MOCCASIN THIRD PENSTOCK ADDITION: INCREASING POWER BY REDUCING HEADLOSSES

By Matthew Gass, Hetch Hetchy Water and Power, Moccasin, California, USA; Mark A. Hammer and David P. Thompson, Harza Engineering Company, Bellevue, Washington, USA; and Wade P. Moore, Harza Engineering Company, Chicago, Illinois, USA

ABSTRACT

The Moccasin Hydroelectric Project (Project) is a major part of the City and County of San Francisco's Hetch Hetchy Water and Power system. The system diverts water from the Tuolumne River, high in the Sierra Mountains of northern California, and conveys it to the City and County of San Francisco (City) and surrounding area. The Hetch Hetchy system was planned in the 1910s and constructed in the 1920s. The Moccasin Project is a critical element of the City's water delivery system. Since the project was commissioned, two penstocks have conveyed water to the Project's powerhouse. Replacement of the original generating units and increased demand for peak power has resulted in relatively large headloss in the tunnel and penstock system at Moccasin. A third penstock has been designed to increase the flow area, reduce water velocities and headloss, and increase energy production.

Introduction

The Moccasin Project consists of an equalizing reservoir, power tunnel, surge shaft, trifurcation downstream of the surge shaft, valve house, exposed steel penstocks, and powerhouse. As originally constructed, only two of the three branches of the trifurcation were connected to penstocks that led to the old Moccasin powerhouse 5,350 feet downstream. These two penstocks then bifurcated into four penstocks downstream of the valve house, which conveyed water directly to four Pelton turbines. The elevation drop of the penstocks is approximately 1,190 feet from the trifurcation to the powerhouse. In the late 1960s, the original powerhouse was abandoned and a new powerhouse with two 57.5 MW Pelton turbines was constructed. At that time, the four lower penstock pipes were joined back together a few hundred feet upstream of the new powerhouse and converged into two new welded steel penstocks, installed to convey water to the new powerhouse.

Increased flows and demands for water delivery have resulted in relatively large headlosses in the tunnel and penstock system. Demands on the system have also focused attention on operating flexibility because the two-penstock system can only be taken out of service for short periods. To address these problems, engineers developed a design to add a third penstock to the existing system by taking advantage of the unused third leg of the trifurcation. The third penstock will run parallel to the existing penstocks and will be connected to one of the existing lower penstocks upstream of the powerhouse. This penstock addition was designed to be implemented with minimal interruption in water delivery and will reduce headloss by 42%, resulting in a 5% increase in power output at maximum turbine flows.

Project Hydraulics

From the Priest Regulating Reservoir to the Moccasin powerhouse, the existing Project water delivery system consists of four distinct sections totaling approximately 11,000 linear feet of conveyance conduit as follows:

Section 1: 5,955 ft of tunnel and buried pipe

Section 2: 1,520 ft of two above-ground, riveted steel pipes

Section 3: 2,451 ft of four above-ground, riveted and forge welded steel pipes

Section 4: 1,021 ft of two above-ground and buried, welded steel pipes

When operating both generating units at full load, the hydraulic capacity of the system is 1,340 cfs, which results in a headloss of about 130 feet, or 10% of the total 1,305 feet of gross head at the plant. The design team constructed a hydraulic computer model of the existing Moccasin penstock system to analyze headlosses in the various system components and to estimate headlosses in a modified system. The computer program KYPIPE[1] was used for the analysis. Figure 1 shows a schematic of the model of the existing water conveyance system.

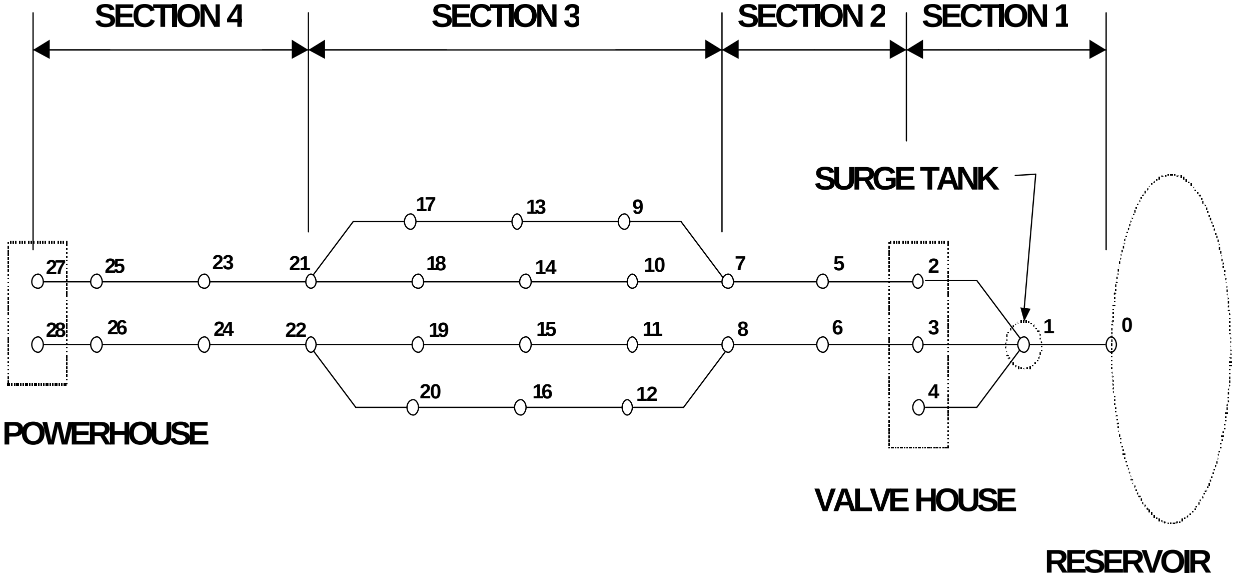

Figure 1 – Existing Conveyance System Schematic

The model used the Darcy-Weisbach formula to compute the headloss from calculated penstock/tunnel friction. Table 1 gives a range of roughness values (10^{-3} ft) for each type of penstock/tunnel material initially included in the model.

Table 1 – Range of Pipe Roughness Values

	Condition of Lining		
Pipeline Material	**New**	**Rough**	**Poor**
Concrete	0.2	2.0	10.0
Welded Steel	0.1	2.0	8.0
Fully Riveted	2.0	10.0	30.0

The model was calibrated using pressure data measured at several locations along the pipeline. The roughness values for each of the pipe materials were adjusted to match the measured data. Based on this calibration process, the team selected the following roughness values for the model:

Concrete Tunnel	24.0
Welded Steel	3.0
Riveted	12.0

The high roughness value for the concrete-lined tunnel section indicates severe deterioration of the lining and/or significant losses both at the intake and through the surge chamber. Figure 2 shows a plot of the energy and hydraulic gradelines along the existing penstock system at a maximum plant flow rate of 1,340 cfs.

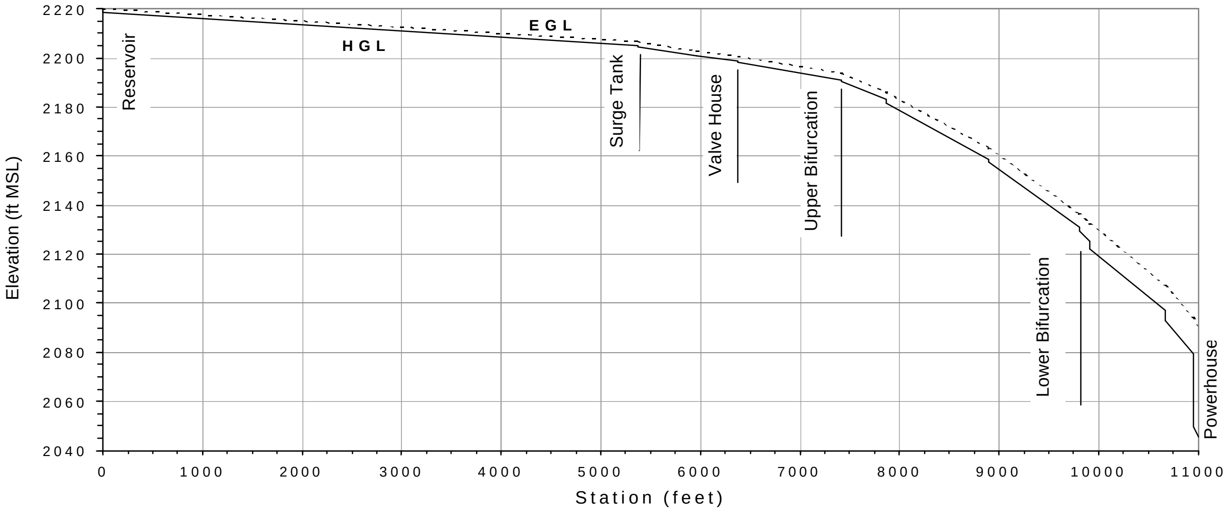

Figure 2 – Hydraulic and Energy Gradelines of the Existing Penstock System

Based on the hydraulic model study, the distribution of the total headloss in the existing conveyance system at maximum flow is as follows:

Section 1: Reservoir-to-Valve House	19.4 feet
Sections 2 and 3: Valve House-to-Lower Bifurcation	68.2 feet
Section 4: Lower Bifurcation-to-Powerhouse	42.3 feet
Total	129.9 feet

At full load (1,340 cfs), losses in the existing tunnel/buried pipe system (Section 1) plus the newer, partially buried penstock (Section 4) under the switchyard and at the powerhouse total 61.7 feet. The losses in these sections of the penstock system are essentially fixed, unless expensive modifications to those conveyance elements are undertaken. The only modification to the conveyance system considered economically feasible is to add a new, third penstock paralleling the existing penstocks from the valve house to the lower bifurcation, a distance of about 3,820 feet.

Penstock Configuration Alternatives

In order to reduce the headlosses in the existing sections of penstock (Sections 2 and 3), the engineering team modeled three alternative configurations. The first configuration involved simply interconnecting the two penstock systems. The other two configurations involved adding a new, third penstock paralleling the existing penstock system. The different penstock configurations are described below.

Configuration 1

Configuration 1 is based on a simple modification to reduce headloss by interconnecting the two parallel penstock systems. In this case, flows for single-unit operation would be spread across both penstocks, as the interconnection would allow flow cross-over. The connection between the systems would be made just downstream of the lower bifurcation, between Nodes 21 and 22 in the model (see Figure 1). The connection would include a butterfly valve to isolate the two systems if desired.

With maximum turbine flow to a single unit (670 cfs), headloss would be reduced from 130 feet to 75 feet as indicated in Figure 3 with the label “Existing Combined System to Unit #1 – Configurations 1 & 2.” As flow increases beyond the maximum flow for a single unit, the second unit would come on-line and flows in the penstock system would be shared between both units. As flow approaches the maximum for two units (1,340 cfs), headloss would approach the value present in the existing penstock system (130 ft) and no cross-flow would occur.

This configuration would be relatively inexpensive to implement, but would not reduce headlosses at higher flows.

Configuration 2

Configuration 2 involves the construction of a new penstock parallel to the existing system from the valve house to the lower bifurcation. The existing four parallel penstocks would be connected together and "funneled" into Unit 1. Referring back to Figure 1, Nodes 19 and 20 would be connected to Node 21 instead of Node 22 and Node 4 would connect directly to Node 22. A blind flange would keep the existing and new systems separate. The roughness value selected for the new penstock was the same as that used for the newer, welded steel penstock (Section 4) of the existing system.

As with the previous configuration alternative, the headloss to Unit 1 would be reduced from 130 feet to 75 feet at maximum turbine flow. The headloss to Unit 2 would depend on the size of the new penstock selected, as indicated by the line in Figure 3 labeled "New Penstock to Unit #2 – Configuration 2." A pipe size of about 76 inches would give the same level of performance as the existing system, while a 104-inch diameter penstock would be required to achieve the same headloss reduction to Unit 2 as was attained for Unit 1 by connecting all existing penstocks to it.

Configuration 3

A further refinement of the two previous configurations involves connecting the two parallel systems and constructing a new penstock paralleling the existing penstocks. In lieu of the blind flange installed in Configuration 2, a valve would be installed and flow would be allowed to self-regulate through the system. The headloss to both Unit 1 and Unit 2 are as shown in Figure 3 under the label "Combined System; Existing and New – Configuration 3." This configuration provides added flexibility of operation but requires an additional, costly valve and other components that complicate the alternative.

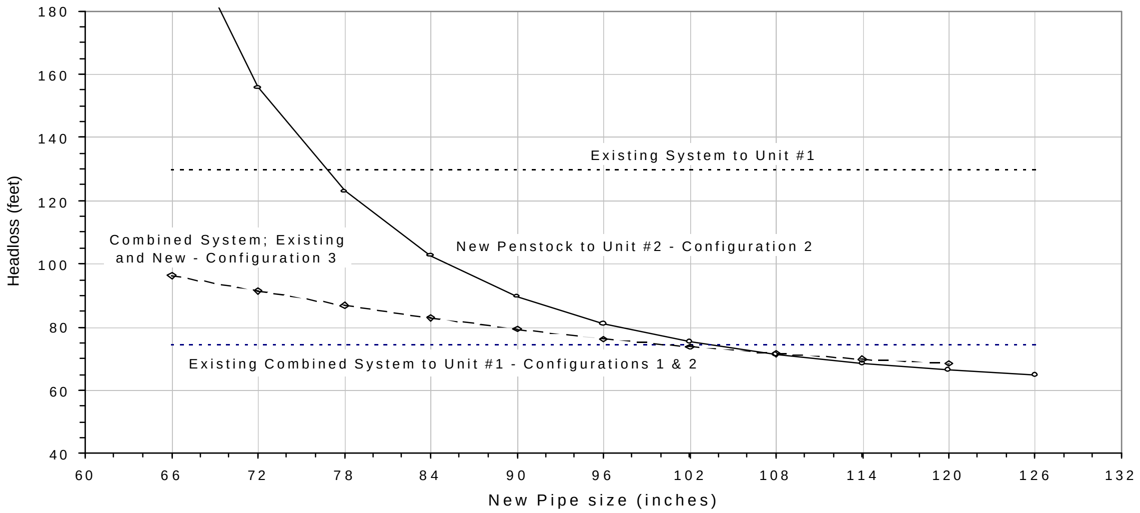

Figure 3 – Headloss versus New Pipe Size with Maximum Unit Flow

Hydraulic Model Results of Penstock Alternatives

Figure 3 shows the model results of the three alternative configurations as described above. The curves show total headloss from the reservoir to the powerhouse versus new pipe size. The headloss for Configurations 2 and 3 approaches 62 feet asymptotically, which is the headloss associated with the elements of the existing system upstream of the valve house (Section 1) and downstream of the lower bifurcations (Section 4). This is the headloss in the portion of the existing system that is not replaced by the new penstock and therefore is the absolute limit of headloss reduction that can be achieved, regardless of the size of the new penstock.

Selection of Penstock Diameter

To maintain simplicity in operation and construction, the City selected Configuration 2 for further study, although the issue of interconnecting the “two” penstock systems was revisited later in the pre-design phase of the work as discussed below and shown in Figure 4. Based on the model results for reducing headlosses, the City and Harza experts conducted power studies and cost estimates for various penstock pipe sizes that could be installed from the valve house, paralleling the existing penstock, to near the lower bifurcations. For each penstock diameter under evaluation, it was assumed that the existing penstock system would be joined together and connected to the existing 72-inch diameter welded steel penstock leading to Unit 1. The new, third penstock would be connected to Unit 2. In addition, the range of potential penstock diameters was selected to match or nearly match the headloss experienced by Unit 1 if all existing penstocks were connected to it.

The pipe sizes selected for study included 90, 102, and 114 inch. After performing a financial analysis[2], the City concluded that a 102-inch penstock would provide the greatest rate of return (7.9%), assuming a 50-year project life and marginal values of power per the 1998 California Energy Commission report[3]. Under 2000/2001 market conditions, the rate of return would be much greater.

Third Penstock Layout and Design

The new penstock will be directly connected to the existing 104-inch butterfly valve at the valve house, and will nearly parallel the existing penstocks. The new pipe will be about 3,820 feet in total length, and will be connected to the existing penstock approximately 80 feet downstream of the existing lower bifurcations.

The penstock will be constructed above ground, using a similar horizontal and vertical alignment as the existing penstock system. A total of 16 anchor blocks will be constructed adjacent to the existing anchor blocks. This design will provide the most consistent visual profile down the hill facing the powerhouse, provide good access along the penstock alignment, and avoid ground-disturbing activities on vegetated ground which has not been disturbed for 75 years. The new penstock will be supported on concrete saddles founded on bedrock.

The penstock pipe was designed in accordance with the guidelines of the American Society of Civil Engineers (ASCE)[4]. The ASCE guidelines define several load cases that need to be examined, including the following applicable cases:

- Static water (ASCE Normal 1)
- Normal operating with normal shutdown of turbines (ASCE Normal 2)
- Normal operating with normal startup of turbines (ASCE Normal 3)
- Static water plus project design basis earthquake (ASCE Intermittent 1)
- Normal operating with normal shutdown of turbines plus project design basis earthquake (ASCE Intermittent 3)
- Normal operating with normal startup of turbines plus project design basis earthquake (ASCE Intermittent 5)
- Construction (ASCE Construction 1)

The design pressure of the penstock varies from 125 psi to 560 psi. The design also included a 10% pressure rise caused by closing of the turbine needle valves. Two penstock diameters were chosen: 104 ¾-inch O.D. at the upper end and 103 ½-inch O.D. at the downstream end. Penstock wall thicknesses vary from 3/8-inch at the top, as governed by minimum handling thickness, to 1 ½-inch at the bottom. Steel conforming to the physical and chemical properties of ASTM A516[5], Grade 60, will be spirally welded for pipe wall thicknesses of ¾-inch and less. Pipe with wall thicknesses of greater than ¾-inch will be conventionally rolled and welded of ASTM A537[6], Class 1 steel. All pipe will be shop pressure tested and either spot or fully radiographed.

The design team decided that the penstock would be joined with mechanical, sleeve-type couplings in lieu of costly field welding. Each penstock section will be supported on saddle-type supports at the upstream and downstream ends. The upstream saddle will be a sliding-type seat and the downstream saddle will have a fixed-type seat.

Lower Penstock Layout and Interconnection

Although the primary purpose of the third penstock is to reduce overall system headlosses, the revised system is also designed to provide operating flexibility during dewatering and servicing of the penstocks by allowing one or both of the existing penstocks to be taken out of service with minimal interruptions in water supply. This was an important consideration because the existing penstocks are original and in need of refurbishment, including recoating of the internal lining.

In developing the options for the lower interconnection, several layouts were considered. In each case, the interconnection alternative was arranged to direct all of the flow in the three penstocks to either unit and also allow one or both of the existing penstocks to be taken out of service while maintaining flow to the generating units. The layouts that were investigated are shown in Figure 4.

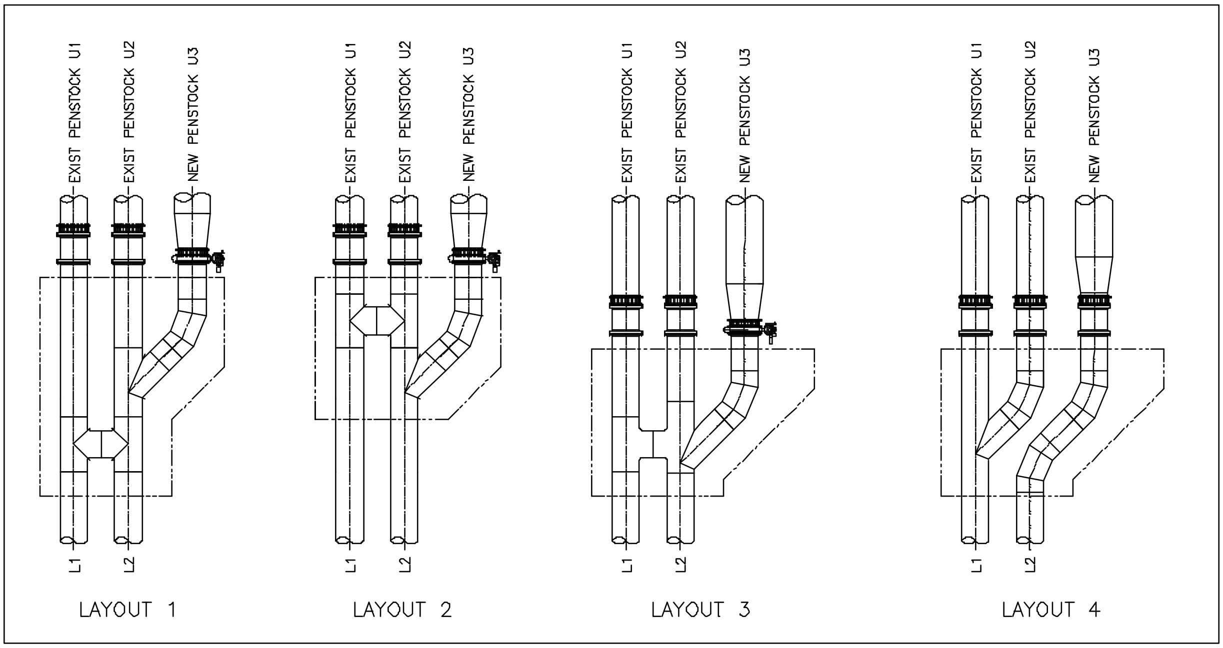

Figure 4 - Lower Interconnection Layouts

Each layout was evaluated based on operational flexibility, hydraulic efficiency, design simplicity, cost, and constructability. The interconnection arrangements differed mainly in the location of the interconnection relative to the point where the third penstock connected to lower Penstock No. 2 (L2). Except for Layout 4, each alternative had a short connection between the two existing penstocks to provide the desired cross-over that would allow both lower penstocks (L1 and L2) to be fed from the third penstock (U3). Because the flow in the short section can be in either direction, there would be no net gain in hydraulic performance from inserting the connection at an angle to the penstocks.

As the evaluation progressed, Layout 4 (Configuration 2 from earlier studies) remained the favored arrangement. Operational flexibility was somewhat compromised, because L1 and L2 could not be fed from U3, but this was not considered a major drawback. The advantages in hydraulics, design simplicity, and constructability made Layout 4 the preferred choice.

From the point of view of phasing the work to interconnect the penstocks, constructability became a key factor in evaluating the preferred layouts. As shown in Figure 5, the first phase of the interconnection could be accomplished without interrupting flow to Unit 1. During this phase of the work, while U3 was being connected to the existing L2, flow would continue in the other half of the penstock system in L1. Conversely, during the second phase of the work, flow to Unit 2 would remain undisturbed while penstocks U1 and U2 are joined to L1, as illustrated in Figure 6.

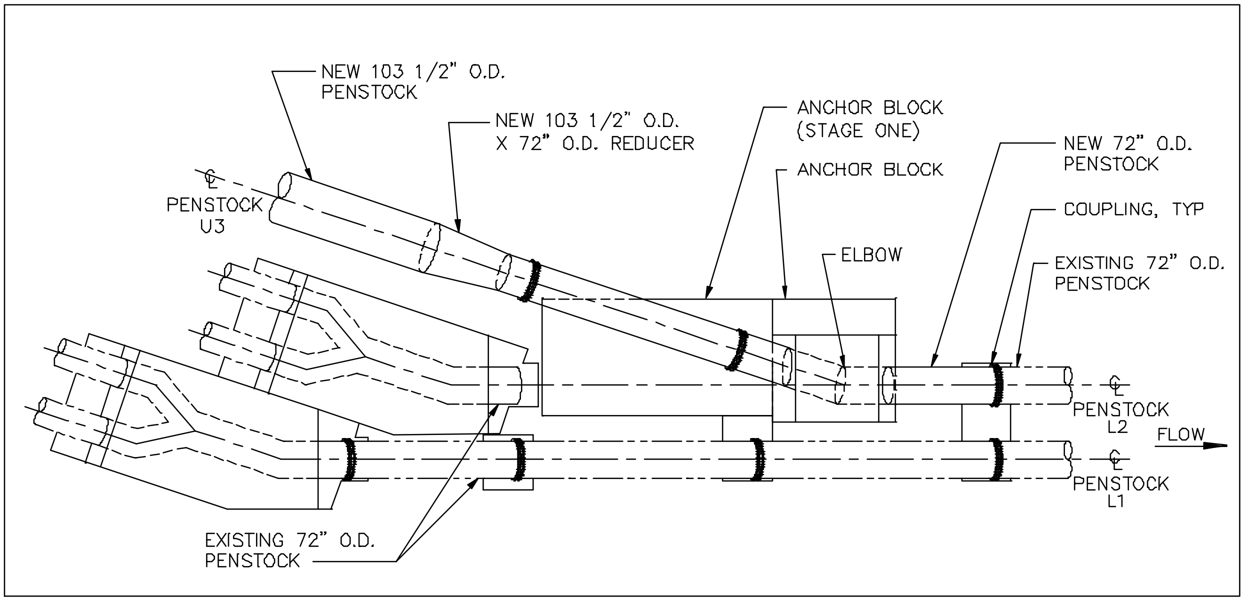

Figure 5 - Phase 1 interconnection of upper and lower penstocks

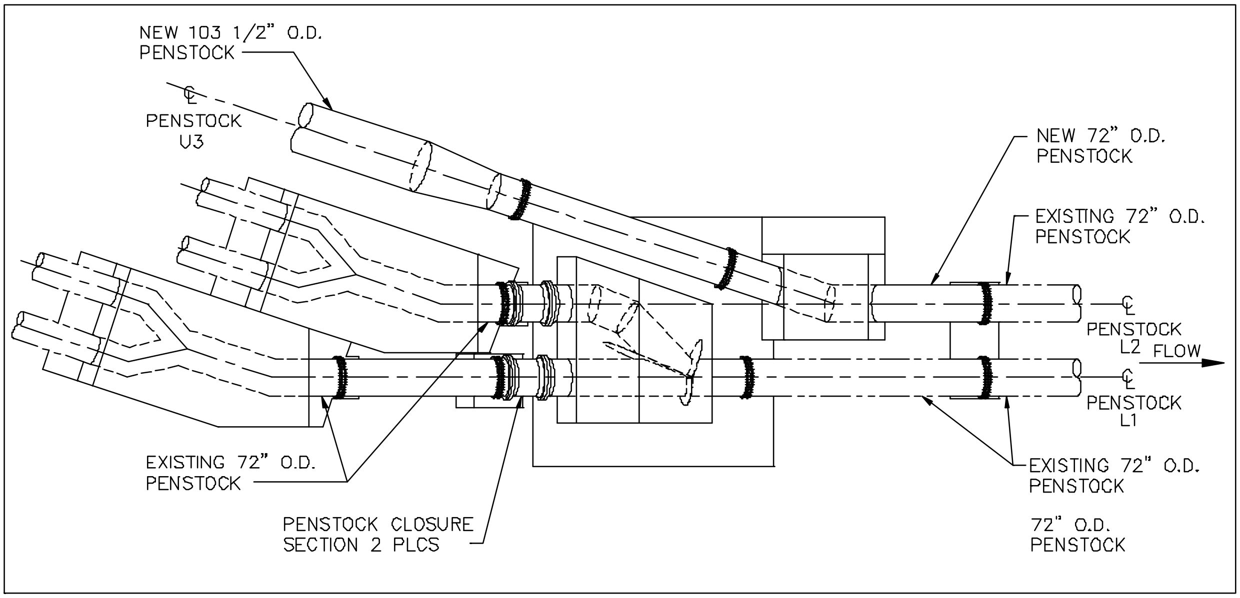

Figure 6 - Phase 2 interconnection of upper and lower penstocks

Lower Penstock Design Issues

In addition to the actual layout of the lower interconnection, two methods for isolating each penstock upstream of the interconnection were investigated. In each case, the alternatives had to accommodate the 560-psi design pressure and the sloping arrangement of the penstocks.

The first method involved installing butterfly isolation valves immediately upstream of the anchor block. The major advantage of using isolation valves is the time, cost savings and general convenience of dewatering the penstocks. The main disadvantage of using the valves is their initial cost and additional headloss.

The second method involved installing removable penstock closure spools in combination with dished heads for isolation. The major advantage of using the spools is the relatively low initial cost. The main disadvantage is the difficulty in removing and reinstalling the spools on a steep incline and longer plant shutdown periods resulting in lost generation. For example, the spools cannot be simply dropped into place during reinstallation, they must be rotated and “shoe horned” into position given the slope of the penstock. Despite these disadvantages, the final design proceeded with removable spool sections after it was determined that penstock isolation for major maintenance would be infrequent and that scheduled dewatering of the penstock could limit the extent of lost generation.

One other design issue worth mentioning is the design of flanged connections at the lower interconnection. Given the relatively high head and large diameter of the connections, standard ASME B16.47[7] and B16.5[8] or AWWA C504[9] flanges could not be used. In addition, there were concerns about how to provide an effective seal at the flanged connections to obtain a leak-free installation.

The design of the custom flanges was done in accordance with ASME requirements. The flange seal design, however, progressed at a much slower pace because of the lack of design data and standards. O-rings were the preferred method of sealing the flanges but little design data could be found to guide the sizing of the rings and dimensioning of the ring grooves for this size and pressure of pipe flange. Discussions with seal manufacturers helped fill in some of the gaps in the design standards and the team was able to move forward with the design; however, it was surprising how little information about O-ring design is available for large diameter, high-pressure flanges. At the time of this writing, the O-ring seal design is being reviewed for completeness.

Penstock Emergency Shutoff Valve

Although the third penstock would be installed downstream of an existing butterfly valve, the ability of the existing valve to close under emergency flows, in the event of a penstock rupture, was not known, given that it had not been operated since being installed 75 years ago and that the original design criteria for the valve was unknown. Consequently, a new emergency shutoff valve will be installed at the upstream end of the third penstock, downstream of the existing butterfly valve. The new valve was designed to close by gravity using a hydraulically-activated counterweight mechanism. The engineers incorporated a tripping mechanism into the valve design that will automatically close the valve when flows in the penstock increase substantially and reach a predetermined setpoint.

Penstock Venting

Another challenging aspect of the design effort was defining and quantifying the requirements for venting the penstock. For the Moccasin penstock, several different design cases were considered that govern the penstock-venting requirements as follows:

1. Normal venting for closure of the penstock emergency shutoff valve against maximum turbine flow (670 cfs).
2. Normal venting requirement for venting air when the penstock is drained.
3. Normal venting requirement for exhausting air when the penstock is filled.
4. Case 1 plus 100% venting redundancy to increase reliability.
5. Emergency venting (3,010 cfs) after penstock rupture.

To meet the normal venting requirements, air valves were provided immediately downstream of the penstock emergency shutoff valve. At this location, one 20-inch air vacuum valve and one 20-inch air inlet valve were installed. The air vacuum valve draws air when the penstock is drained and exhausts air when the penstock is filled. The air inlet valve is used solely to provide air when the penstock is being drained. The combined flow of the two valves is 900 cfs at 1-psi differential pressure, which exceeds the 670 cfs air flow for normal venting.

At this point, the issue of additional venting capacity, over and above normal capacity, was reviewed. The design philosophy applied to the Moccasin penstock was to provide additional venting capacity to ensure full penstock protection and avoid collapsing the penstock due to extreme negative pressure during a penstock rupture condition and emergency closure of the shutoff valve. To provide sufficient venting capacity for emergency closure, four additional air inlet valves were installed in the penstock system.

Summary

The Moccasin Third Penstock planning and design effort was very interesting and challenging given the design issues discussed herein. The new design results in a headloss savings of 55 ft, which results in a 5% increase in power production for the same total penstock flow. The design also provides the desired operational flexibility in isolating penstock sections for maintenance using removable spools. An emergency shutoff valve and penstock air vent valves for full penstock protection are provided in the design. Finally, the third penstock addition can be implemented with minimal disruption to water supply flows to the City.

References

[1] Don Wood, University of Kentucky, *User's Manual - Computer Analysis of Flow in Pipe Networks*, 1980.

[2] Hannaford Consulting, Inc., *Additional Moccasin Penstock Project: Economic Impact*, 10 June 1999.

[3] California Energy Commission (CEC), *1998 Market Clearing Price Forecast for the California Energy Market*, 22 December 1998.

[4] American Society of Engineers (ASCE), *Manuals and Reports on Engineering Practice No. 79, Steel Penstocks,* 1993.

[5] American Society For Testing and Materials, *Specification A516, Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service*, 1996.

[6] American Society For Testing and Materials, *Specification A537, Standard Specification for Pressure Vessel Plates, Heat-Treated, Carbon-Manganese-Silicon Steel*, 2000.

[7] American Society of Mechanical Engineers (ASME), *Standard for Large Diameter Steel Flanges, ASME B16.47, 1*996.

[8] American Society of Mechanical Engineers (ASME), *Standard for Pipe Flanges and Flanged Fittings, ASME B16.5,* 1996.

[9] American Water Works Association (AWWA), *Standard for Steel Pipe Flanges for Waterworks Service, AWWA C207,* 1994.

Authors

Matthew Gass, P.E., is the Engineering Manager for the Hetch Hetchy Project. Mr. Gass has extensive experience with Pelton-type turbines and conceived of the idea of adding a third penstock to the Moccasin Project.

Mark Hammer, P.E., is a senior mechanical engineer for Harza Engineering Company. Mr. Hammer has over 13 years of experience with hydraulic machinery and specialty gates and valves.

Dave Thompson, P.E., is a senior civil engineer for Harza Engineering Company. Mr. Thompson has been involved in the design of a dozen hydro plants ranging in size from 1 MW to 96 MW.

Wade Moore, P.E., is a senior hydraulic engineer for Harza Engineering Company. Mr. Moore has 16 years of experience in the analysis and design of hydraulic structures.