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Rehabilitation of the Outlet Works at Arrowrock Dam
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ABSTRACT

Arrowrock Dam, a gravity arch structure 354 feet high completed in 1916, held the record of the "World Highest Dam" until the construction of Hoover Dam in 1936. The outlet works consist of two rows of ten conduits through the dam at different elevations that are controlled by ensign valves mounted on the upstream face. The ensign valves, an early version of the water-operated balanced needle valves, were the last remaining valves of this type at Reclamation facilities and in need of constant maintenance. However, the need to replace these valves was not realized until an updated flood routing showed that the two-level outlet works configuration did not have the capacity to pass the new probable maximum flood (PMF).

The rehabilitation of the outlet works presented some unique challenges. The existing valves not only had to be removed, but replacement valves had to be selected to provide the additional discharge required. In addition, to resolve the flood routing problems inherent to multilevel outlets, the outlets would have to be located at a level that would be submerged during much of the operating season.

The gates selected for the replacement required the unique capability of both free and submerged discharge. The paper will discuss the physical model testing performed to make the final selection of the valves and demonstrate proof of concept. Unique details of the final design will be discussed such as the location of the control house and gate structure, modification of the bulkhead gate to make it suitable for unbalanced closure, and control system safety features used to prevent oil spills. Finally, construction measures mitigate environmental concerns will be discussed.

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BACKGROUND

Arrowrock Dam, located about 11 air miles east of the city of Boise (17 river miles upstream), was completed in 1915 as part of the Boise Project, and at the time of construction, was the highest dam in the world. Arrowrock Dam is a concrete, gravity-arch structure with a crest length of 1,150 feet, a structural height of 354 feet, and a hydraulic height of 263 feet. The crest width is 21.5 feet and the base width of 223 feet. Arrowrock Dam is operated as one of three storage facilities constructed on the Boise River. Anderson Ranch Dam and Reservoir, located upstream of Arrowrock Dam, was completed by Reclamation in 1950. Lucky Peak Dam and Lake, located about 11 river miles downstream of Arrowrock Dam, was completed by the U.S. Army Corps of Engineers (Corps) in 1957.

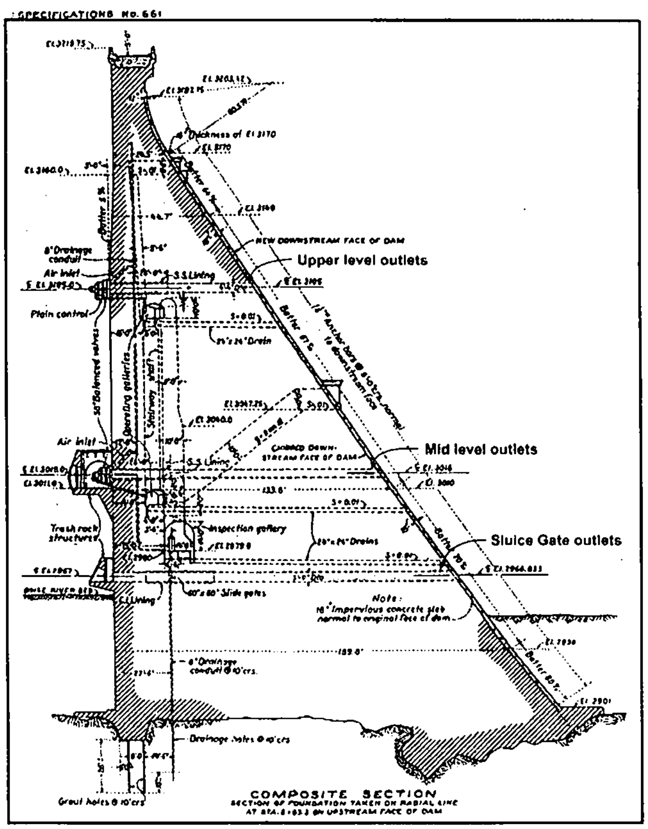

Figure 1 - Section of Dam

Reclamation and the Corps operate the three storage dams in a coordinated method for irrigation water supply, flood control, recreation, and fish and wildlife. Total storage capacity of the system is about 1,058,300 acre-feet: Anderson Ranch Reservoir - 493,200 acre-feet, Arrowrock Reservoir - 272,000 acre-feet, and Lucky Peak Lake - 293,100 acre-feet. Of this total, about 70,000 acre-feet in Anderson Ranch Reservoir and Lucky Peak Lake are inactive storage; an additional 29,000 acre-feet in Anderson Ranch Reservoir is dead storage. All of the active storage space has been contracted to water users or assigned to specific purposes.

The river outlet works consist of two horizontal rows of 10 outlets each. The lower outlets at El. 3018 consist of three 72-inch diameter power tunnel outlets controlled by 58-inch ensign valves. The remaining seven outlets on this level are 52-inch in diameter and are controlled by 58-inch-diameter ensign valves. The three power outlets and the remaining seven valves inlets are protected by two separate trashrack structures. The upper outlets at El. 3105 consist of ten 52-inch-diameter outlet tunnels and each are controlled by 58-inch-diameter ensign valves. Five 60-inch-diameter tunnels with 5 by 5-foot hydraulically operated high pressure gates are located at El. 2967. These gates allow draining of the reservoir. They are used when Arrowrock reservoir is below El. 3018 and Lucky Peak water surface elevation is below the outlets.

Operation of Arrowrock Dam outlet works is constrained by actual and potential cavitation damage to the lower Ensign valves and the sluice gates. Ensign valves in the lower row are not to be operated with a hydraulic head greater than 100 feet without special permission. The sluice gates may be operated only when the hydraulic head is 50 feet or less. In addition, three of the Ensign valves in the lower row and two of the sluice gates have been taken out of service and are considered inoperable or to be operated only in an emergency. The Ensign valves, mounted on the upstream face of the dam, have been in use since 1915 and have exceeded their design life. All of the Ensign valves, and the conduits downstream of those valves, have suffered some cavitation damage, but repairs have kept all the valves in the upper row and most valves in the lower row in service. Maintenance procedures call for periodic inspection and repair of the lower valves which requires the reservoir to be drained. All of the ensign valves except valves Nos. 1,2, and 3 are currently operational.

Arrowrock Dam has been classified as a high hazard structure based on the potential for as many as 80,000 lives-in-jeopardy along a 122-mile reach downstream of the dam which includes Boise Idaho. Several probable maximum floods (PMF) have been developed. The PMF for the intervening area of Arrowrock Dam was routed in combination with the concurrent PMF above Anderson Ranch Dam which resulted in an overtopping of the parapet for 33 hours to a maximum depth of 4.4 feet. In addition, the full Anderson Ranch PMF was routed in combination with the concurrent Arrowrock PMF which resulted in overtopping for 60 hours at a maximum depth of 3.4 feet. All of the flood routing considered the outlets operational.

CONCEPTUAL DESIGN

Since 1985, several concepts had been developed to replace the existing outlet works. All of the concepts removed the Ensign valves on the upstream face of the dam and replaced them with gates mounted on the downstream face at El. 3018 or El. 2967. The reservoir downstream of Arrowrock reaches a summertime level of El. 3055 which submerges the lower outlets. Consequently, the new discharge gate would be required to operate both free and submerged discharge. In 1999 a concept was developed that provided the increased discharge desired and was capable of operating under these unique circumstances, shown in figure 2.

The concept used a recently developed clamshell gate that can operate fully submerged without modification. The concept uses three 66-inch-diameter clamshell gates at the power outlets, and seven 48-inch outlets at the remaining outlets. The clamshell gate was chosen for it high discharge coefficient and its submerged discharge capability. The gates would be connected to steel liners inserted inside of the existing conduit with the annular space filled with grout. The clamshell gates would be located in a gate slot excavated in the downstream face of the dam. The slot would be accessible only in low tailwater elevations, would serve to protect the valves, and would have minimal impact on the original appearance of the dam. Access to the gate slot would be from excavated shaft located near the existing gallery entrance structure. A control house would also be constructed at this location.

Reservoir Elevations	***Flow Requirements***	***Existing Capacity***	***Seven 48" Clamshells Three 66" Clamshells***
Arrowrock @ 3100 Lucky Peak @ 3055	5,000 cfs	4,050 cfs	5,730 cfs
Arrowrock @ 3115 Lucky Peak < 3018	10,000 cfs	8,980 cfs	10,510 cfs
Arrowrock @ 3210 Lucky Peak < 3018	11,000 cfs	9,890 cfs	14,790 cfs

Figure 2 - Flow Requirements

This concept used no guard gates, but a single bulkhead gate which would serve all ten outlets and would be set in place using the existing gantry crane. The decision not to use guard gates was based on the following two premises:

- The large number of outlets (10) reduced the risk of causing downstream disruption due to the uncontrolled release of a single outlet. And the malfunction of multiple outlets at the same time was considered remote.

- Arrowrock Dam, as the middle in a series of three dams, has the flexibility of lowering the reservoir with minimal disruption to downstream water users. An uncontrolled release would not affect the operation of the downstream reservoir and Arrowrock Reservoir can be lowered by holding back water at the upstream reservoir in order to place bulkhead at the malfunctioned gate.

A value engineering study prior to final design recommended moving the gates from a slot in the dam to a platform mounted on the downstream face. This recommendation was incorporated into the final design and a gate house was designed for the downstream face. A control house would be located at the left abutment gallery entrance above the high tailwater elevation.

The existing Ensign valves would be removed from the upstream face of the dam and a bellmouth would be inserted and attached to the steel liner. A single size bulkhead gate would be used for both size outlets. Guide for the bulkhead would run vertically to the top of the dam from each outlet. The bulkhead gate and lifting frame would be handled by the existing gantry crane. A bubbler system would be installed to prevent freezing around the bulkhead guides.

GATE HOUSE DESIGN

The new clamshell gates are located in a gate house ~~located~~ on the downstream face on the dam. The structure is about 150 feet long and consists of two levels. The lower level houses the gates. The 48-inch-diameter gates are separated by divider walls. These walls allow gates to be operated while interior maintenance is performed on adjacent gates. The three 66-inch-diameter gates are located in a single room without divider walls. Interior access to the 66-inch gates would require all three to be out of service. The upper level is the access walkway and provides access to the lower level through hatches in the floor. The walkway also provides access to the roof hatches above the gates and to ladders to a four-foot-wide ledge downstream of the gates. The ladders and ledge allow for access to the downstream end of the gates where the seals are located.

The walkway is connected to a control house by an enclosed stairway. The gate house and lower half of the stairway are located below the maximum tailwater of Lucky Peak Reservoir. Normal operations of Lucky Peak will submerge the entire gate house on a yearly basis.

The design of the gate house was controlled by two loading conditions added to the dead loads. The first was ice loading. During winter operations, the gates will be operated with low tailwater. Spray from the gates could result in a significant ice buildup on the structure. The other controlling load was the dynamic load due to submerged operation. This load was based on the model study results and corresponded to about 4.5 feet of head (static + dynamic).

The structure consists of three cantilevers. The lower cantilever supports the gates, the middle cantilever provides for the access walkway and the roof for the lower level, and the upper cantilever provides the roof for the walkway. The cantilevers are anchored into notches excavated into the face of the dam. This design was intended to limit the amount of excavation in the dam.

PHYSICAL MODEL STUDY

Model Description

A 1:10 Froude-scale model of three adjacent 48-inch clamshell gates and associated gate-house structure was constructed at Reclamations Water Resources Research Laboratory in Denver, Colorado. Figure 3 is a photograph showing the gate arrangement and surrounding gate-house structure as modeled in the laboratory. The primary purpose of the model study was to demonstrate proof of concept. The specific objectives, to that end, included determining hydrostatic and hydrodynamic loading on the gate-house structure and identifying adverse operating conditions for the full range of gate discharge and submergence conditions. Although clamshell-gate technology has been used previously in free-discharge mode, the Arrowrock application represents the first time this concept will be used under submerged operating conditions.

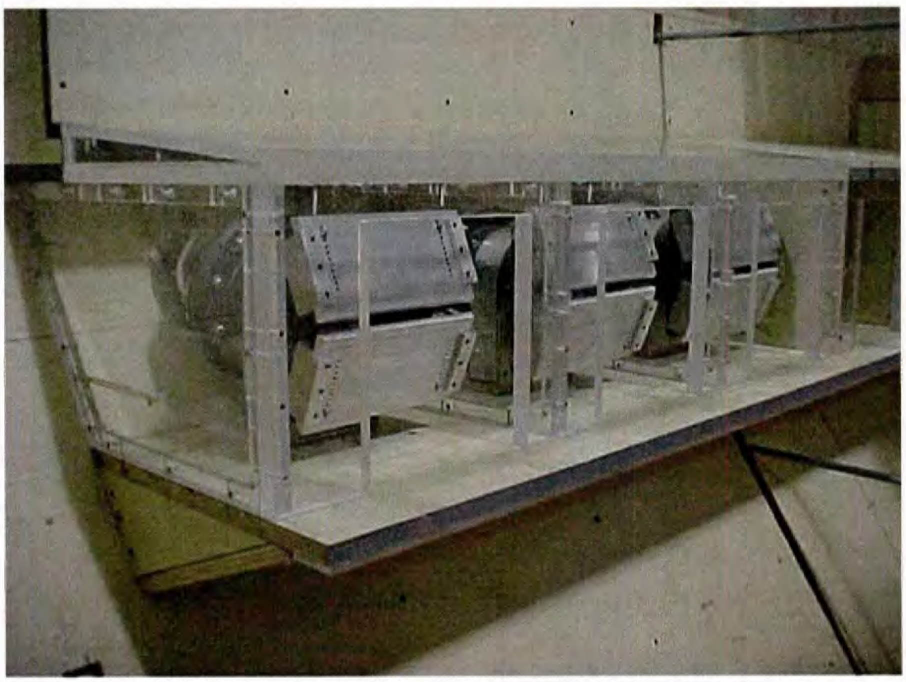

Figure 3 - 1:10 Froude-scale model of three adjacent clamshell gates and appurtenances.

Three adjacent gates were selected as the minimum number necessary to model gate interactions at a sufficiently large scale to produce dynamic characteristics representative of the prototype (i.e. sufficiently high Reynolds number.) These characteristics include turbulence scale and intensity, viscous dissipation, and submerged jet diffusion.

Methods and Testing

Hydrostatic and hydrodynamic loading on the proposed clamshell gate-house structure was determined for submerged operating conditions. Hydrostatic and hydrodynamic pressure measurements were acquired at various locations around the gate-house structure. Internal and external hydrostatic pressures were measured at 38 locations using piezometer taps attached to a single-end manometer board and differential pressures were calculated at corresponding locations. Figure 4 is a schematic layout of the gate-house structure identifying those hydrostatic pressure measurement locations. Following hydrostatic pressure testing, four 30-psi Kistler dynamic pressure transducers were installed at locations that were selected based on observed fluctuations in hydrostatic pressure measurements. The largest fluctuations were consistently observed at locations on the top of the structure above the gates. As such, the dynamic pressure transducers were located inside and outside of the gate-house structure directly above gate 9 and outside of the gate house structure above gates 8 and 10.

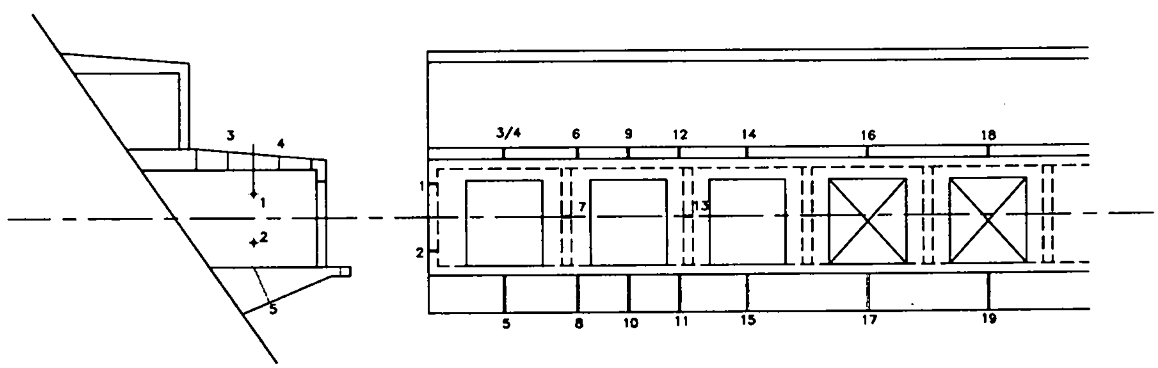

Figure 4 - Piezometer tap locations where hydrostatic pressure differentials were measured.

A total of three gate configurations were evaluated. Each configuration was distinguished by gate position in the gate-house. Configuration 1 represented the clamshell gates set back from the end of the gate-house as illustrated by figure 5. Configuration 2 represented clamshell gates located such that the gate lips were flush with the inside face of the end of the gate-house structure as illustrated by figure 6. And, configuration 3 represented clamshell gates located such that the gate lips protruded outside of the gate-house structure as illustrated by figure 7. For each configuration, three gate settings (10, 50, and 100% gate openings) were tested under two different submergence conditions. The gate settings of 10, 50, and 100 percent open were determined to be adequate to span the range of possible prototype operations. Furthermore, gate operations were tested in various combinations of single, 2-gate, and 3-gate operation. The required prototype clamshell gate discharges were established for each gate opening from the results of a numerical analysis completed during the model design phase of this study. For that analysis, the maximum Arrowrock Dam operating reservoir elevation was chosen as EL. 3210 and corresponds with the spillway-crest elevation. This reservoir elevation represents the maximum discharge conditions expected for the prototype.

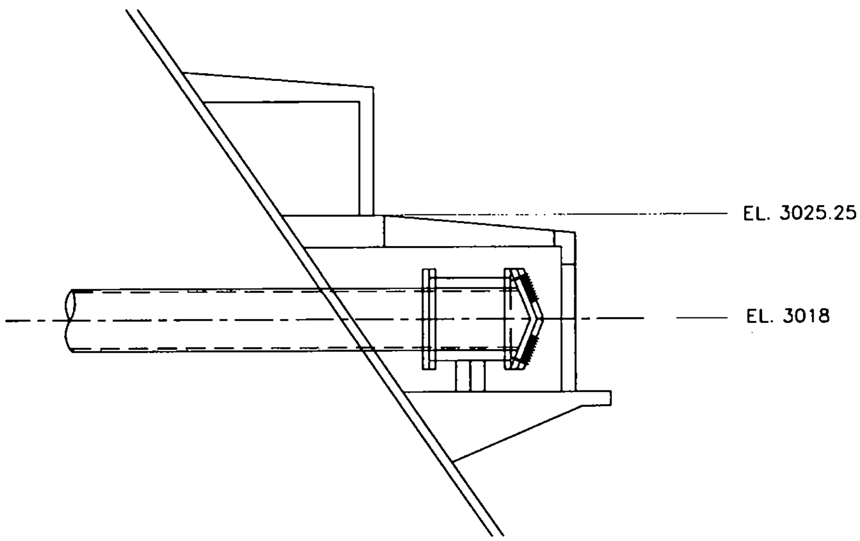

Figure 5 - Configuration 1, gates located back from end of gate house-structure such that gate lips are inside the structure.

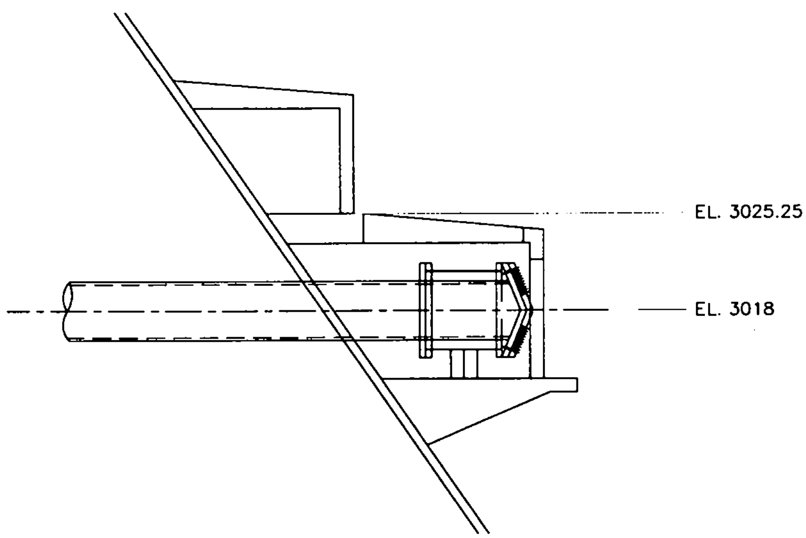

Figure 6 - Configuration 2, gates located forward in gate house-structure such that gate lips are flush with inside of end wall.

The influence of submergence on performance was also evaluated. Submergence, in this case is defined as the depth of tailwater above the outlet conduit centerline (EL. 3018.0).

For all tests, submergence ranged from tailwater elevation 3025.25 – 3055 ft. Since EL. 3025.25 is the top elevation of the gate-house it was used as a lower limit of submergence for these tests. Similarly, EL. 3055 is the normal reservoir elevation for Lucky Peak Reservoir or typical tailwater elevation for Arrowrock Dam and hence was taken as the upper limit of submergence.

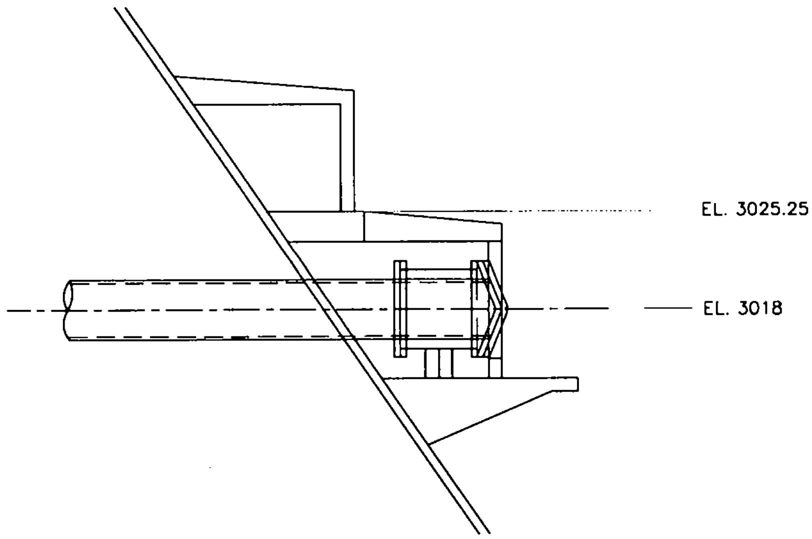

Figure 7 - Configuration 3, gate house-structure shortened and gates set back such that gate lips protrude from structure.

Hydrostatic Pressure Results

The model test results indicate that gate location inside the gate-house has a slight influence on hydrostatic pressure differentials at certain locations. Configuration 3 produced the lowest differentials. In all cases tested the maximum hydrostatic pressure differential was 2.5 ± 0.3 ft (prototype) for configuration 1 and 1.5 ± 0.2 ft for configuration 3. Pressure differentials approaching these upper limits were observed for 2 and 3-gate simultaneous operation. Single-gate operation produced the lowest hydrostatic pressure differentials. Additional general results include:

- At lower submergence conditions, the recirculation zone appears to produce a local draw-down above the gate-house structure. This draw-down produces elevated internal hydrostatic pressures in non-operating gate-bays and results in occasional negative pressure differentials.

- Different operating configurations influence the peak hydrostatic pressure locations.

- The local effect of gate operation on hydrostatic pressure differentials was observed to be reduced with increased gate openings.
- Two-gate operation appeared to be an extension of the single-gate operating results since pressure differentials are elevated in and around those gates that are operating.
- Three-gate operation produced the largest overall pressure differentials.
- In general, operation of the gates produced locally reduced hydrostatic pressures inside the corresponding gate-house and subsequently positive or external pressure differentials.

Hydrodynamic Pressure Results

Peak hydrodynamic pressures were observed to increase with increased gate openings and hence increased flow rates. For 50% gate settings, the maximum measured external hydrodynamic pressure was 0.75 psi (prototype) and occurred for 3-gate operation under submergence conditions produced by a T.W.EL. of 3025.5. For 100% gate settings the maximum measured hydrodynamic pressure was 1.2 psi (prototype) and occurred for 3-gate operation under submergence produced by T.W.EL. 3025.25. For all cases tested, peak pressures were generally reduced with increased T.W.EL. Furthermore, peak pressures tended to be higher external to the gate-house structure as compared with internal pressure measurements.

Surface Vortex Formation and Submergence Results

Qualitative observations during testing indicated a slight difference in the degree of surface vortex action between the three configurations. It appears that configurations 2 and 3 (figures 6 and 7) produce reduced vortex action as compared with configuration 1 (figure 5). This is most likely a result of moving the issuing jet outside of the gate-house structure, thereby reducing the near-field recirculation velocities along the shear zone and consequently reducing vortex strength. In all cases, the vortices were air entraining up to submergences of approximately 10 ft. However, these observations are qualitative and due to scaling relationships between model and prototype, vortex action (strength) will likely increase for the prototype and air entrainment may occur at greater submergences. Air entraining vortices will not affect prototype gate performance, but they are generally considered to be undesirable.

Conclusions

- In general, all three concepts configurations tested appear to perform adequately. However, for submergences below tailwater elevation 3035 ft significant surface vortex action developed. Such operating conditions are not expected to influence clamshell performance, but are generally considered undesireable.

- Locating the clamshell gates in each gate house such that the issuing jet is entirely outside of the structure (configuration 3) appears to produce the lowest hydrostatic and hydrodynamic pressure differentials on the structure, as well as reduced surface vortex action. Thus, a configuration similar to configuration 3 is recommended for the final design.

- Hydrostatic and hydrodynamic pressure differentials may be internal or external depending on which gates are operated and in what manner (i.e. two adjacent operating gates, two operating gates separated by a non-operating gate, two adjacent gates operating at different gate settings, etc...) Although the maximum hydrostatic pressure differential was determined to be 3.0 ft, the results of the hydrodynamic testing indicate that a larger design value of 5.0 ft differential loading is required since the hydrodynamic loading will be superimposed on the hydrostatic loading.

- Tailrace flow patterns, in all cases tested, were observed to be upwelling from below and in front of the gate house structure. Surface re-circulation was observed to be directed laterally along the gate house structure toward the operating gates. In both cases this feature is a result of re-circulation to the shear zone produced by the issuing jet. However, the recirculation strength (i.e. velocities) will likely be diminished for the prototype (at least in the far field from the gate house) since there will be a much larger tailrace extent than was modeled during this study.

- Submergence produced by tailwater elevations at or below EL. 3030 resulted in the greatest air-entraining surface vortex action. Operating limitations for this range of submergence may be desirable.

- Submergence produced by tailwater elevations at the outlet centerline EL. 3018 resulted in unsteady slug-flow and large "rooster-tails" downstream of the gate house for all cases tested. During free release (non-submerged) conditions, no jet impingement on the gate house structure was observed for configuration 3. Configurations 1 and 2 produced some jet impingement on the gate-house. However, this was entirely due to the lateral spray produced by the jet.

FINAL DESIGN

Effects of Environmental Impact Study

The modification of the outlet works required the lowering of Arrowrock Reservoir to El. 3010 to permit the removal of the Ensign valves and other upstream work. An Environmental Impact Study (EIS) was performed to evaluate the impact. The study identified several adverse environmental impacts, including endangered Bull Trout impacts and passing of heavy metals located in sediment that would be transported by the use of the sluice gates. In light of these negative impacts, the EIS recommended that the lowering of Arrowrock Reservoir be limited to El. 3027 which can be accomplished without the use of the sluice gates. This new requirement had the following impact on the final outlet design:

- Stoplogs would be required to unwater the trashrack structure in order to accomplished the upstream valve removal and modifications. This required the design of sufficient stoplogs to isolate groupings of outlets to be modified while the remaining outlets would be used for passing required flows.

- The bulkhead gate would be required to perform unbalanced closure. To accomplish this, the gate was designed with a roller track assembly that could be attached to the gate which would give it the ability to gravity close under an unbalanced head. To counteract the hydraulic downpull forces that occur during unbalanced closure, a water-operated cylinder (hydraulic bumper) would be attached to cushion the gate during closure. Under normal operating conditions, the gate would perform as a typical bulkhead with the gantry crane lowering it down the guide rails to its position in front of the bellmouth. During an emergency when unbalanced closure would be required, roller tract assembly (in-line wheels) would be attached to each side of the gate, the hydraulic bumper would be attached to the front of the gate, and inflatable seals would replace the mechanical seals on the gate.

High Velocities in Outlet Conduit

The outlet was designed to achieve the greatest possible discharge; consequently, the velocities through the conduits are extremely high. In new designs, it is desirable to keep the velocities to 25 ft/sec or less. With this design, the velocities in the conduits at full gate opening at maximum head will exceed 100 ft/sec. Significant damage to the lining of the conduit will occur at velocities greater than 60 ft/sec.

To prevent unnecessary damage to the conduits, discharge tables detailing pipe velocities at various heads and gate positions will be developed and operation of the gates will be categorized as follows:

- Safe operating limits at velocities less than 40 ft/sec.
- Permissible operating limit at velocities between 40 and 60 ft/sec. Some damage to the conduit lining should be expected with prolong operation.
- Emergency operating limit at velocities between 60 and 110 ft/sec. Major damage to conduit lining should be expected with prolong operation

Oil Spill Protection -

The clamshell gates will be hydraulically operated and submerged operation is required. Therefore, there is much concern about oil spill protection measures. The design of the hydraulic control system used Schedule 80 stainless steel pipe with socket weld fittings for all piping outside the hydraulic power unit. Connection to the cylinders operating the clamshell gates required the use of hydraulic hose, so velocity fuses were used at all these connections which would shutoff flow in the event of a line break during operation of the gate. Other measures included counterbalance valves mounted with the velocity fuses which would prevent oil in the piping from leaking if a hose breaks and a low pressure switch that would shut the pumps off with a loss of system pressure.

Construction Sequence

The rehabilitation of the outlet works at Arrowrock Dam is constrained by the environmental concerns and the operation of the downstream Lucky Peak Dam and Reservoir. Each summer Lucky Peak Reservoir reaches approximately El. 3055 which inundates the outlets at El. 3018. Therefore, all of the construction work must be done between mid September through the end of February. With this limited availability of the work site, the construction schedule is spread over three years. All of the downstream work must be completed in the first two construction seasons when Lucky Peak Resrvoir can be kept low and Arrowrock Reservoir is kept high so discharges can be made through the upper outlets. During the third construction season, Arrowrock Reservoir will be lowered so that the upstream construction can be accomplished.

CONCLUSION

The design for the rehabilitation of the outlet works at Arrowrock Dam, contemplated since 1985, was completed in early 2001. Construction is scheduled to begin in the Fall of 2001 with completion scheduled for March 2004.

BIBLIOGRAPHY

[1] Fitzwater, J. R. and K. W. Frizell, (1990) "Laboratory Tests on the 30-inch Clamshell Gate for Grassy Lake," U.S. Department of the Interior, Bureau of Reclamation Report No. R-90-16.

[2] Mefford, B. W., (1987) "Hydraulic Model Study of Submerged Jet Flow Gates for Arrowrock Dam Outlet Works Modification," Bureau of Reclamation Report No. PAP-511.

[3] U.S. Bureau of Reclamation, Technical Service Center, "Arrowrock Dam Outlet Works Rehabilitation Final Conceptual Design," March 2000.

[4] U.S. Bureau of Reclamation, Pacific Northwest Region, Snake River Area Office, "Draft Environmental Impact Statement - Arrowrock Dam Outlet Works Rehabilitation," October 2000.