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Improving Concrete Containment Structures Associated With Fixed-Cone Valves

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IMPROVING CONCRETE CONTAINMENT STRUCTURES ASSOCIATED WITH FIXED-CONE VALVES

by

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ABSTRACT

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Fixed-Cone valves are often used to dissipate energy and regulate flow at the low level outlet works of dams. Fixed-Cone valves, also known as Howell-Bunger valves, create an expanding conical jet allowing the energy of the water to dissipate over a large area. However, in many applications constructing the large stilling basin necessary for these valves is either not possible or not feasible. In order to reduce the relative size of the stilling basin, hoods or concrete containment structures have been used in conjunction with Fixed-Cone valves. This paper compares two methods of energy dissipation used in conjunction with concrete containment structures. The first method of energy dissipation is the use of baffles, and the second is a deflector ring with end sill. In order to determine which type of energy dissipation method was most effective for this particular application, measurements and observations were taken in order to compare the amount of energy dissipated by the structure and the Fixed-Cone valve, the air demand of the structure, the velocities downstream of the structure, and flow stability downstream of the

structure. This information will be useful to engineers allowing them to minimize scour and erosion associated with concrete containment structures.

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NOTATIONS

A = Cross-sectional area (L^2)

A_j = Cross-sectional area of jet exiting valve (L^2)

E_d = Energy dissipated (%)

F = Force in lbs or Newtons

F_j = Theoretical Froude number of jet exiting valve (-)

g = Acceleration of gravity (L/T^2)

h_c = Height of the centroid of cross-section (L)

h = Total energy head minus elevation head (L)

H = Total energy head (L)

H_f = Final energy head (L)

H_i = Initial energy head (L)

L = Length in feet or meters

M = Momentum (L^3)

M_i = Initial momentum (L^3)

M_f = Final momentum (L^3)

P = Pressure at some point (F/L^3)

Q = Flow rate (L^3/T)

R = Radius of Fixed-Cone valve at the exit(L)

t = Thickness of jet exiting Fixed-Cone valve (L)

T = Time in seconds

Z = Elevation head above datum (L)

γ = Unit weight of water (F/ft^3)

CHAPTER I

INTRODUCTION

Dissipating energy from water exiting dams has always been an important endeavor. High energy flow exiting dams can reduce the structural integrity of the dam by eroding at the toe, which could lead to failure. High velocity flows can also be detrimental to the ecosystems downstream of the dam due to the erosive nature of these high energy flows. One innovative solution to help reduce the amount of energy exiting the low level outlet works of dams was the Howell-Bunger valve, also known as the Fixed-Cone valve.

The Howell-Bunger valve was originally introduced by C.H. Howell and H.P. Bunger in 1935. The valve consists of a conical section that is fixed in the end of the valve with a telescoping sleeve that regulates flow. The valve causes the water exiting to expand out radially creating a conical spray. It is common for the water exiting the valve to exit at either 45 or 60 degrees measured from an axis that extends perpendicular to the pipe. These valves are commonly used to dissipate energy through dispersion and regulate flow exiting the outlet works of dams having medium (35 ft – 165 ft) to high (>165 ft) heads. The Fixed-Cone valve is not only an excellent energy dissipater, it is also is an excellent way to aerate water discharged from impoundments. This is primarily due to the fact that the water exiting a Fixed-Cone valve expands out in every direction thus allowing a large flow surface to be in contact with the atmosphere [1].

Although Fixed-Cone valves are fairly effective at dissipating energy, they still require large stilling basins to receive the conical jet exiting the valve and to reduce the amount of energy in the flow even further. In many applications a large stilling basin is either not possible or not feasible. Hoods are sometimes used in conjunction with Fixed-Cone valves to reduce the size and alter the shape of the stilling basin. The concentrated hallow jet exiting requires a long, narrow stilling basin. In order to significantly reduce the size of stilling basin required the hood can be lined with small teeth-like projections or baffles. This combination of a Fixed-Cone valve and a baffled hood are capable of dissipating up to 95 percent of the power upstream from the valve [2].

Another option to reduce the size of the stilling basin downstream from a Fixed-Cone valve is to build a concrete containment structure to receive the discharge. There are many different designs of concrete containment structures, which differ both in geometry and cross-sectional shape. Many of the containment structures that have been modeled and build have used deflector rings and an end sill as the primary method of energy dissipation. The basic theory behind this method of energy dissipation is two-fold. First, the deflector ring is meant to redirect the water jet from the Fixed-Cone valve back into itself. Second, the end sill creates a small stilling basin which allows for considerable energy dissipation. There has been little or no research comparing the effectiveness of these different designs or even to optimize a specific design. Most research in this area has involved constructing small scale models to ensure that the designs will dissipate a sufficient amount of energy.

The purpose of this research is not to complete exhaustive experimentation to determine most effective design of concrete containment structure, but rather to compare two methods of energy dissipation and to provide insight to improve the design of future structures. The methods of energy dissipation that were compared are; the common method of deflector ring and end sill and the use of teeth-like baffles that proved so effective in energy dissipation when incorporated into baffled hoods. It is hoped that this paper will be useful to professionals in the design of future concrete containment structures.

CHAPTER II

LITERATURE REVIEW

Beichley (1966) [5] conducted a hydraulic model study of the Portage mountain low level outlet works. This design consisted of two Fixed-Cone valves discharging into the same channel which had a circular cross-section. The models that were studied included a deflector ring and had various configurations of baffle piers on the bottom and a weir at the end of the channel. The final recommended design only incorporated the deflector ring, which adequately dissipated energy for the desired range of flows and heads.

Beichley (1970) [6] also carried out model studies of an energy dissipater for a Fixed-Cone valve at the Ute Dam outlet works and (1972) [1] of Scoggins Dam fish trap aeration and supply structure. In both models a deflector ring was used as the primary method of energy dissipation. Both models also include diverging ceilings, walls, and floors to prevent submergence of the valve. Pier baffles were also used in both models to spread the jet and dissipate energy.

Colgate (1974) [4] performed a model study for the proposed design of the low-level outlet works of the LG-2 development in Quebec, Canada. It was determined that the location of the deflector ring was too far upstream and was moved 8 feet downstream. This model included two rows of large baffle piers in the original design as opposed to the traditional end sill, but it was determined by the author that only one row of small baffles was necessary to prevent sweep out at low flow conditions. It was advised that the section upstream from the deflector ring, the deflector ring, and the floor baffles be lined with steel to prevent erosion.

Helper and Peck (1989) [3] constructed a model study to investigate the hydraulic performance of a design for concrete containment structures associated with Fixed-Cone valves. The design that they used was similar to three structures that have been built by the Bureau of Reclamation including: Stony Gorge Dam (California), Jordanelle Dam (Utah), and New Waddell Dam (Arizona). It was concluded that the structure performed well through the range of operating conditions. Pressure taps were installed along the roof, sides and bottom of the containment structure, pressure at these locations was less than that expected using momentum. Momentum principles dictate that the force on the walls of the containment structure be proportional to the density of water, the flow rate, and the velocity normal to the surface. It was proposed that the measured values were less than the calculated values due to the fact that the pressure taps were often not located in the center of the jet, where the force would be expected to be a maximum.

Johnson and Dham (2006) [2] completed experiments to determine the effectiveness of teeth-like baffles installed in Fixed-Cone valve hoods as power dissipaters. Fourteen different configurations of baffles were tested. The optimal design in combination with the Fixed-Cone valve was able to dissipate 92 percent of the power available upstream compared to only 42 percent power dissipated by the Fixed-Cone valve and the hood alone. The addition of baffles did increase the amount of backsplash that was exiting the valve through the annular space between the valve and hood. However, it was determined that by reducing the size of this annular space that backsplash could be completely eliminated. The addition of the baffles was found to have no effect on the amount of air required for the hood and no reduction in flow capacity through the hood. This original design using a baffled hood allows for a considerable reduction in the size of stilling basin associated with it.

CHAPTER III

PEER REVIEWED JOURNAL ARTICLE

Improving Concrete Containment Structures Associated With Fixed-Cone Valves

B. Skyler Buck[1], Michael C. Johnson, P.E.[2] and Zachary B. Sharp[3]

Abstract: Fixed-Cone valves are often used to dissipate energy and regulate flow at the low level outlet works of dams. Fixed-Cone valves, also known as Howell-Bunger valves, create an expanding conical jet allowing the energy of the water to dissipate over a large area. However, in many applications constructing the large stilling basin necessary for these valves is either not possible or not feasible. In order to reduce the relative size of the stilling basin, hoods or concrete containment structures have been used in conjunction with Fixed-Cone valves. This paper discusses the use of baffles in concrete containment structures in order to dissipate energy in a considerably confined space. This information will be useful to engineers allowing them to minimize scour and erosion associated with concrete containment structures.

Keywords: Valves, Containment structure, Energy dissipation, Concrete erosion, Outlet works.

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Background

The Howell-Bunger valve, also known as the Fixed-Cone valve, is often used to reduce energy in the water exiting the low level outlet works of a dam. This reduction of energy must happen in order to avoid erosion at the toe of dam or in downstream channels. It is especially important to reduce the velocity in the downstream channel because velocity is the primary source of erosion and scour.

Originally introduced by C.H. Howell and H.P. Bunger in 1935, the valve consists of a conical section that is fixed in the end of the valve with a telescoping sleeve that regulates flow. The valve causes the water exiting to expand out radially creating a conical spray. It is common for the water exiting the valve to exit at either 45 or 30 degrees measured from an axis that extends perpendicular from the pipe. These valves are commonly used to dissipate energy and regulate flow from the outlet works of dams with medium (35 ft – 165 ft) to high (> 165 ft) heads. The Fixed-Cone valve is not only an excellent energy dissipater, it is also is an excellent way to aerate water discharged from impoundments. This is primarily due to the fact that the water exiting a Fixed-Cone valve expands out in every direction thus allowing a large flow surface to be in contact with the atmosphere [1].

When used alone Fixed-Cone valves dissipate energy effectively, however, due to the expanding conical jet, relatively large stilling basins are required to capture the excessive overspray. In many applications a large stilling basin is either not possible or not feasible. In order to reduce the size of the stilling basin, hoods and concrete containment structures have been used in conjunction with Fixed-Cone valves. In applications with medium heads, hoods are often used in conjunction with Fixed-Cone valves creating a concentrated hollow jet. When the hood is attached to the valve it is referred to as a Ring-Jet valve. However, Ring-Jet valves and Hooded Fixed-Cone valves still require a considerable sized stilling basin in order to avoid having a scouring effect take place downstream. In order to dissipate more energy the hoods can be lined with baffles. The combination of a Fixed-Cone valve and a baffled hood are capable of dissipating up to 95 percent of the power upstream from the valve [2].

The United States Bureau of Reclamation (USBR) has several designs using Howell-Bunger valves in conjunction with reinforced concrete containment structures. The containment structures vary in size and cross-sectional shape, but maintain the same general design and similar structural elements. These containment structures usually include an aeration hatch, a Fixed-Cone valve, and a deflector ring followed by an end sill or baffle piers. When in operation this valve produces a conical jet that strikes the walls of the containment structure at approximately 45 degree angles (only if a 90 degree cone is used). After contact most of the flow continues along the surface until the deflector ring redirects the flow to a common point downstream [3].

The USBR has employed these concrete containment structures at a number of dams including: LG-2 Development (Quebec, Canada), Portage Mountain Dam (British Columbia, Canada), Ute Dam (New Mexico, USA), New Waddell Dam (Arizona, USA), Stony Gorge Dam (California, USA), and Jordanelle Dam (Utah, USA). It has been noted that the structure at Jordanelle Dam has a considerable amount of overspray even at low flows. The concrete containment structure at the LG-2 development consists of two Fixed-Cone Valves discharging into a common chamber of oval cross-section with a deflector ring followed by a row of floor baffles [4]. The Portage Mountain Dam structure has a circular cross-section, but in all other regards is the same as the LG-2 structure [5]. The Ute dam has a chamber cross-section that is octagonal, followed by the deflector ring and an end sill instead of the floor baffles [6]. The other dams listed have containment structures with rectangular cross-sections deflector rings and end sills [4].

Experiments

A study was conducted at Utah State University at the Utah Water Research Laboratory (UWRL) to determine if there was a more effective and economical containment structure that could be used with Fixed-Cone valves. A fixed cone valve having 7.8-inch fixed cone diameter and an exit angle of 45 degrees was used for these tests. Six different models were constructed and compared for this study. Figure 1 shows the two different containment structure cross-sections (with their respective dimensions) used for this research, with the dimensions standardized in terms of valve diameter (D). Each cross-section had three configurations that were tested. The first configuration used a deflector ring and an end sill. Figure 2 shows the profile and plan views of the standard containment structure configuration described previously with deflector ring and end sill. The other two configurations used the baffles shown in Figure 3 instead of the deflector ring and end sill, the only difference being that the last two rows of baffles shown in Figure 4 were removed for the third configuration. Once again, note that all dimensions were normalized in terms of the valve diameter in order to easily apply them to any desired prototype. Plywood painted with a latex paint was the construction material used to simulate the concrete containment structures, the deflector ring and the end sill while Plexiglas was used to make the baffles. The six models were run through four different model reservoir heads with five different flow rates for each reservoir head. The model reservoir heads for this experiment were 15.4D, 23.1D, 30.8D, and 38.5D.

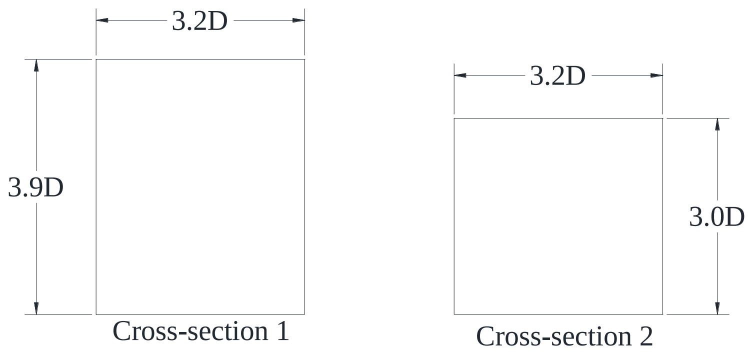

Figure 1. Cross-sections of containment structures.

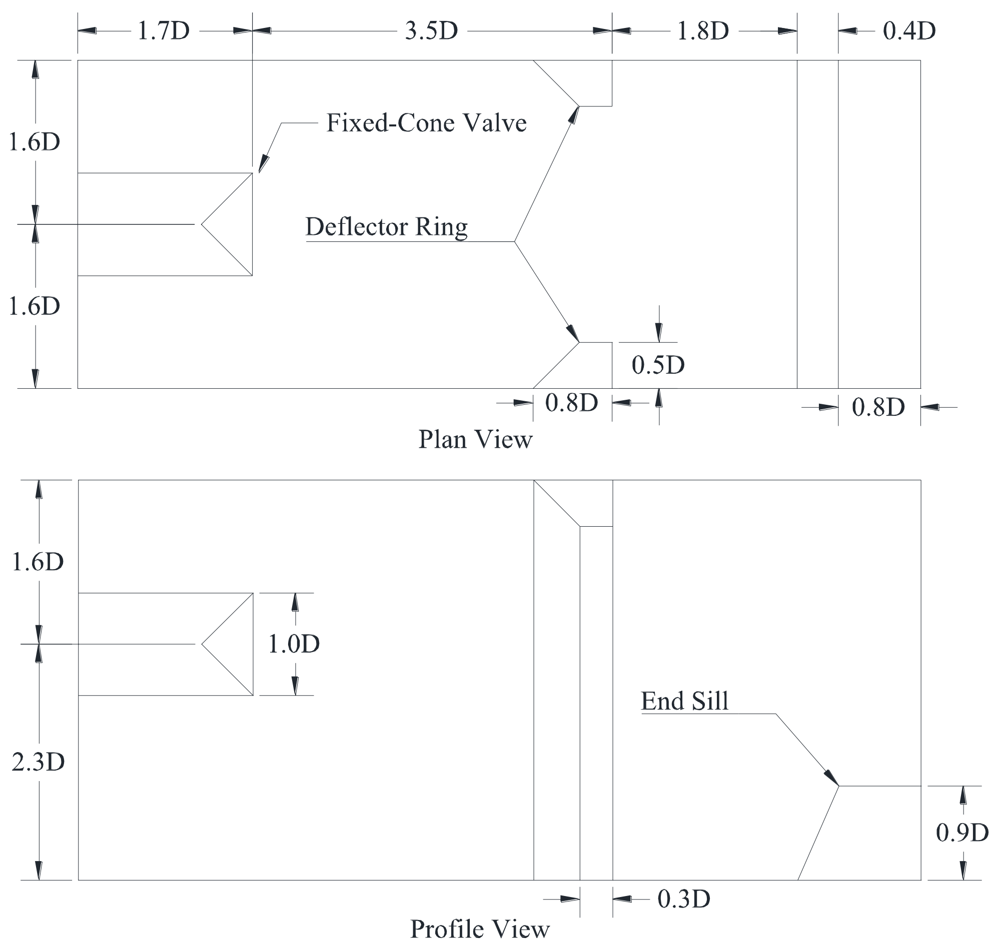

Figure 2. Containment structure with deflector ring and end sill in Cross-section 1.

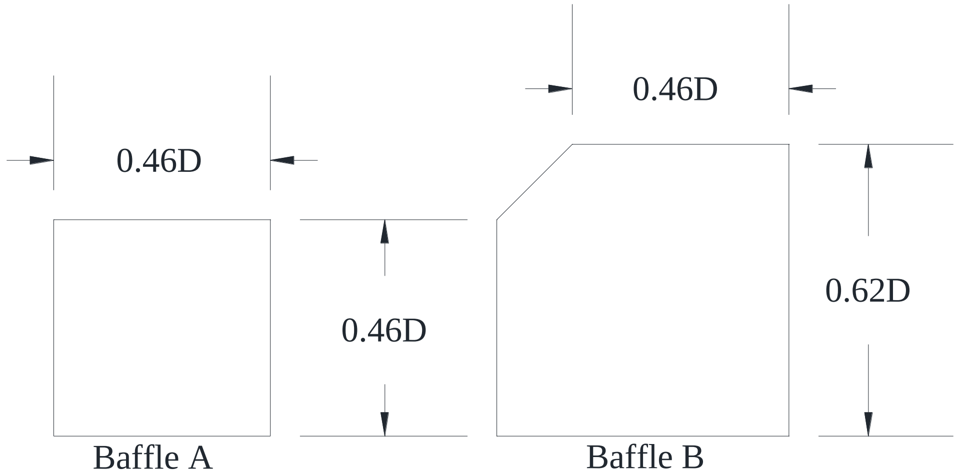

Figure 3. Standard baffle (A) and corner baffle (B).

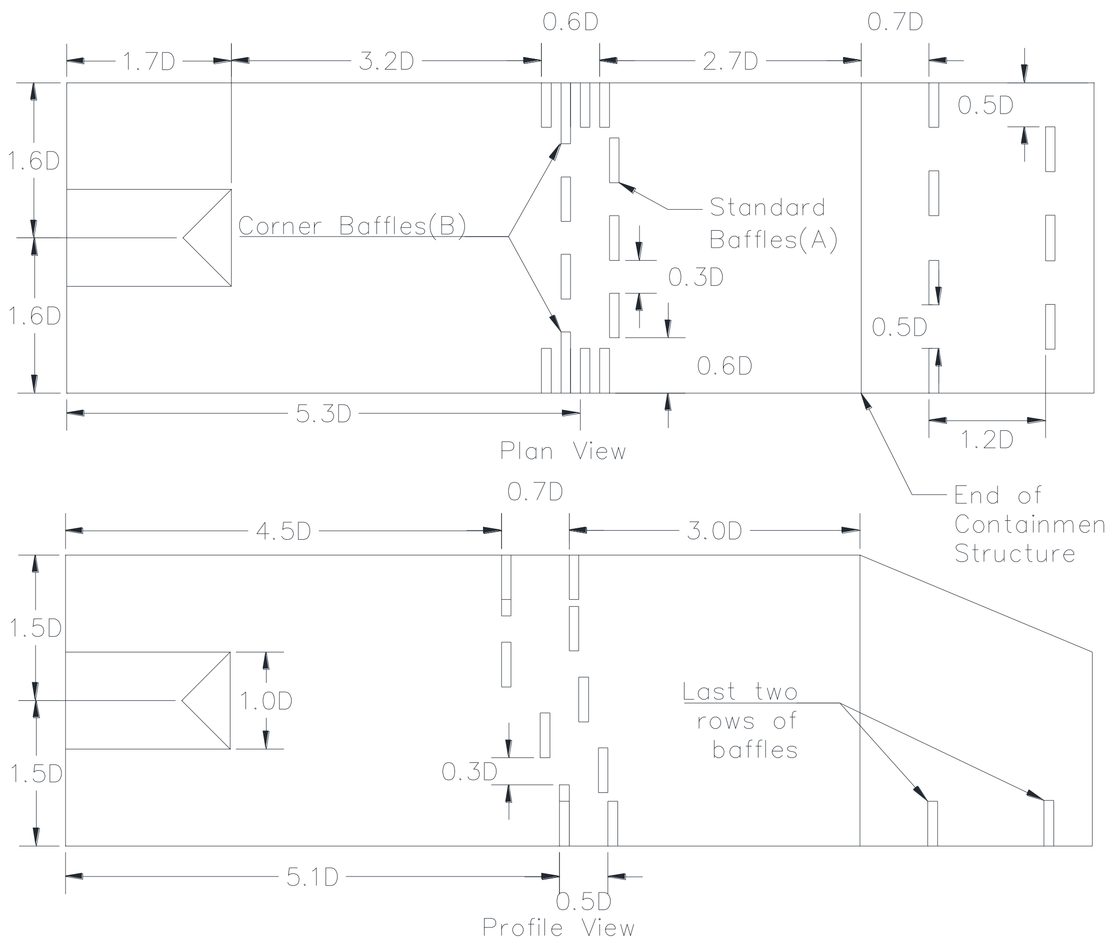

Figure 4. Baffle containment structure with extra two rows of baffles in Cross-section 2.

Evaluation Criteria

All previous research and model studies focused solely on adequate energy dissipation and observations. These are both valid and important criteria and are hence included in this study. However, in order to more thoroughly evaluate the performance of the model containment structures downstream velocities and the downstream flow patterns were also taken into account. These two criterions are of utmost importance. Undesirable flow patterns, including non-uniform flow and unstable hydraulic jumps, require additional design considerations for the downstream channel. These considerations could represent a considerable cost both in time and structures to ameliorate the channel. High velocity flows are of highest significance when considering scour and erosion of material. In this study average velocities in the downstream channel were used for comparison. In order to calculate these velocities the flows were divided by the product of the average depth of flow and the width of the downstream channel. The flow patterns were qualitatively recorded by noting any hydraulic jumps, flow patterns or irregularities.

The amount of energy dissipated (E_d) is given as a percentage of the initial energy head (H_i) minus the final energy head (H_f) over the initial head (1).

$$E_d = \left(\frac{H_i - H_f}{H_i}\right) * 100 \tag{1}$$

The energy head calculation for this experiment employed the following form of the Bernoulli equation (2):

$$H = \frac{P}{\gamma} + Z + \frac{V^2}{2g} \tag{2}$$

Where H is the total head, P is the pipe pressure at the inlet of the Howell-Bunger valve, γ is the specific weight of water, Z is the elevation of the water above datum, g is the acceleration due to gravity, and V is the average velocity. The elevation datum for the water was taken as the bottom of the containment structure. The initial head was calculated from measurements made upstream of the Howell-Bunger valve using a precision pressure gage to measure the pipe pressure and a calibrated magnetic flow meter to measure the flow rate. The final head was calculated using the same flow rate found upstream of the Howell-Bunger valve and a channel depth. The downstream water depth was taken as the average of three depths (at 0.25, 0.5, and 0.75 the width of the channel) which were measured using a point gauge downstream from the containment structure. Measurements were also taken for the geometry of the different containment structures (cross-section 1 or cross-section 2), the percent valve opening, and the velocity of air entering though the aeration hatch.

Results

It was originally planned to record a baseline dissipation measurement using cross-section 1 without any of the energy dissipation structures installed. However, the water exiting the structure was moving at a high rate of velocity and was far too turbulent to get any valid readings. This visually confirmed the fact that simply changing the direction of the jet from a Fixed-Cone valve does little as far as power (energy) dissipation is concerned [2].

The two models with four rows of floor baffles allowed for the greatest uniformity and stability in the flow pattern in the downstream channel. The configurations with the end sills always had a hydraulic jump in the channel though the location changed based on flow, and even then the jumps tended to shift locations. The hydraulic jumps formed because as flow exits the structure it is accelerated off the end sill. Figure 5 shows photographs of these two configurations with the same model head of 38.5 D and the highest flow tested. The hydraulic jump can be seen on the left, but it should be noted that its location did shift while the baffles maintained a uniform flow pattern. The flow patterns observed are representative of both structures throughout the range of flows and heads. The deflector ring with end sill configurations also exhibited a strange V-shaped flow pattern where the depth in the center of the channel was noticeably lower and the velocity noticeably higher than at the sides of the channel. This design also had a lot more overspray at the end of the channel when compared to the baffle designs.

For plotting and comparison purposes dimensionless terms were used, including a theoretical jet Froude number. The theoretical Froude number is calculated assuming that all the head at the valve, excluding the elevation head, converts to velocity head. This assumption is made because the containment structures are vented to the atmosphere therefore the water pressure as the water jet leaves the valve is zero. The Froude number of the jet, F_j, is calculated using equation 3 where h is the summation of the pressure head and the velocity head upstream from the valve, g is the acceleration due to gravity and t is the thickness of the jet.

$$F_j = \frac{\sqrt{2gh}}{\sqrt{gt}} \tag{3}$$

The thickness of the jet, t, was computed using equations 4 and 5:

$$A_j = \frac{Q}{\sqrt{2gh}} \tag{4}$$

$$t = \sqrt{\frac{A_j}{\pi} + R^2} - R \tag{5}$$

Where Q is the flow going through the valve, A_j is the theoretical area of the jet, R is the radius of the cone at the outlet and all other variables are as previously defined.

Figure 5. Comparison of deflector ring with end sill flow (left) to baffle flow with 4 rows of floor baffles (right).

Figure 6 shows the percent of energy dissipated plotted against the theoretical Froude number of the flow exiting the Fixed-Cone valve. It is noteworthy that the larger Froude numbers correspond to low flows with small valve openings, while the lower Froude numbers are higher flows with larger valve openings. It is apparent that at low flows all the containment structures performed similarly and that only at medium to high flows was there a measureable difference in energy dissipation. The design with the deflector ring and the end sill with a larger cross-sectional area and the baffle design with the extra two rows of baffles had no definitive energy dissipation differences. These designs always had energy dissipation measurements within one percent of one another. Larger floor baffles could increase the amount of drag on the water leading to greater energy dissipation; however the baffles more than adequately reduced the velocities in the downstream channel which is most important and it was therefore determined that further experimentation with the size and location of baffles was not needed at this time.

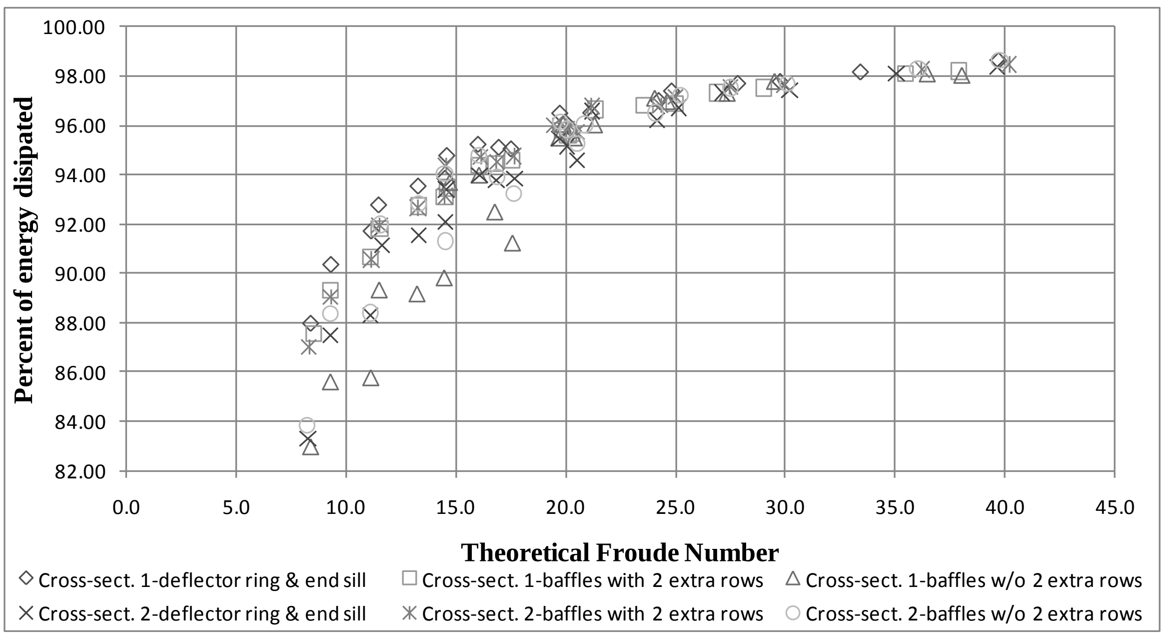

Figure 6. Energy dissipation versus theoretical Froude number.

To compare the downstream velocities of the models, the downstream velocity was divided by the theoretical velocity of the jet exiting the Howell-Bunger valve in order to get a dimensionless quantity. Figure 7 displays this dimensionless velocity number plotted versus the theoretical Froude number. As the figure shows, the relative downstream velocities associated with the baffle configurations that have the extra two rows of floor baffles produced drastically lower velocities exiting the chamber. The higher velocity flows always initiated a hydraulic jump in the channel which often shifted location. The high velocities as well as a rapidly shifting hydraulic jump would require greater engineering considerations to avoid hydraulic damage in the form of scour or up-lift of concrete in the downstream channel. For these reasons and the fact that there was not a pronounced difference in energy dissipation, the baffle configuration with the extra two rows of baffles was the preferred configuration.

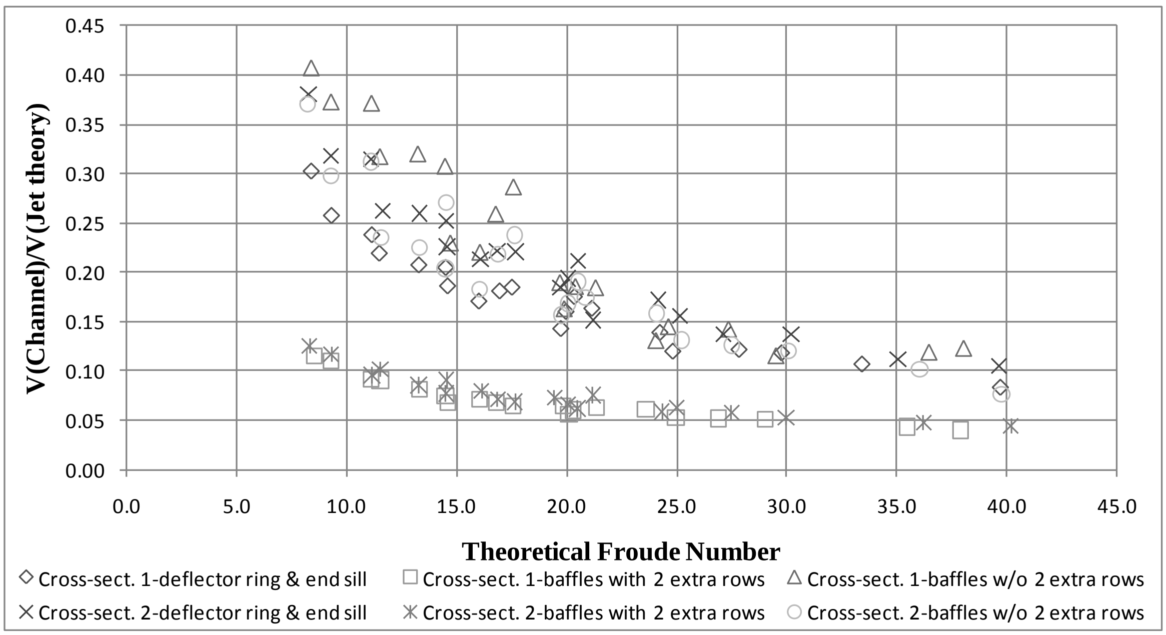

Figure 7. Ratio of downstream velocity/theoretical velocity versus theoretical Froude number.

Figure 8 displays air flow demands of the structures, the ratio of air flow to water flow is plotted against the theoretical Froude number. It is interesting to note that the smaller cross-section had a smaller ratio of air flow to water flow. This could result less effective aeration of the water flowing through the structure, but more likely this is simply a result of less air being evacuated from the chamber with the water.

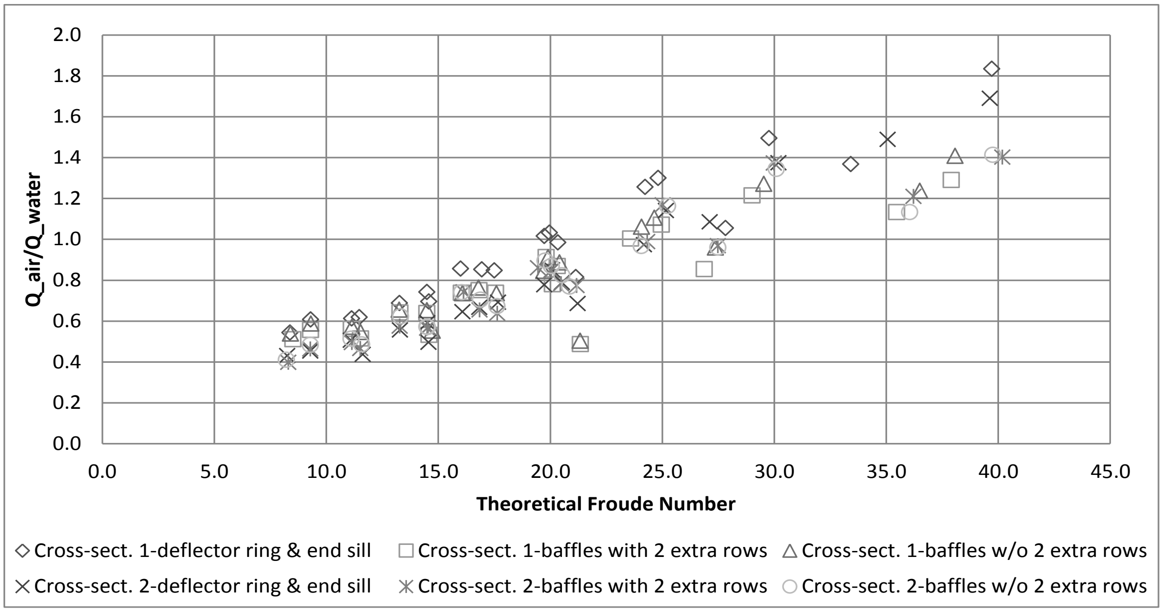

Figure 8. Ratio air flow/water flow versus theoretical Froude number.

Discussion

This study was not an exhaustive study in order to discover the single most efficient containment structure that could be used in conjunction with Fixed-Cone valves, but rather an investigation of baffled teeth energy dissipation with earlier energy dissipation methods. Using teeth like baffles for energy dissipation in concrete containment structures is a novel idea and there is little research in this area, however these teeth like projections have been used in conjunction with Fixed-Cone valve hoods and successfully dissipated energy in that application with the introduction of the baffled-hood [2].

Though energy dissipation has been the primary indicator of the effectiveness of these structures in previous experiments, it became apparent that the downstream water velocities and flow patterns are of even greater importance. Most energy dissipation structures at the low level outlet works are built to minimize scour and damage downstream, while energy dissipation is simply a measure of effectiveness. Though energy is a good indicator of whether or not significant damage will occur, it is more important to know the state that the energy is in. In this case energy in the form of velocity is undesired while energy in the form of elevation head has no negative impact. It has been estimated that roughly 70% of all damage to hydraulic structures is attributed to erosion through high-velocity water flow [7].

Due to the fact that high velocities create considerable destruction and erosion a steel lining is advised. A steel lining is of utmost importance where the water jet exiting a Fixed-Cone valve strikes the walls and the baffles. These are the points where the direction of the water is most altered and water does not change direction easily. Steel liners also allow for any necessary repairs to occur with a fraction of the down time that would be required for concrete repairs. This is not to mention that repairs will not be necessary as often if a steel liner is used. Energy in the form of tail water elevation does not cause any damage unless the water elevation at a given point drops quite rapidly, not allowing the pressure in the underlying soil to equalize which can cause uplift of the concrete. This problem is more a function of downstream flow stability than it is of tail water depth. This is another reason that the baffle configuration with the extra two rows of baffles was the preferred design; because the hydraulic jump occurred over the last two rows of baffles the downstream flow pattern was stable and uniform. This design allows for more economical containment structures to be built because it allows for fewer engineering considerations and structures in the downstream channel (including riprap), it allows for smaller cross-sections without dramatic changes in performance, and less maintenance reconstruction due to scour. In certain applications these reductions in cost could be considerable. With further interest and experimentation it would be possible to provide a design guide to those interested in designing more efficient Fixed-Cone valve containment structures.

CHAPTER IV

DISSCUSSION

This study was not an exhaustive study in order to discover the single most efficient containment structure that could be used in conjunction with Fixed-Cone valves, but rather an investigation of using the method of baffled teeth energy dissipation compared with earlier energy dissipation methods. Using teeth-like baffles as the primary method of energy dissipation in concrete containment structures is a novel idea and there is little research in this area, however these teeth-like projections have been used in Fixed-Cone valve hoods and successfully dissipated energy in that application, thus introducing the baffled-hood as a viable method of energy dissipation [2].

In order to maintain consistent energy measurements in the downstream channel it was planned to measure the depth at three locations across the cross-section (close to each side and in the center) at a specific location of 8.8D downstream from the end of the containment structure. For most of the configurations and test parameters this location was acceptable, however in some instances a hydraulic jump formed in the channel directly below this measurement point. In these cases the measurement point was either moved to an alternate point located at either 4.1D or 11.8D from the end of the containment structure. Actual measurements taken can be found in appendix A and those measurements moved upstream to 4.1D are shaded and the measurements moved downstream to 11.8D are typed in **bold** lettering. When hydraulic jumps did form their location was often unstable and likely formed due to the bend in the channel located 15.3D downstream from the end of the containment structure. As the channel was quite short and therefore very little energy was lost flowing between the two extreme points of measurement all measurements and calculated energies were considered to occur at the same location, neglecting all head loss in the channel.

Due to the fact that hydraulic jumps are an excellent method to dissipate energy it was important to determine if the resultant jump was due to the containment structure or if it was initiated because of downstream conditions. If the jump formed within 2D of the containment structure it was considered as part of the dissipation structure if it occurred downstream of this point energy dissipated by the jump was not included in the dissipation calculations. Though energy is not conserved across hydraulic jumps momentum is as shown in equation 6 below. Equation 7 demonstrates how momentum was calculated.

$$M_i = M_f \tag{6}$$

$$M = Ah_c + \frac{Q^2}{gA} \tag{7}$$

M_i is the initial momentum (before jump), M_f is the final momentum (after jump), M is the momentum, A is the area, h_c is the height of the centroid of the cross-section, Q is the flow rate, and g is acceleration of gravity. Note that for a given flow rate there are two depths of flow that carry the same momentum unless the depth is critical depth in which case a hydraulic jump will not form. These two depths that have the same amount of momentum are called conjugate depths. In cases where the depth measurement was taken downstream from the hydraulic jump the momentum equation was used to back calculate the conjugate depth. In these cases it was the conjugate depth that was used to calculate the final energy and thus the amount of energy dissipated. If the conjugate depth was used it is noted in appendix A underlining both the energy calculation and the average depth calculation

Though energy dissipation was originally the main focus of this study as the primary indicator of the effectiveness of these structures, as in previous experimentation, it became apparent that the downstream water velocities and flow patterns are of even greater importance. Most energy dissipation structures at the low level outlet works are built to minimize scour and damage downstream, while energy dissipation is simply a measure of effectiveness. Though energy is a good indicator of whether or not significant damage will occur, it is more important to know the state that the energy is in. In this case energy in the form of velocity is undesired while energy in the form of elevation head has no negative impact.

It has been estimated that roughly 70% of all damage to hydraulic structures is attributed to erosion through high-velocity water flow [7]. Due to the fact that high velocities create considerable erosion a steel lining is advised. A steel lining is of utmost importance where the water jet exiting a Fixed-Cone valve strikes the walls and the baffles. These are the points where the direction of the water is most altered and water does not change direction easily. Energy in the form of tail water elevation does not cause any damage unless the water elevation at a given point drops quite rapidly, not allowing the pressure in the underlying soil to equalize which can cause uplift of the concrete. This problem is more a function of downstream flow stability than it is of tail water depth. This is another reason that the baffle configuration with the extra two rows of baffles was the preferred design; because the hydraulic jump always occurred over the last two rows of baffles the downstream flow pattern was always stable and uniform.

With further interest and experimentation it would be possible to provide a design guide to those interested in designing more efficient Fixed-Cone valve containment structures.

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APPENDICES

Appendix A: Spreadsheet of data and calculations

Italicized numbers indicate actual measurements.

Run numbers defined:

- The first number represents the cross-section:
    1. Cross-section # 1 (rectangular)
    2. Cross-section # 2 (square)

- The second number represents the configuration:
    1. Configuration with deflector ring and end sill
    2. Baffle configuration with four rows of floor baffles
    3. Baffle configuration with two rows of floor baffles

- The third number represents the model head (where D is diameter of valve):
    1. Model elevation of 15.4D
    2. Model elevation of 23.1D
    3. Model elevation of 30.8D
    4. Model elevation of 38.5D

- The fourth number represents the flow:
    1. Is a flow of 2665 gpm
    2. Is a flow of 2132 gpm
    3. Is a flow of 1599 gpm
    4. Is a flow of 1066 gpm
    5. Is a flow of 533 gpm

Example:

Run: 2234

This means that this run was cross-section 2 with the baffle configuration with four rows of floor baffles. The model head was 30.8 times the valve diameter and the flow was approximately 1066 gpm.

Run:	1111	1112	1113	1114	1115
Flow reading (Hz)	*3475.00*	*2802.00*	*2150.00*	*1449.50*	*703.60*
Flow (gpm)	2606.25	2101.50	1612.50	1087.13	527.70
Flow Q (cfs)	5.81	4.68	3.59	2.42	1.18
Flow Velocity (fps)	6.74	5.77	5.23	4.61	4.12
Pressure P (psi)	*1.45*	*2.15*	*3.10*	*3.80*	*4.20*
Valve position (in)	*14.75*	*13.63*	*12.63*	*11.91*	*11.25*
Valve opening (%)	100.00	72.93	48.87	31.58	15.79
Air Flow reading (fpm)	*707.00*	*638.00*	*498.00*	*378.00*	*215.00*
Air Velocity (fps)	11.78	10.63	8.30	6.30	3.58
Tail Water Depth (ft) (L,M,R)	*0.38*	*0.40*	*0.37*	*0.32*	*0.16*
	0.44	*0.35*	*0.26*	*0.17*	*0.07*
	0.42	*0.40*	*0.36*	*0.26*	*0.18*
Tail Water Depth avg (ft)	0.41	0.39	0.33	0.25	0.14
v_2/v_theory	0.30	0.26	0.22	0.19	0.16
V_theory (fps)	22.25	22.39	23.83	24.77	25.21
Fr_theory	8.38	9.30	11.47	14.58	21.14
Q_air/Q_water	0.54	0.61	0.62	0.70	0.81
Net Head on valve (ft)	9.25	9.34	10.38	11.09	11.43
Net Head Tail Water(ft)	1.11	0.90	0.75	0.58	0.40
Energy Dissipated (%)	87.95	90.34	92.76	94.77	96.51

Run:	1121	1122	1123	1124	1125
Flow reading (Hz)	*3522.00*	*2847.00*	*2103.00*	*1472.80*	*746.40*
Flow (gpm)	2641.50	2135.25	1577.25	1104.60	559.80
Flow Q (cfs)	5.89	4.76	3.51	2.46	1.25
Flow Velocity (fps)	6.48	5.97	5.07	4.36	3.76
Pressure P (psi)	*3.05*	*4.30*	*5.25*	*5.95*	*6.35*
Valve position (in)	*13.81*	*12.88*	*12.19*	*11.69*	*11.19*
Valve opening (%)	77.44	54.89	38.35	26.32	14.29
Air Flow reading (fpm)	*809.00*	*734.00*	*675.00*	*561.00*	*295.00*
Air Velocity (fps)	13.48	12.23	11.25	9.35	4.92
Tail Water Depth (ft) (L,M,R)	*0.43*	*0.34*	*0.33*	*0.30*	*0.21*
	0.48	*0.42*	*0.34*	*0.26*	*0.07*
	0.38	*0.39*	*0.32*	*0.25*	*0.19*
Tail Water Depth avg (ft)	0.43	0.38	0.33	0.27	0.16
v_2/v_theory	0.24	0.21	0.17	0.14	0.12
V_theory (fps)	27.21	28.75	29.71	30.57	30.93
Fr_theory	11.14	13.27	16.00	19.73	27.83
Q_air/Q_water	0.61	0.69	0.86	1.02	1.05
Net Head on valve (ft)	13.06	14.40	15.27	16.07	16.42
Net Head Tail Water(ft)	1.08	0.93	0.73	0.56	0.38
Energy Dissipated (%)	91.70	93.53	95.23	96.49	97.70

Run:	1131	1132	1133	1134	1135
Flow reading (Hz)	*3601.00*	*2828.00*	*2137.00*	*1429.60*	*797.60*
Flow (gpm)	2700.75	2121.00	1602.75	1072.20	598.20
Flow Q (cfs)	6.02	4.73	3.57	2.39	1.33
Flow Velocity (fps)	6.73	6.14	5.56	4.24	3.82
Pressure P (psi)	*5.25*	*6.50*	*7.40*	*8.10*	*8.50*
Valve position (in)	*13.19*	*12.50*	*12.00*	*11.53*	*11.38*
Valve opening (%)	62.41	45.86	33.83	22.56	18.80
Air Flow reading (fpm)	*1002.00*	*904.00*	*827.00*	*697.00*	*409.00*
Air Velocity (fps)	16.70	15.07	13.78	11.62	6.82
Tail Water Depth (ft) (L,M,R)	*0.39*	*0.32*	*0.26*	*0.30*	*0.20*
	0.45	*0.43*	*0.33*	*0.24*	*0.10*
	0.44	*0.34*	*0.32*	*0.26*	*0.21*
Tail Water Depth avg (ft)	0.42	0.37	0.31	0.27	0.17
v_2/v_theory	0.20	0.18	0.16	0.12	0.11
V_theory (fps)	32.87	33.93	34.72	35.37	35.75
Fr_theory	14.49	16.94	19.96	24.82	33.42
Q_air/Q_water	0.74	0.85	1.03	1.30	1.37
Net Head on valve (ft)	18.34	19.44	20.28	20.99	21.41
Net Head Tail Water(ft)	1.13	0.95	0.79	0.55	0.39
Energy Dissipated (%)	93.84	95.10	96.13	97.40	98.17

Run:	1141	1142	1143	1144	1145
Flow reading (Hz)	*3587.00*	*2791.00*	*2040.00*	*1397.30*	*792.50*
Flow (gpm)	2690.25	2093.25	1530.00	1047.98	594.38
Flow Q (cfs)	5.99	4.66	3.41	2.33	1.32
Flow Velocity (fps)	6.91	6.71	5.42	4.69	3.33
Pressure P (psi)	*7.40*	*8.65*	*9.60*	*10.30*	*10.70*
Valve position (in)	*12.81*	*12.25*	*11.78*	*11.44*	*11.13*
Valve opening (%)	53.38	39.85	28.57	20.30	12.78
Air Flow reading (fpm)	*1140.00*	*1030.00*	*961.00*	*783.00*	*545.00*
Air Velocity (fps)	19.00	17.17	16.02	13.05	9.08
Tail Water Depth (ft) (L,M,R)	*0.32*	*0.26*	*0.25*	*0.25*	*0.22*
	0.50	*0.39*	*0.35*	*0.21*	*0.12*
	0.42	*0.33*	*0.30*	*0.25*	*0.23*
Tail Water Depth avg (ft)	0.41	0.33	0.30	0.24	0.19
v_2/v_theory	0.18	0.18	0.14	0.12	0.08
V_theory (fps)	37.38	38.28	39.03	39.70	40.06
Fr_theory	17.51	20.34	24.23	29.76	39.71
Q_air/Q_water	0.85	0.98	1.26	1.49	1.83
Net Head on valve (ft)	23.26	24.32	25.21	26.03	26.48
Net Head Tail Water(ft)	1.15	1.03	0.75	0.58	0.36
Energy Dissipated (%)	95.04	95.77	97.01	97.78	98.64

Run:	1211	1212	1213	1214	1215
Flow reading (Hz)	*3516.00*	*2802.00*	*2092.00*	*1447.30*	*689.00*
Flow (gpm)	2637.00	2101.50	1569.00	1085.48	516.75
Flow Q (cfs)	5.88	4.68	3.50	2.42	1.15
Flow Velocity (fps)	2.60	2.46	2.15	1.69	1.59
Pressure P (psi)	*1.50*	*2.15*	*3.10*	*3.80*	*4.20*
Valve position (in)	*14.75*	*13.69*	*12.63*	*11.94*	*11.28*
Valve opening (%)	100.00	74.44	48.87	32.33	16.54
Air Flow reading (fpm)	*675.00*	*585.00*	*404.00*	*289.00*	*126.00*
Air Velocity (fps)	11.25	9.75	6.73	4.82	2.10
Tail Water Depth (ft) (L,M,R)	*1.06*	*0.84*	*0.82*	*0.70*	*0.35*
	1.02	*0.88*	*0.71*	*0.66*	*0.34*
	1.15	*0.99*	*0.79*	*0.69*	*0.34*
Tail Water Depth avg (ft)	1.07	0.90	0.77	0.68	0.34
v_2/v_theory	0.12	0.11	0.09	0.07	0.06
V_theory (fps)	22.56	22.39	23.71	24.76	25.20
Fr_theory	8.51	9.30	11.53	14.59	21.34
Q_air/Q_water	0.51	0.56	0.51	0.53	0.49
Net Head on valve (ft)	9.47	9.34	10.29	11.08	11.43
Net Head Tail Water(ft)	1.18	1.00	0.84	0.72	0.38
Energy Dissipated (%)	87.54	89.32	91.79	93.46	96.65

Run:	1221	1222	1223	1224	1225
Flow reading (Hz)	*3479.00*	*2814.00*	*2088.00*	*1405.30*	*804.80*
Flow (gpm)	2609.25	2110.50	1566.00	1053.98	603.60
Flow Q (cfs)	5.81	4.70	3.49	2.35	1.34
Flow Velocity (fps)	2.48	2.33	2.12	1.71	1.60
Pressure P (psi)	*3.05*	*4.30*	*5.25*	*5.95*	*6.35*
Valve position (in)	*13.78*	*12.88*	*11.94*	*11.69*	*11.25*
Valve opening (%)	76.69	54.89	32.33	26.32	15.79
Air Flow reading (fpm)	*732.00*	*677.00*	*579.00*	*411.00*	*258.00*
Air Velocity (fps)	12.20	11.28	9.65	6.85	4.30
Tail Water Depth (ft) (L,M,R)	*1.07*	*0.91*	*0.78*	*0.66*	*0.42*
	1.09	*0.92*	*0.73*	*0.66*	*0.40*
	1.17	*1.05*	*0.84*	*0.64*	*0.38*
Tail Water Depth avg (ft)	1.11	0.96	0.78	0.65	0.40
v_2/v_theory	0.09	0.08	0.07	0.06	0.05
V_theory (fps)	27.08	28.67	29.68	30.50	30.96
Fr_theory	11.12	13.29	16.04	20.10	26.87
Q_air/Q_water	0.56	0.64	0.74	0.78	0.85
Net Head on valve (ft)	12.95	14.33	15.24	16.00	16.45
Net Head Tail Water(ft)	1.21	1.04	0.85	0.70	0.44
Energy Dissipated (%)	90.67	92.73	94.40	95.64	97.33

Run:	1231	1232	1233	1234	1235
Flow reading (Hz)	*3641.00*	*2863.00*	*2182.00*	*1409.80*	*703.20*
Flow (gpm)	2730.75	2147.25	1636.50	1057.35	527.40
Flow Q (cfs)	6.08	4.78	3.65	2.36	1.18
Flow Velocity (fps)	2.46	2.28	2.23	1.87	1.53
Pressure P (psi)	*5.25*	*6.45*	*7.40*	*8.10*	*8.50*
Valve position (in)	*13.19*	*12.50*	*12.00*	*11.53*	*11.13*
Valve opening (%)	62.41	45.86	33.83	22.56	12.78
Air Flow reading (fpm)	*874.00*	*807.00*	*748.00*	*567.00*	*299.00*
Air Velocity (fps)	14.57	13.45	12.47	9.45	4.98
Tail Water Depth (ft) (L,M,R)	*1.12*	*0.94*	*0.75*	*0.58*	*0.40*
	1.18	*0.98*	*0.75*	*0.60*	*0.36*
	1.24	*1.07*	*0.84*	*0.61*	*0.33*
Tail Water Depth avg (ft)	1.18	1.00	0.78	0.60	0.36
v_2/v_theory	0.07	0.07	0.06	0.05	0.04
V_theory (fps)	32.97	33.89	34.78	35.35	35.70
Fr_theory	14.49	16.82	19.82	24.96	35.47
Q_air/Q_water	0.64	0.75	0.91	1.07	1.13
Net Head on valve (ft)	18.44	19.39	20.35	20.97	21.36
Net Head Tail Water(ft)	1.27	1.08	0.85	0.65	0.40
Energy Dissipated (%)	93.12	94.44	95.80	96.89	98.12

Run:	1241	1242	1243	1244	1245
Flow reading (Hz)	*3517.00*	*2806.00*	*2192.00*	*1481.80*	*874.00*
Flow (gpm)	2637.75	2104.50	1644.00	1111.35	655.50
Flow Q (cfs)	5.88	4.69	3.66	2.48	1.46
Flow Velocity (fps)	2.40	2.29	2.41	2.03	1.60
Pressure P (psi)	*7.40*	*8.65*	*9.60*	*10.30*	*10.70*
Valve position (in)	*12.78*	*12.25*	*11.88*	*11.50*	*11.16*
Valve opening (%)	52.63	39.85	30.83	21.80	13.53
Air Flow reading (fpm)	*974.00*	*915.00*	*825.00*	*675.00*	*423.00*
Air Velocity (fps)	16.23	15.25	13.75	11.25	7.05
Tail Water Depth (ft) (L,M,R)	*1.11*	*0.90*	*0.66*	*0.50*	*0.46*
	1.17	*0.98*	*0.71*	*0.61*	*0.44*
	1.21	*1.04*	*0.80*	*0.63*	*0.40*
Tail Water Depth avg (ft)	1.17	0.97	0.72	0.58	0.43
v_2/v_theory	0.06	0.06	0.06	0.05	0.04
V_theory (fps)	37.23	38.31	39.22	39.77	40.10
Fr_theory	17.56	20.31	23.59	29.01	37.91
Q_air/Q_water	0.74	0.87	1.00	1.21	1.29
Net Head on valve (ft)	23.08	24.35	25.44	26.12	26.53
Net Head Tail Water(ft)	1.25	1.05	0.81	0.64	0.47
Energy Dissipated (%)	94.57	95.68	96.80	97.54	98.21

Run:	1311	1312	1313	1314	1315
Flow reading (Hz)	*3502.00*	*2824.00*	*2098.00*	*1408.20*	*689.50*
Flow (gpm)	2626.50	2118.00	1573.50	1056.15	517.13
Flow Q (cfs)	5.85	4.72	3.51	2.35	1.15
Flow Velocity (fps)	9.09	8.36	7.52	5.68	4.65
Pressure P (psi)	*1.45*	*2.15*	*3.10*	*3.80*	*4.20*
Valve position (in)	*14.75*	*13.63*	*12.63*	*11.84*	*11.28*
Valve opening (%)	100.00	72.93	48.87	30.08	16.54
Air Flow reading (fpm)	*707.00*	*622.00*	*429.00*	*291.00*	*130.00*
Air Velocity (fps)	11.78	10.37	7.15	4.85	2.17
Tail Water Depth (ft) (L,M,R)	*1.12*	*0.96*	*0.73*	*0.62*	*0.33*
	1.10	*0.95*	*0.76*	*0.52*	*0.33*
	1.11	*0.96*	*0.85*	*0.48*	*0.37*
Tail Water Depth avg (ft)	0.31	0.27	0.22	0.20	0.12
v_2/v_theory	0.41	0.37	0.32	0.23	0.18
V_theory (fps)	22.34	22.45	23.72	24.71	25.20
Fr_theory	8.40	9.31	11.53	14.73	21.34
Q_air/Q_water	0.54	0.59	0.55	0.55	0.50
Net Head on valve (ft)	9.31	9.39	10.30	11.04	11.43
Net Head Tail Water(ft)	1.59	1.35	1.10	0.70	0.45
Energy Dissipated (%)	82.95	85.59	89.32	93.69	96.03

Run:	1321	1322	1323	1324	1325
Flow reading (Hz)	*3551.00*	*2881.00*	*2070.00*	*1475.30*	*772.90*
Flow (gpm)	2663.25	2160.75	1552.50	1106.48	579.68
Flow Q (cfs)	5.93	4.81	3.46	2.47	1.29
Flow Velocity (fps)	10.13	9.22	6.53	5.80	4.41
Pressure P (psi)	*3.05*	*4.30*	*5.25*	*5.95*	*6.35*
Valve position (in)	*13.84*	*12.88*	*12.13*	*11.66*	*11.16*
Valve opening (%)	78.20	54.89	36.84	25.56	13.53
Air Flow reading (fpm)	*760.00*	*707.00*	*571.00*	*467.00*	*278.00*
Air Velocity (fps)	12.67	11.78	9.52	7.78	4.63
Tail Water Depth (ft) (L,M,R)	*1.23*	*1.06*	*0.78*	*0.69*	*0.35*
	1.18	*1.02*	*0.71*	*0.52*	*0.35*
	1.20	*1.01*	*0.61*	*0.46*	*0.34*
Tail Water Depth avg (ft)	0.28	0.25	0.25	0.20	0.14
v_2/v_theory	0.37	0.32	0.22	0.19	0.14
V_theory (fps)	27.29	28.83	29.65	30.57	30.94
Fr_theory	11.15	13.25	16.08	19.71	27.38
Q_air/Q_water	0.57	0.65	0.74	0.84	0.96
Net Head on valve (ft)	13.13	14.47	15.22	16.08	16.43
Net Head Tail Water(ft)	1.87	1.57	0.91	0.72	0.44
Energy Dissipated (%)	85.76	89.16	93.99	95.50	97.31

Run:	1331	1332	1333	1334	1335
Flow reading (Hz)	*3624.00*	*2882.00*	*2154.00*	*1452.80*	*662.10*
Flow (gpm)	2718.00	2161.50	1615.50	1089.60	496.58
Flow Q (cfs)	6.06	4.82	3.60	2.43	1.11
Flow Velocity (fps)	10.12	8.78	5.67	5.14	4.26
Pressure P (psi)	*5.25*	*6.45*	*7.40*	*8.10*	*8.50*
Valve position (in)	*13.19*	*12.50*	*11.94*	*11.50*	*11.00*
Valve opening (%)	62.41	45.86	32.33	21.80	9.77
Air Flow reading (fpm)	*886.00*	*825.00*	*736.00*	*602.00*	*307.00*
Air Velocity (fps)	14.77	13.75	12.27	10.03	5.12
Tail Water Depth (ft) (L,M,R)	*1.27*	*1.06*	*0.63*	*0.62*	*0.32*
	1.21	*1.01*	*0.72*	*0.49*	*0.32*
	1.15	*0.92*	*0.57*	*0.42*	*0.31*
Tail Water Depth avg (ft)	0.28	0.26	0.30	0.22	0.12
v_2/v_theory	0.31	0.26	0.16	0.15	0.12
V_theory (fps)	32.93	33.92	34.74	35.39	35.68
Fr_theory	14.49	16.79	19.91	24.65	36.50
Q_air/Q_water	0.65	0.76	0.91	1.10	1.24
Net Head on valve (ft)	18.40	19.43	20.31	21.01	21.34
Net Head Tail Water(ft)	1.87	1.46	0.80	0.63	0.40
Energy Dissipated (%)	89.81	92.49	96.05	96.98	98.10

Run:	1341	1342	1343	1344	1345
Flow reading (Hz)	*3464.00*	*2755.00*	*2074.00*	*1421.30*	*866.10*
Flow (gpm)	2598.00	2066.25	1555.50	1065.98	649.58
Flow Q (cfs)	5.79	4.60	3.47	2.38	1.45
Flow Velocity (fps)	10.63	7.10	5.12	4.60	4.94
Pressure P (psi)	*7.40*	*8.65*	*9.60*	*10.30*	*10.70*
Valve position (in)	*12.75*	*12.19*	*11.75*	*11.38*	*11.13*
Valve opening (%)	51.88	38.35	27.82	18.80	12.78
Air Flow reading (fpm)	*955.00*	*915.00*	*825.00*	*677.00*	*457.00*
Air Velocity (fps)	15.92	15.25	13.75	11.28	7.62
Tail Water Depth (ft) (L,M,R)	*1.31*	*0.91*	*0.55*	*0.52*	*0.45*
	1.22	*0.91*	*0.68*	*0.46*	*0.38*
	1.14	*0.70*	*0.52*	*0.40*	*0.36*
Tail Water Depth avg (ft)	0.26	0.31	0.32	0.25	0.14
v_2/v_theory	0.29	0.19	0.13	0.12	0.12
V_theory (fps)	37.11	38.22	39.07	39.72	40.09
Fr_theory	17.60	20.42	24.08	29.54	38.07
Q_air/Q_water	0.73	0.89	1.06	1.27	1.41
Net Head on valve (ft)	22.95	24.25	25.26	26.06	26.52
Net Head Tail Water(ft)	2.01	1.09	0.73	0.57	0.52
Energy Dissipated (%)	91.23	95.50	97.11	97.80	98.05

Run:	2111	2112	2113	2114	2115
Flow reading (Hz)	*3541.00*	*2740.00*	*2010.00*	*1454.50*	*697.60*
Flow (gpm)	2655.75	2055.00	1507.50	1090.88	523.20
Flow Q (cfs)	5.92	4.58	3.36	2.43	1.17
Flow Velocity (fps)	8.43	7.07	6.17	5.60	3.81
Pressure P (psi)	*1.35*	*2.15*	*3.10*	*3.80*	*4.20*
Valve position (in)	*14.75*	*13.56*	*12.50*	*11.88*	*11.25*
Valve opening (%)	100.00	71.43	45.86	30.83	15.79
Air Flow reading (fpm)	*571.00*	*465.00*	*329.00*	*270.00*	*179.00*
Air Velocity (fps)	9.52	7.75	5.48	4.50	2.98
Tail Water Depth (ft) (L,M,R)	*1.06*	*0.85*	*0.62*	*0.56*	*0.30*
	1.05	*0.86*	*0.69*	*0.56*	*0.29*
	1.07	*0.81*	*0.68*	*0.51*	*0.30*
Tail Water Depth avg (ft)	0.33	0.31	0.26	0.21	0.15
v_2/v_theory	0.38	0.32	0.26	0.23	0.15
V_theory (fps)	22.15	22.21	23.54	24.77	25.21
Fr_theory	8.26	9.29	11.63	14.56	21.22
Q_air/Q_water	0.43	0.45	0.44	0.49	0.68
Net Head on valve (ft)	8.61	8.65	9.59	10.52	10.86
Net Head Tail Water(ft)	1.44	1.08	0.85	0.69	0.37
Energy Dissipated (%)	83.30	87.47	91.14	93.41	96.58

Run:	2121	2122	2123	2124	2125
Flow reading (Hz)	*3420.00*	*2808.00*	*2070.00*	*1472.30*	*789.20*
Flow (gpm)	2565.00	2106.00	1552.50	1104.23	591.90
Flow Q (cfs)	5.71	4.69	3.46	2.46	1.32
Flow Velocity (fps)	8.46	7.45	6.32	5.65	4.23
Pressure P (psi)	*3.05*	*4.30*	*5.25*	*5.95*	*6.35*
Valve position (in)	*13.63*	*12.81*	*12.13*	*11.63*	*11.38*
Valve opening (%)	72.93	53.38	36.84	24.81	18.80
Air Flow reading (fpm)	*648.00*	*585.00*	*500.00*	*429.00*	*321.00*
Air Velocity (fps)	10.80	9.75	8.33	7.15	5.35
Tail Water Depth (ft) (L,M,R)	*1.04*	***0.90***	***0.71***	*0.53*	*0.36*
	1.06	***0.86***	***0.66***	*0.60*	*0.34*
	1.04	***0.87***	***0.69***	*0.51*	*0.32*
Tail Water Depth avg (ft)	0.32	0.30	0.26	0.21	0.15
v_2/v_theory	0.31	0.26	0.21	0.18	0.14
V_theory (fps)	26.90	28.66	29.65	30.57	30.95
Fr_theory	11.10	13.30	16.08	19.73	27.12
Q_air/Q_water	0.51	0.56	0.64	0.78	1.08
Net Head on valve (ft)	12.23	13.75	14.64	15.50	15.87
Net Head Tail Water(ft)	1.43	1.16	0.88	0.70	0.43
Energy Dissipated (%)	88.30	91.56	93.99	95.47	97.32

Run:	2131	2132	2133	2134	2135
Flow reading (Hz)	*3486.00*	*2848.00*	*2100.00*	*1383.00*	*720.30*
Flow (gpm)	2614.50	2136.00	1575.00	1037.25	540.23
Flow Q (cfs)	5.83	4.76	3.51	2.31	1.20
Flow Velocity (fps)	8.22	7.49	6.72	5.51	3.99
Pressure P (psi)	*5.25*	*6.45*	*7.40*	*8.10*	*8.50*
Valve position (in)	*13.06*	*12.50*	*11.94*	*11.50*	*11.25*
Valve opening (%)	59.40	45.86	32.33	21.80	15.79
Air Flow reading (fpm)	*772.00*	*711.00*	*669.00*	*591.00*	*402.00*
Air Velocity (fps)	12.87	11.85	11.15	9.85	6.70
Tail Water Depth (ft) (L,M,R)	*1.03*	***0.86***	***0.67***	*0.54*	*0.32*
	1.06	***0.89***	***0.74***	*0.55*	*0.31*
	1.01	***0.92***	***0.75***	*0.48*	*0.30*
Tail Water Depth avg (ft)	0.34	0.30	0.25	0.20	0.14
v_2/v_theory	0.25	0.22	0.19	0.16	0.11
V_theory (fps)	32.58	33.86	34.67	35.33	35.71
Fr_theory	14.52	16.84	20.08	25.17	35.06
Q_air/Q_water	0.59	0.67	0.85	1.14	1.49
Net Head on valve (ft)	17.47	18.79	19.65	20.37	20.79
Net Head Tail Water(ft)	1.39	1.17	0.95	0.67	0.39
Energy Dissipated (%)	92.06	93.76	95.17	96.71	98.12

Run:	2141	2142	2143	2144	2145
Flow reading (Hz)	*3388.00*	*2706.00*	*2051.00*	*1352.80*	*795.80*
Flow (gpm)	2541.00	2029.50	1538.25	1014.60	596.85
Flow Q (cfs)	5.66	4.52	3.43	2.26	1.33
Flow Velocity (fps)	8.16	8.07	6.69	5.42	4.21
Pressure P (psi)	*7.40*	*8.65*	*9.60*	*10.30*	*10.70*
Valve position (in)	*12.63*	*12.13*	*11.75*	*11.38*	*11.06*
Valve opening (%)	48.87	36.84	27.82	18.80	11.28
Air Flow reading (fpm)	*878.00*	*799.00*	*748.00*	*697.00*	*504.00*
Air Velocity (fps)	14.63	13.32	12.47	11.62	8.40
Tail Water Depth (ft) (L,M,R)	***1.06***	***0.96***	***0.78***	*0.20*	*0.36*
	1.01	***0.90***	***0.71***	*0.22*	*0.35*
	0.99	***0.88***	***0.64***	*0.18*	*0.31*
Tail Water Depth avg (ft)	0.33	0.27	0.24	0.20	0.15
v_2/v_theory	0.22	0.21	0.17	0.14	0.11
V_theory (fps)	36.95	38.14	39.04	39.66	40.06
Fr_theory	17.67	20.52	24.18	30.19	39.63
Q_air/Q_water	0.69	0.79	0.97	1.37	1.69
Net Head on valve (ft)	22.19	23.58	24.65	25.42	25.91
Net Head Tail Water(ft)	1.36	1.28	0.94	0.65	0.43
Energy Dissipated (%)	93.85	94.59	96.19	97.43	98.36

Run:	2211	2212	2213	2214	2215
Flow reading (Hz)	*3492.00*	*2769.00*	*2102.00*	*1459.20*	*700.80*
Flow (gpm)	2619.00	2076.75	1576.50	1094.40	525.60
Flow Q (cfs)	5.84	4.63	3.51	2.44	1.17
Flow Velocity (fps)	2.78	2.59	2.40	2.24	1.90
Pressure P (psi)	*1.40*	*2.15*	*3.10*	*3.80*	*4.20*
Valve position (in)	*14.75*	*13.56*	*12.63*	*11.94*	*11.28*
Valve opening (%)	100.00	71.43	48.87	32.33	16.54
Air Flow reading (fpm)	*520.00*	*480.00*	*366.00*	*311.00*	*203.00*
Air Velocity (fps)	8.67	8.00	6.10	5.18	3.38
Tail Water Depth (ft) (L,M,R)	*1.02*	*0.85*	*0.68*	*0.52*	*0.30*
	0.97	*0.87*	*0.67*	*0.51*	*0.29*
	1.00	*0.83*	*0.74*	*0.52*	*0.30*
Tail Water Depth avg (ft)	1.00	0.85	0.70	0.52	0.29
v_2/v_theory	0.13	0.12	0.10	0.09	0.08
V_theory (fps)	22.14	22.29	23.73	24.78	25.21
Fr_theory	8.31	9.29	11.52	14.55	21.18
Q_air/Q_water	0.40	0.46	0.46	0.57	0.77
Net Head on valve (ft)	8.60	8.71	9.73	10.52	10.86
Net Head Tail Water(ft)	1.12	0.95	0.78	0.60	0.35
Energy Dissipated (%)	87.02	89.06	91.94	94.35	96.78

Run:	2221	2222	2223	2224	2225
Flow reading (Hz)	*3543.00*	*2835.00*	*2048.00*	*1526.60*	*766.40*
Flow (gpm)	2657.25	2126.25	1536.00	1144.95	574.80
Flow Q (cfs)	5.92	4.74	3.42	2.55	1.28
Flow Velocity (fps)	2.61	2.45	2.37	2.24	1.79
Pressure P (psi)	*3.05*	*4.30*	*5.25*	*5.95*	*6.35*
Valve position (in)	*13.81*	*12.88*	*12.16*	*11.75*	*11.22*
Valve opening (%)	77.44	54.89	37.59	27.82	15.04
Air Flow reading (fpm)	*656.00*	*610.00*	*569.00*	*492.00*	*278.00*
Air Velocity (fps)	10.93	10.17	9.48	8.20	4.63
Tail Water Depth (ft) (L,M,R)	*1.08*	*0.94*	*0.67*	*0.57*	*0.36*
	1.06	*0.88*	*0.69*	*0.54*	*0.34*
	1.09	*0.95*	*0.70*	*0.51*	*0.32*
Tail Water Depth avg (ft)	1.08	0.92	0.69	0.54	0.34
v_2/v_theory	0.10	0.09	0.08	0.07	0.06
V_theory (fps)	27.27	28.72	29.62	30.63	30.94
Fr_theory	11.14	13.28	16.13	19.45	27.49
Q_air/Q_water	0.49	0.57	0.74	0.86	0.97
Net Head on valve (ft)	12.54	13.80	14.61	15.56	15.85
Net Head Tail Water(ft)	1.18	1.01	0.77	0.62	0.39
Energy Dissipated (%)	90.56	92.66	94.71	96.02	97.54

Run:	2231	2232	2233	2234	2235
Flow reading (Hz)	*3535.00*	*2838.00*	*2110.00*	*1402.00*	*673.00*
Flow (gpm)	2651.25	2128.50	1582.50	1051.50	504.75
Flow Q (cfs)	5.91	4.74	3.53	2.34	1.12
Flow Velocity (fps)	2.53	2.40	2.27	2.21	1.71
Pressure P (psi)	*5.25*	*6.45*	*7.40*	*8.10*	*8.50*
Valve position (in)	*13.13*	*12.50*	*12.00*	*11.53*	*11.13*
Valve opening (%)	60.90	45.86	33.83	22.56	12.78
Air Flow reading (fpm)	*748.00*	*695.00*	*669.00*	*614.00*	*305.00*
Air Velocity (fps)	12.47	11.58	11.15	10.23	5.08
Tail Water Depth (ft) (L,M,R)	*1.11*	*0.96*	*0.71*	*0.53*	*0.34*
	1.10	*0.92*	*0.78*	*0.50*	*0.31*
	1.13	*0.95*	*0.72*	*0.49*	*0.29*
Tail Water Depth avg (ft)	1.11	0.94	0.74	0.50	0.31
v_2/v_theory	0.08	0.07	0.07	0.06	0.05
V_theory (fps)	32.70	33.84	34.68	35.34	35.69
Fr_theory	14.51	16.85	20.05	25.02	36.21
Q_air/Q_water	0.56	0.65	0.85	1.17	1.21
Net Head on valve (ft)	17.59	18.77	19.67	20.39	20.77
Net Head Tail Water(ft)	1.21	1.03	0.82	0.58	0.36
Energy Dissipated (%)	93.12	94.51	95.84	97.16	98.28

Run:	2241	2242	2243	2244	2245
Flow reading (Hz)	*3421.00*	*2725.00*	*2018.00*	*1374.20*	*772.90*
Flow (gpm)	2565.75	2043.75	1513.50	1030.65	579.68
Flow Q (cfs)	5.72	4.55	3.37	2.30	1.29
Flow Velocity (fps)	2.54	2.36	2.27	2.07	1.75
Pressure P (psi)	*7.40*	*8.65*	*9.60*	*10.30*	*10.70*
Valve position (in)	*12.69*	*12.19*	*11.78*	*11.44*	*11.06*
Valve opening (%)	50.38	38.35	28.57	20.30	11.28
Air Flow reading (fpm)	*817.00*	*799.00*	*748.00*	*707.00*	*406.00*
Air Velocity (fps)	13.62	13.32	12.47	11.78	6.77
Tail Water Depth (ft) (L,M,R)	*1.04*	*0.92*	*0.70*	*0.54*	*0.37*
	1.10	*0.91*	*0.73*	*0.52*	*0.35*
	1.07	*0.92*	*0.69*	*0.53*	*0.33*
Tail Water Depth avg (ft)	1.07	0.92	0.71	0.53	0.35
v_2/v_theory	0.07	0.06	0.06	0.05	0.04
V_theory (fps)	37.02	38.17	39.00	39.68	40.05
Fr_theory	17.64	20.48	24.33	29.98	40.18
Q_air/Q_water	0.64	0.78	0.99	1.37	1.40
Net Head on valve (ft)	22.27	23.62	24.61	25.44	25.90
Net Head Tail Water(ft)	1.17	1.00	0.79	0.59	0.40
Energy Dissipated (%)	94.75	95.75	96.80	97.67	98.46

Run:	2311	2312	2313	2314	2315
Flow reading (Hz)	*3503.00*	*2744.00*	*2053.00*	*1474.80*	*724.50*
Flow (gpm)	2627.25	2058.00	1539.75	1106.10	543.38
Flow Q (cfs)	5.85	4.59	3.43	2.46	1.21
Flow Velocity (fps)	8.16	6.61	5.56	5.06	4.39
Pressure P (psi)	*1.35*	*2.15*	*3.10*	*3.80*	*4.20*
Valve position (in)	*14.75*	*13.50*	*12.50*	*11.88*	*11.25*
Valve opening (%)	100.00	69.92	45.86	30.83	15.79
Air Flow reading (fpm)	*539.00*	*498.00*	*374.00*	*317.00*	*209.00*
Air Velocity (fps)	8.98	8.30	6.23	5.28	3.48
	1.02	*0.81*	*0.64*	*0.47*	*0.34*
Tail Water Depth (ft) (L,M,R)	*1.02*	*0.76*	*0.58*	*0.57*	*0.34*
	1.05	*0.82*	*0.64*	*0.47*	*0.33*
Tail Water Depth avg (ft)	0.34	0.33	0.29	0.23	0.13
v_2/v_theory	0.37	0.30	0.24	0.20	0.17
V_theory (fps)	22.01	22.22	23.63	24.80	25.23
Fr_theory	8.23	9.29	11.58	14.49	20.86
Q_air/Q_water	0.41	0.48	0.49	0.57	0.77
Net Head on valve (ft)	8.51	8.66	9.66	10.54	10.87
Net Head Tail Water(ft)	1.37	1.01	0.77	0.63	0.43
Energy Dissipated (%)	83.85	88.35	91.99	94.03	96.04

Run:	2321	2322	2323	2324	2325
Flow reading (Hz)	*3458.00*	*2770.00*	*2084.00*	*1465.00*	*766.80*
Flow (gpm)	2593.50	2077.50	1563.00	1098.75	575.10
Flow Q (cfs)	5.78	4.63	3.48	2.45	1.28
Flow Velocity (fps)	8.44	6.42	5.43	4.77	3.90
Pressure P (psi)	*3.05*	*4.30*	*5.25*	*5.95*	*6.35*
Valve position (in)	*13.69*	*12.81*	*12.13*	*11.91*	*11.19*
Valve opening (%)	74.44	53.38	36.84	31.58	14.29
Air Flow reading (fpm)	*667.00*	*648.00*	*579.00*	*492.00*	*276.00*
Air Velocity (fps)	11.12	10.80	9.65	8.20	4.60
	1.05	*0.72*	***0.60***	*0.25*	*0.31*
Tail Water Depth (ft) (L,M,R)	*1.04*	*0.80*	***0.59***	*0.23*	*0.32*
	1.05	*0.83*	***0.64***	*0.26*	*0.31*
Tail Water Depth avg (ft)	0.33	0.34	0.30	0.24	0.16
v_2/v_theory	0.31	0.22	0.18	0.16	0.13
V_theory (fps)	27.02	28.58	29.68	30.56	30.94
Fr_theory	11.11	13.32	16.04	19.77	27.48
Q_air/Q_water	0.51	0.62	0.74	0.90	0.96
Net Head on valve (ft)	12.32	13.67	14.67	15.49	15.85
Net Head Tail Water(ft)	1.43	0.98	0.76	0.60	0.39
Energy Dissipated (%)	88.39	92.81	94.80	96.14	97.52

Run:	2331	2332	2333	2334	2335
Flow reading (Hz)	*3519.00*	*2812.00*	*2112.00*	*1374.50*	*679.50*
Flow (gpm)	2639.25	2109.00	1584.00	1030.88	509.63
Flow Q (cfs)	5.88	4.70	3.53	2.30	1.14
Flow Velocity (fps)	8.83	7.35	5.84	4.64	3.61
Pressure P (psi)	*5.25*	*6.45*	*7.40*	*8.10*	*8.50*
Valve position (in)	*13.13*	*12.44*	*11.94*	*11.50*	*11.00*
Valve opening (%)	60.90	44.36	32.33	21.80	9.77
Air Flow reading (fpm)	*752.00*	*744.00*	*689.00*	*600.00*	*289.00*
Air Velocity (fps)	12.53	12.40	11.48	10.00	4.82
Tail Water Depth (ft) (L,M,R)	*1.13*	*0.87*	***0.63***	*0.23*	*0.29*
	1.07	*0.85*	***0.65***	*0.22*	*0.27*
	1.08	*0.89*	***0.67***	*0.26*	*0.29*
Tail Water Depth avg (ft)	0.32	0.30	0.29	0.24	0.15
v_2/v_theory	0.27	0.22	0.17	0.13	0.10
V_theory (fps)	32.66	33.79	34.68	35.32	35.69
Fr_theory	14.51	16.89	20.04	25.23	36.05
Q_air/Q_water	0.57	0.71	0.87	1.16	1.13
Net Head on valve (ft)	17.55	18.71	19.67	20.36	20.77
Net Head Tail Water(ft)	1.53	1.14	0.82	0.57	0.35
Energy Dissipated (%)	91.30	93.89	95.85	97.20	98.31

Run:	2341	2342	2343	2344	2345
Flow reading (Hz)	*3438.00*	*2706.00*	*2077.00*	*1362.00*	*790.10*
Flow (gpm)	2578.50	2029.50	1557.75	1021.50	592.58
Flow Q (cfs)	5.74	4.52	3.47	2.28	1.32
Flow Velocity (fps)	8.81	7.26	6.19	4.79	3.03
Pressure P (psi)	*7.40*	*8.65*	*9.60*	*10.30*	*10.70*
Valve position (in)	*12.69*	*12.19*	*11.75*	*11.38*	*11.06*
Valve opening (%)	50.38	38.35	27.82	18.80	11.28
Air Flow reading (fpm)	*868.00*	*837.00*	*754.00*	*687.00*	*419.00*
Air Velocity (fps)	14.47	13.95	12.57	11.45	6.98
Tail Water Depth (ft) (L,M,R)	*1.11*	*0.85*	***0.63***	*0.20*	*0.29*
	1.05	*0.82*	***0.71***	*0.23*	*0.23*
	1.07	*0.88*	***0.69***	*0.25*	*0.25*
Tail Water Depth avg (ft)	0.31	0.30	0.27	0.23	0.21
v_2/v_theory	0.24	0.19	0.16	0.12	0.08
V_theory (fps)	37.06	38.14	39.07	39.67	40.06
Fr_theory	17.62	20.52	24.07	30.10	39.76
Q_air/Q_water	0.67	0.82	0.97	1.34	1.41
Net Head on valve (ft)	22.31	23.58	24.69	25.43	25.91
Net Head Tail Water(ft)	1.51	1.11	0.86	0.58	0.35
Energy Dissipated (%)	93.21	95.27	96.51	97.71	98.65