WATER OPERATION AND MAINTENANCE BULLETIN

No. 187 March 1999

IN THIS ISSUE. . .

UNITED STATES DEPARTMENT OF THE INTERIOR
Bureau of Reclamation

This *Water Operation and Maintenance Bulletin* is published quarterly for the benefit of water supply system operators. Its principal purpose is to serve as a medium to exchange information for use by Reclamation personnel and water user groups in operating and maintaining project facilities.

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Cover photograph: *Willow Creek Dam outlet repairs using cured-in-place pipe. Photo shows removal of resin liner from refrigerated truck at downstream tunnel portal, to be pulled upstream along tunnel to final position near regulating gate.*

UNITED STATES DEPARTMENT OF THE INTERIOR **Bureau of Reclamation**

WATER OPERATION AND MAINTENANCE BULLETIN
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BENDWAY WEIRS AND HIGHWAY PROTECTION IN COLORADO: A CASE STUDY ON THE BLUE RIVER

by S.P. Smith[1] and R.J. Wittler[2]

Introduction

Bendway weirs are hydraulic structures that divert flow away from a riverbank. They are useful in bank stability, navigation management, and fishery habitat creation applications. Other names for this class of structure include jetty, groin, dike, barb, and habitat sill. A bendway weir is a mass of rock projecting into the channel, angled upstream, and varying in height between the low water elevation and the 1.5-year flood level. Bendway weirs are sediment accumulators. Scour at the toe or point of the weirs creates fishery habitat. They are low cost and can be installed quickly, efficiently, and with very little construction damage to the surrounding area.

In 1997, the Colorado Department of Transportation (CDOT) faced the problem of the Blue River migrating laterally toward a section of State Highway 9, north of Silverthorne, Colorado. Potential solutions included installation of a retaining wall, riprap revetment, or bendway weirs. This 500-foot reach of the Blue River had migrated roughly 20 feet toward the highway since 1972. CDOT chose the bendway weir option as a progressive choice for bank stabilization.

Figure 1 is an aerial view of the reach following installation of the bendway weirs. This section of the Blue River is just downstream of Dillon Reservoir. This regulated reach shows the remnants of an active geomorphology. The alluvial gravel bed stream is an ideal candidate for bendway weirs. There is a gentle head cut working its way upstream through the reach and an active point bar opposite the reach adjacent to the highway.

Design

CDOT used the U.S. Army Corps of Engineers' “Reverse Sill and Bendway Weir Design Guidance” [4] in the design of the bendway weirs. Figure 2 is a design schematic. The design called for installation of as many as nine bendway weirs. Figures 3 and 4 detail the bendway weirs. The weirs are keyed into the bank and include a geofabric filter placed between the rock material and the riverbed. The bed was marginally excavated in preparation for receiving the bendway weir rock material.

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[2] Hydraulic Engineer, U.S. Bureau of Reclamation, Denver, Colorado 80225.

Figure 1.—Aerial view of Blue River downstream of Dillon Reservoir, near Silverthorne, Colorado (flow is right to left).

Figure 5 shows the general flow patterns over and around a series of bendway weirs. The eddies between the structures deposit bed material load. In the right configuration, bendway weirs are very efficient sediment accumulators and bank builders. Wittler [3] describes the bank building aspect of bendway weirs (barbs).

The specifications for these structures called for a weir height between 30 and 50 percent of the OHW. The length varies but is always less than one-third of the channel width. The key length is greater than one-half of the weir length. The weirs angle upstream between 15 and 30 degrees from perpendicular to the thalweg. Construction proceeded from upstream to downstream and was supervised by engineers experienced in the installation of these types of structures. The design guidance, while useful for specifications, is superseded by expert judgment at the site. Additional research and production of a more sophisticated design guidance are underway by an interagency team composed of engineers from the Bureau of Reclamation, the U.S. Army Corps of Engineers, and HR Walingford Laboratory, UK. This team is also documenting other installations [2][3] of these types of structures. The team will incorporate the performance data of in-place structures into the revised design guidance.

Figures 6 and 7 show views of the site during construction and under spring flows. Figure 7 clearly shows the slack flow near the imperiled bank.

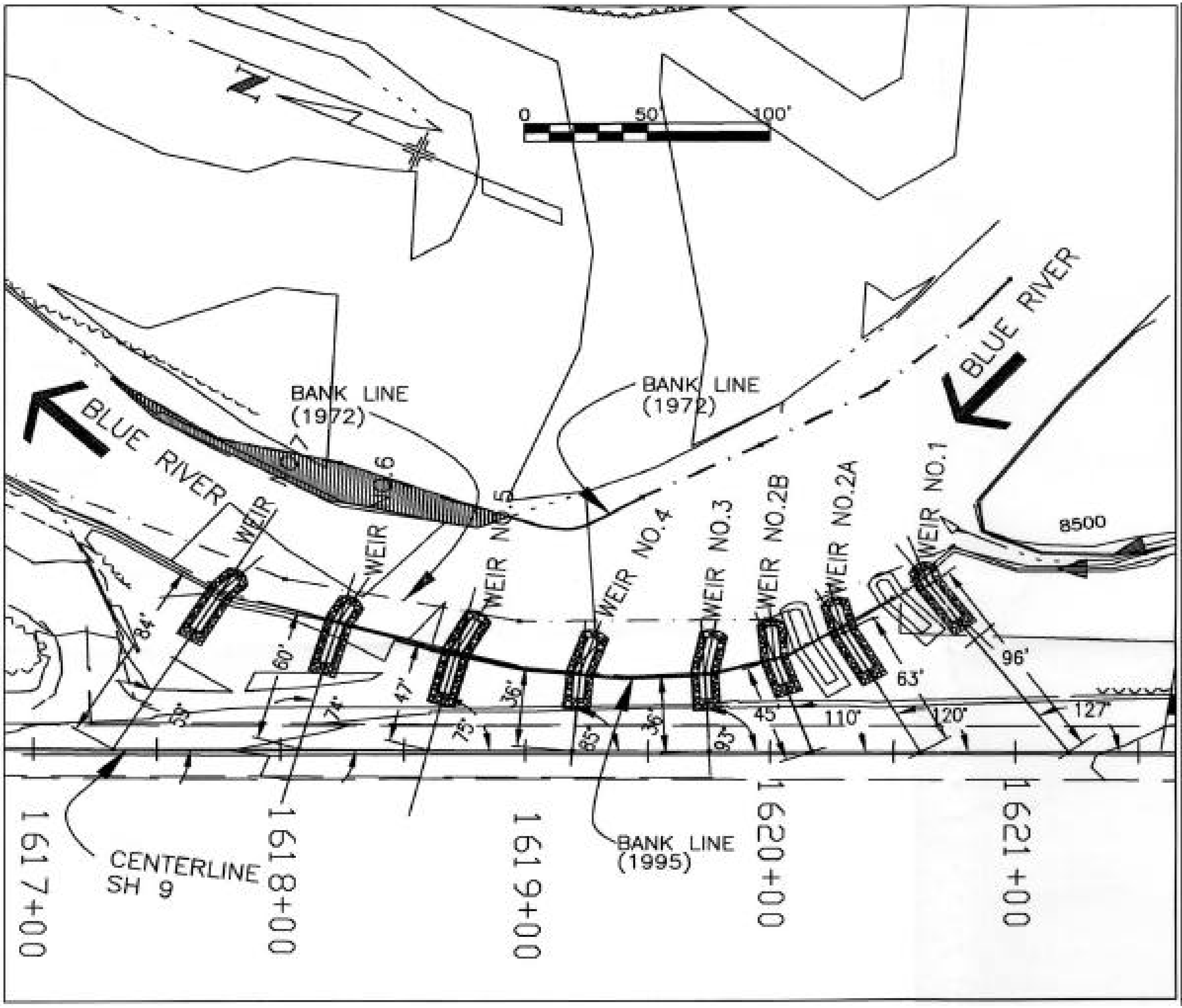

Figure 2.—Plan view of proposed bendway weir installation.

Conclusions

This successful project has generated several useful conclusions. First, bendway weirs are inexpensive structures. The eight structures placed on the Blue River contain roughly 371 cubic yards of rock and were completed in less than 2 days. The weirs are performing as expected while generally following the specifications of the U.S. Army Corps of Engineers' "Reverse Sill and Bendway Weir Design Guidance." There is some minor bank instability between a few pairs of downstream weirs. In their first season, the weirs sustained flows of more than 1,800 cubic feet per second with no noticeable rock displacement. There is some settlement of fill over the keyways. There is no significant bank erosion. There is some deposition of fine-grained sediment between the weirs.

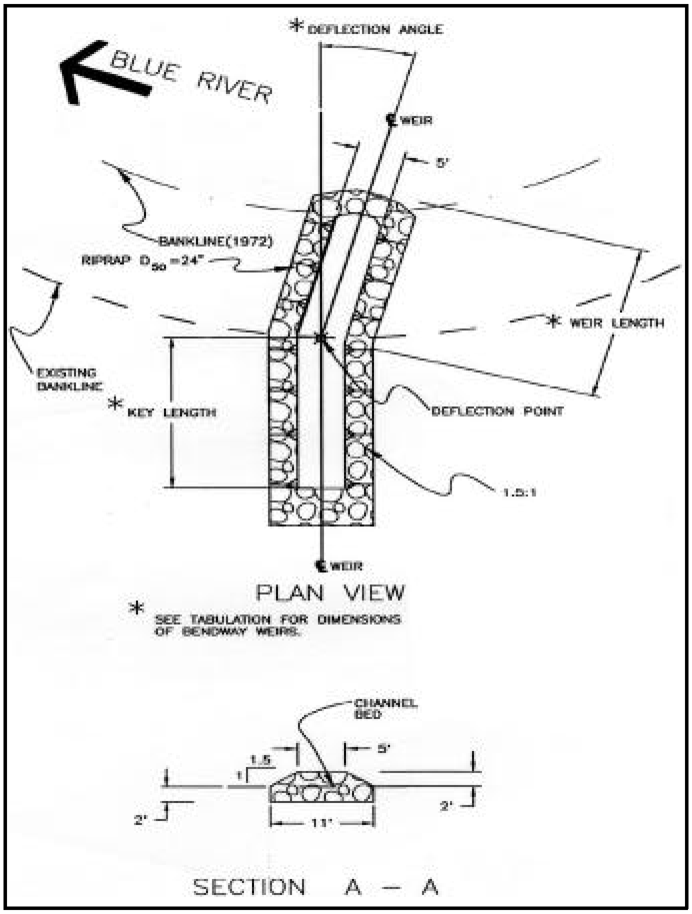

Figure 3.—Bendway weir details.

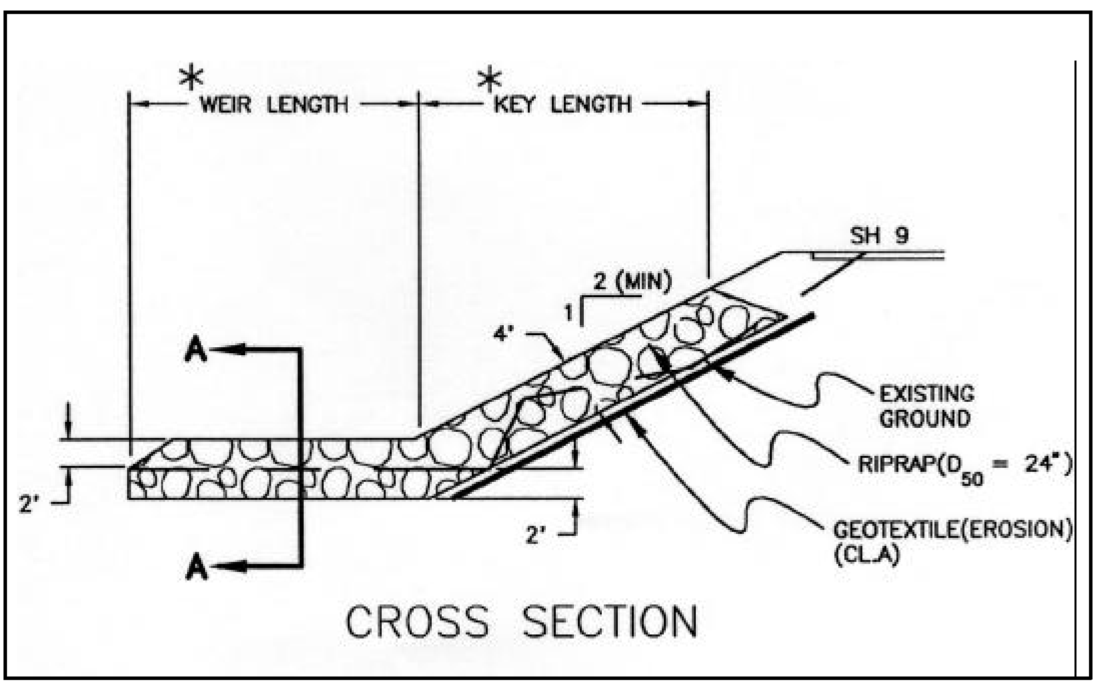

Figure 4.—Bendway weir section.

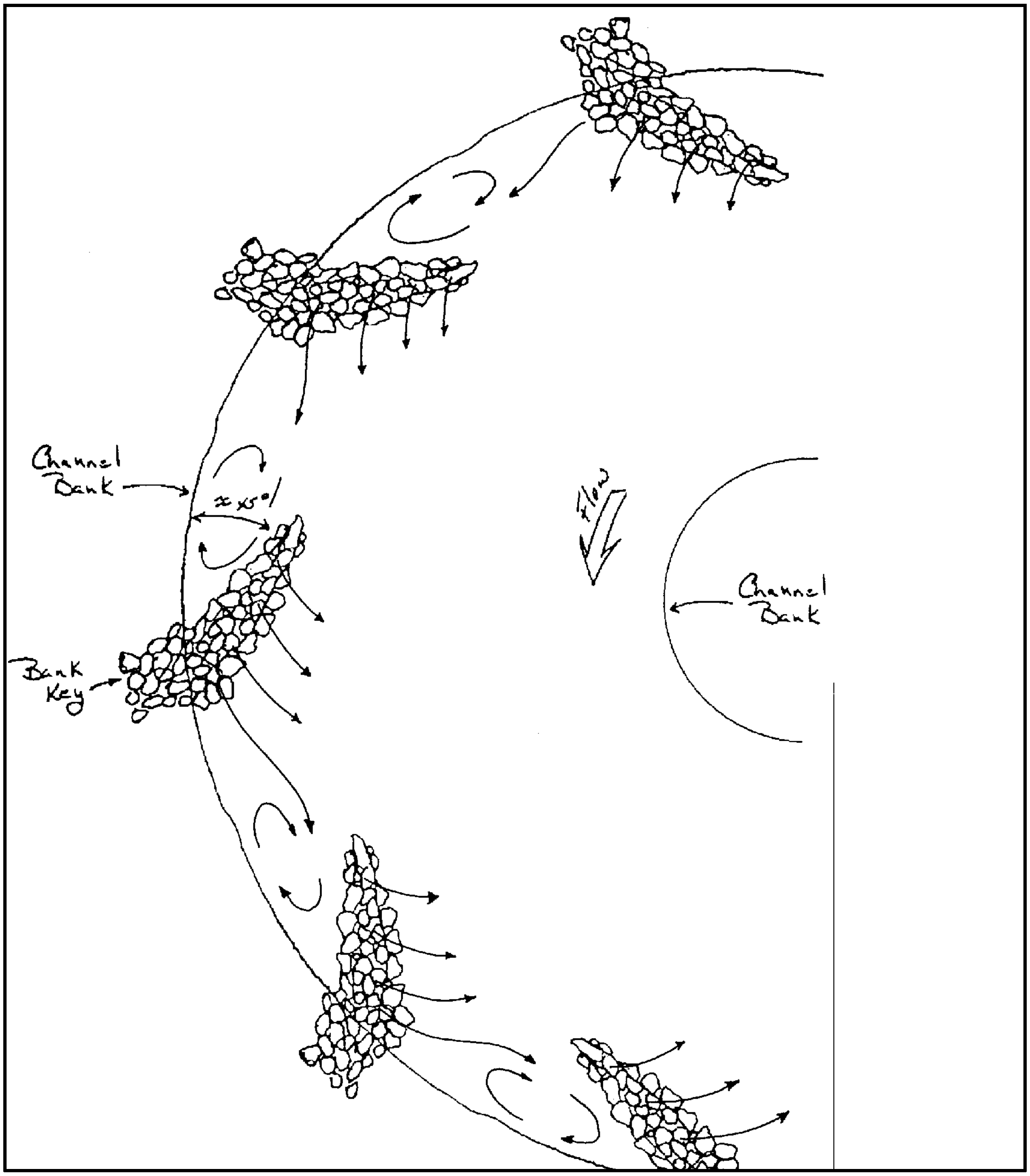

Figure 5.—Diagram showing sequential behavior of bendway weirs.

Figure 6.—View looking downstream while weirs are under construction.

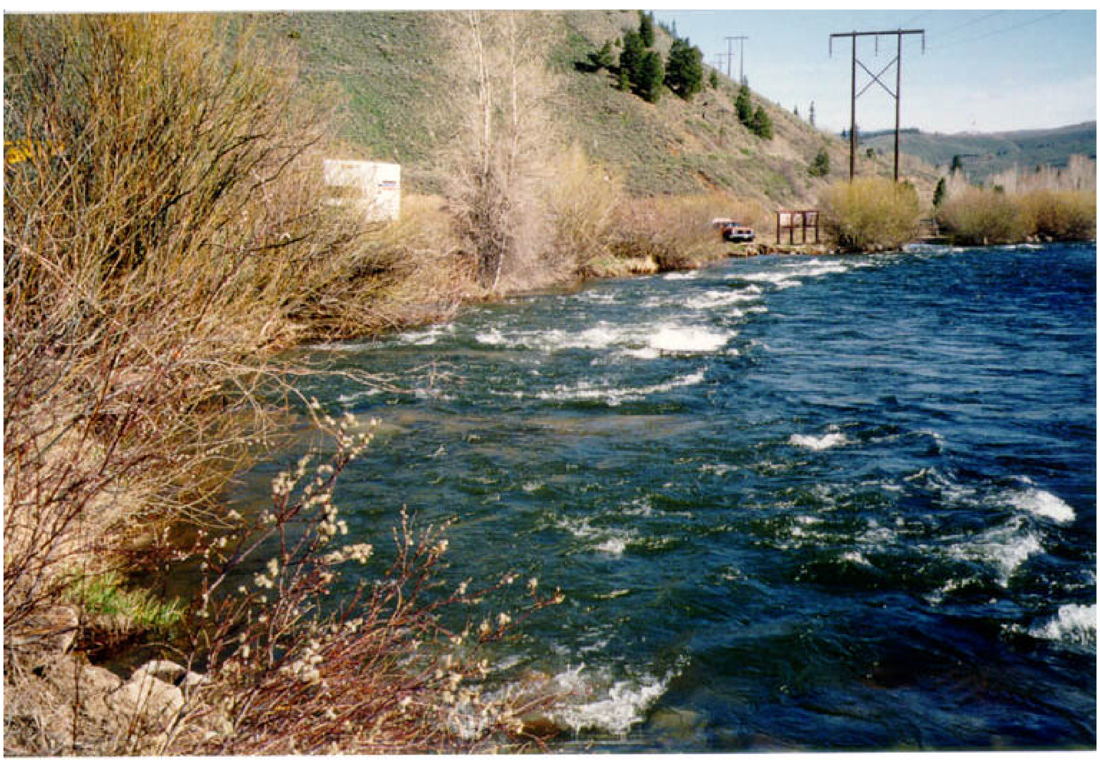

Figure 7.—View looking downstream while weirs are submerged.

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Published Reference

This paper was originally published by Steve Smith (formerly with the Colorado Department of Transportation) and Rod Wittler (D-8560) with the title, *Bendway Weirs and Highway Protection in Colorado: A Case Study on the Blue River*. The American Society of Civil Engineers published the paper in the Proceedings of the 1998 International Water Resources Engineering Conference, August 3-7, 1998, in Memphis, Tennessee.

SUMMARY OF THE SHASTA DAM TEMPERATURE CONTROL DEVICE AND HOW IT IS WORKING

by Tracy B. Vermeyen, U.S. Bureau of Reclamation

Introduction

Dramatic declines in winter-run chinook salmon populations have resulted in their listing as a protected species in 1989 under the Federal and California State Endangered Species Acts. One of several factors limiting salmon populations is egg and fry mortality associated with elevated water temperatures in the upper Sacramento River. The Bureau of Reclamation (Reclamation) investigated several alternatives for selective withdrawal from Shasta Reservoir to improve fishery habitat in the upper Sacramento River while maximizing power generation and operational flexibility. Since 1987, water temperatures in the upper Sacramento River have been managed to protect endangered salmon species by releasing deeper, colder water from Shasta Lake using the low-level outlet works. However, these releases were not passed through the powerplant, so hydroelectric generation was greatly reduced. For example, bypass releases from 1987 through 1996 have an estimated combined cost of $63 million in replacement power costs.

The Central Valley Project Improvement Act (CVPIA) (Title 34 of Public Law 102-575), passed in 1992, elevated fish and wildlife protection and restoration to equal importance with the original project objectives of flood control, irrigation, navigation, and power production. As part of the CVPIA, Reclamation was ordered to construct and operate a selective withdrawal structure at Shasta Dam which would control release water temperatures in the upper Sacramento River to minimize salmon mortality. The primary habitat impacted by the Shasta releases is the river reach between Keswick Dam and the Red Bluff Diversion Dam, a distance of about 60 river miles (95 kilometers [km]). The temperature control device (TCD) was designed to selectively withdraw water from Shasta Lake over a wide range of levels to meet water temperature targets in the upper Sacramento River. Operational plans called for warmer water to be withdrawn from upper levels when possible (spring/early summer) to preserve deeper, colder water for release when most needed for protecting salmon reproduction and rearing habitat (late summer/early fall).

Project History

The Sacramento River and Shasta Dam are part of the Central Valley Project (CVP), one of the largest water storage and transport systems in the world. Developed and managed by the U.S. Department of the Interior's Bureau of Reclamation, the CVP stores and distributes about 20 percent of California's water (7 million acre-feet or 8.6 million cubic meters) and generates more than 5 million megawatt hours (MWh) of energy during years of normal rainfall. Shasta stores 40 percent of the CVP water supply and generates 42 percent of CVP hydroelectric production. Shasta Dam and Reservoir are located 15 miles (24 km) north of Redding, California. Shasta is the largest reservoir in California, with the capacity to store 4.5 million acre-feet (555,000 hectare-meters) of water. Shasta Dam impounds the flow from the Sacramento, McCloud, and Pit Rivers.

Shasta Dam is a 602-foot-high (183-meter) curved concrete gravity structure which was completed in 1945. The dam includes an extensive river outlet works structure with intakes at elevations 942.0, 842.0, and 742.0 feet above sea level. The dam has a gated overflow spillway with a crest elevation of 1037.0. The five power penstock intakes are located near the right abutment with a centerline elevation of 815.0, approximately 240 feet (73 meters) above the old river channel but only 25 feet (7.6 meters) from the reservoir bottom directly in front of the intakes. Shasta Powerplant is located directly below the dam and is a peaking plant that includes five turbines with a combined rated capacity of 539 megawatts. The current discharge capacity of the powerplant is 17,600 cubic feet per second (ft^3/s) (500 cubic meters per second [m^3/s]). Currently, the units are being upgraded and will increase the discharge capacity to 19,500 ft^3/s (552 m^3/s).

Shasta TCD - Design and Construction

In 1989, Reclamation engineers began researching a means to control the release water temperature at Shasta Dam without sacrificing revenue from power generation. The engineers designed a multilevel intake structure to be installed upstream from the existing power penstock intake structures located on the face of Shasta Dam [1]. This massive steel shutter-type device provides selective withdrawal capability for all five power penstocks. The operational scenario requires surface withdrawals during the spring when the surface water temperatures are cool and from deep in the reservoir during summer and fall when the surface water is too warm.

Selective withdrawal is controlled by the 250-foot-wide by 300-foot-high (76.2-meter-wide by 91.4-meter-high) shutter structure. Individual steel frame structures were placed around existing trashrack structures 1, 3, and 5. After these structures were connected to the dam, structural members were installed between them to enclose existing trashrack structures 2 and 4. Cladding panels, gates, and trashracks were installed on each structure in front of all five power penstocks. The shutter structure projects about 50 feet (15.2 meters) upstream from the face of the dam and is open between units to permit crossflow in front of the existing trashrack structures. The TCD, Shasta Dam, and Shasta Powerplant are shown in figure 1.

Three sets of hoist-operated gates and trashracks on the front of each shutter unit allow selective withdrawal at three elevations. The upper gates control withdrawals from the vertically adjustable intake between elevation 1045.0 and 1000.0. The middle gates control the flow through the openings from elevation 900.0 to 945.0, and the pressure relief gates control the flow through the openings from elevation 804.0 to 831.0. The pressure relief gates are equipped with two-way pressure relief panels that prevent excessive differential

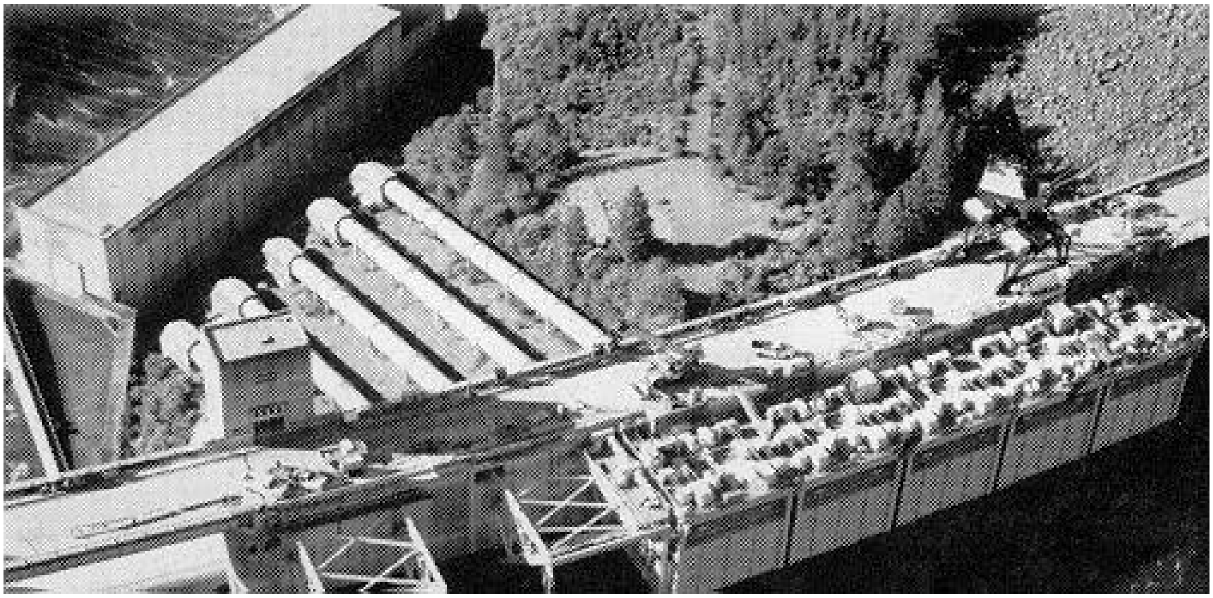

Figure 1.—Photograph of the TCD, Shasta Dam, and Shasta Powerplant. The five TCD bays are on the right, and the low-level intake support structure is on the left.

pressure across the TCD that could be caused by turbine operations or improper TCD operation. Likewise, one-way pressure relief panels opening away from the dam were installed on the middle gates. Additional one-way relief panels, some opening inward and some opening outward, were installed on the side of shutter No. 1 from elevation 808.0 and 855.4. Figures 2 and 3 present schematics of the TCD design.

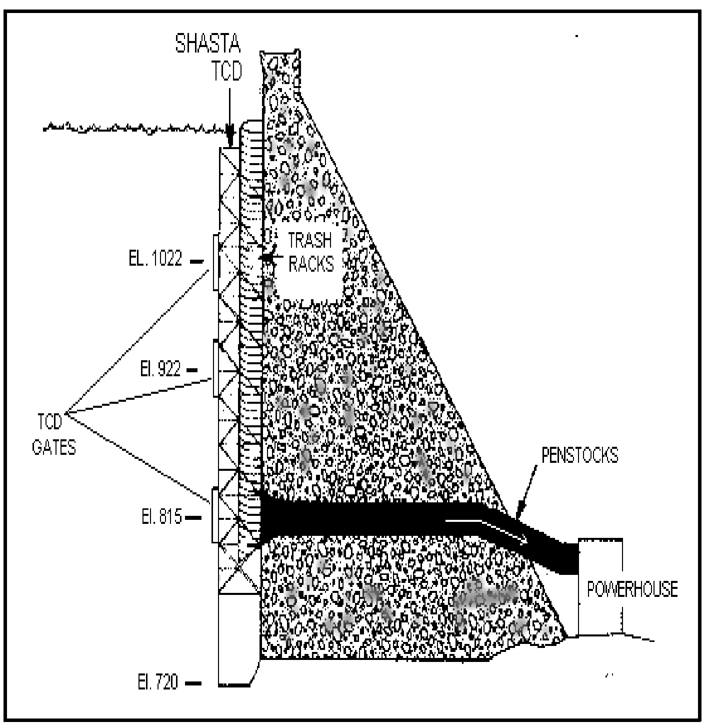

Figure 2.—Profile of Shasta Dam with the TCD.

To the left of the shutter structure is the low-level intake structure. This structure also projects approximately 50 feet (15.2 meters) upstream from the face of the dam. The low-level intake was designed as a conduit extension to access the deeper, colder water near the center of the dam. The 125-foot-wide by 170-foot-high (38.1-meter-wide by 51.8-meter-high) low-level intake structure is comprised of two steel structures. Structural members and cladding panels span low-level intake Nos. 1 and 3 to form low-level intake No. 2. The low-level intakes are open on the bottom at elevation 720.0. Two 130-foot-high

(39.6-meter) side gates, mounted on the side of shutter structure No. 5, control the flow from the low-level intake structure into the shutter structure.

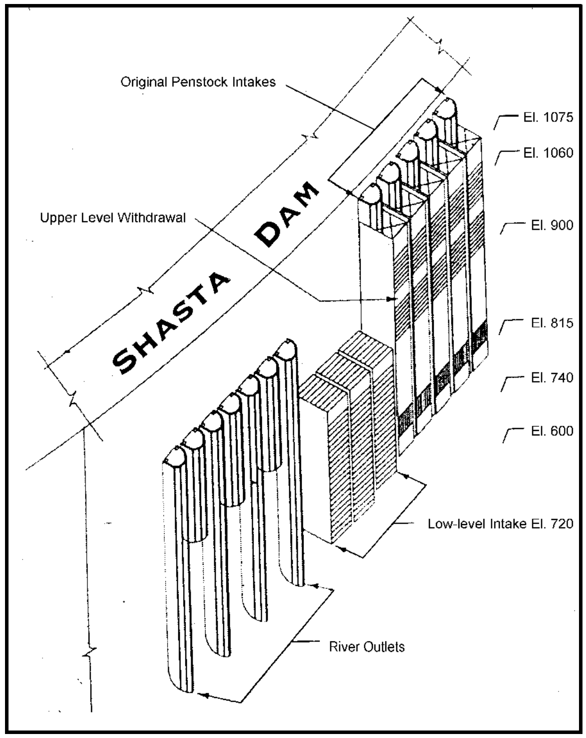

Figure 3.—Schematic of the face of Shasta Dam with the TCD.

The primary purpose of the TCD is to manage the cold water resources by allowing selective withdrawal from four different reservoir elevations. Conservation of the cold water pool is achieved by forcing withdrawal from the highest elevation possible while meeting downstream temperature targets. Normally, the upper gates, followed by the middle shutter gates, then the pressure relief gates, would be operated to maintain the highest permissible level of withdrawal based on the reservoir water surface elevation, gate submergence criteria, and downstream water quality objectives. When downstream water temperature targets can no longer be met by accessing water through the pressure relief gates, the low-level side gates are opened. This inverted siphon delivers the cold water to the left side of the shutter structure, and the gated shutter structure acts as a conduit channeling the cold water to all five penstock intakes while excluding withdrawal from other levels in the reservoir. The sizing of the shutter structure, low-level intake structure, and gated opening between them was established based on predicted head losses and magnitude of water hammer surge pressures expected during operation.

Extensive demolition of existing dam components was required to attach the TCD to the dam and provide construction access. At the dam crest, an outlet gate storage structure and several hundred feet of cantilevered sidewalk were removed. Excavation of the upstream dam face and roadway pockets was also required for attachment of the rigid frames above the shutters and low-level intakes. Additional demolition required by the contractor’s installation method was submitted and approved during construction.

Shasta Dam is a popular tourist attraction in northern California. Consequently, the esthetics of the TCD influenced several design decisions. To reduce the TCD's impacts from downstream vantage points, all features of the TCD were kept below the elevation of the roadway guardrail on top of the dam (elevation 1081.8). This requirement was a major factor in establishing the hoist platform at elevation 1071.9. The main areas addressed to improve the TCD's esthetics from reservoir vantage points were simplicity, repetition of elements, and color. Cladding panel lines were oriented vertically to correspond with the vertical features of the dam. Barrier panels, which are similar in appearance to the trashracks, are installed between the upper and middle gated openings to show a similar profile from the top of the structure down to elevation 900.00. The TCD was also painted gray to allow it to blend in with the face of the dam.

TCD Construction Summary

In November 1994, the TCD construction contract was awarded to Fletcher General Construction of Seattle, Washington. Construction began in January 1995 and was accomplished using a "stick built" erection sequence from the top of the dam. The structural steel and associated hoists were fabricated by Oregon Iron Works and other subcontractors in the greater Portland area. Before the TCD could be lowered into the lake and attached to the upstream face of the dam, anchor bolt holes were drilled and bolts and connecting plates installed. As sections of the TCD were completed, the device was lowered into the reservoir and attached to the dam by Oceaneering International's underwater "saturation" dive team. The "saturation diving" used 4 divers working with a 29-person support crew. The crew worked two 12-hour shifts, 7 days per week, with each diver working 4 hours outside the diving bell, then switching and spending 4 hours inside the bell; after 8 hours, the bell would be recovered and 2 new divers deployed. Using a specially designed remote drilling trolley, the divers drilled holes and installed anchor bolts to secure the TCD in place.

The TCD consists of 9,000 tons of structural steel and metal work. It is supported vertically by steel frames anchored near the top of Shasta Dam with more than 325 concrete anchor bolts. The TCD and low-level intake structure were attached to the dam's upstream face by approximately 136 dam connections, each consisting of two to six grouted anchor bolts, a dam connection plate, and connecting hardware designed to resist structural movement in the upstream, downstream, and cross stream directions. All gravity loads are supported by rigid frames located above each shutter unit. TCD construction was completed on February 7, 1997. Congress appropriated $25,037,000 for the Shasta TCD. The total cost of the TCD was estimated to be $80,000,000.

1996-98 Shasta Reservoir Operations

Reservoir operations for 1996-98 were used to compare pre- and post-TCD operations, respectively. The reservoir filled to elevation 1066 on May 28, 1996, an above normal water year. December 1996 and January 1997 were extremely wet months, and the floodflows brought large volumes of cold water into Shasta Lake. In fact, the large inflow and flood control releases in January 1997 represent nearly one-half of Shasta Lake’s storage capacity of 4.5 million acre-feet (555,000 hectare-meters). Since Shasta is used for flood control, the majority of the January 1997 flood inflows were released to maintain storage capacity for spring runoff. However, spring runoff flows were below normal, and the reservoir elevation topped out at elevation 1045 on May 9, 1997. As a result, 1997 was a below normal water year, and the reservoir was drawn down 73 feet (22.2 meters) to meet contractual deliveries. 1998 was a wet year and was similar to 1996. Figure 4 shows the average monthly releases from Shasta Dam for 1996-98 and where water was released (power intakes or outlet works).

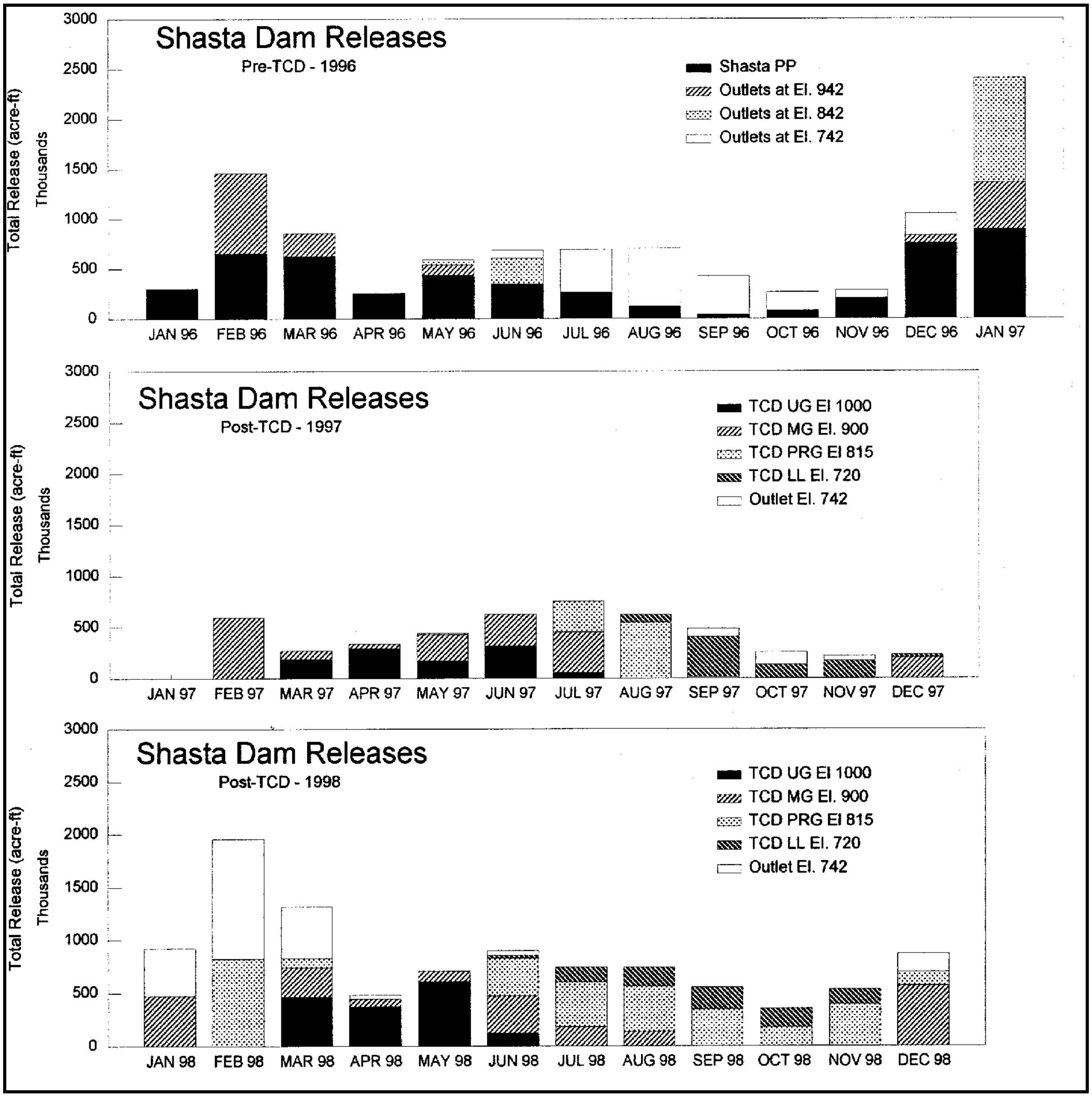

Figure 4.—Shasta Dam releases for the years 1996-98 (1996 is for pre-TCD releases, whereas 1997 and 1998 show the post-TCD releases).

In 1996, temperature control bypass operations began in May and continued through November (see figure 4). The plot of 1997 (figure 4,middle plot) releases show that low-level bypasses were not needed until September, and, even so, they were only 16 percent of the total release. In contrast, low-level bypass flows in September 1996 were 91 percent of the total release. In terms of lost power generation, 672,000 MWh were lost because of low-level bypasses in 1996. In 1997, 65,800 MWh were lost to low-level bypasses; however, if the TCD had not been operational, an estimated 365,300 MWh would have been lost.

The first year of TCD operations allowed project operators to meet downstream temperature targets for most of the summer with minimal flow bypassing the powerplant. However, in mid-September when the low-level intake gates (elevation 720) were opened, the TCD did not perform as expected. It was hoped that low-level bypasses would not be necessary, but a temperature monitoring system inside the TCD identified warm water leakage around the middle gates, which significantly impacted the performance of the TCD's low-level intake structure. The leakage areas were confirmed using a remotely operated submersible video camera system. Seals were designed to fill the gap around the middle gates. The installation of the middle gate seals was completed in January 1998.

In 1998, low-level bypasses were not needed to meet the downstream temperature objectives (figure 4, bottom plot). Because of El Ninõ related weather disturbances, spring runoff was delayed, making 1998 rather unique. As a result, tributaries downstream of Keswick Dam were flowing higher and warmer than normal. Consequently, cooler water had to be released from Shasta Dam earlier than normal in order to meet the temperature targets downstream near Red Bluff Diversion Dam. Even with the early releases of cool water, project operators were able to meet water deliveries and temperatures throughout 1998 without using the low-level outlets. The only time the low-level outlets were used for temperature control operations was during a 1-day test in mid-July.

Figure 5 presents a summary of temperature gain (or loss, degrees Fahrenheit) of Shasta TCD release temperatures. The temperature gains were determined by comparing actual TCD release temperatures with those computed using a numerical model developed to determine pre-TCD release temperature for the same reservoir conditions. This figure clearly illustrates how warmer water is released in the spring and early summer. It also shows how there is little temperature gain when releases are primarily through the pressure relief gates (elevation 815), since this is the same condition as pre-TCD power withdrawals. In the late summer, when the low-level intake is opened, the release temperatures are a couple of degrees colder.

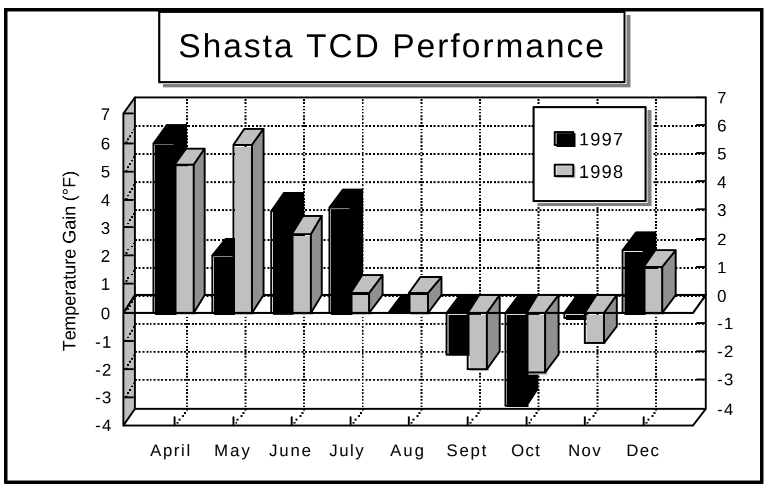

Figure 5.—Summary of temperature gain or loss in degrees Fahrenheit of Shasta release temperatures. The temperature gains were determined by comparing actual release temperatures with those computed using a numerical model developed to determine pre-TCD release temperature for the same reservoir conditions.

Figure 6 contains three plots which show how Shasta Lake progressively warms throughout the calendar year. These temperature profiles were collected monthly by Reclamation as part of the pool is rapidly depleted with pre-TCD operations. In contrast, during 1997 and 1998,

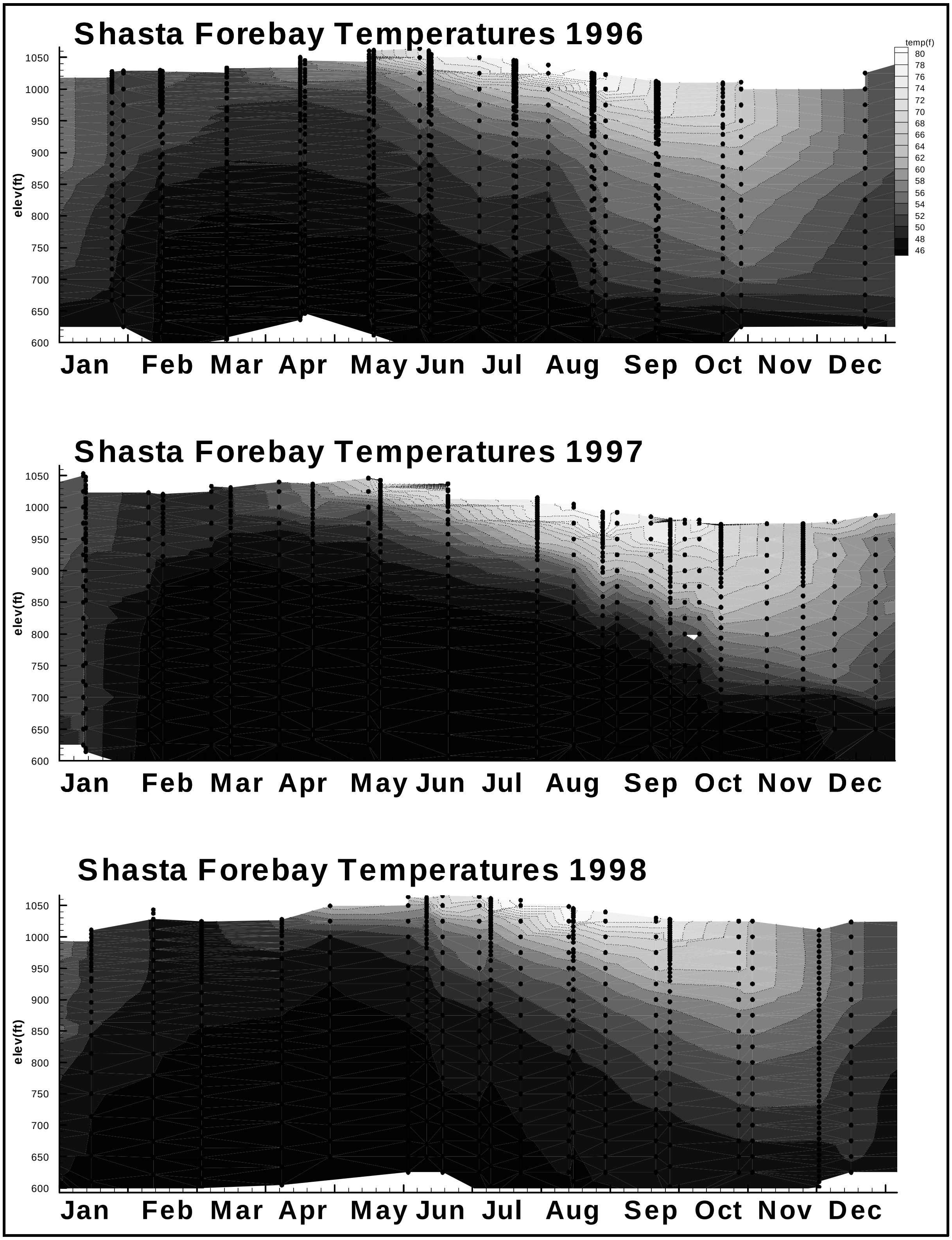

Figure 6.—A comparison of Shasta Dam forebay isotherms for pre-TCD (1996) and post-TCD (1997 and 1998) reservoir operations.

the cold water pool is gradually lowered as the TCD operations move from surface to mid-level and finally low-level withdrawals. The flexibility in what elevation (or depth) we remove water from Shasta Lake allows Central Valley Project operators to maximize power generation and meet Sacramento River water temperature criteria without having to release water through the low-level bypasses.

Conclusions

- During its first 2 years of operation, the Shasta TCD allowed CVP operators to meet downstream river temperature targets while minimizing low-level bypasses and maximizing power generation. Reduced bypasses allowed project operators to generate an additional 300,000 MWh of hydropower.

- Leakage around the middle gates warmed the TCD's low-level withdrawals to the point that low-level bypasses were necessary in September, October, and November. Installation of middle gate seals in January 1998 should improve future TCD performance during low-level releases.

- TCD operations increased the strength of the Shasta Lake's thermocline but did not appreciably increase surface water temperatures. In addition, TCD operations did not significantly delay the onset of reservoir stratification.

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Author

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OUTLET REPAIRS USING CURED-IN-PLACE PIPE

by Thomas E. Hepler, Member, ASCE[1]

Willow Creek Dam is located on Willow Creek near its confluence with the Sun River in western Montana. The 26 m (84 foot) high earthfill embankment impounds a reservoir of 40,000,000 m^3 (32,300 acre-feet), used primarily for irrigation purposes. The outlet works consists of a 1.4 m (54-inch) diameter concrete-lined tunnel through the right abutment, with guard and regulating gates provided within a gate shaft upstream of the dam axis. The dam and outlet works were originally constructed between 1907 and 1911 and were modified in 1917 and 1941. A grass-lined spillway is provided through a dike located 910 m (3,000 feet) northeast of the dam. The dam is owned by the Bureau of Reclamation and operated by the Greenfields Irrigation District.

A large sinkhole was discovered on the crest of the dam by a local fisherman in June 1996. The sinkhole was located directly above the outlet works tunnel, about 15 m (50 feet) downstream from the gate shaft and near the dam axis. It measured approximately 0.9 by 1.8 m (3 by 6 feet) at the crest, widening to approximately 4.0 by 5.5 m (13 by 18 feet) at a depth of 4.6 m (15 feet) within the compacted glacial till embankment materials. Earth materials were found to be piping periodically from a 0.025 m (1 inch) weep hole in the tunnel sidewall. Four weep holes in the tunnel lining were sealed, and the sinkhole was temporarily stabilized by backfilling with sand and gravel materials. Outlet releases of 8.5 m^3/s (300 ft^3/s) were then initiated to lower the reservoir below the embankment-bedrock contact at an average rate of about 0.15 m (0.5 feet) per day, for a total drawdown of 8.2 m (27 feet).

Emergency funding was approved for design and construction of permanent repairs at Willow Creek Dam under Reclamation's Safety of Dams program. Cooperative agreements were reached with the Greenfields and Fort Shaw Irrigation Districts to supply construction equipment and manpower, and repayment contracts provided for reimbursement of 15 percent of the total costs as required by law. Excavation of the embankment revealed the sinkhole extended through 12 m (40 feet) of bedrock to a large cavity surrounding the concrete tunnel lining. Exploratory drilling indicated the bedrock cavity was up to 27 m (90 feet) long, 9 m (30 feet) wide, and 6 m (20 feet) high, and partially filled with collapsed glacial till and bedrock fragments. Bedrock units of siltstone, sandstone, and shale were found to be moderately weathered to decomposed, soft to hard, and moderately to intensely fractured and jointed. Foundation treatment included the placement of 286 m^3 (374 yd^3) of 1:1 tremie grout to fill the voids around the tunnel below elevation 1246 m (4087 feet), followed by the placement of 110 m^3 (144 yd^3) of backfill concrete to the excavated bedrock surface at elevation 1253 m (4110 feet). The embankment was restored by the placement of a 0.6 m

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(2 foot) thick filter blanket on the excavated foundation, followed by the placement of approximately 15,000 m^3 (20,000 yd^3) of compacted glacial till materials to dam crest elevation 1266 m (4154 feet), and replacement of the slope protection on the downstream face. The final embankment repairs were completed within two months, just prior to winter shutdown.

Outlet Works Damage and Repairs

The outlet works tunnel was originally excavated in 1907 by hand-drilling and blasting, with considerable water and soft materials encountered. Heavy timber beams and posts with timber lagging were used to support the tunnel excavation throughout its length, resulting in a square excavated opening for the circular tunnel lining. Although it is unclear how the concrete tunnel lining was actually constructed, the specifications called for a uniform concrete thickness of 0.20 m (8 inches), without reinforcing bars, and the placement of “puddled fill” outside the tunnel lining to the excavated surface. Such construction could have resulted in a significant quantity of fine-grained backfill material along the outlet works tunnel.

The downstream tunnel lining was severely damaged in 1958 when maximum outlet releases of 15.6 m^3/s (550 ft^3/s) were reported. Approximately 21 m (70 feet) of unreinforced concrete in the tunnel invert was removed by the flow, beginning 3 m (10 feet) downstream from the regulating gate, and the foundation rock was eroded to a depth of 0.9 m (3 feet). A 3 to 5 m (10 to 15 foot) long section of the tunnel crown was also removed, revealing a large void surrounding the tunnel. The structural damage is believed to have been initiated by negative pressures resulting from an insufficient air supply to the downstream tunnel during maximum releases due to an undersized, 0.15 m (6 inch) diameter air vent pipe. Repairs included replacement of the missing concrete invert and crown, and placement of rubble fill outside the tunnel lining. A 0.3 m (12 inch) diameter hole was drilled from the dam crest to facilitate completion of the tunnel crown and was then backfilled with earth materials. Weep holes were later drilled in the tunnel lining for pressure relief.

The development of the large tunnel cavity was probably a combination of overexcavation during construction, gradual erosion of the puddled fill and soft bedrock materials, and collapse of the harder bedrock materials into the tunnel following the lining failure. The sinkhole may have developed gradually by internal erosion of glacial till embankment materials through open joints and fractures in the bedrock, progressive collapse or "stoping" of the bedrock into the void below, and piping of earth materials through open cracks and weep holes in the tunnel lining. The 0.3 m (12 inch) diameter hole drilled from the dam crest in 1958 is believed to have been located within 6 m (20 feet) of the gate shaft and may not have contributed to the sinkhole development.

A new 0.25 m (10 inch) diameter air vent pipe was provided for the outlet works in May 1997 under a purchase order with Jensen Drilling Company of Eugene, Oregon. The new pipe was installed from the dam crest in a vertical drill hole, located just outside the gate house to intersect the crown of the tunnel about 2 m (7 feet) downstream from the regulating gate, and was grouted in place. The new air vent pipe provides 2.8 times the cross-sectional area of the original 0.15 m (6 inch) diameter air vent pipe in the gate shaft to better meet the air demand of the regulating gate under reservoir heads up to 20 m (65 feet). The upstream guard gate was refurbished under a contract with Marathon Construction Company of San Diego, California, including the replacement of the bent and corroded gate stem and stem guides. A trashrack was provided for the outlet works intake under the gate repair contract to provide protection from debris-laden flows.

Tunnel Lining Options

Continued concern for the long-term stability and structural integrity of the downstream tunnel lining, and the potential for renewed piping of earth materials through open cracks and joints (despite grouting efforts), resulted in the consideration of potential tunnel lining options. The downstream tunnel extends 130 m (429 feet) from the regulating gate to the downstream portal where outlet releases enter a diffusion-type stilling basin. A structural lining was required for the first 30 m (100 feet) of tunnel, which seemed to be the most susceptible to future problems, since it included the portion damaged in 1958, the sinkhole location, a significant longitudinal crack along the crown, continuing seepage from various other open cracks and joints, and was located directly below the wide dam embankment crest.

The configuration of the stilling basin at the downstream portal, and grade changes within the tunnel (including one of over 3 degrees), made the proposed installation of a rigid structural lining more difficult. Preliminary designs for a steel tunnel lining resulted in the requirement for excavation of concrete and backfill at the downstream portal to provide a flat staging area, and the installation of twenty 1.1 m (45 inch) diameter steel sections only 1.5 m (5 feet) long, to negotiate the tunnel's vertical alignment. Each steel section would have to be pulled into place, with the joints fully welded from within the 1.1 m (45 inch) circular opening, followed by pressure grouting of the annular space between the steel lining and the concrete surface, and the application of a suitable epoxy coating on all exposed surfaces for corrosion protection. The stilling basin would have to be restored to its original configuration, requiring a concrete placement before being placed back into service. The 31 percent reduction in cross-sectional area would reduce the maximum release capacity and potentially impact future maintenance access for both the steel lining and the regulating gate.

The search for alternatives to rigid linings focused on cured-in-place pipe (CIPP) systems originally introduced in the United States by Insituform Technologies in 1977. A CIPP lining consists of a flexible, resin-impregnated, needled polyester felt tube which is expanded under hydrostatic head and cured by the circulation of heated water. ASTM F1216 covers installation of CIPP by the inversion method, for which the entire resin tube is turned inside-out under an hydrostatic head while advancing along the tunnel or pipe being lined, and then is subjected to water temperatures up to 82 ^{o}C (180 ^{o}F) to cure the resin (ASTM, 1993). Construction access through the outlet works gate shaft, for installation of a CIPP lining from the upstream end of the tunnel, would have been severely affected by the gate house and existing mechanical equipment, including the gate operator and stem, air vent pipe, ladders, and landings. Installation of a CIPP lining by the inversion method from the downstream portal would have resulted in the exposure of the entire unreinforced concrete lining to high water temperatures and the requirement of an additional 100 m (329 feet) of waste tube material. A finite element analysis of potential thermal stresses within the 0.20 m (8 inch) concrete lining, using the ABAQUS computer program, predicted large tensile stresses sufficient to produce extensive cracking, which was unacceptable. Use of an alternative low-temperature resin, with a curing temperature of only 27 °C (80 °F), would avoid thermal stresses and produce acceptable results but would require special handling and a longer curing period. Installation of the CIPP lining by the pulled-in-place method, in accordance with the newly developed ASTM F1743 standard, seemed to best suit our application.

Final CIPP Lining Design and Installation

Design specifications for a partial tunnel lining using CIPP were prepared by Reclamation and issued in May 1997. A construction contract was awarded to the low bidder, Western Slope Utilities, Inc. (WSU) of Breckenridge, Colorado, in July 1997. An InLinerUSA licensee, WSU was experienced in the pulled-in-place installation method for linings up to 0.9 m (36 inches) in diameter and obtained the services of an InLinerUSA representative with the required experience for larger diameter linings. The pulled-in-place method utilizes a thin, impermeable felt calibration hose for inflation of the resin lining (ASTM, 1997). Figure 1 shows how the resin-impregnated tube is pulled into place using a winch and cable. Figure 2 shows inflation of the tube inside the old pipe by inversion of a calibration hose under hydrostatic head. The specified contract completion period was 60 days.

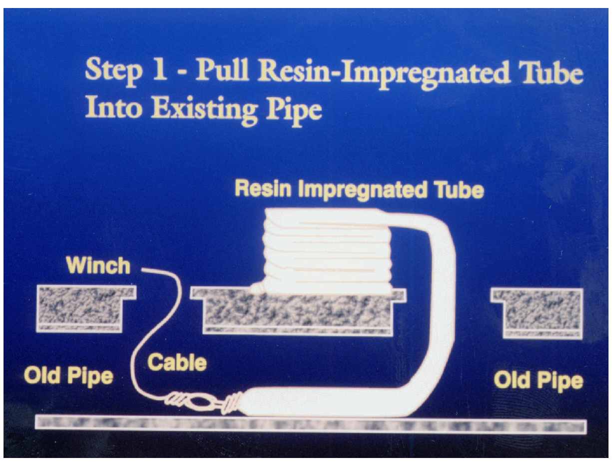

Figure 1

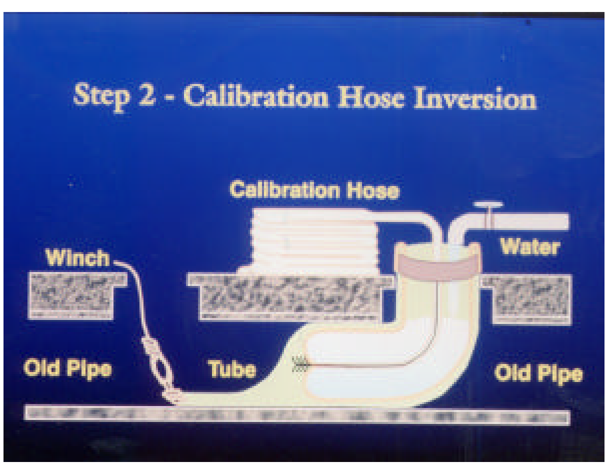

Figure 2

For design purposes, the existing tunnel was assumed to be in a "fully deteriorated" condition (due to the longitudinal crack in the crown) and subject to internal pressure under maximum discharge conditions. Design loads included a 3 m (10 foot) external fill height on the tunnel crown, a 3 m (10 foot) external hydrostatic head on the tunnel invert, and a maximum internal pressure of 0.14 MPa (20 lb/in^2). The CIPP was designed to carry the external loads with no contributing support from the circular tunnel lining, using ASTM Equation X1.3 (ASTM, 1993), with a factor of safety of 2.0. An ovality reduction factor, based on the average minimum and maximum diameters of the tunnel lining, was included to properly estimate the stiffness of the elliptically-deflected pipe. For internal loads, the CIPP was designed as a thin-walled cylinder with uniform pipe wall stresses, using a hoop stress equation for plastic pipe.

An epoxy vinyl ester resin was selected over a polyester resin for greater strength and longevity. Design properties for the resin included an initial flexural modulus of 2,070 MPa (300,000 lb/in^2) and an initial flexural strength of 34.5 MPa (5,000 lb/in^2) for external loads, and an initial tensile strength of 20.7 MPa (3,000 lb/in^2) for internal loads. To characterize the long-term performance of the CIPP over the minimum 50-year design life, a 33 percent creep reduction was assumed for the flexural modulus and flexural strength, and a 50 percent hydrostatic stress regression was assumed for the tensile strength. The final design thickness for the CIPP was 27 mm (1.06 inches), including an additional 5 percent thickness to provide sufficient resin to fill the interior felt of the calibration hose, which was to remain in place.

The contractor began mobilizing equipment at the dam on August 8, 1997. A steel platform was installed 3.7 m (12 feet) above the bottom of the regulating gate shaft, and a steel elbow section was centered within the upstream end of the tunnel to support a short flexible hose for a water column. One end of a 34 m (110 foot) long calibration hose, consisting of a single layer of felt fabric with a watertight polyurethane coating, was carefully lowered down the shaft and through the flexible hose and elbow where it was turned inside-out and securely fastened to the outside of the elbow. A winch and roller were set up at the gate house doorway, and a second roller was positioned at the bottom of the shaft. The tunnel surfaces were swept clean, and utility lines (for lighting, ventilation, and water circulation) were established within the shaft.

The resin-filled tube was delivered to the site on August 11 in a refrigerated truck. The nonwoven fabric tube was manufactured in Houston, Texas, at InLinerUSA headquarters, and the resin was added in Alma, Colorado, at a “wet-out” plant used by WSU. Total weight of the liner was 4,500 kg (10,000 pounds). The liner was removed from the refrigerated truck using a truck-mounted winch and was carefully fed into the tunnel at the downstream portal and slowly pulled upstream (see figure 3). The liner was pulled into final position in the tunnel within about 1.5 hours and was securely fastened to the steel elbow, outside the calibration hose. Reservoir water from the upstream gate shaft was pumped into the water column to begin inversion of the calibration hose under a 0.3 m (1 foot) head. Within 20 minutes, the calibration hose had been turned inside-out and extended the full length of the liner, pressing the liner tightly against the tunnel surface. Two perforated water supply hoses inside the calibration hose were used to circulate heated water from a heat exchanger truck under the full 3.7 m (12 foot) head.

Return water temperatures at the truck reached 57 °C (135 °F) in 2 hours and were held constant for 4 hours and then were raised to 79 °C (175 °F) within 1 hour and were held

Figure 3

constant for 6 hours for curing the resin. After curing was completed, the circulating water was gradually cooled to 38 °C (100 °F) in 4 hours, finishing by noon on August 12. Epoxy vinyl ester resin contains styrene, a possible carcinogen, which is released during the curing process. Styrene vapors are heavier than air and potentially flammable and explosive. Installers and inspectors must follow OSHA regulations pertaining to workers in hazardous and confined spaces. Fresh air had to be introduced into the tunnel before the contractor could cut a small hole in the end of the hardened liner to release the water. The waste water was fully contained within the downstream stilling basin to permit final cooling to 21 °C (70 °F), removal of resin residue from the water surface, and dissipation of dissolved styrene.

Both ends of the liner were trimmed using chain saws and circular saws, and a 0.013 m (0.5 inch) deep groove was provided around the periphery to accommodate installation of end seals. Amex 10/WEKO seals were used, each consisting of a 0.37 m (14.5 inch) wide rubber seal with three stainless steel bands spread by a hydraulic expanding device to ensure a tight fit. The work was completed on August 15, one week after site mobilization, for a total cost of about $145,000. Subsequent laboratory tests on field samples confirmed the design parameters for tensile and flexural properties. Figure 4 shows the finished lining surface and intersection with the 0.25 m (10 inch) diameter air vent pipe at the tunnel crown. Minor wrinkles in the lining resulted from variations in the tunnel dimensions.

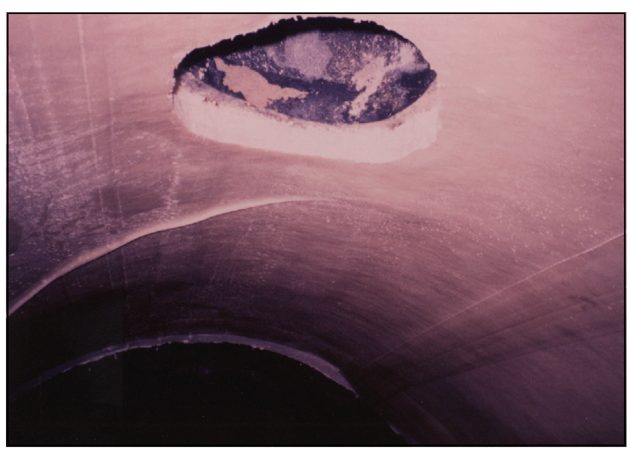

Figure 4

Performance

The upstream WEKO end seal failed during initial operation of the outlet works in May 1998, with flows ranging between 80 and

Figure 5

380 ft^3/s over a two week period. Two of the stainless steel bands had been swept downstream and were found to have buckled under an external pressure well in excess of the design head. The excessive pressure apparently resulted from leakage from the adjoining concrete regulating gate wet-well shaft under a reservoir head of about 65 feet. The remaining band and damaged rubber seal were removed and the grooved end of the CIPP lining was squared off using a radial saw. A stainless steel bellmouth transition was fabricated in a local machine shop and bolted in place in July 1998 (see figure 5). A narrow gap was left between the transition and the CIPP lining for pressure relief. The finished lining seems to be performing well. The concrete gate shaft surfaces will be inspected and repaired to prevent future leakage.

Conclusion

The completed CIPP installation at Willow Creek Dam provides a con-tinuous, watertight structural lining within the most heavily-loaded and damaged portion of the outlet works tunnel beneath the dam to prevent possible future tunnel collapse and/or piping of earth materials through open cracks and joints. A partial tunnel lining was specified to minimize costs while meeting project requirements and was successfully installed using the ASTM pulled-in-place method. The entire process, from site mobilization to installation of the end seals, took only one week to complete and cost about $145,000 for the 30 m (100 foot) length. Although CIPP technology has been available in the United States for over 20 years, this was the first use of CIPP by Reclamation for repair of an outlet works. Installation of CIPP linings within partially or fully deteriorated outlet tunnels or conduits up to 2.4 m (96 inches) in diameter may prove to be a viable alternative to more conventional rigid lining options considered at other dams.

References

"Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube," ASTM Standard F1216-93, August 1993.

"Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe," ASTM Standard F1743-96, May 1997.

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