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Hydraulics/Fluid Power

Moving and Controlling a Very Large Unstable Structure in a Submerged Water Environment

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Introduction

Currently, there is significant controversy and debate focused on the issue of hydroelectric dams creating an impediment to the passage of juvenile salmon on their way downstream to the ocean. There has even been serious consideration given to breaching major dams on the Snake River in order to improve juvenile salmon passage. As a result of this controversy the U.S. Army Corps of Engineers has funded several projects to aid the passage of juvenile salmon past these dams.

Figure 2 – Lower Granite Dam, Snake River, Washington State

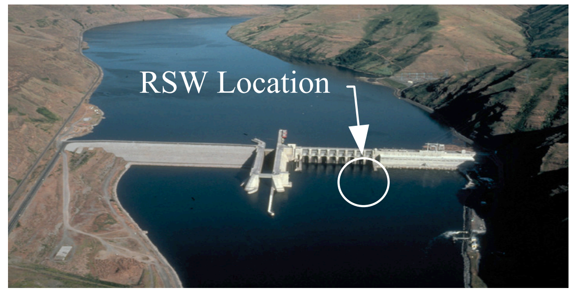

Figure 1A – Lower Granite Dam, Snake River, Washington State

One of these projects is the “Removable Spillway Weir” (RSW), installed at Spillway 1 at Lower Granite Dam on the Snake River near Lewiston Idaho in the spring of 2002. This location is illustrated in Figures 1 and 1A. Without the RSW installed, water flow through the spillway is controlled by a large tainter gate which lifts to allow water flow under the gate. Juvenile salmon, which typically congregate and swim in the upper part of the river, must find their way either through the spillway opening which is about 50 feet underwater or the power generation turbines, which are comparably deep. The RSW modifies the flow over the spillway by moving the passage opening up about 40 feet and placing it at the surface. This allows water to flow over the RSW in a fashion similar to a waterfall and allows the fish to remain in only a few feet of water depth. A view of the RSW structure prior to installation is shown in Figure 2.

Figure 3 – Removable Spillway Weir – Being Loaded onto a Barge Near the Fabrication Shop Prior to Transport to Dam

The RSW normally remains installed in the spillway, except during conditions of extreme flood. At such a time the structure needs to be removed to restore the spillway to its original capacity in order to avoid flooding.

The RSW clears the spillway by rotating into the forebay of the dam about a set of submerged hinges mounted approximately 100 feet underwater. Figures 3 and 4 illustrate the position of the RSW in each position.

The actuation system to move and control the RSW would be critical since the total weight of the structure would be close to 2,000 tons. It was decided to actuate and control the rotating motion of the RSW by adjusting the amount of water ballast in two soft buoyancy tanks, using a system of compressed air supply and bleed valves.

In order to move the RSW between the two positions, the RSW is constructed as a hollow steel structure that is divided into separate tanks, as shown in Figure 5. These tanks may be filled with air or water as required to change the buoyancy and center of gravity of the RSW about its hinge point. This capability allows the RSW to seat or unseat itself from the deployed position and controls the speed of ascent or descent between the two positions. Control of the movement between the two positions is through an electronic programmable logic controller (PLC) control system that regulates the volume of air in the watertight tanks. Although primary control of the actual raising and lowering of the RSW is by the PLC control system, use of this system requires the workers to initialize the system, participate in system checks, manually unlock the RSW from the dam and monitor the descent/ascent for potential hazards.

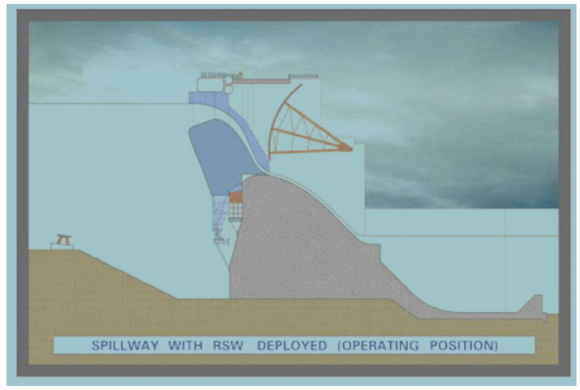

Figure 4 – Cross Section through Spillway, RSW in Operating Position

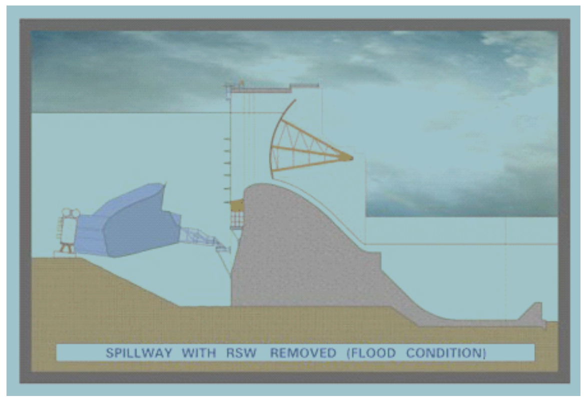

Figure 4 – Cross Section through Spillway, RSW in Stored Position

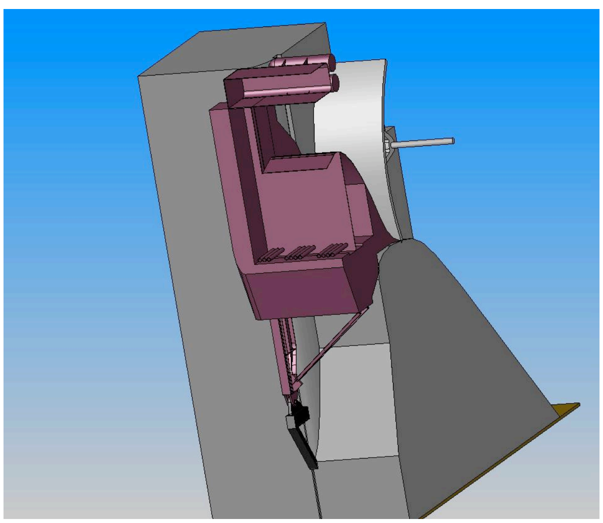

Figure 5 – Partial Section through RSW to Show Internal Tanks

How it Works

Basic Concept

The RSW is hinged to the dam so that it follows a predictable path and to simplify control of the RSW during the descent/deploy process. When the RSW is to be removed, it is rotated away and down until it rests on a landing pad at the bottom of the river. The movement is initiated and controlled by adding or releasing air and water to adjust the RSW ballast.

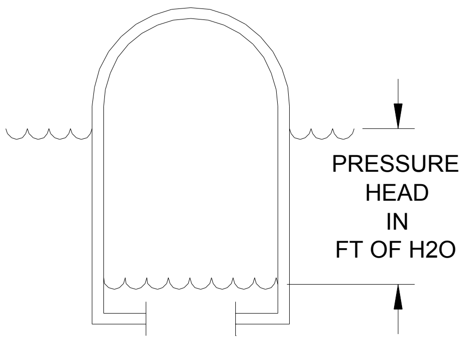

Figure 5 – Diving Bell Analogy

The Lower Granite RSW utilizes air tanks that are open to the river water at the bottom of the tanks, similar to a diving bell or an inverted glass in a sink, as shown in Figure 6. This type of open to water tank is referred to as a “soft tank”.

The soft tanks in the Lower Granite RSW are part of the structure itself and are comprised of large flat surfaces, on the order of 1000 sq ft or more, that have limited pressure capacity. The use of soft tanks limits the net pressure applied to a tank to the height of the air bubble within the tank regardless of depth. However, as shown in Figure 7, a soft tank cannot maintain constant buoyancy as it is submerged.

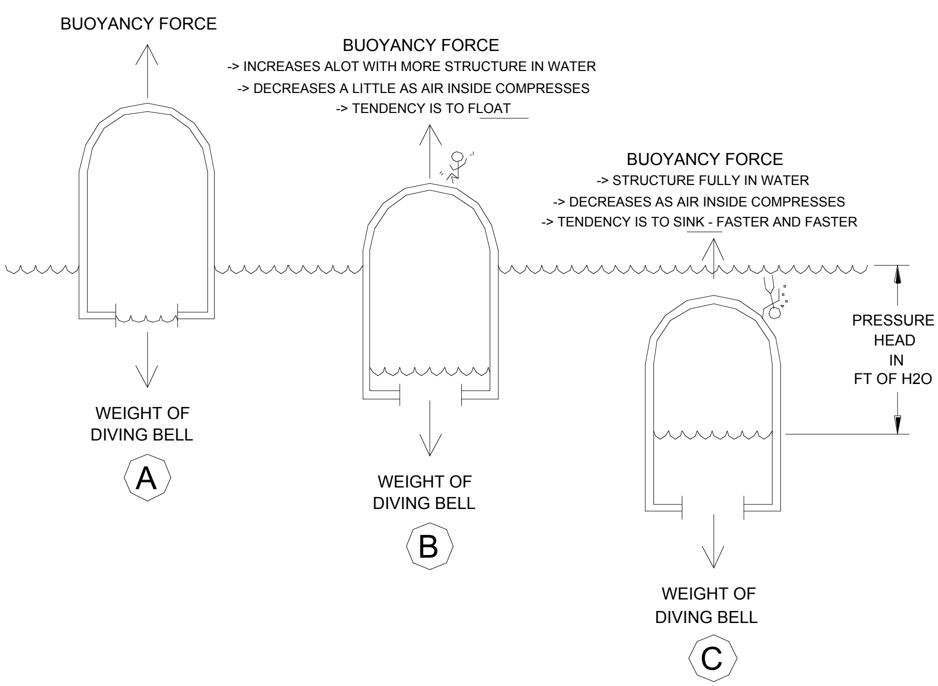

Figure 6 – Diving Bell Buoyancy Example

In Figure 7 (A), the diving bell/soft tank freely floats with air inside the cavity. In this case the air inside the bell is at the same pressure as the water at the bottom of the air bubble within the bell, which is proportional to the distance between the outside water surface and the water surface within the bell.

In Figure 7 (B), an external force is applied to push the diving bell deeper into the water: This increases the distance between the water surfaces and further pressurizes the air. As a compressible gas, the air inside is reduced in volume so some buoyancy is lost. However, since the structure is not fully submerged, it also displaces more water and remains positively buoyant and will float back to the position shown in 7 (A) if the external force is removed.

In Figure 7 (C), the diving bell is fully submerged, with the air pressure increasing as the distance between the water surfaces grows. This compresses the air inside the bell and reduces the volume of the air bubble further. In addition, since the diving bell is fully submerged, it cannot displace more water so the buoyancy is limited to the size of the air bubble contained within the bell. Once submerged the force needed to continue to sink the diving bell progressively decreases with depth because the air bubble, which shrinks as the water pressure increases, becomes less buoyant. Eventually the air bubble will lose enough volume that the weight will be greater than the available buoyancy. Once this point is passed, the diving bell will freely sink to the bottom, accelerating as the air bubble continues to compress with depth.

Figure 8 shows the tank arrangement of the Lower Granite RSW. The upper three tanks, one rectangular tank and two small round tanks, are "hard tanks" that are sealed from the surrounding water and maintain a constant buoyancy force with depth. They counteract part of the overall weight of the structure when

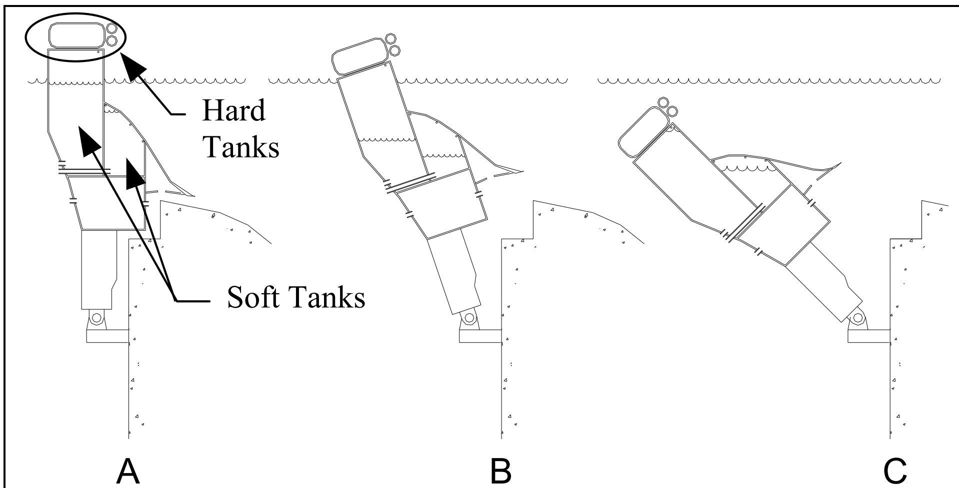

Figure 7 – RSW Tank Ballasting for Descent

they are in the water. The two irregularly shaped lower tanks are "soft tanks" and are used to control the buoyant force as the RSW is removed from the dam. When the Lower Granite RSW is in its operating position against the dam, Figure 8 (A), the soft tanks are fully flooded and the center of gravity of the structure is on the downstream side of the hinge point. In this position the RSW structure "leans" against the dam. To initiate movement away from the dam, compressed air is introduced to the "soft" tanks to push the water out of the tanks. As the water is moved out of the downstream tank, the RSW will become lighter on the downstream side of the hinge and begins to rotate about the hinge, as shown in Figure 8 (B).

Once the Lower Granite RSW has moved some distance from the dam, air is vented from the soft tanks to rotate the structure further. Venting continues as long as some part of the structure is above the water surface. This is analogous to the condition in Figure 8 (B), with the external force being the weight of the water introduced into the tanks. Eventually the RSW is fully submerged, as shown in Figure 8 (C). After the structure is fully submerged, the air inside the soft tanks is progressively compressed as the RSW rotates to lower positions and the structure loses buoyancy. This is analogous to the condition in Figure 8 (C). To make up for this loss of buoyancy, compressed air must be added to the soft tanks to control the speed of descent.

To maintain a safe descent, the Lower Granite RSW has a control system that adds air to the soft tanks once the structure is fully submerged. Careful control of the air is required when the RSW is submerged due to the sensitive nature of the system. Adding too little air leads to loss of control, high acceleration and excessive downward speed that could damage the RSW when it contacts the submerged landing pad. Adding too much air has the opposite effect, causing the RSW to accelerate to the surface and requiring restarting of the descent.

With these factors in mind, a scheme was developed to safely lower the RSW. The basic concept is to closely monitor the position, speed, acceleration of the RSW and then add or release air appropriately. Properly performed, this will allow the structure to slowly rotate downward in small incremental steps. The final system uses a programmable logic controller (PLC) to interpret the position data and react accordingly.

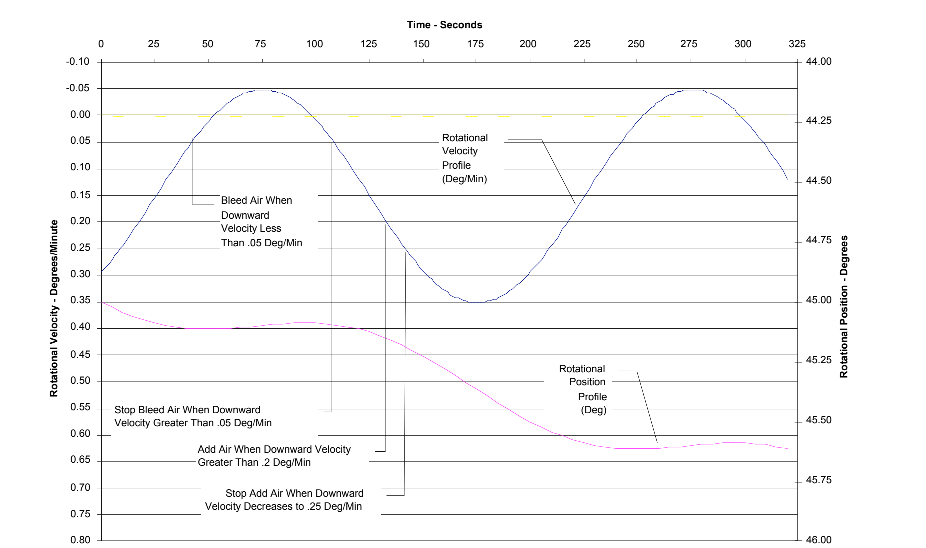

Figure 8 – Expected Motion Profile

As shown on Figure 9, a graph of expected RSW position versus time, the rate of change in position will vary as the control system responds to the position data. For a given cycle of the control system, the RSW may both descend and rise, but with an overall constant downward velocity over many cycles. An analogous situation occurs when driving a car at constant speed (velocity). The driver observes the speedometer and adds or reduces power to maintain the desired speed. At any moment, the actual speed may be above or below the target, but the average speed should be very close to the target speed.

Speed Control

Air is normally supplied to the RSW from an air compressor at the dam. As a back up system, analogous to a car's brake, two large emergency compressed air accumulator tanks mounted on the RSW are used to quickly release air to the buoyancy tanks to arrest an over-speed descent and force the structure to the surface. The emergency tanks also actuate in the event of other trouble such as a power outage. These tanks are charged with air prior to moving the structure and travel with the RSW as it rotates down. Compressed air is provided to the RSW through pipes and flexible hoses routed around the RSW hinges. Three separate air introduction sites are used to supply air to the dam side soft tank to account for the fact that the tank's irregular shape causes the air bubble to shift as the RSW rotates. The port highest in the air bubble during the rotation is used. During normal operation buoyancy air is added or removed from the "Dam Side" and "Pool Side" soft tanks using valves controlled by a Programmable Logic Controller (PLC). A simplified schematic of the basic buoyancy control components are illustrated in Figure 10.

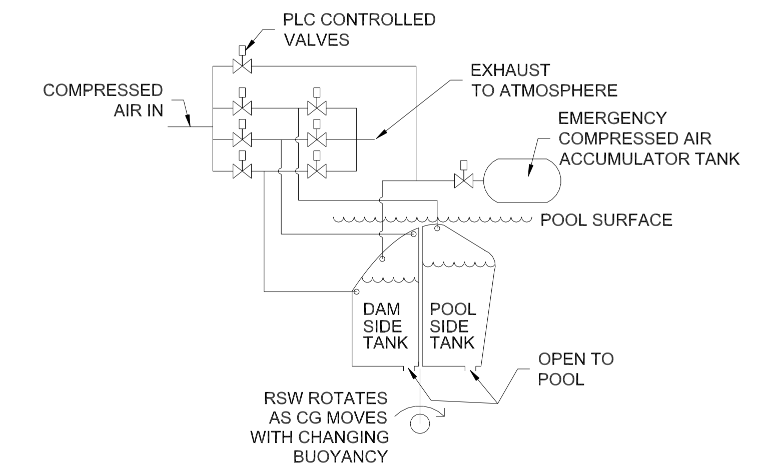

Figure 9 – Simplified Valve Schematic

The design team's mechanical engineer tackled the development of this system using both numerical calculations and model tests. The structural designers constantly calculated the weight and center of mass of the RSW as the details of the structure were developed. The results of this analysis allowed the dead load moment about the hinge to be calculated. Other calculations stepped through the descent of the RSW to determine the volume and location, relative to the hinge, of the trapped air needed to counteract the dead load moment.

A 30:1 acrylic scale model of the RSW was built to test the controlled descent concept. The model was tested manually and yielded important insights into the practicality of manual control and critical positions as the unit descended. Manual control was found to be difficult to master with frequent failures, which confirmed the need to use a PLC to control the descent. The overall result of the physical testing was a general consensus that the controlled descent system was technically feasible and could be made to work.

The operational timing of the bleed and blow valves are controlled by the PLC based on input from an angular position measuring system, illustrated in Figure 11. The angular position measuring system consists of a steel cable and rod arrangement mounted to a cam that is concentric with the hinge point of the RSW. The cable is attached to a pneumatic cylinder mounted on top of the dam. As the RSW rotates this cable is paid in or out in proportion to the angular rotation of the RSW. The pneumatic cylinder is pressurized to keep a constant tension on the cable. As the RSW rotates the cylinder is either extending or retracting and a linear position transducer in real time measures the motion. The transducer uses magnetorestrictive` technology and detects the position of a magnet attached to the piston of the cylinder to less than .001 inches. A typical cylinder with linear position transducer is shown in Figure 12 and a photo of the cylinder used at Lower Granite Dam is showed in Figure 13.

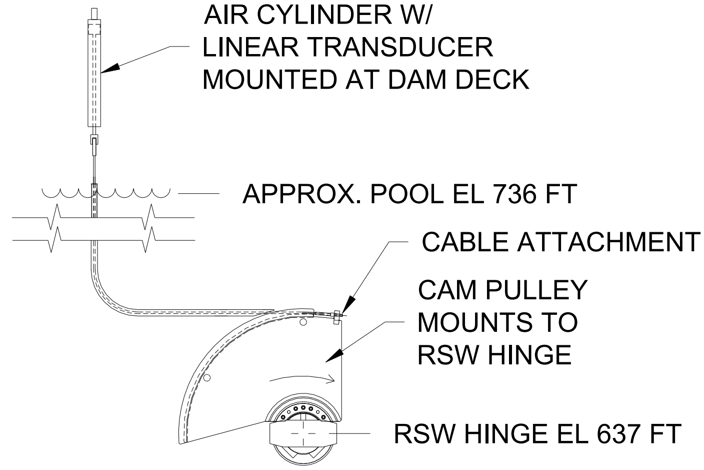

Figure 10 – Detail of Angular Position Measuring System – (Not to Scale)

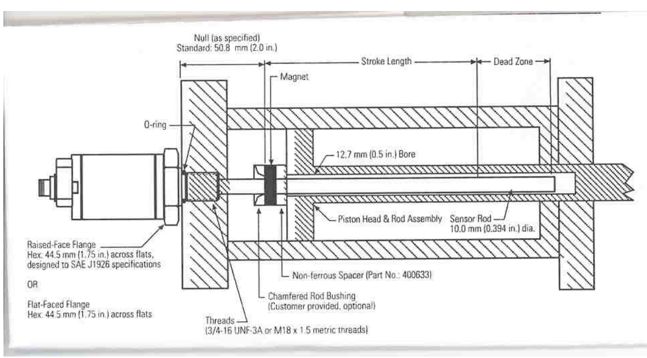

Figure 11 – Linear Position Transducer and Pneumatic Cylinder Detail

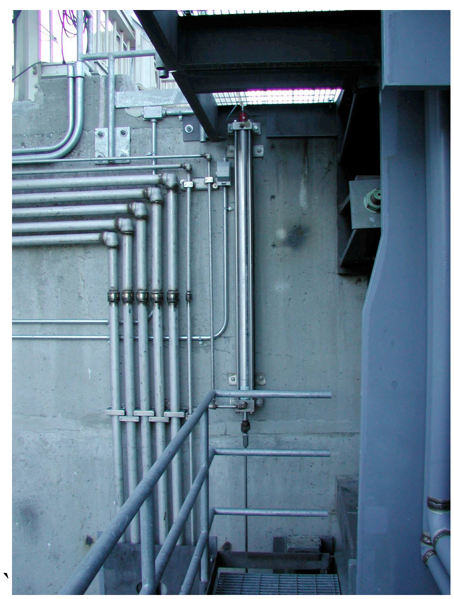

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Figure 12 – Photo of Pneumatic Cylinder and Air Piping as Viewed from RSW

The electrical output from the transducer is then transmitted to the Programmable Logic Controller (PLC). The PLC uses this input to determine the position of the RSW and calculate the rotational velocity and acceleration of the RSW. These values provide the input to a Proportional/Differential/Integral (PID) routine whose output is the timing of the air valves. PID control is a well established control method typically used in heater control and process industries.

Functional Descent Control Testing

Successful testing of the descent control system on the installed RSW structure occurred in the summer 2003. Biological testing of the structure's effect on fish passage was the primary goal of the Corps of Engineers and this limited the time available to test the descent control system, which of course cannot be used for passing fish when rotated from the spillway. Large volumes of air, more than 80,000 standard cubic feet, are used for the initial ballasting of the RSW to allow a controlled descent. With a 900 standard cubic feet per minute compressor available, a few hours were required to fully charge the emergency compressed air accumulator tanks and the soft tanks. Several more hours were required to vent the air back out, using only the head of water on the internal air bubbles to rotate the structure into the water. On average it requires about 10 to 12 hours of venting air to move the RSW to the fully submerged condition, a movement of about 45 degrees from the vertical position. Once all surfaces were underwater, with air being added to prevent acceleration of the RSW, the final 45 degrees of rotation were completed in approximately 90 minutes.

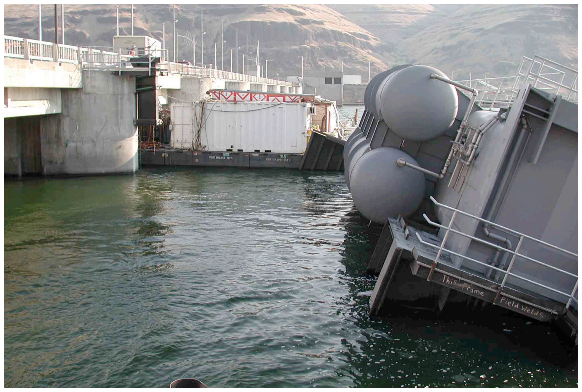

Figure 13 – RSW Rotated Approximately 25 Degrees During Descent Control Testing

Figure 14 – RSW Rotated Approximately 35 Degrees During Descent Control Testing, Almost at Fully Submerged and "Unstable" Position

Several days of testing were required to adjust the control parameters of the PLC with the RSW traveling only a few feet completely submerged before using the emergency compressed air accumulator tanks to bring the structure back to the surface. After the control parameters were set, a full descent of the RSW was completed successfully.

Views of the RSW during physical testing are shown in Figures 14 and 15.

Figure 16 shows actual data collected during the critical submerged motion of the structure. The range of travel shown is from an angular position of about 55 to 62 degrees. An angular position of 0 degrees would be a full vertical position with the RSW upright against the dam and roughly 90 degrees would be with the RSW in the fully stowed position. The figure shows the cyclical nature of the velocity profile and the response of the control system with the air flow from the compressor shown as downward facing "spikes" at the top of the graph. Here one can see that large increases in the velocity would elicit longer periods of time that air was added. For safety of the structure it was desired to keep the impact velocity of the RSW below 2.0 degrees per minute and the graph shows an average rotational velocity of approximately 0.8 deg/minute. Contact with the landing pad at this speed is well within the capabilities of the landing pad energy absorbing system which utilized marine style ship fenders.

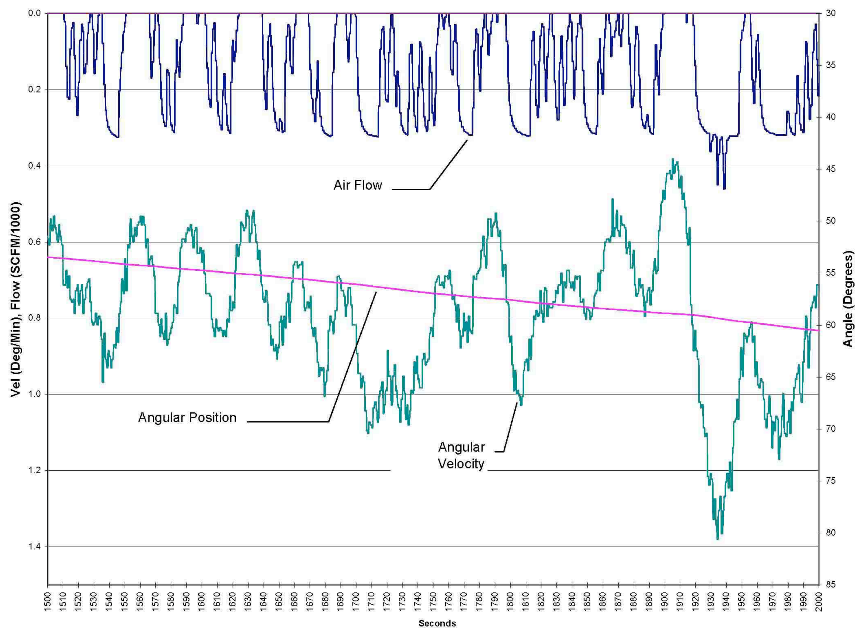

Figure 15 – Descent Control Test Run – RSW Position between 55 Degrees to 62 Degrees – Angular Position, Angular Velocity, and Compressor Air Flow Shown

Conclusion

Control of a large submerged object can be accomplished with the development of an appropriate ballasting system. Careful selection of valves and control equipment is required as well as proper design of the PLC software which was essential to the success of this particular project.

Biological testing of the RSW is ongoing and results indicate that this structure will allow efficient passage of juvenile salmon with much less water required compared to conventional spill. This means more fish passed with more water available for power generation and navigation.

In 2003, the Lower Granite Removable Spillway Weir won the American Council of Engineering Companies "Grand Conceptor Award" in competition with projects nationwide.

In 2004, the Corps of Engineers started work on a second removable spillway weir for another dam on the Snake River.

Figure 17 – RSW Being Prepared for Transport to Lower Granite Dam

Figure 16 – RSW Hinge Just Prior to Installation at Lower Granite Dam

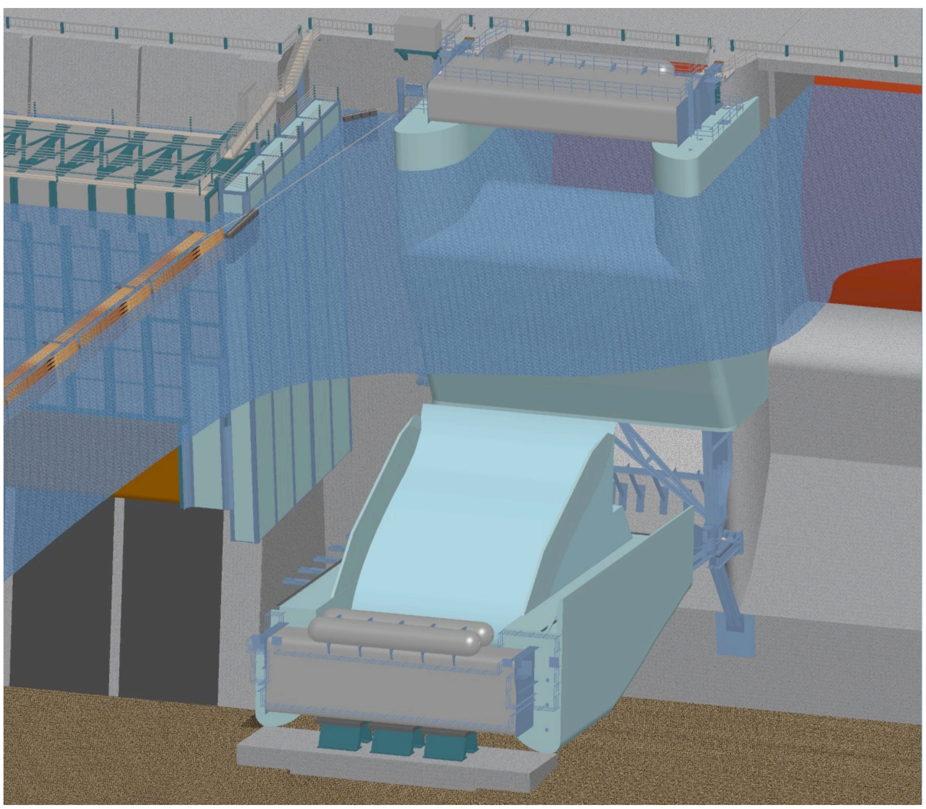

Figure 18 – Graphic of RSW in Full Up and Full Down Positions