An Innovative Rehabilitation Project at the Cobble Mountain Dam Outlet Works

An innovative plugging system provided cost savings and reduced risk on a rehabilitation project for a diversion tunnel high-pressure outlet works facility for a city water supply system.

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Construction of Springfield Water and Sewer Commission's (SWSC) Cobble Mountain Reservoir Dam, located in Granville, Massachusetts, began in 1929 and was completed in 1931. Since then, as part of the Little River Water Supply System, the reservoir has served as the primary drinking water source for the City of Springfield, Massachusetts, and its surrounding communities. In 2001, a rehabilitation project was planned for the diversion tunnel high-pressure outlet works facility, which included the replacement of two existing water-operated 42- by 30-inch Larner-Johnson needle valves. The project also included the rehabilitation of the two existing 40-inch rotary (ball) style guard valves.

The earthen dam is 240 feet high, retains 22.5 billion gallons of water and is one of only a handful of dams constructed using the hydraulic fill method in the United States (see Figures 1 & 2). The Little River system has the capability of delivering 100 million gallons per day (mgd) of finished water to Springfield and its outer lying communities, serving a total population of approximately 250,000. Raw water is conveyed to the West Parish Filters Water Treatment Plant from Cobble Mountain Reservoir and the raw water conveyance system is comprised of the following key facilities:

- Broome gate house, power tunnel, surge tank and hydroelectric facility
- Diversion tunnel, gate house (see Figures 3, 4 & 5) and outlet works (see Figures 6 & 7).

The Broome gate house and power tunnel are

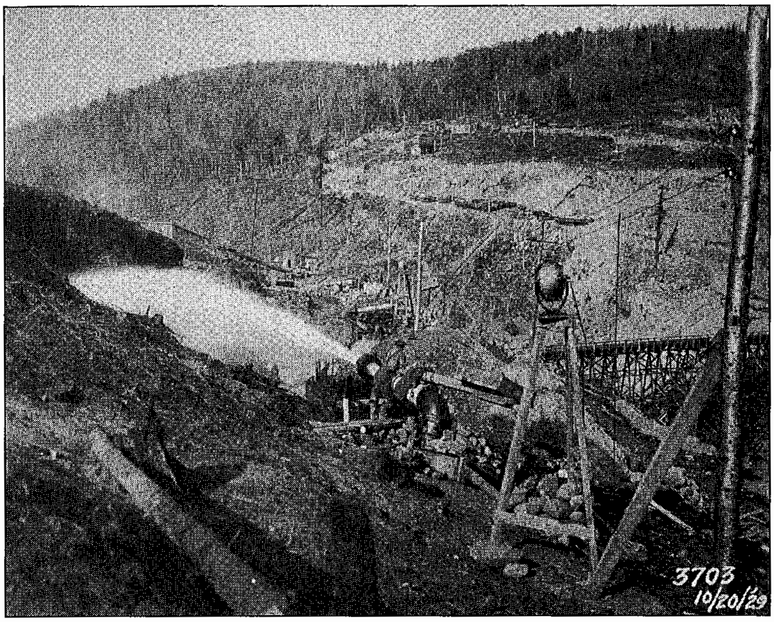


FIGURE 1. Mining giants and grizzlies operating at Cobble Mountain during sluicing operations in 1929.

facility, which contributes up to 33 kilowatts (kW) to the local grid. The tailrace from the hydroelectric facility discharges to the Little River, which flows to the Intake Reservoir. The Intake Reservoir outlet works conveys raw water to the water treatment plant.

The Cobble Mountain diversion tunnel was originally constructed during the late 1920s to divert the Little River flow around the dam construction site. The tunnel was blasted through solid rock at the base of Cobble Mountain, and has an 11.5-foot horseshoe shaped cross-section and concrete lining (see Figures 3 & 4). Upon completion of the dam, a shaft was bored 233 feet down from the dam access road to the tunnel below and a high-pressure outlet works facility was constructed approximately 350 feet into the tunnel from the reservoir (see Figure 6).

the primary conveyance structures used to transfer raw water from Cobble Mountain Reservoir to the West Parish Filters Water Treatment Plant. During normal operations, raw water flows from the Broome gate house through the power tunnel to the hydroelectric

The outlet works includes a concrete bifurcation and twin 42- by 40-inch diameter, 40-foot-long, riveted steel-lined outlet conduits terminating in a gate chamber. A control chamber was constructed above the gate chamber where operators could safely operate the outlet valves.

Flow through the outlet works is regulated (throttled) through two 42- by 30-inch Larner-Johnson differential needle valves. The needle valves free-discharge into the diversion tunnel and direct raw water to the water treatment plant via the Little

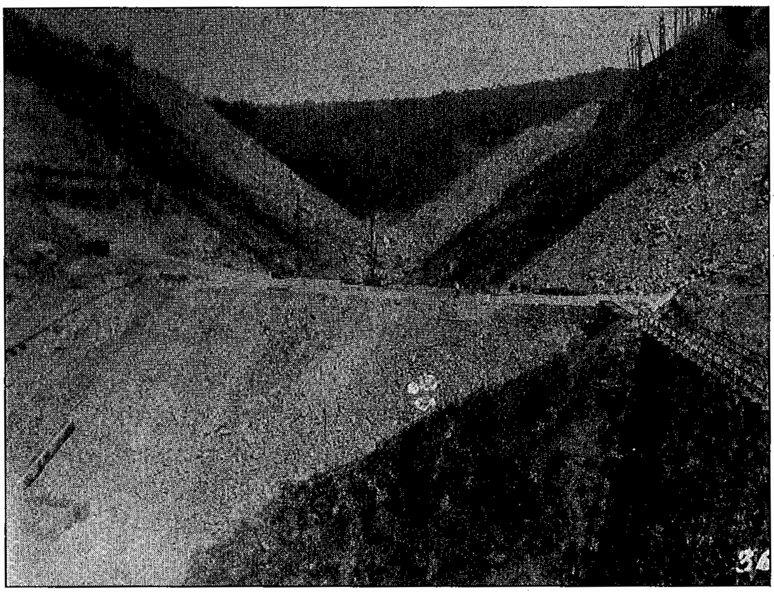


FIGURE 2. Cobble Mountain Dam at about half completion in 1929.

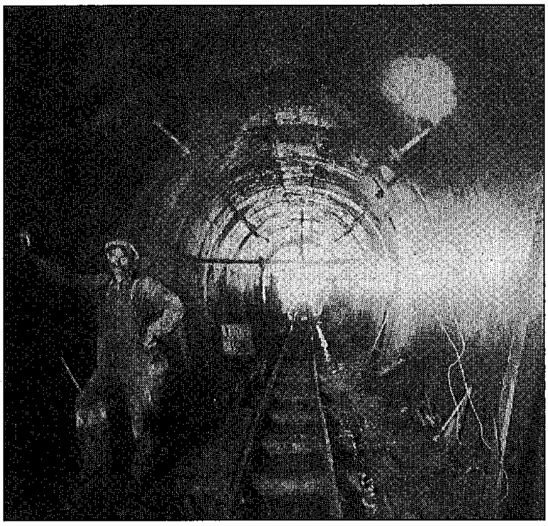


FIGURE 3. The diversion tunnel under construction.

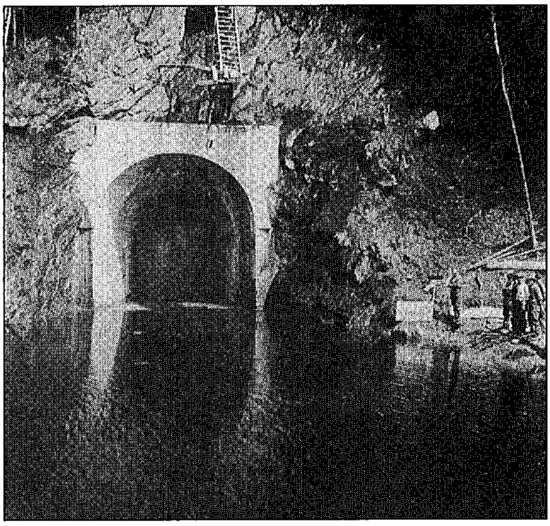


FIGURE 4. The diversion tunnel entrance portal.

River during maintenance outages at the hydroelectric facility. The outlet works' original discharge capacity was 480 mgd with both needle valves fully open and the reservoir water surface at the spillway crest elevation.

Each differential needle valve was isolated from the reservoir when not in use by 40-inch diameter rotary valves (see Figures 10 & 11). The diversion valves were operated from a control chamber constructed above the gate chamber.

Access to the outlet works facility is gained via the Diversion Gate House (see Figures 5 & 6). A forty-flight stairway was constructed within the access shaft from the gate house to the control chamber.

During the years after commissioning, the Larner-Johnson needle valves never functioned properly, and were plagued with mechanical problems. In the 1960s, the needle valves had a major mechanical overhaul (see Figure 12) but this and other attempts to improve reliability were met with limited success. This situation would not change from the 1960s through the 1990s (see Figure 13).

The diversion tunnel outlet works is the secondary raw water conveyance structure from Cobble Mountain Reservoir, so it was critical that the needle valves be fully operational and reliable. In addition, by the early 1990s the power tunnel, surge tank and hydroelectric facility were due for a comprehensive maintenance upgrade, which would require an extended shutdown. In the early 1990s, SWSC included an upgrade to the diversion tunnel facility in its long-term capital improvement plan. However, they had a surprise coming that would place diversion tunnel valve maintenance to the top of its priority list.

The $500,000 4-Inch Gate Valve

In the late 1980s, vandals broke into the

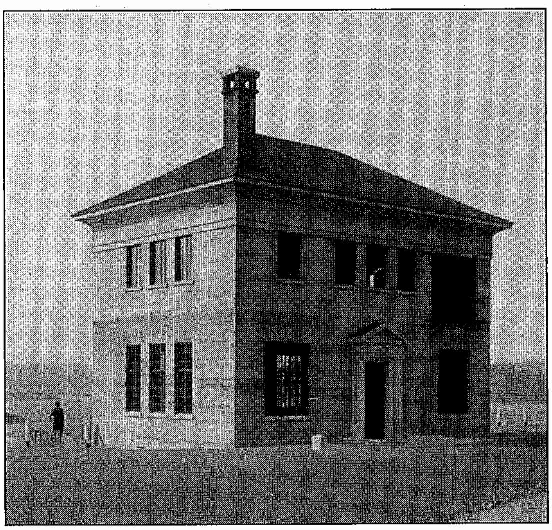


FIGURE 5. The Cobble Mountain Diversion Gate House (1931).

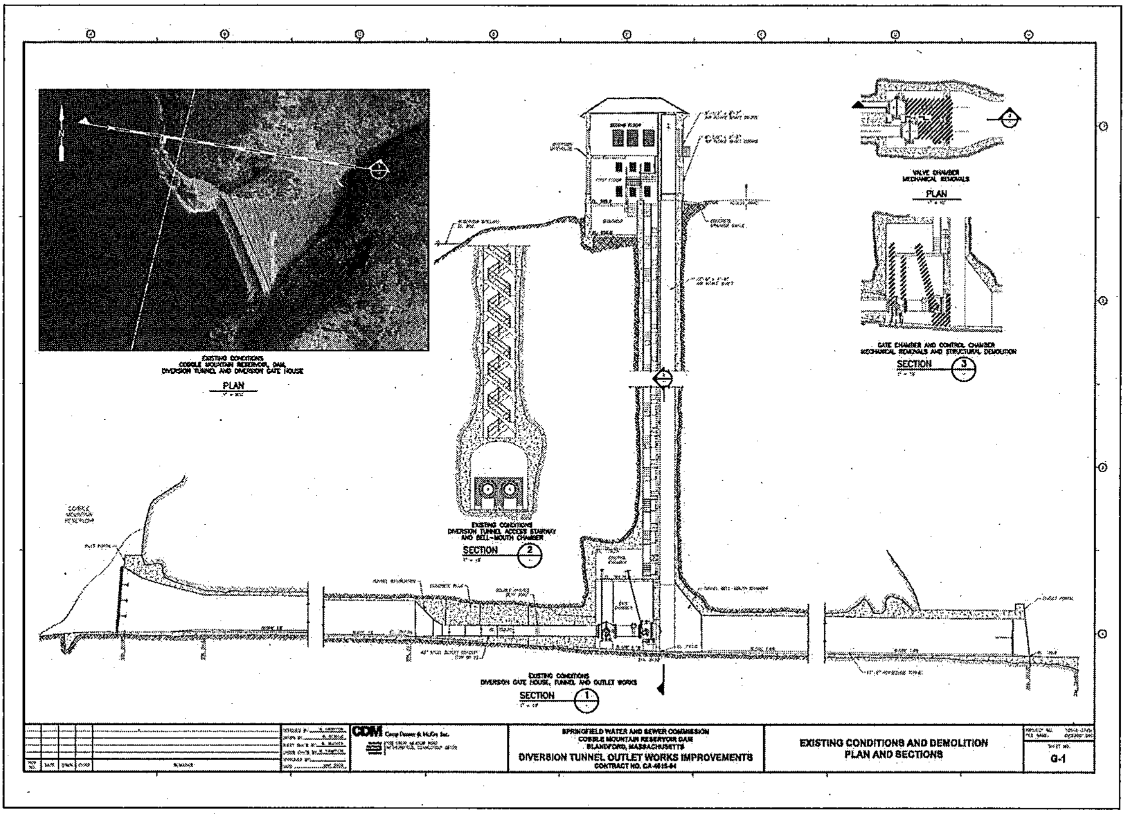


FIGURE 6. The diversion tunnel, gate chamber, access shaft and gate house.

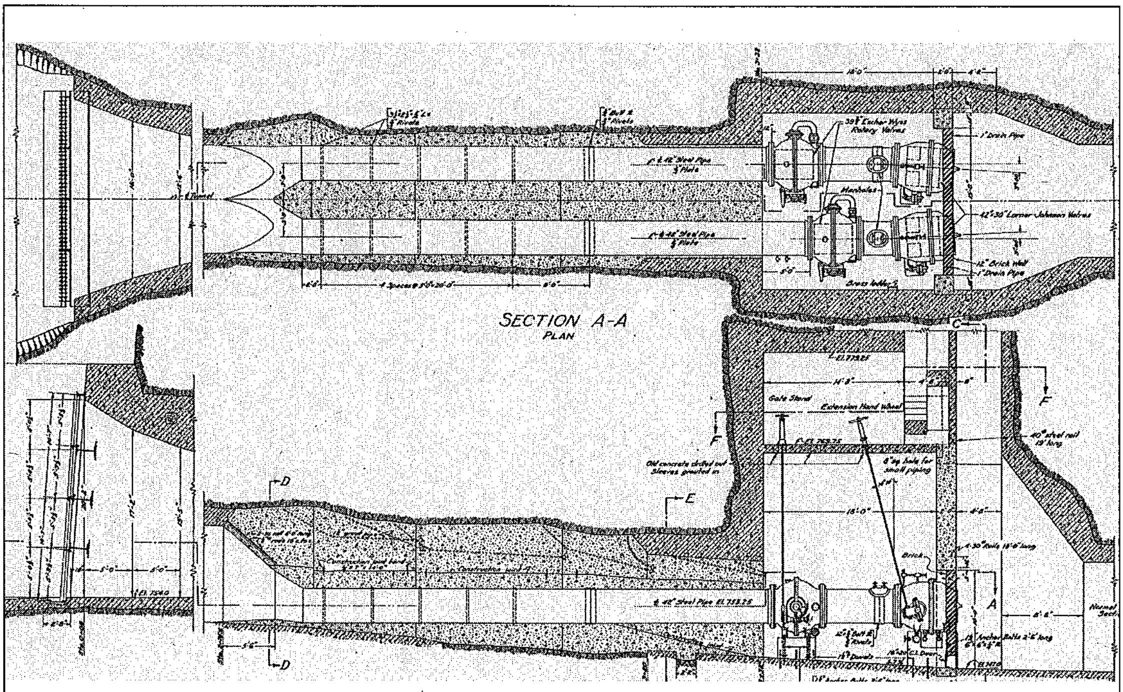


FIGURE 7. The diversion tunnel outlet works.

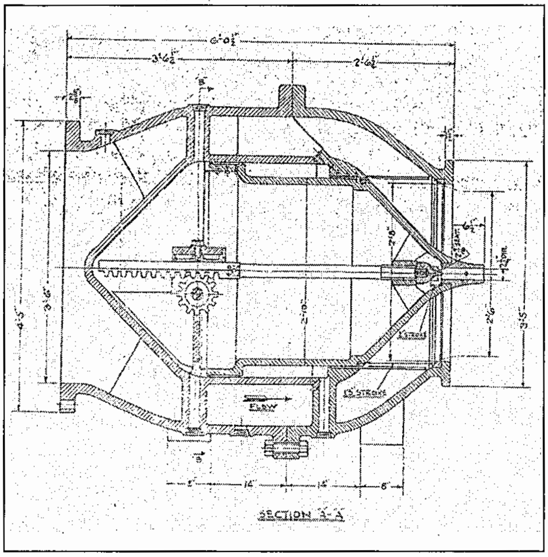


FIGURE 8. Needle valve cross-section.

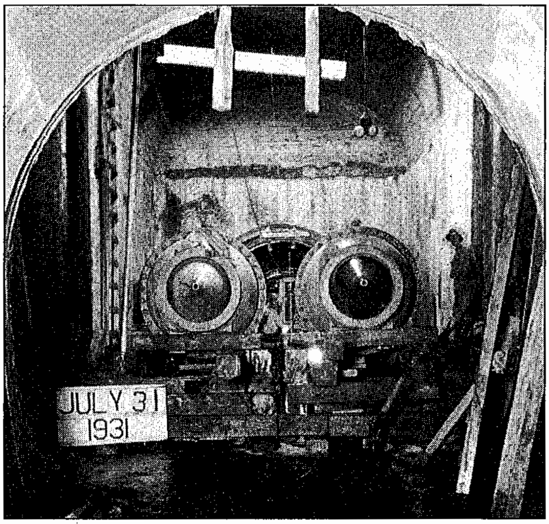


FIGURE 9. A view upstream in the diversion tunnel showing the needle valves installed in the gate chamber.

diversion tunnel gate chamber, and left the damaged access door open after their departure. The opened door allowed cold winter air to blow up the tunnel, causing a rupture in a 4-inch diameter auxiliary blow-off valve attached to rotary valve no. 2. The rupture was due to frozen reservoir water confined in the cast iron valve body. The valve sprang a major leak. In the original facility design, there was no provision for an isolation gate, bulkhead or stop-logs at the tunnel entrance.

The rotary valves are under the full reservoir head of 200 feet at all times and there is no way to drain and depressurize the valves for disassembly. The leak could not be stopped under dry conditions. This predicament turned a simple 4-inch valve replacement job into a much larger and more dan-

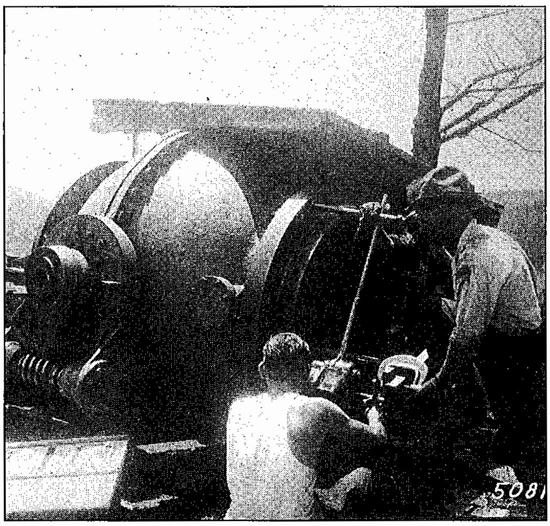


FIGURE 10. The rotary valves that were shipped from Zurich, Switzerland, to the Cobble Mountain site in 1931.

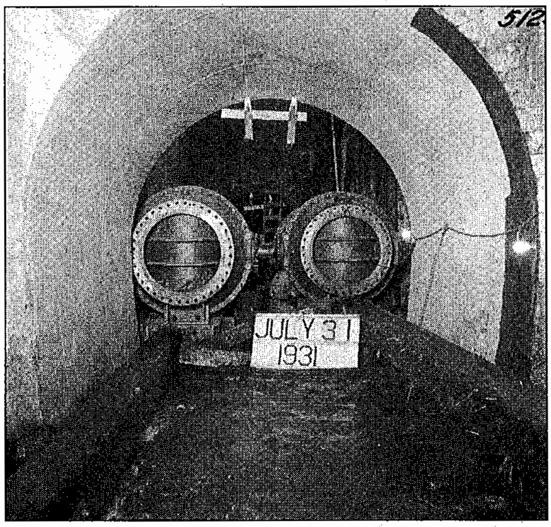


FIGURE 11. A view downstream in the diversion tunnel showing the rotary valves installed in the gate chamber.

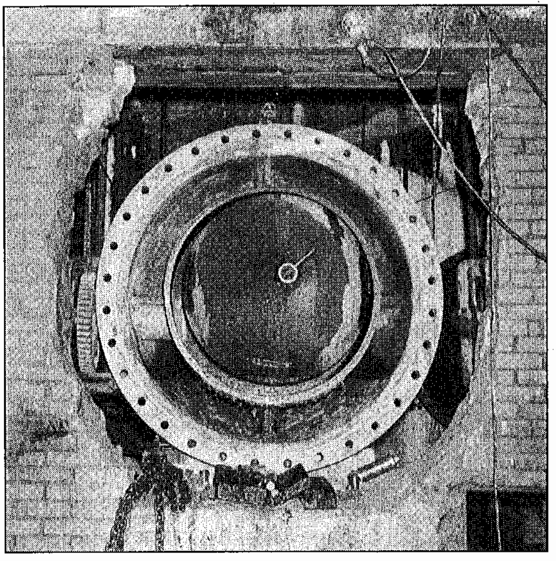


FIGURE 12. A view of needle valve no. 2 showing internals during a mechanical overhaul in the 1960s.

gerous project. After considering several options, the SWSC preferred a plan for the replacement of the valve involving the following:

- Construction of a concrete bulkhead in the bell-mouth of the diversion tunnel, downstream of the gate chamber;
- Filling the gate chamber, control chamber,

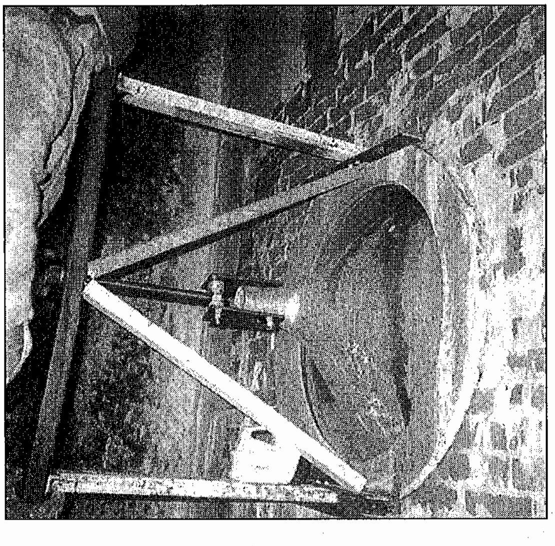


FIGURE 14. Closing the jammed needle valve.

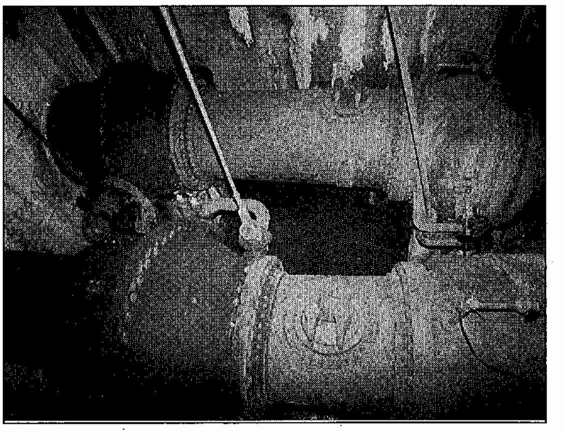


FIGURE 13. The diversion tunnel entrance portal.

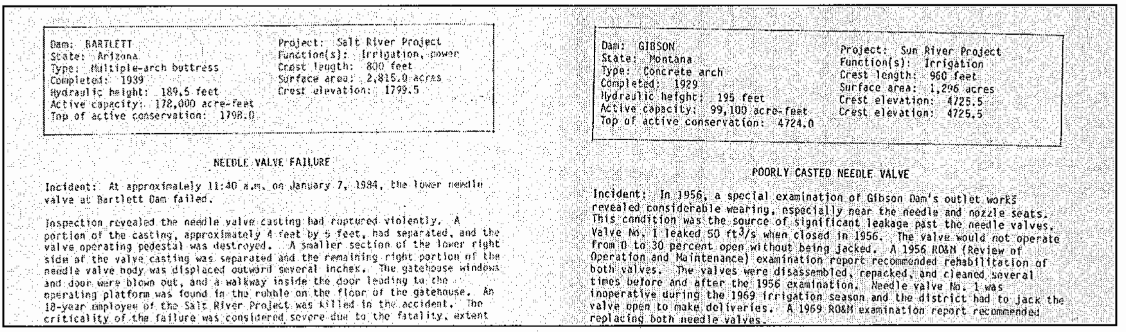
stairway and air shaft with reservoir water to balance the water pressure between the reservoir and diversion facility; and
- Replacement of the valve under submerged conditions by commercial divers.

This alternative was extremely dangerous and expensive (its cost was approximately $500,000). However, the SWSC had no other viable choice at the time, and could not avoid removal and replacement of the leaking valve.

Work began in early 1990. The concrete bulkhead was constructed, the facility was flooded and the divers were able to access the valves in the chamber. For every hour of work time in the chamber, each diver was required to decompress for seven hours to prevent the formation of nitrogen bubbles in their blood (the bends).

The cracked blow-off valve was removed, but the new valve purchased by the contractor could not be used as a replacement valve because the flange pattern on the Swiss-made Escher Wyss valve was drilled to British Standards. Given the circumstances, SWSC decided to remove the blow-off valves from both rotary valves, and replace them with custom fabricated blind flanges.

After installation of the blind flanges, the facility was drained and the concrete bulkhead was removed using a wire saw. This 4-inch gate valve problem cost SWSC more than $500,000, was an extremely risky operation



Dam: BARTLETT
State: Arizona
Type: Multiple-arch buttress
Completed: 1939
Hydraulic height: 189.5 feet
Active capacity: 178,000 acre-feet
Top of active conservation: 1798.0

Project: Salt River Project
Function(s): Irrigation, power
Crest length: 800 feet
Surface area: 2,815.0 acres
Crest elevation: 1799.5

NEEDLE VALVE FAILURE

Incident: At approximately 11:40 a.m. on January 7, 1984, the lower needle valve at Bartlett Dam failed.

Inspection revealed the needle valve casting had ruptured violently. A portion of the casting, approximately 4 feet by 5 feet, had separated, and the valve operating pedestal was destroyed. A smaller section of the lower right side of the valve casting was separated and the remaining right portion of the needle valve body was displaced outward several inches. The gatehouse windows and door were blown out, and a walkway inside the door leading to the operating platform was found in the rubble on the floor of the gatehouse. An 18-year employee of the Salt River Project was killed in the accident. The criticality of the failure was considered severe due to the fatality, extent

Dam: GIBSON
State: Montana
Type: Concrete arch
Completed: 1929
Hydraulic height: 195 feet
Active capacity: 99,100 acre-feet
Top of active conservation: 4724.0

Project: Sun River Project
Function(s): Irrigation
Crest length: 960 feet
Surface area: 1,296 acres
Crest elevation: 4725.5
Crest elevation: 4725.5

POORLY CASTED NEEDLE VALVE

Incident: In 1956, a special examination of Gibson Dam's outlet works revealed considerable wearing, especially near the needle and nozzle seats. This condition was the source of significant leakage past the needle valves. Valve No. 1 leaked 50 ft^3/s when closed in 1956. The valve would not operate from 0 to 30 percent open without being jacked. A 1956 RO&M (Review of Operation and Maintenance) examination report recommended rehabilitation of both valves. The valves were disassembled, repacked, and cleaned several times before and after the 1956 examination. Needle valve No. 1 was inoperative during the 1969 irrigation season and the district had to jack the valve open to make deliveries. A 1969 RO&M examination report recommended replacing both needle valves.

FIGURE 15. USBR reports of needle valve failures on the Salt River Project in Arizona.

and the contractor was not able to actually replace the blow-off valves due to the unusual mechanical design of the rotary valves and construction constraints within the facility. The incident also exemplifies the hazards and high expense associated with construction at this facility, and provided a preview of the challenges that would be faced on the future rehabilitation project.

In 2001, SWSC consulted with an engineering consultant to provide technical assistance in its efforts to rehabilitate and make operational and reliable the valves and appurtenances in the diversion tunnel gate chamber. Unfortunately, soon after the investigation began and an attempt was made to operate one of the needle valves, the needle became jammed in the open position. Millwrights were hired to free the needle and close the valve (see Figure 14). Soon after the initial inspection, it was clear to SWSC and the engineering consultant that the facility needed a major overhaul. During the previous years, the rotary and needle valves had fallen further into disrepair and required mechanical improvements or replacement.

The Needle Valve Problem

Free-discharge regulating valves and gates for high-pressure outlets at dams have seen many developmental variations during the past century with mixed success. Free-discharge end-of-the-line valves accomplish two difficult tasks:

- Throttling high flows; and,
- Energy dissipation, without damage from hydrodynamic cavitation.

Needle valves were originally developed by the United States Bureau of Reclamation (USBR) to regulate irrigation and stream maintenance flows from dams in the western United States. The Larner-Johnson valve uses the differential pressure between an inner pilot valve and the main valve flow passage to hydraulically operate the spider-mounted plunger style "needle" that throttles the flow through the main valve body. This type of valve became commercially available through a patented design by the I.P. Morris Company in the early 1900s. Their installations included 21-foot diameter valves installed at Niagara Falls, New York. The needle valves at the diversion tunnel outlet works had many mechanical malfunctions over the years. The valve on outlet no. 1 was completely inoperable.

After some research by the engineering consultant, in collaboration with specialists at the USBR, several incidents at dams around the country were identified where needle valves had catastrophic failures, causing the deaths of several workers and millions of dollars in damages to hydraulic structures (see Figure 15). The USBR has carried out a needle valve replacement program during the past two decades to mitigate the potential for future failures.

Based on these facts and the history of mechanical problems, the engineering consultant recommended complete replacement of the needle valves. The goals for replacement included selecting a new throttling valve that could meet or exceed the discharge capacity of the existing system (480 mgd), fit into the gate chamber without dimensional con-

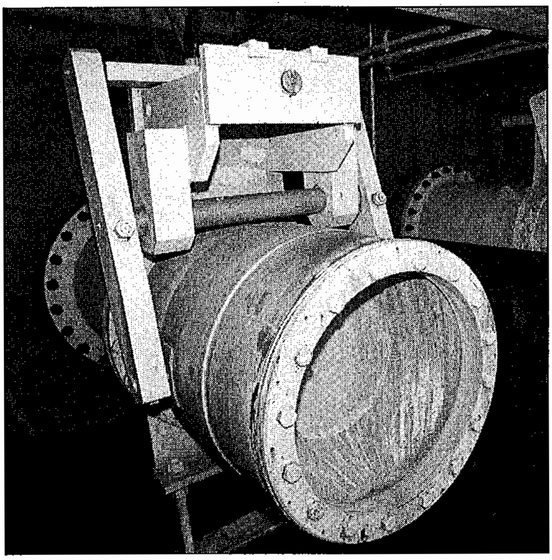


FIGURE 16. A fixed cone valve.

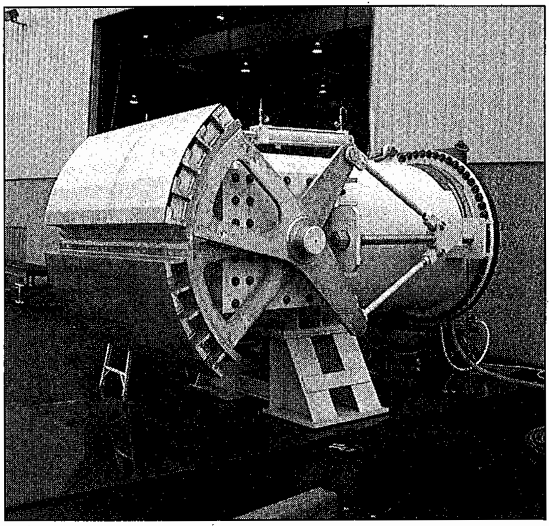


FIGURE 17. A clam shell gate.

flicts or security concerns and provide greater reliability for a project life of eighty years or more. Several replacement valve alternatives were considered including:

- Fixed Cone Valves (see Figure 16). These valves were originally developed by the USBR for use in free-discharge applications at high head dams. There are hundreds of installations of these valves at dams across the United States and abroad. During the past fifty years, the design had several mechanical problems, but they have been worked out of the models that are commercially available today. This valve discharges at a wide angle and would require an energy dissipating hood to direct flow into the diversion tunnel. This aspect of the valve's construction did not make it suitable for installation in the gate chamber. In addition, there were dimensional conflicts that prevented their installation in the diversion tunnel bell-mouth chamber. These valves would not be a good replacement for the needle valves and were not recommended.
- Clam Shell Gates (see Figure 17). These gates are a recent development by the USBR. There are a lot of moving parts on this type of gate, and there were dimensional conflicts in the gate chamber. Based on these facts, and its high price, this gate was not selected to replace the needle valves.
- Jet-Flow Gates (see Figure 18). These gates were originally developed by the USBR for installation at Shasta Dam in the early 1930s. They have gone through several design modifications over the years and the service records for most installations have been very good. The jet-flow gate has the ability to discharge large flows at heads up to 300 feet with smooth operation and very little (if any) vibration. A 30-inch diameter jet-flow gate would increase the capacity of each outlet from 240 to 300 mgd. The 30-inch gate has a short laying length, which had a good fit dimensionally in the gate chamber. Based on the long successful track record of this type of gate, and the project specific goals that were met, the engineering consultant recommended installation of 30-inch diameter jet-flow gates at Cobble Mountain.

Jet-Flow Gates

There are commercially available jet-flow gates from several valve and gate manufacturers. The engineering consultant and SWSC selected to include the design of the gate in the contract drawings. The twin 30-inch gate design was taken from a USBR design used successfully on many projects.

Each gate body is fabricated from A36 steel. The gate leaf is fabricated of Type 304L stainless steel. The gate is operated by a center-mounted, extended shaft 10-inch diameter hydraulic cylinder. Two dedicated 1,500 pounds per square inch (psi) hydraulic power units (HPU) were installed in the control chamber and featured triple redundancy. Two hydraulic pumps would be furnished with each HPU. If both pumps are operated, the gate will rise at 12 inches per minute. If one pump is out of service, the gate will rise using the other pump at 6 inches per minute. If both hydraulic pumps are out of service, the gate can be lifted manually using a hand pump. If the hand pump and the hydraulic pumps malfunction, the dedicated HPU for the other gate can be used to raise both gates. The gate throttles flow through a 30-inch diameter aluminum bronze conical nozzle. In the full open position, the gate leaf is raised 6 inches above the discharge jet.

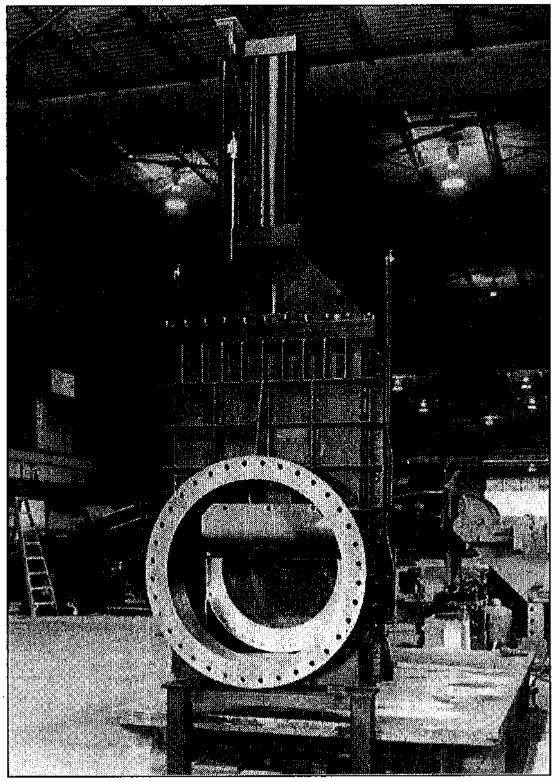


FIGURE 18. A jet-flow gate.

Rotary Valve Rehabilitation

The Cobble Mountain rotary valves were one of the first commercially available large-diameter rotary (ball) valves. Manufactured in the early 1900s, the rotary valve has many design features that are similar to modern AWWA ball valves. The most important of these features is a drip-tight shut-off for isolation of the throttling valves. These valves also exhibit exceptional hydraulic characteristics, which allow the valves to close safely if the throttling valve malfunctions.

The valve has three main components: a trunion-mounted rotating plug, and front and rear body castings. The body castings are steel, which was uncommon at that time. The standard valve model was furnished in cast iron, but the design engineers insisted that cast steel valves be furnished for Cobble Mountain. A bronze seat ring is mounted on the rotating ball, which seals against a bronze stationary seat mounted on the downstream nozzle of the valve. The seats are engaged utilizing the upstream reservoir pressure. The plug seat must be lifted prior to opening the main valve by balancing the pressure between the downstream (dry) side, and upstream side of the seat ring (accomplished by an auxiliary bypass valve and piping mounted on the side of the main valve body — see Figure 19).

The rotary valves cannot be isolated from the reservoir and remain under full reservoir pressure at all times. Isolation of the valves could only be accomplished by plugging the upstream conduit. Upstream plugging would add significant risk, complexity, cost and time to the project. There were no viable alternatives for complete replacement of the rotary valves within the allocated project budget, which was $1.5 million. Rehabilitation of the existing rotary valves was the only viable and cost-effective alternative, and it posed many design challenges.

The main valve body had considerable surface corrosion that would have to be examined to determine the extent of material loss. If the main valve body could be certified as fit for service, the only obstacle to its rehabilitation would be isolation of the main valve

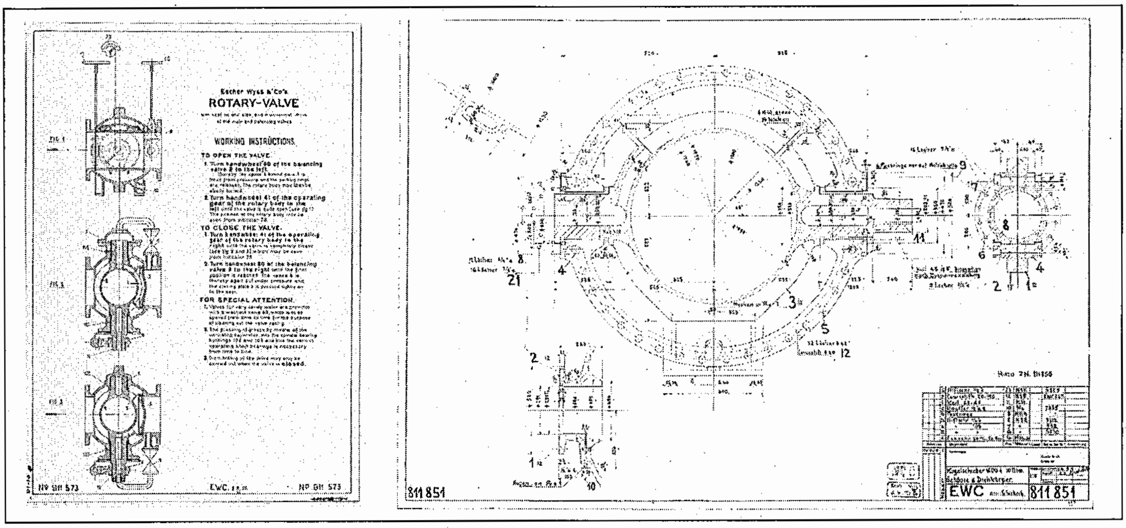


FIGURE 19. Excerpts from the original rotary valve shop drawings (1929).

from the reservoir for disassembly of the auxiliary components in the dry. The engineering consultant and a sub-consultant conducted wet magnetic particle and ultrasonic thickness testing on a 2-inch grid across both halves of the valve body (see Figure 20). Based on the results of this survey, it was determined that the valve body castings were fit for service, and would likely exceed the design life of eighty years.

FIGURE 20. Wet magnetic particle inspection of the steel rotary valve body castings.

The existing auxiliary bypass valves had severe corrosion and material loss requiring complete replacement (see Figure 21). The challenge was the location of the valve, which was always under system pressure and prevented removal of the valve in the dry because the upstream piping was under full reservoir pressure and could not be isolated. The bypass valves were 5 inches in diameter and had British Standard (BS) flanges installed on double-ended studs with British Standard Whitworth (BSW) threads. Ultrasonic thickness testing indicated a bypass pipe wall thickness of less than 0.125 inch. The pipe wall had deteriorated to a point where replacement was the only option.

The bypass piping would be replaced with TIG-welded Type 304L stainless steel pipe. The 5-inch bypass valves would be replaced by 4-inch CF-8 stainless steel gate valves. The existing BS flanges were thinner than modern ANSI flanges, so the existing flange studs would be

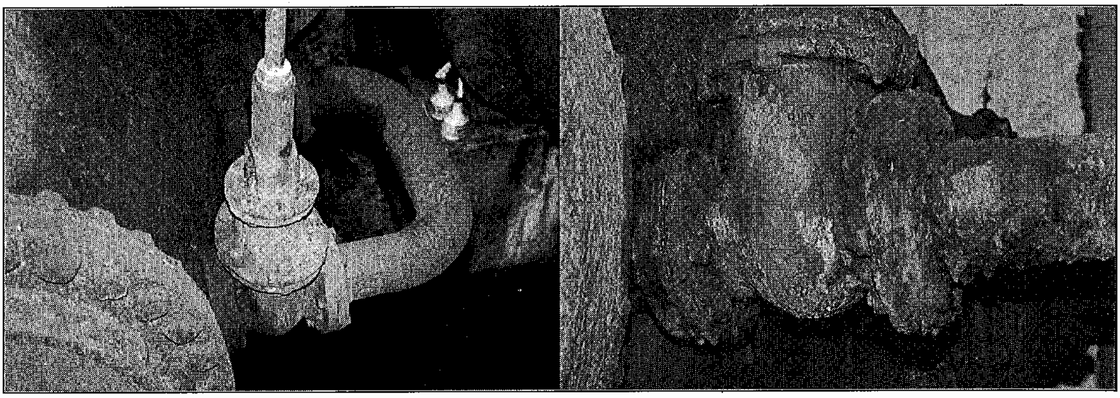


FIGURE 21. Rotary valve 5-inch auxiliary bypass valves showing extensive corrosion.

replaced with custom-designed 304 stainless steel double-ended studs having 55-degree BSW on one end, and 60-degree unified coarse threads on the other. The 4-inch diameter blow-off valves, originally installed on flange bosses located at the bottom of the rotary valves were removed in the early 1990s and replaced with blind flanges (see Figure 22). These valves are essential for flushing rust, silt and rock fragments that are deposited in the main valve body after operation. These valves would have to be replaced.

The existing drive-side shaft seal was leaking on both valves (see Figure 23). Since the valves were under pressure, there was no safe way of disassembling the valve to inspect the existing seal and stuffing box and determine the best replacement alternative. This work would have to be included as a change order during construction after the valves were isolated from the reservoir and drained. A custom-designed shaft seal would be required. In general, the worm gear drive was in good condition and would only require cleaning, painting and replacement of some thrust bearings. The valves are operated by hand-wheels located on floor stands in the control chamber. These components and the intermediate piping between the rotary valves and needle valves would all be replaced.

The valve's manufacturer in Switzerland was able to furnish the original 1929 shop drawings. However, the drawing text was

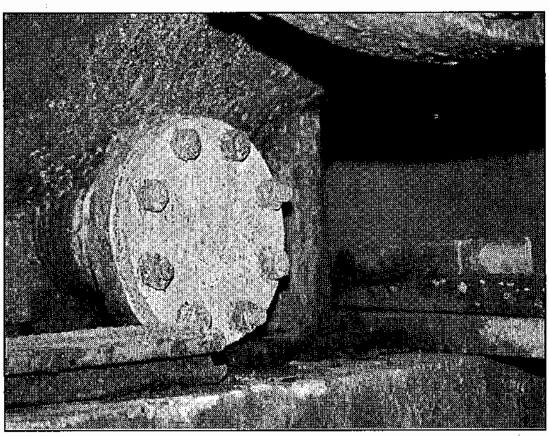


FIGURE 22. The rotary valve's 4-inch auxiliary body flush valve installation location showing the temporary blind flange.

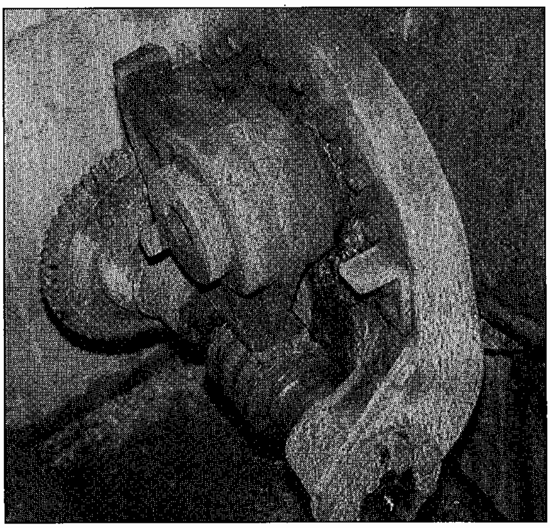


FIGURE 23. The rotary valve's worm gear drive showing the leaking shaft seal.

FIGURE 24. A typical wet-tap installation.

problem of isolating the rotary valves for rehabilitation had not been solved. A plan was developed to install a bulkhead plug in the 40-inch diameter steel-lined conduit directly upstream of the rotary valves. Initially, the use of commercial divers to install the plug was explored and found to be a viable alternative. Unfortunately, this alternative was cost prohibitive at an estimated construction cost of $3 million, nearly twice the allocated budget for the project. A method of plugging the outlet from the gate chamber in-the-dry, at a cost within the project budget allocation, would have to be developed.

written in German and required translation. These documents would be extremely important in the design of the seal and other improvements, but the original manufacturer did not want to participate in the project beyond this assistance.

The Plug

A clear strategy for the rehabilitation of the rotary valves had been developed, but the

Plugging live pipelines has been accomplished successfully in the water and gas industry during the past hundred years at pressures up to 500 psi. Non-entry plugging equipment developed for the pipeline construction industry were reviewed by the engineering consultant to determine if a commercially available device could be used at Cobble Mountain.

Line-stopping and plugging of pipelines while they are still in service is typically accomplished using a combination of wet tapping and line-stopping equipment, which is commercially available from several manufacturers. The procedure involves the following steps:

1. Install a line-stop fitting and tapping valve on the pipeline.

2. Mount a wet-tap drilling machine to the tapping valve, transverse

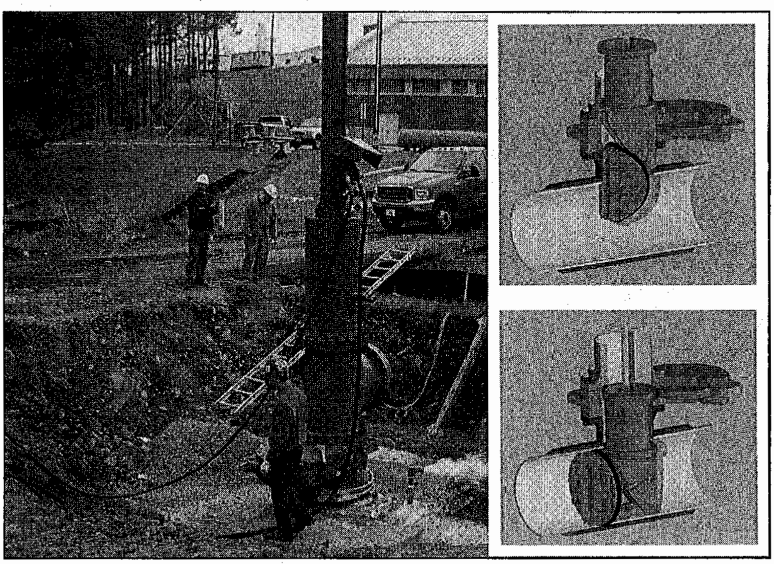


FIGURE 25. Line-stop installation, with an illustration of the internal mechanism.

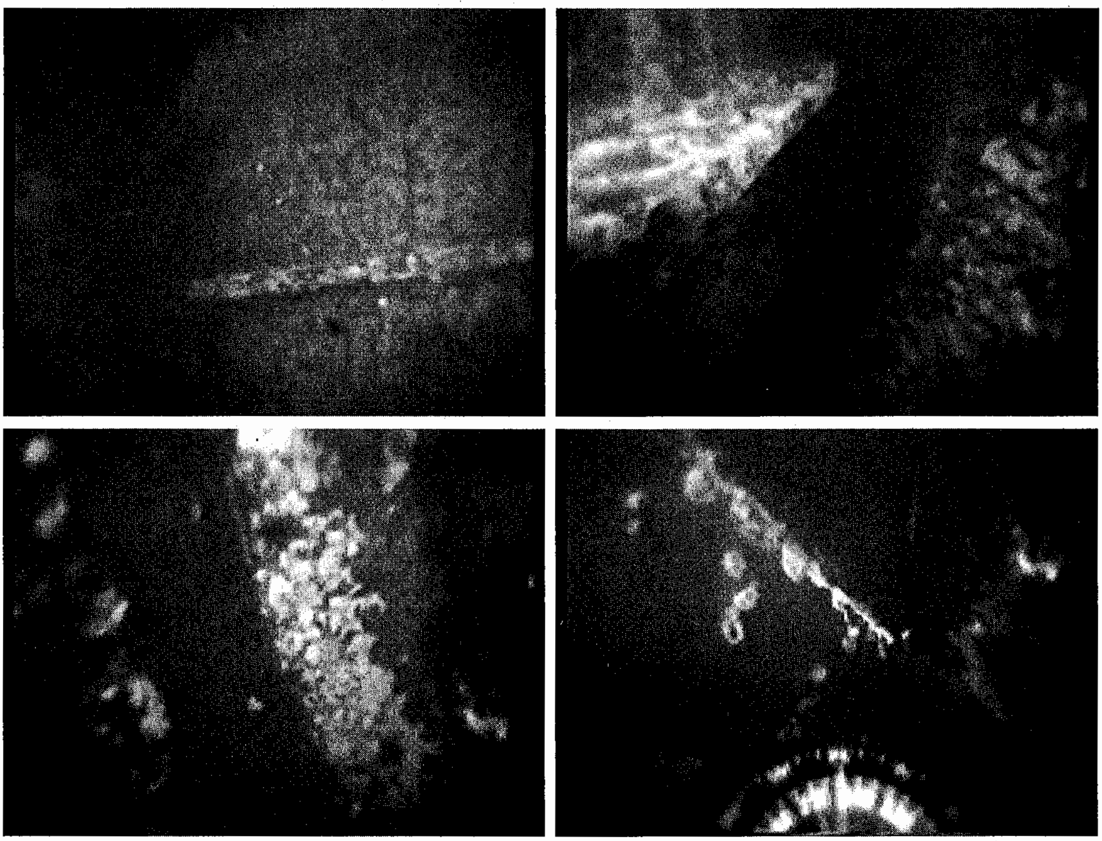


FIGURE 26. Video clips from a remotely operated submersible vehicle inspection: rotary valve ball (top left and right); steel conduit joints showing countersunk rivets at the flange (bottom left); and pipe seams (bottom right).

to the pipeline, and remove a coupon from the pipe wall (see Figure 24).

3. Remove the drilling machine and install a line-stop apparatus on the tapping valve.

4. Insert the line-stop through the tapping valve, into the pipeline and engage the plug seal (see Figure 25).

This procedure could not be used at Cobble Mountain because the upstream 42-inch steel conduit did not terminate far enough into the gate chamber to permit installation of the tapping sleeve. Also, even if it were possible to install the line-stop fitting, there would be serious safety and source water protection concerns associated with drilling into the side of the outlet conduit under 200 feet of head. If the line-stop fitting failed in any way, there would be no means of stopping the reservoir from draining.

After reviewing all of the commercially available technologies, discussing the problem with manufacturers and the USBR, it was clear to the design team that there was no device in existence that could accomplish the project goals. A new custom-designed device had to be developed that could deliver a plug through the rotary valve into the upstream conduit.

Before a plan could be developed, the design team had to find out if there were any tubercules on the conduit walls that would prevent a plug from being installed. The engineering consultant was able to obtain a video inspection, carried out using a remotely operated submersible vehicle, from the diving contractor who installed the blind flanges in the early 1990s (see Figure 26). This

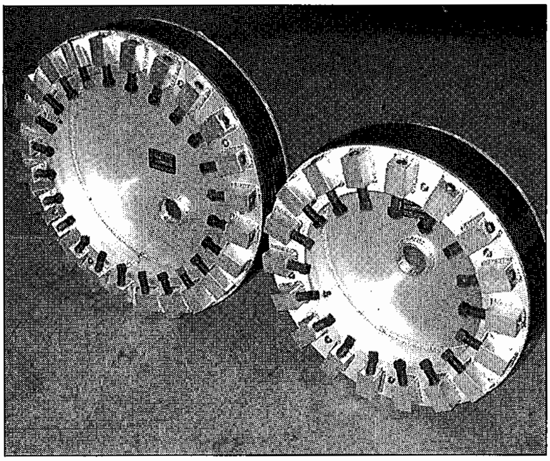


FIGURE 27. Fabricated aluminum pneumatic test plugs.

video inspection was clear enough to show very little corrosion to the valve plug and conduit wall; therefore, a plug could be installed.

The design team started with pneumatic bulkhead style pipeline plugs, which are used for pressure testing pipeline segments. These plugs are available in 40-inch diameter but would have to be specially designed by the plug manufacturer for the design pressure of 150 psi (see Figure 27).

The pneumatic plug would be custom built to the design requirements, but also needed a device capable of inserting the plug through the rotary valve. The engineering consultant developed a plug insertion device that could accomplish this task. The device is illustrated in Figures 28 through 35.

Figure 28 illustrates the device mounted to the closed rotary valve after the needle valves and intermediate piping are removed. The device would have a cylindrical housing that would retain the plug mounted on a shaft (see Figure 29). The shaft would be advanced through the valve and into the conduit by means of a threaded stem and stem nut actuated by a gear box and hand wheel.

To begin the insertion procedure, the existing bypass valve would be opened, and the pneumatic plug housing section filled with reservoir water to balance the pressure and raise the seat disc (see Figure 30). After the seat disc is raised, the main valve ball would be moved to the full-open position.

The design team confirmed from the 1920s shop drawings that the rotating valve ball had the same inside diameter as the connecting pipe, which would allow passage of the plug through the valve ball and into the conduit. After the plug was inserted and in position (see Figure 31), compressed gas would be used to inflate the elastomer seal ring on the periphery of the plug frame through a coiled

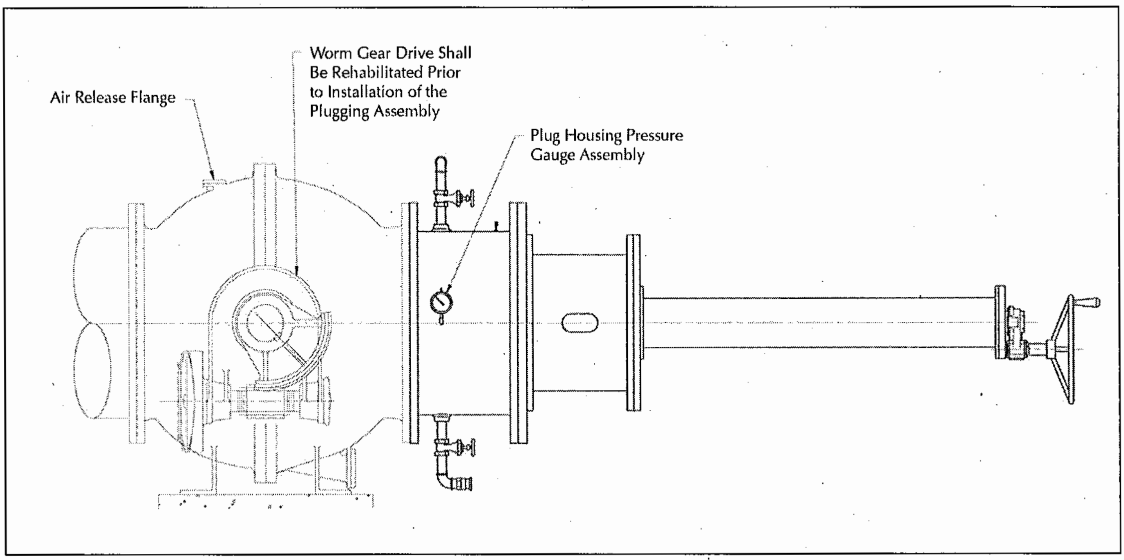


FIGURE 28. The insertion device mounted to the closed rotary valve.

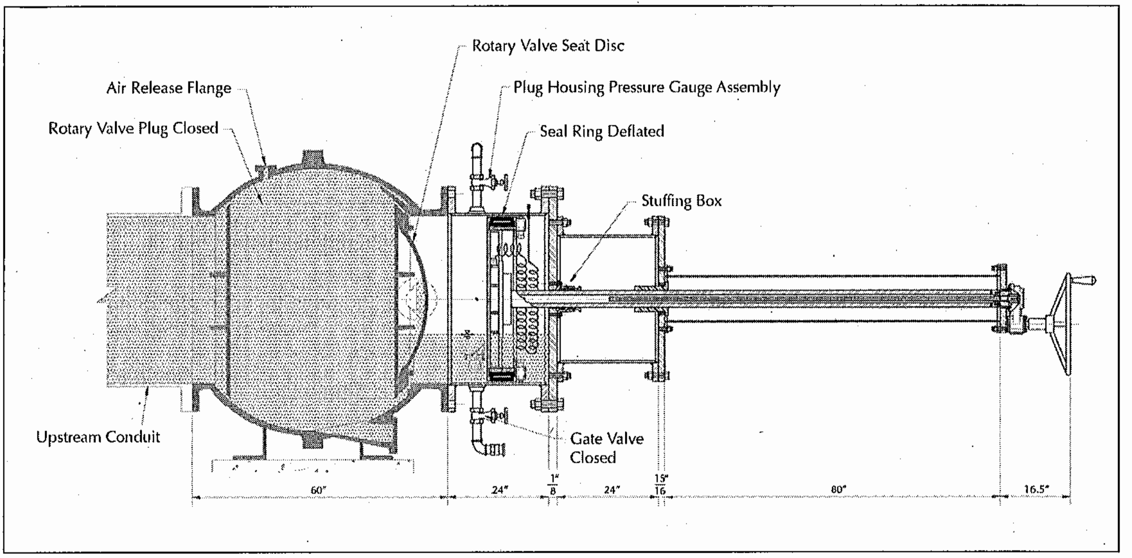


FIGURE 29. The device would have a cylindrical housing that would retain the plug mounted on a shaft.

retractable elastomer hose and bulkhead fitting. This step would provide the sealing mechanism for the system, but a thrust load of 150,000 pounds would be transferred to the shaft as the rotary valve is drained, so a separate means of mechanical restraint would be required. In the preliminary design, the insertion apparatus was removed and a blind flange was bolted to the stuffing box housing behind the shaft, restraining the plug and shaft after the valve is drained (see Figures 32, 33 & 34).

After the plug is installed, restrained and inflated, the rotary valve could then be drained and depressurized allowing safe disassembly of the auxiliary valve components (see Figure 35). The illustrations (Figures 28 to 35) were presented to engineering and operations staff at SWSC, and the system was approved for implementation. The engineering consultant worked with sub-contractors to determine the feasibility of fabricating the device, and to obtain an estimated cost. Based on a performance specification and illustrative

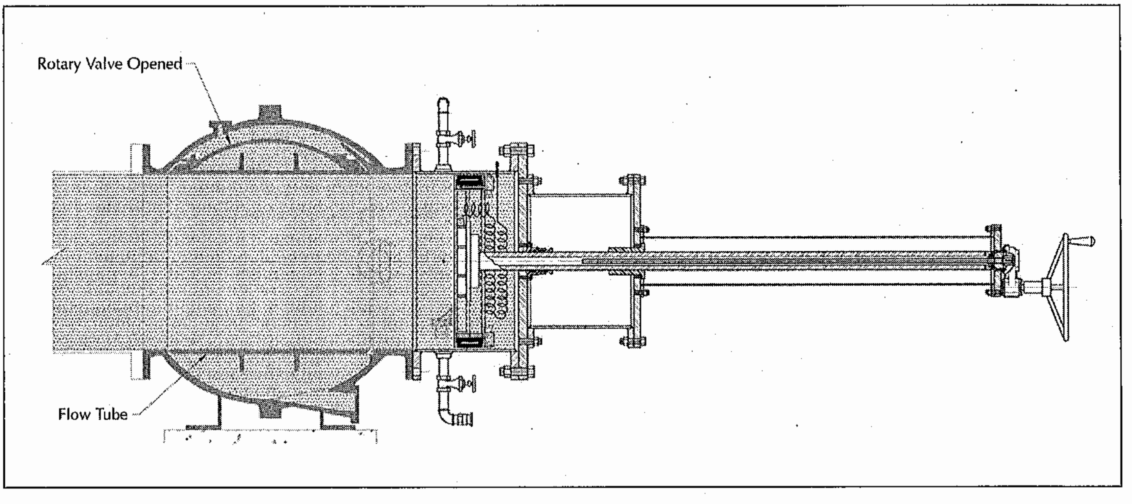


FIGURE 30. To begin the insertion procedure, the existing bypass valve would be opened.

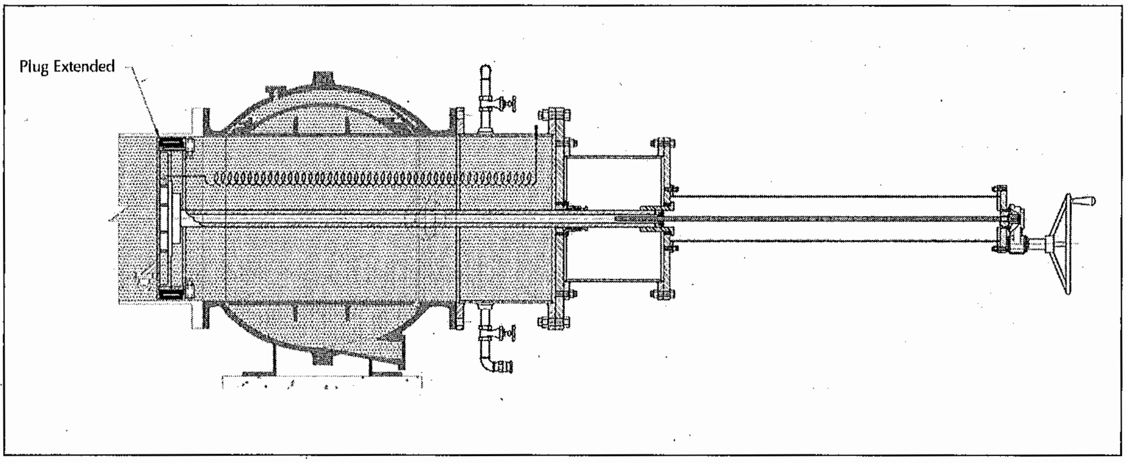


FIGURE 31. The plug would be inserted through the valve.

details of the insertion device included in the contract documents, it had an estimated cost of $100,000.

The Bulkhead

The non-entry plug concept was accepted by SWSC, but the Commissioners were concerned about the potential of a major accident in the gate chamber or catastrophic failure of the plugging system during construction that would drain the reservoir under an uncontrolled discharge. The SWSC wanted a redundant measure of protection.

In order to meet the SWSC's requirement to safeguard public health and safety, the reservoir and the environment, the engineering consultant recommended installing a temporary concrete bulkhead similar to what was installed as part of the blind flange installation in the 1990s. The temporary bulkhead would contain the discharge of a rupture and prevent a catastrophic uncontrolled discharge, but could increase worker's risk in the gate chamber if an accident or failure occurred during working hours.

The engineering consultant contacted the original bulkhead designer from the previous project in the 1990s to have the company review and reissue the proven design. The bulkhead consists of nine cast-in-place concrete beams installed in the bell-mouth of the diversion tunnel (see Figure 36). No work would be allowed in the gate chamber until the bulkhead construction was complete.

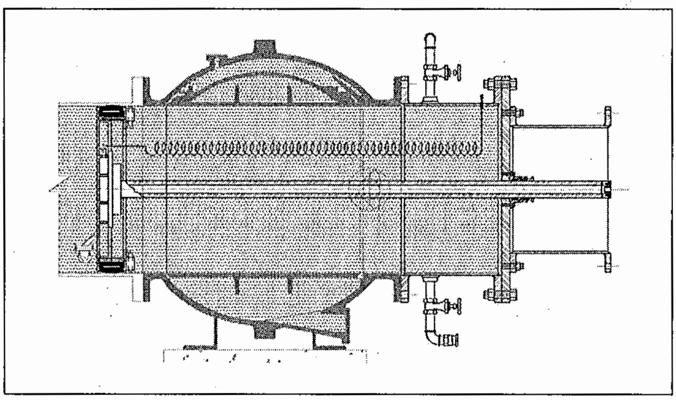


FIGURE 32. The insertion mechanism would be removed.

Construction Overview

The design was completed and requests for bids advertised in December 2004. The highest bid of $2.9 million was based on installing the plug by diving. The three lower bids were based on including the plugging system in the design. The lowest bid was $1.4 million and the second and third lowest bidders were within $200,000 of the low bid. It was clear that the plugging system saved SWSC approximately $1.6 million in construction costs.

Construction of the bulkhead was a priority since no other work could be started in the gate chamber until it was completed (see Figure 37). Work began in June 2005. The diversion tunnel and gate house posed challenges to the contractor.

The only access to the gate chamber was gained through a 10- by 5-foot rectangular air shaft that was 233 feet deep (see Figure 38) or down an unlighted narrow stairway with forty flights of stairs (320 steps), and then down a brass ladder through a 24- by 24-inch access way from the control chamber to the gate chamber (see Figures 39 & 40). It was cool in the summer, but bone-chilling cold and damp during the other three seasons; there were bats hanging from the walls and occasionally flying around; walls were coated with slime and mold; and there were always musty odors present. The tunnel could be used initially but would be inaccessible after the bulkhead was constructed.

Use of the tunnel during bulkhead construction was constrained by its only access road, a 10-foot wide switchback trail

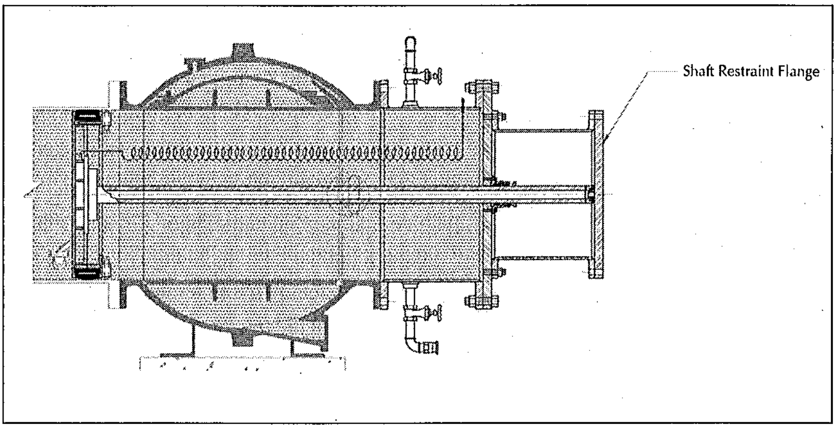


FIGURE 33. A plate would be installed to restrain the plug.

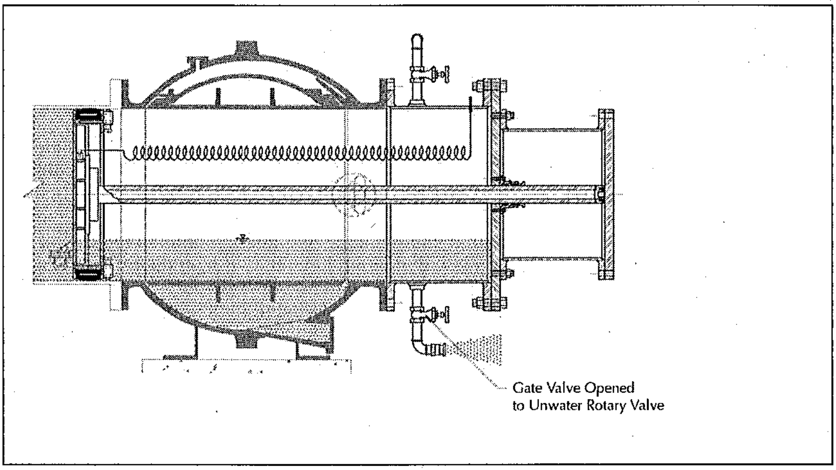


FIGURE 34. The plug would be inflated with nitrogen gas and the valve body drained.

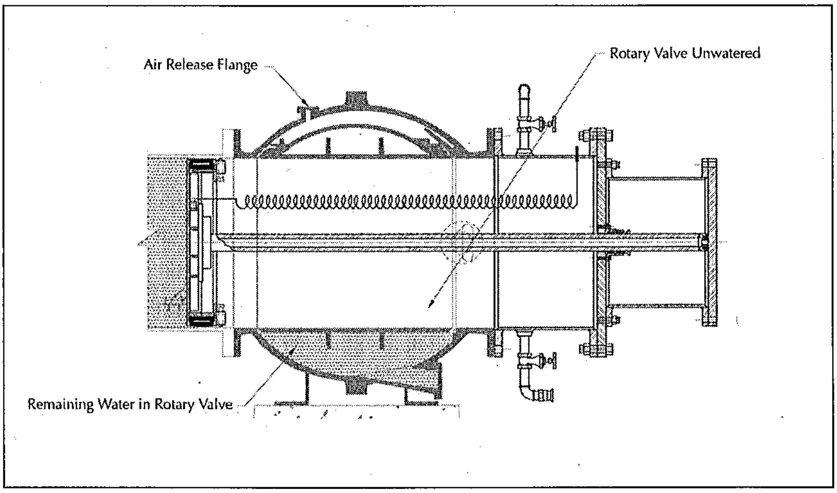


FIGURE 35. After the valve is drained, the auxiliary components can be replaced and the valve rehabilitated.

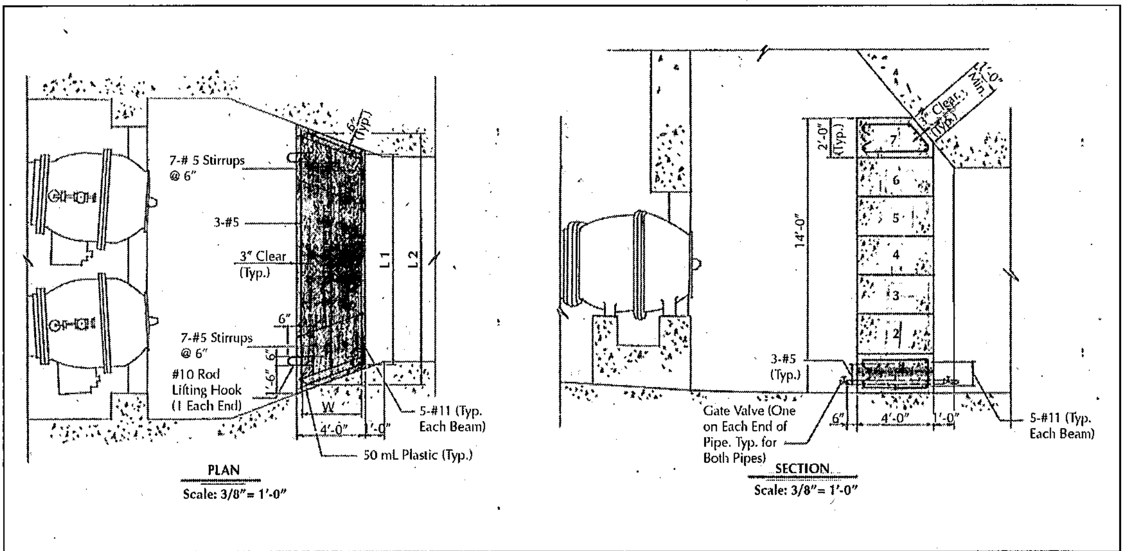


FIGURE 36. Concrete bulkhead plan and profile.

that wove its way down the Little River Gorge to the tunnel portal with 180-degree turns. Passage was difficult during the summer, but impossible during the winter. The air shaft was obviously the best alternative for access to the gate chamber.

The jet-flow gate HPUs posed an additional problem. The HPUs would be installed in the control chamber, and had to be lifted from the gate chamber in pieces through a 24- by 24-inch access-way.

The contractor installed a winch on the inside wall of the gate chamber with a capacity of 15,000 pounds and 225 feet of steel wire rope (see Figure 38). The winch was used to raise and lower materials and equipment to and from the bell-mouth chamber. A single cable was attached to the ceiling of the air shaft that would be used for an electrically operated lift-basket, providing easy access to the bell-mouth chamber by construction personnel and tools. A system of galvanized steel support beams were installed in the gate chamber and monorails were installed above each outlet (see Figure 41).

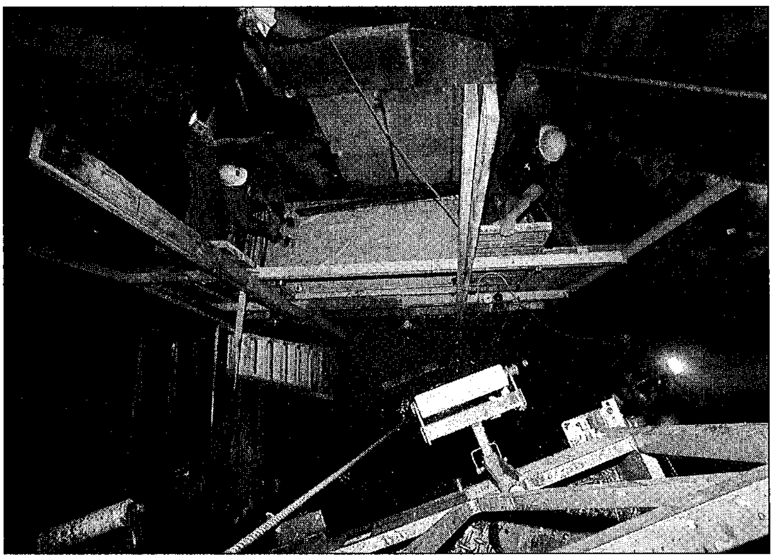


FIGURE 37. Bulkhead construction.

Equipment Fabrication

The contractor and fabricator responsible for the final design, and fabrication of the plug insertion device and the 30-inch jet-flow gates were both based in Massachusetts. The engineering consultant and SWSC project team were pleased that all of the equipment required for the project would be fabri-

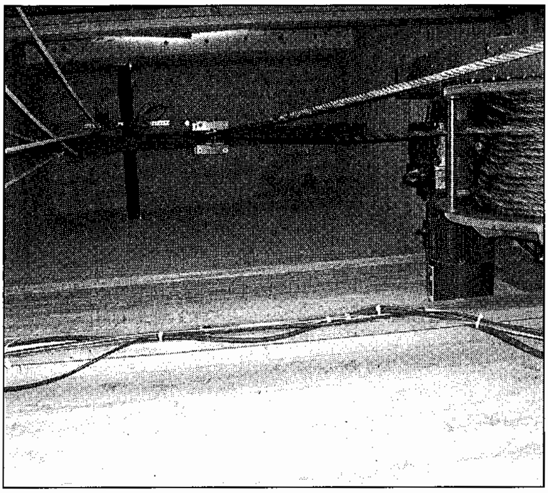


FIGURE 38. Air shaft winch installation.

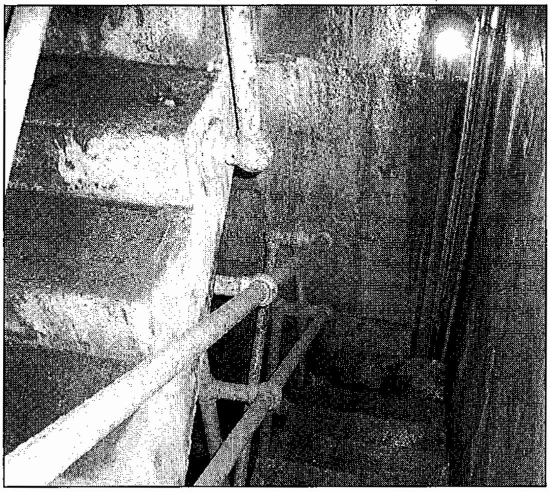


FIGURE 39. Access stairway.

cated locally in Massachusetts (see Figures 42 through 45).

Several improvements to the plug insertion device were developed by the fabricator during the final design and fabrication. Instead of using a blind flange to restrain the plug after inflation, two slots were machined into the insertion shaft to accept a keeper plate that would restrain the plug against a steel bracket mounted on the plug housing. In addition, at the request of project's contractor, the plug itself was designed with double elastomer seal rings back to back in order to provide redundancy and an extra measure of safety. The engineering consultant and SWSC were pleased with these improvements.

The plug frame was constructed of welded aluminum and mounted to the insertion device with a locknut on the threaded end of the shaft. The static pressure in the outlet is approximately 90 psi. The plug would have to be inflated to 50 psi above that pressure to create a seal. Nitrogen gas was selected to inflate both seal rings on the plug. Pressurized nitrogen in steel cylinders at 2,200 psi would provide additional response time in the case of a slow leak in one of the seal rings.

Shop inspections were conducted by personnel from the engineering consultant and SWSC at key milestones during fabrication, and a shop test was specified for both the

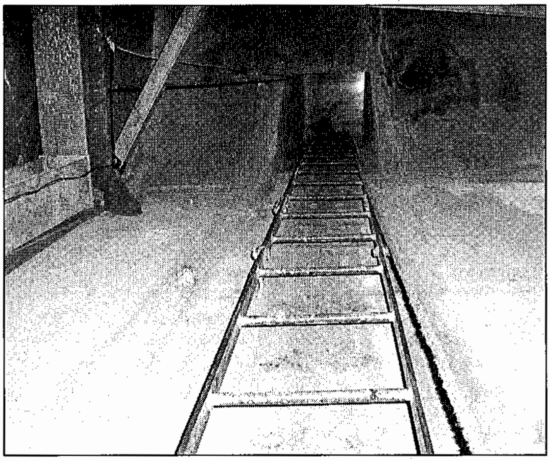


FIGURE 40. Gate chamber access ladder.

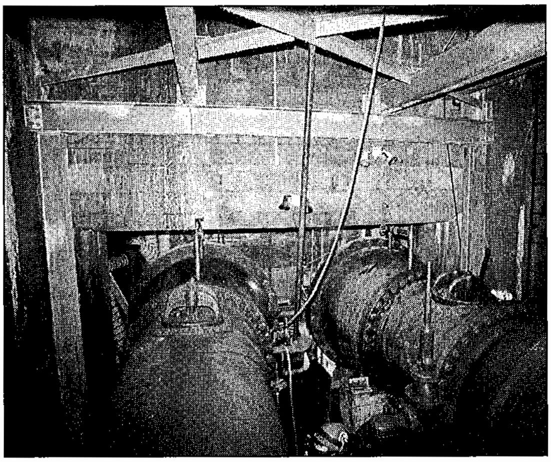


FIGURE 41. Gate chamber rigging equipment.

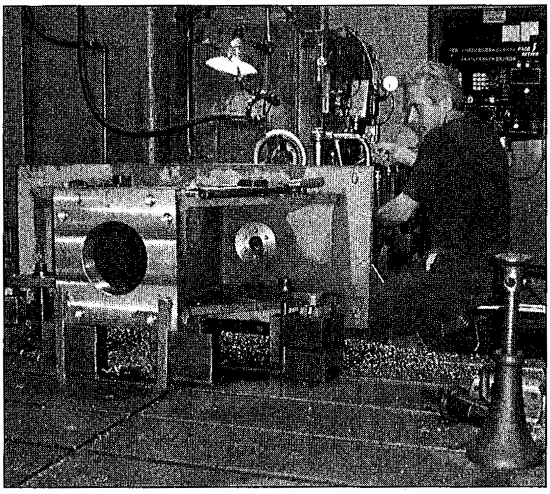


FIGURE 42. Jet-flow gate bonnet cover machining.

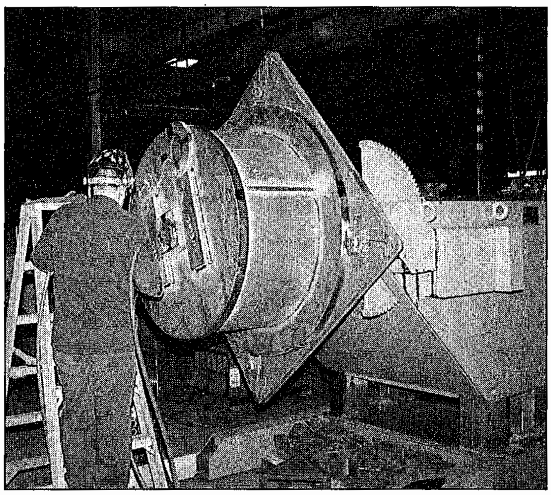


FIGURE 43. Plug insertion device during fabrication.

plugging system and jet-flow gate. The plugging system test was conducted on a test stand that simulated the conditions in the outlet (see Figure 46).

A custom-fabricated pipe spool with the same inside dimensions as the rotary valves and outlet conduit was set up on a test stand. Weld beads 0.375 inches in height were welded on the inside of the test pipe to simulate tuberculation and other obstructions on the inside of the rotary valve and outlet conduit. The plug was attached to the test stand, the pipe was filled with water and pressurized to the test pressure, and the plug was inserted into the pipe. As the plug was inserted, water had to be drained from the test stand to make up for the volume of the shaft.

The plug was inflated at the end of its insertion stroke, keeper plate installed and the water behind the plug drained to the atmosphere. A test pump maintained a pressure of 150 psi in front of the plug to simulate the reservoir plus safety factor, and the leakage was measured. The allowable leakage specified was 5 gallons per minute (gpm) since this flow was easily conveyed into the tunnel through the bulkhead drain pipe. Measured leakage was less than 5 gpm. The plug was retracted, the housing

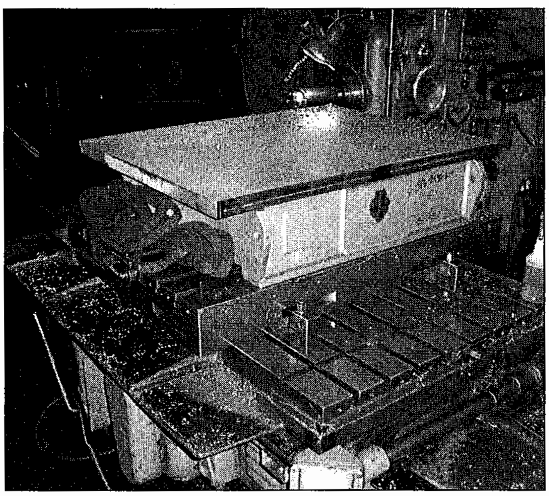


FIGURE 44. Jet-flow gate leaf machining.

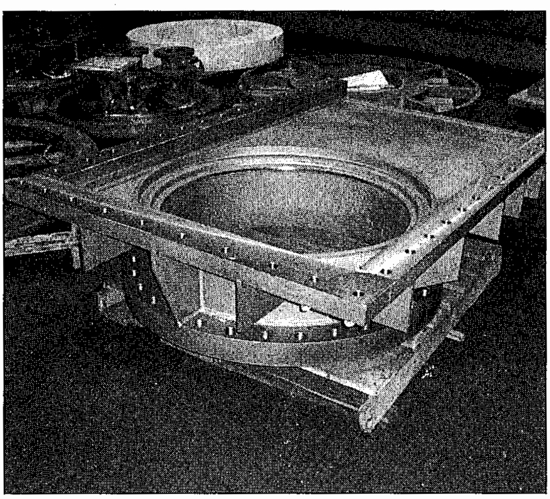


FIGURE 45. Jet-flow gate upstream body.

removed and the plug inspected for damage. The test was a complete success and the plugging system components were shipped to the site.

The jet-flow gate shop test included a hydrostatic leakage test and operational test to confirm smooth operation (see Figure 47). This test was conducted in August 2005 and was a complete success, with leakage measured at the specified limit. Since the jet-flow gate does not act as an isolation gate, the real purpose of the leakage test and functional test was to confirm that the dimensional tolerances were within those specified on the drawings. The test was successful and the gates were stored at the shop until the time of installation.

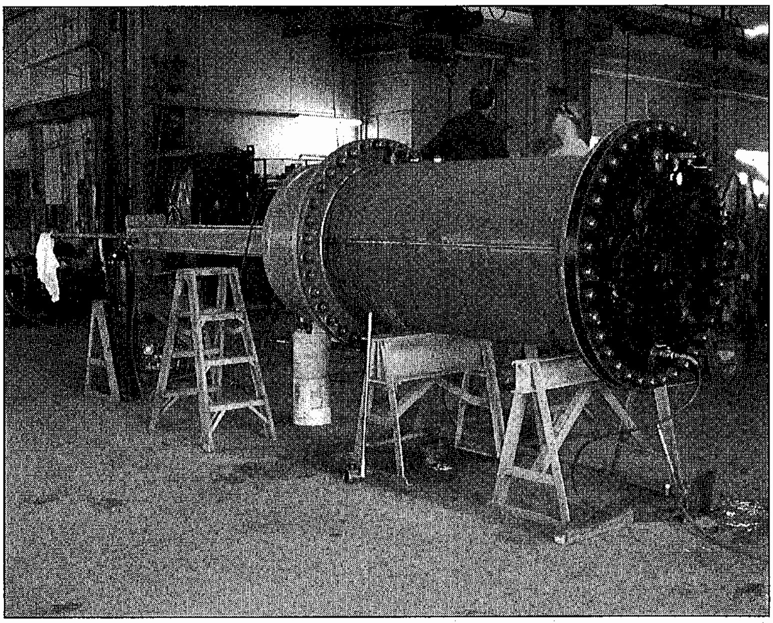


FIGURE 46. Plugging system test stand.

Rehabilitation & Installation Phase

After the bulkhead was completed and all components required for the project were on site (excluding the jet-flow gates), the contractor was allowed to commence demolition of the needle valves and intermediate piping. The gear drives on the rotary valves were disassembled and sent out for cleaning and painting. They would have to be rehabilitated and reinstalled prior to installation of the plugging system.

After demolition, the plugging system was lowered to the gate chamber, assembled and installed on the downstream flange of rotary valve no. 2 (see Figure 48). The plug was inserted through the valves without binding, rubbing or any other dimensional interference. The plug was inflated with nitrogen and there was zero leakage. Initially, it was anticipated that the plug would be installed for a short duration during disassembly and reassembly. The plug remained installed in each valve for over a month with zero leakage.

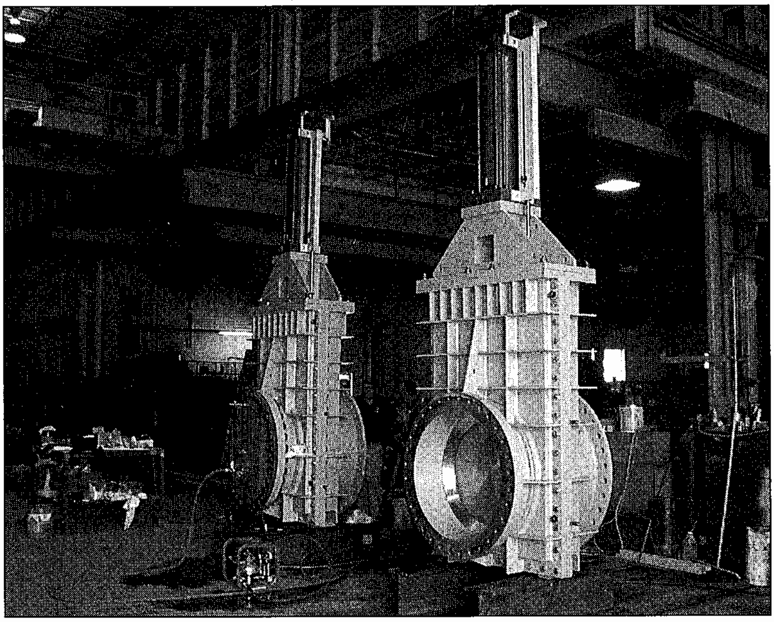


FIGURE 47. Jet-flow gate hydrostatic test during fabrication.

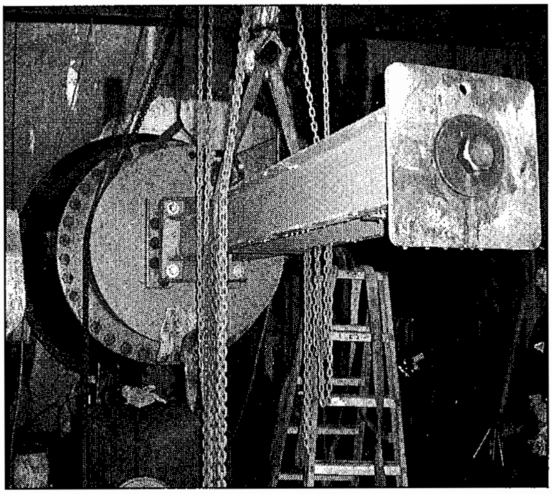


FIGURE 48. Plugging system installed on rotary valve no. 2.

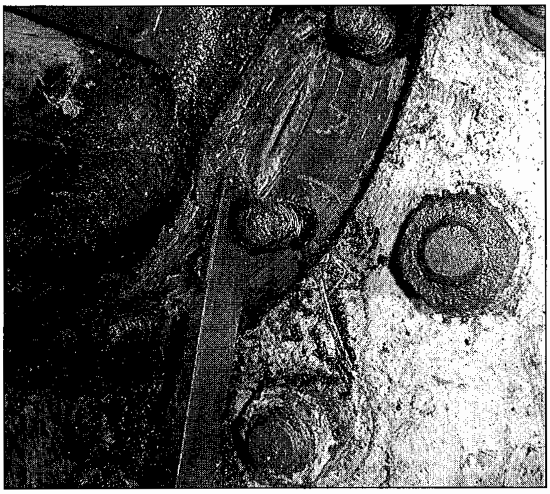


FIGURE 49. Rotary valve showing hat-leather seal and contractor ring.

With the rotary valves totally drained, the contractor was able to prepare the surface of the valves for a new finish coat of a high-performance epoxy coating. The bypass piping and valve, and the bottom flush valve blind flanges were removed, and the new stainless steel piping and valves were installed.

The seal gland was removed from the valve and the project team had its first look at the existing seal. The seal was constructed of leather, which was no surprise given the age of the valve. The configuration was a "hat-leather" flange seal that utilized a steel contractor ring and the hydrostatic pressure in the stuffing box to maintain the seal (see Figures 49 & 50). After removal of the existing seal, dimensions of the stuffing box were taken and a new seal was designed by the engineering consultant for its replacement.

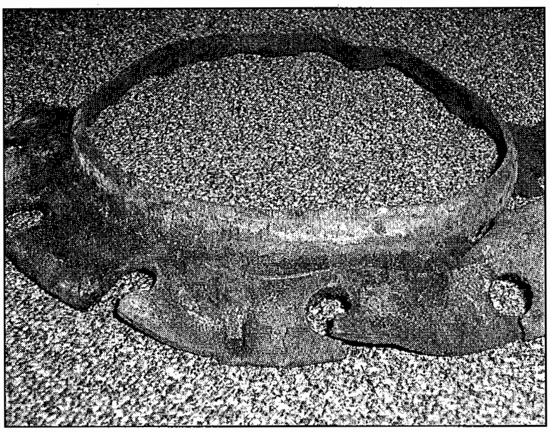


FIGURE 50. Hat-leather seal after removal.

Unlike modern ball valves that have bodies constructed of four separate castings instead of two, the rotary valve stuffing box was split down the middle. Given the split and rough surface finish on the interior, the engineering consultant decided to design a new leather seal in a vee-packing configuration. The seal would consist of three packing rings with cast bronze male and female adapter rings (see Figure 51). The design was completed and a change order was issued for the new seal.

The leather seals were fabricated in Muskegon, Michigan. Custom-machined dies had to be fabricated to form the vee-packing rings due to the metric dimensions and large shaft diameter. The engineering consultant specified a petrolatum-impregnated leather for the rings, which would make them softer and more suitable for the surface finish in the stuffing box. The adapter rings were machined from bronze tubular castings in a local machine shop.

After the rehabilitation of the rotary valves was complete, the jet-flow gate and HPUs were delivered to the site for installation. Hydraulic piping was specified as Schedule 80 stainless steel with 3,000-pound socket welded fittings. The piping was TIG welded on site. By June 2006 the jet-flow gates and HPUs

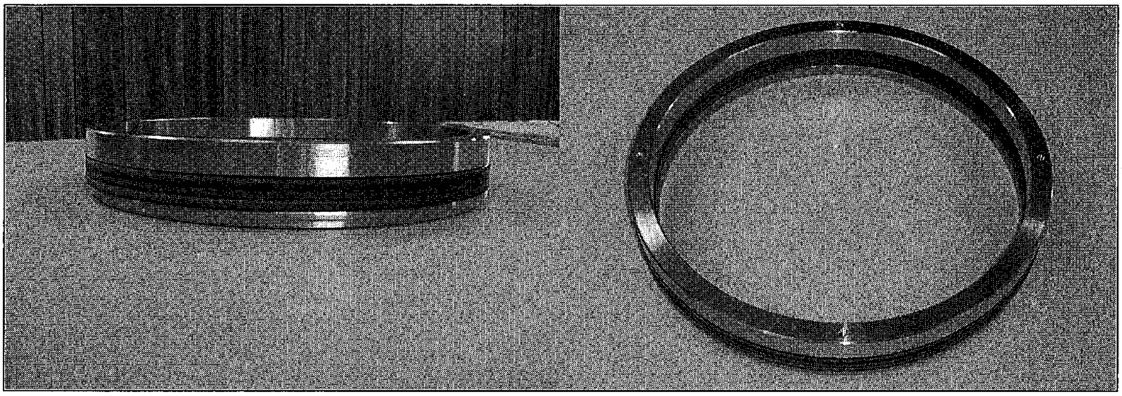


FIGURE 51. New leather vee-packing for the shaft seal.

were installed and ready for testing (see Figures 52 through 55).

Flow Test

In anticipation of the flow test, SWSC maintained the reservoir level at spillway crest elevation. At the maximum head, the jet-flow gates were expected to discharge a maximum flow at full open of 300 mgd (or 210,000 gpm) each. The exit velocity at the jet-flow gate would be approximately 75 feet per second. There was a major rainstorm on the designated test day but its occurrence did not impede the test.

The discharge flow from the gates into the tunnel creates an air demand that must be satisfied. This demand is known as insufflated air and the flow rates can be extremely high. The air demand is caused by the displacement of air by water droplets at high velocity and the aerodynamic drag caused by them. As the high-velocity spray generated by the flow increases, the air demand increases. This demand peaks at approximately 60 percent of gate stroke, and then drops off as the flow becomes a cylindrical jet and the spray diminishes. This phenomenon also occurred during needle valve operation, which is why the air shaft was constructed above the bell-mouth of the tunnel.

It is nearly impossible to accurately predict the air demand from the jet-flow gates but the project team needed to know the effect it would have on the static air pressure between the gate chamber and bell-mouth chamber,

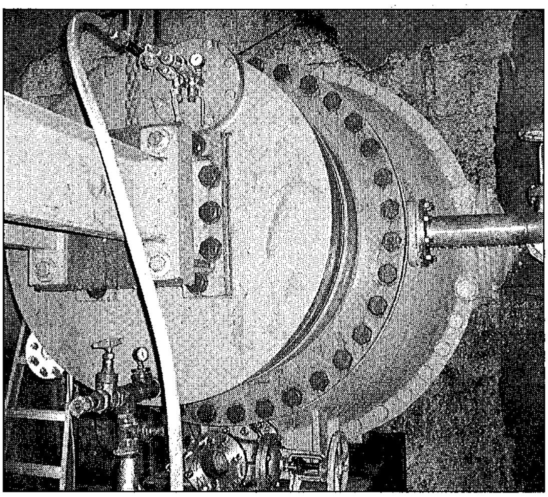


FIGURE 52. Rehabilitated rotary valve with plug.

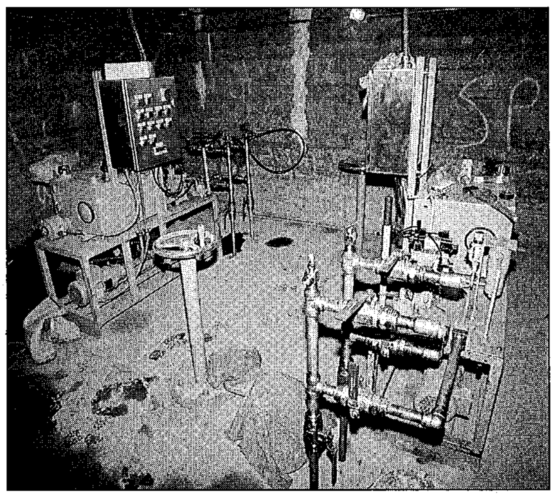


FIGURE 53. Jet-flow gate HPUs.

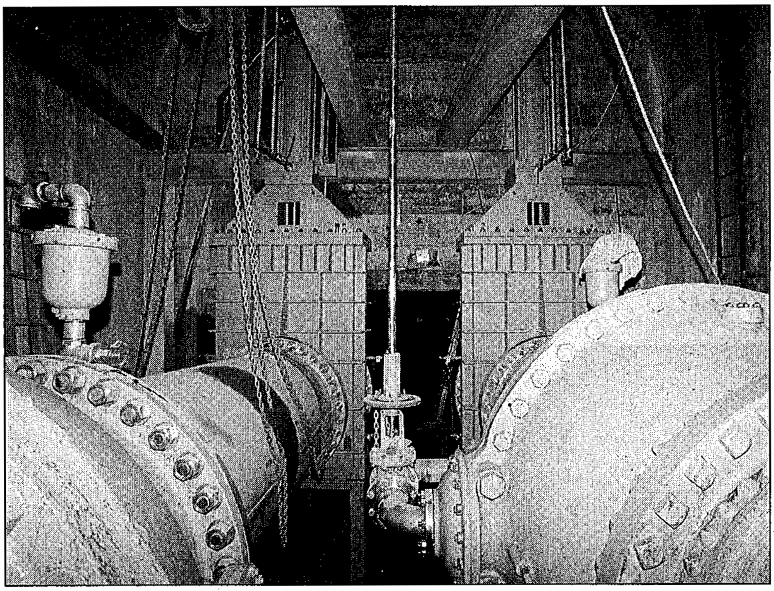


FIGURE 54. Jet-flow gates and rotary valves (view downstream).

reinforced concrete wall instead of masonry, but this wall would limit access to the chamber for future maintenance without the use of heavy demolition equipment. It was better to quantify the differential pressure and provide means for vacuum relief.

which was separated by a new reinforced masonry wall. The wall was designed for a load of 16 pounds per square foot (psf), which equates to a differential static pressure of 3 inches-water-column. If the differential pressure exceeded this value, the wall could fall down. The design team considered installing a

A testing procedure was developed by the engineering consultant and instrumentation was installed to measure hydraulic and other parameters at various locations around the facility. A digital windspeed gauge with data logger was installed in the air shaft to measure air demand. A Magnahelic differential pressure gauge was installed between the tunnel bellmouth and gate chamber to measure differential pressure. A pressure transducer and data logger were installed upstream of the rotary valve on outlet no. 2, and a noise meter was installed in the gate chamber to determine whether hearing protection would be required in the future during operation. The upstream pressure would be used to calculate the flow at different gate positions using data provided from the USBR.

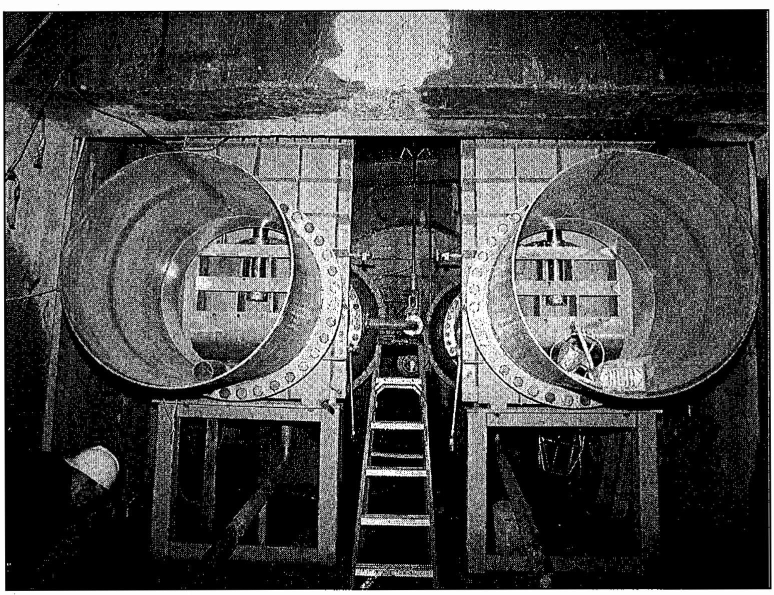


FIGURE 55. Jet-flow gates and discharge piping (view upstream).

The test was a complete success and was well documented. The maximum flow from both jet-flow gates was recorded at approximately 600 mgd, and the 11.5-foot diameter diversion tunnel was flowing full at the discharge portal, under pressure, at this flow rate (see Figure 56). The maximum airflow in the shaft with both gates fully open was 210,000 cubic feet per minute. The differential pressure between chambers was beyond measure, when both gates were opened simultaneously, and the gate chamber access door closed. The door was opened to allow sufficient air to flow down the access stairwell to relieve the vacuum. There was no vibration from the jet-flow gates during the test and noise levels were below OSHA limits at all times, even when the door was opened. The rotary valves created some periodic, loud cavitation that was clearly audible when the jet-flow gates were fully open, but it was not a cause of concern.

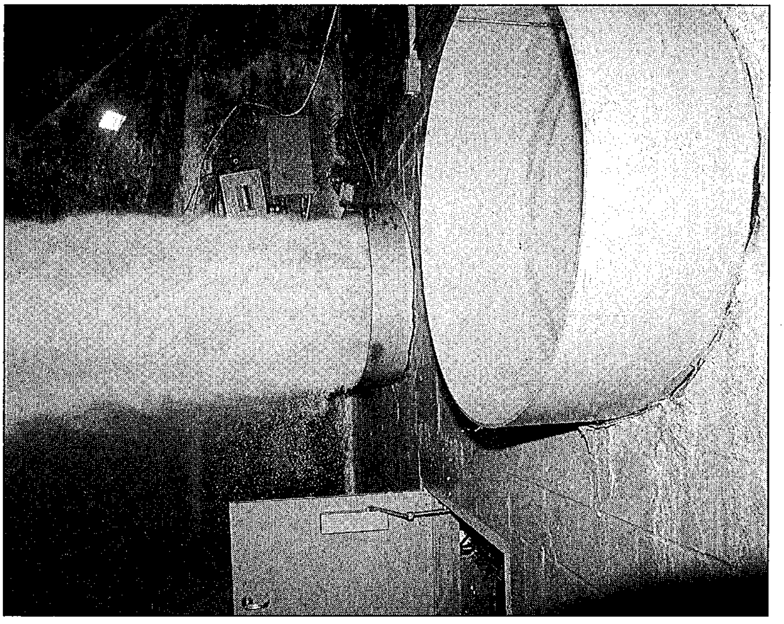


FIGURE 56. Discharge from jet-flow gate No. 2 fully opened.

In order to minimize risk to the water supply and maintain safe working conditions, the construction schedule was extended by nine months beyond the completion date. The time extension had no major impact on the final cost of the project, which was $1.44 million, with less than 3 percent net change orders.

Conclusion

SWSC, the engineering consultant and the contractor were very pleased with the success of this project, which:

- Included design solutions that showed resourcefulness in planning and execution;
- Pioneered the use of a unique non-entry pneumatic bulkhead plugging device for this application;
- Replaced potentially dangerous needle valves with jet-flow gates, the first installation of its type in New England;
- Returned control of the outlet works to the SWSC for safe and reliable service;
- Through innovation saved $1.6 million dollars compared to the use of divers in a dangerous application, requiring decompression diving techniques; and
- Resulted in zero injuries in a high-risk confined space.

NOTES — *CDM provided engineering consulting and project management services. The Larner-Johnson differential needle valves were manufactured by the I.P. Morris Corporation of Philadelphia, Pennsylvania. The rotary valves were manufactured by Escher Wyss & Co., of Zürich, Switzerland, now a business unit in the Andritz Group of companies based in Graz, Austria. CDM and sub-consultant Conam Inspection Services conducted wet magnetic particle and ultrasonic thickness testing on a 2-inch grid across both halves of the valve body. CDM worked with Rodney Hunt Co. of Orange, Massachusetts, and Steel-Fab, Inc. of Fitchburg, Massachusetts, to determine the feasibility of fabricating the device capable of inserting the pnematic plug through the rotary valve, and to obtain an estimated cost. CDM contacted Seigmund Associates of Providence, Rhode Island, the original bulkhead designer from the previous project in the 1990s, to have it review and reissue the temporary bulkhead design. R.H. White Construction Co. was the contractor on the project. Steel-Fab, Inc., of Fitchburg, Massachusetts, was selected by R.H. White to perform the final design and fabrication of the plug insertion device and the jet-flow*

gates. The jet-flow gates were machined at Central Mass Machine in Holyoke, Massachusetts. The plug was designed and fabricated by Mechanical Research Co. in Manitowoc, Wisconsin. The leather seals were fabricated by C.W. Marsh Co. in Muskegon, Michigan.

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