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HYDRAULIC MODEL STUDIES OF A 52-INCH MULTIPORTED SLEEVE VALVE FOR SIXTH WATER AQUEDUCT FLOW CONTROL STRUCTURE

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16. ABSTRACT

The Bureau of Reclamation Hydraulic Laboratory performed scale model tests on the 52-inch multiported sleeve valves to be installed in the flow control structure of the Sixth Water Aqueduct. These valves are designed with a capacity of 400 ft^3/s each, and will operate at heads up to 1,325 ft of water. Several alternative methods of flow control were considered, but the sleeve valve proved to be the most versatile for both controlling the discharges and dissipating the energy present. Model tests using several different sized multiholed orifice plates were used to verify the discharge characteristics of the multiport configuration. The coefficient of discharge ranged between 0.98 and 0.99 (a value of 0.95 was used in the initial design). These tests provided the data necessary to correct for scale effects which were observed in the three dimensional model. A 1:6.6 scale model of the valve and vertical stilling well was used to verify operational characteristics. The seal configuration between the sleeve and valve body performed well. No vibration was noted during model operation, even at scaled heads much greater than the design value. Design of the stilling well was verified in the model and an acceptable discharge from the well was achieved. Impact pressures on the walls of the stilling well were below the limits prescribed for a steel-lined well. Cavitation was present in the free shear layers of the disintegrating jets emanating from the multiple ports. No evidence of cavitation damage appeared on the valve body or sleeve after extensive operation of the model valve at heads in the model of up to 575 ft of water.

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K. Warren Frizell

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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

Sixth Water Aqueduct will be located 20 miles southeast of Provo, Utah. It will deliver water to Sixth Water Creek, 8 miles southwest of Strawberry Reservoir. The aqueduct begins at the outlet of Syar Tunnel and terminates at Sixth Water Creek, figure 1. Its features include a steel pipeline, a steel-lined shaft and tunnel, and a high-head outlet works on Sixth Water Creek. The Sixth Water flow control structure will contain two spherical valves for isolation and two vertical multiported sleeve valves for flow control and energy dissipation. The sleeve valves will be 52 inches in diameter and are designed for 1,325 ft of water pressure head, figure 2. Prior to this application, Reclamation has not designed a sleeve valve for this pressure range.

The concept for the sleeve valve grew out of Reclamation's early investigations on low-head vertical stilling wells in 1947 (Schuster and Simmons, 1949). Reclamation designed the first sleeve-type valve for the Wanship Dam in 1954 (Falvey, 1962). Burgi (1975) summarized 25 years of Reclamation research and experience in the design of vertical stilling wells. Miller (1968), of Glenfield & Kennedy, Ltd., in Great Britain, studied a valve similar to the Wanship design, but added an attachment which converted the standard sleeve valve to a ported sleeve valve. He noted more effective energy dissipation resulting from the numerous small individual jets leaving the valve.

At about the same time (1969), engineers with the Metropolitan Water District of Southern California were testing a 12-inch vertical sleeve valve based on the Wanship design. As might be expected, they discovered problems with cavitation damage to the valve's sleeve and pedestal at heads greater than about 100 ft. They developed an outer sleeve with a large number of small nozzles and attached it to the valve they had been studying (Johnson, 1970). They tested this multiport sleeve valve at heads up to 600 ft. They found that with properly spaced nozzles, cavitation damage to the valve body and stilling well surfaces was eliminated.

In the past twenty years, numerous multiport sleeve valves have been designed, tested, and installed (Watson, 1977) (Burgi, 1977). The size and head ranges are slowly being increased through further testing and prototype operating experience.

The investigations detailed in this report include a series of tests on multihole orifice plates and a 1:6.6 Froude-based hydraulic scale model of a 52-inch-diameter multiport sleeve valve. The orifice plates were used to determine the appropriate discharge coefficient for the design port configuration. We used the scale model of the sleeve valve to study operational concerns as well as to optimize the stilling well design.

CONCLUSIONS

This report summarizes scale model tests performed on the 52-inch multiported sleeve valves which will be installed in the flow control structure of the Sixth Water Aqueduct. These valves are designed with a capacity of 400 ft^3/s each, and will operate at heads up to 1325 ft of water. Several alternative methods of flow control were considered, but the sleeve valve proved to be the most versatile for both controlling the discharges and dissipating the energy present. Model tests using several different sized multiholed orifice plates were used to verify the discharge characteristics of the multiport configuration. The coefficient of discharge ranged between 0.98 and 0.99 (a value of 0.95 was used in the initial design). These tests provided the data necessary to correct for scale effects which were observed in the three dimensional model. A 1:6.6 scale model of the valve and vertical stilling well was used to verify operational characteristics. The seal configuration between the sleeve and valve body performed well. No vibration was noted during model operation, even at scaled heads much greater than the design value. Design of the stilling well was verified in the model and an acceptable discharge from the well was achieved. Impact pressures on the walls of the stilling well were below the limits prescribed for a steel-lined well. Cavitation was present in the free shear layers of the disintegrating jets emanating from the multiple ports. No evidence of cavitation damage appeared on the valve body or sleeve after extensive operation of the model valve at heads in the model of up to 575 ft of water.

METHODS

We used two experimental setups to test various features of the sleeve valve and its associated structure. One arrangement was used to determine the discharge coefficient for the design port configuration. This testing was also used to develop procedures for correcting scale effects present in the three dimensional model. The other test setup was a 1:6.6 Froude-based three dimensional hydraulic model.

Port Discharge Characteristics

We tested seven multiholed orifice plates in the Hydraulic Laboratory's high-head test facility. Each plate contained multiple holes with length-to-diameter ratios of three (short tubes). Of these plates, four had cylindrical holes (constant diameter) and two had tapered holes with a total included angle of 15 degrees, figure 3. Each plate was installed near the end of an 8-inch pipeline and we were able to adjust pressures on each side of the plate. The plates tested are summarized in table 1. The spacing between holes was scaled based on the prototype design which considered an areal velocity effect from each port.

Table 1. — Dimensions of multiholed orifice plates tested.

Plate No.	Hole diameter (inch)	No. holes	L/D	Spacing (Centers) (inch)	Hole type
1	0.089	153	3	0.5	Cylindrical
2	0.125	76	3	0.72	Cylindrical
3	0.25	16	3	1.00	Cylindrical
4	0.25	16	3	1.00	Cylindrical
5	0.25	16	3	1.00	Tapered (15°)
6	0.5625	4	3	2.25	Cylindrical
7	0.5625	4	3	2.25	Tapered (15°)

The discharge was monitored with a strap-on acoustic flowmeter. The flowmeter was calibrated against the high-head pump system venturi meter. The test procedure consisted of setting an upstream head using the system pressure gauge and then adjusting the downstream head. When steady-state conditions were reached, we took 500 readings from the flowmeter and averaged them. Each discharge reading posted by the flowmeter is the result of collecting 100 valid measurements. Using the head and discharge measurements, we calculated the coefficient of discharge based on the minimum hole diameter (exit diameter).

Valve Scale Model

A 1:6.6 scale hydraulic model of the 52-inch multiported sleeve valve was constructed and tested in Reclamation's high-head test facility, figure 4. The model included a section of horizontal pipe, the elbow leading to the valve, and the valve itself. The valve was housed in a square stilling well with an overflow weir-type outlet. The valve was constructed from steel and geometrically scaled, figure 5. Tolerances between the sleeve and valve body were adjusted and kept as an RC3 class fit (ASME, 1987). The 1020 (quantity) 0.5625-inch tapered ports for the prototype valve were modeled with cylindrical holes (0.089 inch) to facilitate model fabrication. To pass similar discharges, the holes were resized (enlarged by 7.6 percent in diameter to equal 0.089 inch) based on the differences between the theoretical coefficient of discharge for a cylindrical short tube (0.82) (Brater and King, 1976), and the theoretical coefficient for a tapered short tube (0.95). We measured the valve opening with a string transducer. The discharge was monitored with a strap-on acoustic flowmeter. We evaluated the vertical stilling well performance by looking at the energy dissipation and side wall pressures. A capacitance-type wave probe was placed in the stilling well to monitor the water surface. A number of modifications to the well were tested and compared, figure 6. These modifications were symmetric in all four corners.

Wall pressures were measured at two locations on the sidewalls. We used flush-mounted pressure transducers centered on each of two adjacent walls and 5.6 ft (prototype) above the well floor, figure 7. Additional impact pressure tests were completed using both the cylindrical and tapered 0.25-inch-diameter multiholed orifice plates. These tests simulated impacts by placing a vertical wall at the scaled distance from the valve body to the stilling well wall and then measuring average pressures on this wall with flush mounted pressure transducers.

RESULTS

Coefficient of Discharge

The data collected on the seven multiholed orifice plates provided some interesting information on the performance of short tubes of various sizes at high differential pressures. The coefficient of discharge was determined from the equation:

$$Q = C_d A \sqrt{2g\Delta h}$$

where:

Q = discharge (ft^3/s)
C_d = coefficient of discharge
A = total open flow area (ft^2)
g = gravitational constant (ft/s^2)
Δh = pressure drop across orifice (ft)

The coefficients of discharge for the various plates tested appear in table 2.

Table 2. — Coefficient of discharge results for multi-holed orifice plates.

Plate No.	Hole size (inch)	C_d	Type	Comments
1	0.089	0.50	Cylindrical	Sharp edged
2	0.125	0.59	Cylindrical	Sharp edged
3	0.25	0.66	Cylindrical	Sharp edged
4	0.25	0.86	Cylindrical	Deburred (bevel)
5	0.25	0.98	Tapered (15°)	Sharp edged
6	0.5625	0.59	Cylindrical	Sharp edged
7	0.5625	0.99	Tapered (15°)	Sharp edged

These data report the coefficient once it had approached a constant value. The 0.125-, 0,25- and 0.5625-inch-diameter cylindrical short tubes all tended toward a coefficient of discharge of about 0.6 at high Reynolds numbers (Re > 10^5). The 0.089-inch-diameter short tubes showed a lower coefficient, 0.50. The converging short tubes were measured to have a C_d of 0.98 to 0.99 (based on the minimum diameter) for both the 0.25-inch- and 0.5625-inch-diameter tubes. These coefficient data allowed us to make the necessary corrections in head to the 1:6.6 scale model in order to model similar discharges. [The C_d value (0.50) for the 0.089-inch-diameter holes was verified at a 100-percent opening in the three-dimensional model.] Using the measured coefficient of discharge (0.98), we computed a prototype discharge curve for a fully opened valve, figure 8.

Stilling Well Design

We evaluated the stilling well design by measuring the mean water surface in the well and by measuring the impact pressures of the valve discharge on the side walls. Table 3 shows the water surface data for all the modifications tested. Based on a rating system which included the average, maximum, and range (maximum-minimum) of the data collected, Modification f was the best overall performer. However, modification c, the small gusset plates with the angle, is recommended because it performed almost as good and it offers a much simpler installation. Loading on the exposed portion of the small gusset plates was derived from pressure distributions measured in the model and converted to a force, figure 9. These forces are in the upward direction. The instantaneous minimum and maximum forces were recorded for a 100-percent valve opening and were 637 lb and 938 lb, (prototype), respectively.

Prototype jet impact pressures are summarized on figures 10 and 11. Figure 10 shows the influence of the cylindrical nozzles versus the tapered nozzles. These impact pressures were measured using the flat-plate test setup. Figure 11 shows the effect of the 6- by 6-inch (prototype) angle mounted around the well perimeter [10 ft (prototype) above the well floor] on the pressure field. Impact pressures generated by the recommended well design (modification c) with design discharge are shown on figure 12.

Table 3. — Water surface measurements in the stilling well for all modifications tested (see figure 6).

Valve opening (%)	Water surface above sill EL. 6311 (ft)															
	a	b			c			d			e			f		
	Avg	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max
20	-	1.283	1.382	1.464	1.420	1.464	1.552	1.376	1.508	1.552	1.282	1.376	1.552	1.238	1.420	1.508
40	-	2.036	2.438	3.054	1.948	2.394	2.834	2.124	2.394	2.658	1.904	2.394	2.746	1.904	2.124	2.614
60	-	2.790	3.103	3.412	2.658	3.147	3.632	2.834	3.324	4.165	2.614	3.103	3.852	2.790	3.054	3.588
80	-	3.324	4.077	5.051	3.412	3.989	4.826	3.010	4.077	4.606	3.147	4.033	4.875	3.632	4.077	4.694
100	6.157	4.033	4.650	5.580	4.297	4.694	5.447	4.385	4.875	5.359	4.033	4.782	5.981	4.385	4.826	5.403

DISCUSSION

The laboratory tests revealed some interesting features about the performance of standard and tapered short tubes at high differential pressures. It is generally known that there is a Reynolds number effect on the coefficient of discharge for orifices, but C_d should converge to a single value at high Reynolds number (Re ≥ 200000). Initially, we had assumed a C_d for a cylindrical short tube (L/D=3) to be about 0.82 (Brater and King, 1976). The first multiholed orifice plate we tested (0.25-inch deburred), gave a C_d of 0.86. We then decided to test a variety of hole sizes to verify the coefficient as well as see if any other scale effects might be present. The 0.125-inch-diameter short tube had a coefficient of about 0.59. This result was confusing, especially when the 0.5625-inch diameter short tube gave us a similar value. These two plates both had cylindrical holes which had been left with sharp, 90-degree edges. The beveled edges on the deburred holes (0.25-inch plate) appeared to be the only difference. Looking back at the reference on short tubes, we found that the coefficient of discharge data presented was obtained at low differential pressures (<40 ft of water) across the tube. At very high differential pressures across the plates, separation occurs at the leading edge of the short tube (coefficient of contraction ~0.6), and the flow does not reattach within the interior walls of the sharp edged holes. All the sharp-edged short tubes had coefficients of discharge similar to a thin sharp-edged orifice (0.61). The deburred holes were beveled on the leading edge, which allowed the flow to reattach within the short tube (coefficient of contraction ~1.0). Figure 13 shows what the streamlines look like at both low and high differential pressures for sharp-edged and deburred holes.

The very small holes (0.089-inch) showed an additional scale effect caused only by their small size, which further reduced the C_d to 0.5. This coefficient was verified in the 1:6.6 scale model.

The converging tapered holes which we tested approached a C_d of 0.99, figure 14. We found this coefficient at high Reynolds numbers with the 0.25-inch holes and also with the prototype size (0.5625-inch) holes. The findings from the coefficient work allowed us to make adjustments in the 1:6.6 scale model of the valve. Straight Froude scaling of head did not produce an appropriate discharge because of the difference in the coefficient of discharge. We had to increase the head in excess of the correct scaled value to simulate scaled velocities and discharges. This simulation was important in the evaluation of the stilling well both from the appearance of the water surface and the pressures on the side walls. To pass the design discharge of 400 ft^3/s, a head of 407.5 ft was needed in the model. This head corresponds to a scaled prototype head of almost 2,700 ft. A head ratio of approximately 2 was required to overcome the coefficient of discharge differences between the model and prototype. The discharge and flow velocity exiting the valve can be predicted with the appropriate Froude scaling relationships as long as this excess head adjustment is made.

Once the corrections were made so that proper discharges were modeled, properties of the stilling well were evaluated. The effect of tapered short tubes versus cylindrical short tubes led to an increase in the wall impacts of only 0.5 to 1.5 lb/in^2 (prototype). This difference was attributed to the higher C_d of the tapered short tubes. Impact pressures measured in the 1:6.6 scale model were taken in conjunction with modifications to the stilling well. The addition of a 6- by 6-inch (prototype) angle around the perimeter of the well was done to deflect the rising wall jets created by the valve discharge impacting on the side walls. The angle did not affect the magnitude of the wall impact pressures, figure 11. However, the mean water surface was decreased by 1.5 ft (prototype). In fact, the peak water surface recorded was almost 0.6 ft (prototype) below the mean water surface for the plain well. Corner plates and wedges were installed based on previous work on vertical stilling wells.

Both the smaller plates and wedges were effective in improving the overall performance of the stilling well. The corner gusset plates are much simpler and less expensive to install. Although impact pressures on the side walls were not overly affected by these modifications, overall energy dissipation was increased as was evidenced by a lower and calmer water surface in the well.

General valve operation was satisfactory in all aspects. The sealing configurations appear to be satisfactory. No evidence of any valve vibration caused by hydraulic phenomena was noticed. Cavitation in the free shear layers of each discharge port was present. However, no damage occurred on the valve body or sleeve and the cavitation clouds dissipated prior to impact on the side walls. One area of concern in the prototype is the vibration characteristics. Although the model contained all the features which could possibly affect the valve vibration, the model is relatively stiff in comparison to the prototype. This difference in stiffness may result in altered vibration characteristics in the prototype and should be monitored upon startup.

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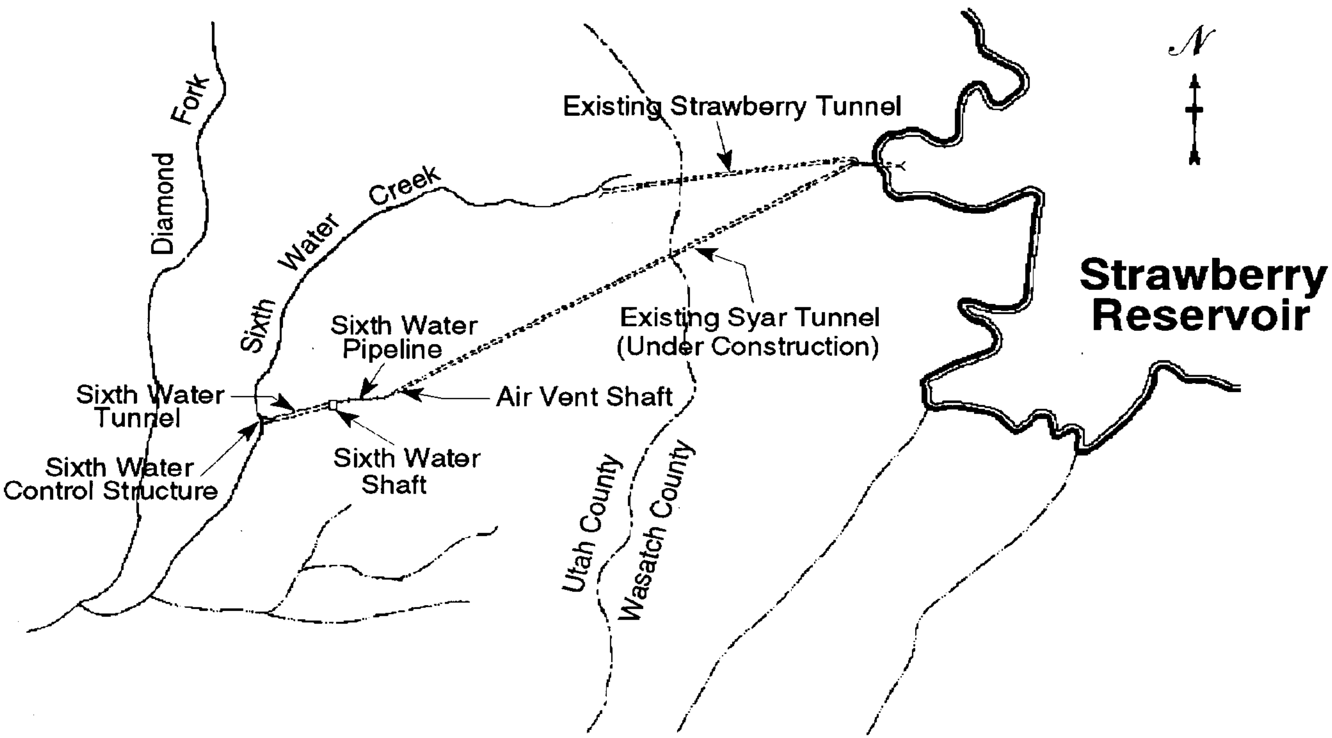


Figure 1. – Location map of the Sixth Water conveyance project.

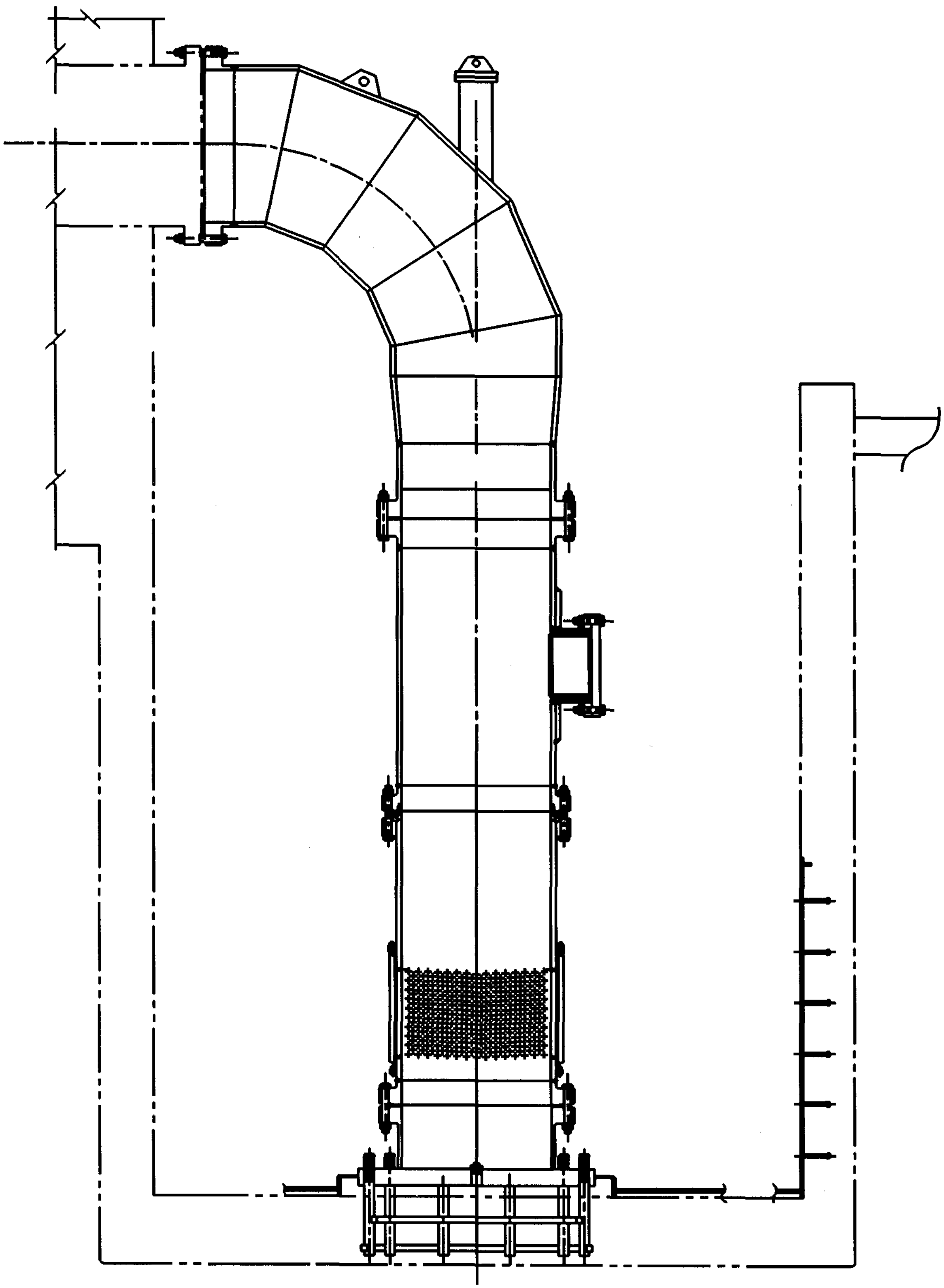


Figure 2. – 52-inch vertical multiport sleeve valve in 18-ft by 18-ft stilling well.

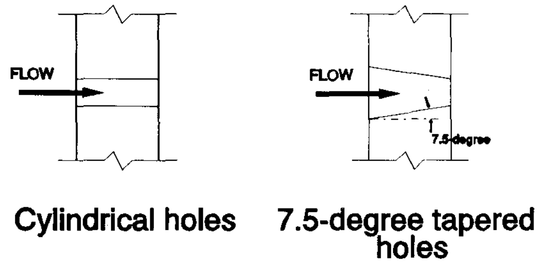


Figure 3. – Short tube designs tested in multiholed orifice plates.

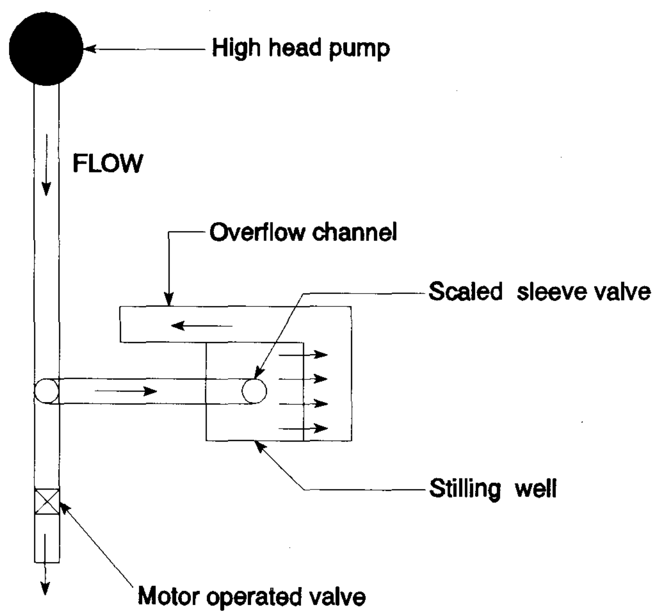


Figure 4. – Schematic of 1:6.6 scale hydraulic model of the 52-inch sleeve valve for Sixth Water Aqueduct.

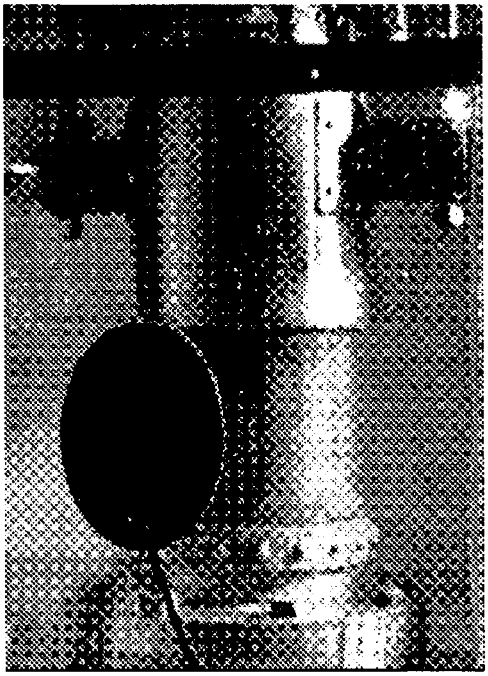


Figure 5. – Valve body, 1:6.6 scale hydraulic model.

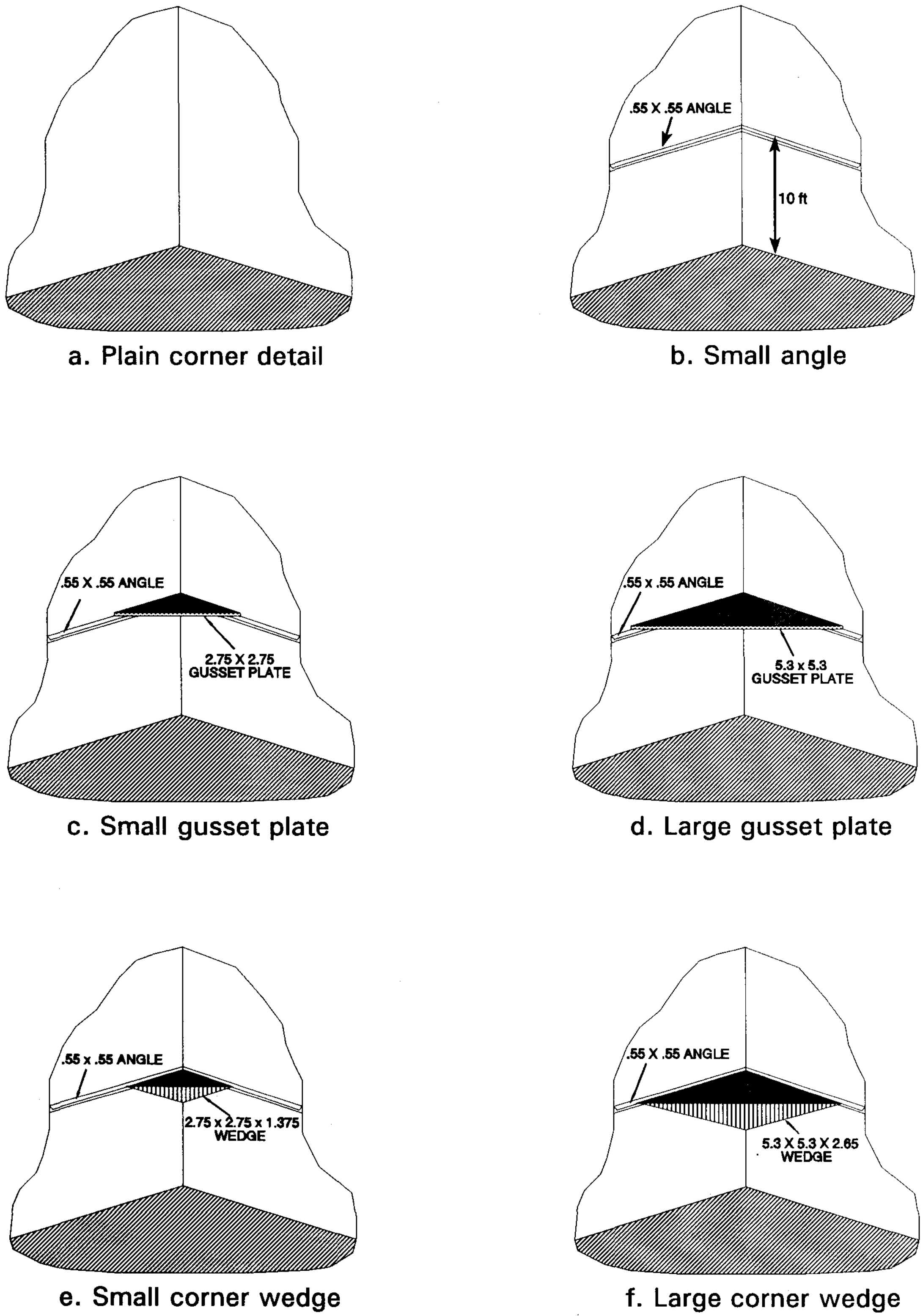


Figure 6. – Stilling well modifications tested, dimensions in prototype feet.

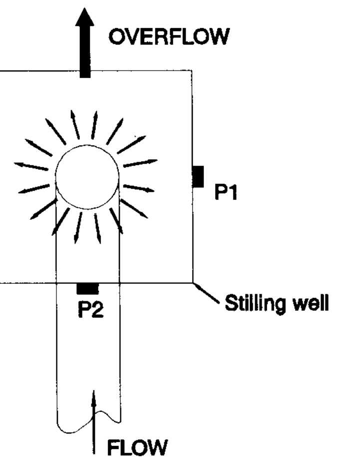


Figure 7. – Schematic showing location of pressure transducers (flush mounted) to measure jet impact on walls.

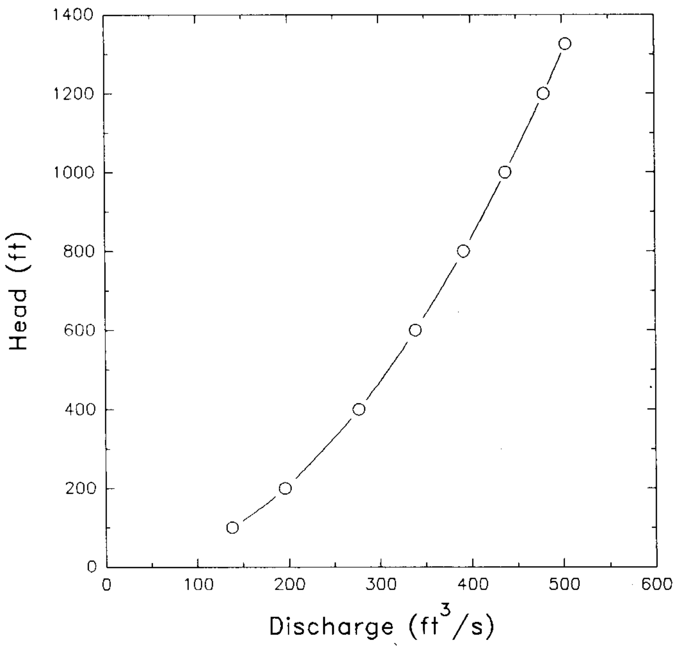


Figure 8. – Calculated prototype discharge curve for one valve, 100 percent open, using measured C_d value.

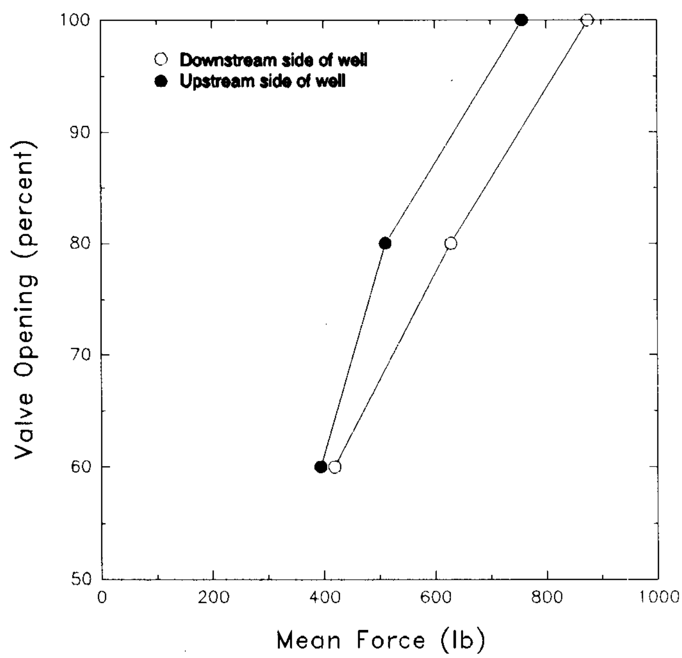


Figure 9. – Forces on the small corner gusset plates.

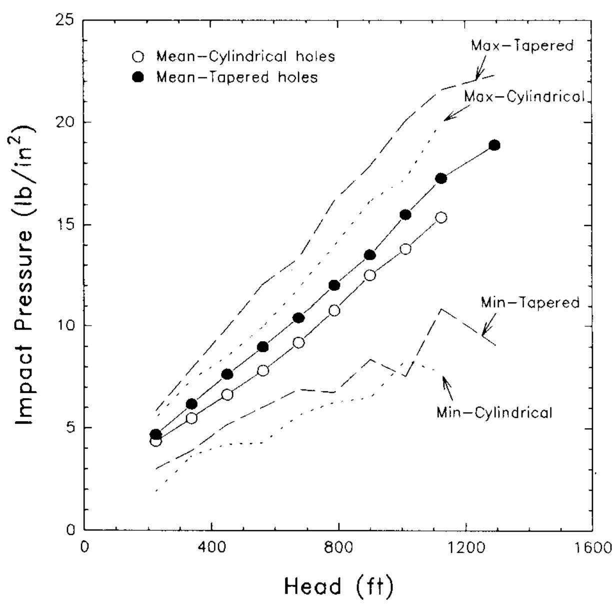


Figure 10. – Variation of jet impact pressures with cylindrical or tapered wall short tubes.

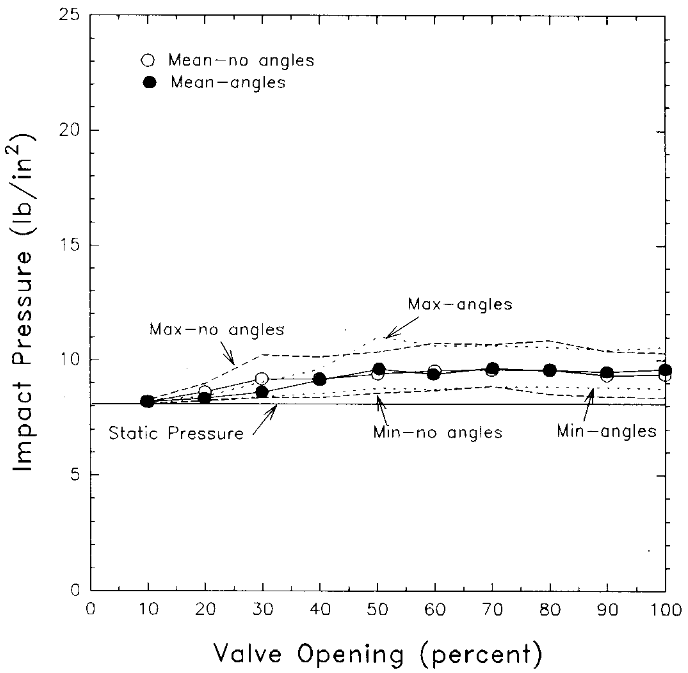


Figure 11. – Impact pressures at design discharge (400 ft^3/s) measured at P2, showing the effect of the angle at the top of the steel liner.

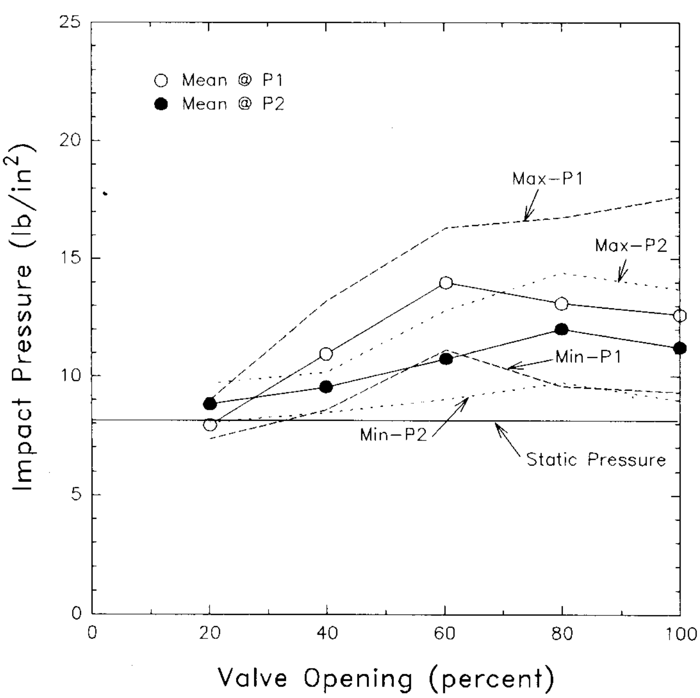
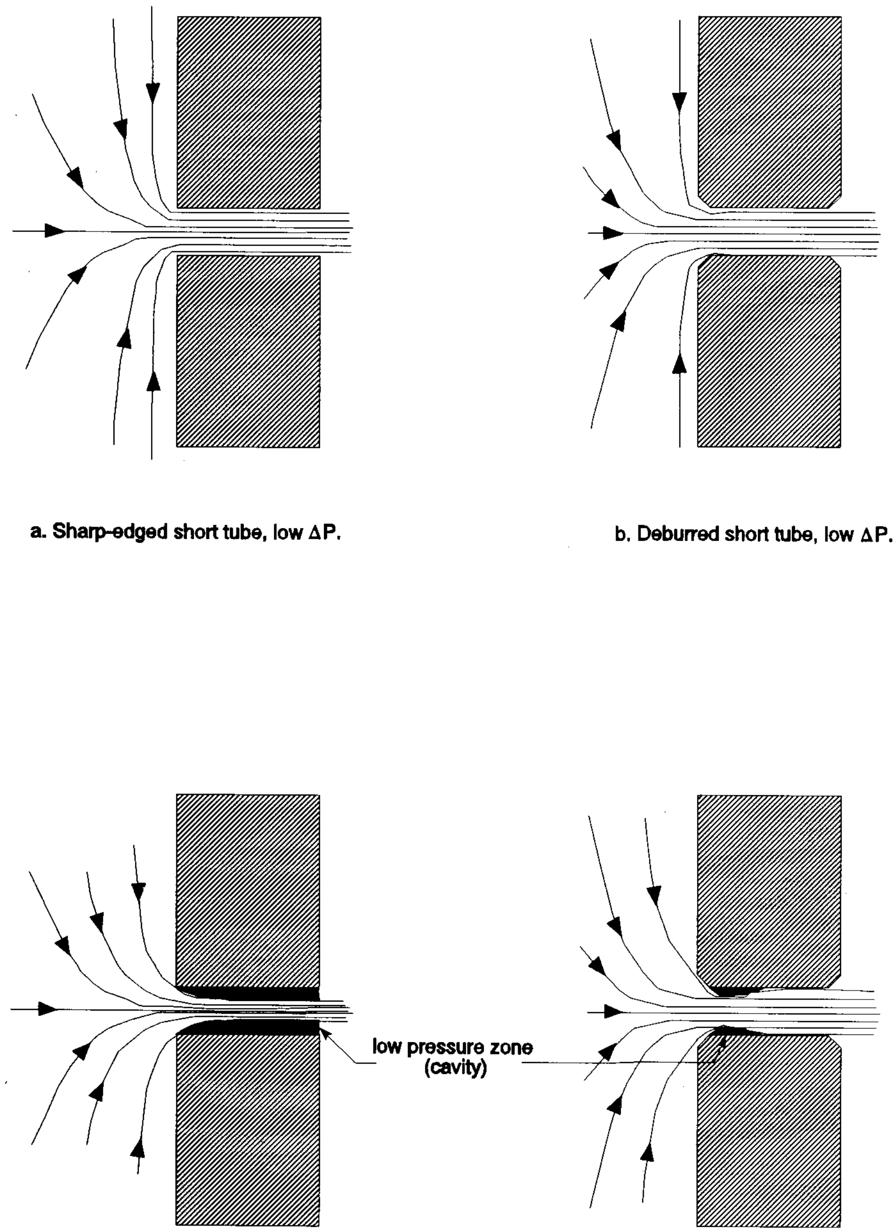


Figure 12. – Impact pressures generated by the recommended well design on stilling well side walls at design discharge.



a. Sharp-edged short tube, low ΔP.

b. Deburred short tube, low ΔP.

c. Sharp-edged short tube, high ΔP.

d. Deburred short tube, high ΔP.

Figure 13. – Streamlines for sharp-edged and deburred short tubes at low and high differential pressures.

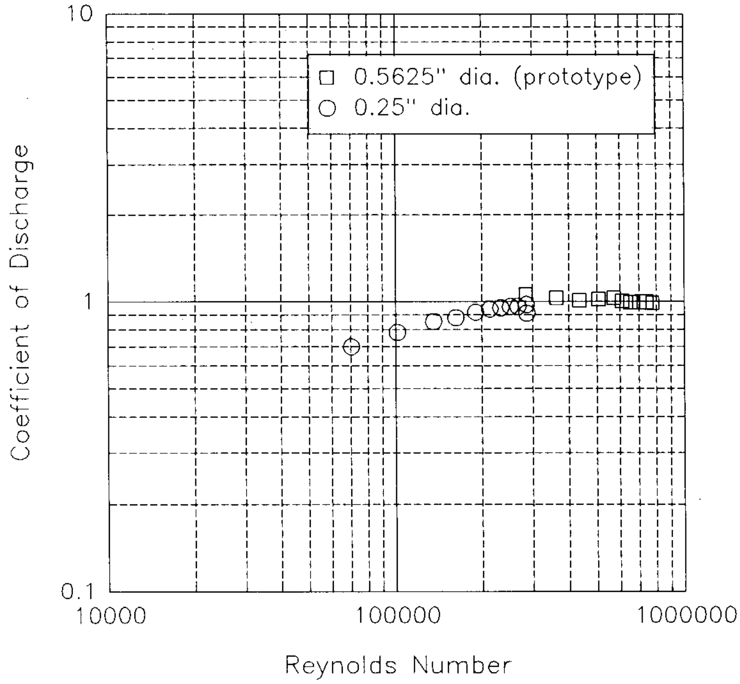


Figure 14. – 15-degree tapered short tubes, variation of C_d with Reynolds number.

Mission

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