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IMPROVED TUNNEL-SPILLWAY FLIP BUCKETS

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Denver, Colorado

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SYNOPSIS

This paper discusses several buckets, of the type used to deflect or flip tunnel spillway discharges downstream, in terms of their desirable or undesirable features. Several new types of buckets developed from hydraulic model tests are then described. Using data from these tests, dimensionless curves are presented to aid in determining the jet trajectory length, the spreading of the jet, the tail water drawdown at the bucket, and the pressures on the floor and side walls of the bucket.

IMPROVED TUNNEL SPILLWAY FLIP BUCKETS

by

T. J. Rhone and A. J. Peterka, Engineers

INTRODUCTION

A tunnel spillway is composed of two basic parts--an upstream spillway crest, free or controlled, and a downstream tunnel, part of which is sloping and part near horizontal. From the standpoint of economy the tunnel diameter must be kept to a minimum. Since the tunnel is never allowed to flow full because of the possibility of siphonic action producing dangerous flow conditions, it is necessary to keep flow velocities high and to prevent turbulent areas in the tunnel. Spillway tunnels are usually designed to flow from 3/4 to 7/8 full at maximum discharge, making the outflow at the tunnel portal relatively deep. The combination of depth and velocity produces the highest possible concentration of energy and increases the difficulty of obtaining satisfactory flow conditions where the flow spills into the river. As an example, on the Glen Canyon tunnel spillways,1/ the maximum discharge of 276,000 cfs produces 159,000 horsepower per foot of width at the tunnel portals. On Grand Coulee,2/ an overfall spillway, where the maximum discharge is 1,000,000 cfs, the energy per foot of width is only 15,650 horsepower, or one-tenth that on Glen Canyon.

If it were feasible to construct an efficient hydraulic jump stilling basin at the end of one of the Glen Canyon tunnels, the basin depth, from apron to tail water elevation, would need to be 170 feet deep. The hydraulic jump lengt would be over 1,000 feet and would require a basin 700 to 800 feet long or more.

1/2/See Table 1.

Basin appurtenances such as baffle piers could not be used effectively because the high entrance velocity, 165 feet per second, would produce cavitation problems. The cost of a structure this size would be prohibitive, and it is readily seen why other types of structures are used at the end of tunnel spillways. Buckets are the most common of these structures and were probably derived from the slight upturns placed at the base of early overfall spillways. It is not clear whether the designers intended that these buckets operate free or submerged. In some cases, the upturn was too slight to produce a measurable effect on a thick jet, but probably the intended purpose was to deflect the jet downstream to prevent undermining of the spillway structures. Buckets of this type are referred to variously as "ski-jump," deflector, diffuser, trajectory, or flip buckets. For ease of expression, the term flip bucket will be used in this paper.

Flip buckets are not a substitute for energy dissipators because such a bucket is inherently incapable of dissipating energy within itself. The purpose of a flip bucket is to throw the water downstream where the riverbed damage, which is usually certain to occur, does not endanger the safety of the dam, powerplant, or other structures including the flip bucket itself. In accomplishing this primary function, buckets are also designed to spread the flow across as much of the downstream channel as is considered desirable in order to reduce riverbed damage as much as possible. The jet trajectory is modified as necessary to cause the jet to impinge on the tail water surface at the desired location, and when possible, the steepness of the jet trajectory at the point of impingement is selected to produce horizontal and vertical velocity components which produce most favorable flow conditions in the river channel.

Although with the present state of knowledge it is impractical to generalize the design of flip buckets, it is intended in this paper to present certain basic facts which have been found to be true as a result of extensive hydraulic model testing and prototype observation. It is hoped that by extension of the ideas presented that sufficient data and experiences by others may be brought out into the open to provide a better understanding of the requirements necessary for improved flip bucket design.

BUCKET DESIGN PROBLEMS

It is usually difficult or impossible to predict the flow pattern to be expected from a particular bucket by mere inspection of the bucket shape. Because of variations in velocity and depth, the spreading and trajectory characteristics of a given bucket can be determined only by testing in a hydraulic model. Since the authors have had the opportunity to test various types of buckets and to observe or hear first hand of their performance in the field, the findings of these tests should, therefore, be of interest to designers who must often select a bucket type before the hydraulic model tests are made.

In the course of developing and improving bucket designs, a number of difficulties have been found and overcome. The following examples indicate the problems which may be encountered in bucket design and which may not be generally known.

The flip buckets on the tunnel spillways at Hungry Horse Dam,3/ Yellowtail Dam 4/ of the USBR projects, and Yanhee Dam 5/ and Wu-Sheh Dam 6/ being built in Thailand and Formosa, respectively, are similar and are what may be called a "standard" type. The buckets are placed downstream from a transition which changes the circular or horseshoe shaped tunnel to a flat bottom to correspond to the flat bottom of the bucket. High velocity flow in the tunnel makes it difficult to design a short transition; long transitions are usually costly. If the transition is not carefully designed, and preferably checked by model studies, there is the possibility of dangerous subatmospheric pressures occurring in the corners. The transition, therefore, becomes as much of a design problem as the bucket.

The Fontana Dam 7/ spillway buckets do not have an upstream transition. The bucket inverts are circular, the same as the tunnel inverts, Figure 1.* The buckets were shaped by trial in a 1:100 scale model tested in the TVA Hydraulic Laboratory. The curved surfaces of the finally developed buckets could not be expressed by ordinary means or even by mathematical equations. That the bucket was well designed has been proved by subsequent operation of the structure, but the methods necessary to convert the model dimensions at a scale of 1:100 to prototype dimensions were quite laborious. Because of the high velocity flow in the bucket, dimensions taken from the model could not be scaled up directly. Any small irregularity or misalinement when multiplied by 100 could have been sufficiently large to produce cavitation in the prototype bucket. It was, therefore, necessary to convert the dimensions to a 1:10 scale bucket, and after smoothing these, to convert the corrected dimensions to a 1:1 scale.

On some buckets, particularly those on foreign dams, a serrated or toothed edge has been placed at the downstream end of the bucket. The teeth are to provide greater dispersion of the jet before it strikes the tail water surface. High velocity flow passing over the sharp edges may produce cavitation damage on the concrete surfaces.

The problem of draining a tunnel which has a flip bucket at the downstream end provides a challenge in design. The drain must be placed in a surface

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*Photographs from Technical Monograph No. 68, Hydraulic model studies, Fontana Project, Tennessee Valley Authority.

exposed to high velocity flow. Even though it is possible to design or develop in the laboratory a drain opening which will not produce cavitation pressures, it is difficult to obtain field construction to the necessary tolerances to prevent cavitation from occurring. An ideal bucket design would be self-draining and would not present a cavitation problem at the drain structure.

IMPROVED BUCKET DESIGNS

Recently a number of tunnel spillway flip buckets have been developed in the USBR Hydraulic Laboratory that seem to offer simple but very effective methods of directing the flow away from the structure and which also overcome, in part, the difficulties described in the preceding paragraphs. Although no single bucket eliminates all of the undesirable features of a bucket, the use of the principles described in the following pages will help the designer to provide an improved bucket on a particular structure. To review, an ideal bucket should provide (1) easy drainage of the tunnel, (2) a bucket shape which can be defined and expressed in prototype size by ordinary means on ordinary drawings, (3) no need for an upstream transition, and (4) an impingement area which may be shaped, by simple additions to a basic bucket, to fit the existing topographic conditions. Some of the buckets described are unique and probably cannot be generally used without some adaptation; however, the others are basic in type and have only minor additions to accomplish some specific function.

One of the unique designs was the Trinity Dam 8/ spillway bucket developed on a 1:80 scale model. The spillway tunnel enters one side of a wide shallow river channel and the flow tends to cross the river diagonally. It was necessary to discharge the flow into this channel without creating excessive eddies that might erode the riverbanks or cause disturbances in the vicinity of the powerhouse tailrace. The spillway is an uncontrolled morning-glory and, consequently, the flow can vary from a few second-feet to a maximum of 22,000 cfs. The velocity at the bucket is 122 feet per second. Because small flows may occur for days, it was desirable for low flows to leave the bucket as close to the riverbed elevation as possible to prevent excessive erosion near the base of the structure. On the other hand, large flows should be flipped downstream away from the structure with as much dispersion as possible to prevent erosion and induced eddies from damaging the structure. In the usual flip bucket, a hydraulic jump forms in the bucket for small flows and the water dribbles over the bucket end and falls onto the riverbed. This could cause erosion which would undermine the structure. When the jump is first swept out of the bucket, the jet usually lands near the structure and erosion and undermining of the structure may still occur. At Trinity Dam, the foundation conditions at the end of the tunnel were such that it was deemed necessary to protect against the possibility of erosion and undermining. In order to place the bucket near riverbed level, the semicircular channel constructed downstream from the tunnel portal was curved downward in a trajectory curve, and the flip bucket structure was placed at the end, Figure 2. The flip bucket surface consisted of three plane surfaces so placed that they spread and shape the jet to fit the surrounding topography. Large flows are spread into a thin sheet having a contact line with the tail water surface a considerable distance downstream, Figure 3A. However, even small flows are thrown downstream well away from the base of the bucket.

A training wall was used to prevent spreading of the jet on the high, or land side, of the bucket. There was no wall on the low or river side of the bucket. At flows less than 1,000 cfs, a hydraulic jump formed over the horizontal surface and part way up the slope of the bucket; the flow spilled out of the low side of the bucket into the river channel. The open side of the bucket was only 4 or 5 feet above the river. Had the flow been confined on both sides and forced to spill out the end, the drop would have been over 40 feet and additional protection of the bucket foundation would have been required. At discharges greater than 1,000 cfs, the jump swept out of the bucket without hesitation and with sufficient velocity that the flow was carried well downstream away from the structure. As the discharge increased, the jet was flipped further downstream and became increasingly dispersed. The long contact line between the jet and the tail water reduced the unit forces on the tail water, and the eddies induced at the ends of the contact line were thereby found to be a minimum. Since one side of the bucket is entirely open, the bucket is self-draining. Other advantages of this design are that the bucket may be defined for prototype construction with a few simple dimensions, and no curved or warped forms are necessary for prototype construction.

Another unusual type of flip bucket was developed for the Wu-Sheh Dam tunnel spillway. Construction schedules and geologic conditions in the field made it necessary to modify this bucket from the standard type described earlier in this paper. After the line of the tunnel had been established and construction of the tunnel started, it was found necessary as a result of model tests to change the direction of the flow entering the river channel. Earth and rock slides, during the diversion period, made it necessary to construct retaining walls in the tunnel portal area which restricted the length of the flip bucket. Hydraulic model studies were made to determine how much turning of the jet was required and whether the turning could be accomplished in the tunnel. The tests showed that it was undesirable to turn the tunnel and that all turning should be accomplished in the bucket. The final bucket determined from model studies used curved walls to turn the flow--a batter in the left wall to prevent congestion in the bucket and reduce hydraulic loads at the larger discharges, and a fillet at the junction of the left wall and floor to smooth up or control the jet undernappe, Figure 4. The resulting bucket was "tailor-made" to direct the flow to impinge near the middle of the river channel and to obtain the greatest dispersion possible at all discharges. The surfaces in this bucket could also be defined by ordinary dimensioning.

Piezometers placed in the side walls of the bucket showed above atmospheric pressures at all discharges. The maximum pressure recorded on the left wall was 91 feet of water, Figure 4. Before the wall was battered, the maximum pressure probably would have been much larger due to a more direct impact on the converging wall.

The Yellowtail Dam tunnel spillway flip bucket is a dual purpose bucket similar in some respects to the standard buckets. The tunnel is a curved bottom horseshoe-type conduit. Two hundred fifty feet upstream from the portal, the tunnel changes to a flat bottom horseshoe conduit, and the invert drops 26.25 feet by means of a combination transition-trajectory curve 170 feet long. The bucket has a flat horizontal floor 130 feet long and a 62-1/2-foot long upward sloping sill, Figure 5. At spillway flows up to 12,000 cfs, a hydraulic jump forms in the bucket and relatively quiet water is discharged into the downstream channel. As the spillway discharge increases, the jump moves downstream and at 13,000 cfs sweeps out of the basin; for greater discharges and up to the maximum, 173,000 cfs, the basin acts as a flip bucket, Figure 3B. The basin or bucket is placed low in solid rock so that discharges in the unstable zone, 12,000 to 13,000 cfs, cannot harm or undermine the structure. This basin was developed in the Hydraulic Laboratory to serve the specific purpose of acting as a hydraulic jump basin for the most prevalent spillway discharges--discharges expected to be exceeded only every 10 years, and acting as a flip bucket to prevent damage to the structures during large floods. The reason for using the hydraulic jump for part of the discharge range was to protect the river channel against clogging with talus which was present in the canyon in large quantities and was expected to move if a high velocity stream contacted it. Following large discharges, it was expected that reopening of a channel to achieve full power head would be necessary.

The flip buckets for the Glen Canyon Dam tunnel spillways are an example of buckets developed to eliminate the tunnel transition and the need for a flat bucket invert. The buckets at the portals of the 41-foot diameter tunnels are on opposite sides of the river and are aimed to discharge at acute angles with the center of the river. The left bucket is farther downstream than the right. Each bucket is designed to handle the maximum discharge of 138,000 cfs at a velocity of about 165 feet per second. This represents over 13,000,000 horsepower in energy turned loose into the river during maximum discharge.

In the preliminary design, there was a 70-foot long transition between the circular tunnel and the rectangular channel containing the flip bucket. Hydraulic model studies indicated that the transition was too short, and that subatmospheric pressures would be sufficiently low to produce cavitation and damage to the structure. Two alternatives were developed during the model studies; one was to use a 100-foot long transition in which the change in cross section was accomplished without dangerous pressures occurring and the other was to eliminate the transition by continuing the circular tunnel invert downstream to intersect the upward curve of the flip bucket. The latter scheme was developed and will be constructed in the prototype structure, identical buckets on the twin spillways. In effect, the transition and the bucket are combined into the bucket structure without complicating the design of the bucket.

Because the flat bottom portion of these buckets diverges in plan, small flows are spread laterally more than for the flat-bottomed bucket. As the discharge increases, the rate of spreading decreases so that it is easier to accommodate the jet for flood flows in a relatively narrow channel. Figure 6 shows a comparison of the flow from the two types of buckets. In the flat-bottomed bucket which is preceded by a transition, the flip curve extends across the full width of the bucket for its entire length; all of the flow elements at a given elevation are turned simultaneously. In the alternate bucket, the flip curve turns the lower flow elements in the center of the stream first and gradually widens its zone of influence as the flow moves downstream, resulting in greater dispersion of the jet. In effect, the flow along the center line of the bucket is turned upward while the flow elements on either side of the center are turned upward and laterally. Training walls may be used to limit the lateral spreading. In subsequent testing, deflectors were added to the bucket training walls to make the jets conform to the shape of the river channel and surrounding topography, Figure 7.

The flip bucket used on the Flaming Gorge Dam tunnel spillway was of the same type as used on the Glen Canyon spillways. The maximum design flow for Flaming Gorge spillway is 28,800 cfs; the velocity of the flow at the portal of the 18-foot diameter tunnel is about 140 feet per second. The energy in the jet at the flip bucket is equivalent to 1,000,000 horsepower. In operation the flow appearance of the Flaming Gorge bucket was entirely different than the Glen Canyon buckets. The Flaming Gorge jet was well dispersed at the lower discharges and became more compact as the discharge increased, Figure 8. The Glen Canyon jets were well dispersed for all flows, and the change in lateral spreading with discharge was not so apparent. In the Flaming Gorge bucket, the water rose on the sides of the bucket at low flows, forming in effect a "U" shaped sheet of water in which the bottom and sides were of equal thickness. The vertical sides of the "U" followed the line of the bucket side walls after leaving the bucket, while the bottom sheet of water had a tendency to diverge to either side. The vertical fins had a shorter trajectory than the lower sheet and on falling would penetrate the lower jet, tending to spread or disperse it; this can be seen in the photographs on Figure 8. As the discharge increased, the size of the fins relative to the thickness of the lower sheet became insignificant and no longer had this spreading effect. The differences in the Glen Canyon and Flaming Gorge jets might be explained by the fact that the flow depth for maximum discharge was about 61 percent of the diameter of the Glen Canyon tunnel and 81 percent of the diameter of the Flaming Gorge tunnel. For a flow 0.61D in Flaming Gorge, the jet was still well dispersed.

Both the Flaming Gorge and Glen Canyon buckets were modified by reducing the height of the river side wall. The Flaming Gorge bucket is located well above the maximum tail water elevation so that the wall could be cut down to the spring line of the tunnel invert curve without tail water interference. The effect was to eliminate the fin that formerly rose along the wall. The jet spread out evenly to the right and was better dispersed than before. The Glen Canyon buckets are located more closely to the maximum tail water elevation and in order to prevent the tail water from interfering with the jet, the river wall could be cut down to only 5 feet above the spring line of the tunnel invert. Sufficient wall remained to train the jet and very little difference in the flow pattern could be detected.

DESIGN CONSIDERATIONS

Tunnel spillways usually make use of part of the river diversion tunnel. The downstream portion of the diversion tunnel becomes the horizontal portion of the spillway tunnel--the bucket is added after diversion needs have been satisfied. Since the diversion tunnel is one of the first items of construction, it is often necessary, because of time limitations and construction schedules, to determine line and grade for the diversion tunnels before the details of the spillway are known. Care in selecting the exact position and elevation of the diversion tunnel, while keeping in mind its ultimate use as a spillway tunnel, will help to provide a dual purpose tunnel which will satisfy the temporary as well as the final demands with the least amount of modification when the bucket is added.

The following sections cover the items which should be considered during design and which will help to provide a simple bucket structure having desirable performance characteristics.

Elevation of Bucket Invert

It is desirable to construct the bucket and tunnel inverts at the same elevation. Since diversion requirements make it necessary to keep the diversion tunnel low to provide the diversion capacity, the greatest danger is that the tunnel will be set too low for ideal spillway operation. This will require building up the bucket lip to prevent the tail water from submerging the bucket. As a general rule, maximum tail water should be no higher than the elevation of the center line of the tunnel. If the bucket is set lower, difficulty may be experienced in obtaining free flow at low spillway discharges. The shape of the tail water curve will determine the exact requirements. The drawdown in tail water elevation at the bucket caused by the ejector action of the jet may also affect the vertical placement. Drawdown is discussed later.

Flow Direction

The bucket center line should be a continuation of the tunnel center line, and the portion of the diversion tunnel used for the spillway tunnel should be straight. It is, therefore, desirable to aim the diversion tunnel so that it may be used as is for the spillway tunnel. The tunnel direction should be set so that spillway flows will be aimed downriver and so that the design discharge impinges on the tail water in the center of the discharge channel. The flow should be directed to minimize the diameter of induced eddies at the sides of the jet since these can be very damaging to channel banks. In an ideal arrangement, the jet will be exactly as wide as the channel so that there will be little return flow from the downstream tail water.

Figure 9A shows the angle of divergence of one side of the jet leaving the bucket for two types of buckets--the flat-bottom type and the transition bucket used on Glen Canyon and Flaming Gorge spillways. In both cases, the angle of divergence is plotted versus the angle of inclination θ for a range of Froude numbers (of the flow entering the bucket). The flat bottom bucket produced very little change in angle of divergence for a range of Froude numbers or inclination angles. The transition bucket showed considerable change in divergence angle--from 4° to 12° for a Froude number range of 6 to 11. Since the higher Froude numbers occur at low discharges, the jet divergence is greatest at low flows. As the discharge increases the Froude number becomes smaller and the divergence angle decreases. In most designs this is a favorable characteristic and results in improved river flow conditions for all discharges.

Drawdown

For the conditions just described, the jet will act as an ejector to lower the tail water upstream from the jet impingement area. From the Hungry Horse Dam model tests, 26 feet of drawdown were predicted for 35,000 cfs discharge, and it was recommended that a weir be constructed in the powerplant tailrace to prevent unwatering of the turbines. Prototype tests made for 30,000 cfs showed 25 feet of drawdown and demonstrated that the weir was indeed necessary. At Hungry Horse the flow leaves the bucket at a 15° angle, making the trajectory relatively flat; the jet is as wide as the downstream channel,

Figure 10. The drawdown is maximum under these conditions. At Glen Canyon the spillway jets do not occupy the entire width of channel, and the jet trajectory is steeper, but the discharge is considerably greater. Hydraulic model tests have indicated that up to 25 feet of drawdown may be expected.

Other hydraulic model bucket tests have shown the drawdown to be appreciable, particularly when the jet occupies a large proportion of the channel width. No means have been found to calculate the amount of drawdown to be expected, except by making careful measurements on a hydraulic model. However, by using measurements obtained on several model studies and from limited prototype observations, the curve in Figure 9B was derived. It is presented here as a means of estimating the drawdown that can be expected with a tunnel spillway and flip bucket.

The intensity of the ejector action and the resulting lowering of the tail water at the bucket have been found to be a function of the energy in the jet and the amount of resistance encountered when the jet strikes the tail water. In the curve of Figure 9B the abscissa is the cross-sectional area of the river flow near the point of impact of the jet divided by the cross-sectional area of the flow at the tunnel portal. The river flow area is the product of the difference between the no flow tail water elevation and the tail water elevation for the discharge being investigated, and the average width of the river near the point of impact. The area of the flow at the portal is obtained by dividing the spillway discharge quantity by the average velocity. The ordinate is the ratio of the amount of drawdown to the depth of tail water. The depth of tail water is the same depth used to determine the river cross-sectional area.

The curve, defined by the test points shown, indicates with reasonable accuracy the drawdown at each dam site for which data were available. The test points include various shapes and depths of channel and various types of bucket jets. Further, the two prototype tests on Fontana and Hungry Horse Dams showed good agreement between model and prototype test results. However, it is not known that the curve is infallible in predicting drawdown at future sites and should be used with caution until more data are available.

Effect of Trajectory Shape

In addition to the effects of drawdown explained above, the jet trajectory is important in other ways. The angle of the bucket lip with respect to horizontal determines the distance the water will be thrown downstream. However, the steeper the angle, the more the jet will be broken up and slowed down by air resistance. Both of these effects cause the jet to enter the tail water at a steeper angle. With a steep entry, the vertical component of velocity will be greater, and the jet will tend to dig into the channel bottom. With flatter trajectories, the horizontal component will be greater, the drawdown will be greater, and the forward velocity will be higher. High velocity channel flow may persist downstream from the impingement area for a considerable distance if the channel bottom does not erode to produce a deep pool. High velocity flow along the channel banks will then occur. If the bottom erodes, an energy dissipating pool will be formed, and flow downstream will be smoother. Bucket flip angles are usually constructed from between 15° and 35°. Angles less than 15° do not give enough lift to clear the bucket structure, and little is usually gained, from any viewpoint, by increasing the angle beyond 35°.

Figure 11 contains a family of curves which may be used to estimate the trajectory length for inclination angles up to 45° and velocities up to 160 feet per second. These curves were obtained from the simple equations for the path of a projectile, $X = V^2 \sin 2\theta/g$. For a given angle θ the equation may be simplified as shown by the equations to the right of the trajectory curves. For $\theta = 15°$, $X = H'$; for $\theta = 45°$, $X = 2H'$ etc., where H' is the velocity head at the bucket entrance. To estimate H', the curve in the lower right of Figure 11 may be used. Here, H', expressed as a percentage of the total head H, is plotted versus the percentage of maximum tunnel discharge. H' is seen to vary from about 61 percent for 20 percent of maximum discharge, to about 75 percent for maximum discharge. Maximum discharge is considered to occur when the tunnel is about three-fourths full at the outlet portal. The points which determine the curve have ratios of vertical drop to horizontal tunnel length, H/L, from 0.15 to 1.9.

Trajectory lengths taken from these curves have been found to be reasonably accurate when checked by hydraulic models. Some difference between model and prototype trajectory lengths may be expected to occur, however. Little is known regarding model and prototype trajectory length agreement, but from measurements estimated or scaled from photographs, and from actual measurements reported by the author,** it appears that the differences are not critical in nature. The prototype trajectory is shorter than the model or theoretical jet and has a steeper angle of entry into the tail water. The difference is believed to be caused by the greater air resistance encountered by the high velocity prototype jet. From sketchy information on a few structures, the trajectory length in the prototype for 20 percent of maximum discharge is believed to be 15 to 20 percent shorter than in the model, Figure 12. There also are indications that the difference becomes less as the prototype discharge increases.

In determining the radius of the bucket curve, it is necessary to provide a radius at least four times as great as the maximum depth of flow. This

**Model and Prototype Studies on Unique Spillway, Part III of Symposium on Fontana Dam Spillway, by A. J. Peterka, Civil Engineering for June 1946, Vol 16, No. 6.

provides an incline sufficiently long to turn most of the water before it leaves the bucket and provides assurance that the jet will be thrown into the desired area downstream.

Pressures in the Transition Bucket

Because of the simplicity and effectiveness of the transition bucket, it will probably be used on many future tunnel spillways. Extensive pressure measurements were therefore made on several buckets having two different inclination angles, 15° and 35°, to indicate that the buckets were safe against cavitation pressures and to provide data for structural design. The results of these tests have been summarized in Figures 13, 14, and 15 and may be helpful in making preliminary designs.

Figure 13 shows pressures along the center line of the transition bucket floor. The envelope curve includes inclination angles from 15° to 35° and flows in the Froude number range 6.8 to 10.3, the usual range of operating conditions. The maximum pressure was found to be slightly greater than given by Gumensky*** from theoretical considerations. The theoretical pressure P_t, is expressed:

$$P_t = (1.94\ w^2 R + 62.5)\ D_1$$

where

$$w = \frac{V}{R}$$

This maximum pressure occurred about 0.6 of the bucket length from the upstream end. Pressures rapidly became less toward the downstream end of the bucket and reached atmospheric at the bucket lip.

***Design of Sidewalls in Chutes and Spillways, by D. B. Gumensky, Paper No. 2675, Transactions of ASCE, Vol 119, 1954.

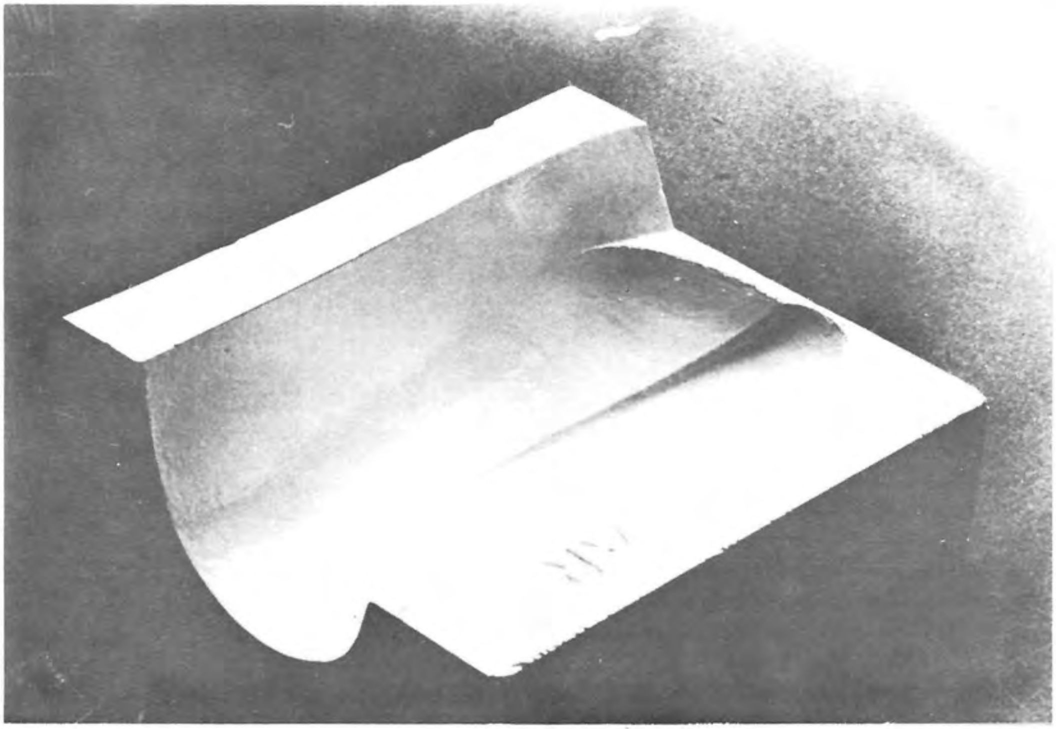
For some tests a piezometer placed just upstream from the bucket lip, Figure 14, indicated below atmospheric pressures, a phenomenon which has not been satisfactorily explained. Experiments on model buckets showed that the pressure on this piezometer was affected by the shape or angle of the downstream portion of the bucket lip. The curve of Figure 14 shows the relation between pressure and the angle β. The curve indicates that for a given angle of inclination θ, β should be 35° or more to insure atmospheric pressures or above at the lip piezometer. The curve also indicates that if β is 0° the pressure will be atmospheric. This is not a practical solution, however, since if $\beta = 0°$ the piezometer will then be upstream from the lip and a new problem will be created at the end of the extended bucket. It should be noted that the bucket side walls extend beyond the lip piezometer as shown in Figure 14.

The curves of Figure 15 indicate the pressures to be expected on the side walls of the transition bucket from the base of the wall to the water surface. For an inclination angle θ of 35° the maximum pressure is about 11 times as great as hydrostatic and occurs near the base of the wall at about the three-quarters point, $x/l = 0.75$, of the bucket length. At the end of the bucket, $x/l = 0.99$ the maximum pressure is only four times as great as hydrostatic. For $\theta = 15°$ the maximum pressure is four times greater than hydrostatic at $x/l =$ 0.26, 0.55 and 0.80 and is only twice as great as static at $x/l = 0.99$. Other data are presented for different bucket radii, R/l values, and stations along the bucket, x/l values. Although the data are not complete, sufficient information is presented to make a preliminary structural design. On the Flaming Gorge Dam spillway bucket, one side wall was cut down to the spring line of the tunnel without objectionable spreading of the jet occurring when the flow depth exceeded the height of the wall. This procedure simplified the structural design of the bucket by reducing the overall load on a wall which had no rock behind it.

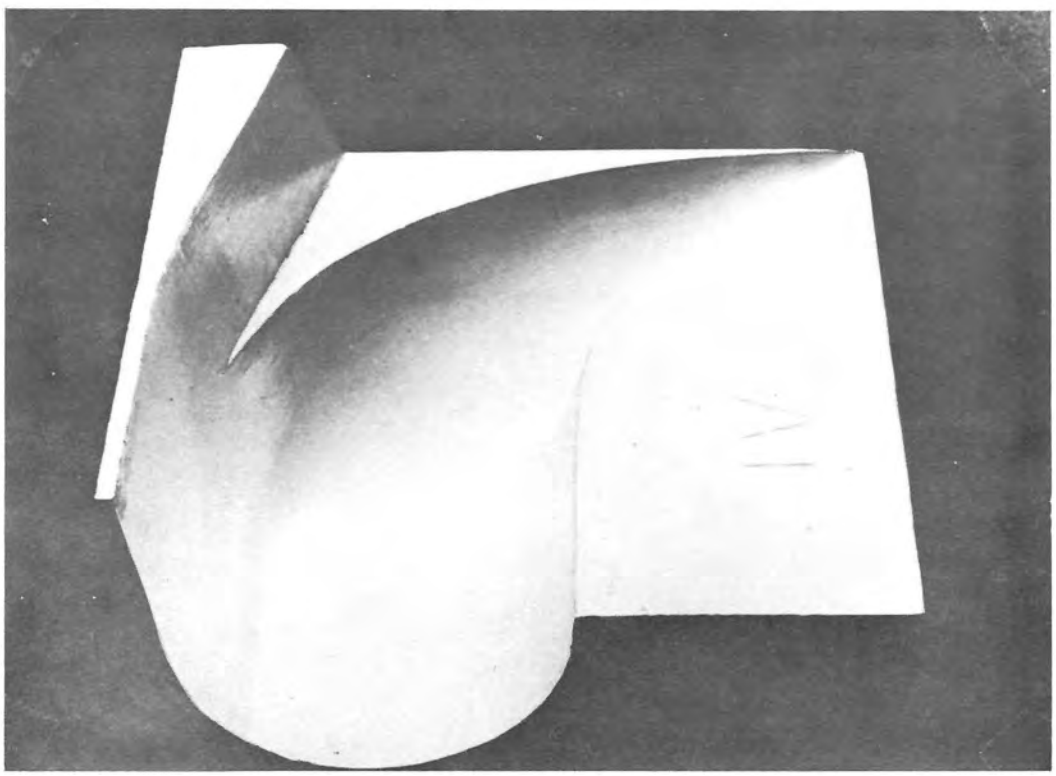
Table 1

DESCRIPTION OF PROJECTS

Reference No.	Name and location	Agency	Maximum discharge	Fall max headwater to bucket invert	Tunnel dimensions
1	Glen Canyon Dam Colorado River Storage Project, Arizona	Bureau of Reclamation	276,000 cfs	588'	2 tunnels each 41' diameter
2	Grand Coulee Dam Columbia Basin Project Washington	Bureau of Reclamation	1,000,000 cfs	420'	Overfall spillway 1,650' wide
3	Hungry Horse Dam Hungry Horse Dam Project Montana	Bureau of Reclamation	50,000 cfs	488'	31' diameter
4	Yellowtail Dam Missouri River Basin Project Montana	Bureau of Reclamation	173,000 cfs	512'	20.5' diameter horseshoe conduit
5	Yanhee Dam, Thailand	Kingdom of Thailand Ministry of Agriculture Royal Irrigation Department	212,000 cfs	402'	2 horseshoe tunnels 37.08' diameter
6	Wu-Sheh Dam Taiwan, China	Taiwan Power Company	66,000 cfs	387'	27' diameter
7	Fontana Dam North Carolina	Tennessee Valley Authority	180,000 cfs	423'	2 tunnels each 34' diameter
8	Trinity Dam Central Valley Project California	Bureau of Reclamation	24,000 cfs	475'	20' diameter

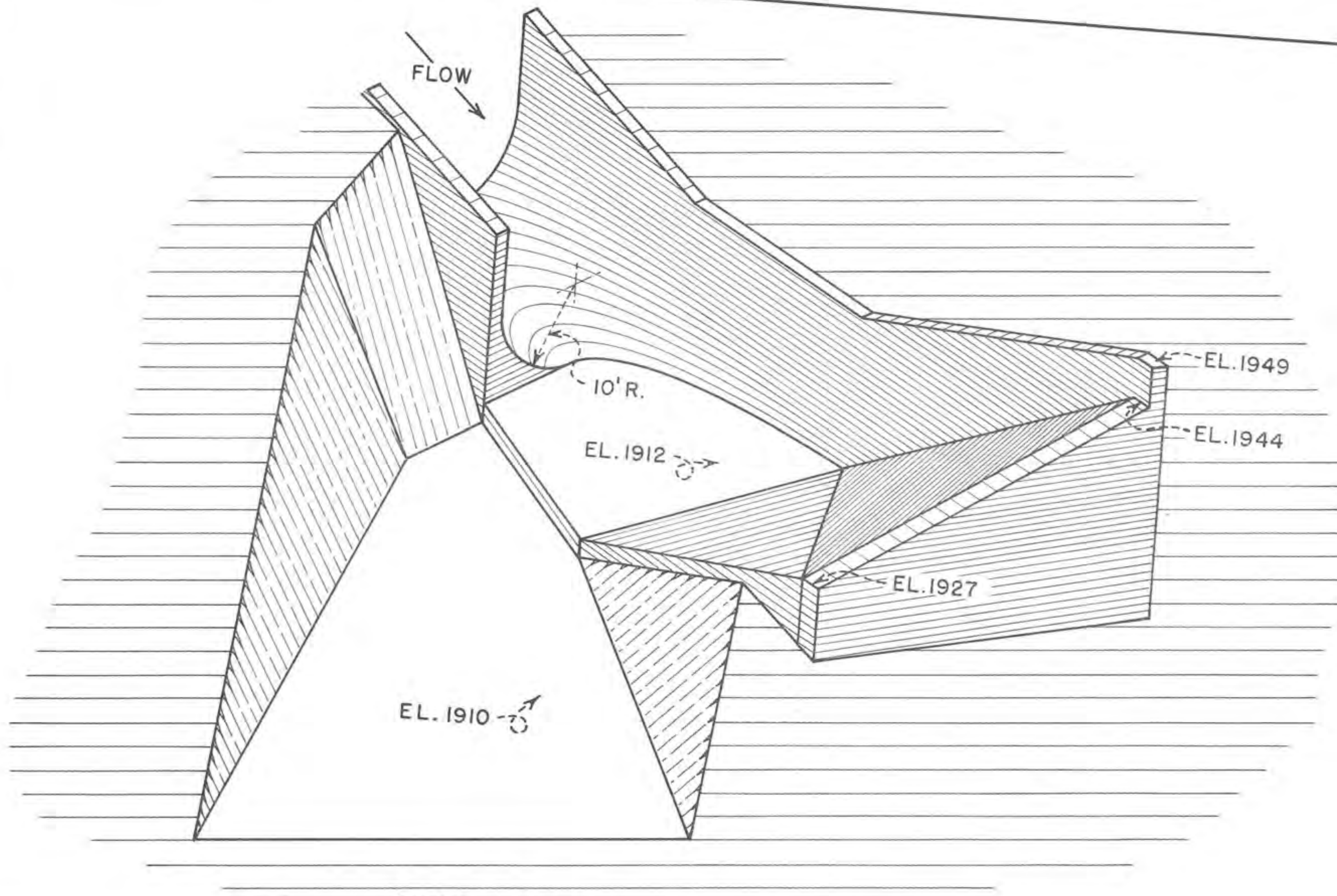


Bucket used at Tunnel 1 outlet. PX-D-17043



Bucket used at Tunnel 2 outlet. PX-D-17042

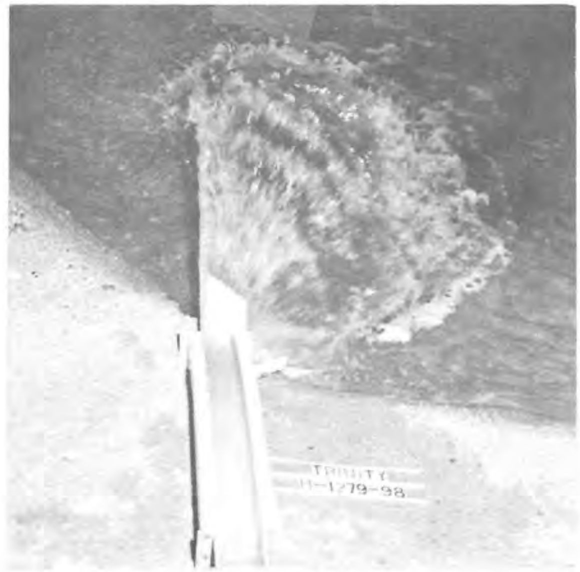
FONTANA DAM SPILLWAY FLIP BUCKETS



DISPERSION FLIP BUCKET

Figure 2

Figure 3

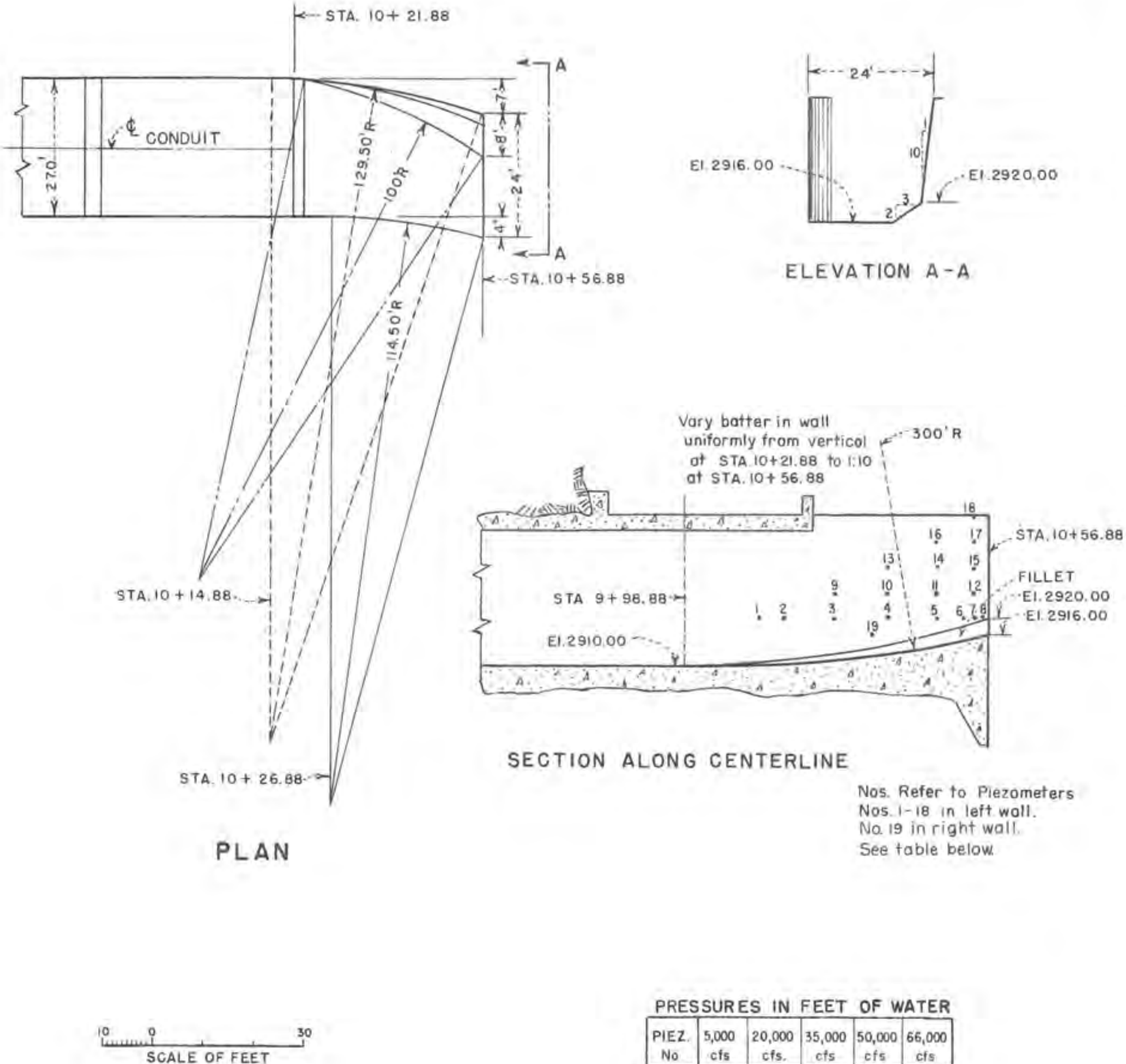


A. DISPERSION TYPE FLIP BUCKET P-208-D-17044

Q = 12,000 cfs Hydraulic jump in Basin P-459-D-17045

Q = 13,000 cfs, Basin acts as Flip Bucket P-459-D-17046

B. COMBINATION HYDRAULIC JUMP BASIN - FLIP BUCKET

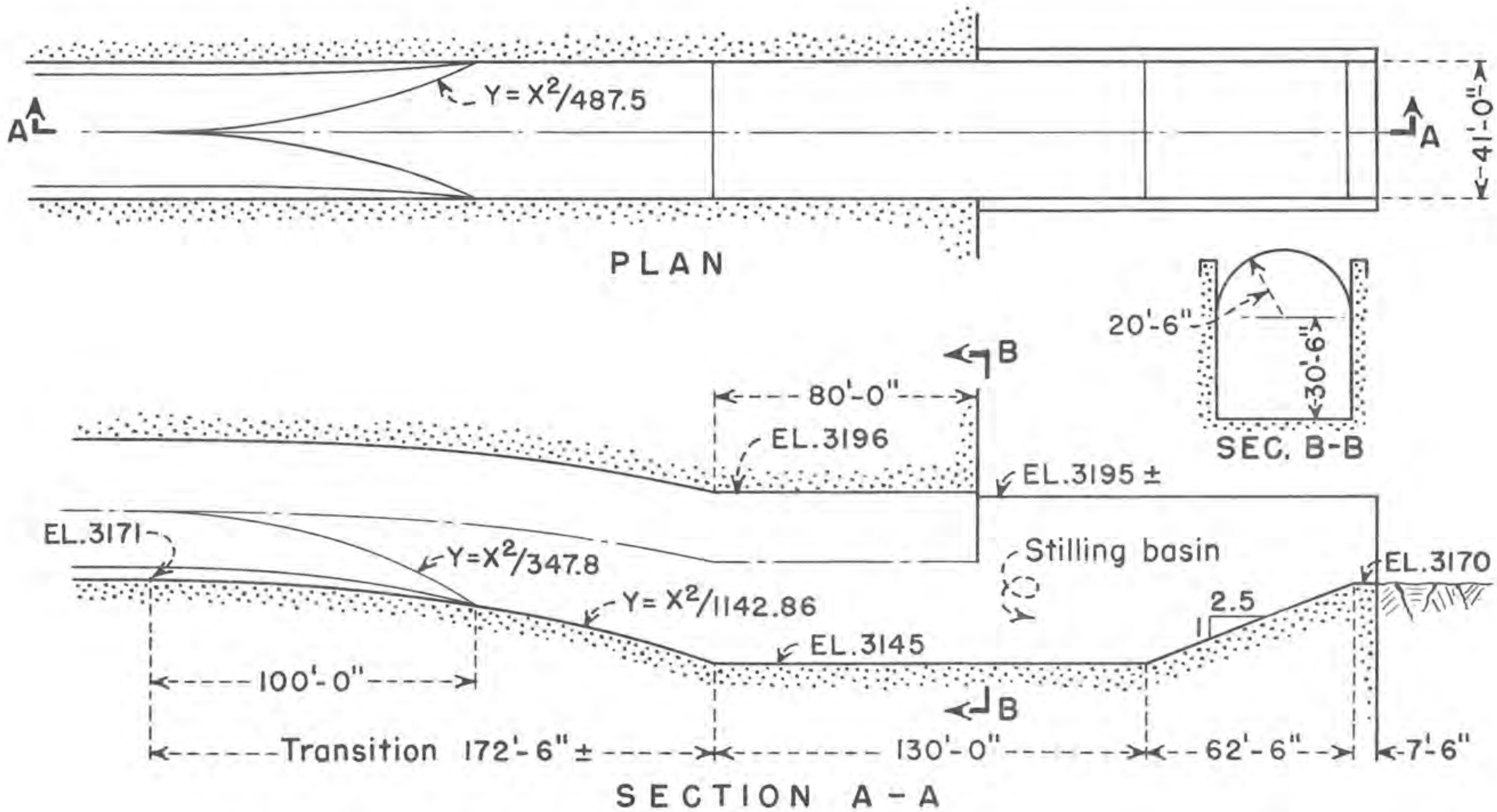


PRESSURES IN FEET OF WATER

PIEZ. No	5,000 cfs	20,000 cfs.	35,000 cfs	50,000 cfs	66,000 cfs
1	–	–	+9.0	+28.4	+50.2
2	–	+0.2	20.0	43.6	66.6
3	0	12.1	43.2	70.3	90.9
4	+2.3	23.3	50.6	70.7	89.0
5	6.4	36.5	59.2	72.7	84.0
6	6.1	30.8	45.4	53.6	62.0
7	4.4	23.8	35.0	41.2	46.8
8	2.1	13.9	19.4	22.6	26.3
9	-0.7	0	11.7	38.8	65.6
10	0	6.4	26.8	51.2	74.1
11	+0.9	20.5	42.4	58.0	70.2
12	2.7	17.7	32.6	41.0	46.9
13	–	1.0	4.3	21.1	47.5
14	–	-2.1	+5.2	21.1	37.1
15	–	+8.4	17.6	28.2	36.2
16	–	–	0.3	8.0	24.7
17	–	2.6	8.6	16.1	26.8
18	–	–	2.5	4.0	9.0
19	+3.6	+13.8	19.5	22.5	26.8

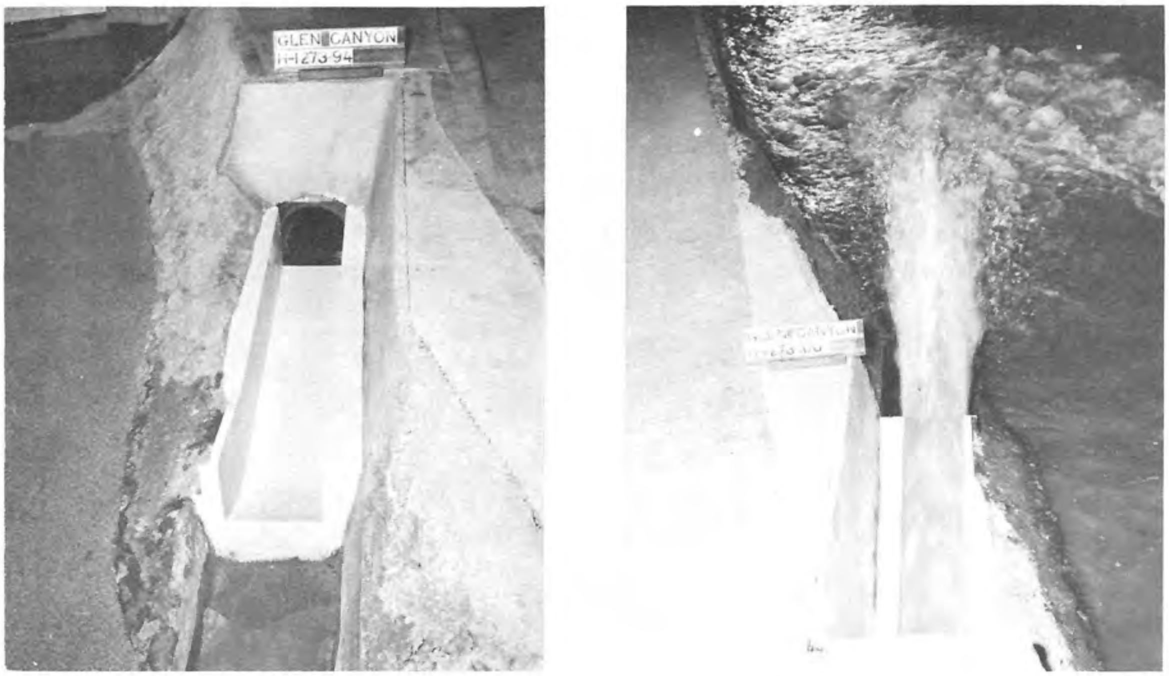
WU SHEH DAM
TUNNEL SPILLWAY
HYDRAULIC MODEL STUDIES
1:41.25 SCALE MODEL
RECOMMENDED BUCKET

568

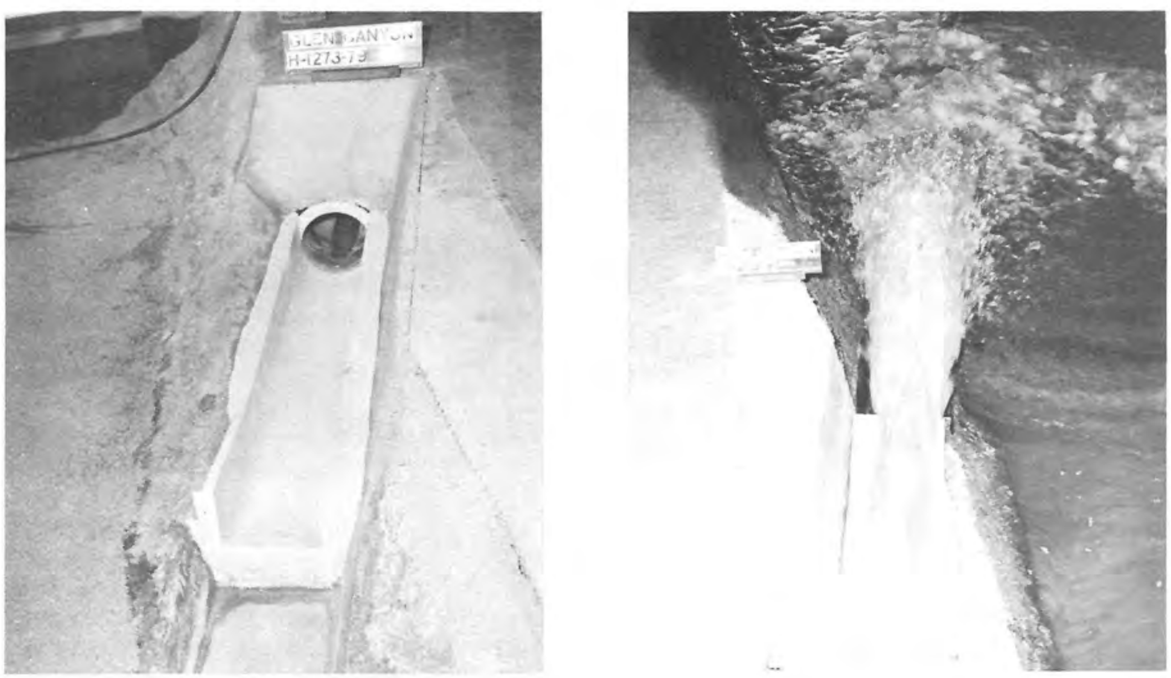


YELLOWTAIL DAM STILLING BASIN

Figure 5



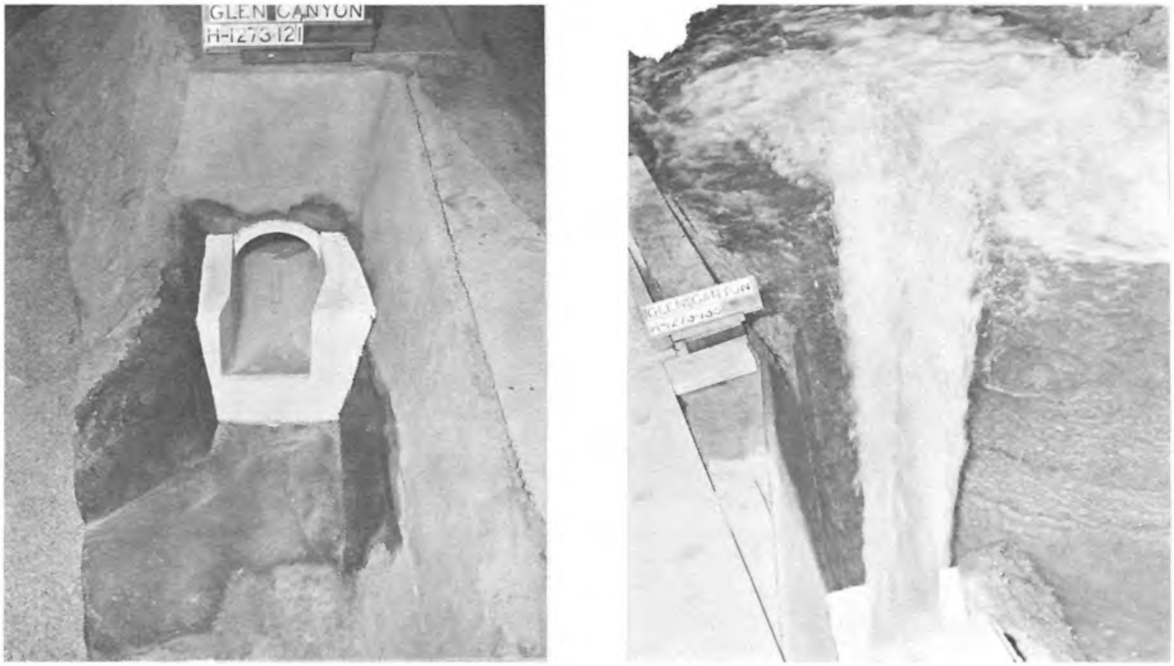
STANDARD FLAT BOTTOM FLIP BUCKET
Flow at Froude No. = 7.89 P-557-D-17047 & P-557-D-17048



TRANSITION FLIP BUCKET
Flow at Froude No. = 5.64 P-557-D-17049 & P-557-D-17050

GLEN CANYON DAM

FLIP BUCKET STUDIES



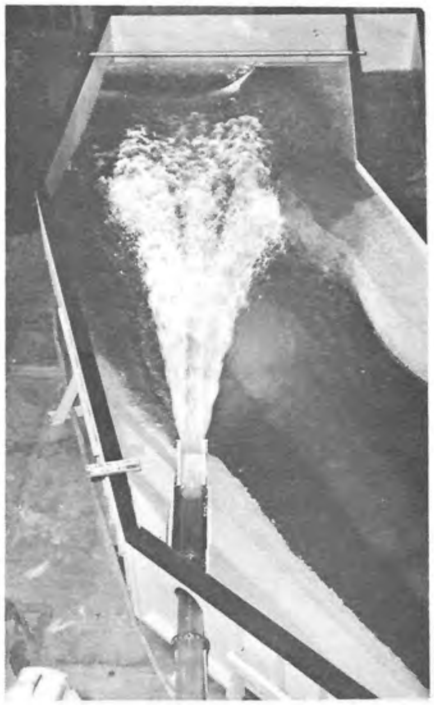
TRANSITION FLIP BUCKET WITH SIDE WALL DEFLECTOR
Froude No. = 5.64 P-557-D-17051 & P-557-D-17052

TYPICAL JET PROFILE

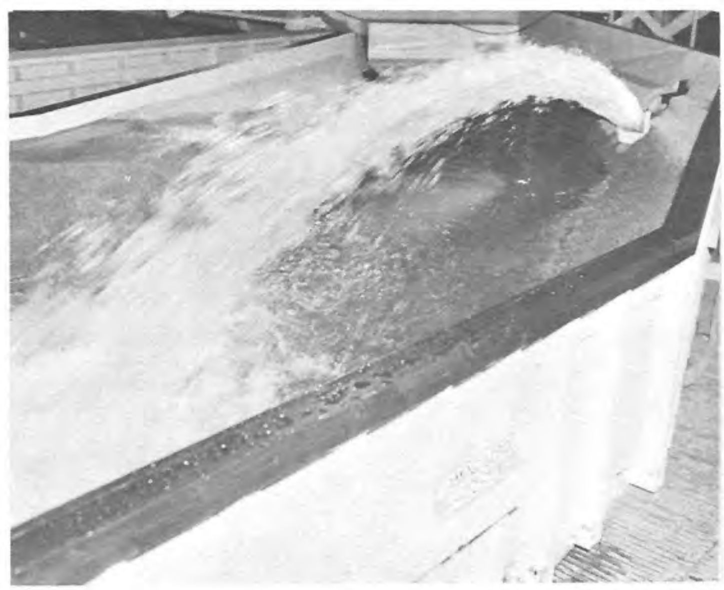
35° TRANSITION FLIP BUCKET P-557-D-17053

GLEN CANYON DAM

FLIP BUCKET STUDIES



Well dispersed jet at low flows
Froude Number = 10.3 P-591-D-17054 & P-591-D-17055

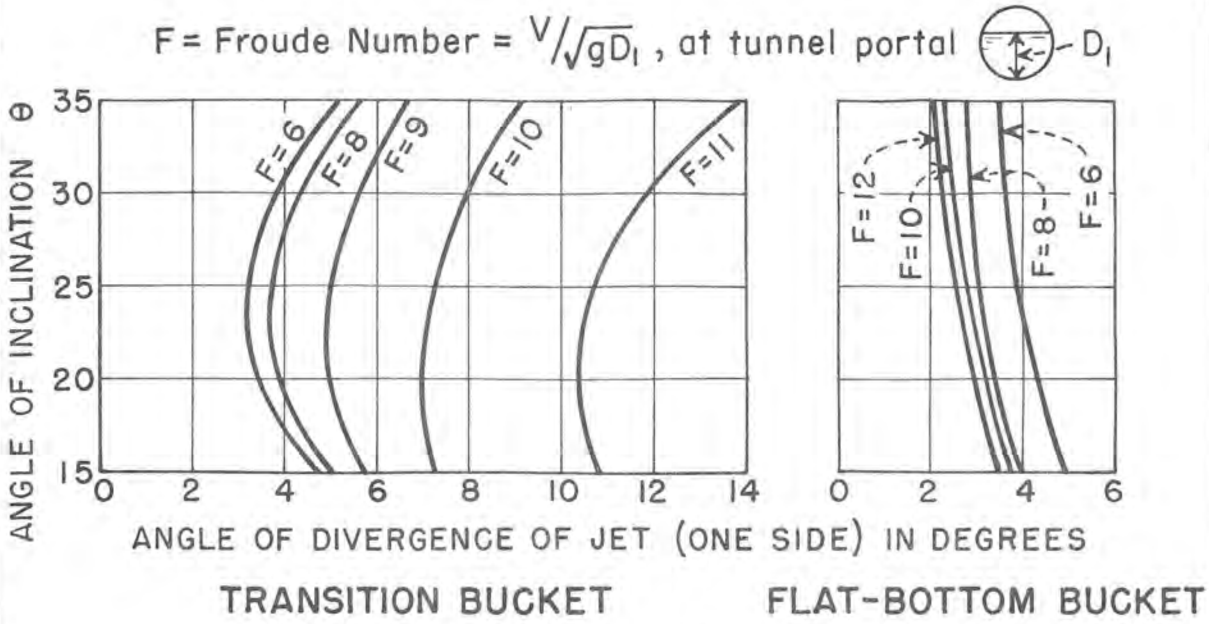


Maximum Discharge - F - 6.8
A more compact jet forms for larger flows.
P-591-D-17056 & P-591-D-17057

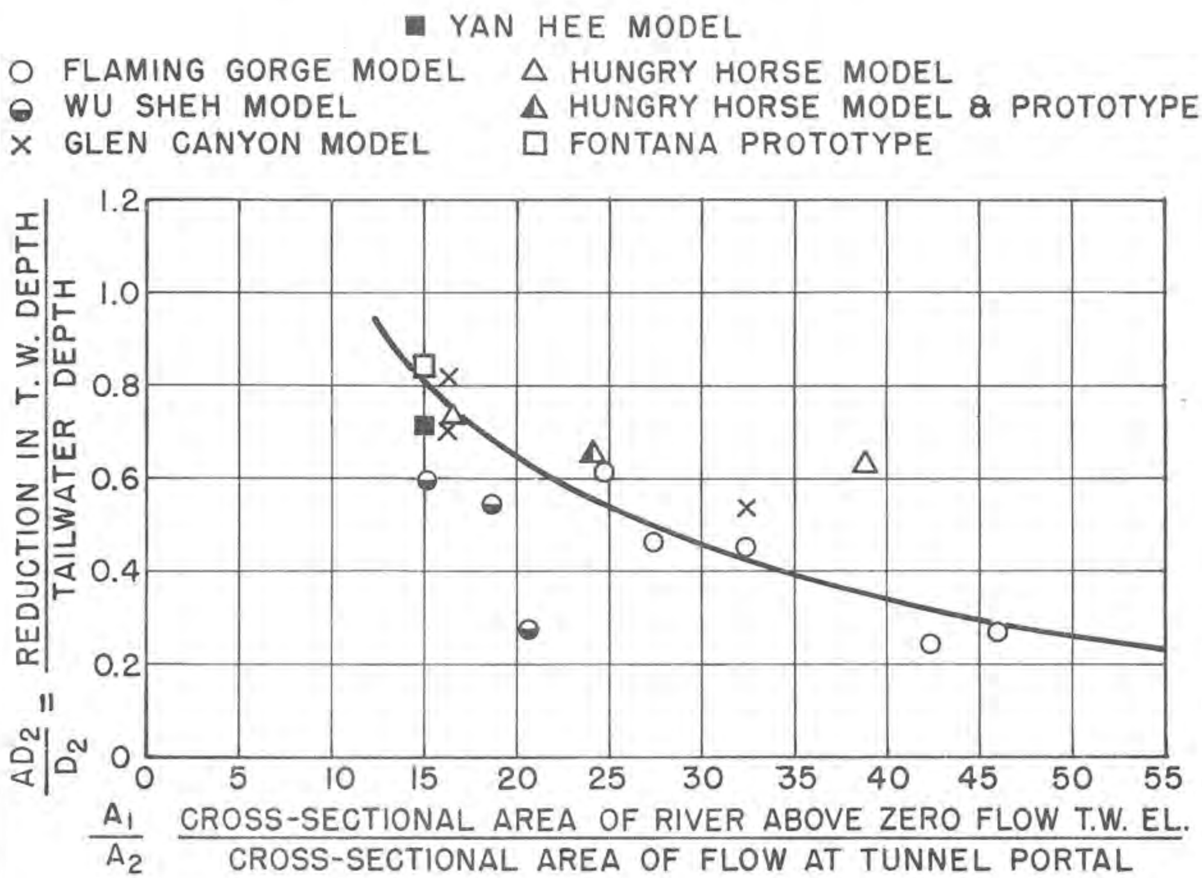
FLAMING GORGE DAM

FLIP BUCKET STUDIES

35° - Transition Bucket



A. SPREADING OF JET



B. TAILWATER DRAWDOWN

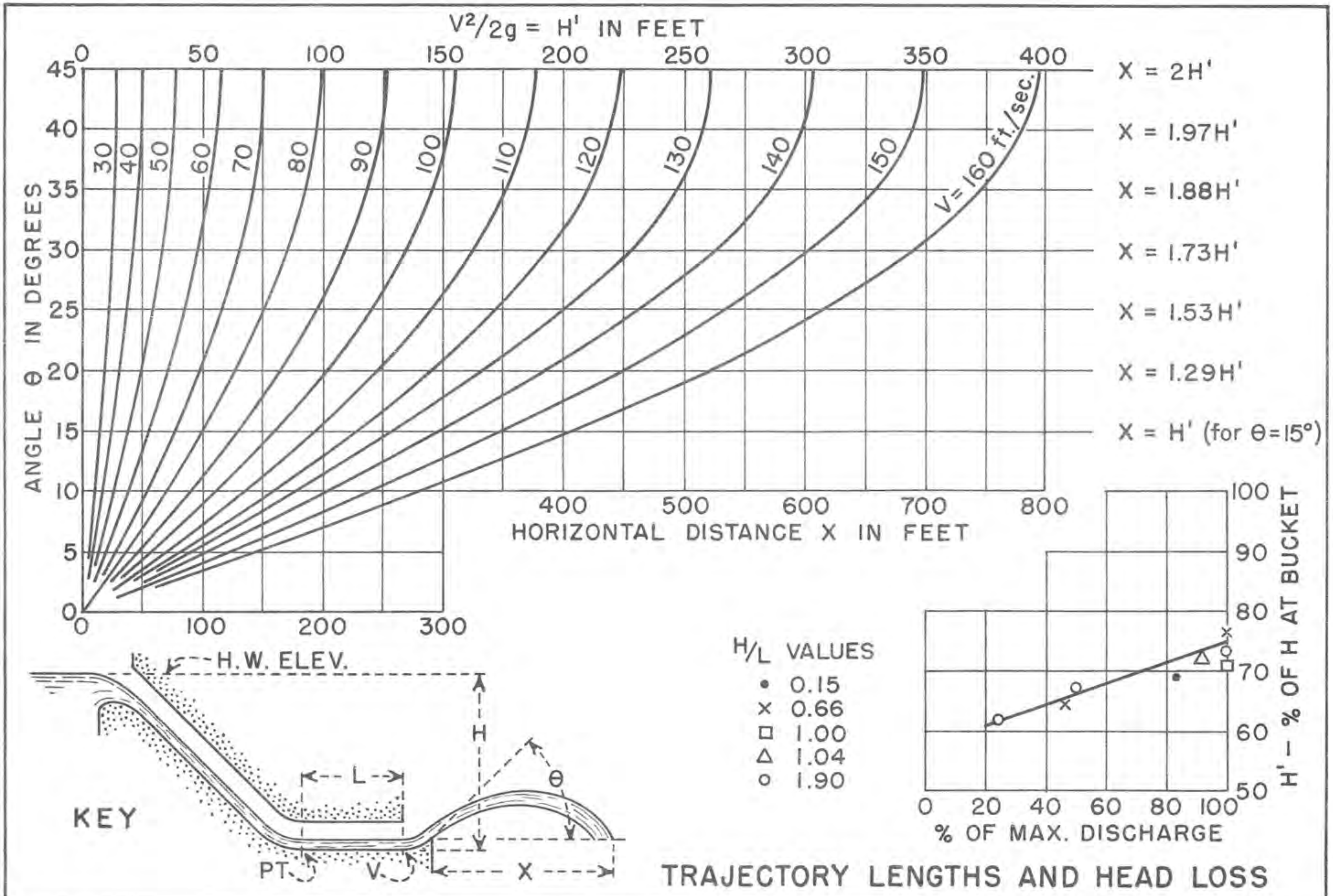
Figure 10

HH-5921 - Hungry Horse spillway tests. Spillway discharge 30,000 c.f.s. Side view of jet under cables. 5:30 p.m. 7-13-54

Hungry Horse spillway model discharge = 35,000 cfs
P-447-D-17058

Model-Prototype Comparison

Hungry Horse Spillway
Flip Buckets



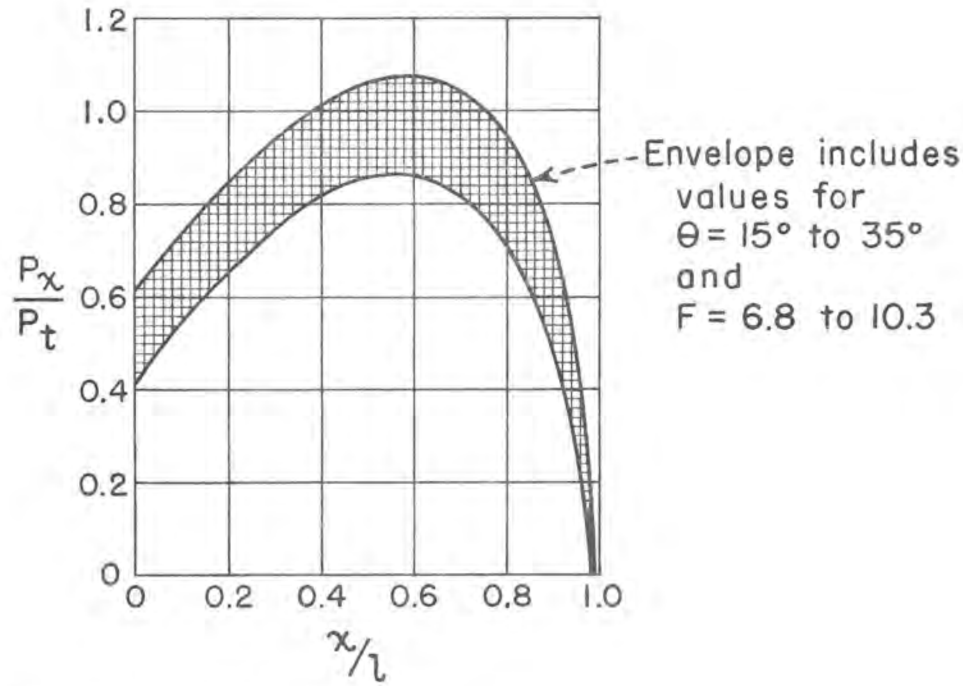
TRAJECTORY LENGTHS AND HEAD LOSS

Figure 11

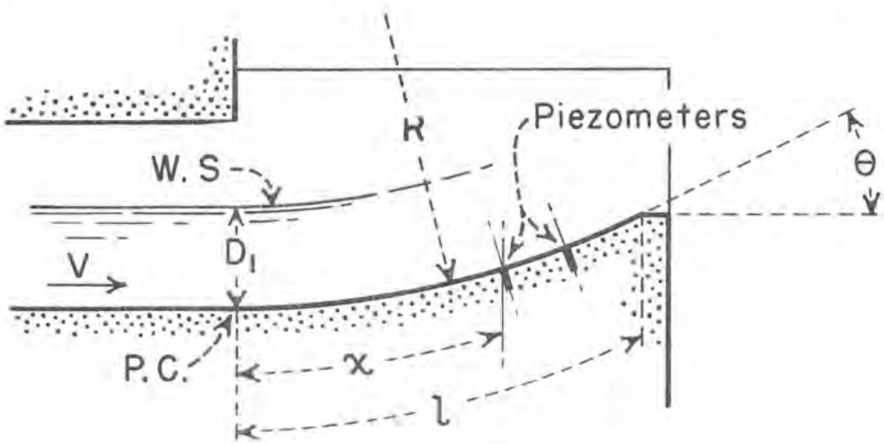
Both Prototype Tunnels discharging 10, 000 cfs each. P-232-D-17059

Both Model Tunnels discharging 12, 500 cfs each. P-232-D-17060

FONTANA DAM SPILLWAY
FLIP BUCKETS
Model-Prototype Comparison

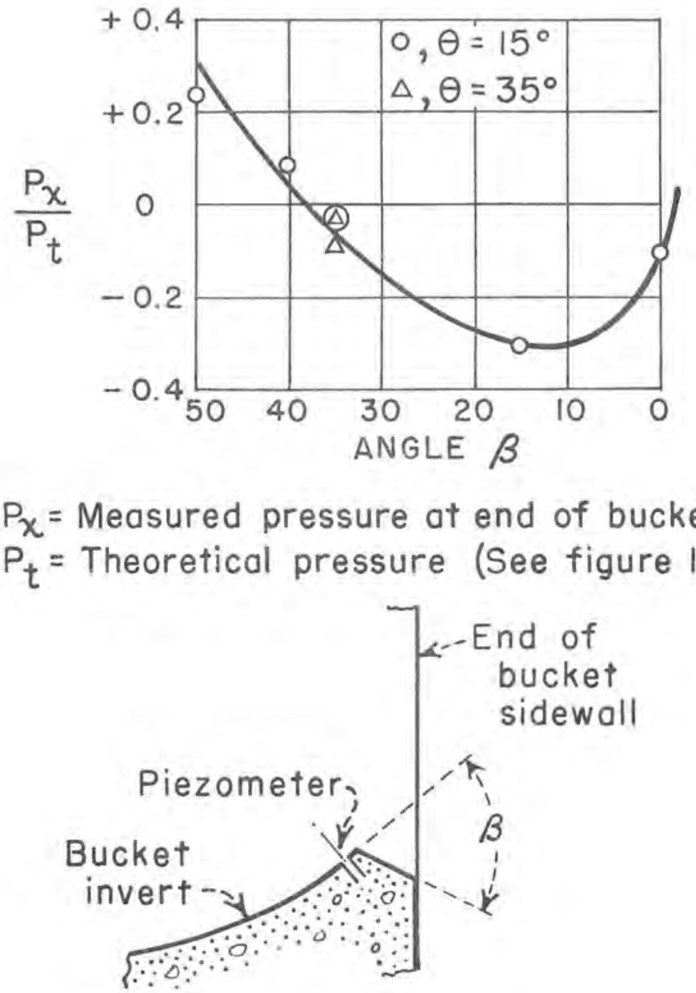


P_x = Measured pressure
P_t = Theoretical pressure; $(1.94\omega^2 R + 62.5) D_1$;
where $\omega = V/R$
x = Developed distance from P.C. to piezometer
l = Developed distance from P.C. to end of bucket
F = Froude number, computed from V and D_1 at P.C.



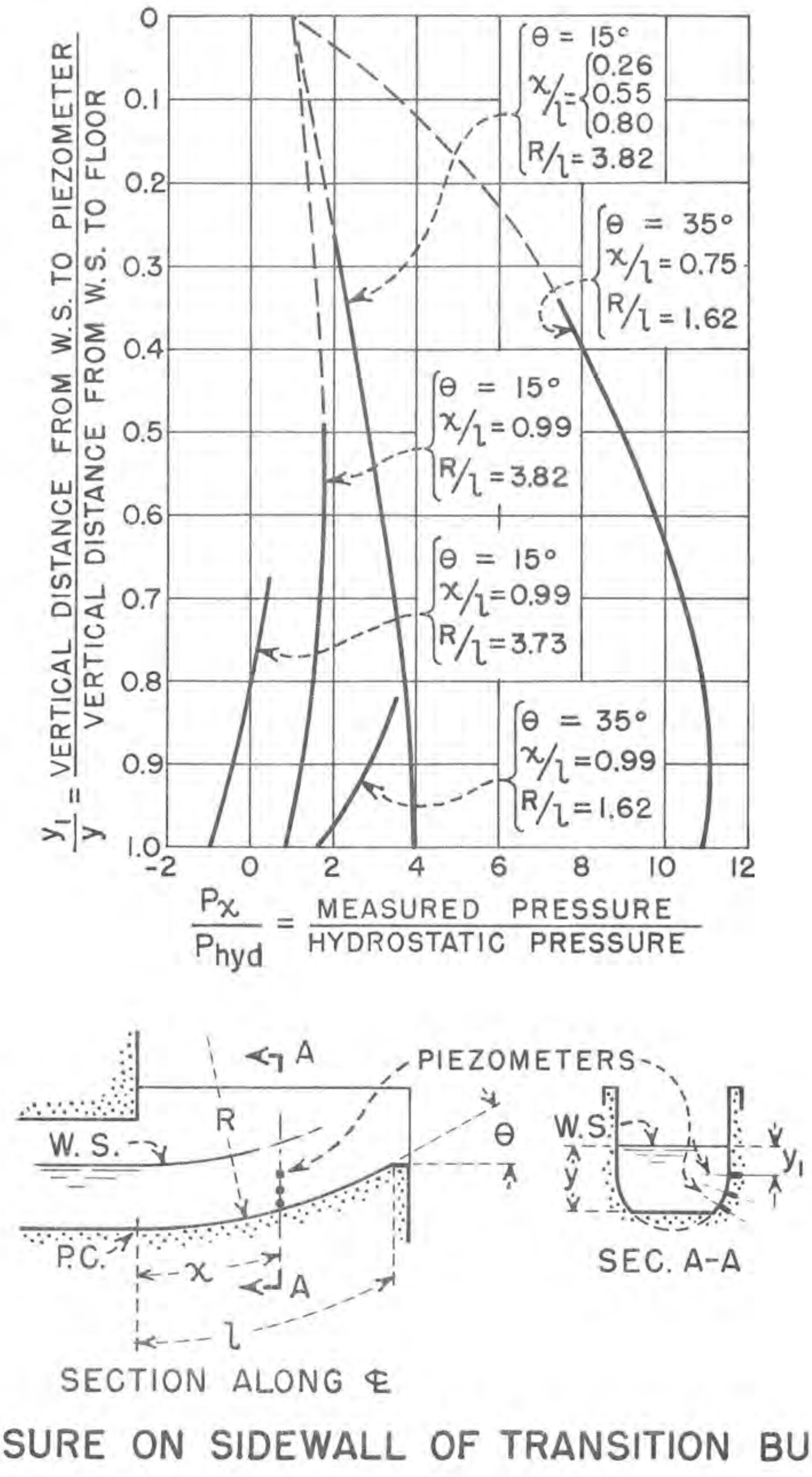
SECTION ALONG ℄

PRESSURES ON TRANSITION BUCKET FLOOR



P_x = Measured pressure at end of bucket
P_t = Theoretical pressure (See figure 13)

PRESSURES AT END OF BUCKET



PRESSURE ON SIDEWALL OF TRANSITION BUCKET