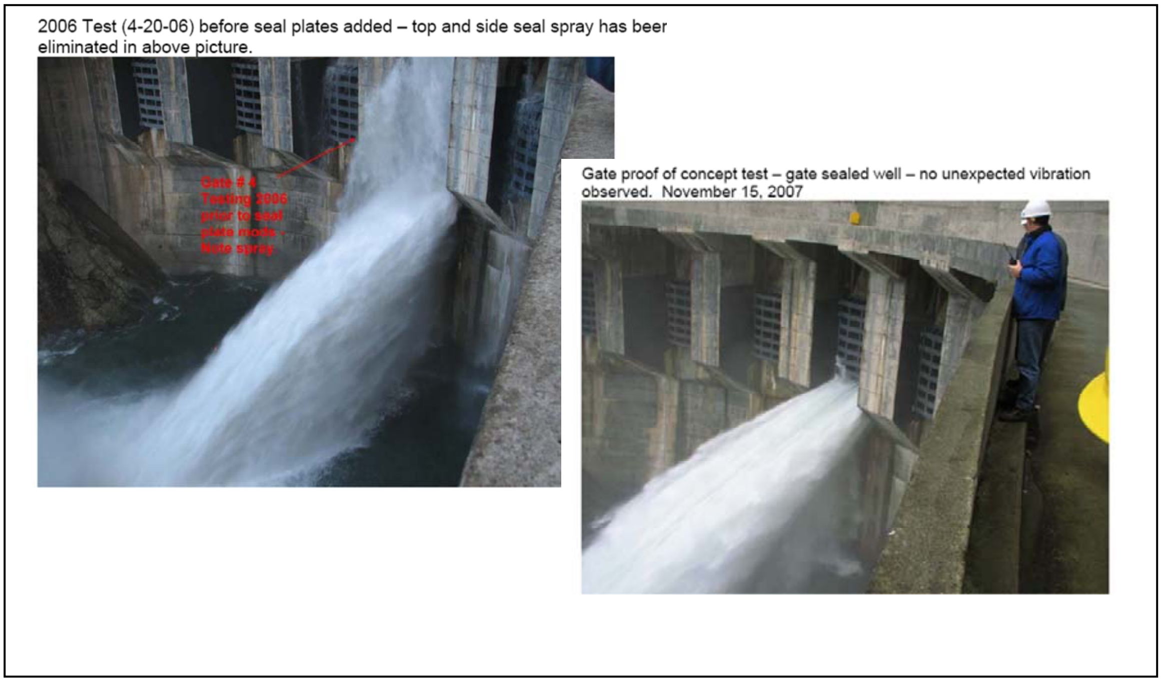
Several brainstorming sessions were held to develop TDG mitigation concepts. A shortlist was further developed and evaluated by knowledgeable experts in geology, dam construction, hydraulics, TDG issues, gate design, and structural design. The experts' qualitative evaluation included the following criteria for alternative selection:

- Low risk of fish injury
- High likelihood of improving TDG conditions downstream
- Technically feasible for construction and permitting;
- Minimal dam safety concerns
- Lower cost for implementation
- Maintenance and access are not impaired
- Existing Project operations are not impacted
- Ability to prototype concept
- Concept can be phased and adjusted

Three alternatives were selected for more detailed examination:

1. Throttle Sluice Gates, which involves modification of the sluice gate sealing system so they can be operated in partially open positions (see Figure 4);
2. Roughen Sluice Flow, which entails modification of the sluice gate outlets to break up and spread flow (see Figure 5); and
3. Spillway Flow Splitter/Aerator, which entails modifying the spillways to aerate, break up and spread flow (see Figure 6).

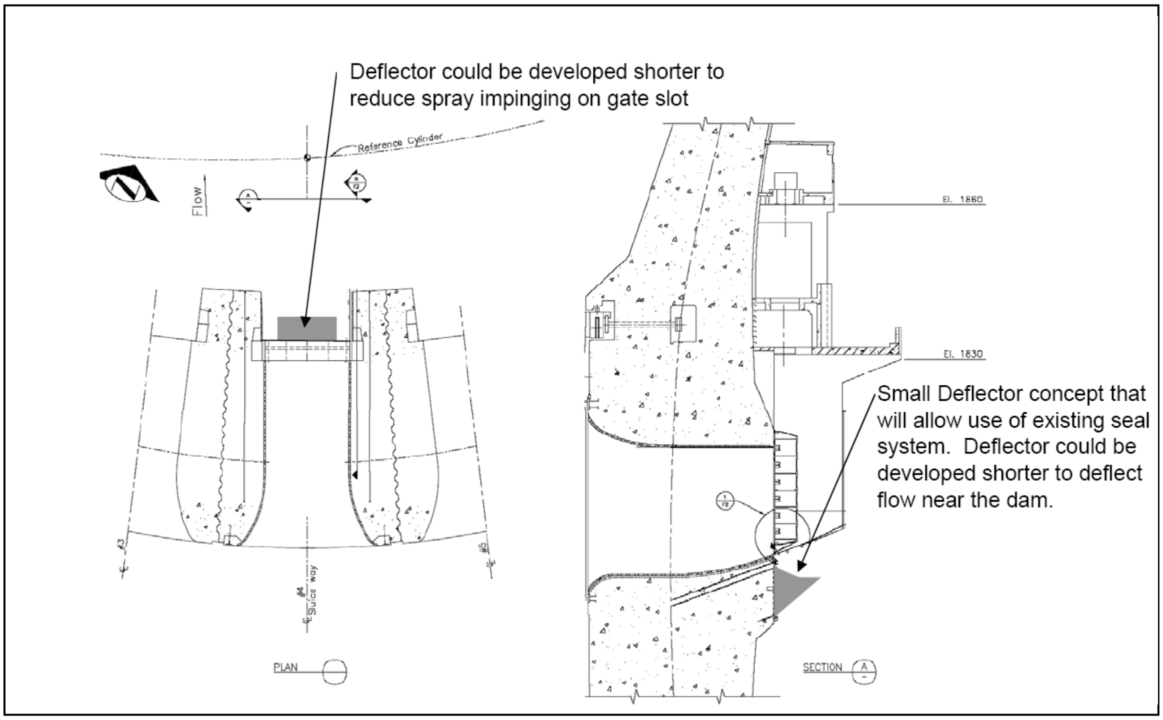
These three gate alternatives all involve spilling flow through existing outlets (the seven sluice gates and two spillway gates) into the plunge pool and rely on reduction in TDG production by spreading the flow and limiting plunging effects of the confined jets. The historical performance of these outlets at small gate openings indicates potential for successfully reducing tailwater TDG levels.



2006 Test (4-20-06) before seal plates added – top and side seal spray has beer eliminated in above picture.

Gate proof of concept test – gate sealed well – no unexpected vibration observed. November 15, 2007

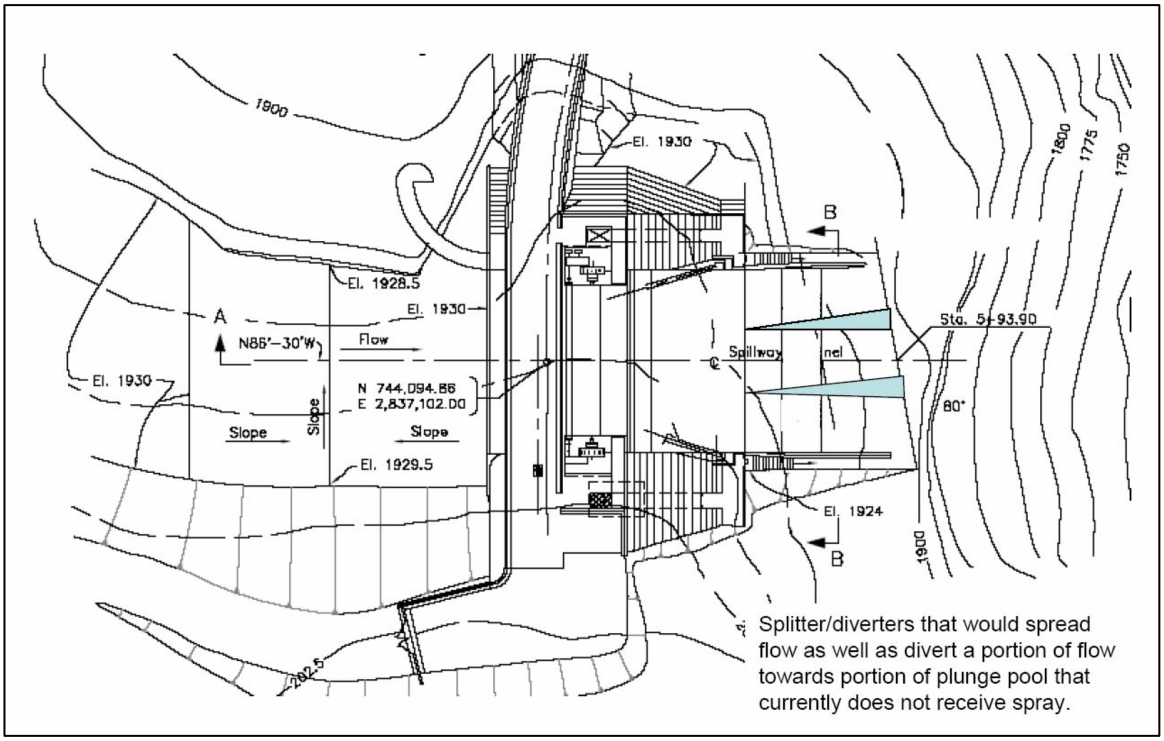
Figure 4. Throttled Sluice Gate Operation



Deflector could be developed shorter to reduce spray impinging on gate slot

Small Deflector concept that will allow use of existing seal system. Deflector could be developed shorter to deflect flow near the dam.

Figure 5. Roughen Sluice Flow



Splitter/diverters that would spread flow as well as divert a portion of flow towards portion of plunge pool that currently does not receive spray.

Figure 6. Spillway Flow Splitter/Aerator

Analysis of Alternatives

Resolution of many of the hydraulic design issues will rely heavily on the results of both physical and numerical hydraulic models. Both models will be used in complementary roles in order to maximize their particular strengths. The greatest strength of the numerical model is the capability it offers designers to explore, develop, and compare various design concepts relatively quickly and easily. Modifications can be made quickly in our “numerical flume”, and tested to ensure a proposed design alteration performs as expected. The model will also be used in the near future to assist in predicting the relative TDG performance of each of these alternatives.

Physical Hydraulic Modeling

The physical hydraulic modeling will be performed using the 1:25 scale model constructed in 2008, shown in Figures 7 and 8, and which is presently being calibrated.

The physical model will provide a tool that can be used to test various sluice and spill gate operational scenarios and visualize the resulting jet interactions, water surface impact areas, and subsurface flow conditions and mixing in the plunge pool (This operational testing can be more readily done and results interpreted using a physical model than using a CFD model). The physical model will also provide a basis for verification of CFD models of the Project outflow release structures.

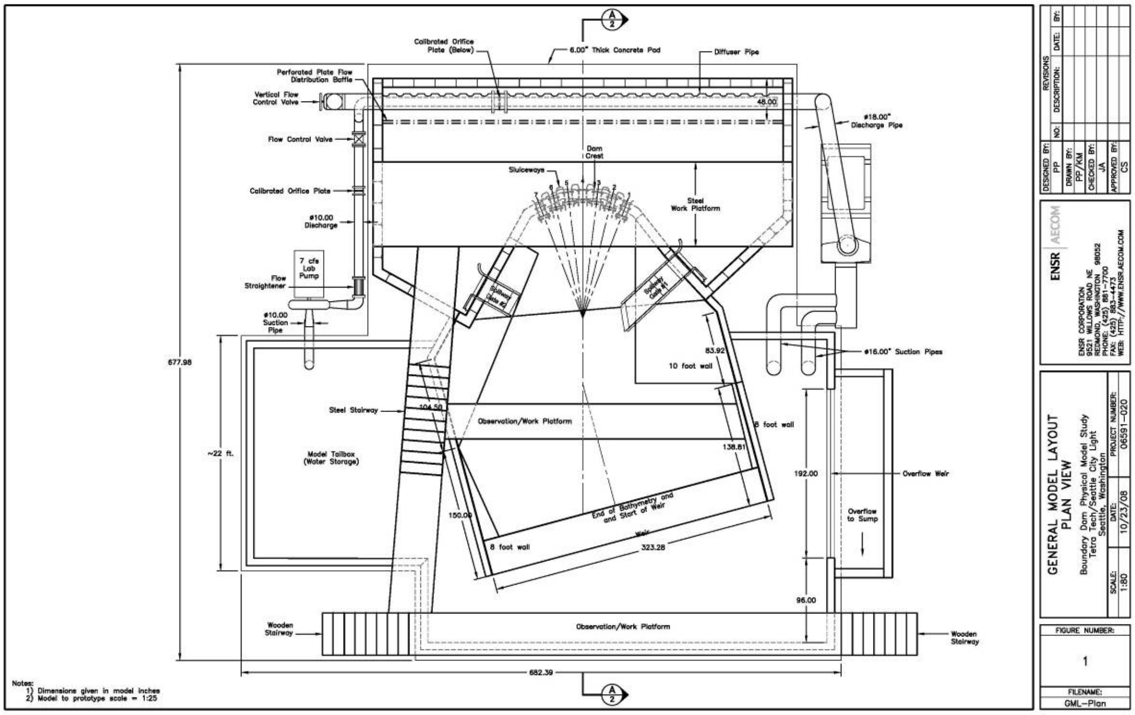


Figure 7. Physical Model Layout

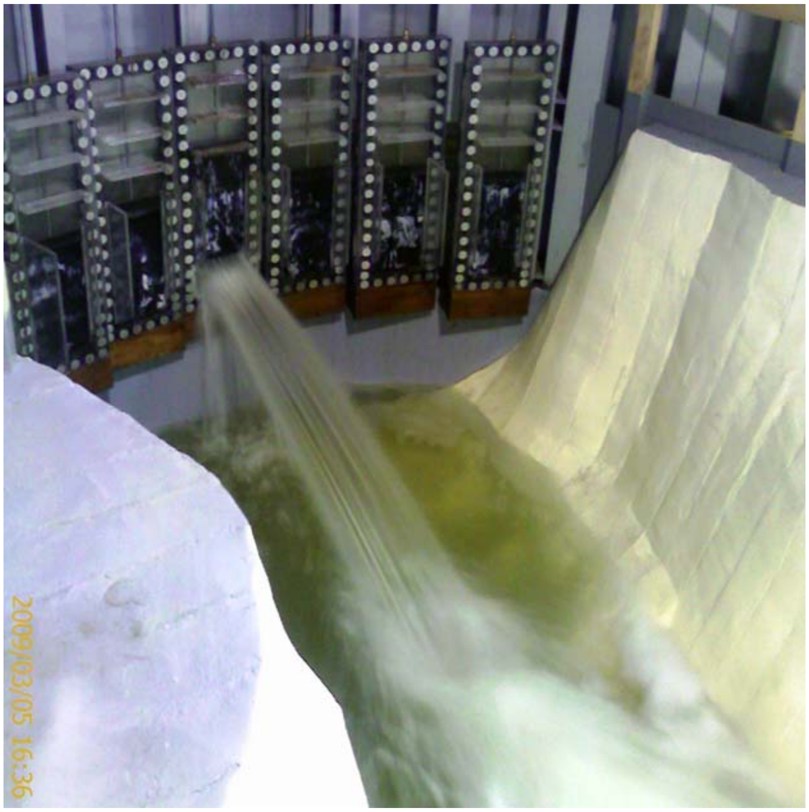


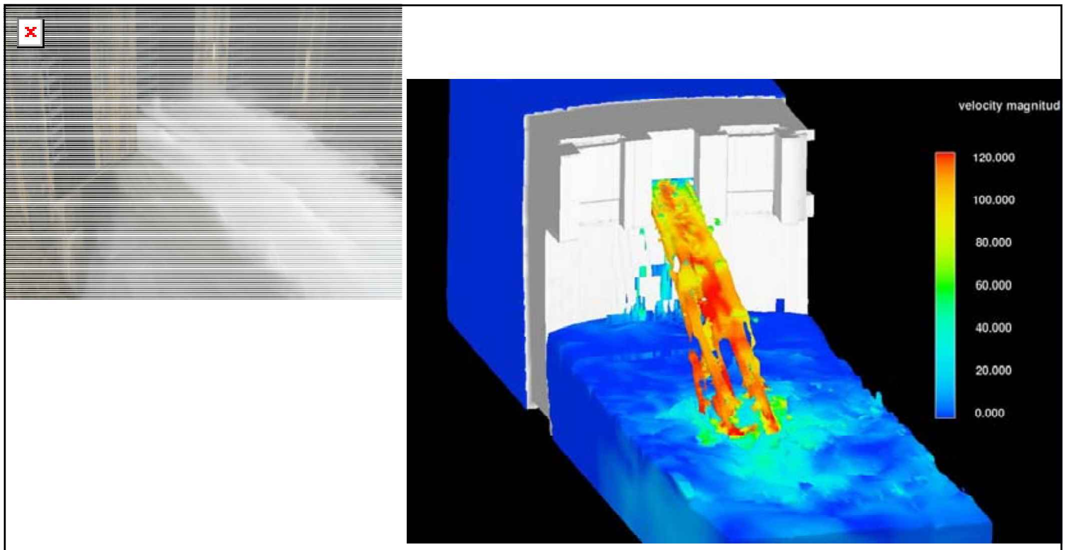
Figure 8. Physical Model Operation – Sluice Gate 4 at 3 Opening

Relative performance of the varying gate operations and modifications of the outlets will be judged on the depth and amount of air entrainment and the distance downstream that carries entrained air. We expect that air entrainment and transport should be reduced by maximizing the surface area of jet impact. To a large degree, the relative performance will be judged on the basis of qualitative observations: jet impact zones on water surface through visual assessment, photography, and video; and air entrainment through visual assessment, photography, and underwater video.

Computational Fluid Dynamic Modeling

The computational fluid dynamic (CFD) models of the sluices and spillways will continue to be developed and verified versus the physical model and field test results. The goal will be to have tools that can be used, in conjunction with the physical model, to analyze modifications to the sluices and spillways to provide greater dispersion of the jets and lower jet momentum entering the tailwater. Eventually these models will be incorporated into an overall CFD model of the plunge pool area and downstream river that will provide the hydrodynamic framework for an overall TDG predictive model for the Project.

In 2008, the far field CFD model was developed for the entire Project area and a more detailed near field model of the sluice gate area using the FLOW-3D software. The CFD model of the sluice gate has been compared to field observations, as shown in Figure 9.



Breakup of jet at entry

Figure 9. Comparison of CFD Model of Sluice with Field Observation

Once physical model test results are available, an additional series of tests will be performed to compare the CFD model results directly to physical model test results. These validation tests will be performed for a single operating bay (either sluiceway or spillway). The CFD model will first be translated into a model scale to ensure complete compatibility with the physical model results, then both models would be run for an identical test.

Once both models have been run, a more rigorous comparison will be made between model results, including: downstream flow patterns and velocities, jet trajectory measurements, dimensions of jet impact area, and qualitative observations of depth and extent of air entrainment.

As required, pertinent CFD model parameters may be adjusted to achieve a better match with those of the physical model. Once a suitable match is obtained, the CFD model will be rerun at a prototype scale to identify and document any scaling effects in moving to the larger, actual size prototype dimensions. These results will be compared to prototype observations to ensure a continued good fit between the CFD and prototype results. Once a suitable match has been obtained, and the models have been validated, the final model results will then form the “baseline” for operation of a single sluiceway and single spillway bay. These runs will form the baseline data against which the performance of structural modifications can be compared.

Following completion of the baseline and validation runs, the CFD and physical models will be changed to include the structural modifications proposed for potential TDG structural abatement at the sluiceway and spillway structures. CFD analysis will be performed iteratively with the design team to test the performance of various concepts.

At the completion of each run, comparisons will be made with the baseline runs to determine the overall impacts on jet trajectory, impact area, and calculated air entrainment. These comparisons will be used to rank various alternative designs in the search for an optimal solution.

Numerical TDG Predictive Tool

One of the key components of the numerical modeling exercise will be the eventual application of the CFD models to help predict the final TDG performance associated with each of the proposed modifications.

Two separate approaches are being considered to achieve prediction of TDG performance. The first is the most comprehensive, and allows for the continuous computation of TDG directly within the FLOW3D model. This will require some customization of the FLOW3D software. The second approach involves application of the CFD and physical models to perform TDG calculations independently of the actual FLOW3D code. Both approaches will be employed to compare results, check sensitivity, and ultimately, ensure compatibility and consistency between the approaches.

Direct Modeling of TDG

The CFD models will be modified to predict the TDG contribution of the Project. Source/sink terms are incorporated in the mass transport algorithm of FLOW-3D to simulate TDG. These source and sink terms represent the generation of TDG and also the escape of excess TDG at the free surface. FLOW-3D’s existing capabilities will be utilized to determine the volume of entrained air, shear stress, and pressure in the water phase. The simulation of TDG within the water column will be accomplished by implementing the following steps:

1. Determine the number and size of air bubbles and their corresponding surface area in each computational cell as a function of shear stress and volume of entrained air;
2. Determine the transfer of air mass to the dissolved phase as a function of pressure, time, temperature, air/water interface area, and initial (background) TDG concentration;
3. Apply a boundary condition on the free surface to allow release of excess dissolved air into the atmosphere; and
4. Utilize the existing transient capability of FLOW-3D to transport TDG throughout the flow field by: i) solution of an advection-diffusion equation; and ii) simple “mass” transport.

Hydraulic equations relating flow characteristics with the number and size of bubbles, transfer of air from bubbles to water, and release of dissolved gas into the atmosphere will be obtained from the work reported by Urban et al. (2008). No new research work will be involved in developing source/sink terms. However, incorporation of these processes into a transient 3-D CFD model will represent significant improvements over currently available methods.

Use of Discrete Particle Tracking

The second approach is considerably simpler in nature, and similar to a technique developed and used on other studies to simulate TDG transfer, that has provided reasonable estimates of TDG performance.

This technique involves the “sprinkling” of a representative number of history particles within the air entraining area of a jet. These particles are given a buoyancy equivalent to a standard air bubble, and then their position is tracked as they move throughout the computational domain. The CFD model tracks time, pressure, air entrainment fraction, and velocities experience by these “bubbles” as they move through the mesh.

This information is then exported from the CFD model, and imported into a special spreadsheet model to estimate gas transfer. This spreadsheet estimates the amount of gas transfer which might occur for each bubble based on the pressure and velocity hydrographs experienced by each. The gas transfer associated with each bubble is then integrated to determine a total TDG percentage for the main flow field.

Summary and Conclusions

To summarize, the TDG attainment plan will have both operational and structural abatement components. Implementation of abatement alternatives will utilize an "Adaptive Management" approach:

- Develop engineering plans to identify possible structural and operational improvements to meet standards;
- Identify improvement(s) and implementation schedule;
- Implement prototype modifications;
- Monitor to assess success based on defined goals;
- Refine ability to predict performance; and
- If the target not met, go back to 1st step.

The numeric and physical models will allow exploration of potential structural abatement alternatives and opportunities to develop methods for predicting performance. Prediction of performance can be adjusted and improved as the modeling progresses and the prototype abatement alternatives are installed and tested.

The envisioned TDG abatement program is expected improve the Boundary project TDG performance in a measured and practical way and provide improved tools for prediction of TDG performance in projects.

References

Ecology (Washington State Department of Ecology). 2005. Water Quality Certifications for Existing Hydropower Dams, Guidance Manual. March 2005, Revised April 2005.

Moen, K., J. Groeneveld, P. Oblander, C. May, C. Simonsen, P Rodrigue, S. Smith, C. Sweeney, E. Roy, S. Balsky, P. Grutter, J. Gulliver, K. de Rubertis, and W. Bowles. 2009. Final Report Boundary Hydroelectric Project (FERC No. 2144) Study No. 3 - Evaluation of Total Dissolved Gas and Potential Abatement Measures. Prepared for Seattle City Light

SCL (Seattle City Light). 2006. Proposed Study Plan for the Boundary Hydroelectric Project (FERC No. 2144). Seattle, Washington. October 2006.

Sweeney, C.E., Elizabeth W. Roy, Kim Pate, Shane Bickford, Keith Moen, and Lois A. Loesch. 2008. Analysis of Operational Effects on Total Dissolved Gas Production at Boundary and Wells Dams. Proceedings of HydroVision 2008. Sacramento, CA.

Urban, A.L., J.S. Gulliver, and D.W. Johnson. 2008. Modeling total dissolved gas concentration downstream of spillways. Journal of Hydraulic Engineering [in press].

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