A NEW LOOK AT PENSTOCK ENTRANCE DESIGNS

by

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Abstract

Experience with a half-open, fixed-wheel gate covering a penstock bellmouth entrance indicated that conventionally designed penstock bellmouths might be larger than economically justifiable. A formal Value Engineering Study of the problem was made and a modified entrance structure was designed. A smaller bellmouth and gate were used based on the premise that entrances for low velocity penstocks need not be as large as those for high velocity conduits. Hydraulic model tests were used to prove this concept and develop the design for comparison with an existing conventional design. It is estimated that savings of $13,000,000 in construction costs will be realized when similar bellmouth, gate, hoist, trashrack, and appurtenant structures are used in the new Grand Coulee Third Powerplant penstock entrances. This powerplant, to be added to the existing Grand Coulee Dam is planned to ultimately contain twelve 600,000-kilowatt units. Hydraulic model tests, made to confirm general hydraulic concepts and to develop an exact bellmouth shape for the Grand Coulee Third Powerplant, indicated that smaller bellmouths were not only economically desirable but could be designed to perform better hydraulically.

This "new look at penstock entrance designs" has been a rewarding effort and application of these principles in future designs should provide similar benefits.

1. INTRODUCTION

Two factors influenced the decision to take a new look at the procedures used in penstock entrance design. The first, an occurrence at Anderson Ranch Powerplant, came to attention because of a war-time shortage of hoist equipment. The make-do hoist could only raise the fixed-wheel penstock gate to the half-open position. After the war, the proper hoist was installed and the gate could be fully raised. As the gate was opened from the half to the fully opened position, no measurable decrease in head loss could be detected. The second factor arose while trying to explain the first. Penstock bellmouths have historically been designed using the same criteria used in designing bellmouths for high-velocity conduits, resulting in very large bellmouth openings. It did not seem reasonable that low-velocity bellmouth entrances would need the same long-radius transition curves that are required in high-velocity entrances. It was believed, because of these factors, that a smaller and less costly entrance structure could be designed having economically acceptable hydraulic losses.

The trend toward using hydroplants primarily to produce peaking power has made it economically desirable to build larger individual turbine-generator units. These larger units require larger bellmouth entrances, gates, penstocks, and auxiliary equipment such as hoists, trashracks, and many other associated items. Consequently, even a moderate reduction in the entrance bellmouth size could result in considerable aggregate savings in construction cost. The decision to provide for twelve 600,000-kilowatt units (instead of several times as many smaller units) in the new Grand Coulee Third Powerplant is an example of this economic trend. The penstocks will be 40 feet in diameter and each will discharge up to a maximum of 34,850 cfs at a velocity of 27.7 feet per second.

2. VALUE ENGINEERING STUDY

A Value Engineering Team was formed to conduct a formal value engineering study. Five experienced engineers, each a specialist in one phase of turbine penstock design, were assigned to work together collectively and individually until conclusions were reached and a report written. During the 6-month-long study period of about 500 man-hours, normal supervisory channels were temporarily by-passed.

The team methodically investigated and questioned every assumption and procedure used to design an entrance structure in the conventional and accepted manner. Practices which could not be justified by sound reasoning or by factual data were thrown out and replaced using the best judgment and experience of the team members, keeping in mind the basic and secondary functions of an intake system. When the team did not in itself feel qualified, expert advice from within the Bureau of Reclamation was obtained directly from the engineers engaged in the work. As a result of this detailed investigation, the team concluded that present designs could be modified to provide a substantial reduction in costs without sacrificing the basic functions or safety of the structure.

Using its best judgment to reduce the bellmouth and gate sizes, simplify the designs, and reduce the costs, the team designed an entrance structure and the associated equipment. To provide a basis for comparison, the team designed a penstock entrance for the Flaming Gorge Powerplant and compared it with the recently and conventionally designed entrance. This installation contains three hydroelectric units, each of 36,000 kilowatts capacity. Penstocks 10 feet in diameter supply each turbine with up to 1,400 cfs. Figure 1 shows the conventional design used for the Flaming Gorge Dam penstock entrance. Figure 2 shows the modified design proposed by the VE team. A comparison of the two entrances is given in Table 1.

2.1 MODIFIED ENTRANCE AND ASSOCIATED EQUIPMENT

The changes made in the entrance structure and in the associated equipment are discussed under the following headings. The reader should bear in mind that the conditions discussed concern the present problem and may or may not be applicable to other designs.

2.1.1 Bellmouth, Gate, and Transition

Designs for penstock bellmouths and transitions have been based on the same criteria used to design bellmouths for high-velocity outlet conduits. Because of the considerably lower velocities in penstocks, the team believed that bellmouths did not have to be as large, or the transition as gradual, as those conventionally designed. Experience on hydraulic models had shown that relatively simple rounding of the corners eliminated most of the entrance losses when velocities were low. Also, with low velocities, pressure gradients in the bellmouth area were less critical.

By changing the gate from a face-type gate with picture-frame seals to a type of seating on a compression seal on the penstock invert, the gate could be located downstream from the bellmouth curve and its size reduced. The gate was designed so that the gate slot was as narrow as possible to reduce losses caused by the slot. Also, the modified design allows inclusion of penstock filling valves in the gate that can be operated by overtravel of the hoist stem.

The team also believed that a gate area only slightly larger than the penstock area would be adequate. Therefore, a gate 6.5 feet wide by 13.00 feet high was substituted for the 8.27- by 15.82-foot gate used in the original and conventional design. The ratio, gate area to the penstock area, was thereby reduced from 1.66 to 1.06. The gate area was made slightly larger than the penstock to allow the water to accelerate, slightly, during passage through the transition from rectangular to round. A rectangular bellmouth with rounded upstream corners was provided upstream of the gate.

2.1.2 Trashracks

No deeply submerged trashracks have ever been replaced (Bureau of Reclamation experience) due to rusting, nor have they had to be raked because of trash accumulations in large reservoirs except during the first reservoir filling. Operators have stated that racks would be cleaned to increase power production if only a few inches of head were being lost because of trash. Fully submerged racks require less maintenance than those alternately wet and dry. Present practice is not to repaint trashracks after installation.

In consideration of these facts, the team concluded that a simpler trashrack structure could be used. The narrower gate makes it possible to use a narrower trashrack. The team therefore recommended an all-metal semicircular trashrack (no concrete structure) designed for 5 feet of differential head across the racks. The modified rack is shown in Figure 2; the conventional trashrack is shown in model form in Figure 3. Since computations show that a large percentage of the rack area would have to be plugged to produce a 5-foot differential head, the team concluded there is no need to design racks for 20 feet or more of differential head as has been done in the past. Experience has shown that steel will last indefinitely if fully submerged. However, by bolting the rack sections to the concrete with stainless steel bolts the racks can be replaced by divers if necessary.

2.1.3 Gate Guides, Stoplogs, and Stoplog Guides

Present practice is to provide metal tracks for emergency gates and metal guides and seats for stoplogs extending the full height of the gate slot and hoist structure. With the vertical (or nearly) alinement of the structure, stoplog and gate wheel loads normal to the supporting face are relatively small except in areas of differential water loads. Stoplog seats and guides above the upper log seal and gate tracks above the open position of the gate

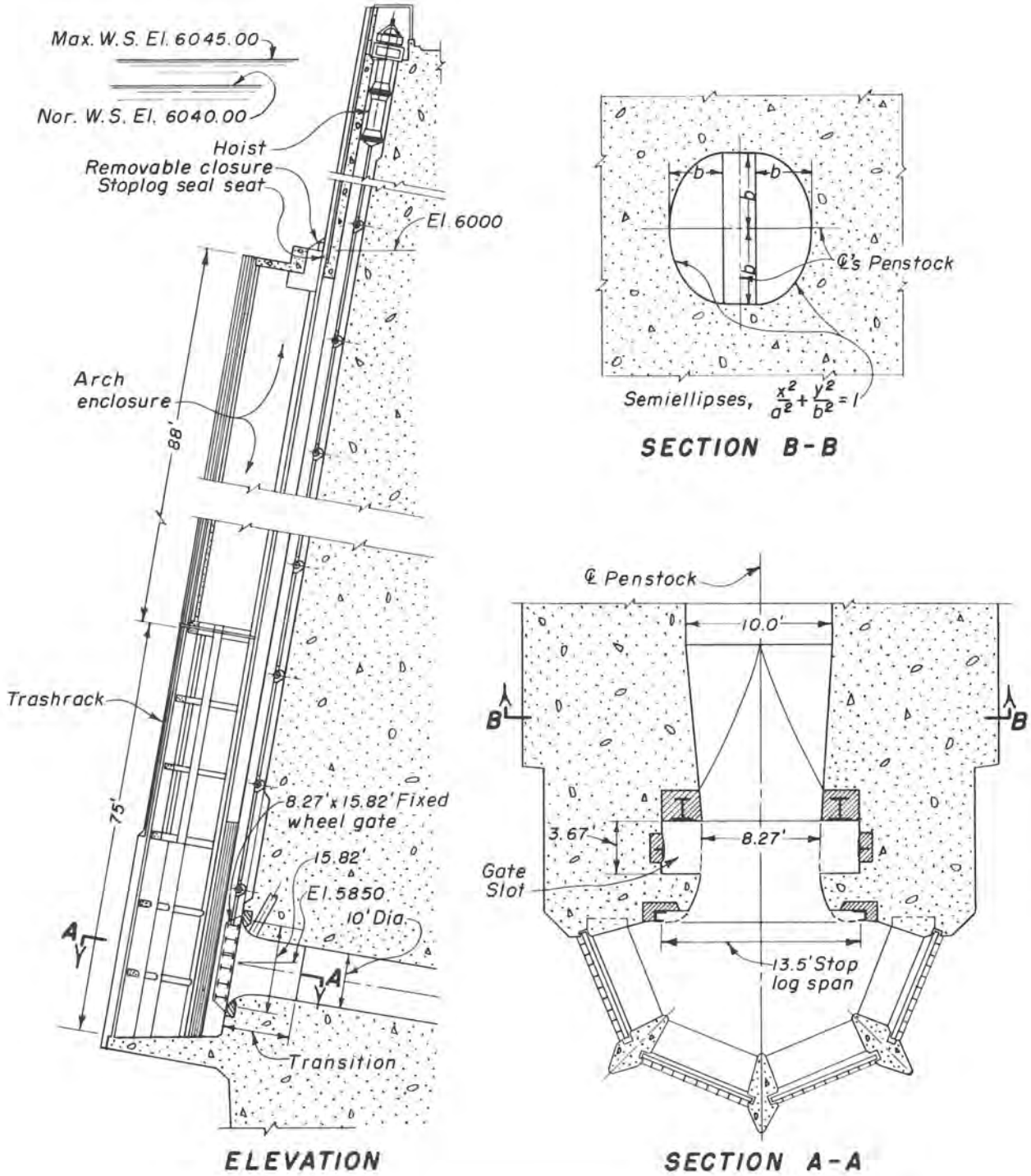


FIGURE 1. FLAMING GORGE PENSTOCK ENTRANCE -- CONVENTIONAL DESIGN

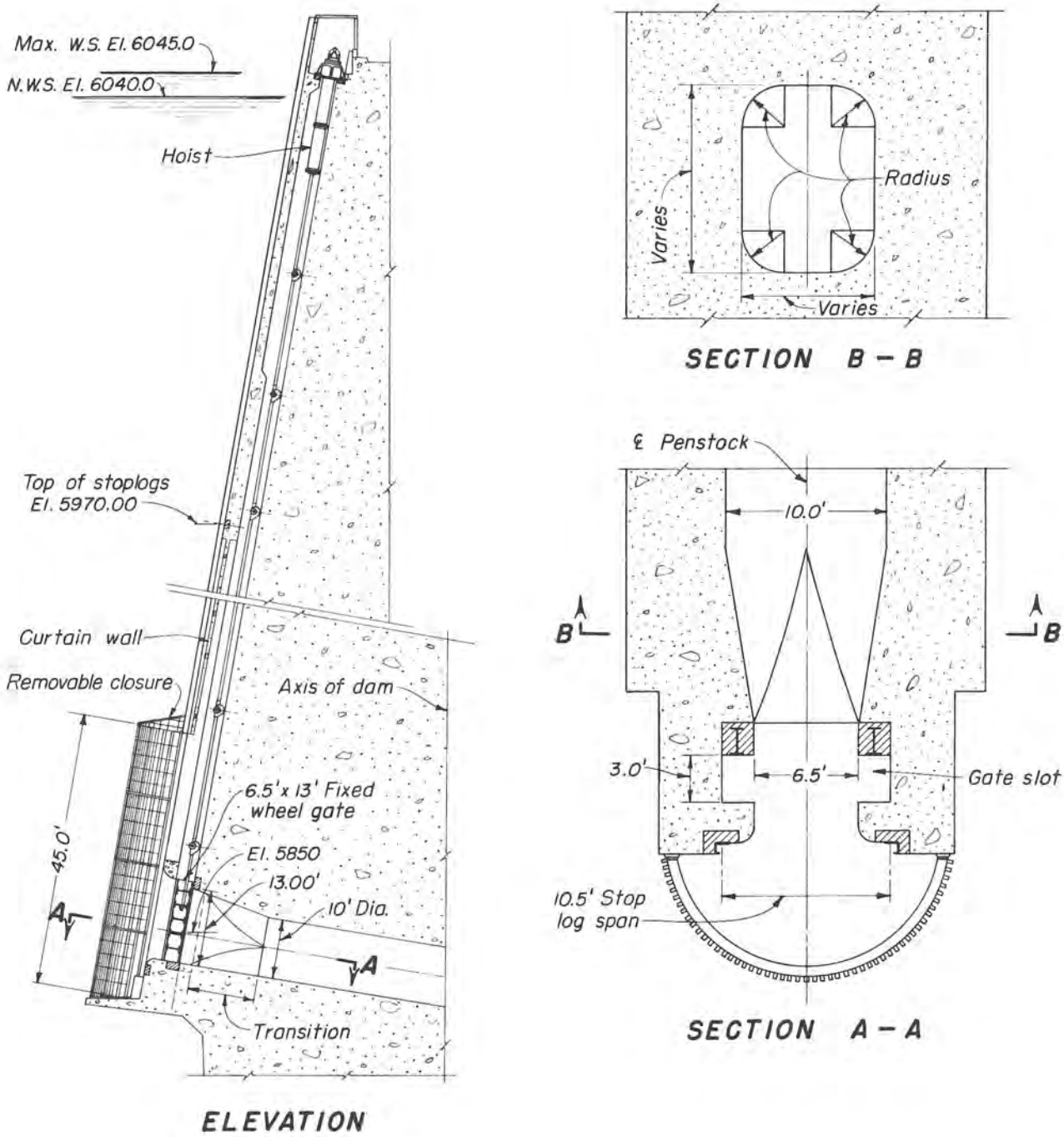


FIGURE 2. FLAMING GORGE PENSTOCK ENTRANCE -- PROPOSED MODIFIED DESIGN

TABLE 1

COMPARISON OF CONVENTIONAL AND MODIFIED ENTRANCE DESIGNS

Flaming Gorge Dam

Feature	Conventional design	Modified design
Trashracks		
Type	Concrete structure--Carbon-steel racks	All carbon steel in sections
Height	75 feet	45 feet
Radius	12.75 feet	8.25 feet
Design head	20-foot differential (Yield point)	5-foot differential (Yield point)
Average velocity	0.85 fps	1-1/2 fps
Removable	Racks only (Has never been required)	All--by diver
Can be raked	Yes--Has never been required	Yes
Erection time	Usual	Fast
Entrance		
Type	U-shaped with elliptical sides	Rectangular with straight sides and entrance radius
Stoplogs		
Span	13.25 feet	10.5 feet
Height	162 feet 1-1/2 inches	130 feet
Guides	To top of the dam	To be investigated for a lower position
Gate		
Type	Picture frame face-type seal	Seats on a flat seat
Size	8.27 by 15.82 feet = 131 sq ft	6.5 by 13 feet = 84.5 sq ft
Hoist capacity	125 tons	51 tons
Frames	Heavy at opening--Light to top of dam	Heavy at opening--None to top of dam
Gantry-capacity	70 tons	30 tons
Transition		
Length	11 feet	11 feet
Ratio $\frac{\text{Area at gate}}{\text{Area of pipe}}$	1.66	1.06
Method of transition	Rectangular with side ellipses	Rectangular with corner radii

may therefore be omitted. The narrower width of the modified penstock opening allowed a reduction to be made in the span of the stoplogs from 13.5 feet to 10.5 feet and consequently a reduction in the weight of the stoplogs and guides. Stoplogs were provided only to the height below which the gate slot wall (enclosing the upper portion of the gate slot) can no longer withstand the resulting water load when the gate area is unwatered because of the limited thickness of the wall. The necessary height of stoplogs was thereby reduced from 162 to 130 feet, as shown in Figure 2.

2.1.4 Gate Hoist and Gantry Crane

Reducing the gate size and weight permitted a reduction in the capacity of the gate hoist, from 125 to 51 tons, and the gantry crane from 70 to 30 tons. Although the size of the cantilever overhang on the top of the dam may be reduced because of reduced crane loads, this reduction was not included in the cost reduction figures.

FIGURE 3

FLAMING GORGE PENSTOCK ENTRANCE

Trashrack used in hydraulic model studies of conventional bellmouth.

2.2 ECONOMIC FEASIBILITY

To determine the economic feasibility of the modified entrance structure, computations were made to determine the comparative costs of the conventional and modified structures. The effect of the two structures on the net head at the powerplant was also considered. Based on a flow of 1,400 cfs in the Flaming Gorge Dam penstock, the hydraulic losses were estimated to be:

Head loss modified entrance	0.96 feet of water
Head loss conventional entrance	0.70 feet of water
Increase in head loss for modified entrance	0.26 feet of water

The value of 0.26 feet of head at Flaming Gorge Powerplant capitalized over a 50-year period, was determined to be $53,600. Total estimated field construction costs in round figures, without contingencies, are as follows:

Conventional entrance	$1,236,500
Modified entrance	596,500
Difference in cost	$ 640,000

At this point in the study, a preliminary report on the VE study was prepared and submitted to the Chief Designing Engineer with recommendations that hydraulic model studies and other studies be made to verify the findings. The report and the recommendations were accepted. The highlights of the hydraulic model studies are summarized below.

3. HYDRAULIC MODEL TESTS

The hydraulic model testing program was necessary for two reasons. First, the validity of the hydraulic conclusions reached by the VE team study was established, particularly the estimated head loss values. Second, a performance datum was established for a conventional design that would indicate the degree of hydraulic improvement obtained in the modified designs. The hydraulic model and instrumentation, as used in some of the later tests, is shown in Figure 4.

FIGURE 4

GRAND COULEE THIRD POWERPLANT PENSTOCK ENTRANCE

Hydraulic model, utilizing 11.5-inch-diameter plastic pipe for the penstock, includes bellmouth entrance and trashrack structure. Electronic instrumentation was used to determine pressures and hydraulic losses throughout entrance system. Model also served to indicate location and tendency for vortex formation and the minimum necessary submergence of bellmouth.

3.1 FLAMING GORGE PENSTOCK ENTRANCE

The conventional Flaming Gorge entrance, Figures 1 and 5, was modeled using 8-inch-diameter transparent plastic pipe to represent the penstock. Included in the model were the trashrack structure

and trashracks, bellmouth, transition section (rectangular to circular) and about 15 feet of penstock.

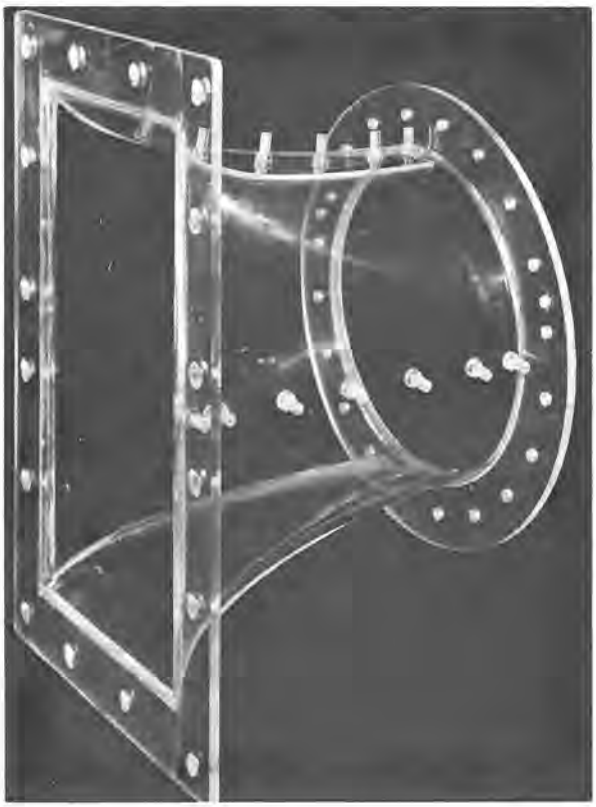


FIGURE 5

FLAMING GORGE PENSTOCK ENTRANCE

Hydraulic model of conventional bellmouth

Piezometers which actuated electronic transducers were connected to sophisticated totalizing and recording equipment to make a record (average with respect to time) of pressures, and other hydraulic data. The studies showed that the head loss through the entrance amounted to about 0.14 velocity head, based on the average penstock velocity. Trashracks increased the loss by about 10 percent. Pressure distribution curves and pressure drop coefficients showed the entrance design to be ultraconservative in that very low hydraulic losses were in evidence. Over 50 percent of the overall loss was caused by the gate slot.

It had been planned to next model the modified entrance, as designed by the VE team, for the Flaming Gorge Powerplant. However, because of the immediate need for data for the design of the penstock entrance for the Grand Coulee Third Powerplant, model studies were conducted instead on an entrance intended for possible use at Grand Coulee.

3.2 GRAND COULEE THIRD POWERPLANT PENSTOCK ENTRANCE

The first hydraulic model of the modified entrance, as suggested by the VE team study, utilized a gate with a 2:1 height to width ratio, a gate area to penstock area ratio of 1.06, a very small bellmouth entrance curve (simple radius), a moderately wide gate slot, and a constant area transition, Figure 6. The penstock was represented by 11.5-inch-diameter transparent plastic pipe.

Head losses were measured to be about twice as high as in the conventional entrance. Pressure distribution and pressure drop coefficients were not as favorable upstream of the gate. Downstream of the gate, the pressure distribution and pressure drop coefficients were satisfactory. Therefore, the ratio gate area to penstock area was reduced to 1.00. Improvements upstream of the gate were obtained when the simple radius bellmouth curves were replaced with compound curves of slightly longer radius. Also, changing the gate height to width ratio from 2:1 to 1.5:1 improved the hydraulic performance.

On the basis of these preliminary tests, a bellmouth entrance, Figure 7, was detailed, incorporating a bellmouth curve configuration further modified to accommodate stoplogs. Surprisingly, the head loss for this entrance was measured to be about 0.11 velocity head, somewhat less than the 0.14 measured for the Flaming Gorge entrance. Head loss coefficients, expressed as a decimal part of one velocity head (based on average velocity), were determined for Reynolds numbers ranging from 3.0×10^5 to 1.4×10^6 for both the conventional and modified designs. Over most of the useful range the curves were nearly straight lines as shown in Figure 8.

Thus, the modified entrance structure proposed for use at the Grand Coulee Third Powerplant will not consume as much head as would a relatively larger and more elaborate conventional entrance structure. One reason for the reduced overall head loss is the relative width of the gate slot in terms of the penstock diameter. The Flaming Gorge gate is 3.67 feet thick, and the Grand Coulee gate is 5.00 feet thick. In terms of the penstock diameter, the ratios are 0.367 and 0.125, respectively.

Pressures measured in the modified entrance were lower than those to be expected in a conventional design, but were not near the cavitation range. This is because of the relatively low velocities in the penstock and bellmouth. It is therefore inconceivable that cavitation erosion damage could occur in the full-size structure as a result of local unintentional irregularities causing a further local reduction to cavitation-producing pressures. The pressure drop coefficient measured in the bellmouth entrance indicated that penstock discharges higher than the turbine can possibly accommodate are needed to produce cavitation pressures in the entrance. These facts are in keeping with the VE team's analysis and contention that smaller bellmouths may be designed for low-velocity entrances.

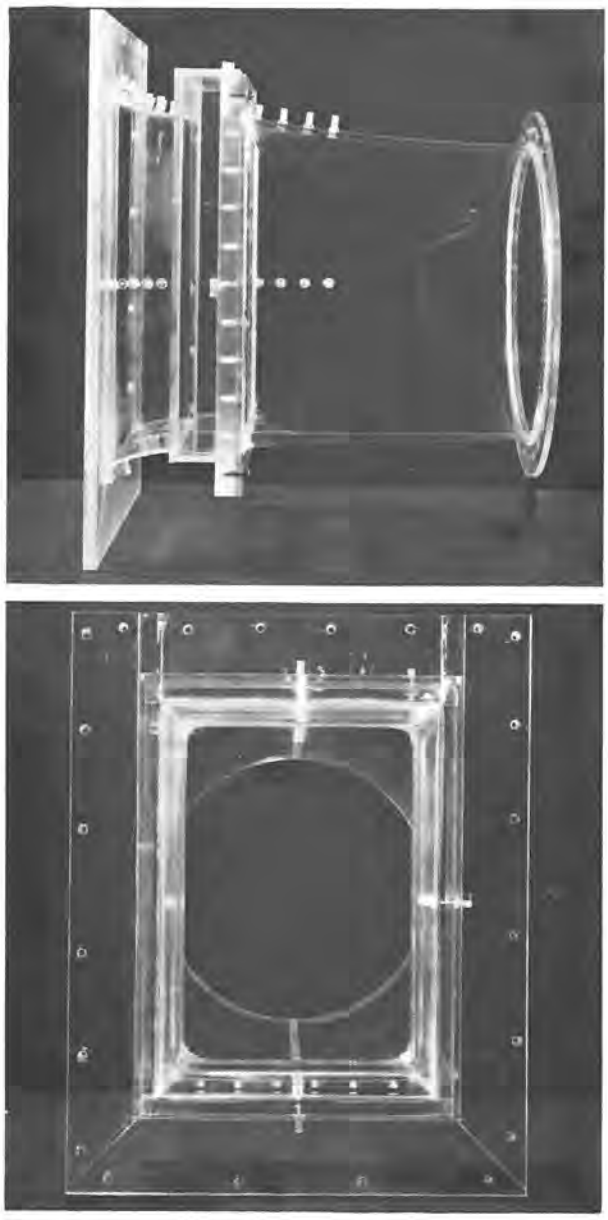


FIGURE 6

GRAND COULEE THIRD POWERPLANT
HYDRAULIC MODEL
MODIFIED PENSTOCK ENTRANCE

Note that emergency gate span is less than penstock diameter and that bellmouth is smaller (with respect to penstock diameter) than in Figure 5.

4. CONCLUSIONS AS APPLIED TO THE THIRD GRAND COULEE AND FUTURE POWERPLANTS

The value engineering study conducted on the Flaming Gorge Powerplant penstock entrances indicated that smaller bellmouths and their associated entrance structures are economically feasible, even if the hydraulic losses in the entrance system are slightly higher than those expected in conventional designs.

The hydraulic model studies conducted on the Grand Coulee Third Powerplant penstock entrances showed that the analyses made by the VE team in regard to bellmouth, gate, trashrack, and transition sizes were basically sound and that not only could the sizes be reduced, but the hydraulic losses for the system could also be reduced. For the considerably simpler and smaller entrance proposed for the Grand Coulee Third Powerplant, the hydraulic loss coefficient was reduced from about 0.14 velocity head for a conventional entrance, to about 0.11 of a velocity head. It is conservatively estimated that the possible savings in construction costs of the penstock entrances for the proposed Third Coulee Powerplant will be about $13,000,000. These figures do not include the additional revenue to be expected as a result of the lower hydraulic losses in the intake system.

It is intended to continue the hydraulic model and design studies in an attempt to further improve the penstock entrances and, if possible, further reduce the bellmouth and gate sizes. For example, tests will be made on a system with the gate area only 0.9 the area of the penstock. Other factors will be investigated to develop design criteria aimed at reducing intake costs to a minimum consistent with the required functions. Also, special structural analyses of some elements of the intake system will be made to see if further reductions in construction costs can be made. The dollar savings in construction costs resulting from modifying penstock intake systems can be also realized in future designs.

5. ACKNOWLEDGMENTS

In addition to the authors, the Value Engineering Team members were Messrs. Manuel Lopez, Arthur Power, and Duane Erickson. Mr. Donald Mountjoy substituted for Mr. Lopez during his absence from the office.

Mr. Thomas Rhone assisted the team with hydraulic computations and conducted the hydraulic model investigations.

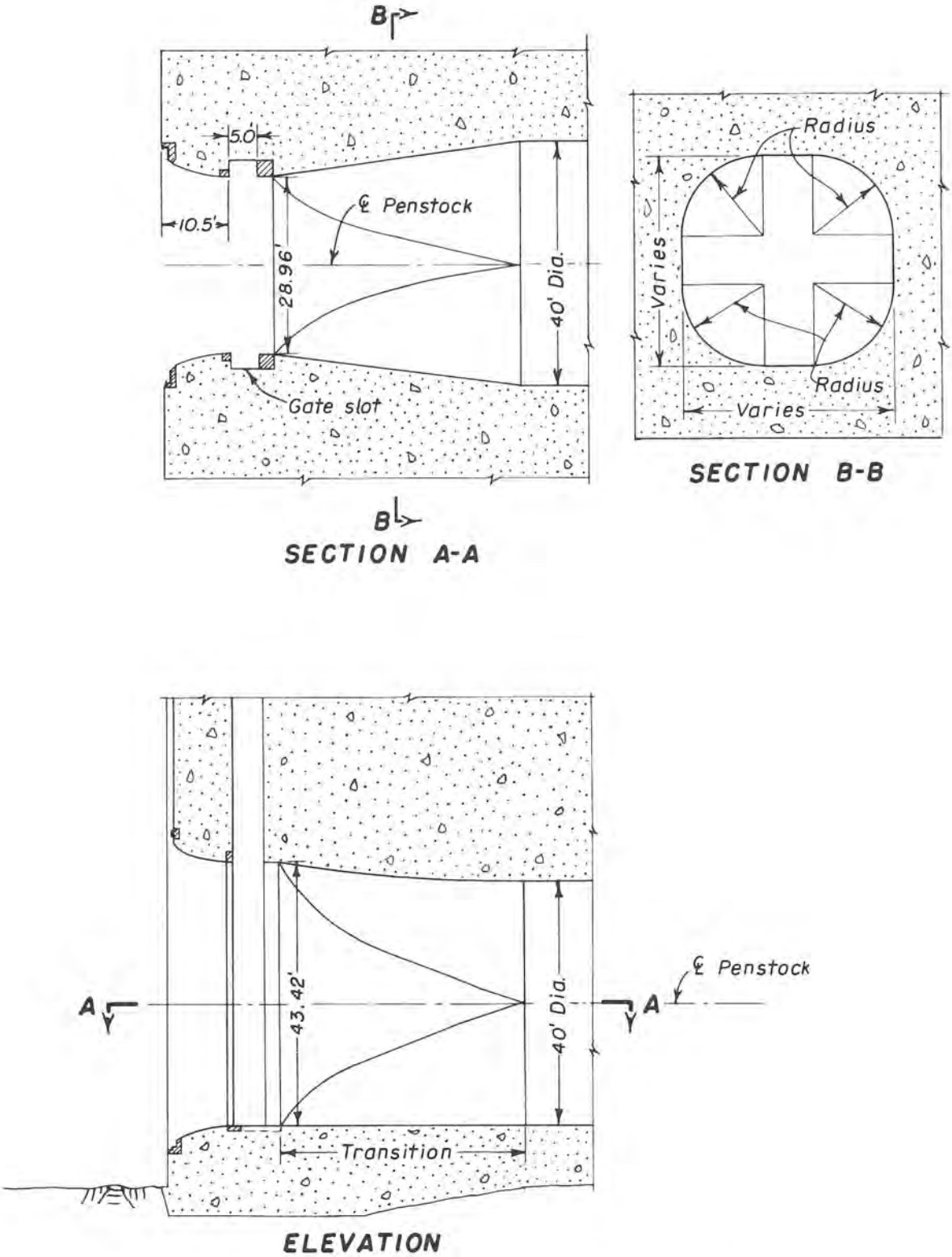
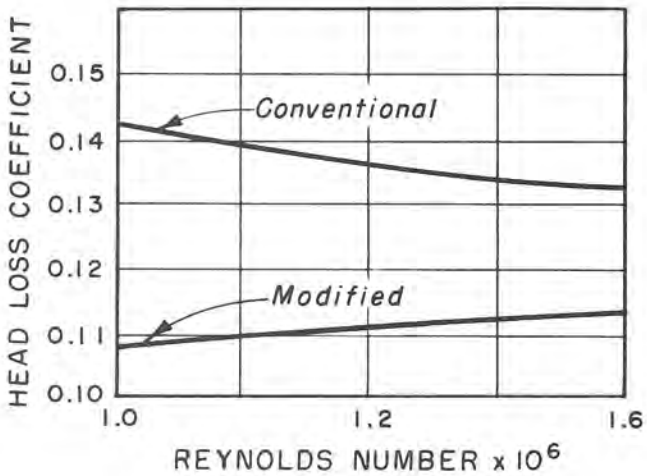


FIGURE 7 - PROPOSED PENSTOCK ENTRANCE FOR GRAND COULEE THIRD POWERPLANT



ENTRANCE HEAD LOSS
COEFFICIENT COMPARISON

FIGURE 8

GPO 840-901