R-94-05

HYDRAULIC MODEL TESTS: TWIN PEAKS PUMPING PLANT

May 1994

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16. ABSTRACT

The Bureau of Reclamation used a 1:8.74 scale model in the Denver Office Hydraulic Laboratory to evaluate the effects of pump sump geometry on submerged vortex formation at Twin Peaks Pumping Plant. These tests verified the presence of a submerged floor vortex in each sump. Effective sump geometry modifications developed during this evaluation were installed in bay No. 1 at Twin Peaks Pumping Plant for prototype verification tests.

Plant operations were studied to evaluate the formation of both submerged and free-surface vortices in all pump sumps. The same sump modification which was installed in sump No. 1 was also installed in sumps No. 2 and 3. In addition, a series of fillets and splitters were added to sump No. 4 (multi-pump). These modifications performed well in the model, eliminating all vortex activity for a variety of operational sequences.

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by

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Research and Laboratory Services Division
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Denver, Colorado

May 1994

UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

U.S. Department of the Interior
Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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INTRODUCTION

Twin Peaks Pumping Plant is located about 26 km northwest of Tucson, Arizona, in Pima County. It is the fourth in a series of six relift plants on the Tucson Aqueduct, and raises project water about 23 m in one lift. The plant contains six vertical turbine pumps driven by synchronous motors. Three are 1.42-m^3/s units which share a common sump, and three are 4.25-m^3/s units in individual sumps. At a rated head of 24 m, the rated total capacity is 17.58 m^3/s. The six units discharge directly into a single manifold. The discharge manifold connects to a 3.05-m-diameter steel pipe before it exits the pumping plant and conveys water from the manifold to an outlet structure. The outlet structure passes the flow back to the upper canal, connecting previously built sections of the Tucson Aqueduct. In addition to Twin Peaks Pumping Plant, another CAP plant, Sandario Pumping Plant, was built from the same specification.

Following startup at Twin Peaks, it was apparent that several problems existed. First and foremost was a measured deficiency in pump capacity of about 10 pct, and a 15-pct decrease in efficiency over what was measured during shop tests. This shortfall in discharge and efficiency was only present with the larger pumps (4.25 m^3/s). This drop in flow was independently verified by a dye-dilution test performed by Alden Research Laboratories (Nystrom, 1992). In addition, unit No. 3 at Twin Peaks has had a failure of the diffuser bearings after less than 100 h of operation. The pump manufacturer contends that the problems encountered with these pumps have been the result of poor flow conditions in the sumps, which result in a submerged vortex that enters the pump bells. Prototype observations filmed with underwater video equipment between May 12-18, 1993, have indicated that vorticity is present, and with the injection of compressed air, a thin (25- to 50-mm-diameter) submerged vortex core can be visualized.

The 1:8.74 model was used to evaluate the effects of pump sump geometry on submerged vortex formation. First, we verified the present operational observations, i.e., presence of a submerged vortex. Following this verification, we developed modifications to the pump sumps which eliminated all vortices over a wide range of operating conditions. These modifications were then installed in bay No. 1 at Twin Peaks Pumping Plant for prototype verification tests.

CONCLUSIONS

Scale model tests verified the presence of a submerged floor vortex in each of the sumps. The model vortex was thin (about 3 mm in diameter) and fairly stable. Injection of dyes or air bubbles was required to make the vortex visible.

Comparison of the model vortex to the prototype vortex revealed many similarities. The prototype vortex core was only consistently visible when air bubbles were injected near the vortex location (on the floor, centered under the pump bells). In addition, the size of the visible core appeared to scale geometrically with the model vortex core. Neither the model nor the prototype installations displayed any indication of a sustained vapor core vortex.

Modifications to bay No. 1 were tested which eliminated all submerged vortices in the model. These modifications consisted of 45° splitters and fillets placed on the sump floor, extending from the back wall to one pump bell diameter upstream from the pump bell. In addition, a vertical splitter, located on the centerline of the back wall and extending up to near the minimum water surface, was used. These modifications were very effective in eliminating the vortex and creating a uniform flow distribution in the pump column at the impeller location. On September 22, 1993, a test was performed at Twin Peaks pumping plant with the recommended modifications installed in bay No. 1. With two underwater video cameras installed and air bubbles supplied as tracers, no submerged vortices were observed in the sump during almost 6 h of operation. However, the discharge and efficiency were unchanged from the values prior to the modifications and still well below the specified values. Therefore, we concluded that the deficiency in pump capacity and decrease in efficiency were not directly caused by the sump configuration.

Plant operations were studied in the model to evaluate the formation of both submerged and free-surface vortices in all pump sumps. The same sump modification which was installed in sump No. 1 was also installed in sumps No. 2 and 3. In addition, a series of fillets and splitters were added to sump No. 4 (multi-pump). These modifications performed well in the model, eliminating all vortex activity for a variety of operational sequences.

METHODS

A 1:8.74 undistorted geometric scale model of Twin Peaks Pumping Plant was constructed in the Denver Office Hydraulic Laboratory (fig. 1). The model included a short portion of the Tucson Aqueduct, the inlet transition, and four sumps (fig. 2). Within the four sumps were six pumps, three 4.25-m^3/s units each in their own sump, and three 1.42-m^3/s units in a common sump. The pump bells and columns were constructed from acrylic and connected to PVC piping (fig. 3). Each pump column was connected to a common manifold, which formed a closed loop system delivering flow back to the head box. An 11.2-kW centrifugal pump located in-line provided recirculation, and an orifice-venturi meter was used to measure discharges. Each pump column was equipped with an elbow meter so that individual unit flows could be adjusted when more than one unit was operating simultaneously.

Model similitude was based on equal Froude numbers in the model and the prototype. Froude scaling is generally used in models where turbulent free-surface flows are being represented. The corresponding ratios between model and prototype properties are: L_r = 8.74, V_r = 2.96, t_r = 2.96, and Q_r = 225.83, where L, V, t, and Q are length, velocity, time, and discharge, respectively. The model scale was chosen to ensure that viscous and surface tension effects were kept to a minimum. The critical Reynolds number to reproduce similar swirl in the model involves the velocity of approach and incoming depth in each sump. The model Reynolds number (2.4×10^4) is slightly below the recommended value of 3×10^4 suggested by Knauss (1987), but close enough that any distortions should be minimized.

In addition to making visual observations with air bubbles and dye as tracers, we made several different measurements to help us evaluate the sump performance. These measurements included velocity profiles in the sumps approaching the pumps, pre-rotation in the pump column, and velocity profiles in the pump column. The sump velocity profiles were taken with either an Ott propeller-type meter or a two-component Marsh-McBirney electromagnetic velocity meter. The pre-rotation measurements were taken with a vortimeter. This meter measured tangential velocity in the pump column, assuming solid body rotation (Lee and Durgin, 1980). The velocity profiles in the pump columns at the impeller location were measured using a standard pitot-static tube, traversed across the column on lines at 45° increments.

RESULTS

Initial operating observations indicated that submerged vortices were present in all bays when pumps were operating individually or in combination. Because no observable difference in vortex strength existed between bays, we decided to attempt to eliminate the vortex in bay No. 1 with only unit No. 1 operating.

Unit No. 1

Initial tests were performed on the as-built sump. Figure 4 shows prototype sump dimensions. A prototype flow rate of 4.39 m^3/s was used for all tests. No decline in discharge was assumed. All tests were run with the minimum water surface elevation, which resulted in a depth of 5.08 m in the sump at the pump location. Figures 5 and 6 show velocity profiles taken in the sump at the entrance (in front of the trashracks) and at the stoplog slot. Figure 7 shows the velocity distribution one pump bell diameter in front of the pump column. The vortimeter revealed very small values of pre-rotation entering the pump column. The average swirl angle determined from vortimeter tests was about 0.8°. Instantaneous swirl angles approached 2° (5° is generally the accepted limiting condition at which problems begin to occur [Knauss, 1987]). Figure 8 shows the velocity profile taken inside the pump column near the impeller location. The data have been normalized using the average of all the point velocity readings taken.

Modification A. - The first modification was the placement of a small cone on the floor of the sump directly below the centerline of the pump column. A vortex was still clearly present when visualized with a tracer (fig. 9). Because of the continued presence of the vortex, this modification was abandoned.

Modification B. - The second modification was placement of a relatively thin splitter wall on the floor directly beneath the longitudinal centerline of the pump bell (fig. 10). After initial tests, the floor vortex was still present, and this scheme was also abandoned.

Modification C. - This modification was the first in a series of floor splitters and fillets made up of 45° sections. The first trial was with a floor splitter which extended from the back wall to one pump bell diameter upstream from the pump column. The height of the splitter was half of the distance from the floor to the bottom of the pump bell (fig. 11). This modification was successful in eliminating the floor vortex; however, horizontal side-wall vortices formed because of the circulation patterns created by the splitter wall.

Modification D. - This modification included adding side- and back-wall fillets to the floor splitter of modification C (fig. 12). These side-wall and back-wall fillets eliminated all submerged vortex action. The velocity distribution in the pump column for this case is shown on figure 13. A fairly strong circulation of flow still occurred behind the pump bell, so a back-wall splitter was proposed.

Modification E. - The final modification tested included all appurtenances of modification D plus a back-wall splitter placed vertically from the floor to above the minimum water surface (fig. 14). The edge of the splitter wall was placed about 150 mm (prototype) away from the back edge of the pump bell (Nakato, 1989). The velocity distribution in the pump column for this modification is shown on figure 15. This configuration did show some tendency for the formation of surface vortices, originating near the back-wall splitter. A fairly strong surface current circulated behind the pump column and actually separated off the back-wall splitter, causing a very tight eddy which organized into an air-entraining surface vortex. We reduced the height of the back-wall splitter, which allowed the surface currents to recirculate (without separation) and seemed to eliminate the formation of the free-surface vortices.

In addition to modification of the sump, a larger diameter pump bell was built and tested. A pump bell 2400 mm in diameter was installed in sump No. 3 of the model. The larger pump bell alone did not preclude the formation of the submerged floor vortex. However, the reduced velocity at the impeller location allowed a more uniform velocity distribution to be achieved with less modification to the sump.

Multiple Pump Sump Operation

Multiple pumps operating simultaneously were also studied. We tried to identify the worst approach flow conditions which resulted from multiple pump operation. Through trial and error, we identified this condition to be in sump No. 1 when unit No. 1 was operating along with units No. 4, 5, and 6 (combined sump). This condition generally results in a strong flow perpendicular to the sump intakes, flowing from sump No. 4 toward sump No. 1. However, the resulting velocity distribution in the pump column at the impeller location of unit No. 1 was about the same as when unit No. 1 was operating alone (fig. 16).

The smaller pumps, units No. 4, 5, and 6, also exhibited submerged vortex activity in the model. These units delivered the specified capacity when measured in the field. We worked on modifications which eliminated the vortices (both submerged and free-surface) in the model (fig. 17). This series of splitters and fillets is of similar design to that used in sumps No. 1, 2, and 3. In addition, the openings at the backs of the intermediate piers were closed off with a 50-pct open area perforated plate. No detailed measurements (i.e., velocity profiles in the pump columns) were taken in support of this work, only visual observations.

DISCUSSION

Submerged vortices (floor-attached) directly beneath the pump bell were verified in all sumps. This type of vortex is usually generated by local flow conditions near the pump bell. Considering the uneven velocity distributions approaching the pump bells and that several of the sump dimensions (based on the supplied pump bell diameter) were outside of the recommended guidelines, the conditions were prime for submerged vortex formation (Triplett et al., 1988; Sweeney et al., 1979). Although improving the flow distribution in the sump helps in reducing vorticity, many researchers have approached the elimination of submerged vortices by placing fillets and splitters in the sump near the pump bell. Very little information is available about scale effects present in the modeling of submerged vortices because of the difficultly in actually visualizing prototype vortices. Our ability in this case to observe the prototype vortices through underwater video and actually compare them to the vortices observed in the model was especially meaningful. In the past, many techniques have been used to assist in the modeling of vortices. In general, the current feeling is that a model should be of a large enough scale ($L_r < 12$) that the Reynolds number remains large enough ($Re > 10^5$) that viscous effects are negligible. In the past, many researchers conducted studies using discharges up to 1.5 times the scaled discharge to aid in the production of vortices in models. However, the majority of present-day studies have abandoned this technique, especially on larger scale models, because of the distortion which results from the increased flows in correctly modeling the streamlines and shear zones around and near sump boundaries.

Perhaps the most meaningful of all the model measurements are the velocity distributions taken in the pump column at the impeller location. As previously mentioned, the pre-rotation at this location was small (2° maximum), with a swirl angle much below the suggested 5° limit. The floor vortex which is present in the original configuration is small in diameter and essentially passes straight up through the pump column. Observations have shown that the submerged vortex does not appear to have a significant influence on the large-scale swirl (or pre-rotation) at the impeller location. In general, insufficient pump capacity has normally been related to large scale swirl. The velocity distribution taken at the impeller location for the original design showed point velocity measurements deviated up to 10 pct from the mean velocity. This uneven velocity distribution has been shown to be consistent with higher head losses in the pump bell and the presence of vorticity. Once the submerged vortices were eliminated (addition of fillets and splitters to the sump), the velocity distributions evened out, with all measured point velocities staying within ±5 pct of the mean velocity. The final configuration actually showed all measurements between -3 and +2 pct. This uniform velocity distribution indicates a lack of vorticity and essentially uniform flow approaching the impeller location.

The testing of a larger diameter pump bell (1.75*D*, where *D* is the discharge column size) still indicated the presence of a submerged vortex. The pumps were specified in a performance specification (Bureau of Reclamation, 1986), along with the sump configuration and discharge column size (1371.6 mm). In general, most design guidelines (Hydraulic Institute Standards, 1975; Prosser, 1977; Knauss, 1987) suggest that the pump bell diameter be between 1.5 to 1.8 times the diameter of the discharge column (1372 mm). This guideline would put the pump bell diameter in the range of 2057 to 2469 mm in diameter. The current pump bells are 1664 mm in diameter (1.2*D*) and were sized within the guidelines assuming that the diameter ratio was based on the minimum diameter at the impeller (914 mm), not the size of the discharge column. Because of the size of the pump bell, the spacing from the back wall to the edge of the bell is too large, and the total width of the sump is too wide to comply with suggested design standards. The formation of a submerged vortex with the larger pump bell does reinforce the idea that local flow conditions at the pump location are predominantly the cause of submerged vortex formation. However, as expected, the larger pump bell was more responsive to sump modifications because of lower mean velocities in the pump bell (Nakato, 1993).

Additional tests with combined operation of multiple pumps did not reveal any major differences in either vortex formation or appearance, or velocity distributions. Observations of approach flow conditions within each sump for a variety of operating conditions did not reveal any more severe a condition than that exhibited when unit No. 1 was operating alone. In general, all pump operations cause a clockwise rotation in the inlet transition, causing flow to sweep across the sump intakes from left to right looking downstream (fig. 18a). On occasion, when unit No. 1 was started first, we observed a counter-clockwise rotation in the inlet transition (fig. 18b). This pattern however, depended highly on the conditions which existed in the inlet transition and probably will be affected by factors in the field such as wind direction, wind magnitude and sediment deposits in the inlet transition. In addition to the separate sumps for units No. 1, 2, and 3, vortex activity was present in sump No. 4. In general, vortex problems in a sump with multiple pumps can be more difficult to resolve. With the addition of floor splitters and fillets similar to those used in the other sumps, and blocking the open area in the intermediate piers at the back wall, satisfactory flow conditions were achieved. Initial observations in sump No. 4 showed a higher level of free-surface vortex activity, which could be indicative of the higher level of noise noted at the plant during operation of units No. 4, 5, and 6.

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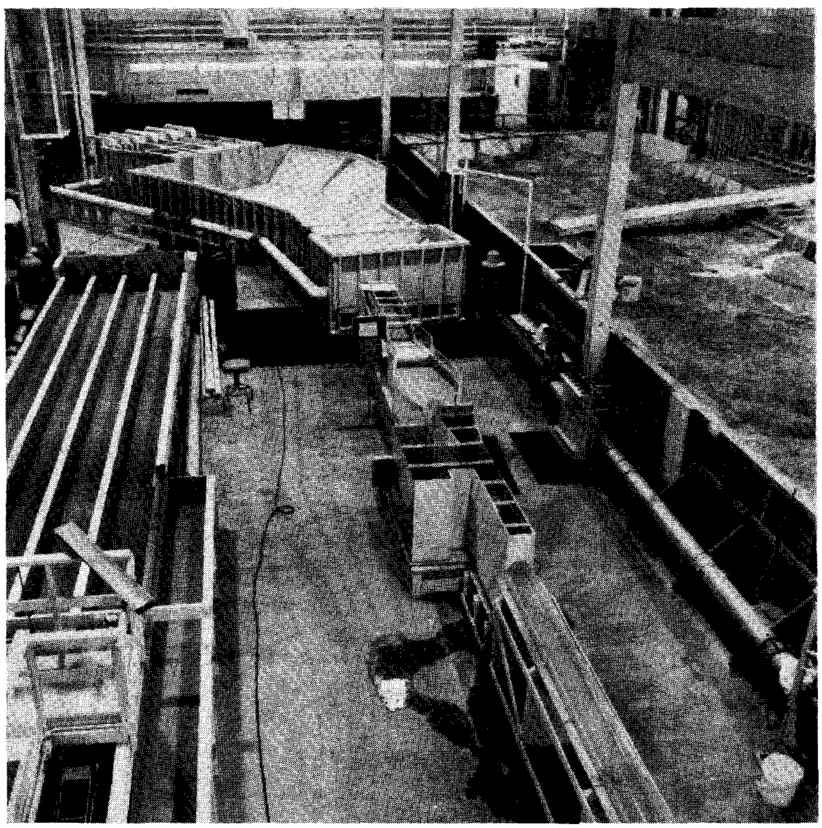


Figure 1. - 1:8.74 scale model of Twin Peaks Pumping Plant, constructed in Reclamation's hydraulic laboratory.

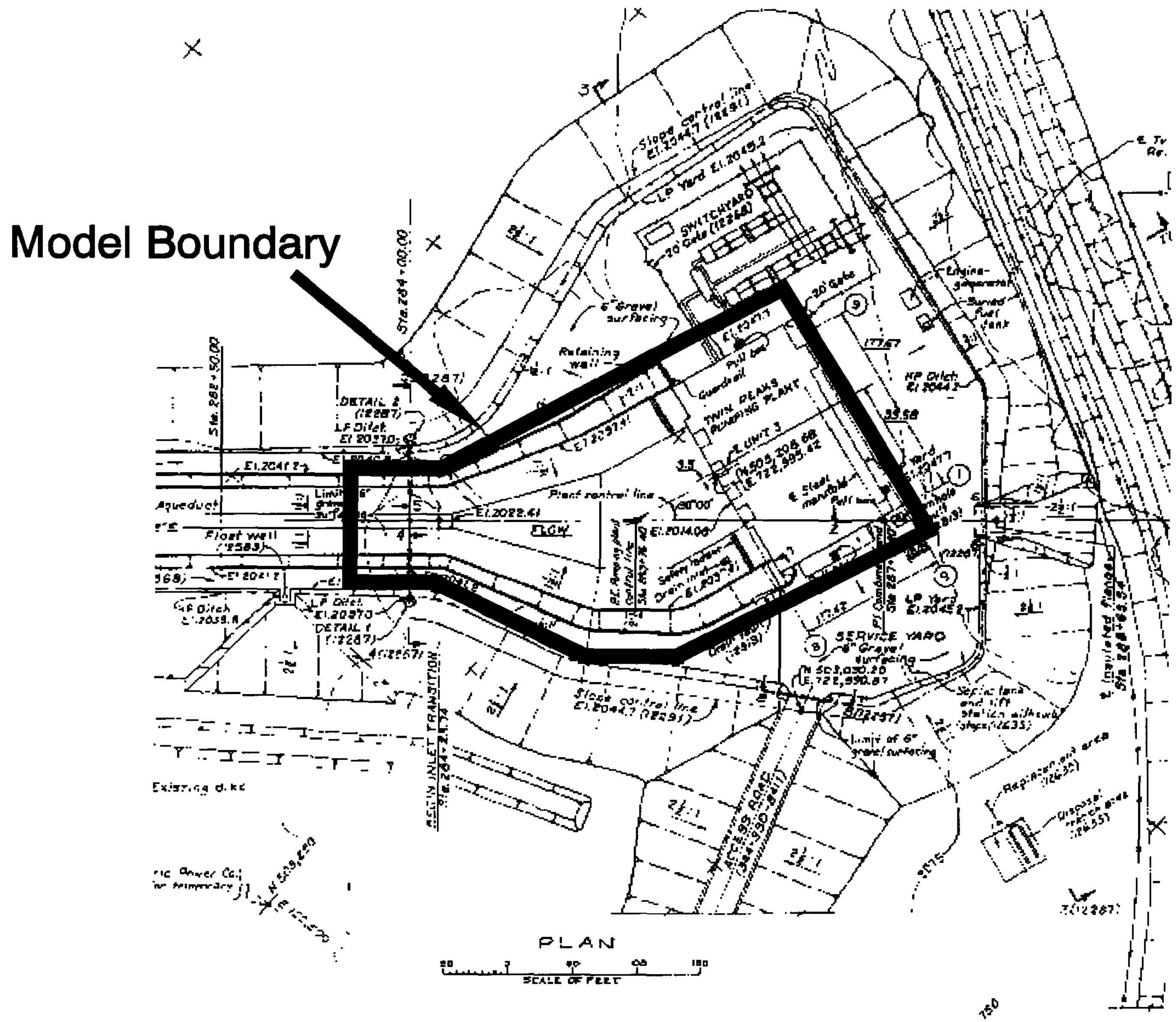


Figure 2. - Approximate model boundaries overlaid on plan view of Twin Peaks Pumping Plant.

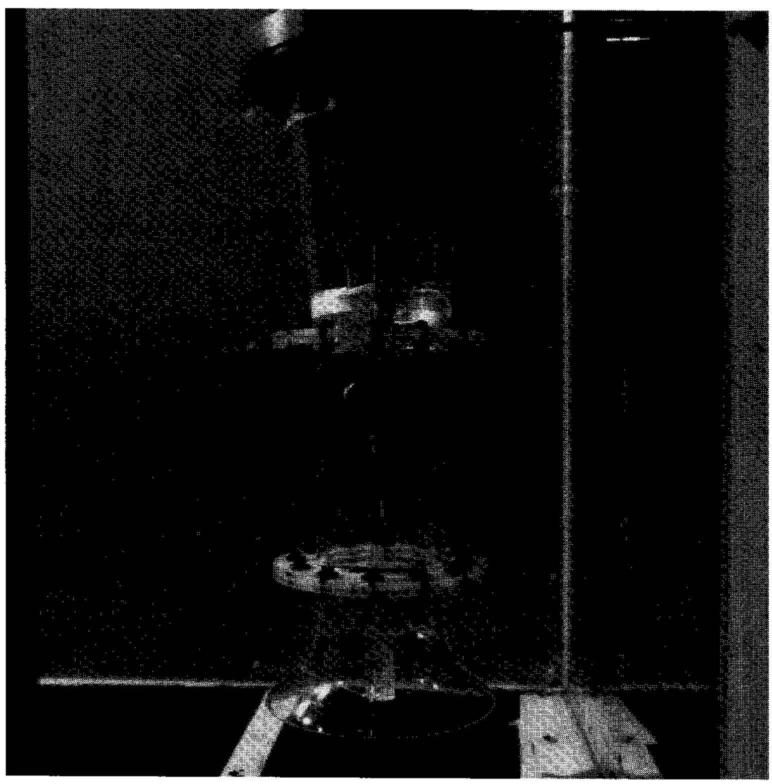


Figure 3. - Acrylic pump bells fabricated for use in model.

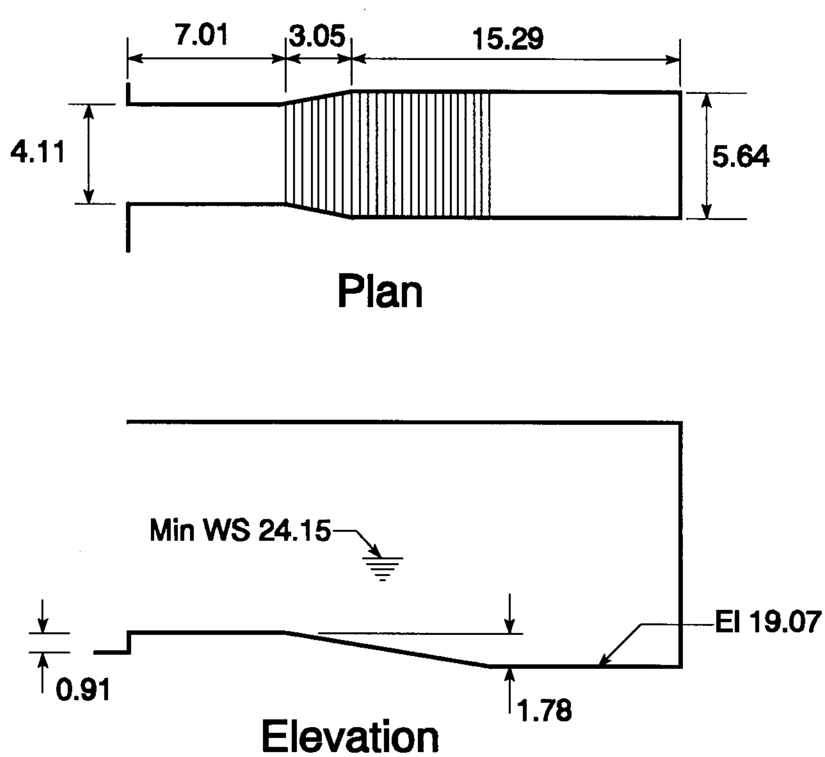


Figure 4. - Basic sump dimensions (prototype meters) for units No. 1-3, Twin Peaks Pumping Plant.

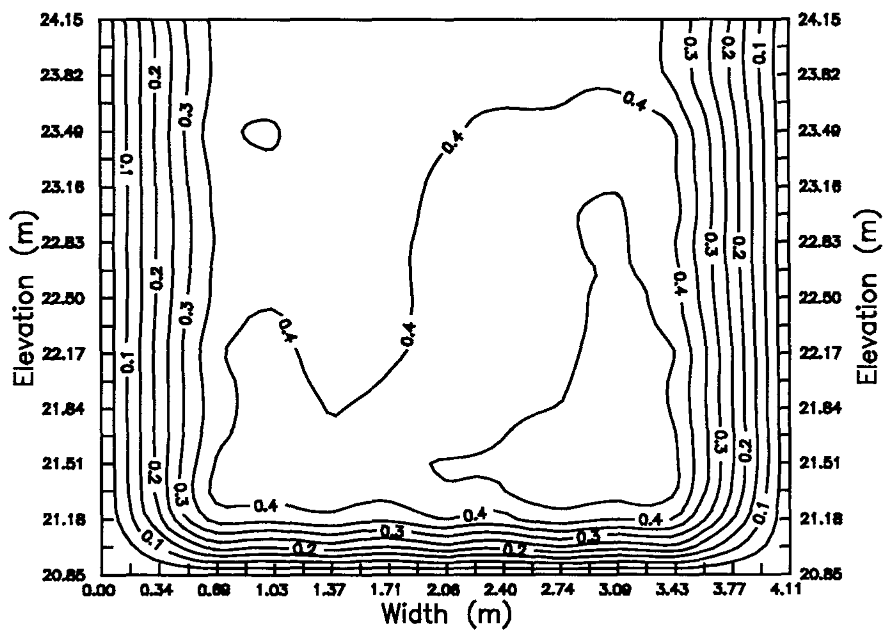


Figure 5. - Velocity profile at entrance to sump No. 1. Minimum water surface elevation 24.15 m, Q = 4.39 m^3/s, looking toward pump. Dimensions are prototype, velocities in m/s.

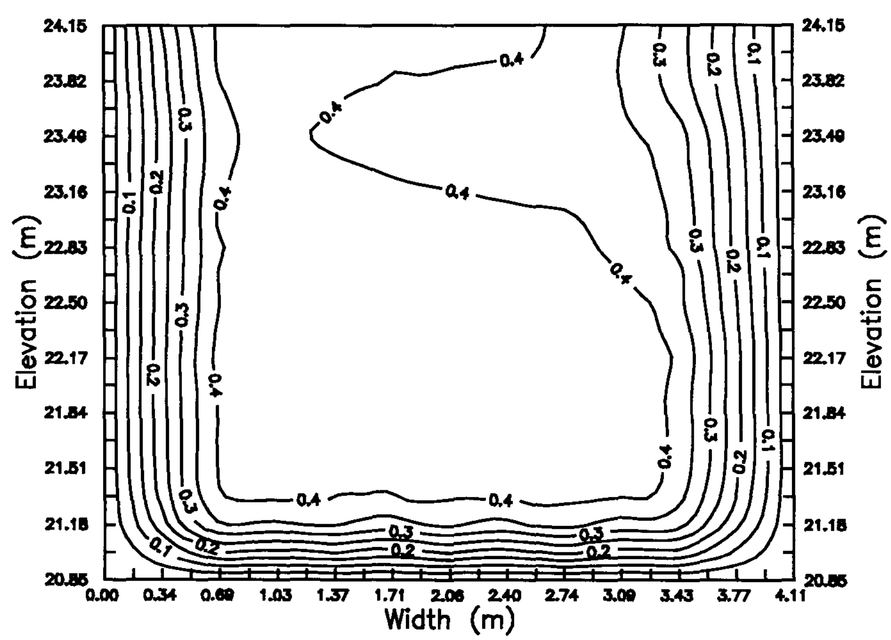


Figure 6. - Velocity profile in sump No. 1 at the stoplog slot. Minimum water surface elevation is 24.15 m, Q = 4.39 m^3/s, looking toward pump. Dimensions are prototype, velocities in m/s.

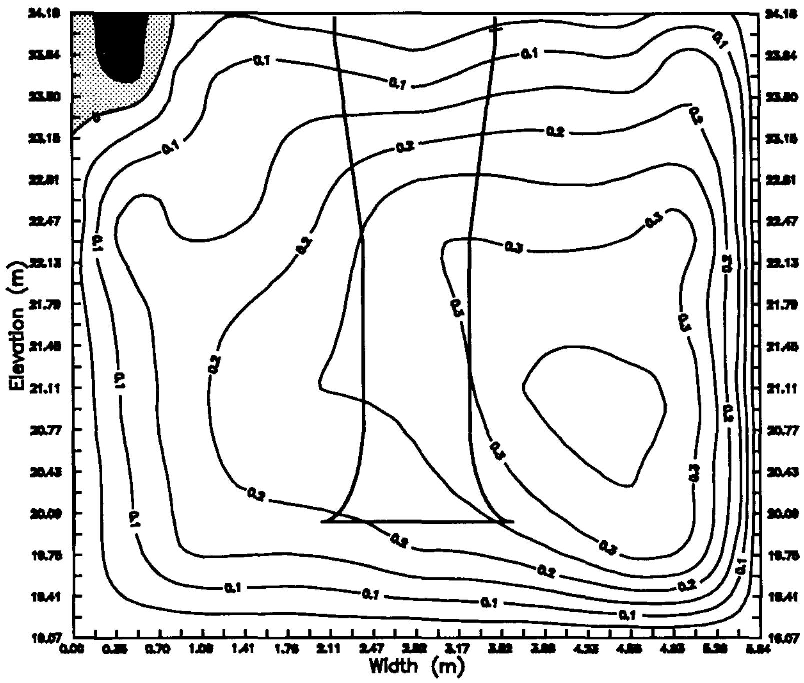


Figure 7. - Velocity profile in sump No. 1, one pump bell diameter in front of the pump bell. Minimum water surface elevation is 24.15 m, Q = 4.39 m^3/s, looking toward pump. Dimensions are prototype, velocities in m/s.

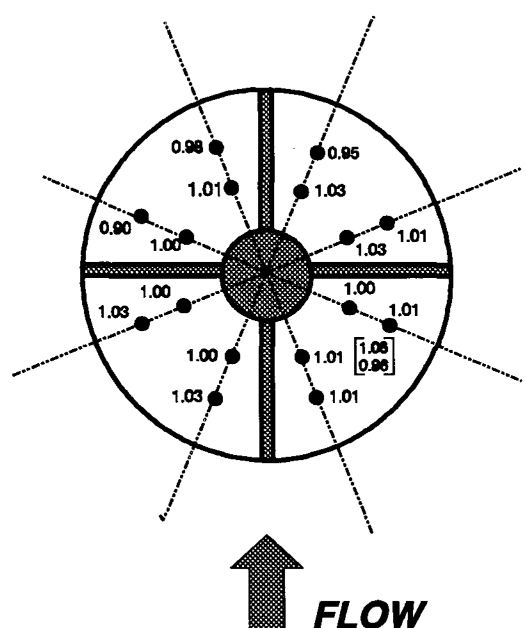


Figure 8. - Velocity profile in pump column, unit No. 1, original configuration. Q = 4.39 m^3/s, values in parentheses show range of data due to fluctuations caused by the submerged vortex.

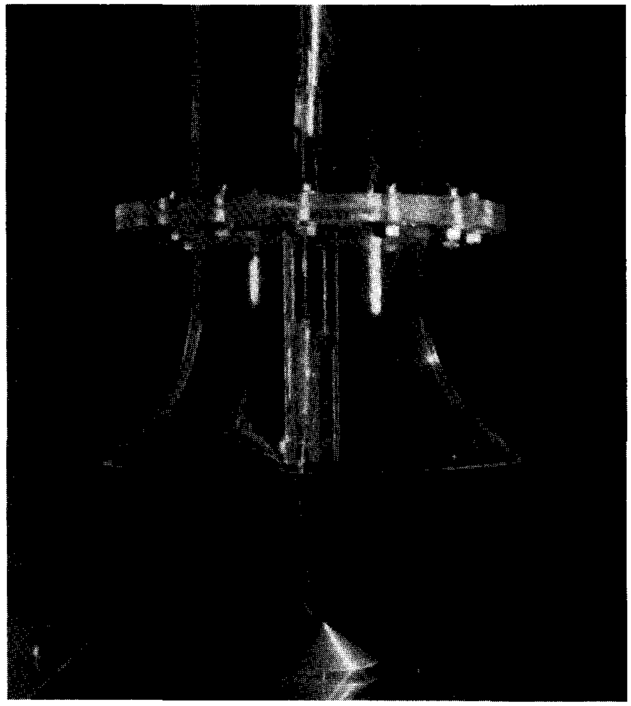


Figure 9. - Submerged vortex attached to floor cone. Vorticity actually increased over plain floor.

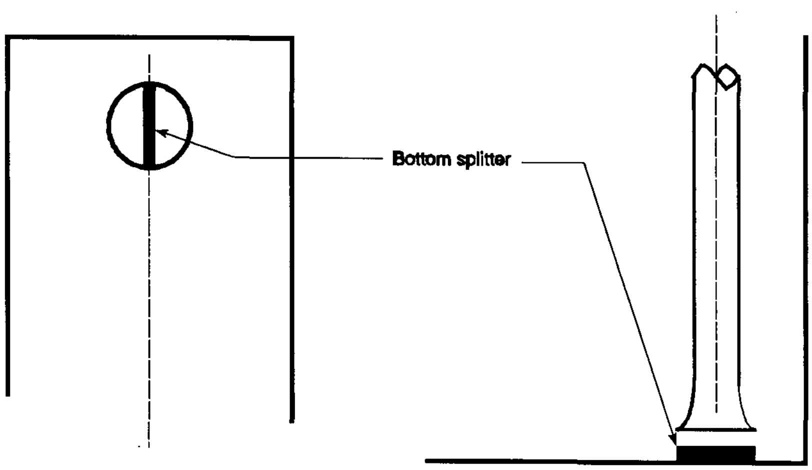
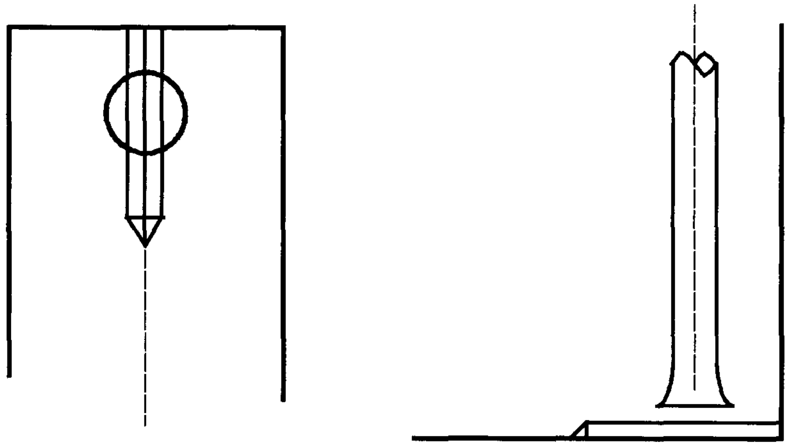
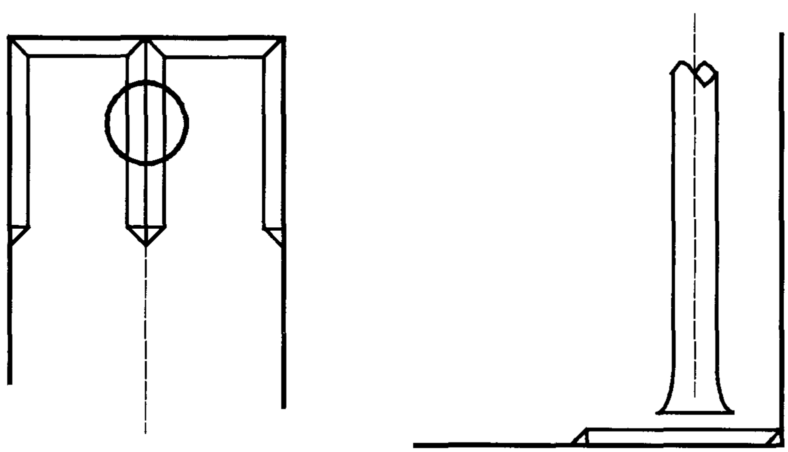


Figure 10. - Short bottom splitter wall. Height is 0.40 m prototype.



PLAN ELEVATION

Figure 11. - Modification C, 45° floor splitter.



PLAN ELEVATION

Figure 12. - Modification D, 45° floor splitter and fillets.

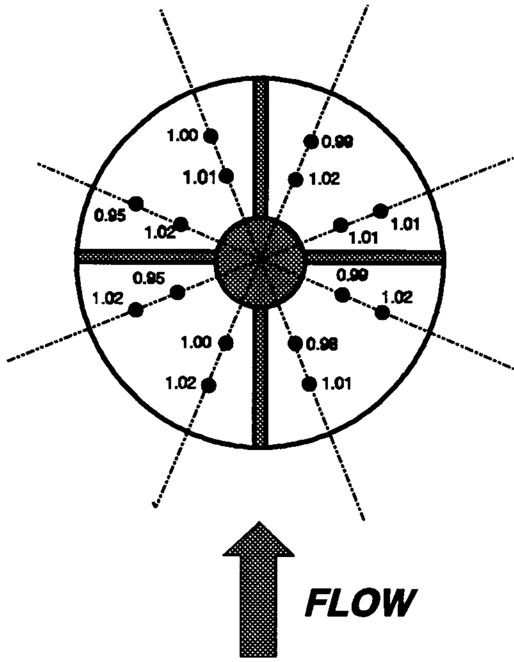


Figure 13. - Normalized velocity profile in pump column, modification D installed.

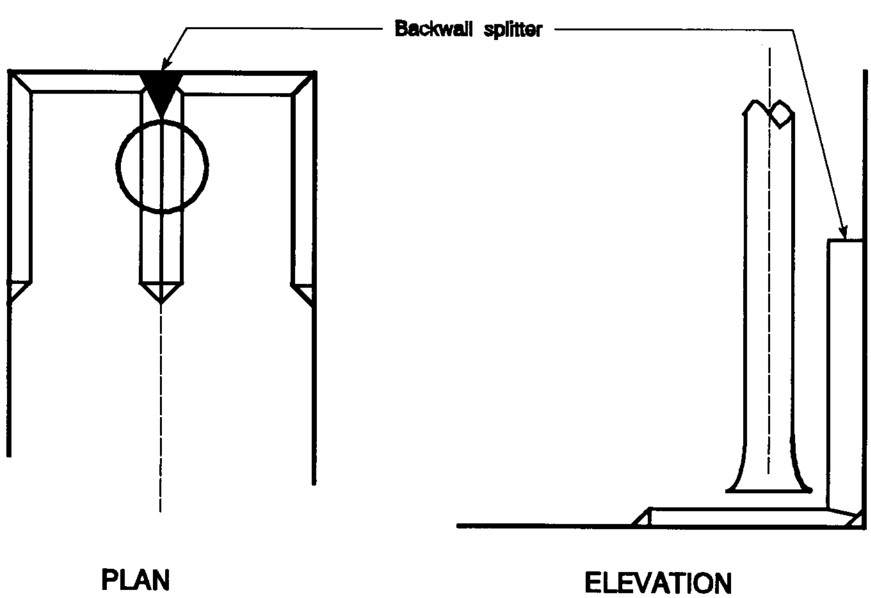


Figure 14. - Modification E, back-wall splitter installed—recommended design.

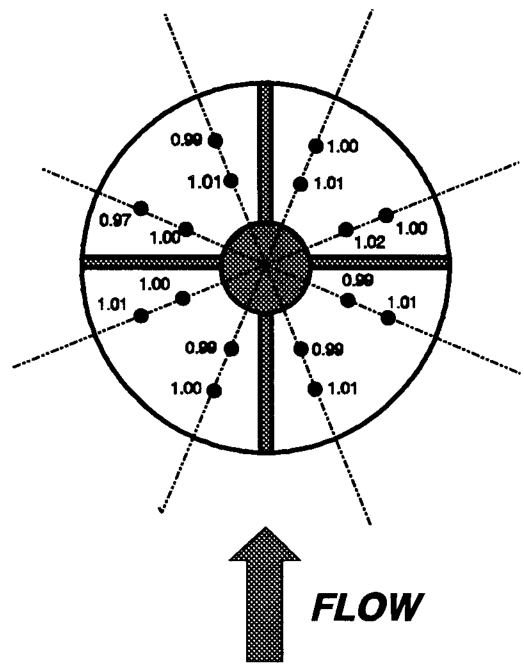


Figure 15. - Normalized velocity profile in pump column, modification E installed—recommended configuration.

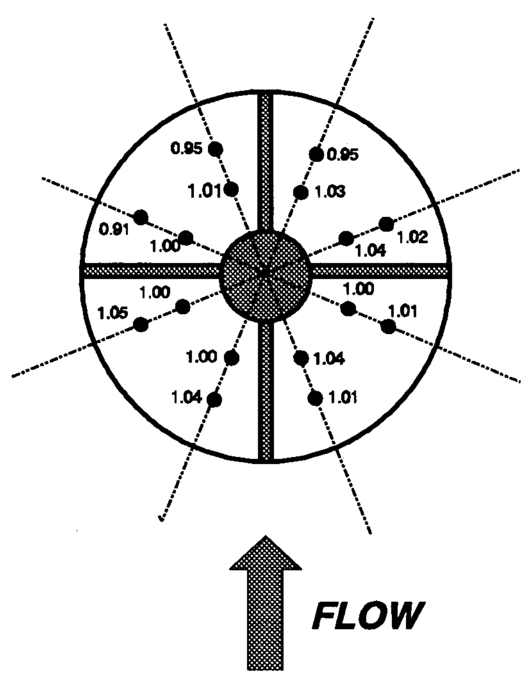


Figure 16. - Velocity profile at impeller location, unit No. 1, with worst case approach flow conditions.

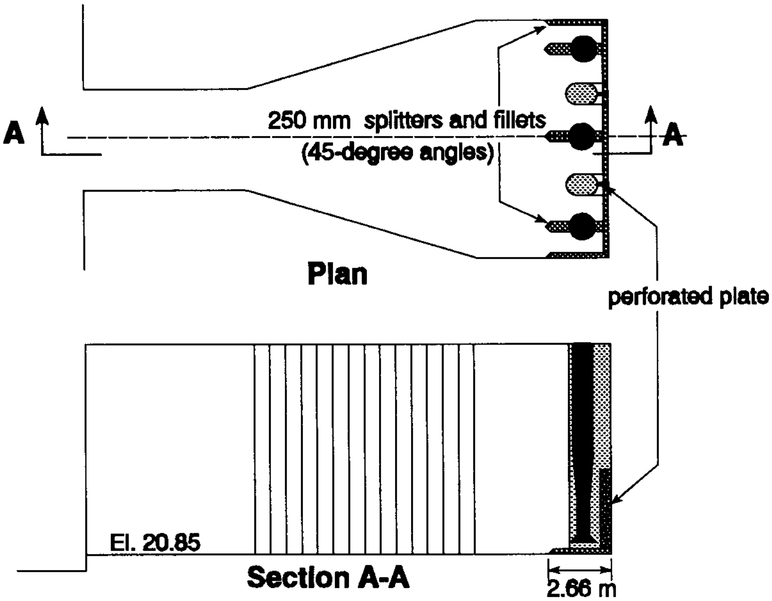


Figure 17. - Sump No. 4, modifications used to prevent submerged vortex formation.

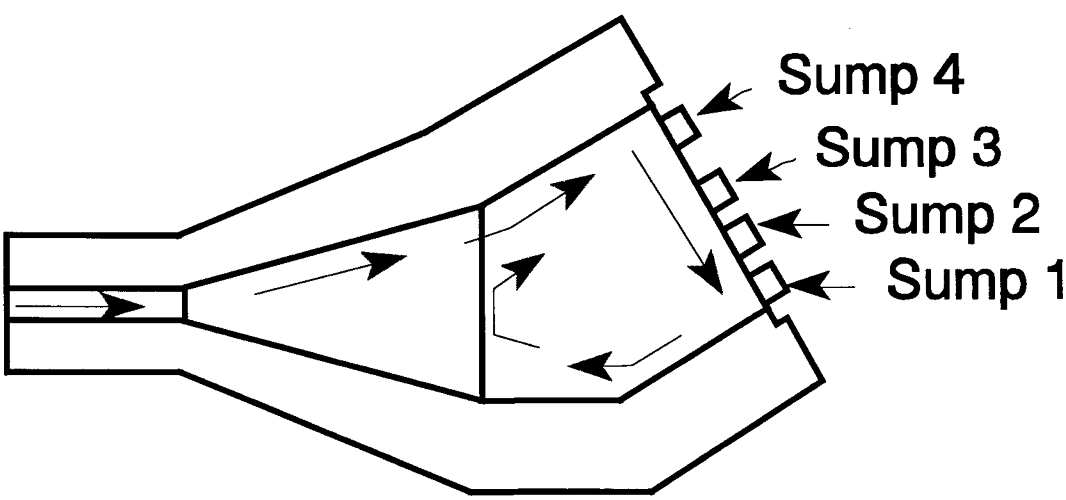


Figure 18a. - Normal circulation pattern seen in inlet transition for most operations.

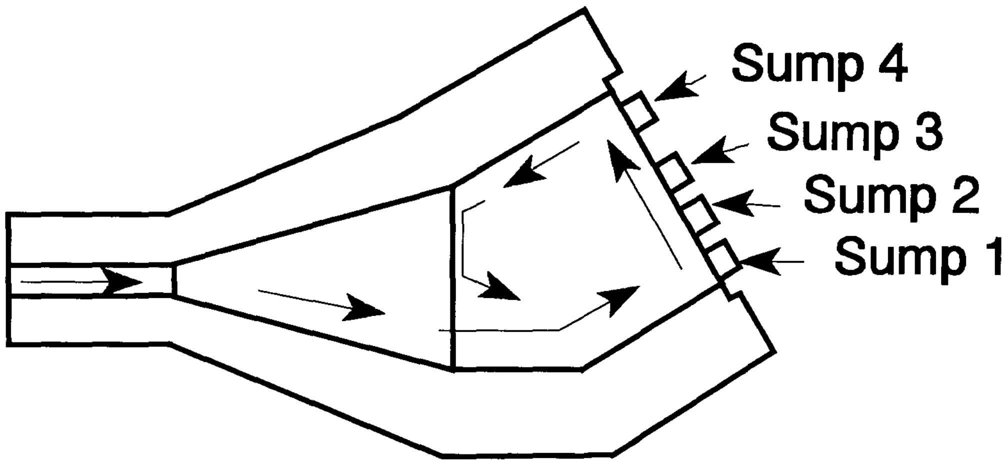


Figure 18b. - Occasional flow circulation pattern if unit No. 1 is turned on first. Pattern depends on conditions in inlet transition.

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.