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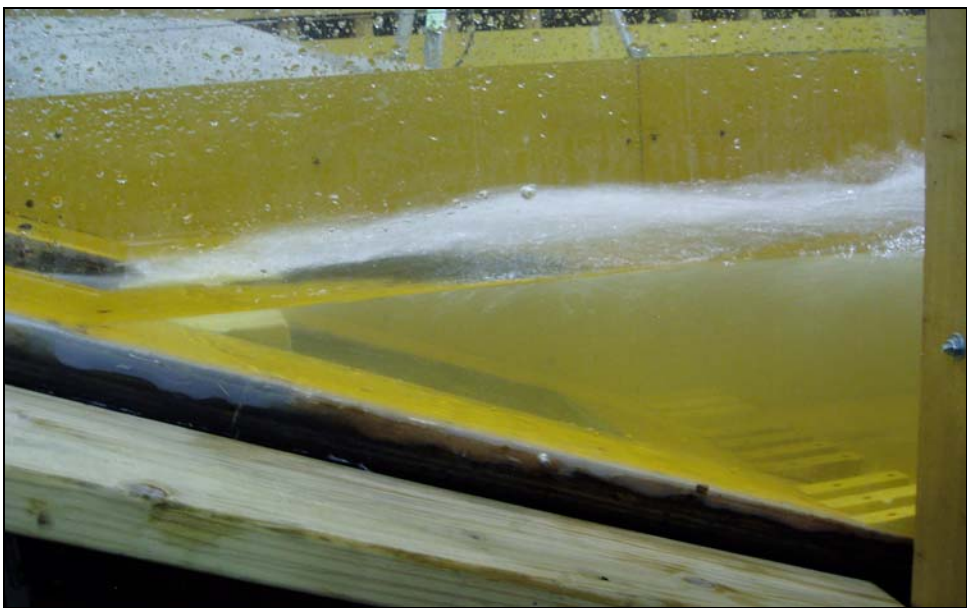
Hydraulic Model Study of Arthur R. Bowman Dam Total Dissolved Gas Deflector



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Bureau of Reclamation
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A 1:24-scale physical hydraulic model of Arthur R. Bowman Dam was studied at the Bureau of Reclamation’s Hydraulics Laboratory. A wedge-shaped deflector was installed on the face of the spillway as a potential alternative for reducing total dissolved gas levels downstream of the dam. The location and size of the deflector was varied to optimize deflector performance. Full removal of the splitter walls in the stilling basin was recommended to produce the greatest total dissolved gas abatement. Observations during spillway flows were recorded to provide information regarding how deflector installation may affect dam safety goals.

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Connie DeMoyer

U.S. Department of the Interior
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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Disclaimer

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Background

Arthur R. Bowman Dam (formerly Prineville Dam) is an earthfill structure on the Crooked River about 20 miles upstream from Prineville, Oregon (figure 1). This Bureau of Reclamation (Reclamation) dam has a height of 245 ft, a crest length of 800 ft, and a volume of 1,424,000 cubic yards of material. Prineville Reservoir has an active capacity of 152,800 acre-feet and a surface area of 3,030 acres at the spillway crest elevation 3234.8 ft (United States Department of the Interior, 1981). Figure 2 shows an aerial view of A.R. Bowman Dam.

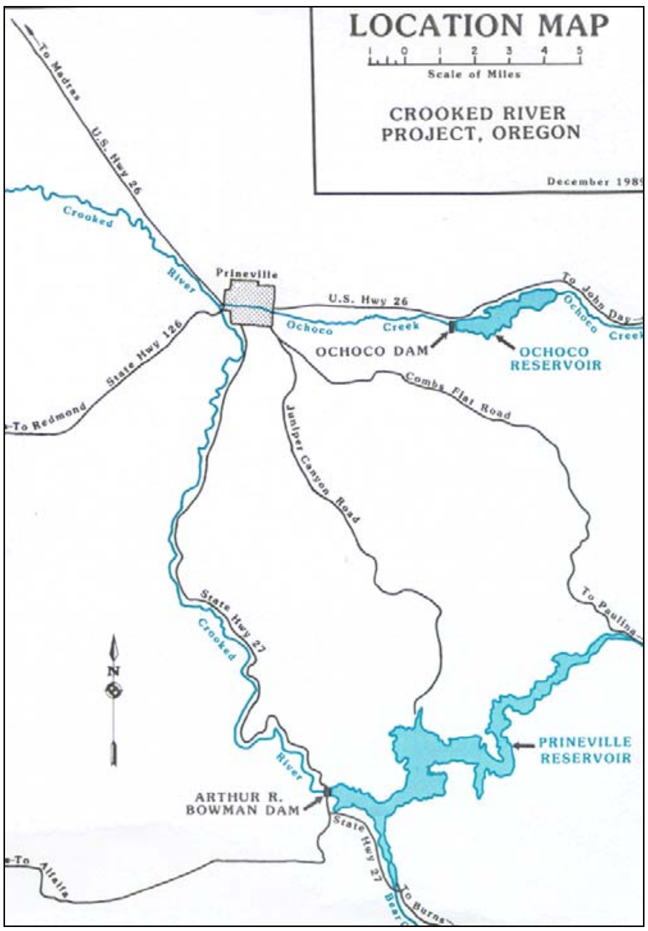

Figure 1. Location map of Arthur R. Bowman Dam.

Figure 2. Aerial view of A.R. Bowman Dam looking downstream with the spillway on the right abutment.

The spillway structure is an uncontrolled ogee crest with curved inlet walls, a spillway chute, and a stilling basin. At the design maximum water surface elevation 3257.9 ft, the capacity of the spillway is 8,120 ft^3/s. The outlet works consist of an 11-ft-diameter circular tunnel upstream from the gate chamber, two 4-ft by 6-ft slide gates, and an 11-ft horseshoe-shaped tunnel downstream from the gate chamber. The capacity of the outlet works at a maximum gate opening of 5.5 ft is 2,900 ft^3/s with the water surface at the top of the spillway crest (elevation 3234.8 ft). Flow from the outlet works daylights onto the spillway face and enters the shared stilling basin. Two 28.5-ft-high splitter walls are constructed in the stilling basin, one on each side of the outlet works opening. The splitter walls prevent flow attachment to the basin sidewalls and improve flow conditions in the stilling basin when only the outlet works are operating (Bureau of Reclamation, 1959).

When water is released through the outlet works or over the spillway, air is entrained in the plunging flow, increasing the concentration of total dissolved gas (TDG) in the water. At A.R. Bowman Dam, flow through the stilling basin can produce TDG levels that exceed Oregon State and Federal water quality standards of 110 percent. Supersaturation levels of 110-115 percent can injure or kill adult trout (Weitkamp and Katz, 1980). Typical outlet works flow releases of less than 200 ft^3/s do not generate excessive supersaturation, but higher spring runoff flows have been shown to do so. Unpublished field measurements collected by Reclamation from 2006-2007 show a TDG level in the upstream reservoir of

104 percent and TDG levels just downstream of the stilling basin of 108 percent during a 500 ft^3/s release and 121 percent during a 3,000 ft^3/s release.

Several gas abatement alternatives were considered in a 1992 physical model study of A.R. Bowman Dam at Reclamation's Hydraulic Investigations and Laboratory Services facility (Johnson, 1992). Design of a shallower, heavily baffled stilling basin was considered, but it was determined that this design would not significantly reduce supersaturation and could cause cavitation damage. Installation of a downstream check structure across the entire channel, such as a weir with a roughened downstream ramp, was considered. The weir would have to create a white water riffle to strip entrained air from the water. Due to the flat river gradient, this alternative would likely only be effective at stripping gas during low flows when saturation levels do not exceed water quality standards.

The preferred alternative from the 1992 study was to install mass concrete to raise the stilling basin floor by 15 ft from elevation 3054 ft to elevation 3069 ft. The raised basin floor would reduce the plunge depth for entrained air, but uncontrolled energy dissipation would occur downstream of the basin during high flows. Corrective action alternatives are currently being investigated to safely pass inflow floods exceeding the existing spillway capacity (Reclamation, 2009). Installing mass concrete in the stilling basin would not be favorable to dam safety goals, so this alternative is not being pursued.

There has been ongoing discussion regarding the potential addition of a powerplant at A.R. Bowman Dam. The passage of water through penstocks does not produce aerated plunging flow, so the TDG level downstream of the dam should be equivalent to the TDG level upstream in the reservoir. Adding a powerplant to the dam in the future might help abate TDG production by reducing the amount of flow that passes through the outlet works, thereby incrementally providing benefit. However, depending on the capacity of the powerplant compared to the normal outlet works releases, the TDG reduction produced by passing a portion of the flow through the powerplant may not be deemed adequate alone. The addition of a powerplant will not be discussed here further.

Model Objective

The purpose of this study was to examine whether the installation of a wedge-shaped flow deflector on the face of the spillway downstream from the outlet works tunnel exit can reduce TDG levels downstream of A.R. Bowman Dam. When operating properly, flow deflectors produce skimming flow in the top portion of the water column, preventing the release jet from plunging deep into the basin. The installation of a deflector to improve water quality, however, also directly impacts operations and maintenance goals, and dam safety goals. For this reason, the following three study objectives were identified:

1.) Determine the optimal flow deflector geometry to reduce TDG levels downstream of the stilling basin during outlet works releases.

2.) Determine whether flow patterns resulting from the installation of the deflector may increase the potential for abrasion damage in the stilling basin.

3.) Determine whether the installation of a permanent TDG deflector on the spillway face may cause dam safety concerns during high spillway releases due to high energy flow exiting the stilling basin.

Model Description

A physical hydraulic model of A.R. Bowman Dam was constructed at Reclamation's Hydraulic Investigations and Laboratory Services facility in Denver, Colorado in 2003. The model was used to examine spillway performance under increased flows associated with a raised water surface elevation from the installation of a proposed top of dam parapet wall (DeMoyer, 2008). The model was used again in 2008 for this gas abatement study.

The physical hydraulic model was built at a 1:24 geometric scale. Similitude between the model and the prototype is achieved when the ratio of the major forces controlling the physical processes are the same. Since gravitational and inertial forces dominate open channel flow, Froude scale similitude was used to establish a kinematic relationship between the model and the prototype. The Froude number is expressed as

$$F_r = \frac{\sqrt{v}}{gd}$$

where v = velocity, g = gravitational acceleration, and d = flow depth. Based on Froude scale modeling, the following relationships exist between the model and prototype where r refers to the ratio of the prototype to the model:

Length ratio: $L_r = 1:24$

Velocity ratio: $V_r = L_r^{1/2} = (24)^{1/2} = 4.90$

Discharge ratio: $Q_r = L_r^{5/2} = (24)^{5/2} = 2821.8$

The lateral extent of the model included about 1/3 of the length of the dam on the left side. Concrete topography was installed 240 ft upstream of the dam crest in the headbox and 650 ft downstream of the toe of the dam in the tailbox. Inflow to the hydraulic model was measured by the calibrated laboratory Venturi system. Reservoir and tailwater elevations were measured with point gages inside stilling wells in the headbox and tailbox. Vertical slats at the downstream end of the model were used to adjust the tailwater elevation in the model. Figures 3 and 4 compare the prototype and model structures.

Figure 3. A.R. Bowman prototype spillway structure.

Figure 4. A.R. Bowman model spillway structure.

Upstream features included the concrete approach channel, high-density polyurethane foam spillway crest, sheet metal curved inlet structures, and a plywood roadway (figure 5). The marine-grade plywood spillway chute flared from 20 ft wide at the spillway crest to 54 ft in the stilling basin (figure 6). The horseshoe-shaped outlet works tunnel, two 4 ft by 6 ft slide gates, and the transition chamber were constructed of clear acrylic (figure 7). A clear acrylic viewing area was installed next to the transition chamber in order to observe flow patterns in the region where the outlet works daylight onto the spillway face. Stilling basin details included chute blocks, a dentated endsill, and two splitter walls (figure 8).

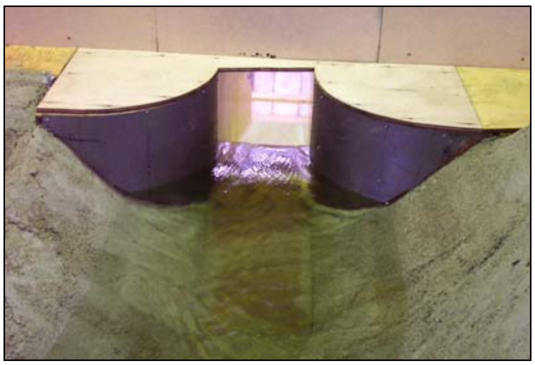

Figure 5. Spillway crest structure.

Figure 7. Outlet works tunnel.

Figure 6. Spillway chute.

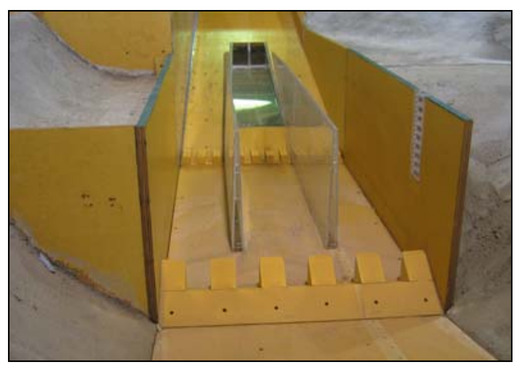

Figure 8. Stilling basin configuration.

For this water quality study, a wedge-shaped horizontal flow deflector was installed between the splitter walls of the existing model on the spillway chute face downstream of the outlet works opening (figures 9 and 10). During testing, the length of the deflector was varied from 12.5 ft to 20 ft long and the elevation of the deflector was varied from 3070.3 ft to 3073.3 ft.

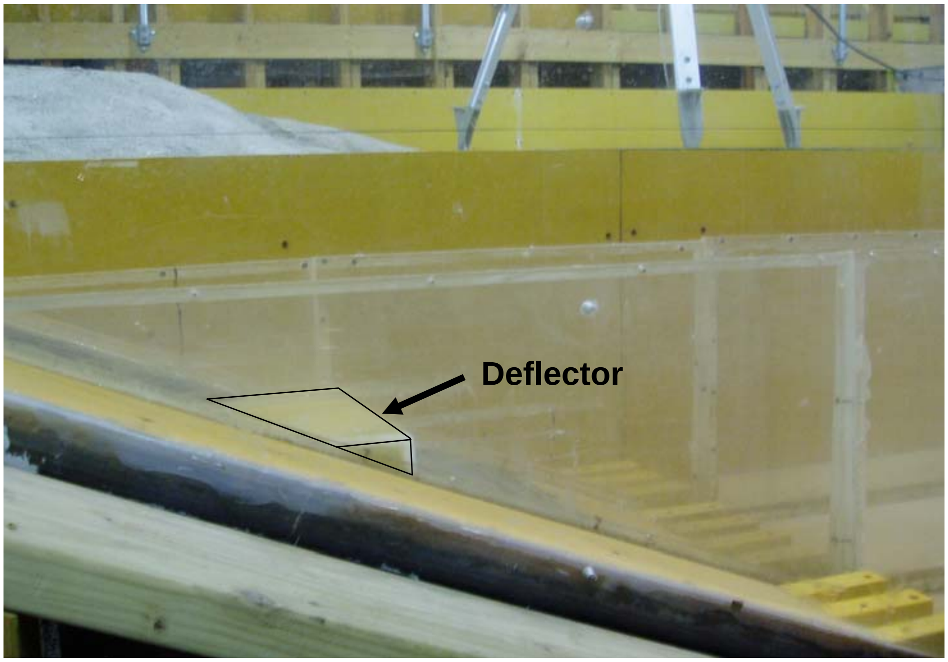

Figure 9. Side view of a 12.5-ft-long horizontal flow deflector installed downstream of the outlet works opening at elevation 3073.3 ft.

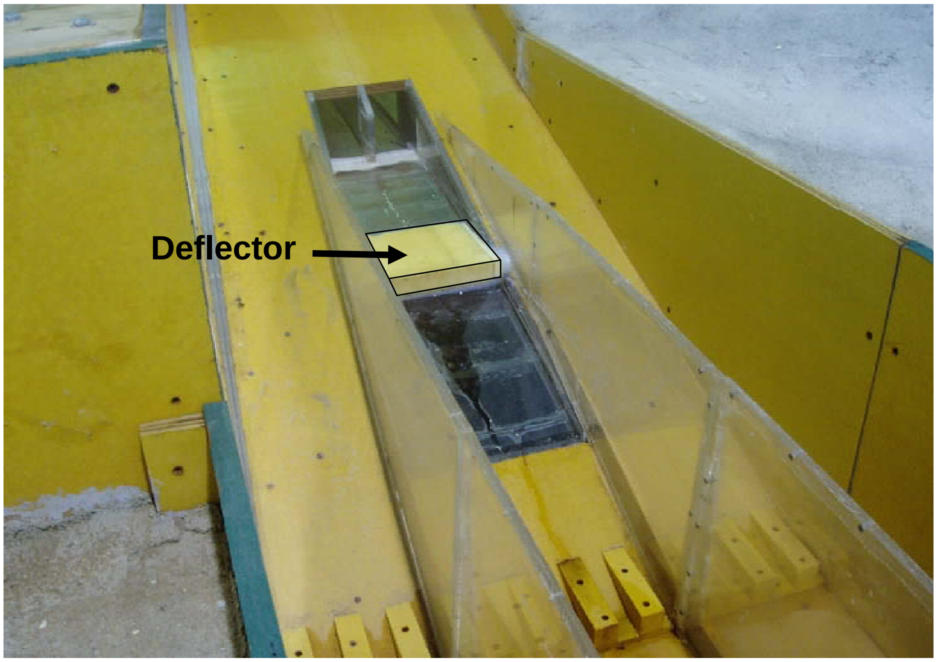

Figure 10. Upstream view of a 12.5-ft-long horizontal flow deflector installed at elevation 3073.3 ft.

Test Plan

The test plan included identifying the geometry and submergence of the deflector to maximize TDG abatement in the flow range of concern. The operational flows of concern were determined by discussions between Reclamation's Hydraulic Investigations and Laboratory Services Group and the Bend Field Office. The Bend Field Office coordinated discussions between the Ochoco Irrigation District and local resource agencies. The result was to not be concerned with TDG abatement for low-frequency spillway flows, but to produce skimming flow for outlet works flows of 500 to 3,000 ft^3/s (unit discharges of 64 to 273 $ft^3/s/ft$).

The initial deflector length, shape, and elevation were based on the results from a hydraulic model study at the U.S. Army Corps of Engineers Walla Walla District (Cain, 1996). The deflector was designed with a 12.5 ft long horizontal projection from the spillway face. The initial deflector elevation was set to achieve a submergence value in the range of 4 to 9 ft. Submergence is defined as the tailwater elevation minus the deflector elevation.

Based on standard operating procedures, a reservoir elevation of 3225.0 ft was set for discharges between 700 and 1,000 ft^3/s and an elevation of 3234.8 ft was set for discharges in the range of 2,000 to 3,000 ft^3/s. Tailwater elevations were based on historical field data from a USGS station downstream of A.R. Bowman dam. Before model testing began, a field measurement was collected at the stilling basin to verify that this tailwater curve was valid.

Performance of the deflector was evaluated by observing the flow condition and depth of bubble penetration in the stilling basin. Flow from the deflector was classified in six categories: plunging, unstable, skimming, undular, roller at deflector, or submerged jump. Plunging flow is the current condition where the jet plunges deep into the basin, entraining air to the full basin depth. An unstable condition may exist when the flow regime alternates between plunging and skimming flow. Skimming flow shoots across the water surface, producing a shallow bubble depth. During undular conditions, the jet deflects upward and replunges downstream to some intermediate depth in the basin. Rollers and submerged jumps are produced when submergence is too high. Figures 11 and 12 show the deflector flow categories as defined by Cain (1996).

Qualitative model observations were made regarding the increased potential for abrasion damage resulting from altered flow conditions. Observations of flow attachment to the basin sidewalls, velocity distributions, and slack water and eddy zones were made. After the best deflector configurations were determined from model testing, high spillway discharges of 4,000 to 14,965 ft^3/s were released to observe the effect of the deflector on stilling basin performance. Observations included: hydraulic jump location and strength, turbulence in the exit channel, wave run-up, splash, and velocity measurements at the endsill, in the exit channel, and along the right bankline. Flow conditions were documented using a digital camera or video camera for each deflector elevation and configuration.

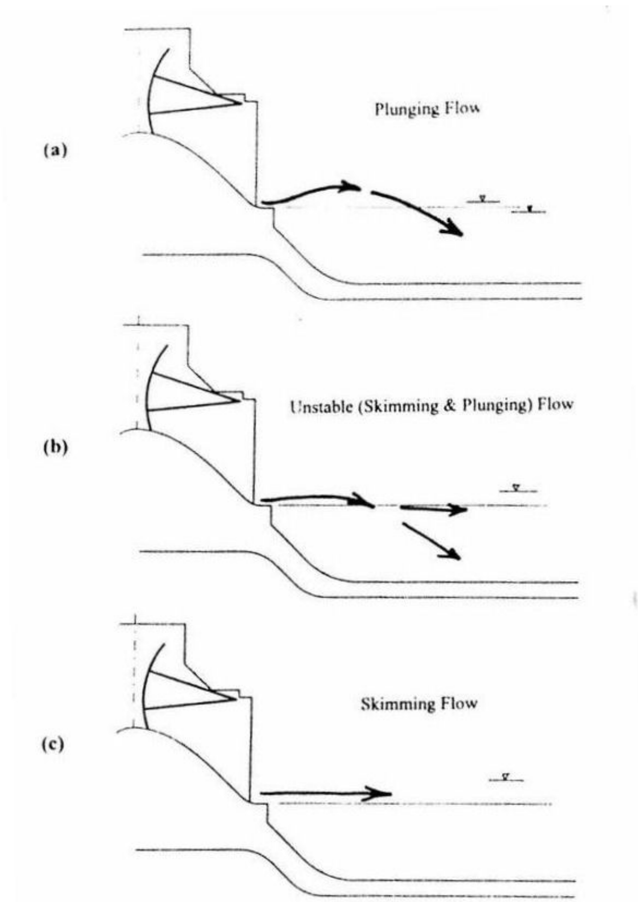

Figure 11. Plunging, unstable, and skimming flow conditions produced by a deflector (reproduced from Cain, 1996).

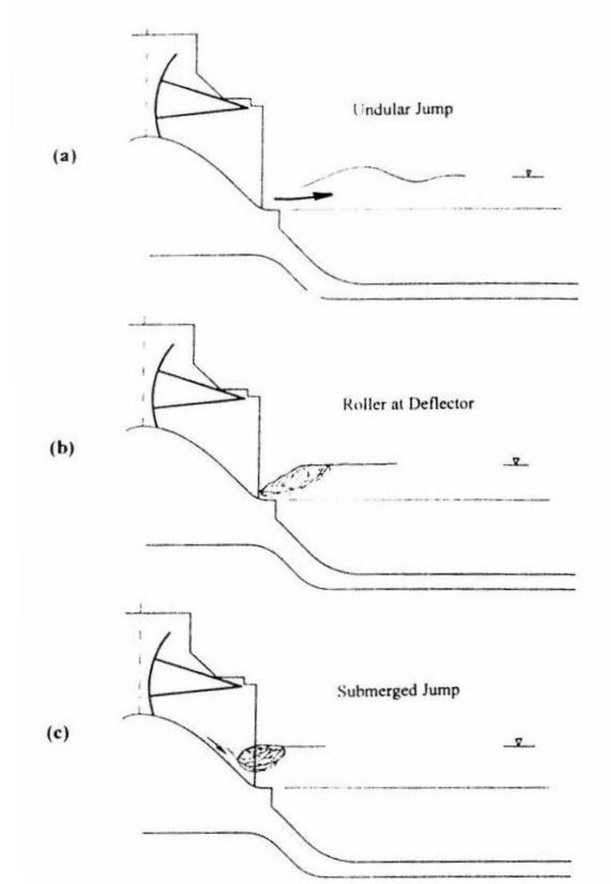

Figure 12. Undular, roller at deflector, and submerged jump flow conditions produced by a deflector (reproduced from Cain, 1996).

Results

No Deflector with Existing Stilling Basin Geometry

Outlet works flows of 700, 1,000, 2,000, and 3,000 ft^3/s were tested in the model to document baseline flow conditions without a deflector installed (figures 13-20). As the discharge increased, the bubbles plunged deeper into the basin.

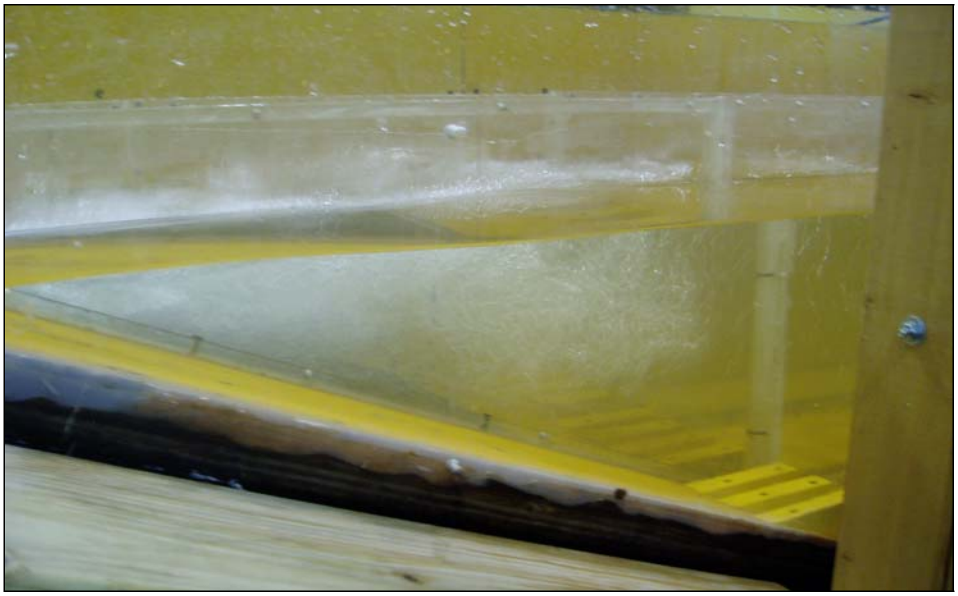

Figure 13. Side view with no deflector installed and existing stilling basin geometry. At a discharge of 700 ft^3/s, plunging flow was observed.

Figure 14. Surface view with no deflector installed and existing stilling basin geometry. At a discharge of 700 ft^3/s, plunging flow was observed.

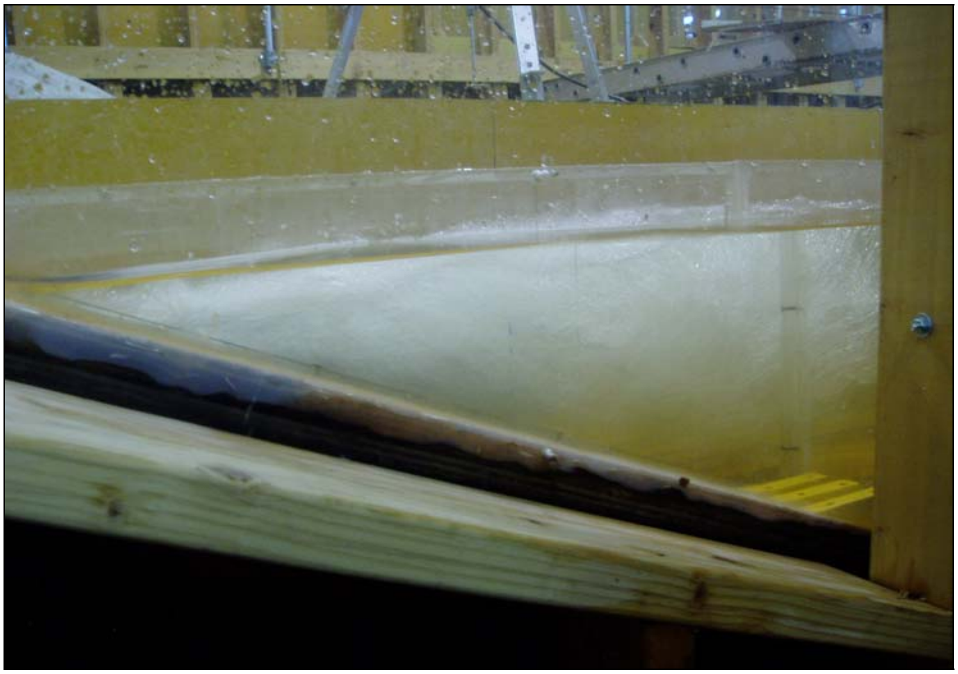

Figure 15. Side view with no deflector installed and existing stilling basin geometry. At a discharge of 1,000 ft^3/s, plunging flow was observed.

Figure 16. Surface view with no deflector installed and existing stilling basin geometry. At a discharge of 1,000 ft^3/s, plunging flow was observed.

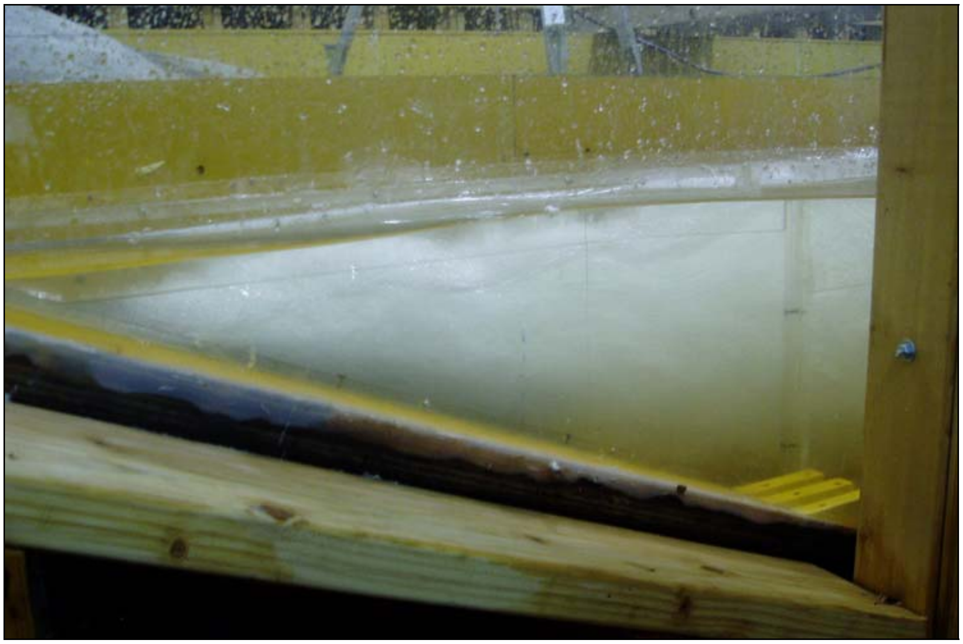

Figure 17. Side view with no deflector installed and existing stilling basin geometry. At a discharge of 2,000 ft^3/s, plunging flow was observed.

Figure 18. Surface view with no deflector installed and existing stilling basin geometry. At a discharge of 2,000 ft^3/s, plunging flow was observed.

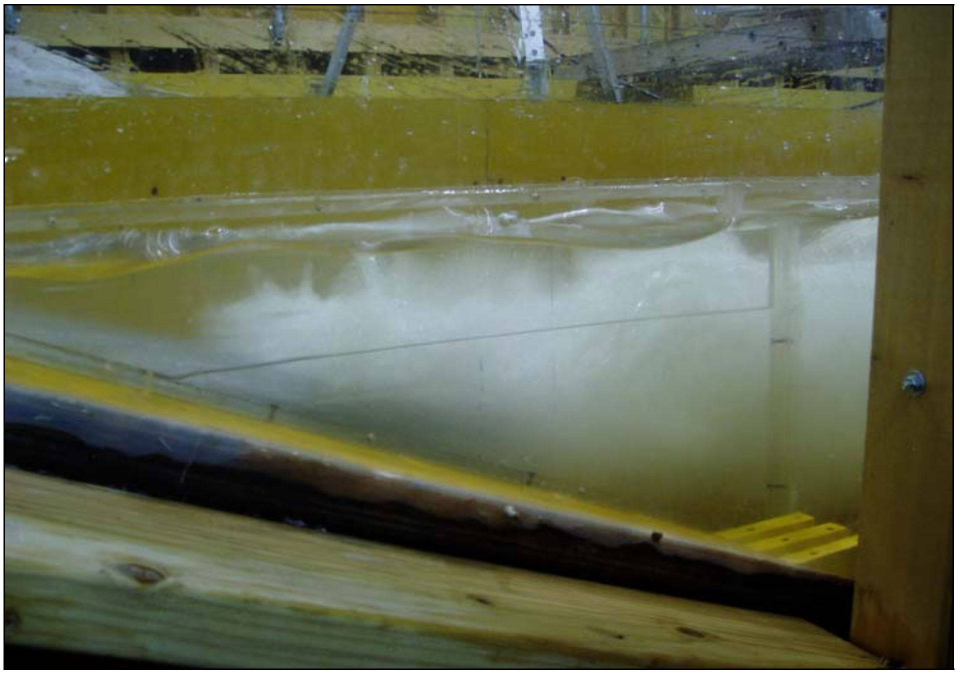

Figure 19. Side view with no deflector installed and existing stilling basin geometry. At a discharge of 3,000 ft^3/s, plunging flow was observed.

Figure 20. Surface view with no deflector installed and existing stilling basin geometry. At a discharge of 3,000 ft^3/s, plunging flow was observed.

Deflector Installed with Existing Stilling Basin Geometry

Deflector Elevation 3073.3 ft

A 12.5-ft-long deflector was initially installed at elevation 3073.3 ft, because submergence values for discharges from 500 to 3,000 ft^3/s were in the "skimming flow" range in Cain's model study (Cain, 1996). In the model, undular flow conditions occurred with a small initial wave and a replunging zone for discharges from 700 to 1,000 ft^3/s (figures 21 and 22). Undular flow limits the amount of TDG reduction due to air entrainment in the replunging zone. From 2,000 to 3,000 ft^3/s, the outlet works jet plunged deep into the basin, indicating that the submergence was too low. Based upon measurements of bubble plunge depths, there was no noticeable improvement in performance between the baseline condition without a deflector and the plunging flow condition with a 12.5-ft-long deflector installed at elevation 3073.3 (figures 23 and 24).

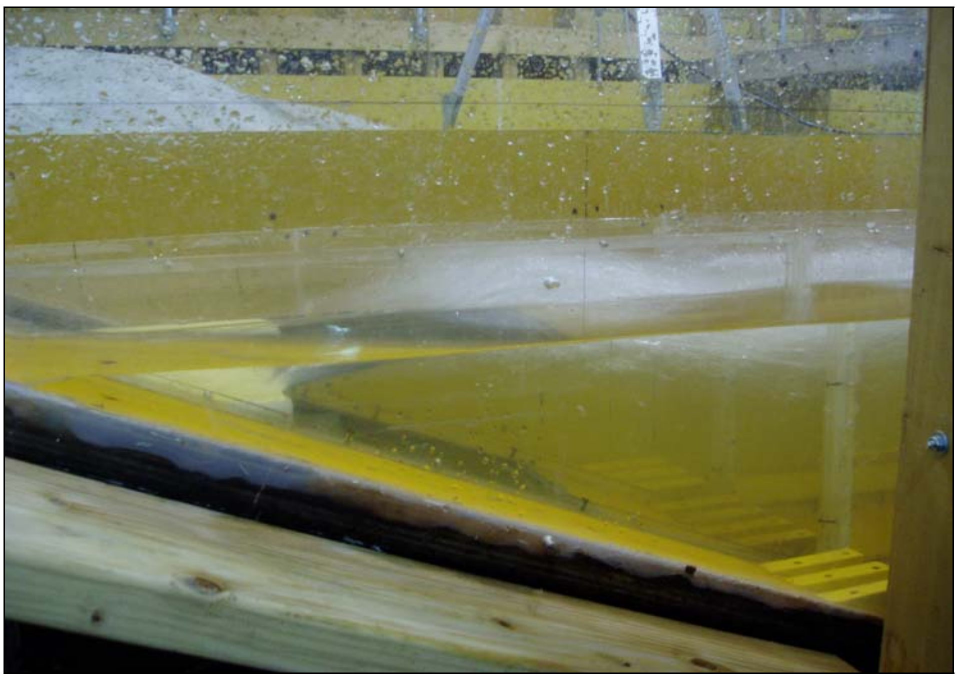

Figure 21. Side view with a 12.5-ft-long deflector installed at 3073.3 ft and existing stilling basin geometry. At a discharge of 1,000 ft^3/s, undular flow was observed.

Figure 22. Surface view with a 12.5-ft-long deflector installed at 3073.3 ft and existing stilling basin geometry. At a discharge of 1,000 ft^3/s, undular flow was observed.

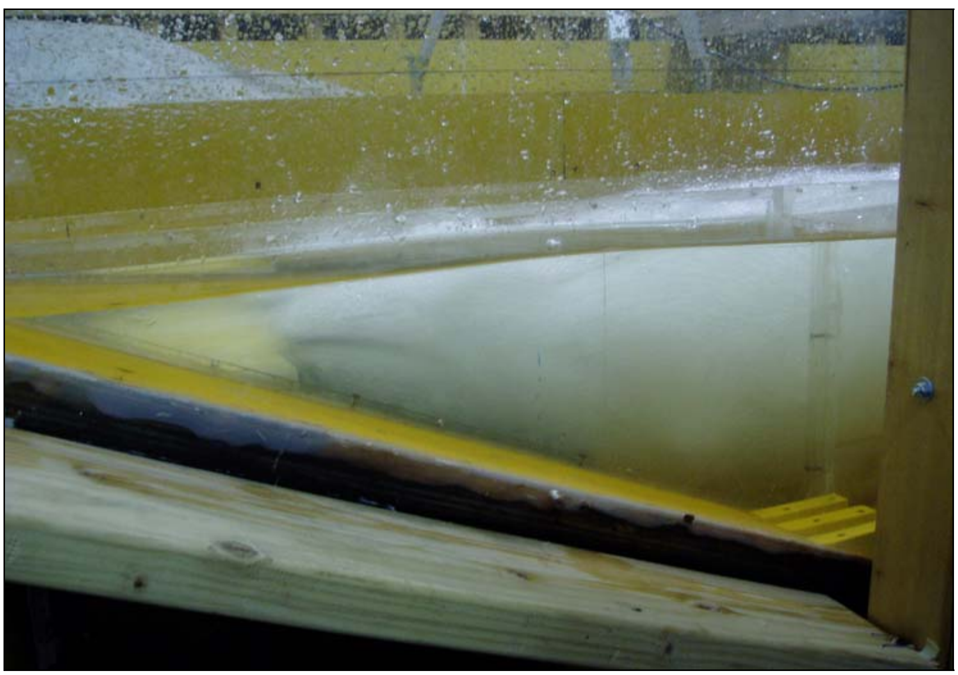

Figure 23. Side view with a 12.5-ft-long deflector installed at 3073.3 ft and existing stilling basin geometry. At a discharge of 2,000 ft^3/s, plunging flow was observed.

Figure 24. Surface view with a 12.5-ft-long deflector installed at 3073.3 ft and existing stilling basin geometry. At a discharge of 2,000 ft^3/s, plunging flow was observed.

Deflector Elevation 3071.5 ft

The 12.5-ft-long deflector was lowered to elevation 3071.5 ft to increase the submergence. For discharges of 700-1,000 ft^3/s, undular flow conditions were produced with a small initial wave and a replunging zone (figures 25-28). Undular flow conditions were stronger at 2,000 ft^3/s (figures 29 and 30). During a release of 3,000 ft^3/s, plunging flow occurred. There was no true skimming condition at any discharge.

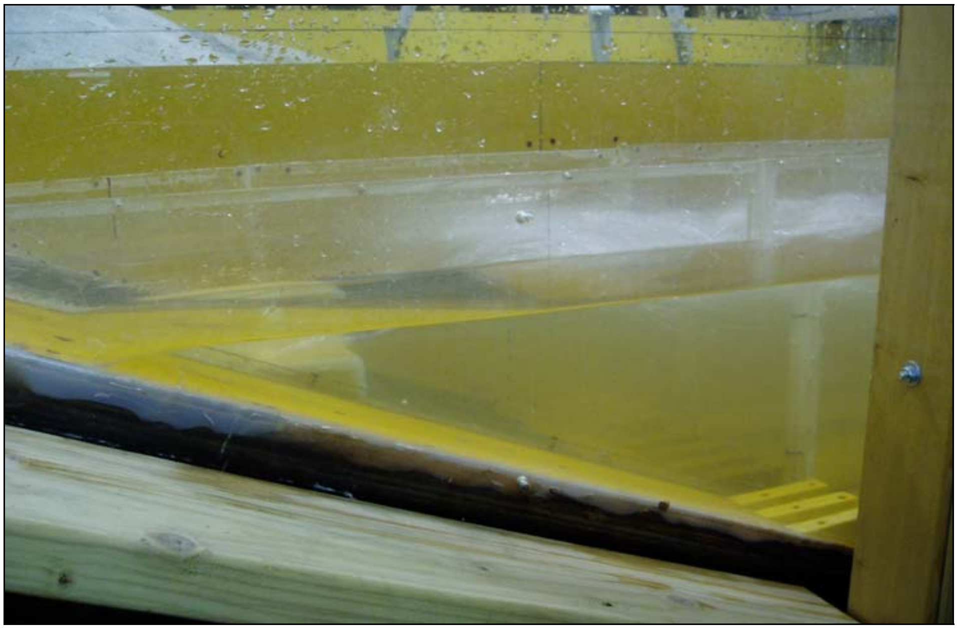

Figure 25. Side view with a 12.5-ft-long deflector installed at 3071.5 ft and existing stilling basin geometry. At a discharge of 700 ft^3/s, mild undular flow was observed.

Figure 26. Surface view with a 12.5-ft-long deflector installed at 3071.5 ft and existing stilling basin geometry. At a discharge of 700 ft^3/s, mild undular flow was observed.

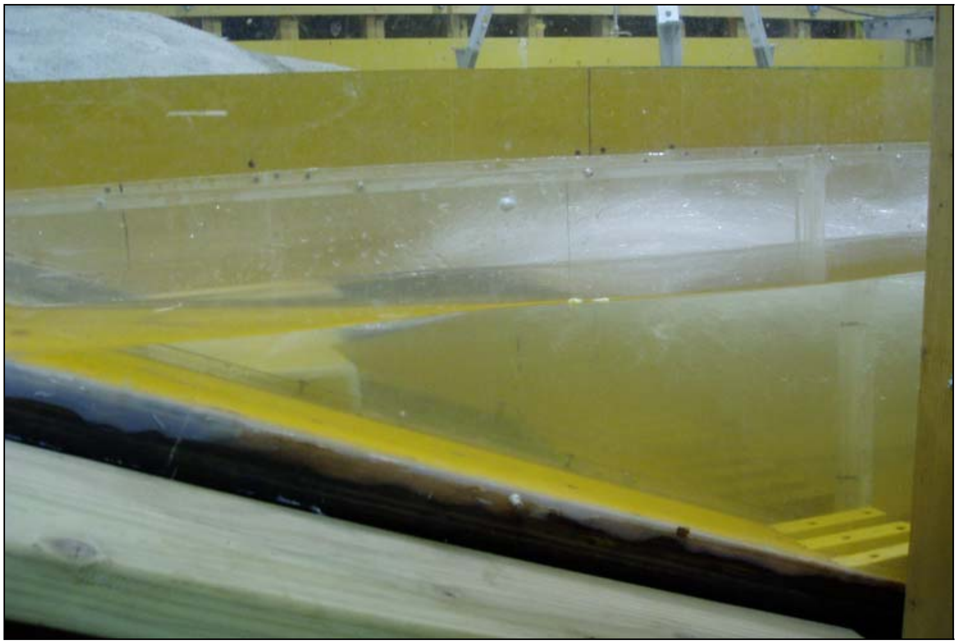

Figure 27. Side view with a 12.5-ft-long deflector installed at 3071.5 ft and existing stilling basin geometry. At a discharge of 1,000 ft^3/s, mild undular flow was observed.

Figure 28. Surface view with a 12.5-ft-long deflector installed at 3071.5 ft and existing stilling basin geometry. At a discharge of 1,000 ft^3/s, mild undular flow was observed.

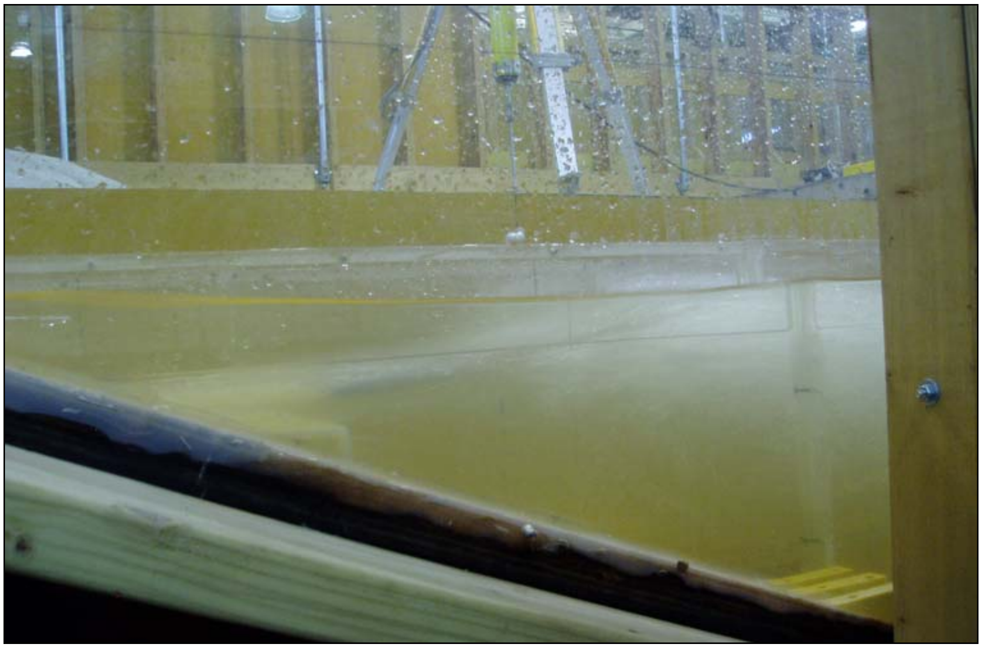

Figure 29. Side view with a 12.5-ft-long deflector installed at 3071.5 ft and existing stilling basin geometry. At a discharge of 2,000 ft^3/s, undular flow was observed.

Figure 30. Surface view with a 12.5-ft-long deflector installed at 3071.5 ft and existing stilling basin geometry. At a discharge of 2,000 ft^3/s, undular flow was observed.

Deflector Elevation 3070.3 ft

To improve flow conditions at 3,000 ft^3/s, the deflector was moved down to elevation 3070.3 ft. The horizontal length of the deflector was increased from 12.5 ft to 20.0 ft in an attempt to provide additional support for the jet. The increased submergence at deflector elevation 3070.3 ft produced strong undulation in the water surface for discharges of 1,000 and 2,000 ft^3/s (figures 31-34). During a 3,000 ft^3/s release, the flow was unstable, meaning that the performance varied from plunging flow to undular flow with a disturbance in the water surface or a slight variation in the tailwater elevation (figures 35 and 36). Because the basin conditions were unfavorable at low flows and unstable at high flows, deflector elevation 3070.3 ft was not considered further.

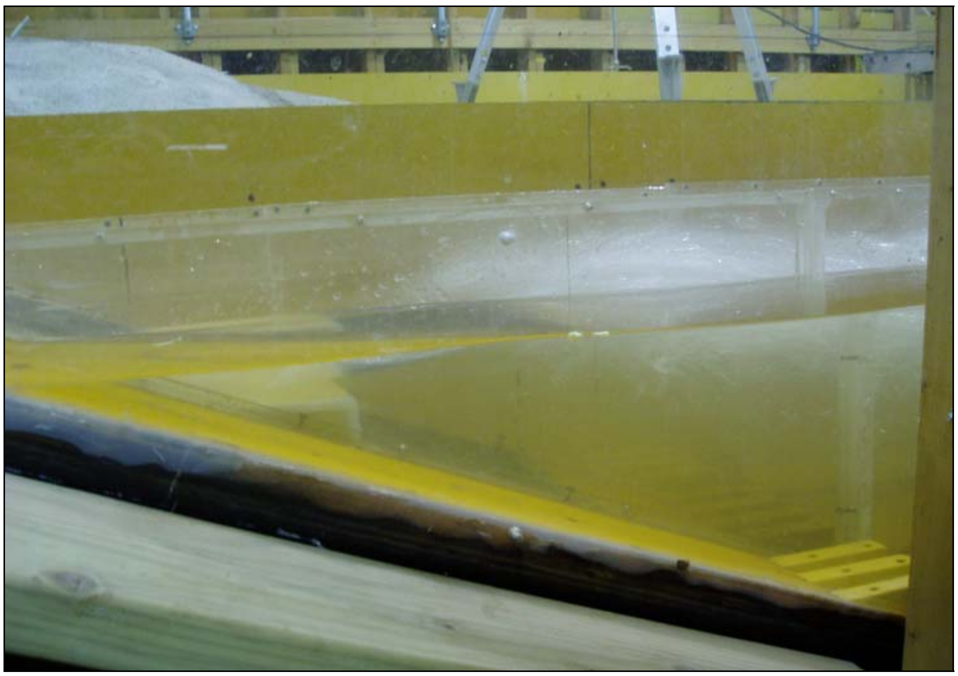

Figure 31. Side view with a 20-ft-long deflector installed at 3070.3 ft and existing stilling basin geometry. At a discharge of 1,000 ft^3/s, undular flow was observed.

Figure 32. Surface view with a 20-ft-long deflector installed at 3070.3 ft and existing stilling basin geometry. At a discharge of 1,000 ft^3/s, undular flow was observed.

Figure 33. Side view with a 20-ft-long deflector installed at 3070.3 ft and existing stilling basin geometry. At a discharge of 2,000 ft^3/s, strong undular flow was observed.

Figure 34. Surface view with a 20-ft-long deflector installed at 3070.3 ft and existing stilling basin geometry. At a discharge of 2,000 ft^3/s, strong undular flow was observed.

Figure 35. Unstable undular flow at 3,000 ft^3/s with a 20-ft-long deflector installed at elevation 3070.3 ft. Existing stilling basin geometry.

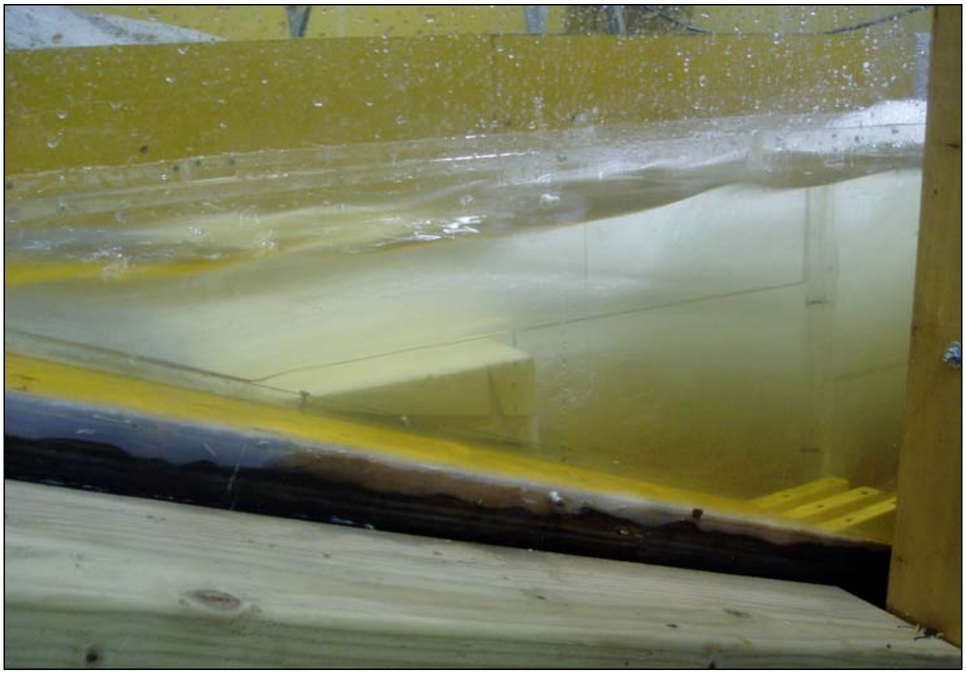

Figure 36. Unstable plunging flow at 3,000 ft^3/s with a 20-ft-long deflector installed at elevation 3070.3 ft. Existing stilling basin geometry.

Discussion of Deflector Performance with Existing Stilling Basin Geometry

The 20-ft-long deflector produced similar performance to the 12.5-ft-long deflector. The 12.5-ft-long deflector was chosen as the preferred alternative, because the longer deflector causes additional concerns about constructability and cost during spillway discharges. A similar conclusion regarding deflector length was reached in the 1982 model study of Yellowtail Afterbay Dam (Young, 1982).

Another performance consideration was the angle of the deflector. In the Yellowtail Afterbay Dam model, horizontal deflectors worked best at low discharges and adverse slope (upturned angle) deflectors worked best at high discharges (Young, 1982). A horizontal deflector was selected, because lower discharges occur more frequently at A.R. Bowman and an adverse slope would likely accentuate the surface undulation.

Model testing was completed with the horizontal deflector installed at various elevations on the vertical curve downstream from the outlet opening. Results show that the basin flow condition went from plunging to undular without ever achieving a true skimming condition. At best, mild undular flow conditions could be reliably attained for low flows of 700-2,000 ft^3/s at a deflector elevation of 3071.5 ft, although higher discharges produced a plunging flow condition.

Flow over the deflector did not behave as expected based on the previous experience of Reclamation and the U.S. Army Corps of Engineers. The unstable nature of the deflector led to discussions with Reclamation's Bend Field Office and Pacific Northwest Region regarding options to improve reliable deflector performance. It is possible that the flat slope of the outlet tunnel may have inhibited good deflector performance, because typical deflector installation locations have steeper approach slopes. However, the most likely explanation for the unexpected performance of the deflector is the presence of the two splitter walls in the stilling basin.

The splitter walls were installed to prevent flow attachment to the basin outer sidewalls and to improve energy dissipation in the stilling basin during outlet works flows (Bureau of Reclamation, 1959). The function of the splitter walls in producing a hydraulic jump and the function of the total dissolved gas deflector in preventing a jump by forcing skimming flow are contradictory to each other. The splitter walls prevent the jet from spreading laterally, so the outlet works jet is not supported by the surrounding tailwater. As a result, it is difficult to obtain skimming flow conditions. From personal communication, researchers at the U.S. Army Corps of Engineers' Coastal and Hydraulics Laboratory at the Engineer Research and Development Center have observed good deflector performance in three dimensional physical models, but unstable deflector performance when channelized in a two dimensional flume restrained by the flume walls (Glenn Davis, personal communication, June 2008).

Splitter Walls Removed and Reduced

The model test plan was expanded to include the removal or height reduction of the splitter walls to allow spreading and support of the outlet works jet.

Splitter Walls Fully Removed

The splitter walls in the basin were removed and the deflector was placed at three trial elevations. The deflector was first installed at elevation 3071.5 ft, because this configuration produced the best flow conditions with the existing stilling basin geometry. When the walls were fully removed, a small undular wave occurred, indicating that the deflector had too much submergence (figure 37).

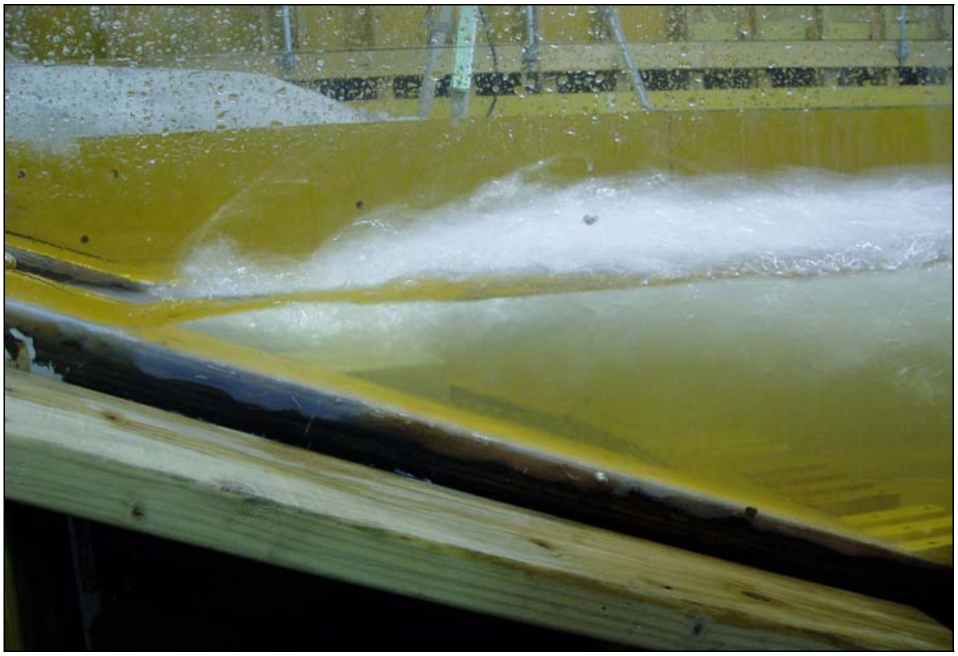

Figure 37. Deflector installed at 3071.5 ft with splitter walls fully removed. At a discharge of 2,000 ft^3/s, undular flow was observed.

At elevation 3075.3 ft, the deflector did not have enough submergence. At this elevation, the jet skimmed across the water surface, but bubbles were still entrained deep in the stilling basin (figure 38).

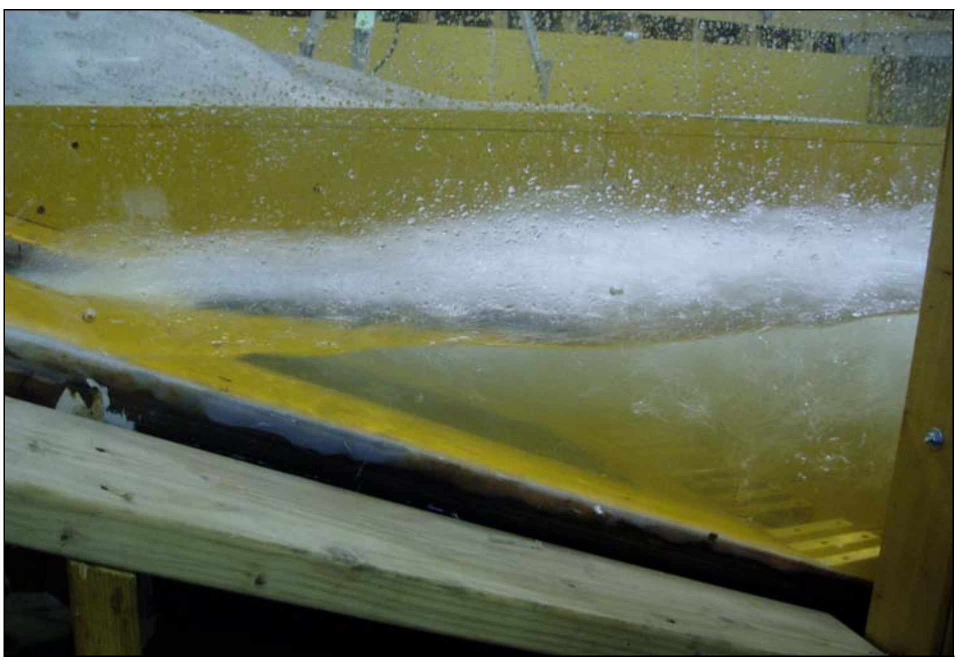

Figure 38. Deflector installed at 3075.3 ft with splitter walls fully removed. At a discharge of 2,000 ft^3/s, some plunging bubbles were observed.

The best deflector elevation was 3073.3 ft. Not surprisingly, this deflector elevation corresponded to the initial elevation chosen for this study based on past literature. Skimming flow was produced for all discharges between 700 and 3,000 ft^3/s (figures 39-42).

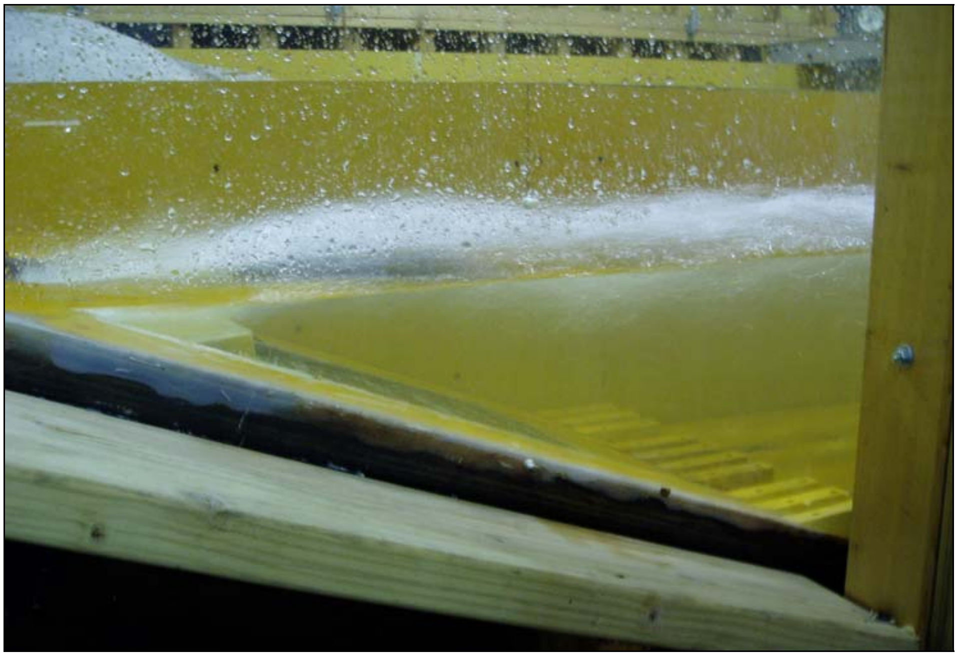

Figure 39. Deflector installed at 3073.3 ft with splitter walls fully removed. At a discharge of 700 ft^3/s, skimming flow is observed.

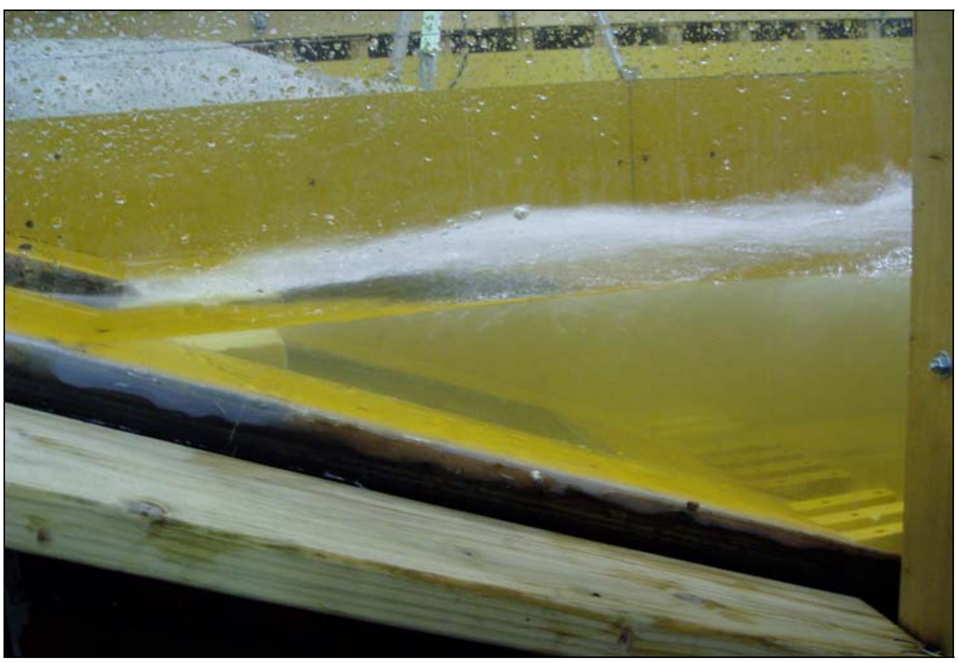

Figure 40. Deflector installed at 3073.3 ft with splitter walls fully removed. At a discharge of 1,000 ft^3/s, skimming flow is observed.

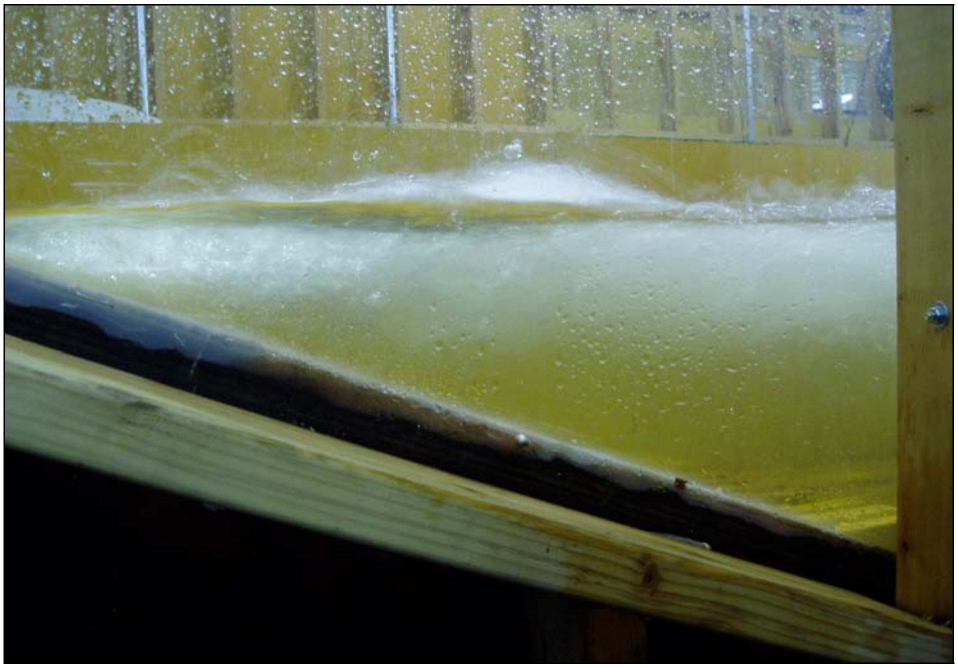

Figure 41. Deflector installed at 3073.3 ft with splitter walls fully removed. At a discharge of 2,000 ft^3/s, skimming flow is observed.

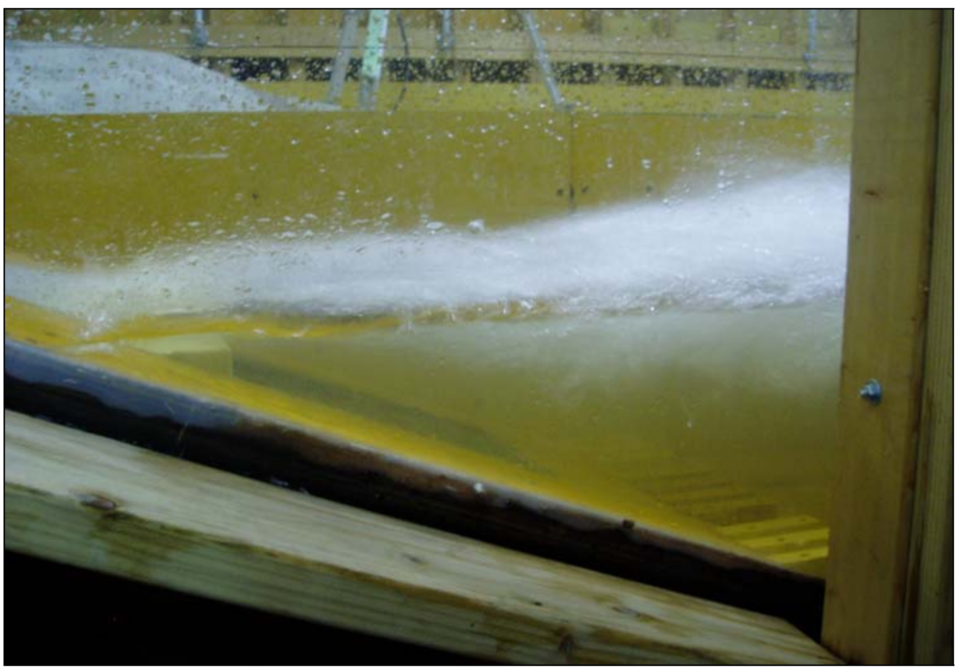

Figure 42. Deflector installed at 3073.3 ft with splitter walls fully removed. At a discharge of 3,000 ft^3/s, skimming flow condition observed.

Splitter Walls Partially Removed

Due to the complexity and cost associated with removing the splitter walls on the face of the spillway, the wall section upstream of the construction joint at Station 12+36.87 was left in the existing configuration and the resulting flow conditions were compared. When the upper wall section was left in place, the outlet works jet was confined to the width of the deflector and directed upward, producing a large undular wave (figure 43). When the splitter walls were fully removed with a deflector installed at elevation 3073.3 ft, skimming conditions occurred with a surface bubble layer, but no plunging flow. Full removal of the splitter walls proved to be a better alternative for TDG reduction.

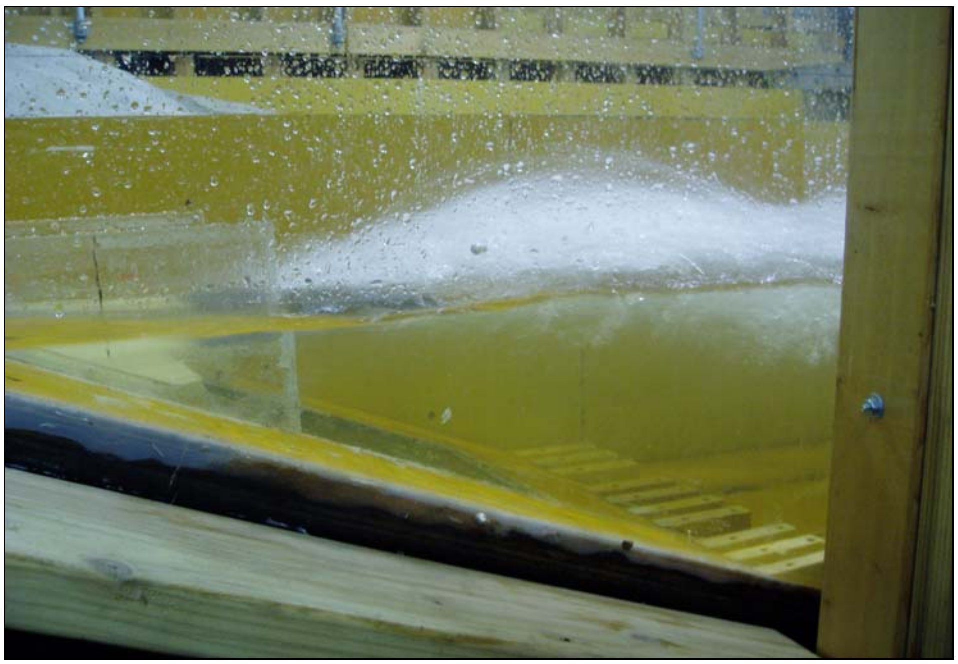

Figure 43. Deflector installed at 3073.3 ft with the upper section of the splitter walls left in the existing configuration. At a discharge of 2,000 ft^3/s, undular flow was observed.

Splitter Walls Reduced in Height

The possibility of reducing the height of the splitter walls was also explored. Reducing the height of the splitter walls rather than completely removing the walls could potentially reduce construction costs if TDG abatement was still adequate. Discussions were held with the Bend Field Office and structural designers at Reclamation's Technical Service Center to determine whether cutting off the top portion of the splitter walls was feasible. The maximum wall reduction was set to 15 ft from the top, because there are vertical steel bars placed in the concrete walls up to elevation 3067.5 ft.

The splitter walls were first reduced by 12 ft from elevation 3082.5 ft to elevation 3070.5 ft. The deflector was placed at elevation 3073.3 ft, the optimal elevation with the splitter walls fully removed. During a 2,000 ft^3/s release, the outlet works jet spread and it appeared that secondary rollers developed along the shortened walls causing bubble to plunge deep into the basin (figure 44).

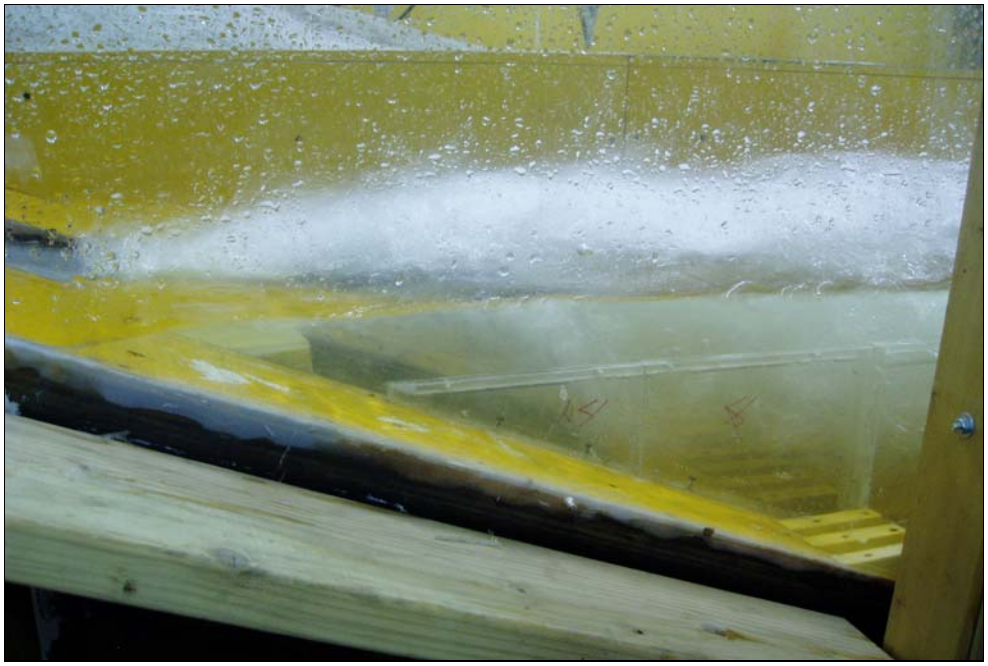

Figure 44. Deflector installed at 3073.3 ft with splitter walls reduced by 12 ft. At a discharge of 2,000 ft^3/s, skimming flow occurred on the surface, but bubbles plunged deep in the water column.

The splitter walls were reduced by an additional 3 ft to elevation 3067.5 ft and the deflector remained at elevation 3073.3 ft. During a 2,000 ft^3/s release, skimming flow was produced on the surface, but some bubbles still plunged near the floor of the basin (figure 45). Dye tests showed some interaction between the bays but the flow continued to plunge in the center bay. Dye injected in the side bays moved upstream. Although this condition did produce some improvement in flow conditions, fully removing the splitter walls provided the best opportunity for reduction of TDG levels downstream.

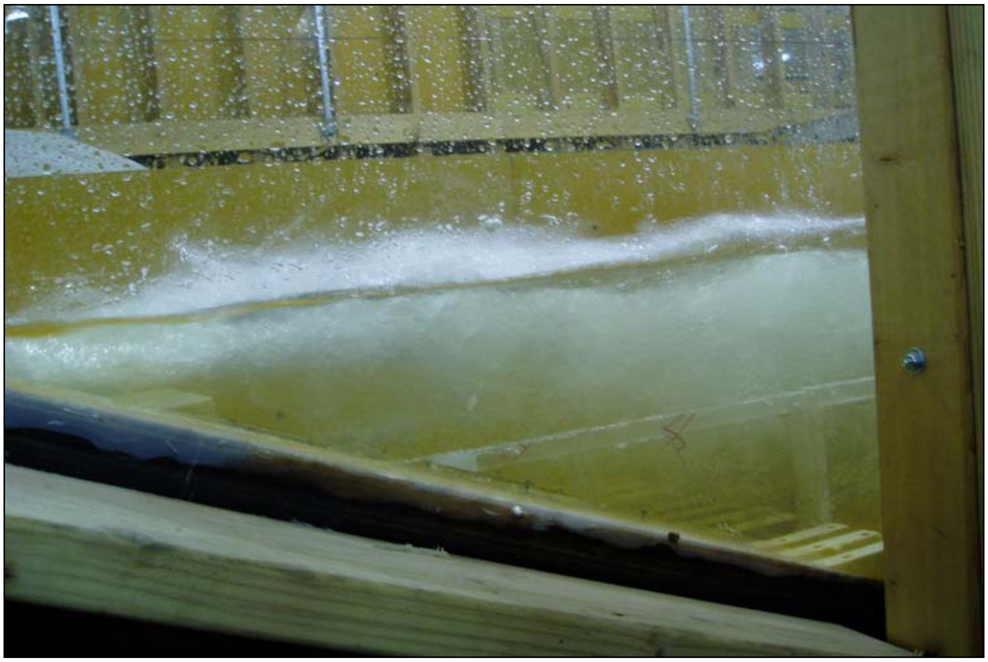

Figure 45. Deflector installed at 3073.3 ft with splitter walls reduced by 15 ft. At a discharge of 2,000 ft^3/s, skimming flow occurred on the surface, but some bubbles were observed deep in the basin.

Calculated Total Dissolved Gas Predictions

Model observations of bubble plunge depths under the best deflector elevations with and without splitter walls are shown in Table 1. Predicted TDG levels based on the bubble plunge depths were calculated by using the methods outlined in "Prediction of Dissolved Gas at Hydraulic Structures (Johnson, 1975). These predicted values are shown in Table 2 and Figure 46. Unpublished field measurements collected by Reclamation from 2006-2007 report a TDG level in the upstream reservoir of 104 percent. The saturation concentration of nitrogen was based on the average temperature of 6.6 degrees C in the field tests. The k and t parameters were back-calculated from the field data and used in subsequent TDG concentration predictions. Because the stilling basin at A.R. Bowman Dam is relatively shallow, the benefit of gas abatement alternatives is reduced because not as much reduction in plunge depth can be achieved.

TDG reductions of approximately 1.3 to 2.6 percent can be expected with the existing splitter walls in place. The Oregon water quality standard of 110 percent can be achieved for releases of up to about 1,000 ft^3/s. TDG reductions of approximately 3.6 to 6.5 percent can be expected with the splitter walls removed. It is anticipated that the 110 percent TDG standard could be achieved for outlet works releases of up to 2,000 ft^3/s.

Table 1. Model observations of bubble depths under different deflector scenarios.

		MODEL OBSERVATIONS OF BUBBLE DEPTH		
Discharge (ft^3/s)	Tailwater (ft)	No Deflector	Deflector Installed with Existing Stilling Basin	Optimal Configuration: Deflector Installed with Splitter Walls Removed
700	3077.8	2/3 depth	1/2 depth	3/8 depth
1,000	3078.7	3/4 depth	2/3 depth	1/2 depth
2,000	3080	full depth	7/8 depth	5/8 depth
3,000	3080.9	full depth	full depth	2/3 depth

Table 2. Predicted prototype TDG levels under different deflector scenarios.

		PREDICTED PROTOTYPE TDG LEVELS FROM MODEL RESULTS			PREDICTED PERCENT REDUCTION IN TDG	
Discharge (ft^3/s)	Tailwater (ft)	No Deflector	Deflector Installed with Existing Stilling Basin	Optimal Configuration: Deflector Installed with Splitter Walls Removed	Deflector Installed with Existing Stilling Basin	Optimal Configuration: Deflector Installed with Splitter Walls Removed
700	3077.8	110.1%	107.2%	106.1%	2.6%	3.6%
1,000	3078.7	112.2%	110.7%	107.6%	1.3%	4.1%
2,000	3080	117.5%	115.1%	110.4%	2.0%	6.0%
3,000	3080.9	121.1%	121.1%	113.2%	0.0%	6.5%

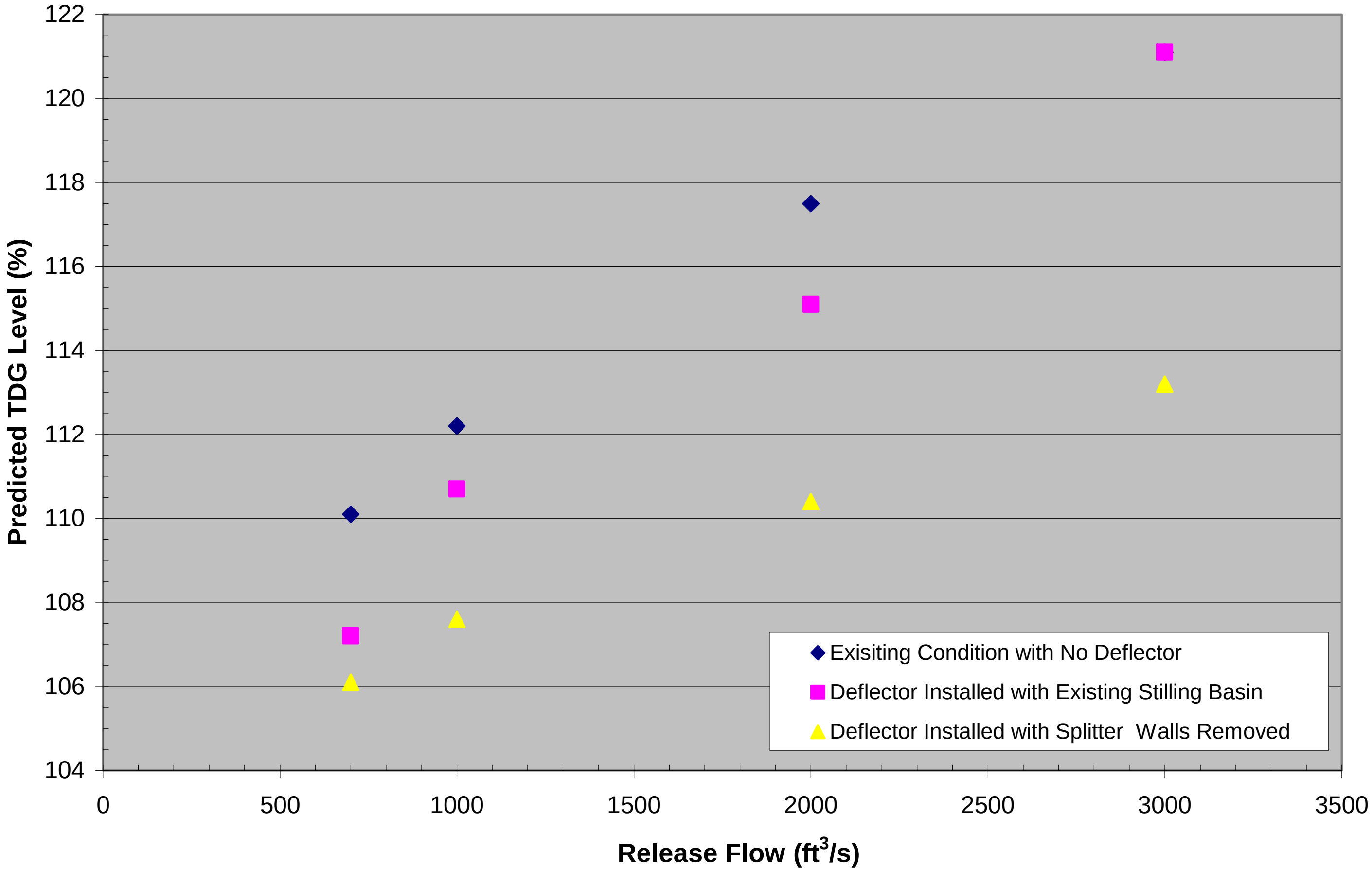

Figure 46. Graphical depiction of predicted TDG levels based on model observations of bubble plunge depths.

Stilling Basin Abrasion Damage

Results from the original physical model study for A.R. Bowman Dam recommended the installation of 28.5-ft-high splitter walls in the stilling basin (Bureau of Reclamation, 1959). The splitter walls prevented flow attachment to the basin sidewalls and the formation of a strong eddy that pulled riverbed material into the stilling basin. The splitter walls improved jet stability and hydraulic jump formation during outlet works flows. Even with the splitter walls installed, loose material located downstream from the endsill moved upstream into the basin in the model.

Since construction, the stilling basin has had a history of abrasion damage, requiring repair in 1987 and 2007. Although beneficial for TDG abatement, removing the splitter walls will likely worsen abrasion problems in the stilling basin. Like the original physical model, the outlet works jet in this model wandered from side to side in the basin when the splitter walls were removed. The vertical velocity distribution at the endsill was inverted during skimming flow with velocities at the top of the water column higher than velocities at the bottom. Loose material in the exit channel may be brought into the basin near the bed in slack water or eddy zones. The addition of a powerplant could reduce usage of the outlet works, thus limiting the increased potential for abrasion damage with deflector installation.

High Spillway Flow Performance

Installation of a permanent deflector on the spillway face caused concerns about performance of the stilling basin during high spillway flows. Spillway flow would deflect off of the wedge, resulting in less energy dissipation in the stilling basin and higher velocities in the exit channel and along the right and left downstream banks. To investigate this concern, spillway discharges of 4,000, 8,120, and 14,965 ft^3/s were tested under three conditions:

Condition 1: No deflector with existing stilling basin geometry

Condition 2: Deflector installed with existing stilling basin geometry

Condition 3: Deflector installed with splitter walls removed

During tests with a deflector installed on the spillway face, spillway flow projected off of the deflector in the center part of the spillway. Greater turbulence was observed in the exit channel with a deflector installed than in the existing condition with no deflector installed. Wave run-ups on the right and left banks were also higher, and velocities along the right bank, above the endsill, and in the exit channel were higher.

Flows greater than the design discharge of 8,120 ft^3/s swept out of the basin for all three test conditions, regardless of whether a deflector was installed. At a discharge of 14,965 ft^3/s, a large turbulent boil in the exit channel was produced for all three tested conditions, however the boil was larger and more energetic with a deflector installed. During condition 3 with the splitter walls removed, a large nonuniform boil attached to the right basin sidewall and boiled over the right sidewall.

Photographs of all spillway flow tests are shown in figures 47-63. Detailed model observations are provided in the appendix.

Spillway Flow of 4,000 ft^3/s

Figure 47. Condition 1: Side view with no deflector and existing stilling basin geometry at a discharge of 4,000 ft^3/s.

Figure 48. Condition 1: Surface view with no deflector and existing stilling basin geometry at a discharge of 4,000 ft^3/s.

Figure 49. Condition 2: Side view with deflector installed and existing stilling basin geometry (deflector elevation 3071.5 ft). Release flow was 4,000 ft^3/s.

Figure 50. Condition 2: Surface view with deflector installed and existing stilling basin geometry (deflector elevation 3071.5 ft). Release flow was 4,000 ft^3/s.

Figure 51. Condition 3: Side view with deflector installed and splitter walls completely removed (deflector elevation 3073.3 ft). Release flow was 4,000 ft^3/s.

Figure 52. Condition 3: Surface view with deflector installed and splitter walls completely removed (deflector elevation 3073.3 ft). Release flow was 4,000 ft^3/s.

Spillway Flow of 8,120 ft³/s

Figure 53. Condition 1: Surface view with no deflector and existing stilling basin geometry at a discharge of 8,120 ft^3/s.

Figure 54. Condition 2: Side view with deflector installed and existing stilling basin geometry (deflector elevation 3071.5 ft). Release flow was 8,120 ft^3/s.

Figure 55. Condition 2: Surface view with deflector installed and existing stilling basin geometry (deflector elevation 3071.5 ft). Release flow was 8,120 ft^3/s.

Figure 56. Condition 3: Side view with deflector installed and splitter walls completely removed (deflector elevation 3073.3 ft). Release flow was 8,120 ft^3/s.

Figure 57. Condition 3: Surface view with deflector installed and splitter walls completely removed (deflector elevation 3073.3 ft). Release flow was 8,120 ft^3/s.

Spillway Flow of 14,965 ft^3/s

Figure 58. Condition 1: Surface view with no deflector and existing stilling basin geometry at a discharge of 14,965 ft^3/s.

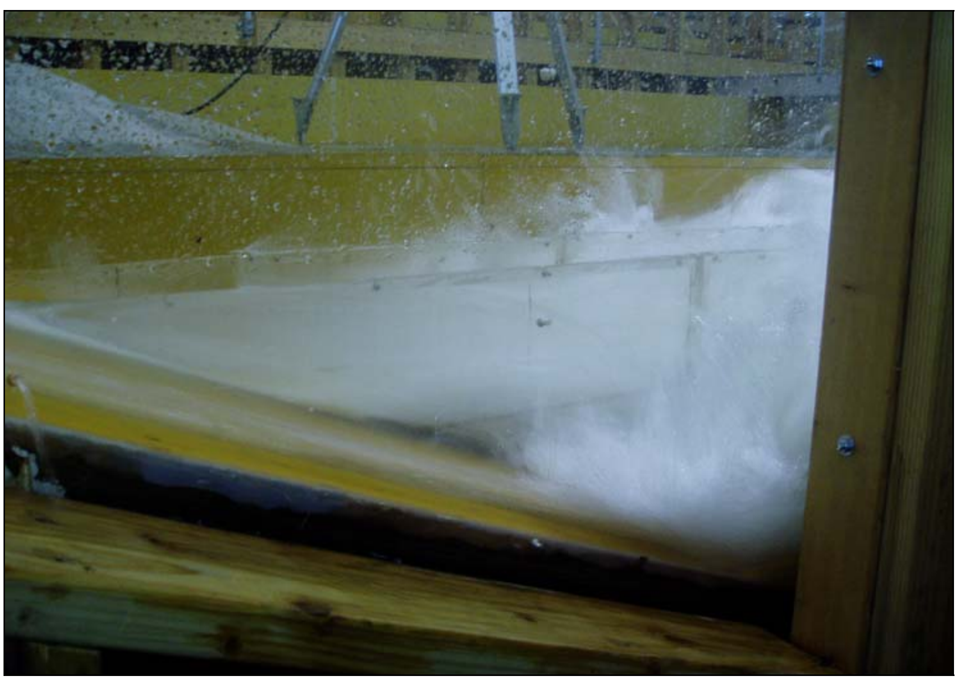

Figure 59. Condition 2: Side view with deflector installed and existing stilling basin geometry (deflector elevation 3071.5 ft). Release flow was 14,965 ft^3/s.

Figure 60. Condition 2: Surface view with deflector installed and existing stilling basin geometry (deflector elevation 3071.5 ft). Release flow was 14,965 ft^3/s.

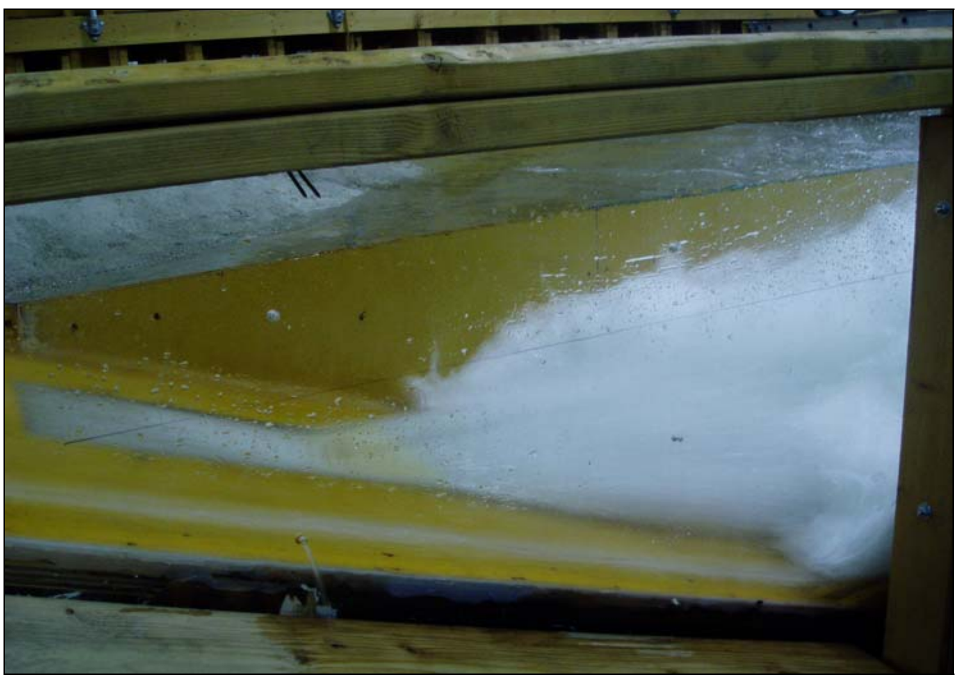

Figure 61. Condition 3: Side view with deflector installed and splitter walls completely removed (deflector elevation 3073.3 ft). Release flow was 14,965 ft^3/s.

Figure 62. Condition 3: Surface view with deflector installed and splitter walls completely removed (deflector elevation 3073.3 ft). Release flow was 14,965 ft^3/s. Note the uneven flow distribution in the stilling basin. Flow moves over right stilling basin wall and up the right bankline.

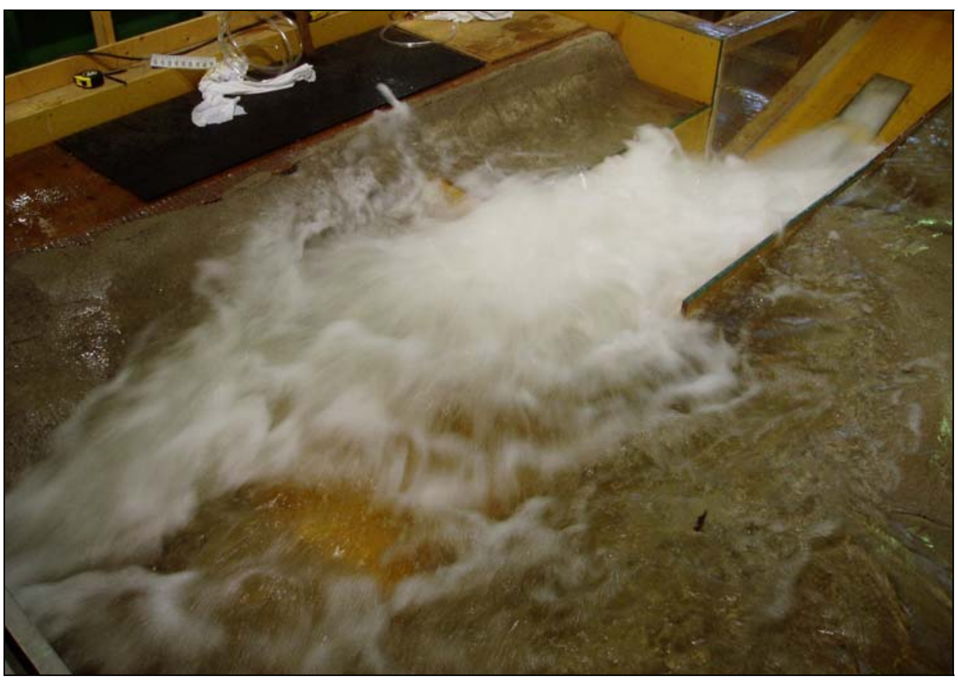

Figure 63. Condition 3: Side view with deflector installed and splitter walls completely removed (deflector elevation 3073.3 ft). Release flow was 8,120 ft^3/s. Note the uneven flow distribution in the stilling basin. Flow moves over right stilling basin wall and up the right bankline.

Conclusions

A TDG deflector elevation that effectively produced skimming flow could not be found without structural modifications to the splitter walls. At best, undular flow conditions could be reliably attained for low flows of 700 to 2,000 ft^3/s with a 12.5-ft-long deflector installed at elevation 3071.5 ft. During undular flow, the jet replunged in the stilling basin just downstream of the initially deflected flow. Bubble depths were not reduced as much as they would be during a skimming flow condition. There was no benefit from the deflector at 3,000 ft^3/s, because plunging flow still occurred.

These model tests show that the presence of the two splitter walls in the stilling basin prohibits the deflector from producing adequate flow conditions to reduce TDG levels. Notable improvements in basin flow conditions were observed when the splitter wall heights were reduced by 15 ft to elevation 3067.5 ft, but the greatest dissolved gas benefit was observed when the splitter walls were completely removed. With the splitter walls removed, the optimal elevation was 3073.3 ft for a 12.5-ft-long deflector that spanned the full width of the outlet works opening. Skimming flow was produced for all discharges between 700 and 3,000 ft^3/s. The splitter walls should be completely removed from the spillway face to ensure proper spreading of the jet as it exits the outlet works tunnel. To prevent excavation of the basin floor, a short section of the splitter walls can be left at the floor, as determined by the structural designers, but it should be minimized for optimal benefit.

Total dissolved gas predictions with the addition of deflector were calculated based on bubble plunge depths observed in the model. With no modifications to the stilling basin, TDG reductions of approximately 1.3 to 2.6 percent could be expected. The Oregon water quality standard of 110 percent could be achieved for releases up to 1,000 ft^3/s. With the splitter walls removed, TDG reductions of approximately 3.6 to 6.5 percent could be expected. It is anticipated that the Oregon water quality standard could be achieved for releases up to 2,000 ft^3/s.

It must be noted that removal of the splitter walls will likely increase movement of loose material into the stilling basin. This may worsen existing problems with abrasion damage. Because the splitter walls were installed to prevent flow attachment to the basin sidewalls, the jet wanders from side to side in the basin when the splitter walls are removed, producing laterally skewed flow patterns. Skimming flow from the deflector produces high velocities near the water surface and low velocities near the bed, so loose material in the exit channel may be pulled into the basin near the bed in slack water or eddy zones.

During spillway releases in the model, spillway flow projected off of the deflector in the center part of the spillway and greater turbulence was observed in the exit channel. Compared to the existing stilling basin condition, the wave run-up on the right and left banks was higher, and velocities along the right bank, above the endsill, and in the exit channel were higher with a deflector installed. When the basin splitter walls were completely removed in conjunction with the installation of a spillway deflector, an asymmetric boil attached to the right basin wall and boiled over right sidewall during a release of 14,965 ft^3/s.

The observed flow conditions warranted a discussion as to whether the installation of a deflector increased the risk of stilling basin failure under high flow releases. The TDG deflector was included in a stilling basin risk assessment study conducted on February 2-3, 2009 to determine whether the installation of a deflector produced unacceptable risk to dam safety goals (Bureau of Reclamation, 2009). Results of the risk assessment showed that there was no significant risk of dam failure associated with failure of the stilling basin with or without a deflector. Therefore, the deflector can be installed as desired for water quality improvements realizing the potential for increased maintenance in the stilling basin.

Recommendations

If a TDG deflector is installed at A.R. Bowman dam for gas abatement, it is recommended that stilling basin inspections for abrasion damage continue at regular intervals. Loose material should be periodically removed from the exit channel to reduce the source material available for abrasion damage. Installation of a vertical flat metal flow deflector above the endsill was recommended in the 2007 Comprehensive Facility Review to reduce movement of material into the stilling basin (Reclamation, 2007). Although this flow deflector could achieve abrasion reduction goals, it would negate the intended benefit of the TDG deflector by forcing flow to plunge underneath of the flow deflector (Hanna, 2001). It is recommended that the TDG deflector on the face of the spillway not be installed in conjunction with the flow deflector at the basin endsill.

During post-assessment for the spillway deflector, water quality levels downstream of the stilling basin should be monitored and recorded. Further biological studies should be conducted to document changes in the occurrence of gas bubble disease in fish in the Crooked River.

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Appendix

High Flow Observations

Table A-1. Model observations at a spillway discharge of 4,000 ft^3/s.

	CONDITION 1 No Deflector Installed with Existing Stilling Basin	CONDITION 2 Deflector Installed with Existing Stilling Basin	CONDITION 3 Deflector Installed with Splitter Walls Removed
Right Bank Wave Run-up	1-2 ft	4 ft	1-3 ft
Left Bank Wave Run-up	2 ft	6 ft	4 ft
Right Bank Velocity 72 ft Downstream of the Stilling Basin	3.1 ft/s at 60 degree angle into the bankline	6.4 ft/s at 60 degree angle into the bankline	6.2 ft/s at 60 degree angle into the bankline
Right Bank Velocity 108 ft Downstream of the Stilling Basin	Not recorded	Not recorded	5.9 ft/s parallel to the bankline
Endsill Centerline Velocities			
1.) Surface Velocity	5.1 ft/s	23.0 ft/s	19.0 ft/s
2.) Velocity 2.4 ft from the Surface	4.4 ft/s	20.5 ft/s	9.1 ft/s
3.) Velocity 4.8 ft from the Surface	3.6 ft/s	17.7 ft/s	4.3 ft/s
4.) Velocity 7.2 ft from the Surface	2.8 ft/s	Not recorded	2.6 ft/s
Turbulence in Exit Channel	No turbulence downstream of the endsill. Hydraulic jump is even across the 3 bays.	Some turbulence downstream of the endsill.	Some turbulence downstream of the endsill.
Jet Impact Downstream from Endsill	Jet does not impact the bed.	Jet does not impact the bed.	Jet does not impact the bed.
Observations of Splash	No splash over the sidewalls.	Splash over the right sidewall accumulates in catchment. May need to install additional drainage. Some splash over the left sidewall. May need additional bank protection.	Splash over the right sidewall accumulates in catchment. May need to install additional drainage. Some splash over the left sidewall. May need additional bank protection.
Outlet Works Tunnel	None	None	None

Table A-2. Model observations at a spillway discharge of 8,120 ft^3/s.

	CONDITION 1	CONDITION 2	CONDITION 3
	No Deflector Installed with Existing Stilling Basin	Deflector Installed with Existing Stilling Basin	Deflector Installed with Splitter Walls Removed
Right Bank Wave Run-up	4 ft	8 ft	8 ft
Left Bank Wave Run-up	4 ft	7 ft	7 ft
Right Bank Velocity 72 ft Downstream of the Stilling Basin	9.8 ft/s at 60 degree angle into the bankline	9.9 ft/s at 60 degree angle into the bankline	6.7 ft/s at 60 degree angle into the bankline
Right Bank Velocity 108 ft Downstream of the Stilling Basin	11.1 ft/s at 10 degree angle into the bankline (no direct impingement)	13.8 ft/s at 60 degree angle into the bankline	9.5 ft/s at 10 degree angle into the bankline (no direct impingement)
Endsill Centerline Velocities			
1.) Surface Velocity	3.3 ft/s	36.1 ft/s	13.6 ft/s
2.) Velocity 2.4 ft from the Surface	5.4 ft/s	37.1 ft/s	9.2 ft/s
3.) Velocity 4.8 ft from the Surface	8.1 ft/s	27.3 ft/s	5.3 ft/s
4.) Velocity 7.2 ft from the Surface	11.5 ft/s	16.1 ft/s	4.6 ft/s
5.) Velocity 9.6 ft from the Surface	13.6 ft/s	Not recorded	2.8 ft/s
6.) Velocity 12.0 ft from the Surface	15.9 ft/s	Not recorded	2.1 ft/s
7.) Velocity 6.0 ft Above the Endsill	15.8 ft/s	3.6 ft/s	2.5 ft/s
Channel Centerline Velocity at End of 5:1 Slope	9.1 ft/s at the surface and 5.8 ft/s at mid-depth	15.5 ft/s at the surface	9.8 ft/s at the surface
Channel Centerline Velocity at Approximatly 240 ft Downstream from the Endsill	6.7 ft/s at the surface	7.1 ft/s at the surface	7.3 ft/s at the surface

Table A-2 continued. Model observations at a spillway discharge of 8,120 ft^3/s.

	CONDITION 1 No Deflector Installed with Existing Stilling Basin	CONDITION 2 Deflector Installed with Existing Stilling Basin	CONDITION 3 Deflector Installed with Splitter Walls Removed
Turbulence in Exit Channel	Some moderate turbulence downstream of the endsill, but energy is dissipated in the basin. Hydraulic jump is even across the 3 bays.	Jet moves out of the stilling basin. Water depths in the right and left bays are lower than the center bay by approximately 12 ft. Hydraulic jumps in the right and left bays sweep downstream from the toe of the spillway while the center jet projects horizontally from the deflector. Low velocities toward the bottom of the water column at the endsill may draw in loose material.	The deflected jet produces significant turbulence, but the jet does not exit the basin. Water boils up over the sidewalls. The turbulence does not extend as far downstream as it does in Conditions 1 and 2. The turbulence is centered toward the left side of the basin with greater splashing on the left side. The water level is consistent across the basin. Low velocities toward the bottom of the water column at the endsill may draw in loose material.
Jet Impact Downstream from Endsill	Jet does not impact the bed.	Jet impacts the bed 72 ft downstream from the endsill, since the bed elevation rises up to the jet thickness.	Jet does not impact the bed.
Observations of Splash	No splash over the sidewalls.	Significant splash over the right and left sidewalls may require additional bank protection.	Significant splash over the right and left sidewalls may require additional bank protection.
Outlet Works Tunnel	Some water moves upstream into the outlet works tunnel.	Water backs up into the outlet works tunnel with a deflector installed.	Water backs up into the outlet works tunnel with a deflector installed.

Table A-3. Model observations at a spillway discharge of 14,965 ft^3/s.

	CONDITION 1 No Deflector Installed with Existing Stilling Basin	CONDITION 2 Deflector Installed with Existing Stilling Basin	CONDITION 3 Deflector Installed with Splitter Walls Removed
Right Bank Wave Run-up	10-12 ft	10-12 ft	Greater than 14 ft (above contour 3105 ft)
Left Bank Wave Run-up	The left bank is almost submerged to the top of the riprap section. Water is at the toe of the dam, but there is no turbulence.	The left bank is almost submerged to the top of the riprap section. Water is at the toe of the dam, but there is no turbulence.	The left bank is almost submerged to the top of the riprap section. Water is at the toe of the dam, but there is no turbulence.
Right Bank Velocity 72 ft Downstream of the Stilling Basin	12.2 ft/s at 60 degree angle into the bankline	18.5 ft/s at 60 degree angle into the bankline	20.1 ft/s at 60 degree angle into the bankline
Right Bank Velocity 108 ft Downstream of the Stilling Basin	12.6 ft/s at 60 degree angle into the bankline	14.2 ft/s at 60 degree angle into the bankline	21.1 ft/s at 60 degree angle into the bankline
Endsill Centerline Velocity at Mid-Depth (boil too turbulent for accurate readings at multiple depths)	20.4 ft/s	18.5 ft/s	18.5 ft/s
Channel Centerline Velocity at End of 5:1 Slope	10.6 ft/s at the surface	14.9 ft/s at the surface	15.7 ft/s at the centerline of the slope; 20.7 ft/s at maximum velocity region closer to right bank.
Channel Centerline Velocity at Approximately 240 ft Downstream from the Endsill	7.7 ft/s at the surface	7.6 ft/s at the surface	9.4 ft/s at the surface

Table A-3 continued. Model observations at a spillway discharge of 14,965 ft^3/s.

	CONDITION 1	CONDITION 2	CONDITION 3
	No Deflector Installed with Existing Stilling Basin	**Deflector Installed with Existing Stilling Basin**	**Deflector Installed with Splitter Walls Removed**
Turbulence in Exit Channel	Boil begins inside the basin and extends approximately 54 ft beyond the endsill. The hydraulic jump spans across all 3 bays. Without the deflector, the flow is less turbulent in the exit channel. More energy is observed near to the endsill because the energy is dissipated closer to the basin.	The hydraulic jump occurs in the center of the basin at the end of the splitter walls. The toe of jump is about 12 ft upstream from the end of the splitter walls. A large boil extends about 72 ft downstream of the endsill with a height of about 8 ft above the sidewalls. There is strong flow impingement on the right bank. Recirculation occurs behind the left sidewall.	A large asymmetric boil attaches to the right sidewall and boils over the wall with significant run-up on the right bank. The toe of the jump is about 12 ft upstream from the end of the splitter walls. Water projecting from the deflector pushes out the tailwater causing the upstream section of the basin to sweep out. Water boils over the left sidewall with a recirculation zone behind the left sidewall. The asymmetric boil extends about 72 ft downstream of the endsill to the right side with a height of 8 ft above the sidewalls.
Jet Impact Downstream from Endsill	Jet does not impact the bed, but there is a large boil in the exit channel.	Jet does not impact the bed, but there is a large boil in the exit channel that impacts the bed at about 72 ft downstream of the endsill.	Jet does not impact the bed, but there is a large asymmetric boil in the exit channel that impacts the bed at about 72 ft downstream of the endsill.
Observations of Splash	Moderate splashing.	Significant splash over the right sidewall accumulates in catchment. Additional drainage may be needed.	Water pours over the right sidewall, fills the catchment, and flows over the downstream wall. Flow impinges on the right bank.
Outlet Works Operation	No instability occurs downstream of the deflector when the outlet works are opened. With combined spillway and outlet works releases, the basin is more turbulent with a higher differential across splitter walls. The boil extends almost completely out of the basin.	When the outlet works are opened, backflowing water is pushed out of the outlet works. Negative pressures occur downstream of the deflector where the outlet works jet projects. There is an audible suction noise as air backs up to the downstream end of the deflector, pushes downstream away from the deflector, and then backs up to the deflector again (unstable condition).	When outlet works are opened, there are no negative pressures. The basin flow is much more uniform with outlet works flow than without outlet works flow, but the flow does oscillate from the left to the right side of the basin over time.