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Flow Deflectors for Mitigation of Stilling Basin Abrasion Damage

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Model investigations were conducted by Reclamation’s Hydraulic Investigations and Laboratory Services group in Denver to develop standard guidelines for the design of flow deflectors to reduce or eliminate stilling basin abrasion damage. Abrasion damage has been a long-standing problem for stilling basins throughout Reclamation for many years and a number of studies have been conducted to try to understand the problem and to come up with cost effective solutions. Through these investigations it was determined that flow deflectors can be used to mitigate abrasion damage by redirecting flow currents responsible for carrying abrasive materials into stilling basins, for Reclamation type II and type III stilling basins of standard design. In addition, field evaluations of the stilling basins at Mason Dam and Choke Canyon Dam were conducted to correlate with the models and to help refine and verify the final design.

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Flow Deflectors for Mitigation of Abrasion Damage

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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.

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Executive Summary

Model investigations were conducted by Reclamation’s Hydraulic Investigations and Laboratory Services group in Denver to develop standard guidelines for the design of flow deflectors to reduce or eliminate stilling basin abrasion damage. Abrasion damage has been a long-standing problem for stilling basins throughout Reclamation for many years and a number of studies have been conducted to try to understand the problem and to come up with cost effective solutions. Through these investigations it was determined that flow deflectors can be used to mitigate abrasion damage by redirecting flow currents responsible for carrying abrasive materials into stilling basins, for Reclamation type II and type III stilling basins of standard design. In addition, field evaluations of the stilling basins at Mason Dam and Choke Canyon Dam were conducted to correlate with the models and to help refine and verify the final design.

This document is a culmination of what has been learned from these studies. This document addresses deflector geometry, angle, and positioning for Reclamation stilling basins of standard design. The first step in the design process will be to determine how well stilling basin geometry follows guidelines presented in Reclamation’s Engineering Monograph No. 25 [1]. In addition, how the stilling basin is operated will impact how the flow deflector is designed and will determine if one deflector is adequate or whether two staggered deflectors are required to provide effective performance.

This study only addresses deflector design for stilling basins less than 25 ft in width. This is because wider stilling basins often exhibit additional flow characteristics that need to be addressed in the design of the flow deflector. In addition a flow deflector spanning a distance greater than 25 ft may require additional structural support. For these wider basins a flow deflector can be designed to be effective in preventing materials from entering the stilling basin, however a physical model study is recommended.

In the future, for stilling basins that fit the above criteria, a field evaluation at a potential site, along with the guidelines produced from this study, will be used to design deflectors without the need for a physical model study for each individual basin.

Purpose

Model investigations were conducted by Reclamation’s Hydraulic Investigations and Laboratory Services group in Denver to develop standard guidelines for the design of flow deflectors to reduce or eliminate stilling basin abrasion damage. Abrasion damage has been a long-standing problem for stilling basins throughout Reclamation for many years and a number of studies have been conducted to try to understand the problem and to come up with cost effective solutions. In addition, field evaluations of the stilling basins at Mason Dam and Choke Canyon Dam were conducted to correlate with the model and to help refine and verify the final deflector design. This document is a culmination of what has been learned from those studies and presents the methods used to develop guidelines for determining deflector geometry, angle, and positioning for Reclamation stilling basins of standard design. In the future, a field evaluation at a potential site, along with the guidelines produced from this study, will be used to design deflectors without the need for a physical model study for each individual basin.

Introduction

Stilling basin abrasion damage is a widespread problem for river outlet works at Bureau of Reclamation (Reclamation) dam sites throughout the western United States. Abrasion damage occurs when materials, such as sand, gravel, or rock, are carried into the basin by recirculating flow patterns produced over the basin end sill during normal operation of a hydraulic jump energy dissipation basin (figure 1). Once materials are in the basin, turbulent flow continually moves the materials against the concrete surface, causing severe damage, often to the extent that reinforcing bars are exposed. When repairs are made, many basins experience the same damage again within one or two operating seasons. As a result, hundreds of thousands of dollars are repeatedly spent by Reclamation to repair this type of damage. The total calculated present value benefit for installing the flow deflectors at Mason and Choke Canyon Dams is $451,173. This is comprised of $306,129 in water cost savings and $145,044 in improved water reliability benefits.

Water cost savings result from reduced maintenance costs. Water reliability savings are derived from reduced risk of water delivery interruptions. Benefit calculations are in terms of total values in 2007 dollars [2]. This demonstrates that the implementation of flow deflectors could result in substantial cost savings by reducing recurring O&M costs for basin repairs, dewatering, and interruptions in water deliveries

Figure 2 shows typical abrasion damage that has occurred at the Choke Canyon Dam outlet works stilling basin. Damage occurs most commonly in Reclamation type II and type III stilling basins (figures 3 and 4). Both basins are Reclamation standard designs for hydraulic jump energy dissipation basins, typically used for Froude numbers greater than 4.5. The type II basin is designed for entrance velocities greater than 60 ft/s and uses chute blocks and a dentated sill at the end

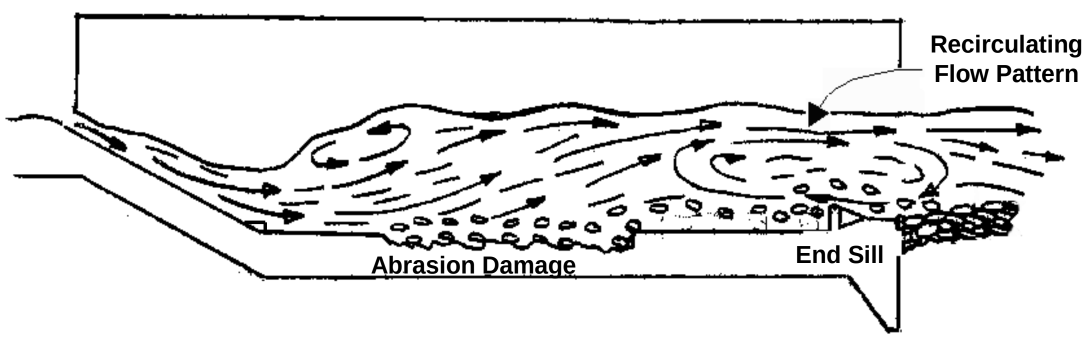

Figure 1. Recirculating flow pattern is produced over end sill during normal operations.

of the basin to help stabilize the jump to dissipate the high velocity flow before it enters the river channel. The type III basin is similar to a type II basin except that it uses baffle blocks in addition to chute blocks, and a simpler end sill in place of the dentated sill, to shorten the length of the jump. The type III basin is designed to dissipate the high velocity flow for basins with entrance velocities less than 60 ft/s.

Research funded by Reclamation's S&T(Science and Technology) program and conducted by Reclamations Hydraulic Investigations and Laboratory Services group in Denver was used to identify flow currents that carry damaging materials into the basins and then to identify cost effective solutions for mitigating this type of damage. This led to the development of flow deflectors that can be used to change flow patterns occurring over the basin end sill, thus minimizing or eliminating the potential for abrasive materials to be carried into the basin (figure 5). Collaboration with Reclamation's PN region and Snake River Area office resulted in the first prototype deflector being installed at Mason Dam in October 2002. In addition, another set of flow deflectors were installed in December of 2006 at the Choke Canyon Dam outlet works stilling basin as a result of a collaborative effort with the Texas-Oklahoma Area Office and the city of Corpus Christi. A U.S. patent for the flow deflection design on March 20, 2007.

Figure 2. Typical abrasion damage (Choke Canyon stilling basin).

Conclusions

The following conclusions were based upon the results from the hydraulic model testing of various deflector configurations studied to improve flow conditions at the end of type II and type III stilling basins. The studies began with evaluating the existing conditions for a range of operations up to maximum design flow for each basin, then progressed with testing a series of different configurations using one or more deflectors through the same range of operations, until an optimal deflector configuration was determined. Optimal is defined as producing the maximum downstream average bottom velocity exiting the stilling basin over the largest range of operations. All dimensions and measurements reported here are scaled to prototype dimensions and are referenced to the upstream edge of the lowest elevation on the deflector.

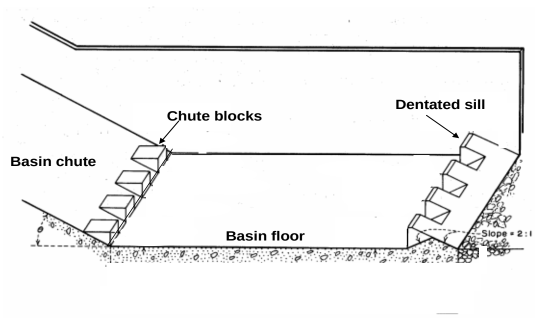

Figure 3. Reclamation type II stilling basin.

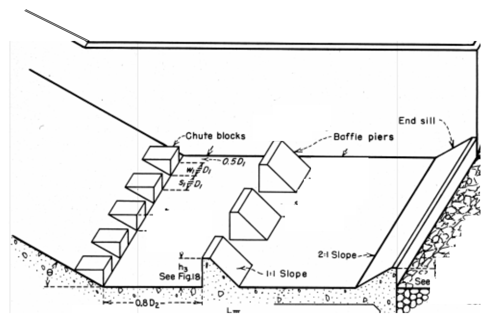

Figure 4. Reclamation type III stilling basin.

Model Evaluation
(Mason, Choke Canyon, and Haystack basins)

1) Results from model investigations indicate that the installation of a flow deflector in stilling basins can help improve flow conditions to minimize the potential for carrying materials into the basin, thereby extending basin life, and reducing long-term O&M costs.

2) Model investigations were used successfully to generate standard guidelines for deflector design, so that in the future, a deflector can be designed for a specific site using these guidelines along with velocity data acquired from an on-site field evaluation.

3) Model investigations demonstrated that either a single mobile deflector or two stationary staggered deflectors (staggered in position both vertically and horizontally) can be effective at sites where large ranges of operations (discharge or tailwater variations) need to be considered in the design.

4) Without a deflector in the basin, the average bottom velocities measured in the model at the end of each basin were predominantly in the upstream direction and ranged from -0.8 ft/s for Mason Dam to -1.8 ft/s for Choke Canyon Dam for gate openings ranging from 20% to 100% (negative values indicate velocities were upstream into the basin). Maximum instantaneous velocities in the upstream direction were about -3.0 ft/s for Mason Dam, – 5.0 ft/s for Haystack dam, and -15 ft/s for Choke Canyon Dam.

5) With the optimal deflector design in place, the maximum instantaneous bottom velocities measured at the end of the basin were redirected downstream and were as high as 5.0 ft/s for Mason Dam, 7.0 ft/s for Haystack Dam, and 20 ft/s for Choke Canyon. Average bottom velocities measured in the model under the same flow conditions were 1.75 ft/s for Mason Dam, 3.2 ft/s for Haystack Dam and 10 ft/s for Choke Canyon Dam. Therefore, minimal erosion is expected downstream from the stilling basin.

6) Model investigations indicated that with a deflector installed in a type II stilling basin, flow releases in the range of about 30% to 60% gate opening can be used to flush materials from the basin in many cases. The exact size of materials that can be flushed from a basin with the deflector in place will depend on deflector configuration and basin operations. Without a deflector, it may only be possible to flush materials from the basin with releases close to 100% gate opening at maximum reservoir.

7) Model investigations demonstrated that a deflector installed in a type III stilling basin will prevent upstream currents from carrying materials into the basin, but materials entering the basin from other sources may remain trapped within the basin (i.e. no self-flushing).

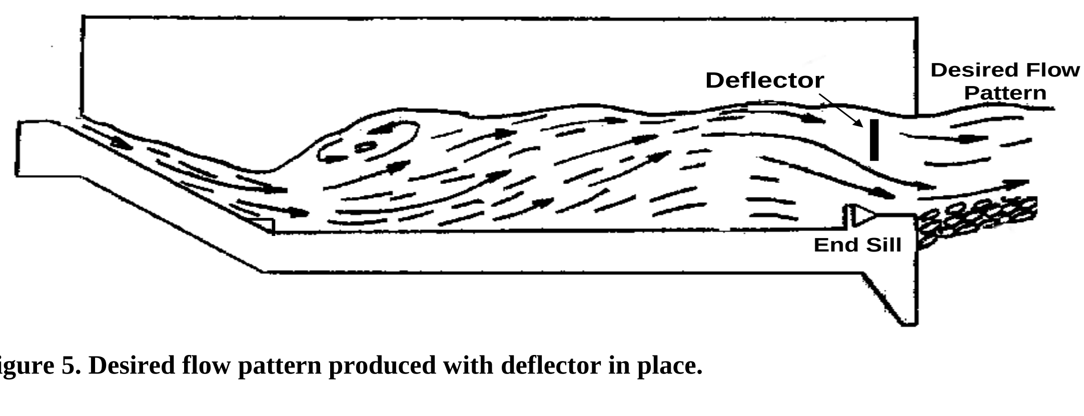

Figure 5. Desired flow pattern produced with deflector in place.

8) The difference in water surface profiles measured along the basin side walls, with and without the deflector installed, was negligible.

9) Piezometer taps were used to measure the differential loading across the deflector for model operations up to 100% gate opening at maximum reservoir elevation. The maximum force on the prototype deflector due to steady state hydraulic loading was predicted to be about 12,600 lbs (1.0 lb/in^2) for the Mason Dam deflector, 13,500 lbs (1.9 lb/in^2) for the Choke Canyon Dam deflector and 12,800 lbs (1.9 lb/in^2) for the Haystack deflector. These values do not include a factor of safety.

Field Evaluations - Mason Dam and Choke Canyon Dam

Field tests were conducted over the normal operating range at Mason Dam and Choke Canyon Dam with and without deflectors installed in the basin. Velocities measured at the end of the basin at each site were used in conjunction with model data to evaluate and refine guidelines for deflector design. Field data were also correlated with the models to refine model operations to best represent prototype flow conditions. The following conclusions are based on an analysis of field data acquired at each stilling basin site.

1) Average velocity profiles measured in a vertical plane at the exit of the stilling basin, without a deflector, correlated well with the velocities measured in the models, especially those velocities measured near the bottom where air entrainment was minimal. This demonstrated that the physical models provided an accurate representation of prototype flow conditions.

2) Average velocities measured at the Mason Dam stilling basin exit, with the deflector in place, correlated well with the model for discharges up to 30% gate opening and demonstrated that the deflector was effective in redirecting flow near the basin end sill from upstream to downstream in direction. Prototype velocities measured at gate openings greater than 30% were inconclusive due to high air concentration in the flow that interfered with data collection.

3) Average velocities measured at the Choke Canyon Dam stilling basin exit, with the deflector in place, correlated reasonably well with the model for discharge releases up to 40% gate opening and demonstrated that the deflector was effective in redirecting flow near the basin endsill from upstream to downstream in direction. Prototype velocities measured at gate openings greater than 40% were inconclusive due to high air concentration in the flow that interfered with data collection

4) The dive team inspecting the Mason Dam stilling basin in June 2005 and July 2006, found only a few stones in the basin, but no indication that upstream currents had carried rocks into the basin. The stones that were found in the basin appeared to be aggregate dislodged from new concrete used to repair the basin at the time the deflector was installed. Temperatures well below freezing were experienced immediately after repairs to the basin and may have affected the ability of the concrete to cure properly and thereby may have contributed to a weakened upper layer in the concrete, resulting in release of aggregate. In addition, divers found no signs of erosion immediately downstream from the end of the basin.

5) The results from the field evaluations and the high correlation between model and prototype data indicates that the installation of a deflector into a basin can help improve flow conditions to minimize the potential for entraining materials in the basin, thereby extending basin life, and reducing long-term O&M costs.

The Models

Three separate models, representing Reclamation stilling basins of standard design, were studied in the Denver laboratory. The model studies were used to:

1) Identify factors contributing to the basin damage by identifying the extent and strength of flow currents in standard outlet works stilling basins over a range of operating conditions.

2) Develop guidelines for the generalized design of flow deflectors that include:

    a) Deflector position (lateral and vertical position within the basin)
    b) Deflector angle
    c) Deflector geometry

3) Develop flow deflector design guidelines that can be applied to sites operating over a large operating range (discharge and tailwater variations). These investigations included the evaluation of using a single movable deflector and using two separate deflectors staggered in position (both laterally and vertically).

4) Evaluate deflector performance over the full range of operations.

Prototype features modeled for each stilling basin included:

1) High pressure regulating gates.

2) The hydraulic jump stilling basin with sloping or curved chutes.

3) Topography downstream from the stilling basin, extending to the river channel entrance.

Froude scale similitude was used to establish the kinematic relationship between model and prototype because hydraulic performance depends predominantly on gravitational and inertial forces. The three physical models studied were:

1) Mason Dam outlet works stilling basin (Reclamation drawing No. 569-D-24) (A-1) – This is a typical Reclamation type II stilling basin. The basin Froude number is 14.5 at design flow and consists of twin bays and 2:1 sloping chutes [1]. Reclamation type II stilling basins are the most common type of stilling basins to experience abrasion damage. The Mason Dam stilling basin was modeled on a 1:7 geometric scale. Froude scale similitude produced the following relationships between the model and the prototype:

Length ratio $L_r = 1:7$

Velocity ratio $V_r = L_r^{1/2} = 1:2.65$

Discharge ratio $Q_r = L_r^{5/2} = 1:130$

2) Choke Canyon Dam outlet works stilling basin (Reclamation drawing No. 1012-D-100) (A-3) – This is a Reclamation type II stilling basin with a Froude number of 12 at design flow. Just one bay of the twin bay design with curved chutes was modeled on a 1:10 geometric scale. Froude scale similitude produced the following relationships between the model and the prototype:

Length ratio $L_r = 1:10$

Velocity ratio $V_r = L_r^{1/2} = 1:3.16$

Discharge ratio $Q_r = L_r^{5/2} = 1:316$

3) Haystack outlet works stilling basin (Reclamation drawing No. 112-D-2179) (A-5) – This is a Reclamation type III stilling basin [1] with a Froude number of 13 at design flow. Type III stilling basins are the second most common type of basin within Reclamation to experience abrasion damage. The stilling basin was modeled on a 1: 6.5 geometric

scale. Froude scale similitude produced the following relationships between the model and the prototype:

Length ratio $L_r = 1:6.5$

Velocity ratio $V_r = L_r^{1/2} = 1:2.55$

Discharge ratio $Q_r = L_r^{5/2} = 1:108$

Model Measurement Methods

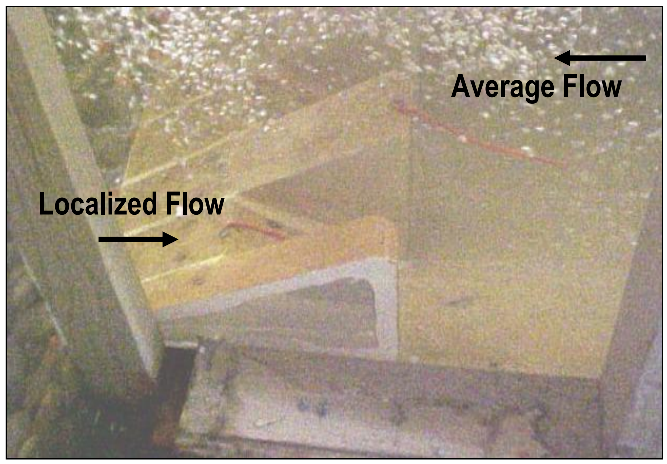

Figure 6. Strings indicate flow is upstream into the stilling basin

Model investigations were conducted to evaluate hydraulic conditions in each of the three stilling basins for the range of operating conditions expected in the prototype. Water was supplied and measured from the permanent laboratory venturi meter system and routed to each model through the pipe chase surrounding the perimeter of the laboratory. Velocity data were collected and analyzed to define basin performance over the operating range for each stilling basin. In addition, dye and strings attached to the endsill of each basin were used as a visual aid in identifying the flow direction of currents near the bottom of the basin (figures 6 and 7). Velocity measurements and flow visualization were used to help establish guidelines to define the most effective deflector design including best deflector location within the basin, both laterally (X_d) and vertically (Y_d), and the best angle to position the deflector, for optimizing flow conditions (figure 8). The deflector design variables investigated are illustrated in figure 8.

Figure 7. Strings and dye indicate flow near the bottom is redirected downstream after the deflector is installed in the Mason Dam (L) and Haystack Dam (R) stilling basin models.

Velocities were measured with a Sontek ADV (Acoustic Doppler Velocimeter) probe at numerous locations within and downstream from each stilling basin to define velocity profiles for each discharge tested. Initial velocity measurements included mapping vertical profiles measured at the downstream end of the stilling basin for each gate opening at maximum reservoir elevation. Velocities were measured beginning several inches above the basin invert and continuing upward along a vertical line until air entrained in the flow prevented further measurements.

Early investigations showed that average velocities measured at the end of each basin, at its centerline, and about 6 inches (prototype dimensions) above the top elevation of the basin end sill (between dentates for the type II basin), provided a good representation of the bottom velocities that carry materials into the basin. Therefore average velocities measured at this location were used as a basis to define deflector performance and will be referenced as index velocity or Vi for all type II and type III stilling basins tested (figure 8). The higher the index velocity in the positive or downstream direction the better the performance (negative velocities indicate flow is upstream into the basin).

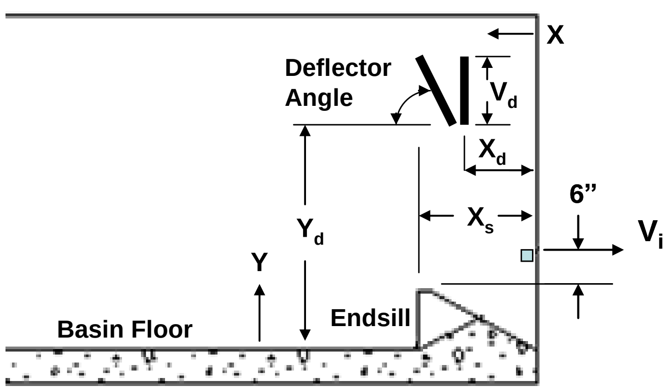

Figure 8. Sectional view showing the downstream end of typical stilling basin

In addition, deflector differential loading was measured with piezometer taps installed equally spaced across the upstream and downstream faces for the Mason Dam and Choke Canyon Dam deflectors. The taps were connected to a manometer board to measure differential static hydraulic loading for flow rates up to the maximum discharge at 100% gate opening.

Evaluating Performance

When evaluating stilling basin or deflector performance, relative performance was determined by comparing index velocities (Vi). Figure 9 shows an example of a histogram with data distribution for a case where the index velocity measured was near 0.0 ft/s. An index velocity near zero may seem to represent a flow condition where velocities are not strong enough to carry materials into the basin and thus good performance; however this is not necessarily the case. Figure 9 shows that instantaneous velocity measurements for this flow condition range from 5 ft/s to -5 ft/s, therefore, some materials may be carried into the basin during upstream flow surges. This demonstrates that an index velocity near zero does not necessarily indicate adequate performance. Figure 10 shows the data distribution for a case where Vi measured 2.3 ft/s. This figure shows that although the index velocity is positive and directed downstream, some flow velocities in the upstream direction are as high as those in the previous example, shown in figure 9. However, in this case, since the majority of the velocity samples measured are positive or downstream in direction, the potential for moving materials into the basin is much lower than that of the condition where Vi was near zero. Thus, higher positive index velocities indicate better performance.

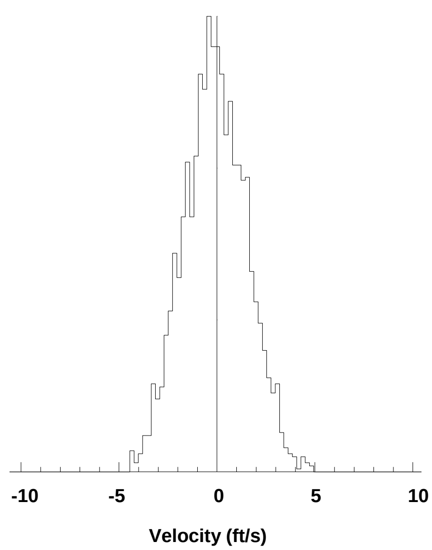

Figure 9. Example histogram for data distribution of 3,000 samples. Index velocity is near 0.0 ft/s.

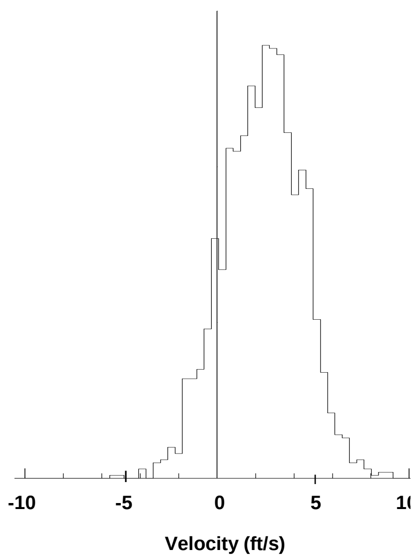

Figure 10. Example histogram for data distribution of 3, 000 samples. Index velocity is 2.3 ft/s.

Mason Dam Outlet Works Stilling Basin

Mason Dam Model Study - No Deflector

The Mason Dam outlet works stilling basin, which is a typical type II basin, was an excellent candidate for the first demonstration project since it has a long history of abrasion damage and repeated repairs, and results would be directly applicable to many other facilities. Mason Dam is located on the Powder River in Baker County Oregon approximately 17 miles southwest of the city of Baker. The 1:7 scaled model was constructed in Reclamation's Hydraulics Laboratory in Denver (figure 11). Both high pressure regulating gates of the twin bay design for the Mason Dam model were operated symmetrically at all times as required by the SOP. Tailwater elevation was set for each flow condition tested, using tailwater data obtained during Mason Dam outlet works operations (table 1). Although model investigations were conducted up to the maximum possible discharge of 870 ft^3/s (100% gate opening at maximum reservoir, elevation 4077 ft), the optimum design for the prototype deflector was based only on discharges up to 575 ft^3/s (60% gate opening at maximum reservoir). This is because Mason Dam's SOP limits outlet works discharges to the maximum downstream river channel capacity of 500 ft^3/s. As a result, velocity profiles were measured at the downstream end of the stilling basin for gate openings of 20, 40, and 60 percent, with corresponding discharge calculated using Froude scale similitude and based on maximum reservoir as indicated by the Mason Dam Outlet Works-Discharge curves (A-2).

Figure 11. Mason Dam stilling basin model operating at 60% gate opening.

Table 1. Prototype flow conditions tested in the Mason Dam outlet works model (based on Froude scale similitude).

Gate Opening (%)	Prototype Discharge Corresponding to Maximum Reservoir Elevation (ft^3/s)	Tailwater Depth (ft)
20	230	18.2
40	420	18.8
60	575	19.5
80	735	20.0
100	870	20.7

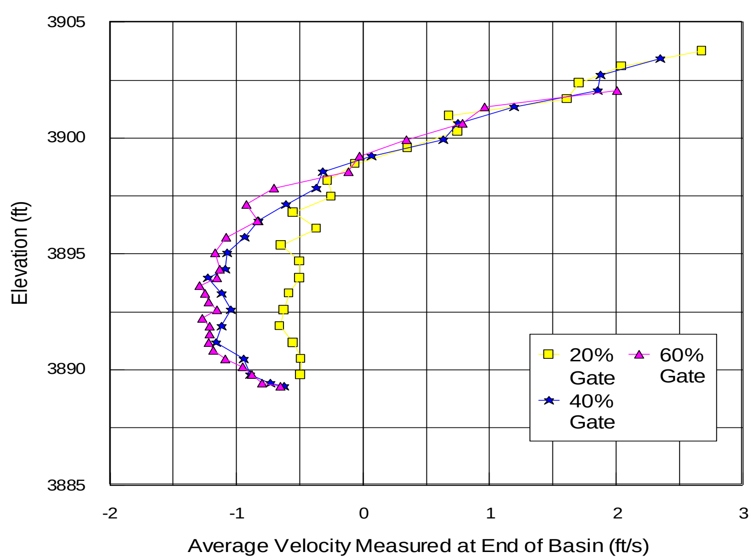

Figure 12. Vertical velocity profiles measured at downstream end of stilling basin at Mason Dam stilling basin

Figure 12 shows the average velocity profiles measured in the vertical plane in the model for gate openings of 20 percent, 40 percent and 60 percent, The figure demonstrates that average velocities measured within the bottom 9 ft to 10 ft of the water column are directed upstream into the basin (negative values indicate index velocity is directed upstream), thereby demonstrating a strong potential to carry materials into the stilling basin.

Mason Dam Model Study - With Deflector

The initial deflector design was modeled with a flat section of sheet metal with a 5 ft vertical dimension, spanning the 17 ft wide basin and mounted on guides attached to the basin sidewalls, to allow vertical movement of the deflector within the stilling basin (Figure 13). Velocity data were collected and analyzed to determine the most effective deflector angle and the best lateral and vertical locations within the stilling basin (figure 8).

Figure 13. Deflector and ADV velocity probe installed in the Mason Dam stilling basin model.

Mason Dam Model Results

Optimal Positioning and Size

Velocity data were evaluated and analyzed to determine the optimal deflector design parameters. The results from this analysis are described below (Deflector position is referenced to the upstream edge of the lowest elevation of the deflector):

1) Best lateral (X_d) and vertical (Y_d) deflector positioning - Initial investigations were conducted with a deflector vertical dimension (V_d) of 5 ft, angled at 60 degrees from horizontal and spanning the width of the stilling basin (figure 8). Lateral location was defined as the distance from the downstream end of the stilling basin (defined as the downstream end of the basin sidewalls) to the upstream face of the deflector (X). Lateral locations were varied from 0 ft to 14 ft. The best position for the deflector laterally along the length of the basin was determined by setting the deflector a specified distance from the end of the basin and then measuring index velocities at the end of the basin, for each flow condition tested. Then, for each lateral position, the deflector was moved in vertical increments so that index velocities could be measured for a range of deflector elevations. Deflector vertical location (Y) was varied from 4 ft to 15 ft above the elevation of the basin floor (floor elevation 3889 ft).

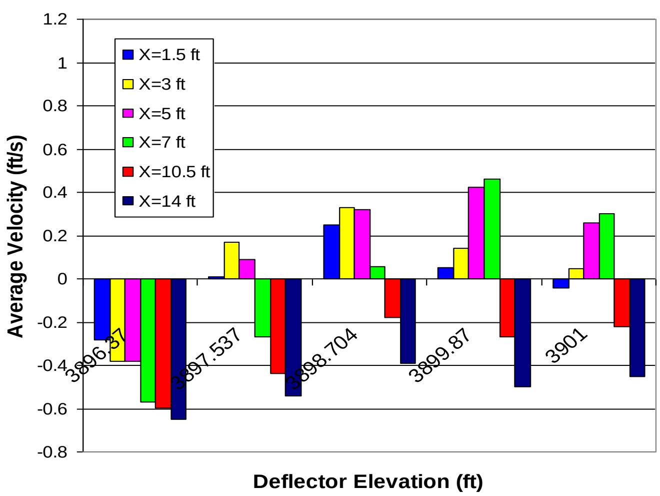

Figure 14. Index velocity measured at the end of the basin as a function of deflector elevation for 6 lateral deflector positions for basin operating at 60% gate opening.

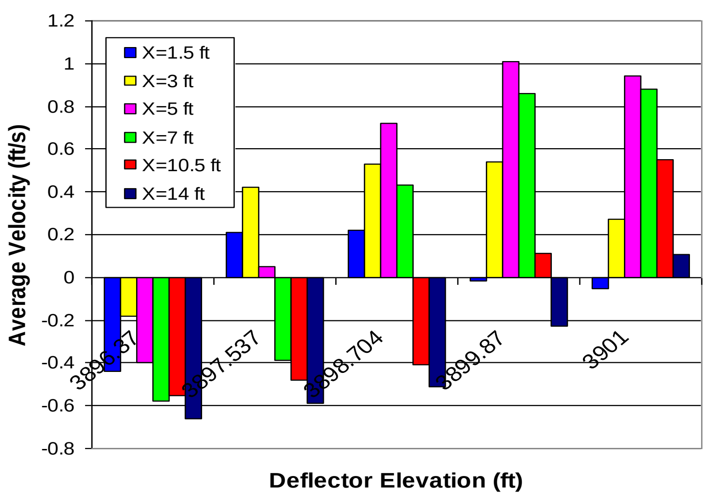

Figure 15. Index velocity measured at the end of the basin as a function of deflector elevation for 6 lateral deflector positions for basin operating at 40% gate opening.

Deflector performance for each variable was determined by comparing these velocities; i.e. the higher the index velocity (Vi) in the positive direction, the better the performance. Positive values indicated that index velocity was in the downstream direction, away from the stilling basin. Figures 14 and 15 show average bottom velocities (Vi) measured as a function of deflector elevation for six lateral positions tested for 40% and 60% gate opening, respectively.

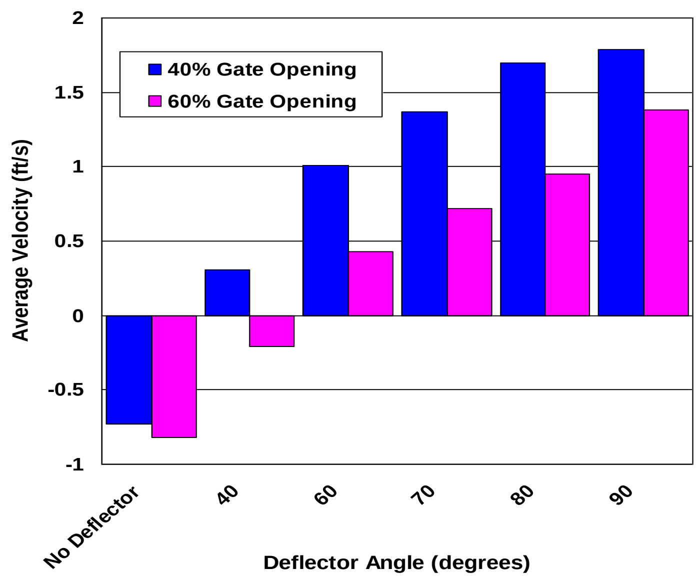

Figure 16. Index velocity measured at the end of the basin as a function of deflector angle.

The figures demonstrate that best deflector performance occurs with the deflector located about 5 ft upstream from the end of the basin walls and positioned at an elevation in the range of 3899 ft to 3901 ft (Y_d equal to 10 ft to 12 ft above basin floor).

2) Angle – Deflector angle was varied to determine what angle would produce best performance. For this case, lateral positioning was kept constant at 5 ft and deflector elevation was varied from 7 ft to 12 ft above the basin floor. Index velocities were measured for deflector angles ranging from 40 to 90 degrees referenced from the horizontal plane.

Figure 16 shows index velocity as a function of deflector angle for 40 and 60 percent gate opening, with the lateral position (X_d) held constant at 5 ft and elevation held constant at 3900 ft (Y_d = 11 ft). The figure demonstrates that best performance occurs with the deflector angled at 90 degrees (oriented vertically).

3) Size - The next step was to determine if the deflector could be reduced in size in order to reduce costs and still maintain acceptable performance. For this set of tests, deflector lateral positioning was kept constant at 5 ft and deflector elevation was kept constant at 3900 ft. Deflectors with vertical dimensions (V_d) of 3 ft and 4 ft were tested at 80 and 90 degrees. Figure 17 shows that although performance is acceptable for the smaller deflectors, it is reduced compared with the performance of the 5 ft deflector.

As a result of these investigations, it was determined that best deflector performance, based on index velocities (Vi) measured at the downstream end of the basin, occurred with a deflector vertical dimension (V_d) of 5 ft, mounted 5 ft upstream from the end of the basin (X_d) at elevation 3900 ft (Y_d = 11 ft) and angled at 90 degrees (figure 8). This was used as the basis for designing the first prototype flow deflector for the Mason Dam stilling basin.

For future analyses deflector vertical dimension was normalized in terms of tailwater depth at design flow. In these terms, the vertical dimension for the final deflector design was equal to about 25 percent of tailwater depth. The deflector's lateral positioning was also normalized in terms of the horizontal dimension of the basin's end sill. In these terms, best lateral position was about 2/3rds the horizontal dimension measured upstream from the end of the stilling basin (2/3

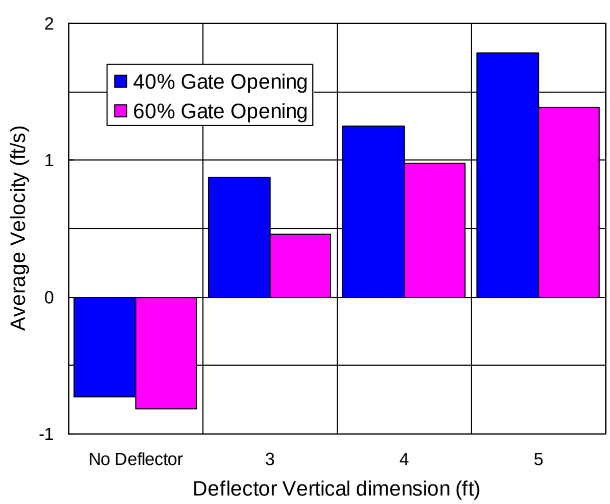

Figure 17. Index velocity measured at the end of the basin as a function of the vertical dimension of the deflector.

X_s, figure 8). In addition it was noted that the best deflector performance for each flow condition tested was produced with the bottom of the deflector positioned just above an elevation corresponding to the bottom of the jet exiting the stilling basin where velocities transition from upstream (negative) in direction to downstream (positive). Best deflector elevation corresponded to where velocities were in the range of about 0.75 ft/s to 1.25 ft/s in the downstream direction.

Mason Dam Field Evaluation

The first prototype flow deflector was installed at Mason Dam in October 2002 (figure 18). In August 2003, a field evaluation was conducted on-site at Mason Dam to evaluate the performance of the deflector and verify the model. When field tests were conducted, reservoir elevation was 73 ft below what was represented in the model, therefore actual prototype discharges tested compared with the discharges tested in the model for the same gate openings in table 1 are listed in table 2. The initial evaluation was conducted with the deflector raised above the water surface to evaluate flow currents carrying materials into the basin (figure 19). Vertical velocity profiles were measured at the basin exit with an ADP (Acoustic Doppler Profiler) probe for each 10% increment of gate operations ranging from 10% to 60 % gate opening. A dive team was used to assist in mounting the ADP probe at the end of the basin because the probe must be installed near the bottom of the basin on the downstream face of the endsill and directed upward (figure 20), since air near the water surface can interfere with data acquisition.

Figure 18. Installation of first prototype deflector at Mason Dam in Oct 2002.

Figure 19. Flow deflector is raised above the water surface for the initial field evaluation.

Figure 20. ADP probe mounted underwater at the downstream end of the stilling basin and directed upward through water column.

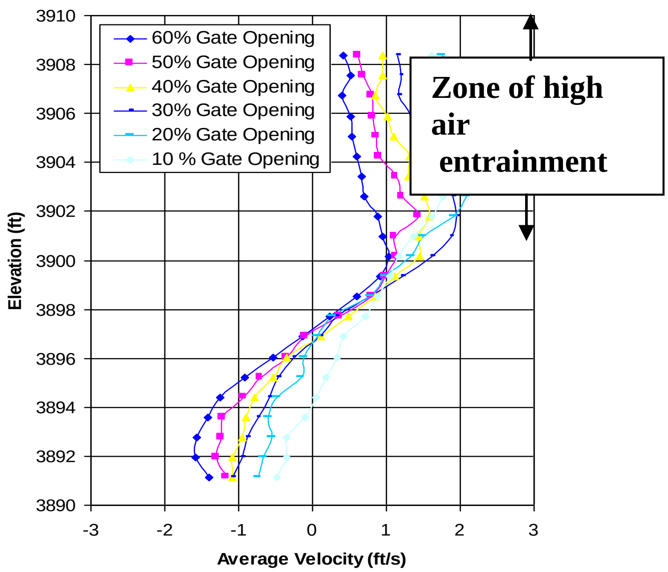

Figure 21. Vertical velocity profiles measured at Mason Dam stilling basin with the deflector raised out of the flow.

Figure 21 shows the average velocity profiles measured at the end of the stilling basin. The figure demonstrates that velocities measured within the bottom 7 to 8 feet of the water column (referenced from the basin floor elevation 3889 ft) are directed upstream into the basin. This correlates well with the velocities measured in the model and therefore verifies that the model provided a good representation of the prototype. However note that average velocities measured above elevation 3900 ft are not accurately represented since they were measured in a zone of high air concentration.

Table 2. Prototype discharges tested at Mason Dam.

Gate Opening (%)	Prototype Discharge tested in Model - Corresponding to Maximum Reservoir (Elevation 4075 ft, ft^3/s)	Prototype Discharge tested at Mason Dam at Low Reservoir (Elevation 4005 ft, ft^3/s)
10	N/A	85
20	230	163
30	N/A	250
40	420	330
50	N/A	400
60	575	500

The same measurements were repeated with the deflector lowered into optimal position, with bottom elevation set to 3900 ft and angled at 90 degrees (figure 22). Figure 23 compares average prototype velocities, measured at elevation 3891 ft (2 ft above the basin floor elevation) in both the model and in the prototype, at the end of the basin for each gate opening tested, with and without a deflector. The correlation between the two sets of data looks reasonable considering that the model study discharges were set based on maximum reservoir elevation, and the reservoir elevation was actually 73 ft below that level at the time prototype testing was conducted at Mason Dam. However, this strong correlation may be due, in part, because Froude scaling of discharges in the model often underestimate prototype velocities downstream from energy dissipaters. As a result, a close correlation was produced with the model when field testing was conducted at a lower reservoir.

Figure 23 shows there is significant improvement in flow conditions at the downstream end of the basin with the prototype deflector lowered into optimal position for 10% to 30% gate opening (discharges up to 250 ft^3/s). Average prototype velocities are greater than 0.75 ft/s and have changed from upstream in direction to downstream, with the deflector in place.

Figure 22. The Mason Dam flow deflector is submerged in optimal position as determined from the model study

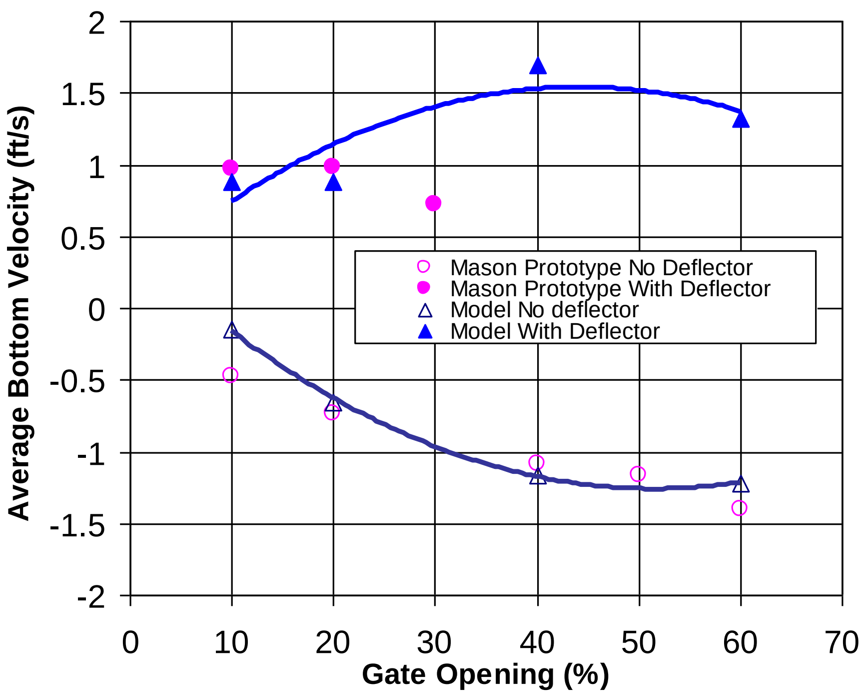

Figure 23. Comparison of average prototype exit velocities measured in the model and in the prototype with and without a deflector

For prototype gate settings ranging from 40% to 60%, no reliable velocity measurements were obtained due to the inability of the ADP probe to accurately measure velocities when large quantities of air are entrained in the flow. The deflector was designed to redirect the concentrated jet, exiting the basin, down toward the basin end sill. Therefore, at high discharges, when the jet is highly aerated, entrained air was also redirected downward towards the end sill where the ADP probe was located. As a result, accurate velocity measurements were not possible at the higher discharges.

For the model study, an ADV probe was used to measure velocities. This type of probe was not as sensitive as the ADP probe to high concentrations of air. In addition air entrained in the model is not as substantial as it is in the prototype (this is a common "scale effect" that becomes more significant at smaller model scales), therefore velocity measurements were possible for all gate openings tested. Although model and prototype discharges were not identical, Figure 23 shows a strong correlation between model and prototype velocities measured at the same location for the same gate openings. Therefore, it is reasonable to assume, with the field verified data already acquired, that model data, for gate openings ranging from 40% to 60% are also a reasonable representation of prototype flow conditions, thus the prototype deflector is likely performing as desired to reduce the potential for entraining materials.

Dive inspections of the Mason Dam stilling basin were conducted and documented in June 2005 and July 2006, after several seasons of operations with the deflector in place [3]. There were several small stones, and some relief in the concrete noted during each of these inspections. In addition many indentations were observed where aggregate had apparently been released from the basin floor. Analysis of these findings determined that the stones in the basin had most likely been dislodged from the new concrete that was used in the repair of the basin in October 2002, at the time the flow deflector was installed. After some discussion it was concluded that temperatures well below freezing experienced at the site within a few days of the repair may have contributed to a weakened upper layer in the concrete, causing aggregate to become dislodged from the new concrete into the stilling basin. In addition there were no signs of any rock or debris encroaching on the endsill from the area downstream from the stilling basin, as had been noted before the deflector was installed. The conclusion from these findings was that the deflector was performing as intended to prevent significant amounts of rock or other materials from being carried upstream into the stilling basin. This analysis also demonstrated the importance of implementing proper, state-of-the-art techniques in concrete repairs at the time a deflector is installed [4].

Mason Dam Deflector – Extended Studies

For the Mason Dam deflector, the optimal design was based only on gate operations up to 60% gate opening due to SOP limits on maximum discharge. Within this limited operating range, there was minimal shift in the position of basin flow patterns; and therefore a single stationary deflector was adequate to produce effective performance. Figure 24 shows average bottom velocities measured in the Mason model without a deflector, compared with those measured with the deflector set into optimal position (as determined from the model study) for gate openings ranging from 20% to 100%. The figure shows that performance at gate openings within the Mason deflector design range (20% to 60% gate opening) was very good. Index velocities for this range of discharges were greater than 1.0 ft/s and were directed in the downstream direction. The figure also shows that for gate openings of 80% and 100%, performance was reduced significantly; although still improved over having no deflector. The reason performance is reduced at higher discharges is because as discharge is increased, the point at which the main jet lifts off the basin floor moves downstream considerably. As a result the concentrated jet remains below the elevation of the deflector when it exits the basin and cannot be effectively redirected. This demonstrates that the deflector design developed for the Mason Dam stilling basin would not have been adequate if effective performance had been required for operations up to 100 % gate opening.

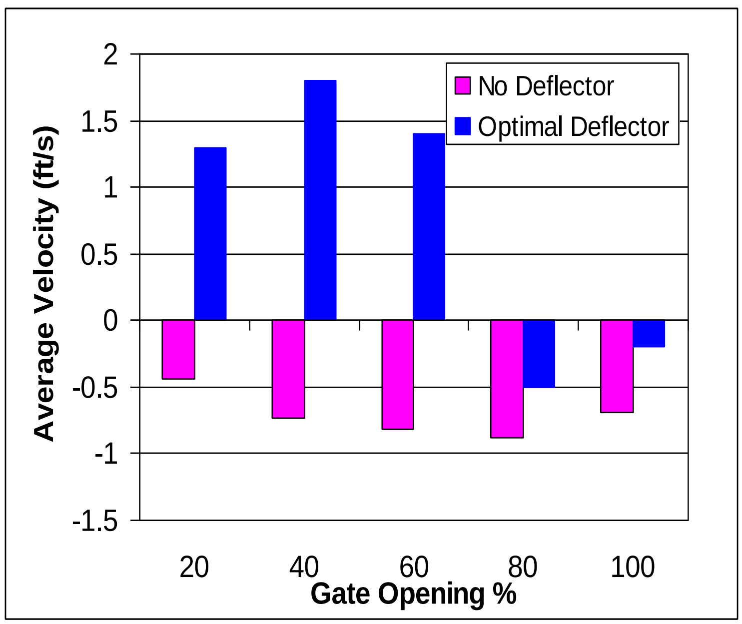

Figure 24. Average prototype index velocities measured in the Mason stilling basin model with and without optimal deflector

Figure 25 shows index velocities measured in the Mason Dam model at the basin exit, for operations ranging from 20% to 100% gate opening, and for deflector elevations ranging from 4 ft to 15 ft above the basin floor. The figure demonstrates that when the deflector was moved to a lower elevation, performance at higher gate settings was significantly improved (while performance at lower gate settings was compromised). As a result, optimal performance with a single deflector could be achieved for the full operating range of the stilling basin with a design that allows the deflector elevation to be adjusted. This could be accomplished with a moveable deflector supported on guides to allow vertical adjustments in position. However this would also require detailed velocity data to identify operations where the deflector requires adjustment for all reservoir elevations. It would also require a more complicated design to allow mobility and would require operating personnel or automation to make the necessary adjustments. As a result, in most cases, this may not be a practical solution.

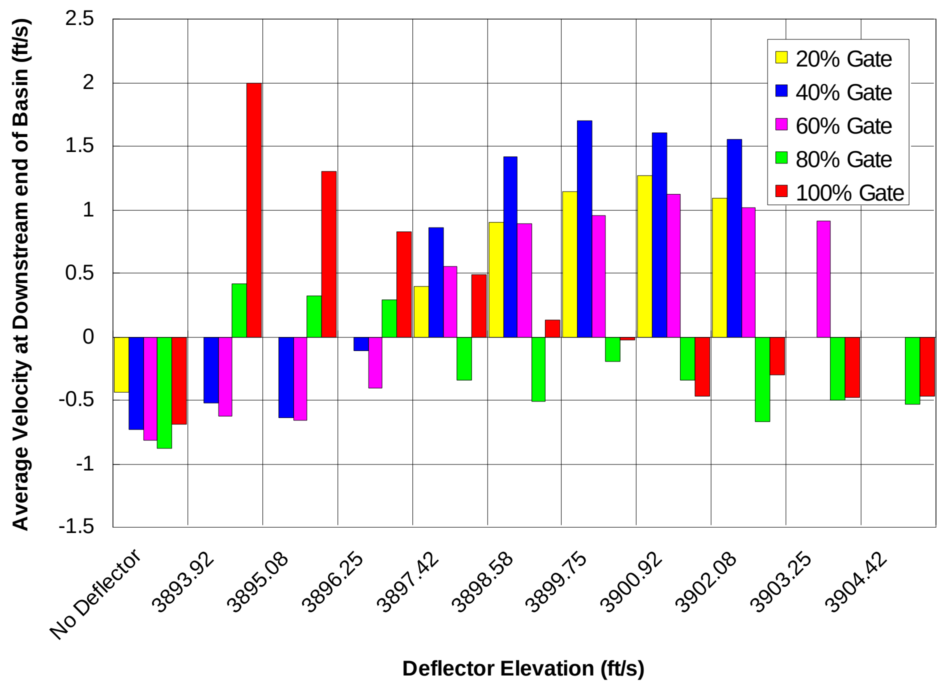

Figure 25. Index velocity as a function of deflector elevation for the Mason dam stilling basin model.

Staggered Deflectors

A more practical approach that can be considered to achieve effective performance over a large operating range for a type II stilling basin, is to use two stationary staggered deflectors. This option would require two separate deflectors staggered in position, both vertically and horizontally, so that flow conditions can be improved throughout the full range of operations without having to adjust deflector positioning (figure 26). Model investigations were conducted to determine the viability of this solution.

Figure 26. Mason stilling basin staggered deflector configuration

The Mason Dam model was used for the initial investigations of the staggered deflector option (figures 26 and 27). The initial test set-up consisted of keeping the original (primary) deflector in place and adding a secondary deflector. The secondary deflector was 3 ft in height (15% of design flow tailwater depth) and spanned the 17 ft width between stilling basin side walls. Since the original deflector was designed to provide optimal flow conditions for gate operations up to 60% gate opening, the secondary deflector was positioned at an elevation (Y_{d2}) that would provide optimal flow conditions for gate operations above 60% gate opening. This was accomplished by identifying the location of the exiting jet for operations greater than 60 % gate opening using analyses of dye streak data and vertical velocity profiles measured in the model at the end of the basin. Once this position was established (deflector elevation 3895 ft or Y_{d2} = 6 ft), lateral positions of 0 ft, 1.25 ft, and 2.5 ft were investigated to determine which would provide the best performance for gate operations up to 100% gate opening. Figure 28 shows that performance is good for all three staggered deflector test cases, with positive velocities demonstrating that flow near the bottom of the basin has been redirected downstream away from the basin. The figure also demonstrates that the most effective configuration of the three

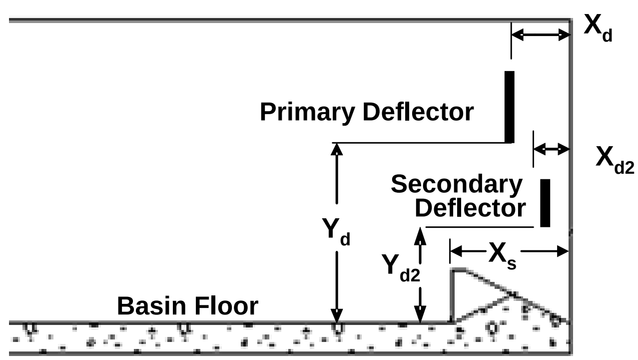

Figure 27. Staggered deflector configuration.

cases tested is with the lateral position (X_{d2}) for the secondary deflector equal to 2.5 ft or half the lateral distance of the primary deflector (X_{d2}=1/2 X_d). Although further testing may be desired, investigations thus far have shown that the staggered deflector design option may be a practical solution for many type II stilling basins.

At the conclusion of these tests, best deflector lateral location was again normalized with respect to the horizontal dimension of the basin end sill. As a result it was determined that best performance was produced when the primary deflector was located, whether in a single or staggered configuration, at a distance equal to about 2/3rds the horizontal component of the basin end sill (2/3 Xs) and measured upstream from the end of the stilling basin. For a staggered configuration, the best lateral position for the secondary deflector was at a distance equal to half the distance from the downstream end of the basin end sill to the upstream face of the primary deflector (1/3 Xs)

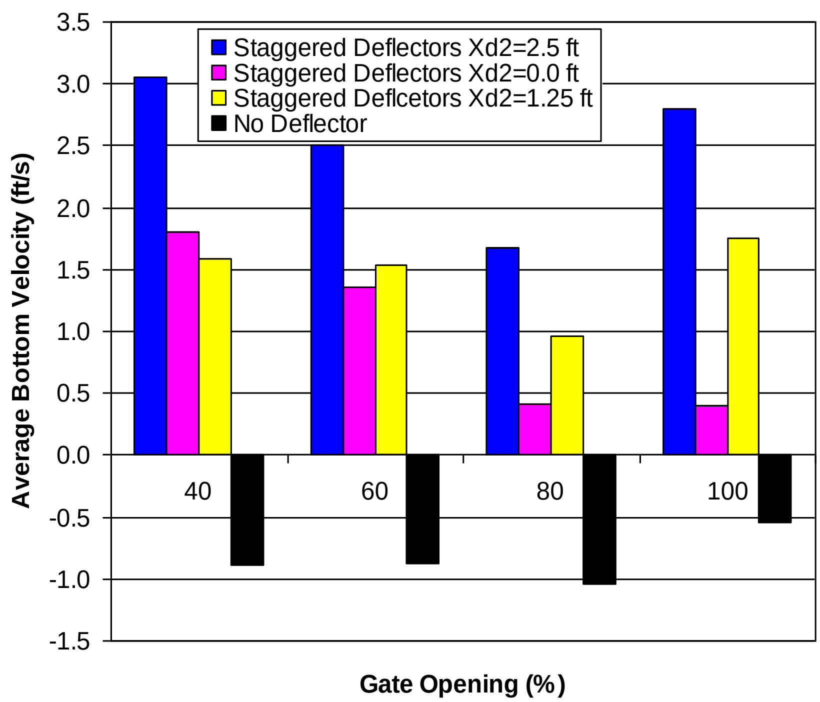

Figure 28. Index velocities measured for 3 staggered deflector configurations for the Mason Dam stilling basin model.

Choke Canyon Dam Outlet Works Stilling Basin

Initial Field Evaluation

The Choke Canyon Dam outlet works stilling basin is a Reclamation type II stilling basin, with a curved chute, that has experienced entrainment of materials and abrasion damage for many years (figure 29). Choke Canyon Dam is located on the Frio River midway between Corpus Christi and San Antonio Texas. In June 2004, a field evaluation was conducted at the site to evaluate the flow conditions at the basin exit to determine whether or not materials were being carried into the basin by upstream currents (figure 30). An ADP probe mounted on the downstream face of the basin endsill was used to measure velocity profiles in a vertical plane at the exit of the basin. Figures 31 and 32 show velocity profiles measured at the end of the basin for each 10% increment of gate openings ranging from 10 to 80 percent (both gates operated symmetrically). Reservoir elevation at the time the field evaluation was conducted was 220 ft and the corresponding discharge for each gate opening is listed in table 3. Figure 31 shows that velocities measured within the bottom 7 to 8 feet of the water column (referenced from floor elevation 116.8 ft) are directed upstream into the basin, demonstrating a strong potential for materials to be carried into the basin for operations up to 40% gate opening. Figure 32 shows that for gate openings of 50 percent and greater, velocity measurements become very erratic due to turbulence near the end of the basin and high concentrations of entrained air, and are therefore unreliable.

Figure 29. Gravel and rock found in the Choke Canyon Dam outlet works stilling basin

Figure 30. Choke Canyon Dam outlet works stilling basin operating at 70 percent gate opening during field evaluation.

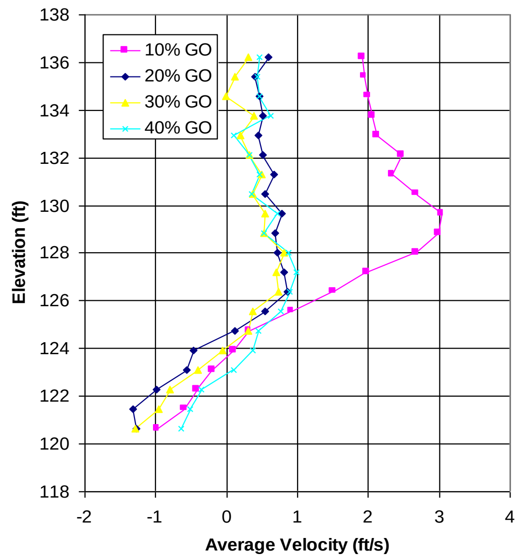

Figure 31. Average velocities measured at the end of the Choke Canyon stilling basin as a function of elevation (no deflector)

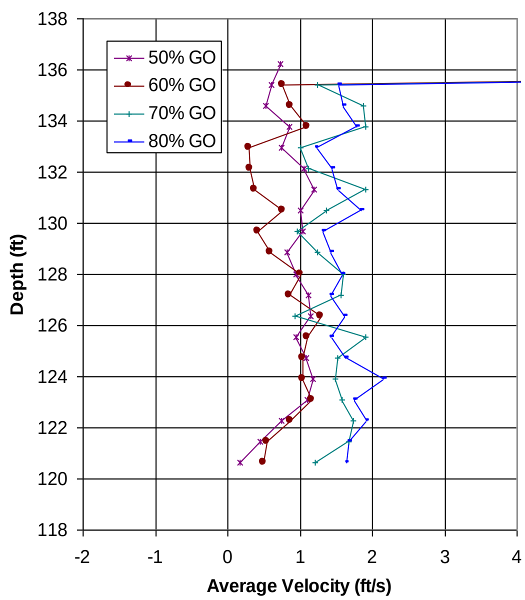

Figure 32. Average velocities measured at the end of the Choke Canyon stilling basin as a function of elevation (no deflector)

Table 3 Choke Canyon stilling basin discharges tested in June 2004 before flow deflectors were installed.

Gate Opening (%)	Discharge tested in 2004 (ft^3/s) (reservoir El. 220 ft)
10	300
20	593
30	855
40	1084
50	1257
60	1437
70	1624
80	1773

Choke Canyon Dam Model study

Figure 33. Choke Canyon stilling basin model operating at 50% gate opening

Choke Canyon Model – No Deflector

In October 2004 a sectional model of the Choke Canyon Dam outlet works stilling basin was constructed on a 1:10 geometric scale in the Denver laboratory to determine the optimal design for a flow deflector. For this model study, it was determined that one bay of the twin bay design was adequate to represent the stilling basin (figure 33).

As with the Mason model study, velocity measurements included mapping velocity profiles at the downstream end of the stilling basin. Initial observations of flow conditions indicated that for operations above 40% gate opening, the concentrated jet entering the basin does not rise from the basin floor before it reaches the end of the basin. A design analysis of the basin revealed that this probably occurs because the concrete length of the stilling basin was designed only to fully contain the hydraulic jump for flows corresponding to gate openings up to about 40 percent (based on maximum reservoir). Looking at the history of outlet works operations at Choke Canyon Dam shows that they have rarely operated above that level in the last 20 years of operations, therefore this is a logical economical design for the stilling basin. For flows greater than 40% gate opening (maximum reservoir), the jump is simply allowed to extend out onto the riprap apron. As a result, for operations above 40% gate opening, instead of a well defined exiting jet there is a significant amount of turbulence that occurs near the end of the basin. However, because the jet remains along the floor for nearly the full length of the basin, it also appears that this turbulence may provide a hydraulic barrier resulting in less potential for materials to be carried into the basin at operations greater than 40% gate opening. As a result, the optimal design for the Choke Canyon deflector was based primarily on gate operations up to 40% gate opening, with discharge based on maximum reservoir (A-4).

Table 4. Prototype discharges tested in Choke Canyon stilling basin model representing prototype discharges tested at Choke Canyon Dam in June 2004.

Gate Opening (%)	Prototype Discharge (2 bays) Represented in Model (Corresponding to Reservoir Elevation 220 ft) (ft^3/s)	Tailwater Depth (ft)	Prototype Discharge (2 bays) in the Model to match Prototype Vertical Velocity profiles (ft^3/s)	Percent increase in Model Discharge (2 bays) to match Prototype Vertical Velocity profiles (%)
10	**300**	**14.2**	**460**	**55**
20	**593**	**15.7**	**803**	**37**
30	**855**	**16.6**	**1107**	**30**
40	**1084**	**17.3**	**1233**	**13**
50	**1257**	**17.9**	**1385**	**10**
60	**1437**	**18.3**	N/A	N/A
80	**1773**	**19.1**	N/A	N/A
100	**2017**	**19.7**	N/A	N/A

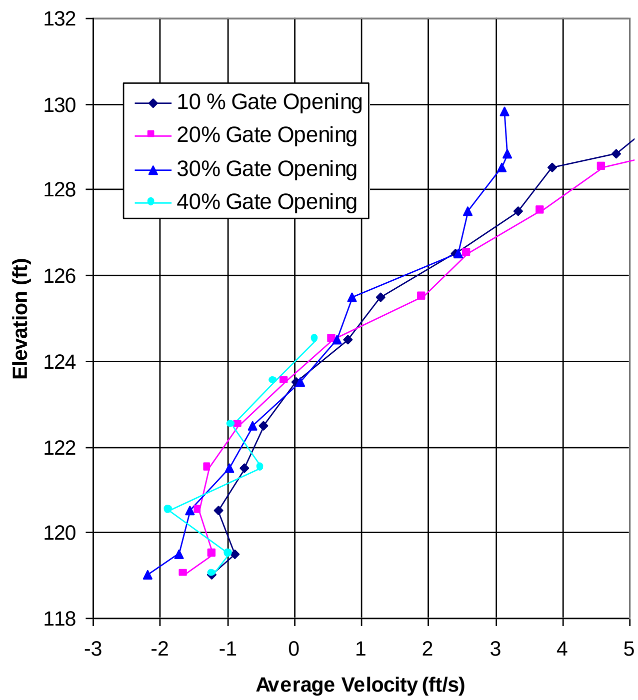

Figure 34. Vertical velocity profiles measured in the choke Canyon stilling basin model.

Initial velocity data for the Choke Canyon model were collected and compared with field data that had already been collected. This comparison showed that due to Reynolds number effects in the tailrace area immediately downstream from the basin, the model had under-predicted the magnitude of the average velocities measured at the end of the stilling basin. This is because Reynolds number is defined as the ratio of inertial forces to viscous forces and in the model viscous effects are relatively over represented in the region where the hydraulic jump transitions into the tailrace, causing more energy dissipation and predicting lower velocities exiting the basin. Therefore model discharge had to be increased above the values normally calculated from Froude scale similitude, to accurately simulate flow conditions in the prototype. Investigations to better define this phenomena is being proposed to Reclamation's S & T Research program, so that future stilling basin studies can be adjusted to accommodate this scaling effect. However in this case, because field data was available, model discharge was increased until the vertical velocity profiles closely matched those measured in the prototype (figure 34). The prototype flow conditions represented and tested in the model are listed in table 4. As a result of the flow adjustment, basin exit velocities measured in the model correlated well with those measured in the prototype, especially near the bottom where air entrainment is least. (figure 35).

Choke Canyon Model With Deflector

A deflector, similar to the one used in the Mason model, was constructed with a flat section of sheet metal spanning the 10 ft wide basin and mounted on guides attached to the basin sidewalls, to allow vertical movement of the deflector within the basin. The initial vertical dimension and angle of the deflector were based on the parameters defined during the Mason model study, since these had produced good results previously. Therefore a deflector vertical dimension equal to 25% tailwater depth (based on maximum discharge) or 5 ft and angled at 90 degrees (vertical) was used. Model velocity data was collected to determine the most effective lateral and vertical deflector locations within the stilling basin. Figures 36 through 39 show index velocity as a function of deflector elevation for four different lateral positions and for gate openings of 10, 20, 30 and 40 percent. Analysis of model and field data determined that the most effective lateral position for the deflector was a lateral distance (X_d) of 4.58 ft or about 2/3rds the horizontal dimension of the basin end sill (X_s) and with the bottom of the deflector positioned at elevation 125 ft (Yd = 8.2 ft). This elevation again corresponds to the location of the bottom of the exiting jet or just above the transition point where velocities become positive. Once the final design was established, the basin deflector was tested throughout all gate operations up to 100% gate opening. Figure 40 shows positive values for average velocities measured in the model with the deflector in place, demonstrating that the deflector design was effective in redirecting flow currents downstream throughout the full range of possible discharges.

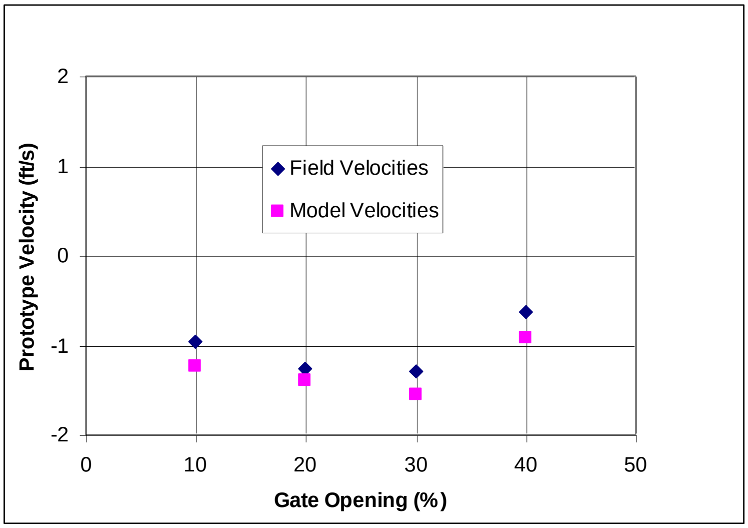

Figure 35. Average bottom velocities measured in the Choke Canyon Model compared with velocities measured in the prototype.

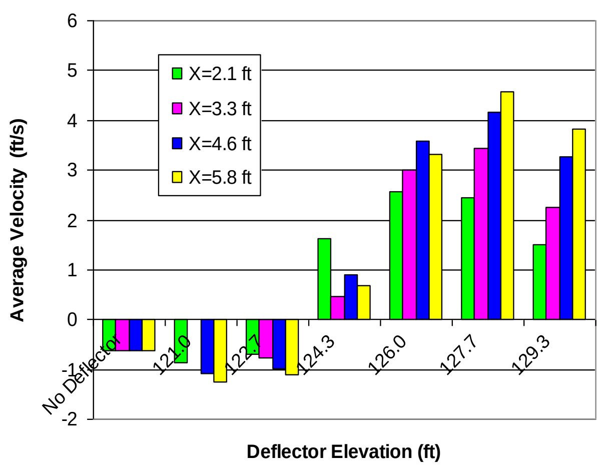

Figure 36. Index velocities measured at the end of the Choke Canyon stilling basin model at 10% Gate opening, as a function of deflector elevation for 4 lateral deflector positions.

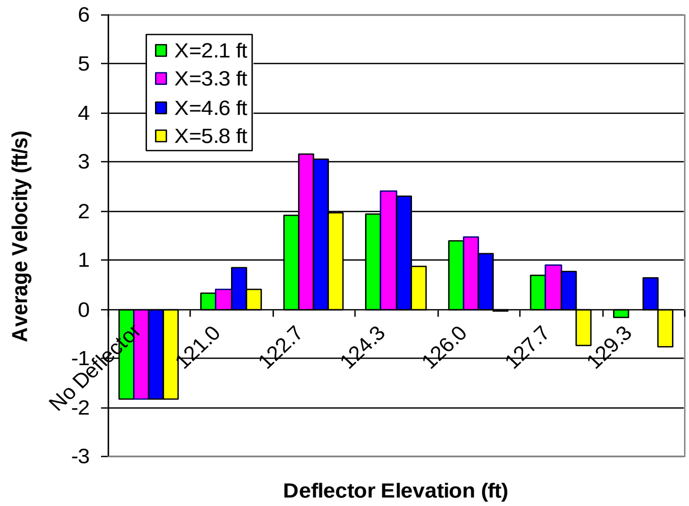

Figure 37. Index velocities measured at the end of the Choke Canyon stilling basin model at 30% Gate opening, as a function of deflector elevation for 4 lateral deflector positions.

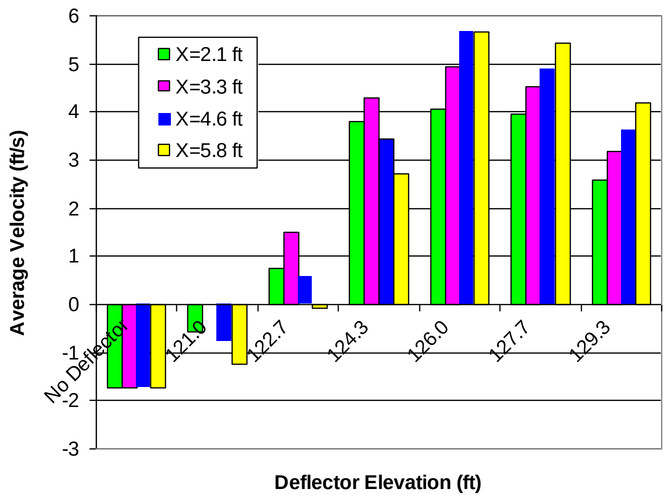

Figure 38. Index velocities measured at the end of the Choke Canyon stilling basin model at 20% Gate opening, as a function of deflector elevation for 4 lateral deflector positions

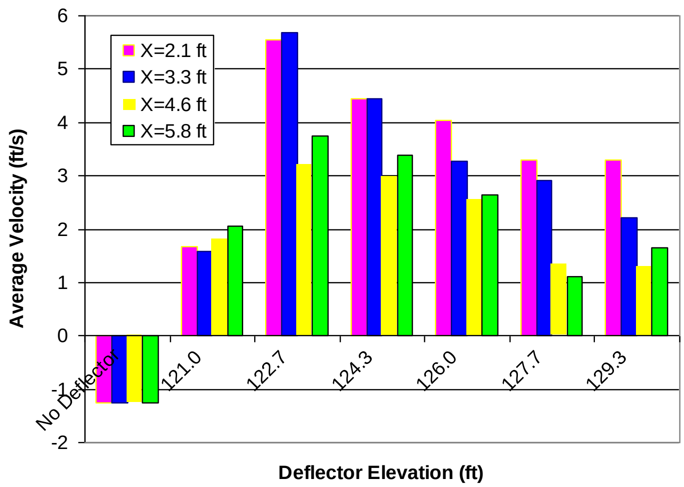

Figure 39. Index velocities measured at the end of the Choke Canyon stilling basin model at 40% Gate opening, as a function of deflector elevation for 4 lateral deflector positions.

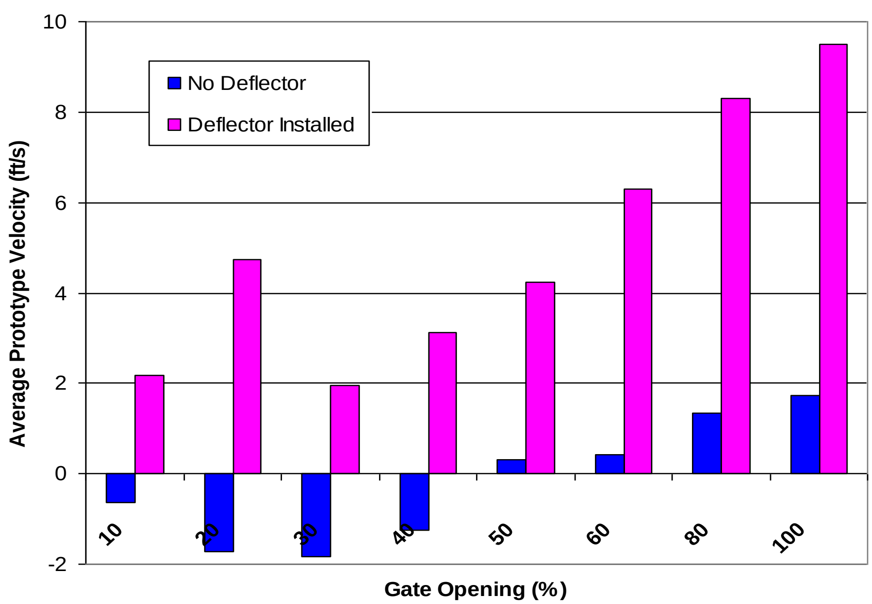

Figure 40. Index velocities measured in the Choke Canyon stilling basin model at the end of the basin with and without optimal deflector.

Figure 41. Installation of Choke Canyon stilling basin deflectors in December 2006.

Choke Canyon Deflectors Field Test Verification

Figure 42. ADV probe just prior to installion on stilling basin end sill.

In December of 2006 flow deflectors were installed in each of the twin bays of the Choke Canyon outlet works stilling basin (figure 41). Each deflector had a vertical dimension of 5 ft spanning 10 ft across the width of the bay with bottom elevation set to 8.2 ft above the basin floor as determined from the model study and field data collected in 2004. In February of 2007 field tests were conducted to verify the effectiveness of the flow deflector design. Divers installed an ADV (Acoustic Doppler Velocimeter) probe in a bracket mounted on the downstream face of the endsill (figure 42). The probe was used to measure velocities at the end of the basin, near the bottom, to determine if average velocities had been effectively redirected from upstream to downstream. The flow conditions tested with deflectors installed are shown in Table 5. The velocities measured are shown in figure 43 and are compared to velocities measured at the same location before the deflectors were installed. The velocities measured with the deflectors installed are positive in direction indicating flow has been successfully redirected downstream away from the stilling basin, thereby minimizing the potential for materials to be drawn into the stilling basin. However, it is worth noting that in the range of 600 ft^3/s to 800 ft^3/s, basin turbulence appears to enter a zone of instability, producing a fair amount of upstream surging. This occurrence of instability in the hydraulic jump is not unusual for these types of stilling basins and although the average flow is still in the downstream direction away from the stilling basin it may be worthwhile to avoid operations within this zone if they aren't necessary. However, under these conditions, only a minimal amount of materials are expected to be entrained within the basin. An inspection of the Choke Canyon Dam stilling basin is planned for the fall of 2011.

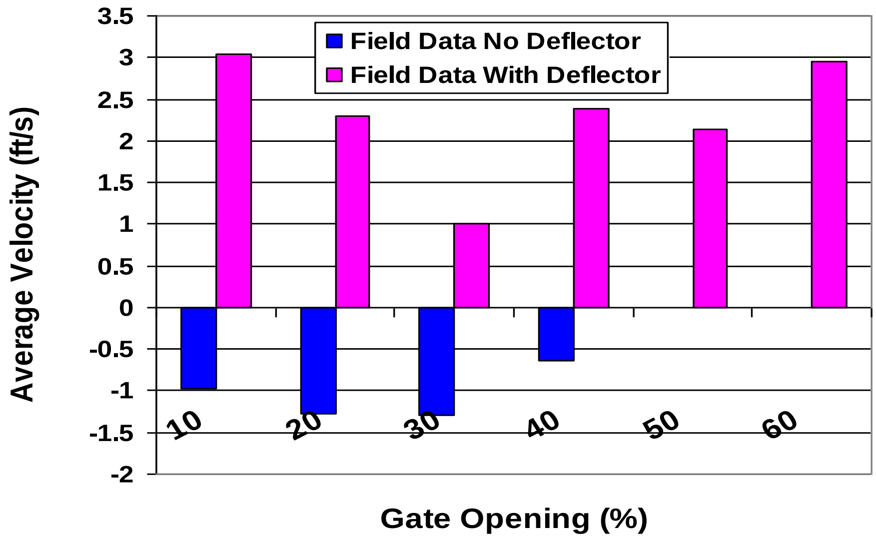

Figure 43. Field data collected in February 2007 with deflectors compared with field data collected in June 2004 before the deflectors were installed. (Positive values indicate flow is in the downstream direction away from the stilling basin).

Table 5. Choke Canyon stilling basin discharges tested in February 2007 with flow deflectors installed.

Gate Opening (%)	**Discharge tested in 2007 (ft^3/s) (reservoir El. 213 ft)**
10	289
20	565
30	812
40	1035
50	1208
60	1377

Haystack Dam Outlet Works Stilling Basin

Haystack Model Study

Figure 44. Haystack stilling basin model operating at 100% gate opening

The Haystack Dam outlet works stilling basin was selected for the study of Reclamation's type III stilling basins. Haystack Dam is located in Jefferson County on Haystack Creek, about 11 miles south of Madras, Oregon. The stilling basin was modeled on a 1:6.5 geometric scale and included the 3.25 ft by 3.25 ft high pressure regulating gate discharging into the curved chute and stilling basin (figure 44). To simplify the model, the horseshoe tunnel approaching the chute was shortened and the basin wing walls were removed. In addition the concrete apron downstream from the basin was replaced with riprap to more closely simulate a typical type III stilling basin of standard design. The protoytype flow conditions represented in the model are listed in table 6.

Initial model investigations began with the measurement of velocity profiles at the end of the basin at its centerline for 20, 40, 60, 80 and 100 percent gate opening with corresponding discharges based on maximum reservoir elevation (A-6). Figure 45 shows that the velocity profiles measured in a vertical plane at the end of the basin were well defined and closely grouped throughout the full range of discharges tested, thus helping to simplify deflector design. This grouping is partially due to the effect of the baffle blocks, typical of a type III stilling basin design, that help to lift the jet off the basin floor at a consistent distance upstream from the end of the basin for each discharge tested (figure 4). This produces a fairly consistent profile at the end of the stilling basin, throughout its full operating range. A deflector similar to the one used in the Mason and Choke Canyon models was constructed with a flat section of sheet metal spanning the 11ft wide basin and mounted on guides attached to the basin sidewalls, to allow vertical movement of the deflector within the basin (figure 46). The initial vertical dimension and angle of the deflector were based on the parameters defined during the Mason and Choke Canyon model studies, since these parameters have consistently produced good results. Therefore a deflector with a vertical dimension equal to 25% tailwater depth (based on daily flow) or 4.2 ft. and angle at 90 degrees (vertical) was used.

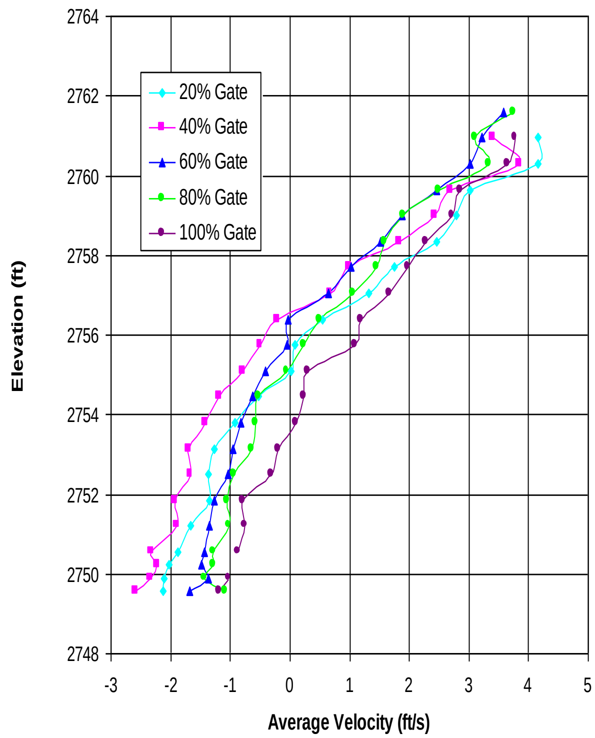

Figure 45 Vertical velocity profiles measured in the Haystack stilling basin model (no deflector).

Figure 46. Haystack stilling basin model with deflector and ADV probe.

Table 6. Prototype discharges represented in the Haystack stilling basin model.

Gate Opening (%)	Prototype Discharge Represented in Model) (ft^3/s)	Tailwater Depth (ft)
20	90	14.5
40	187	15.2
60	288	16.1
80	390	16.5
100	506	16.8

Model velocity data was collected to determine the most effective lateral and vertical deflector locations within the Haystack Dam stilling basin. Lateral positions (X_d) ranged from zero, with the deflector positioned at the downstream end of the stilling basin, to 8.7 ft, where deflector performance began to diminish for most discharges. Figures 47 through 49 show index velocity as a function of deflector elevation for the five lateral positions tested and for gate openings of 20, 60, and 100 percent.

Analysis of model data determined that the most effective deflector positioning was with the bottom of the deflector positioned at elevation 2757.4 ft (Y_d = 9.65 ft). This elevation again corresponds to a position where vertical velocity profiles indicate the bottom of downstream jet is located. The most effective lateral position (X_d) for the deflector was a lateral distance of about 6.5 ft which is well upstream (in terms of end sill horizontal dimension) compared with the location determined from previous studies. Figure 50 demonstrates that this design will be effective throughout all gate operations up to 100% gate opening

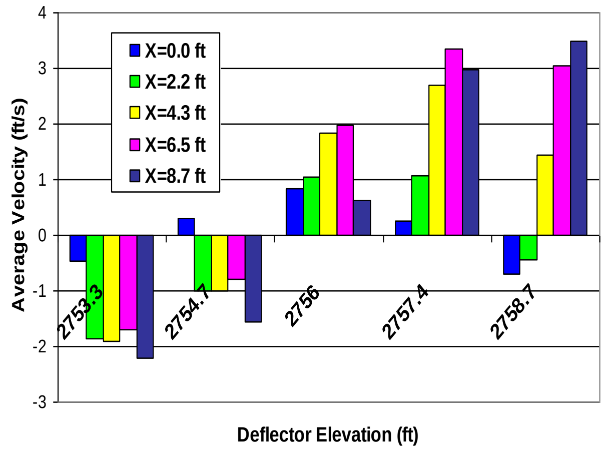

Figure 47. Index velocities measured in the Haystack stilling basin model at 20% gate opening.

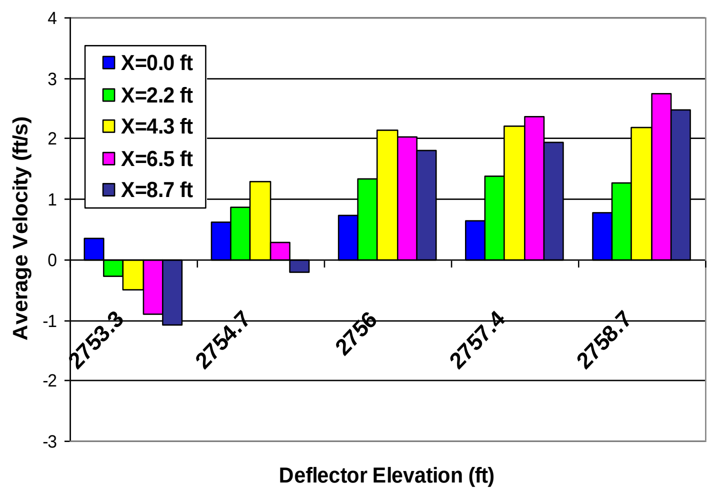

Figure 48. Index velocities measured in the Haystack stilling basin model at 60% gate opening.

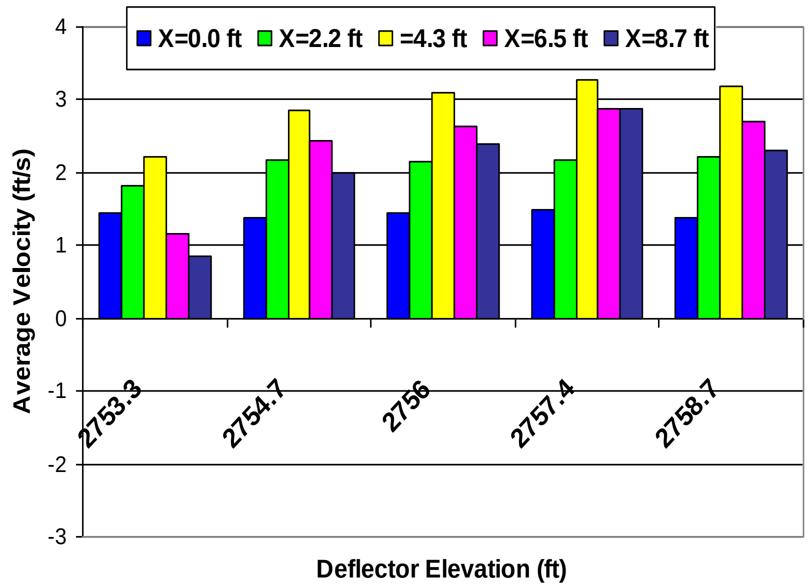

Figure 49. Index velocities measured in the Haystack stilling basin model at 100% gate opening

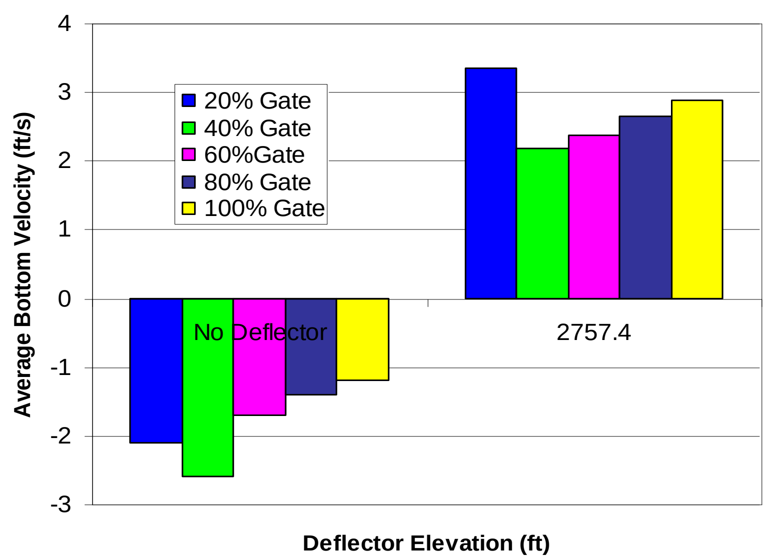

Figure 50. Index velocities measured in the Haystack stilling basin model with and without optimal deflector.

Type III Standard Stilling Basin Design

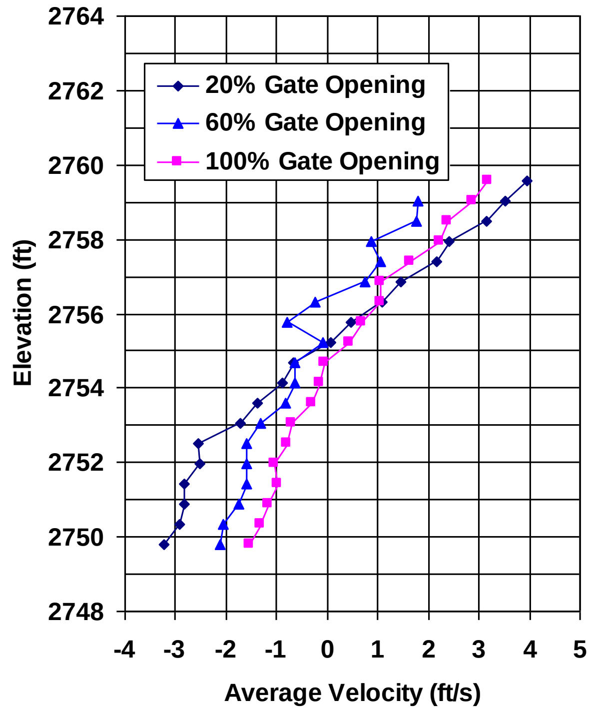

Figure 51. Vertical velocity profiles measured for the Type III Standard Design stilling basin model (no deflector).

Basin design parameters for the Haystack Dam stilling basin were calculated using Engineering Monograph No. 25 so that a correlation could be made for best deflector positioning based on basin geometry and design discharge. These calculations showed that the length for the Haystack outlet works stilling basin is over-designed by about 9.5 ft and the baffle blocks were 1.9 ft upstream from the standardardized design position. As a result, further investigations were conducted with the Haystack basin modified to more closely represent a typical type III stilling basin of standard design based on the design discharge for the site. A second series of tests were conducted with the basin length shortened from 53 ft to 43.5 ft as calculated using the design parameters in Engineering Monograph No. 25 (based on a maximum design discharge of about 500 ft^3/s). In addition, the baffle blocks were moved 1.9 ft downstream from their original position to the position recommended from Engineering Monograph No. 25. All other aspects of the basin geometry remained the same. Conditions identical to those used for the original Haystack model were then tested in the standard-design type III stilling basin. Initial investigations began with the measurement of velocity profiles at the end of the basin at its centerline for 20, 60 and 100 percent gate opening with corresponding discharges again based on maximum reservoir elevation (table 4).

Figure 51 shows that the velocity profiles measured at the end of the basin were similar to those measured with the longer basin shown in figure 45.

Next the deflector used for the Haystack model investigations was tested in the standard-design type III basin. Model velocity data were again used to determine the most effective lateral and vertical deflector locations. The most effective position was with the bottom of the deflector at elevation 2757.5 ft (Y_d = 9.75 ft). This is nearly the same elevation determined from the previous study of the original Haystack stilling basin. The best deflector lateral location (X_d) for the standard Type III basin was determined to be 2.35 ft. This lateral location is equal to 2/3 X_s and corresponds well with the best position determined for the type II stilling basins and with previous investigations conducted for type III stilling basins [5]. Figure 52 shows index velocity measured with the deflector positioned at elevation 2757.5 for the 3 lateral positions tested compared with the velocities measured with no deflector. In this case when the deflector was moved further upstream to a distance of 3.5 ft, although performance is still good, it was somewhat reduced. Figure 52 demonstrates that a lateral deflector position of either 2.35 ft or 3.5 ft will be effective throughout all gate operations up to 100% gate opening for the standard Type III stilling basin.

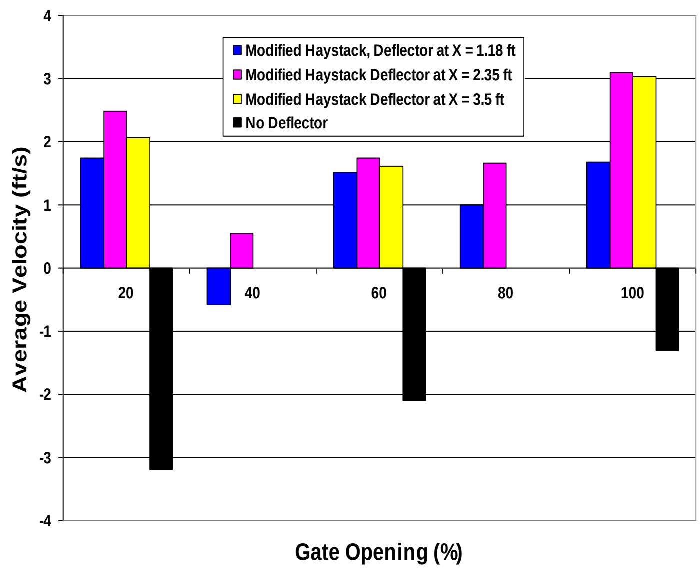

Figure 52. Index velocities measured at the basin exit for the standard-design type III stilling basin model.

For the original Haystack stilling basin, performance was still improving at lateral locations further upstream from the end sill where previous studies have shown performance is normally reduced. The reason that the deflector for the original Haystack basin performs effectively positioned so far upstream into the basin may be because the length of the basin is over-designed by normal standards; therefore the jet is stronger at this location and can be redirected more effectively than with the deflector positioned further downstream. This case demonstrates the importance of comparing actual basin geometry with the design parameters presented in Engineering Monograph No. 25 in order to fully understand basin flow conditions so that effective deflector design and positioning can be achieved when a model study is not performed. The only locations where performance is poor for either the Haystack or the standard type III design basins is when the deflector is positioned near the extreme downstream end of the basin. Therefore it may be reasonable to generalize the best lateral location for type III stilling basin deflectors as any location between X_s and 2/3 X_s.

Variable Tailwater

Tailwater elevation can have a significant effect on the performance of a hydraulic jump stilling basin and therefore may affect basin performance with a deflector in place. As a result, testing was conducted to determine the performance of a single deflector and staggered deflectors when large variations of tailwater occurred at a site.

Mason Dam

Initial tailwater investigations were conducted using the Mason dam stilling basin model with target values of plus or minus 20% of the actual tailwater depth for each gate setting. The original tailwater values for the stilling basin were elevated by 20% for the high tailwater test conditions. However, due to model constraints, low tailwater conditions averaged about 18% below normal tailwater elevation for each condition tested. The first set of tests were conducted with the primary deflector only, over the design range of the deflector. Figure 53 shows index velocity as a function of gate opening for normal, high, and low tailwater conditions for operations ranging from 20 to 60 percent gate opening. The figure shows that performance remains good when tailwater drops 18 percent below normal levels. However when tailwater is raised 20% above normal, average velocities are near zero. Although performance is not as good for the high tailwater test condition, and some materials would be expected to be drawn into the basin, performance is improved over having no deflector. Next, the staggered deflector configuration was tested under variable tailwater conditions. Figure 54 shows that performance remains good for the low tailwater condition for an operating range of 20 to 100 percent gate opening. Again performance is reduced under high tailwater conditions, but improved over having no deflector.

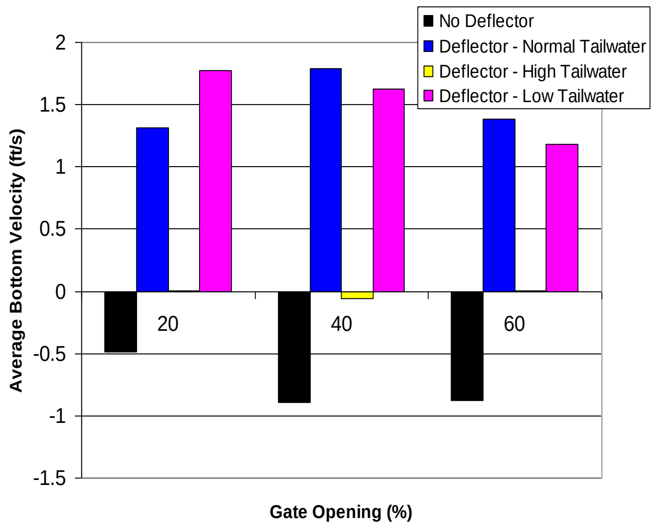

Figure 53. Index velocities measured in the Mason stilling basin model with the optimal deflector tested with 3 different tailwater conditions.

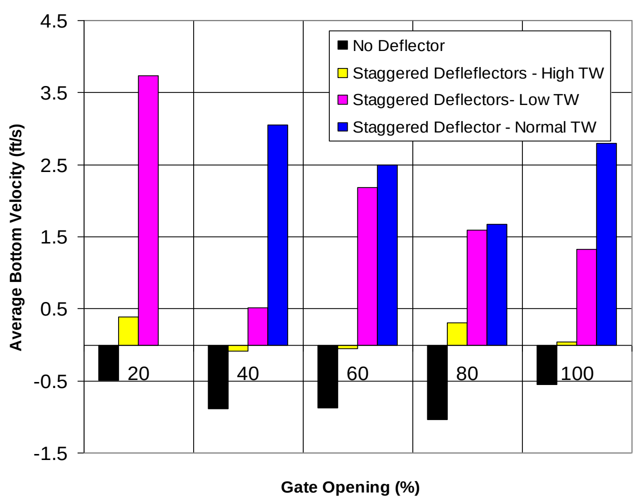

Figure 54. Index velocities measured in the Mason stilling basin model with staggered deflectors tested under 3 different tailwater conditions.

Choke Canyon Dam

For the Choke Canyon model, tailwater was set to 10 percent above normal for the high tailwater condition and averaged about 7.5% percent below normal for the low tailwater condition, due to model limitations. Figure 55 shows that performance is again good for the low tailwater condition throughout the full range of operations. For the high tailwater condition, performance is good for gate openings of 20 percent and above. For 10 % gate opening, at high tailwater, performance is poor but still improved over not having a deflector.

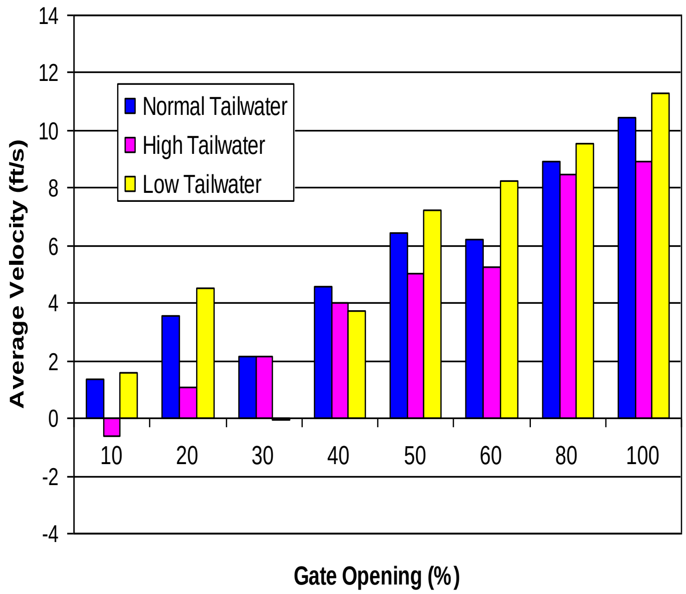

Figure 55. Index velocities measured in the Choke Canyon stilling basin model with the deflector tested with 3 different tailwater conditions.

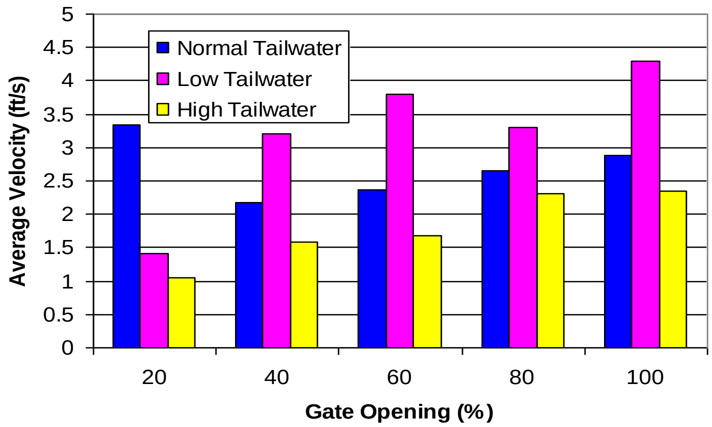

Figure 56. Index velocities measured in the Haystack stilling basin model with the deflector tested with 3 different tailwater conditions.

Haystack Dam

For the Haystack model, tailwater was set to 15 percent above normal for the high tailwater condition and 15 percent below normal for the low tailwater condition. Figure 56 demonstrates that performance is again good for the low tailwater condition throughout the full range of operations. For the high tailwater condition, performance is still reasonably good although not as good as with the other tailwater conditions.

Peformance produced under the high tailwater condition is better with the type III stilling basin than for the type II stilling basins. This can again be attributed to the baffle blocks that help to lift the jet from the basin floor at a fairly consistent distance upstream from the end of the basin, producing good performance over a larger range of discharge and tailwater variations.

Deflector Loading

Piezometer taps installed on the upstream and downstream faces of the model deflector were used to measure differential static hydraulic loading for each deflector. The maximum loads predicted for the Mason Dam prototype deflector were 6,000 lbs (0.5 lb/in^2) and12,600 lbs (1.0 lb/in^2) respectively for basin operations of 60%, and 100% gate openings.

The maximum differential load predicted for the Choke Canyon dam flow deflector was about 13,500 lb (1.9 lb/in^2) at 100% gate opening.

The maximum differential load predicted for the Haystack dam flow deflector was about 12,800 lb (1.9 lb/in^2) at 100% gate opening.

In addition to measuring average deflector hydraulic loading in the model study, loading on the Mason Dam deflector was calculated based on the momentum equation and head drop across the deflector, to determine how closely it matched with experimental results; thus:

$\sum Fx = \rho Q(V_1 - V_2) + P_1 - P_2$

Where

Fx = the total force on the deflector in the direction of flow

V_1 = average velocity impacting deflector upstream face

V_2 = average velocity impacting deflector downstream face

$Q = V_1 A$

$P_1 - P_2 = \gamma A (h_1 - h_2)$ = differential pressure due to the head drop across the deflector

ρ = density of water = 1.94 slugs/ft^3

γ = specific weight of water = 62.4 lb/ft^3

A = area of the upstream face of the deflector = 85 ft^2

Taking a conservative approach V_2 is assumed to be zero, $(h_1 - h_2)$ is assumed to be about 1 ft, and V_1 = 7 ft/s based on the exiting jet occupying a depth equal to about 30 % of tailwater depth at maximum flow.

So $Fx = \rho A V_1^2 + \gamma A (h_1 - h_2)$

Fx = 8100 lb + 5300 lb = 13,400 lb

This value is about 6 percent higher than the load measured in the Mason model, and given the assumptions that were made, provides a reasonable method for calculating deflector loading for future deflector installations. However, a factor of safety should be added to this value for design purposes.

Hydraulically Self Cleaning Operations

Type II Stilling Basins

For Reclamation type II stilling basins, model investigations showed that without a deflector, materials can be flushed from the basin throughout the range of operations tested, due to the nature of the flow patterns occurring within the basin. This phenomenon occurs because turbulence within the basin periodically tosses materials high enough into the water column to be caught and subsequently carried out by the concentrated jet exiting the basin. However the fall velocity of these suspended materials is often reached near the end of the basin and as a result they are deposited near the basin end sill, thereby making them readily accessible to be carried right back into the basin by the upstream current. So, for a large range of discharges, although materials are flushed out, the inflow of materials is constant, thereby resulting in significant abrasion damage. With the optimal deflector design in place (a single moveable deflector or two staggered deflectors), model investigations demonstrated that the upstream component of velocity at the downstream end of the basin is no longer strong enough to carry a significant amount of material back into the basin; therefore most materials that are flushed from the basin will not be carried back in. As a result, the basin potentially becomes hydraulically self-cleaning, thereby reducing abrasion damage significantly. The range of sizes of materials that can be flushed from the basin will depend on deflector configuration and outlet works operations. It also appears from the initial investigations that two staggered deflectors may be more effective than a single deflector in flushing materials from the basin.

Type III Stilling Basins

General observations of stilling basin performance with the optimal deflector design in place indicate that Reclamation type III stilling basins do not have the same tendency to self-clean as the type II stilling basins. This is because of localized recirculation that is produced immediately downstream from the baffle blocks. So although a deflector will prevent most materials from being drawn into the type III basin, if materials should get into the basin from another source such as being thrown in or falling from a steep adjacent hillside, they will not be easily purged from the basin under normal operations.

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8. Dodge, Russ, 1992. Hydraulic Model Study of Taylor Draw Dam Outlet Works.@ Report No. R-92-10, Bureau of Reclamation, Denver, Colorado, March 1992.

9. Zeigler, Eugene, 1978. "Research on Abrasive Material in Stilling Basin." Report No. PAP-720, Bureau of Reclamation, Water Resources Research Laboratory, Denver, Colorado, August 1978.

10. Hanna, Leslie, "Flow Deflectors for Mitigation of Abrasion Damage," Hydraulic Laboratory Report HL-2010-03E, Bureau of Reclamation, Denver, Colorado, May 2010

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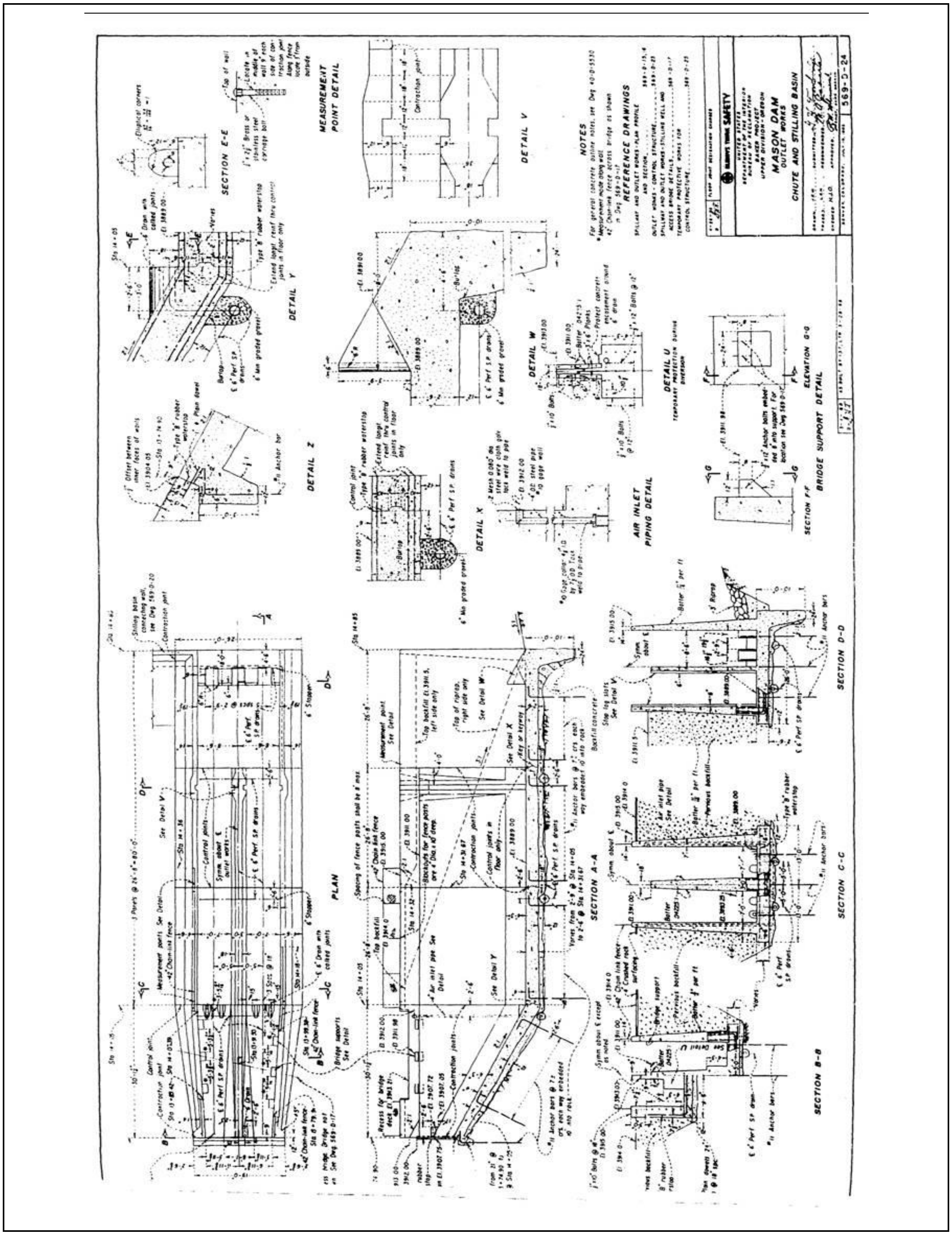
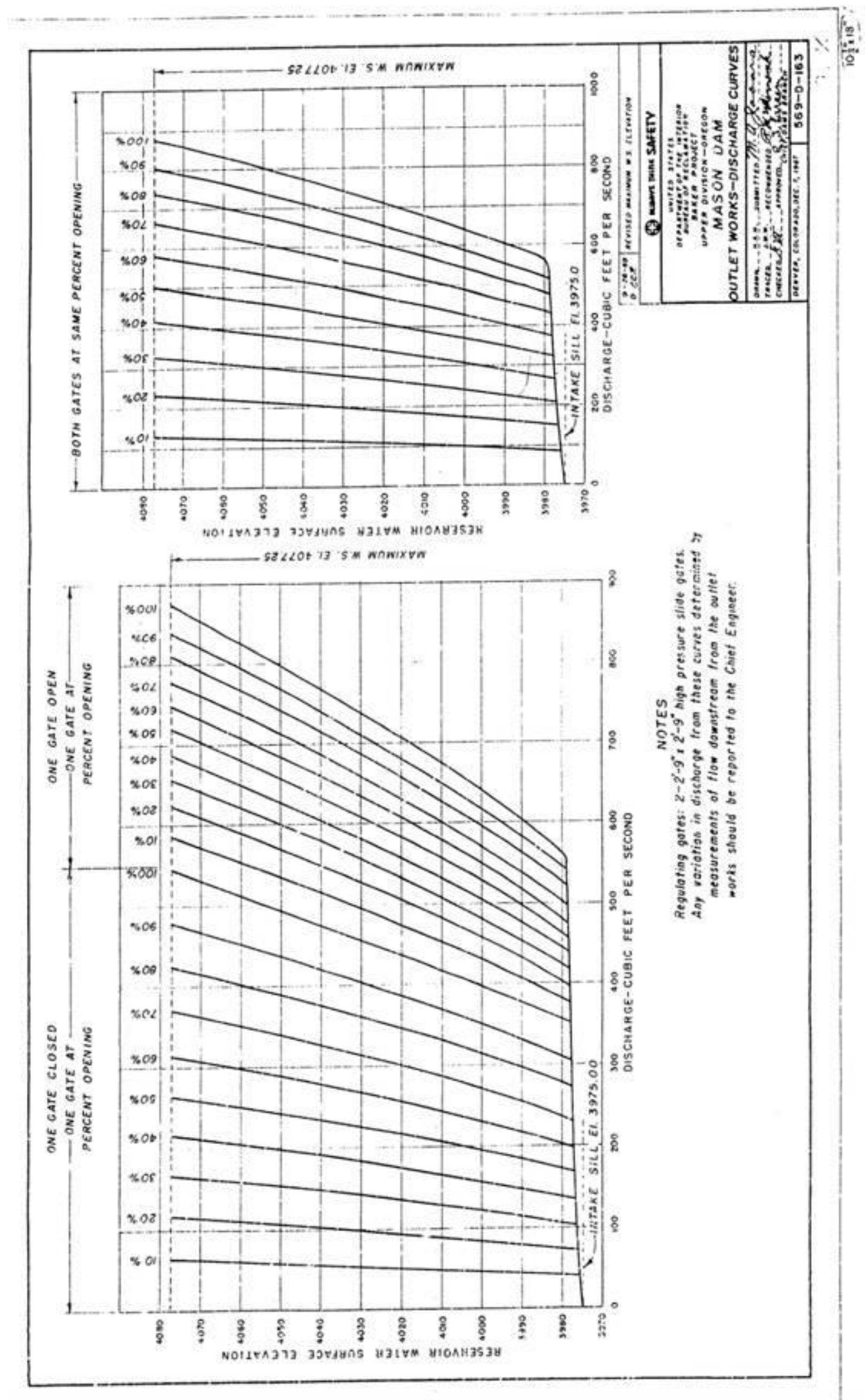
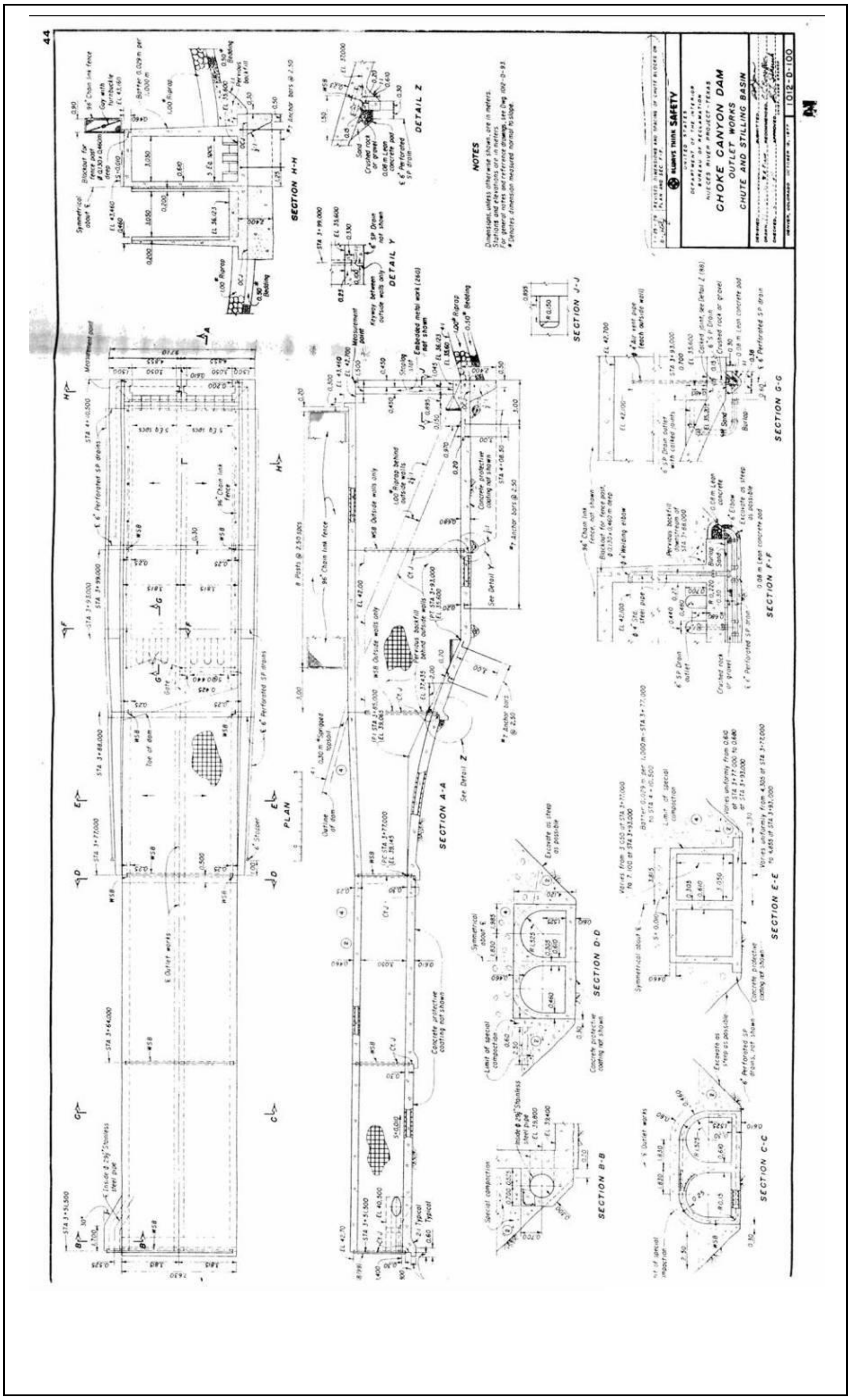
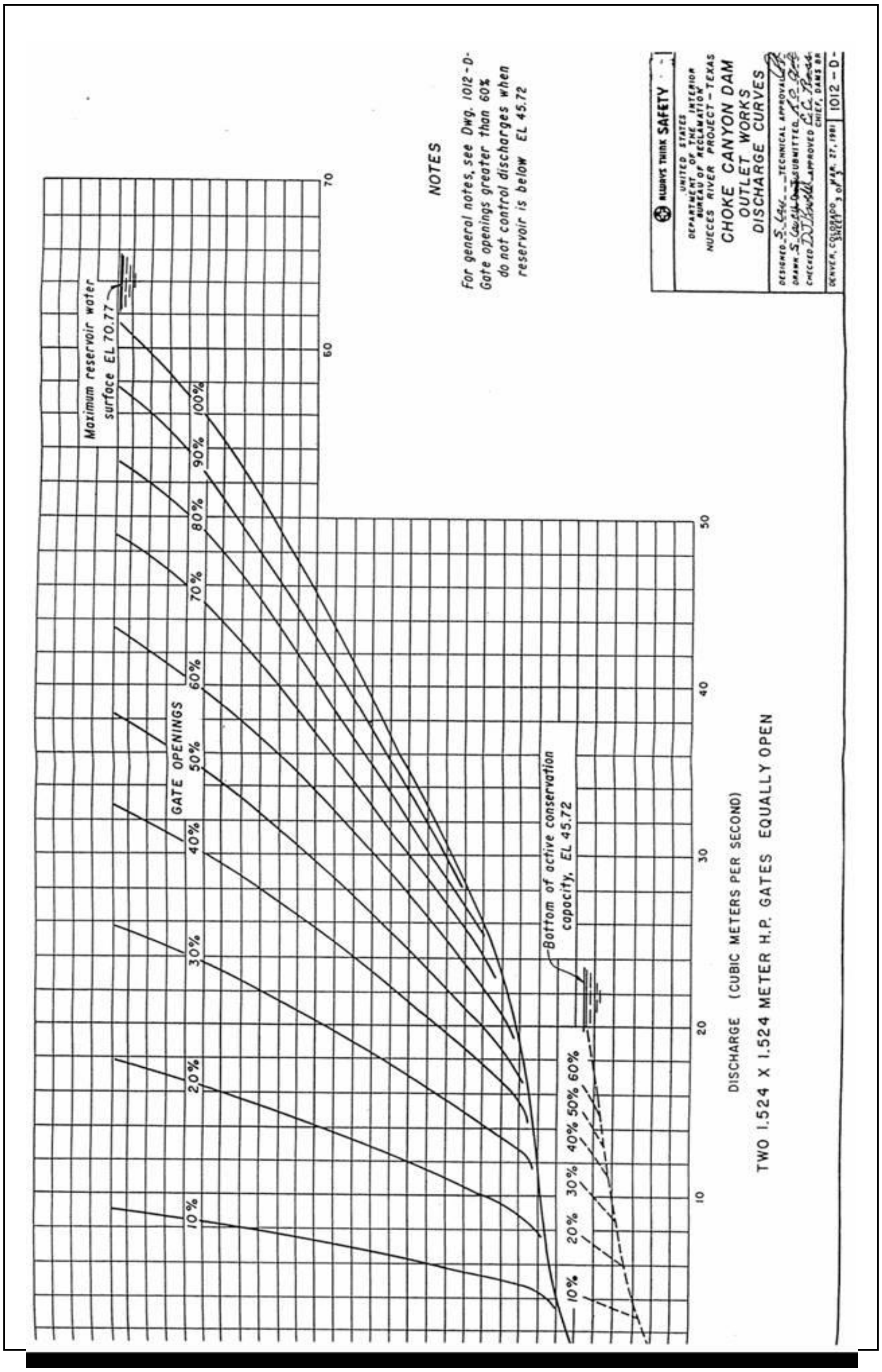
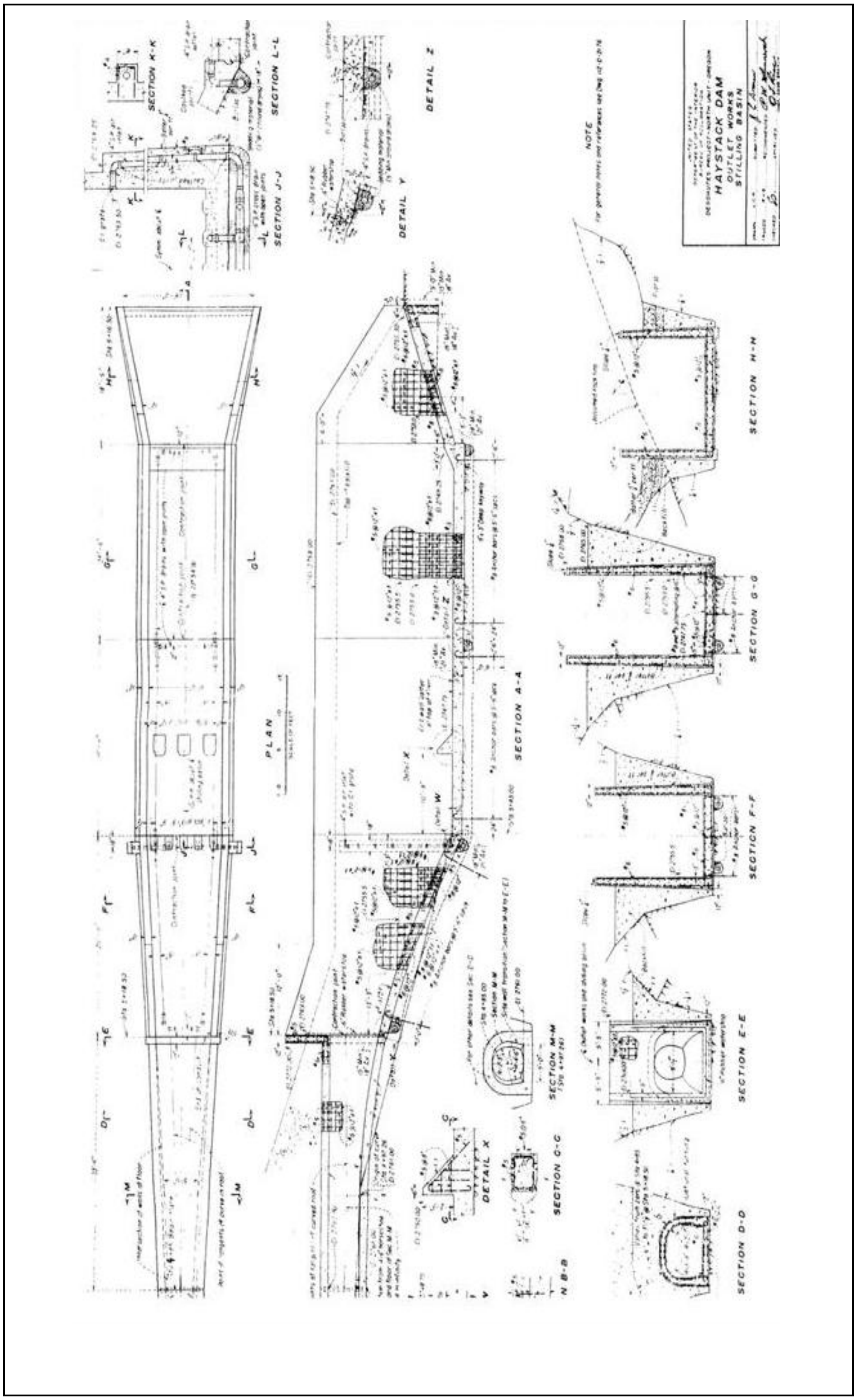
Appendix A


PLAN
SECTION A-A
SECTION B-B
SECTION C-C
SECTION D-D
SECTION E-E
DETAIL Z
DETAIL X
DETAIL Y
DETAIL W
DETAIL V
DETAIL U
MEASUREMENT POINT DETAIL
AIR INLET PIPING DETAIL
BRIDGE SUPPORT DETAIL
NOTES
REFERENCE DRAWINGS
MASON DAM
OUTLET WORKS
CHUTE AND STILLING BASIN
569-D-24

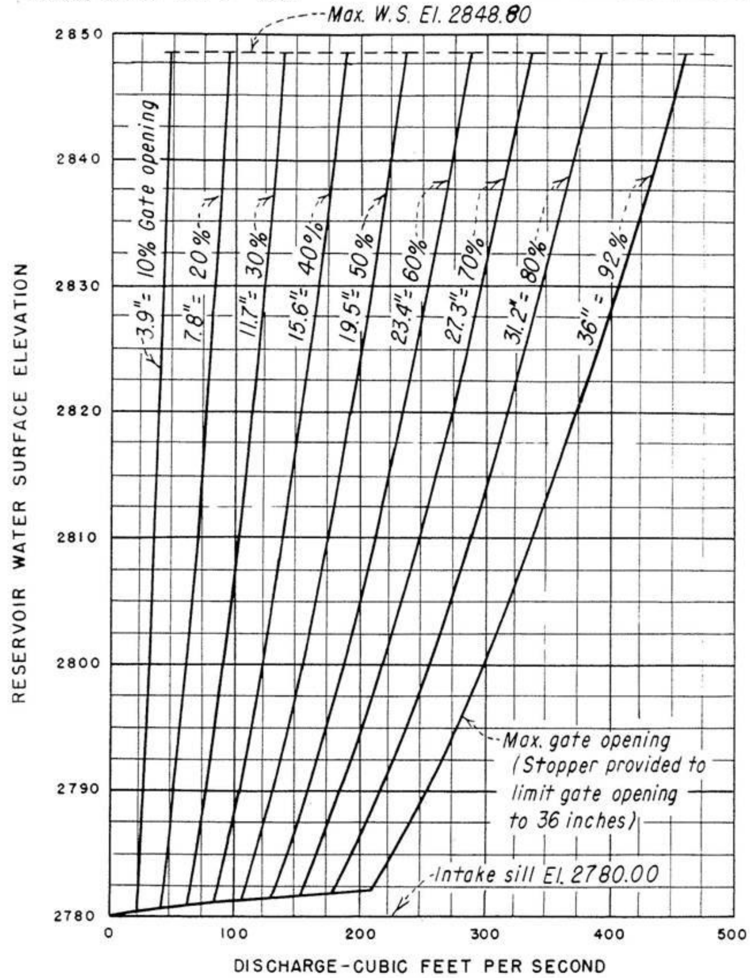

BOTH GATES AT SAME PERCENT OPENING
ONE GATE CLOSED
ONE GATE AT PERCENT OPENING
ONE GATE OPEN
ONE GATE AT PERCENT OPENING
MAXIMUM W.S. EL. 4077.25
RESERVOIR WATER SURFACE ELEVATION
DISCHARGE–CUBIC FEET PER SECOND
INTAKE SILL EL. 3975.0
INTAKE SILL EL. 3975.00
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
NOTES
Regulating gates: 2-2'-9" x 2'-9" high pressure slide gates.
Any variation in discharge from these curves determined by measurements of flow downstream from the outlet works should be reported to the Chief Engineer.
REVISED MAXIMUM W.S. ELEVATION
ALWAYS THINK SAFETY
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
BAKER PROJECT
UPPER DIVISION–OREGON
MASON DAM
OUTLET WORKS–DISCHARGE CURVES
DENVER, COLORADO, DEC. 7, 1967
569-D-163


CHOKE CANYON DAM
OUTLET WORKS
CHUTE AND STILLING BASIN
PLAN
SECTION A-A
NOTES
DETAIL Z
DETAIL Y
1012-D-100


Maximum reservoir water surface EL 70.77
GATE OPENINGS
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Bottom of active conservation capacity, EL 45.72
10% 20% 30% 40% 50% 60%
10
20
30
40
50
60
70
DISCHARGE (CUBIC METERS PER SECOND)
TWO 1.524 X 1.524 METER H.P. GATES EQUALLY OPEN
NOTES
For general notes, see Dwg. 1012-D-
Gate openings greater than 60%
do not control discharges when
reservoir is below EL 45.72
ALWAYS THINK SAFETY
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
NUECES RIVER PROJECT-TEXAS
CHOKE CANYON DAM
OUTLET WORKS
DISCHARGE CURVES


SECTION K-K
SECTION J-J
SECTION L-L
DETAIL Y
DETAIL Z
NOTE
HAYSTACK DAM
OUTLET WORKS
STILLING BASIN
PLAN
SECTION A-A
SECTION H-H
SECTION G-G
SECTION F-F
SECTION E-E
SECTION D-D
SECTION C-C
SECTION M-M
DETAIL X

THIS IS A MARKED-UP DRAWING
Structure Stability Branch
Water and Power Resources Service
PN Region
Boise, Idaho OCT 9 1981



NOTES

Any variations in discharge from these curves as determined by measurements of flow downstream from the outlet works should be reported to the Chief Engineer.

Regulating gate:
3'-3" x 3'-3" H.P. Slide Gate.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
DESCHUTES PROJECT
NORTH UNIT — OREGON
HAYSTACK DAM
OUTLET WORKS — DISCHARGE CURVES

DRAWN L.R.H. SUBMITTED R.W. Whinnerah
TRACED V.M.M. RECOMMENDED
CHECKED APPROVED
ASST. CHIEF DESIGNING ENGINEER
DENVER, COLORADO, DEC. 26, 1957 112-D-2198