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Paonia Outlet Tunnel Blowback Model Study

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14. ABSTRACT

A 1:11-scale physical hydraulic model of Paonia Dam outlet works tunnel was constructed at Reclamation’s Hydraulics Laboratory in Denver, Colorado to study how existing standard operating procedures could be adjusted to allow heavy sediment loads to pass through the outlet works. The model included elements representing the reservoir, intake structure, and conduit downstream to the outlet works control gate structure in the outlet tunnel. Theoretical analyses indicated the potential for modified operations to cause blowback and blowout from the outlet tunnel due to air accumulation. Blowback and blowout are problematic since they could cause major damage to the trash rack structure at the inlet to the outlet tunnel and/or the gates in the gate chamber. The results of this study indicate that blowback can occur for a range of discharges between 450-550 ft^3/sec in the range of reservoir elevations between 6360.88-6361.35 ft. Model results also indicate that installing a 16-in (prototype) air vent at the start of the 11-ft-diameter (prototype) horizontal section of conduit should allow enough air to escape the structure to prevent blowback for the proposed modified operations of the outlet works.

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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.

Acknowledgments

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Cover Photo: Paonia Outlet Tunnel Trashrack Structure 2017-10-11 (Photo by Alexander Stephens)

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Executive Summary

The Hydraulic Investigations and Laboratory Services Group of the Bureau of Reclamation was asked to analyze operational modifications that would allow the lifting of the current 200 ft^3/sec operating restriction on the Paonia Dam outlet works. The existing restrictions are in place to prevent potential blowback from damaging the outlet works intake structure trashracks and bulkhead. The source of the blowback phenomenon is small quantities of air that are drawn in at the intake structure. This air accumulates and coalesces within the pipeline until the air bubble grows to a size that enables it to migrate back upstream along the crown of the pipe and be expelled explosively through the intake. The blowback problem has been observed since 1962, and caused significant damage prior to the implementation of the operating restriction.

A proposed solution for operations without restriction involves installing an air vent with an air release valve to safely remove air that accumulates in the tunnel just upstream of the gate chamber. Existing analytical methods are not adequate to predict the location of air accumulation or the quantity of air that might accumulate, which makes correctly sizing and locating reliable air venting extremely difficult. To meet the requirements of this project and reduce uncertainties associated with air accumulation, a 1:11.1 scale physical model of the Paonia outlet works from the upstream intake structure through the downstream regulating gate chamber was constructed.

The model study focused on characterizing the hydrodynamics associated with air-water interactions when operating the outlet works at maximum capacity, unrestricted by the regulating gates. The primary purpose of the study was to identify adverse conditions (blowback and/or blowout) and, if necessary, propose and evaluate potential solutions.

Rating curves were generated to simulate conditions associated with both filling and draining of the reservoir. The model was constructed using existing as-built drawings. Blowback was consistently observed for discharges in the range of 450-550 ft^3/sec with corresponding water surface elevations between 6360.88-6361.35 feet. Air vents of varying sizes and in varying locations were considered to prevent the blowback from occurring. Model results indicate that installing a 16-in (prototype) air vent at the start of the 11-ft diameter (prototype) horizontal section of conduit should allow enough air to escape the structure to prevent blowback for the proposed modified operations of the outlet works.

Introduction

The outlet works at Paonia Dam are currently undergoing design for rehabilitation of the emergency and regulating gates. The project is also facing challenging sediment management issues that have impacted operations. One proposed solution to improve sediment management includes changes in operations to allow releases through the outlet works at low reservoir elevations during which the crest at the intake may be controlling. Since initial filling of the reservoir, the outlet works has been under an operating restriction limiting discharges to 200 ft^3/s or less for reservoir levels below El. 6373 ft and 30 ft^3/s or less for reservoir levels below El. 6362 ft. These restrictions have been in place to prevent potential blowback damage to the intake structure. Blowback damage was first documenting in 1962, when explosive blowback damaged the exiting trashrack structure as shown in Figure 1.

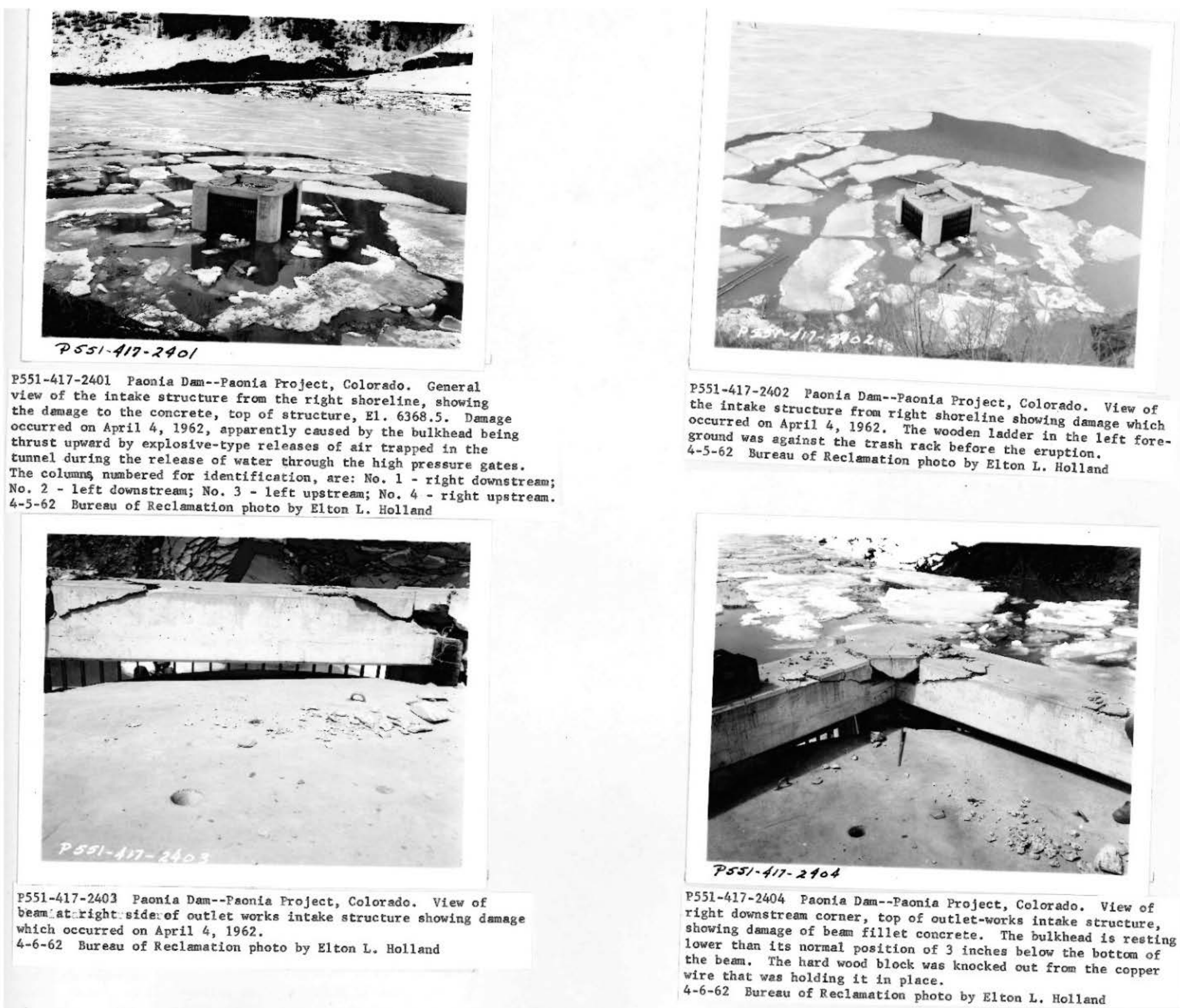

Figure 1. Four historical photos of existing blowback that occurred April 4, 1962 at Paonia outlet tunnel.

Blowback and blowout can occur because of air entrainment at the intake, especially when the reservoir water levels approach and enter the range in which flow is controlled at the crest.

Depending on operating conditions, air entrained at the intake does not pass all the way through the outlet, but instead can accumulate in the outlet works tunnel between the intake and the gate chamber. When a sufficient amount of air accumulates it will either be released through the regulating gates resulting in blowout or travel back up the intake resulting in blowback. Both cases can be damaging due to rapid release of compressed air-water mixtures and surging. The blowback phenomenon is discussed in detail by Falvey (1980) in Engineering Monograph 41, *Air-Water Flow in Hydraulic Structures*.

A solution for operations without restriction has been proposed (Memorandum dated 10/17/13, Paonia Reservoir Dam, Upstream Conduit Air Vent) and involves installing an air vent with a blow-off valve to release air that accumulates in the tunnel just upstream of the gate chamber. Existing analytical methods are not adequate to predict location or quantity of air that might accumulate which makes correctly sizing and locating reliable air venting extremely difficult.

Given the requirements of this project and uncertainties associated with air accumulation, Reclamation's Hydraulic Investigations and Laboratory Services Group constructed a 1:11.1 scale physical model of the Paonia outlet works from the upstream intake structure through the downstream regulating gate chamber.

Project Background & History (Dressel, 2018)

Paonia Dam is located 16 miles northeast of Paonia, Colorado, on Muddy Creek, upstream from its confluence with Anthracite Creek. The two creeks together form the North Fork of the Gunnison River. The construction contract for the dam was awarded in January 1959 and construction was completed in January 1962. Upon completion of construction, Paonia Reservoir had an active storage capacity of 18,150 acre-feet. Due to sediment accumulation in the reservoir, the current active storage capacity estimate is approximately 15,600 acre-feet. The reservoir provides summer irrigation water to approximately 15,300 acres of land, of which 2,230 acres were not under irrigation before the construction of the dam. In addition, the reservoir provides recreational and flood control benefits. The dam is owned by Reclamation and is operated and maintained by the Fire Mountain Canal and Reservoir Company (FMCRC) under contract with the North Fork Water Conservancy District (NFWCD).

The dam is a zoned earth fill structure with a structural height of 199 feet, a crest width of 35 feet, and a crest length of 770 feet at elevation 6401 ft. The spillway is an uncontrolled overflow structure founded on bedrock at the right abutment of the dam. The reinforced concrete structure consists of an ogee crest and chute section with a common spillway and outlet works stilling basin. The stilling basin is 120 feet long by 42 feet wide by 42.2 feet deep at maximum tail water elevation of 6285.2 ft. The spillway has a design discharge capacity of 12,570 ft^3/sec at a reservoir water surface elevation of 6454.1 ft. The outlet works passes through the bedrock which forms the right abutment of the dam. It consists of a vertical drop intake structure with trashracks (intake crest elevation 6358 ft), a pressurized 11-foot-diameter concrete lined tunnel, a gate chamber (invert

[1] All elevations in this document are reported in Reclamation's project vertical datum used during construction of Paonia Dam.

elevation 6289 ft) with two pairs of 2-foot 9-inch by 2-foot 9-inch hydraulically operated slide gates (two upstream emergency gates and two downstream regulating gates), and a 10-foot 6-inch by 10-foot 6-inch horseshoe shaped discharge tunnel. The discharge tunnel exits through the spillway chute (invert elevation 6275 ft) into a common stilling basin. The discharge capacity of the outlet works is 1,250 ft^3/sec at reservoir elevation 6454.1 ft.

Based on the most recent bathymetric survey of the entire reservoir, conducted in June 2016, the estimated average annual rate of sedimentation has been 101 acre-feet per year. Approximately 25% of the reservoir's original total storage capacity of 20,950 acre-feet has been lost to sediment deposition.

In 2010, the outlet works at Paonia Dam became partially blocked with sediment and debris, indicating an impending sediment deposition issue. Following the 2010 blockage, a sediment sluicing/flushing plan was implemented. Operations were changed to include drawing the reservoir down in early spring and using high spring run-off discharges to flush suspended sediment through the outlet works before closing the gates to refill the pool for irrigation season.

Until fall 2014, the flushing strategy was able to pass a significant amount of sediment through the long, narrow reservoir (the pool is approximately 3 miles long and 0.2 miles wide). However, reservoir drawdown in late October 2014 revealed the reservoir dead pool had completely filled with sediment, and the outlet works intake had become partially plugged with cohesive sediment and submerged debris. Due to this discovery of lost dead pool capacity and sediment deposition at the intake sill elevation, the original study objective of developing a long-term plan to manage inflowing and deposited sediment more efficiently was altered to include short-term strategies for water delivery during the 2015 irrigation season.

The FMCRC, NFWCD, Colorado River Water Conservation District (CRWCD), and Reclamation's Western Colorado Area Office (WCAO) in Grand Junction requested the Sedimentation and River Hydraulics Group within Reclamation's Technical Service Center (TSC) to numerically model the 2015 irrigation season and potential dam operation scenarios to support decisions on short-term facility operations and sediment management. The results of the numerical sediment transport modeling simulations were used to formulate recommendations for the operation of Paonia Dam following the lowering of the reservoir for the end of the 2015 irrigation season. In addition, the request to the TSC included providing interim reservoir operation guidance, developing alternatives for outlet works intake structure repair, and developing structural and nonstructural alternatives for long term sediment management. A multi-year modification alternatives analysis addressing long term sediment management is currently being performed.

As documented in the Special Intake Structure Inspection Report issued in 2012 and the 2013 Periodic Facility Review (PFR), the concrete outlet works intake structure has sustained significant damage such that the concrete bulkhead no longer functions for its designed purpose. When the reservoir elevation is lowered, the discharge into the outlet works transitions from submerged control to weir control. During weir control, air can become entrained and accumulate in the horizontal pipe section upstream of the gate chamber. Pockets of air can then combine and become large enough such that buoyancy overcomes the drag forces of the water and the air pockets travel upstream and out of the intake structure imparting an explosive force on the intake structure.

Similar damage to the bulkhead occurred during initial testing of the outlet works and a contract was issued for repair.

In recent years, Reclamation, in a joint effort with the water users, has developed a procedure to drawdown the reservoir with minimal blowback to the intake structure. However, the intake needed to be repaired and there were distinct advantages to eliminating the problem altogether. To this end, the concrete bulkhead was removed in October 2017 and installation of an air vent upstream of the gate chamber with an air release valve in the gate chamber was proposed to help reduce the blowback potential.

As noted in the 2017 Outlet Works Special Examination Report and 2018 CR Examination Report there has been extensive erosion damage to all four of the outlet works gates, the seats, and the surrounding concrete. The damage to the regulating gates prevents both gates from sealing properly with significant leakage observed. Furthermore, each of the regulating gates has been rendered inoperable in the past. The stem nut on each regulating gate has come loose and fallen off resulting in the stem pulling away from the gate leaf. Additionally, the left emergency gate became stuck in the closed position in July 2017 and could not be opened until late August 2018 after the reservoir was lowered approximately 20 feet. Following extensive inspections and troubleshooting, this malfunction of the emergency gate was thought to be caused by excessive wear of the gate seat due to abrasion by sediment.

The rehabilitation of the outlet works gates has been a part of the alternatives analysis currently underway. Given the recent gate malfunctions and because there is no other means to provide affordable water to the downstream users should the outlet works not function, the TSC has been requested to accelerate the final design of the work required to replace the outlet works gates.

Model Description

Model Objectives

The model study focused on characterizing the hydrodynamics associated with air-water interaction during unrestricted operation of the outlet works. The primary purpose of the study was to identify adverse operating conditions (blowback and/or blowout) and, if necessary, propose and evaluate potential solutions.

Model Scale

Similitude between the model and the prototype is achieved when the ratios of the major forces controlling the physical processes are equal in the model and prototype. Since gravitational and inertial forces typically dominate open channel flow, Froude-scale similitude was used to establish similitude between the model and the prototype. The Froude number is defined as

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

where v = velocity, g = gravitational acceleration, and d = flow depth. When Froude-scale similitude is used for a 1:11.1 scale (scale was selected to utilize clear PVC pipe that was already available at the lab, and to ensure that air-water scale effects would be minimized), the following relationships exist between the model and prototype where the r subscript refers to the ratio of model to prototype:

Length ratio:	$L_r = L_{model}/L_{prototype} = 1:11.1$
Pressure ratio:	$P_r = 1:11.1$
Velocity ratio:	$V_r = L_r^{1/2} = (11.1)^{1/2} = 1:3.33$
Time ratio:	$T_r = L_r^{1/2} = (11.1)^{1/2} = 1:3.33$
Discharge ratio:	$Q_r = L_r^{5/2} = (11.1)^{5/2} = 1:410.74$

Model Features

A 1:11.1 scale physical hydraulic model was constructed at Reclamation's Hydraulics Laboratory in Denver, Colorado. All hydraulic and structural components from the reservoir through the outlet works control gates were modeled (Figure 1) including the trashrack structure (Figure 2), inlet (Figure 3), vertical 6-ft-diameter conduit (Figure 4), transitional expansion elbow (Figure 6 and Figure 7), horizontal 11-ft-diameter tunnel (Figure 5) and the outlet gates transition section (Figure 6 and Figure 7). Gates were simulated using a single wood slide gate that could operate from the fully open to the fully closed position (Figure 10 and Figure 11).

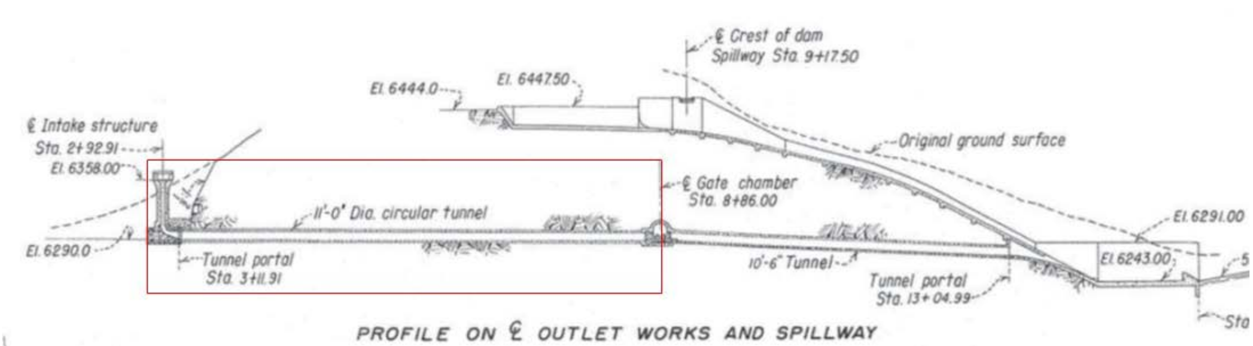

Figure 2. Profile of Paonia outlet works along the centerline of the outlet tunnel and spillway (the red box highlights the features that were modeled).

Figure 3. Paonia outlet works trash rack structure.

Figure 4. Paonia inlet without trashrack structure in place.

Figure 5. Vertical shaft and horizontal outlet conduit.

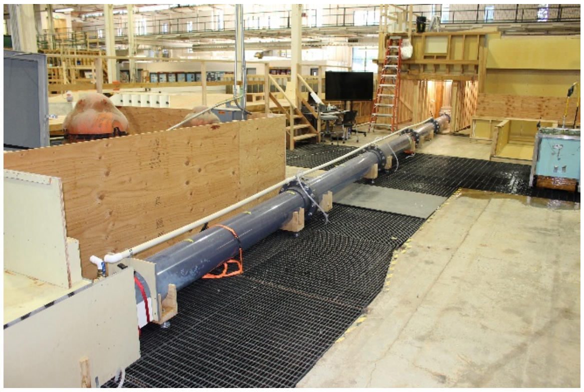

Figure 6. Horizontal outlet conduit.

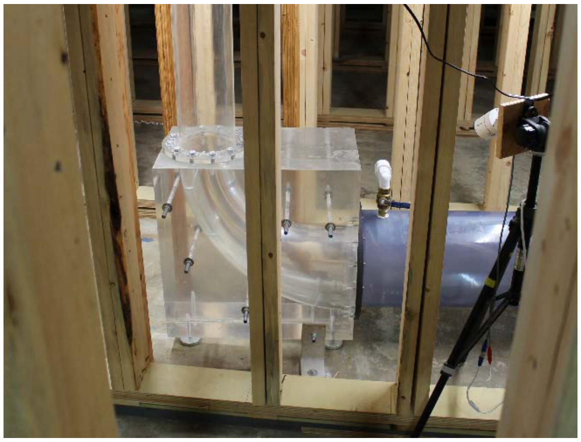

Figure 7. Transitional expansion elbow.

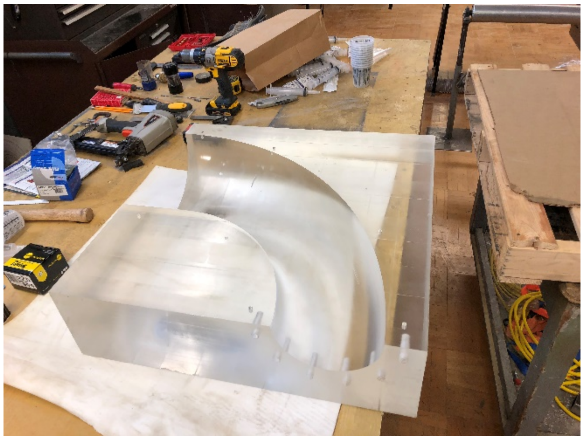

Figure 8. One half of the transitional expansion elbow.

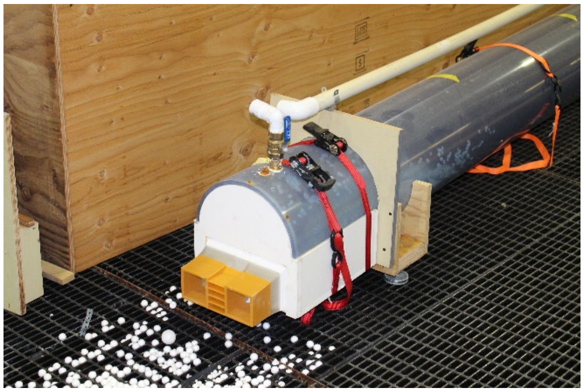

Figure 9. Outlet works gate chamber.

Figure 10. Outlet works gate chamber without the conduit installed.

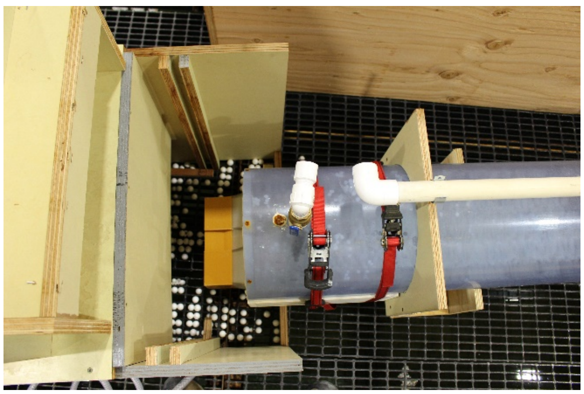

Figure 11. Outlet works gate chamber with tailbox.

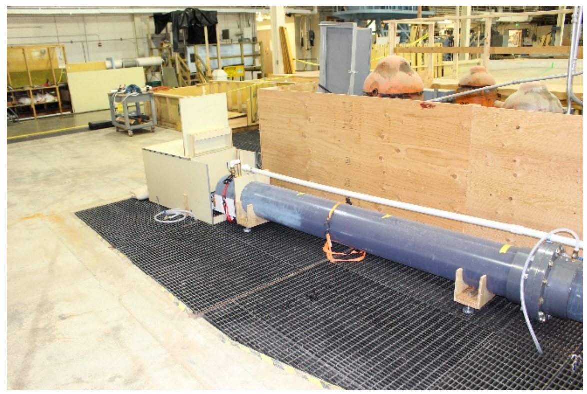

Figure 12. Outlet works gate chamber and tailbox with the slide gate installed in the open position.

The model was constructed from several different materials. The intake and trashrack structure were printed on a 3D printer and glued together with plastic epoxy. The vertical shaft was constructed of clear acrylic pipe. The transitional expansion elbow was machined from 2 pieces of clear acrylic and then bolted together. The horizontal outlet conduit was constructed of 12-inch-diameter clear PVC. The outlet gate transition and bifurcation were printed on a 3D printer and then fastened to the horizontal conduit with screws and silicone to make a water tight union.

Instrumentation

A 240,000-gallon storage reservoir under the laboratory floor supplied water for the model through an automated discharge delivery and measurement system. Inflow to the model was measured using venturi meters with an accuracy of ±0.25%.

Reservoir water levels were measured using a Massa PulStar series ultrasonic level sensor with a resolution of 0.01 inches and an accuracy of ±0.1% over the target range of test conditions. The sensor was mounted above the reservoir approximately 4 feet (model) from the morning glory structure to allow for a steady pool outside of the drawdown zone of the outlet. Measurements were recorded using a data acquisition system with DasyLAB software.

A video surveillance system was used to record discharge events simultaneously from 4 different camera angles (Figure 12):

- Camera 01: Upstream reservoir looking straight down into the intake structure.
- Camera 02: Upstream reservoir oblique view of the intake structure.
- Camera 03: Horizontal tunnel and transitional elbow viewed from the side.
- Camera 04: Gate chamber and downstream piping section viewed from the side.

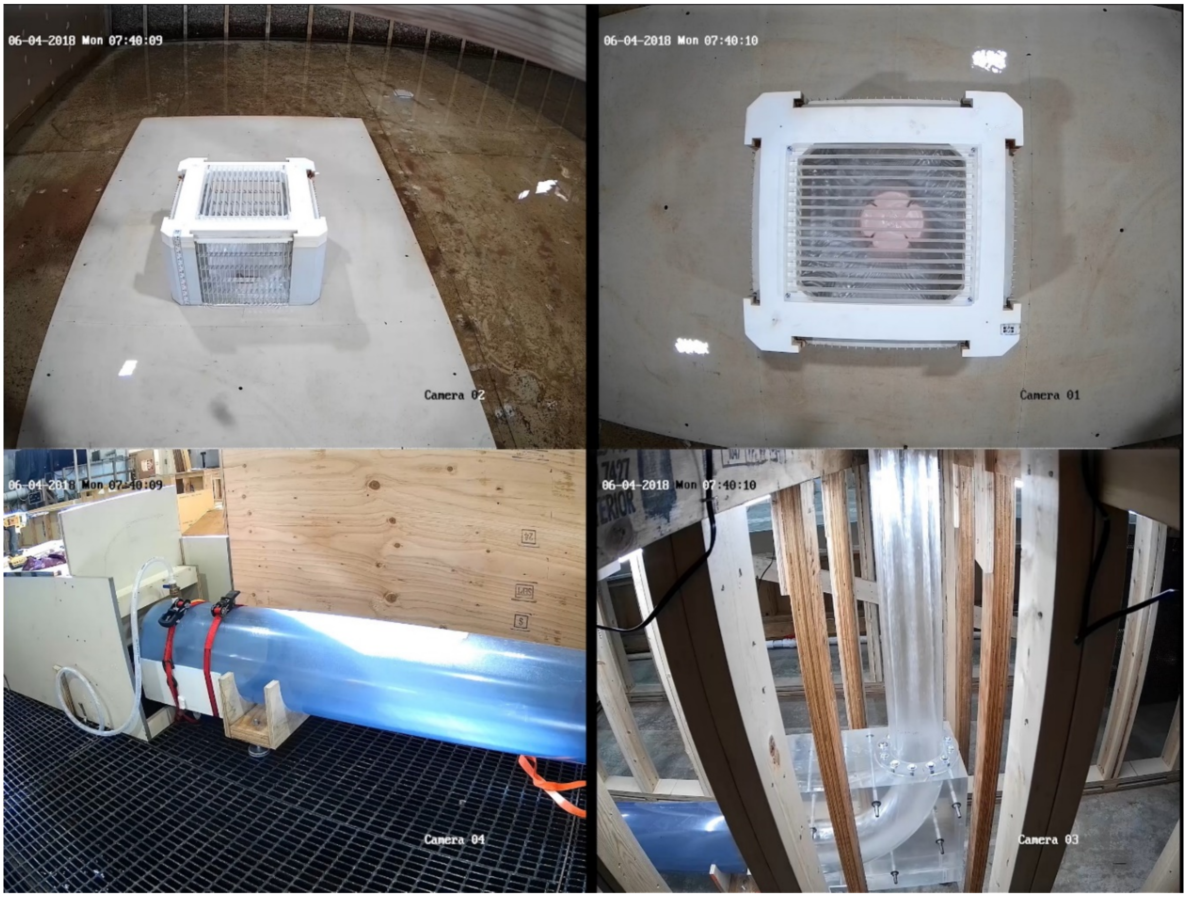

Figure 13. Security camera footage collage showing the 4 camera angles for which video was acquired.

Model Results

Rating curves were generated for reservoir filling and draining conditions. During the data collection visual observations were made to determine what flowrates had issues regarding blowback at the intake structure. Surveillance camera footage was recorded for each flowrate with time stamp information to allow comparisons of all four camera angles. One of the main objectives during this study was to identify flowrates and water surface elevations that create blowback. Figure 13 shows the filling and draining rating cures for the as-built conditions with the outlet regulating gates fully open. Varying degrees of blowback were identified at discharges between 450 and 550 ft^3/sec with water surface elevations between 6360.88 and 6361.35 ft. In this range blowback was repeatable and would vary from slight (minor surface bulges) to extreme (complete burst of air spraying water several model feet in the air). Although blowback did not occur at regularly timed intervals, it was always present in the indicated discharge and water surface elevation range.

Video analysis showed that a complex interaction between the intake transition from submerged to unsubmerged discharges would result in small surges of water in the outlet tunnel. These surges would cause discharges at the gate chamber to temporarily seal any air from exiting the outlet tunnel through the regulating gate chamber. This momentary seal would force air to accumulate upstream from the gate chamber, travel up the horizontal conduit and eventually be forced out of the vertical shaft resulting in blowback at the intake structure. The degree of surging at the gate chamber would affect the degree to which the blowback occurred.

Discharges above 800 ft^3/sec (prototype) were different during the draining and filling reservoir ratings due to an oscillating water surface in the model caused by control shifts within the tunnel. This is typical for discharge control transition zones. Video documentation revealed that with a constant inflow the reservoir would never reach a stable water surface elevation because the control in the model would shift from inlet control (intake or transition elbow) to outlet control (gate chamber) and back again. Figure 14 provides the model water surface elevations (prototype scale) logged over an extended period to show the oscillating water surface with a constant inflow of 900 ft^3/sec. Similar plots could be produced for each flowrate tested above 800 ft^3/sec. Regardless of whether the reservoir was draining or filling, the same results were present above 800 ft^3/sec. As a result, the curves for the filling and draining reservoir cases were established by recording the maximum and minimum water surface elevation the reservoir reached during an 8 hour period. The size of the model headbox representing the reservoir is much smaller in volume than the existing prototype reservoir, so the timing of oscillations will be much different in the prototype from that seen in the model. With a larger prototype reservoir, the oscillations in the water surface would likely be realized an an unstable discharge from the outlet works that would change unexpectedly depending on how long it takes to fill the reservoir to the point where the control shifts.

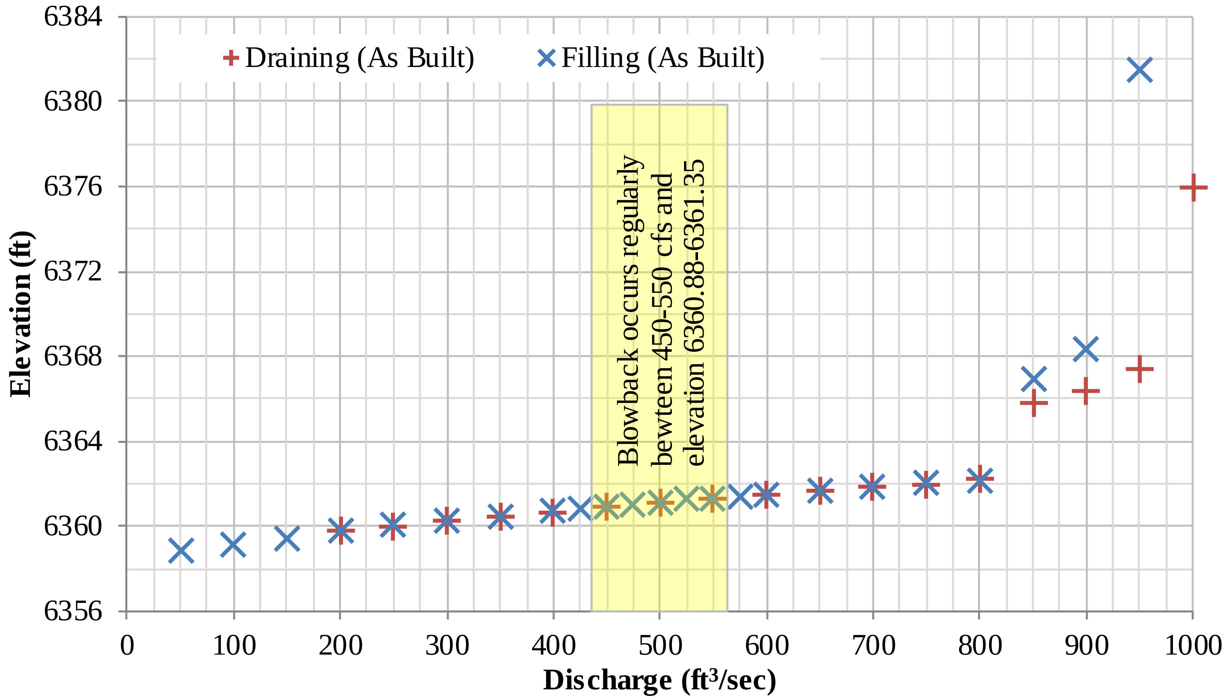

Figure 14. Paonia outlet tunnel rating curves for the as-built configuration with blowback area identified.

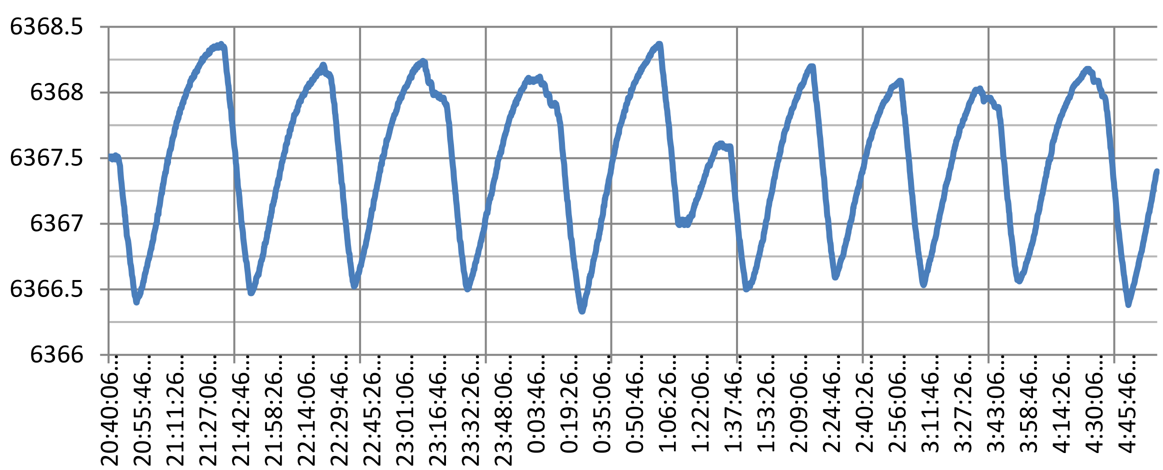

Figure 15. Oscillating reservoir water surface elevation for 900 ft^3/sec discharge logged over an 8 hour interval.

To reduce the blowback potential and dampen the effects of the control shift causing an unstable water surface for discharges above 800 ft^3/sec, four ½-in model (5.55-in prototype), air vents were installed at the locations shown in Figure 15. Half-inch model vents were selected based on a recommendation from the design team that 6-in prototype vents were likely the best choice from a construction standpoint. These vents were installed by drilling and tapping ½-in holes on the crown of the pipe and allowing the vent to discharge just beyond the crown through a ½-in ball valve threaded into the pipe but not protruding into the flow path. Model discharges between 450 and 550 ft^3/sec were tested with each of the air vents opened individually while the others remained closed. Blowback was reduced in all cases but was still present regardless of which air vent was open. Additional tests were run leaving all four air vents opened which prevented the blowback across most flowrates. When the discharges were changing rapidly blowback still occurred, especially when the reservoir was filling rapidly. Discharge entering the outlet tunnel would impact the gate chamber and rapidly fill the tunnel conduit, trapping air at the crown of the horizontal conduit. As the tunnel would fill with water, the trapped air would move upstream toward the intake structure. With the four air vents opened, air would escape from each vent until the pipe was full at the vented location, at which point water would be released through each vent. The air-water interface and hydraulic jump in the pipe would transition further upstream and the farthest upstream vent located at the transitional elbow became the last available vent to release the air before blowback occurred (farthest left vent shown in Figure 15). It was noted that the ½-in vent at this location was not large enough to always prevent the blowback. Due to the transitioning interface of the hydraulic jump, the upstream air vent (at the transitional elbow) operated over a wider range of discharges.

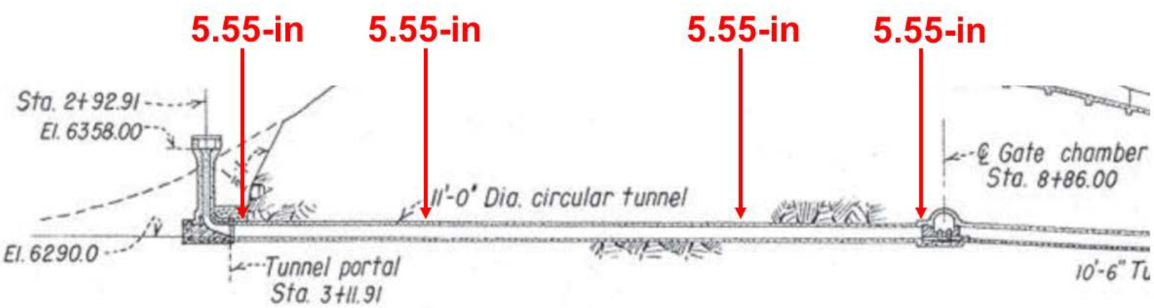

Figure 16. Locations for four 5.55-in air vents installed on the Paonia outlet tunnel model.

The air vents were modified based on the preceding findings to include a 1-in (model) vent at the crown of the horizontal conduit near the transitional elbow and just upstream of the gate chamber as shown in Figure 16. These vents were installed to determine if a single 12-in prototype vent could be used to evacuate enough air to protect the intake structure from blowback at all discharges and elevations, including rapid filling and draining. The 1-in ball valves were threaded into the crown of the pipe so that they did not protrude into the flow path. Air was discharged just above the crown of the pipe. Observations indicated that either vent location was sufficient to prevent blowback at any flowrate, but only the vent at the transitional elbow relieved the blowback caused by a rapid filling of the reservoir. The air vent near the gate chamber would seal off as soon as a hydraulic jump formed in the 11-ft-diameter horizontal conduit, making the air vent at the transitional elbow the best location for an air vent to be installed.

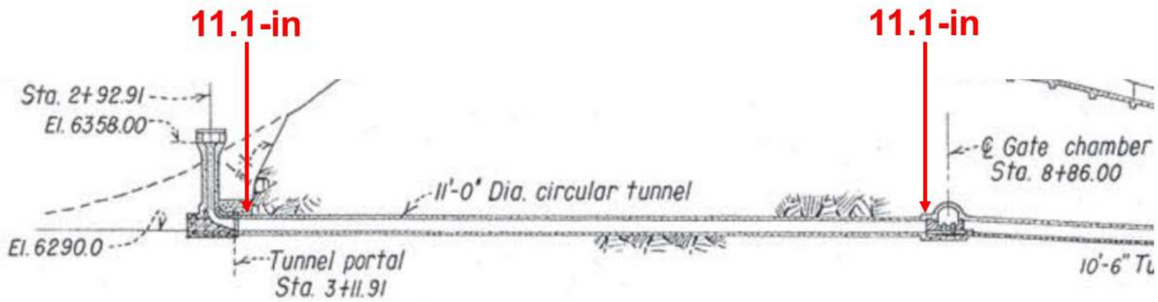

Figure 17. Locations for two 11.1-in air vents installed on the Paonia outlet tunnel model.

The following three possible methods for constructing the vent at the transitional elbow were identified:

- Install the vent with a drilled vertical pipe connected to the crown of the tunnel and vented above the reservoir water surface.
- Attach the air vent to the inside of the 6-ft-diametervertical conduit and vent above the reservoir water surface.
- Attach the air vent to a conduit that runs inside the 11-ft-diameter tunnel along the crown. The vent would be passed downstream through the gate chamber to the downstream 10.5-ft-diameter discharge tunnel.

All three options were investigated in the physical model. A length of conduit was installed to simulate the vertically drilled pipe, and results showed good performance with effective venting over the full range of testing. A vertical vent pipe with a curved end was then held inside the 6-ft-diameter (prototype) vertical section and resulting venting was also successful. The addition of the vent pipe to the inside of the vertical conduit resulted in natural venting around the installed pipe also. The third option of installing the vent line inside the 11-ft-diameter tunnel was investigated by connecting 1-in (model) PVC pipe from the ball valve vent along the top of the modeled horizontal conduit to the location of the gate chamber. The PVC pipe was not installed inside the model conduit due to the complicated construction that would have been involved. When attached to the full length of conduit necessary to route the vent out of the gate chamber, the vent was unable to expel the necessary air due to the additional losses in the conduit. The vent size was then increased to 1.25 inches (model) which resulted in the vent operating as intended.

The three venting options were presented to the design team to determine which would be best suited for implementation. The team determined that installing the vent by attaching a conduit on the inside of the 11-ft-diameter (prototype) tunnel would be the best option. To keep debris from entering while allowing the air to be collected in one spot, a small deflector was designed and installed (Figure 17). The 1.25-in (model) vent was run inside the horizontal tunnel for a distance of about 10 ft (model) and then passed through the tunnel wall and run the remainder of the distance to the gate chamber on the outside of the tunnel (Figure 18) to see if the orientation of the conduit entrance would impact its effectiveness. The trashrack and vent on the interior of the pipe was successful at removing air for all discharges tested, including rapid filling and draining. Scaling up the 1.25-in (model) vent conduit results in an air vent with an inside diameter of 13.875 inches (prototype). Further increasing the air vent size would be expected to increase effectiveness.

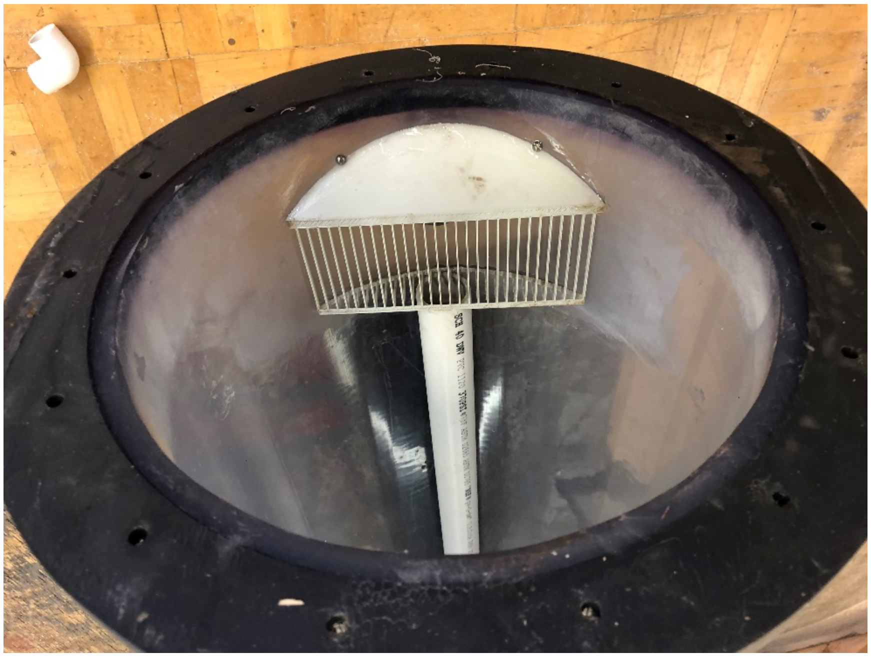

Figure 18. Trashrack and air collection chamber with the 1.25-in (model) PVC vent pipe attached. The conduit is rotated 180 degrees for visualization purposes.

Figure 19. 1.25-in (model) air vent installed at the crown of the tunnel for one section of pipe and then exiting the pipe and continuing downstream to the gate chamber.

Figure 19 contains rating curves for both the filling and draining reservoir conditions. With the trashrack and vent installed at the crown of the 11-ft-diameter (prototype) horizontal conduit near the transitional elbow, the vent was effective in relieving blowback. Based on model study results, it is expected that installing a 16-in-diameter vent will protect the outlet works from blowback. A few quick tests were performed with floating debris added into the model. The trashrack structure was able to pass floating debris that was larger than the spacing without trouble. Some floating debris passed through the trashrack structure, but successfully passed through the entire air vent pipe without clogging.

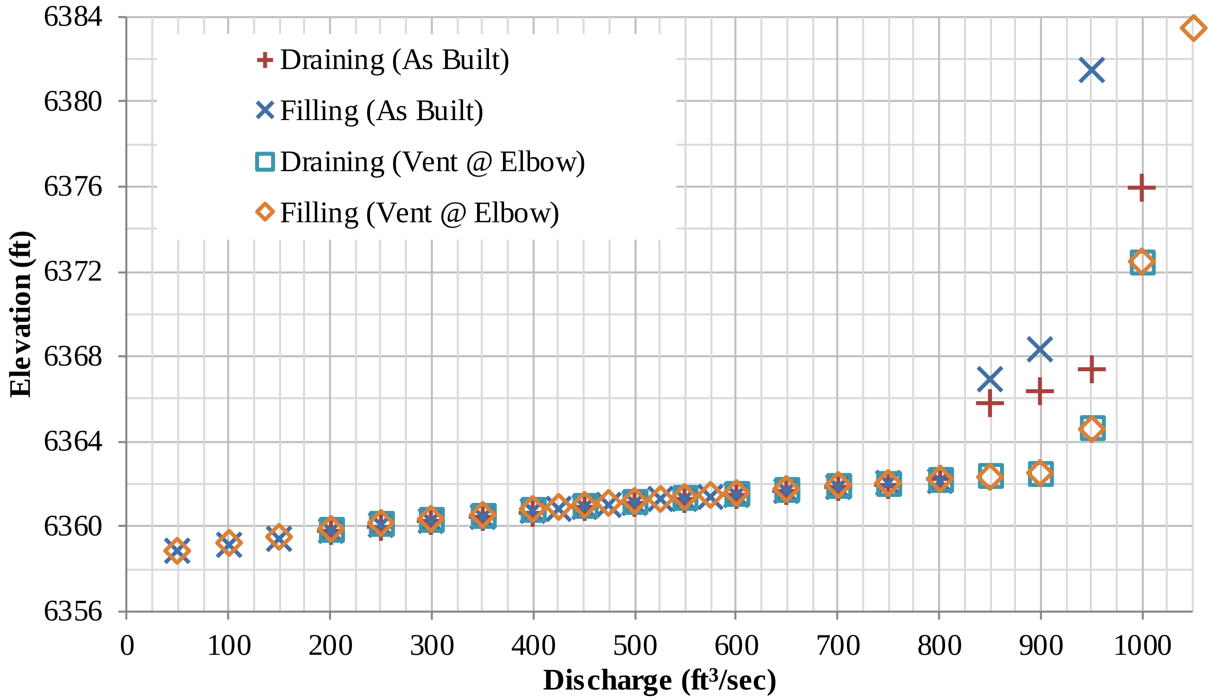

Figure 20. Paonia outlet tunnel rating curves for the as built and the vented configuration.

Conclusions

During uncontrolled releases (outlet control gates wide open), it was determined that blowback would likely occur for discharges between 450 and 550 ft^3/sec and reservoir elevations of 6360.88 and 6361.35 feet. Blowback was consistent in these discharges and elevation ranges and would often blowback violently which is of concern for the longevity of the structure.

The model results indicate that installing a 16-in (prototype) air vent at the start of the 11-ft-diameter (prototype) conduit would allow enough air to escape the structure to prevent blowback for the proposed modified operations of the outlet works.

References

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Appendix A – Rating Curve Data

Rating curves presented in the report can be plotted using the data shown below. For each set of data the following items were recorded:

- Column 1 – Prototype discharge in cubic feet per second
- Column 2 – Water surface elevation based on Reclamation's project vertical datum used during construction of Paonia Dam.
- Columns 3 & 4 – Inlet velocity at model and prototype scale was calculated by taking the discharge and dividing by the cross-sectional area of the inlet.
- Column 5 – Depth over the morning glory crest
- Column 6 – Minimum depth required to submerge the morning glory crest and prevent airflow down the shaft calculated using equation 105 in Air Water Flow in Hydraulic Structures, Engineering Monograph No. 41, United States Department of the Interior. $S=D*0.47*F^{1/2}$, where S = submergence depth, D = shaft diameter, F = Froude number $(V/(gD)^{1/2})$.

Table 1. As Built Draining Rating

Discharge (ft^3/sec)	Water Surface Elevation (ft)	Model Inlet Velocity (ft/sec)	Prototype Inlet Velocity (ft/sec)	Water Surface Depth about Crest (ft)	Minimum Submergence Depth (ft)
1000	6375.94	10.61	35.36	17.94	4.50
950	6367.37	10.08	33.60	9.37	4.38
900	6366.33	9.55	31.83	8.33	4.27
850	6365.80	9.02	30.07	7.80	4.15
801	6362.21	8.50	28.33	4.21	4.03
750	6362.00	7.96	26.53	4.00	3.90
700	6361.85	7.43	24.75	3.85	3.76
650	6361.69	6.90	22.98	3.69	3.63
600	6361.50	6.37	21.22	3.50	3.48
550	6361.34	5.84	19.45	3.34	3.34
500	6361.13	5.31	17.68	3.13	3.18
450	6360.88	4.78	15.92	2.88	3.02
400	6360.68	4.25	14.15	2.68	2.85
350	6360.48	3.71	12.38	2.48	2.66
300	6360.29	3.18	10.60	2.29	2.46
250	6360.02	2.66	8.85	2.02	2.25
200	6359.75	2.12	7.07	1.75	2.01

Table 2. As Built Filling Rating

Discharge (ft^3/sec)	Water Surface Elevation (ft)	Model Inlet Velocity (ft/sec)	Prototype Inlet Velocity (ft/sec)	Water Surface Depth about Crest (ft)	Minimum Submergence Depth (ft)
50	6358.83	0.53	1.77	0.83	1.01
100	6359.10	1.06	3.53	1.10	1.42
150	6359.44	1.59	5.30	1.44	1.74
200	6359.77	2.12	7.07	1.77	2.01
250	6360.06	2.66	8.85	2.06	2.25
300	6360.29	3.18	10.60	2.29	2.46
350	6360.50	3.71	12.38	2.50	2.66
400	6360.69	4.25	14.15	2.69	2.85
425	6360.79	4.51	15.04	2.79	2.93
450	6360.88	4.78	15.92	2.88	3.02
475	6361.00	5.04	16.79	3.00	3.10
500	6361.13	5.31	17.68	3.13	3.18
525	6361.26	5.57	18.57	3.26	3.26
550	6361.35	5.84	19.45	3.35	3.34
575	6361.42	6.10	20.34	3.42	3.41
600	6361.50	6.37	21.22	3.50	3.48
650	6361.69	6.90	22.98	3.69	3.63
700	6361.85	7.43	24.75	3.85	3.76
750	6362.01	7.96	26.53	4.01	3.90
800	6362.17	8.49	28.30	4.17	4.02
850	6366.97	9.02	30.07	8.97	4.15
900	6368.37	9.55	31.83	10.37	4.27
950	6381.51	10.08	33.60	23.51	4.38

Table 3. 1.25-in (model) Vent at Transitional Elbow Draining Rating

Discharge (ft^3/sec)	Water Surface Elevation (ft)	Model Inlet Velocity (ft/sec)	Prototype Inlet Velocity (ft/sec)	Water Surface Depth about Crest (ft)	Minimum Submergence Depth (ft)
1000	6372.51	10.62	35.37	14.51	4.50
950	6364.65	10.08	33.60	6.65	4.38
900	6362.56	9.55	31.83	4.56	4.27
850	6362.40	9.02	30.07	4.40	4.15
801	6362.23	8.50	28.33	4.23	4.03
750	6362.09	7.96	26.53	4.09	3.90
700	6361.92	7.43	24.75	3.92	3.76
650	6361.78	6.90	22.98	3.78	3.63
600	6361.61	6.37	21.22	3.61	3.48
550	6361.4	5.84	19.45	3.40	3.34
500	6361.19	5.31	17.68	3.19	3.18
450	6360.98	4.78	15.92	2.98	3.02
400	6360.8	4.25	14.15	2.80	2.85
350	6360.57	3.71	12.38	2.57	2.66
300	6360.38	3.18	10.60	2.38	2.46
250	6360.18	2.66	8.85	2.18	2.25
200	6359.90	2.12	7.07	1.90	2.01

Table 4. 1.25-in (model) Vent at Transitional Elbow Filling Rating

Discharge (ft^3/sec)	Water Surface Elevation (ft)	Model Inlet Velocity (ft/sec)	Prototype Inlet Velocity (ft/sec)	Water Surface Depth about Crest (ft)	Minimum Submergence Depth (ft)
50	6358.87	0.53	1.77	0.87	1.01
100	6359.22	1.06	3.53	1.22	1.42
150	6359.55	1.59	5.30	1.55	1.74
200	6359.89	2.12	7.07	1.89	2.01
250	6360.17	2.66	8.85	2.17	2.25
300	6360.4	3.18	10.60	2.40	2.46
350	6360.59	3.71	12.38	2.59	2.66
400	6360.79	4.25	14.15	2.78	2.85
425	6360.89	4.51	15.04	2.89	2.93
450	6361.02	4.78	15.92	3.02	3.02
475	6361.09	5.04	16.79	3.09	3.10
500	6361.2	5.31	17.68	3.19	3.18
525	6361.27	5.57	18.57	3.27	3.26
550	6361.39	5.84	19.45	3.39	3.34
575	6361.53	6.10	20.34	3.53	3.41
600	6361.63	6.37	21.22	3.63	3.48
650	6361.77	6.90	22.98	3.77	3.63
700	6361.93	7.43	24.75	3.93	3.76
750	6362.08	7.96	26.53	4.08	3.90
800	6362.24	8.49	28.30	4.24	4.02
850	6362.37	9.02	30.07	4.37	4.15
900	6362.55	9.55	31.83	4.55	4.27
950	6364.61	10.08	33.60	6.61	4.38
1000	6372.51	10.62	35.37	14.51	4.50
1050	6383.51	11.15	37.14	25.51	4.61
1100	6384.51	11.68	38.90	26.51	4.72