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TO WHOM IT MAY CONCERN:

The thesis "An Experimental Study of the Characteristics of Slotted Bucket Energy Dissipators" is the result of my own work in substance, form and expression.

I typed the above thesis, but did not participate in the collection or organization of the material or in the writing of the thesis.

Dorothea R. Clark

This Thesis for the M.S. degree by

Glenn Lester Beichley

has been approved for the

Department of

Civil Engineering

by

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Date May 18, 1954

AN EXPERIMENTAL STUDY OF THE CHARACTERISTICS
OF SLOTTED BUCKET ENERGY DISSIPATORS

by

Glenn Lester Beichley

B.S., Kansas State Agricultural College, 1939

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Beichley, Glenn Lester (M.S., Civil Engineering)
An Experimental Study of the Characteristics of Slotted Bucket Energy Dissipators
Thesis directed by Associate Professor Warren DeLapp.

This investigation began with the testing of the Angostura type slotted bucket and four modifications to develop the most suitable characteristics for the slots and teeth. Three other model buckets were also tested for comparison with the slotted buckets, including: first, the Angostura type without teeth and slots; second, a solid bucket; and third, a bucket used for rehabilitation of Black Canyon Dam. Bucket Modification II produced the best hydraulic performance, but from a design standpoint, the high teeth required for its use are probably not practical to construct for a large dam. For practical use the Angostura type slotted bucket performed as well or better than any of the other buckets tested; therefore, its characteristics were adopted for recommendation.

The investigation was also concerned with determining the minimum bucket radius required for use of the Angostura type slotted bucket at any dam, and the minimum and maximum allowable tail water depths that should not be exceeded. Experimental data were obtained from 6-, 9-, 12-, and 18-inch radius buckets used in combination with a 5-foot-high model spillway. With each of these buckets the minimum and maximum allowable tail water depths were determined for a range of discharges, and the capacity of each bucket was estimated. For convenient use of these data in designing a slotted bucket these tail water depths and the bucket radii were expressed as dimensionless ratios while the discharge entering the bucket was represented by the Froude number. Design curves were developed so that the Froude number can be used for determining the minimum bucket radius and the minimum and maximum allowable tail water depths required for proper performance of the Angostura type slotted bucket at any dam. Finally, application of the experimental data was illustrated and the results checked with an earlier, independent, partial investigation on this subject.

This abstract of about 250 words is approved as to form and content. I recommend its publication.

Signed Warren W. DeLapp
Instructor in charge of dissertation

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INTRODUCTION

Flow over a spillway usually requires the use of some sort of energy dissipating device below the spillway to control erosion in the channel near the spillway. A stilling basin with a horizontal apron and high training walls along each side in which the hydraulic jump is made to occur is the device often used. However, wherever feasible a deeply submerged upturned bucket, usually called a roller bucket, is a very satisfactory energy dissipating device. The use of a bucket eliminates the need for a long concrete apron and high training walls; and, therefore, is an economical design. Two types of roller buckets are shown in Figure 1.

The dissipation of energy by use of the bucket is, in general, accomplished in the same manner as in the stilling basin. The high velocity flow that enters the bucket contains kinetic energy most of which must be destroyed or transformed to a less destructive type. Some of the energy is transformed into potential energy while some is destroyed by creating turbulence which dissipates the energy in the form of heat.

The bucket directs the high velocity flow upward to the water surface, part of which rolls back into the bucket and part of which plunges into the tailwater downsteam. In either case air is entrained in the flow and numerous eddies, both large and small, are set in motion. It is the numerous small eddies that are of most value in dissipating the energy. Large eddies while dissipating a small amount of energy are most valuable in creating small eddies. However, large eddies may be destructive to channel banks or channel bed; and, therefore, the turbulence must be controlled by use of the energy dissipating device. The following poem, author unknown, describes the dissipating action quite well:

Big whirls have little whirls
that feed on their velocity
Little whirls have smaller whirls
and so on to viscosity.

There are two general types of roller buckets: the solid bucket developed for Grand Coulee Dam, Figure 1A, and the slotted bucket developed for Angostura Dam, Figure 1B. Both types, with some modification in the solid bucket, are shown operating in Figure 2. The solid bucket used in Figure 2 does not have the 1 to 1 tangent at the end of the bucket arc as in the Grand Coulee bucket. Instead the solid bucket in Figure 2 is identical to the slotted bucket except for the absence of the slots. Both are operating with the same discharge and tail water depth.

The slotted bucket as developed for Angostura Dam differs from the solid type only in the slots and short apron downstream. The hydraulic action, however, is considerably different. In the solid bucket the high velocity flow from the bucket moving through the still tail water creates a high boil on the water surface and a violent ground roller that deposits loose material from downstream at the bucket lip. The water surface downstream from the boil is quite free of turbulence. Deposition at the bucket lip instead of erosion, is good except that when all spillway gates are not operating, side eddies carry loose material into the bucket. The loose material is then likely to cause considerable damage to the concrete as it is moved about both longitudinally and laterally in the bucket. The material may then remain in the bucket until the entire spillway is operated at a large discharge.

In the operation of the slotted bucket both the high boil and the violent ground roller are absent. Some of the flow is through the slots and some is over the upturned portion of the bucket arc. As a result the flow to the surface is less concentrated than in the case of the solid bucket and the boil is reduced. The apron downstream from the slots serves to spread the jet laterally as well as to direct the flow away from the channel bottom. Thus the flow is dispersed and leaves the bucket at a much flatter angle than in the solid bucket. As a result the violent ground roller is absent but the water surface downstream is more turbulent.

If tail water depth over the invert of the slotted bucket becomes too low, the flow sweeps out; if the tail water depth becomes too high, the flow dives from the apron lip to scour the channel bed, as shown in Figure 3. While in the solid bucket diving is impossible except in rare cases and sweepout requires the tail water depth to be less than for the slotted bucket, the tail water depth range for which the solid bucket will operate satisfactorily is greater than for the slotted bucket. In general, however, the slotted bucket is an improvement over the solid type and will operate well over a wide range of tail water depths.

HISTORY OF THE SLOTTED BUCKET DEVELOPMENT

The slotted bucket was first developed in 1945 at the Bureau of Reclamation laboratory, Denver, Colorado, for the spillway at Angostura Dam. It is reported in United States Bureau of Reclamation Hydraulic Laboratory Report No. 192(1)* and is summarized in the following paragraphs. Dimensions of the bucket for use at other installations have been standardized in terms of the bucket radius as shown in Figure 1B.

For the spillway at Angostura Dam, Figure 4, a model investigation was made to develop a suitable roller bucket type energy dissipator. A 1:42 scale sectional model was used, Figure 5, as well as a complete 1:72 scale model of the spillway structure.

The first stage in the development was to determine the approximate radius of bucket required to handle the maximum design flow and to determine the approximate elevation of the bucket invert for the existing tail water conditions. Solid type buckets shown in Figure 6 were used in the model to determine these approximate values since the slotted bucket had not yet been anticipated. Some of the buckets operating with the maximum design flow of 277,000 second feet are shown in Figures 7 and 8. The 100-foot and 63-foot radius buckets were found to be unnecessarily large. The 42-foot radius bucket was the smallest usuable bucket to maintain satisfactory performance. This bucket in operation discharging the maximum design flow of 277,000 second feet is shown in Figures 8A and 8B with invert at elevation 3046 and 3070 respectively. Tail water depth was too shallow for good performance when bucket invert was at elevation 3070. The

*Small numerals in parenthesis refer to reference number in Bibliography at end of thesis.

performance was better with the invert at elevation 3046, but in any case a ground roller occurred which deposited bed material from downstream along the bucket lip.

The second stage in the development of the bucket was to find a way to prevent the ground roller from piling loose rock along the downstream lip of the bucket. The first idea was to install tubes through the bucket lip through which jets of water would flow to sweep loose material away from the lip. Results were satisfactory at low discharges, but for the higher flows the ground roller piled the loose material deep over the tube exits virtually closing them. Larger tubes might have proved more satisfactory.

The second idea for preventing the piling of material along the bucket lip was to use slots instead of tubes. The slots would probably not only provide means of keeping the bucket lip free of loose material, but would also provide exits for material that became trapped in the bucket during periods of unsymmetrical operation of the spillway. The slots would also not be so likely to clog as would the tubes, and the former would probably be more economical to construct.

In order that the effectiveness of the bucket in dissipating the energy of the spillway flow would not be lost, the slots were made no larger than was believed necessary to keep the loose material from depositing at the bucket lip. The first slots tested were 1 foot 9 inches wide, spaced at three times that distance apart. The slots were sloped upward on an 8° angle so that the flow through them would not scour the channel bottom. They were also made tangent to the bucket radius. The spaces between the slots became known as teeth and were 5 feet 3 inches wide. Three tooth designs were tested as shown in Figure 9.

Tests using Tooth Design I were encouraging. The energy dissipating action of the bucket and the prevention of material from piling along the bucket lip were both satisfactory. However, small eddies immediately downstream from the teeth lifted loose gravel to produce abrasive action on the downstream face of the teeth. Therefore, a sloping apron was installed downstream from the teeth to spread the jets from the slots and keep loose material away from the teeth. The apron was sloped upward slightly steeper than the slope of the slots, to provide better spreading of the jets. The apron was found to perform as intended, however, the best degree of slope for the apron and the shortest possible apron length were not determined until after the tooth design and the tooth spacing were determined.

Pressures were observed on Tooth Design I at the piezometer locations shown in Figure 9. In general, the pressures proved satisfactory except for subatmospheric pressure recorded at Piezometers 1 and 3 shown in Figure 9.

Tooth Design II in Figure 9, which conformed to the radius of the bucket, was installed. This proved more satisfactory than Tooth Design I because the energy in the spillway flow was dissipated more readily and a smoother water surface occurred downstream. The pressures on this tooth were subatmospheric at Piezometers 1, 2, 3, 4, 6, 7, and 8, the majority of which were located on the downstream face as shown in Figure 9. The rounding of the edges of the teeth was determined by testing model radii ranging from 0.1 inch to 0.3 inch. The larger radius (12.6 inches prototype) was found to be the most desirable because the pressures at Piezometers 7 and 8 were not as much below atmospheric.

A third tooth design shown in Figure 9 was tested. It was similar to the second design except that the downstream portion of the tooth was shaped to improve pressure conditions on the downstream face. The sides of the teeth were tapered 2° in plan to raise pressures on the sides of the teeth, and the radius of the rounded edges was increased to 15 inches prototype. The subatmospheric pressures were found on the downstream face of the teeth at Piezometers 3, 4, and 5 shown in Figure 9. However, the subatmospheric pressures were well above the critical cavitation range. Also dissipation of the energy was excellent; therefore, the tooth design was considered quite satisfactory and recommended for prototype construction.

The next step was to determine the most desirable spacing of these teeth. Some performance tests for various tooth spacings are shown in Figure 10. Tests showed that by spacing the teeth close together the pressures on the sides were increased, but if the teeth were too close, rocks and debris would likely be caught between them. If the teeth were spaced too far apart, pressures on the sides dropped far below atmospheric and dissipation was impaired. An intermediate value of 2 feet proved to be a satisfactory space width for 5-foot 3-inch-wide teeth which corresponds to a ratio of 2.62 to 1 spacing. With this spacing the pressures were reasonably high and dissipation of energy, which was principally a spreading action rather than a roller action, was satisfactory. In no case did loose bed material come in contact with the teeth. The 2-foot spacing was therefore recommended for the prototype.

The slope and length of the apron downstream from the teeth was the final important requirement to be determined for satisfactory operation of the bucket. The apron served to spread the jets from the slots, and the stability of the bucket action was dependent upon it. A 16° upward sloping apron was found to be most satisfactory. Using a 12° slope, the flow became unstable intermittently diving from the end of the apron to scour the river bed. Using a 20° slope the spreading action of the flow was less effective.

Two apron lengths, one 10 feet and one 20 feet, were tested to determine the minimum length required for satisfactory operation. The longer of the two, which was approximately the same as the length of the teeth, was found necessary to spread the jets and produce a uniform flow leaving the apron. The 20-foot apron on a 16° slope was therefore recommended for the prototype.

This final bucket design operated well over the entire range of discharge and tail water conditions. It was only necessary to install the design, as developed thus far, in the 1:72 scale model to study side effects which were absent in the 1:42 sectional model.

In the 1:72 model minor changes were made before installation of the final recommended design. The bucket radius was changed from 42 feet to an even 40 feet, and the bucket invert was lowered from elevation 3046 to elevation 3040. Figure 11 shows the 1:72 model of the final recommended design in operation with 277,000 second feet and also the erosion after 20 minutes of operation and after 1-1/2 hours of operation. The design performed better than any of the solid buckets or any of the other slotted bucket designs tested. The water surface was smoother and the erosion of the river bed was a minimum.

Reviewing the development of the slotted bucket three factors were involved: (1) the radius of the bucket and elevation of the invert with respect to tail water for the given flow conditions; (2) the shaping and spacing of the teeth; and (3) the pitch and length of apron downstream from the teeth. All of these factors are important in the design of a bucket that will produce the desired energy dissipation, a smooth water surface, and the minimum amount of river channel erosion. Dimensions of the bucket teeth, slots, and apron were expressed in terms of the bucket radius for standard use at other installations as shown in Figure 1B.

THE CURRENT INVESTIGATION

Purpose and Scope

The current investigation had two purposes: First, Part I, to compare the hydraulic performance of the slotted bucket energy dissipator as developed for Angostura Dam with the performance of buckets incorporating additional modifications, in an attempt to develop the very best type of bucket energy dissipator. Four Angostura slotted bucket modifications were tested plus the Angostura type bucket without teeth and slots, a solid bucket, and a bucket to be used for the rehabilitation of Black Canyon Dam.

A second purpose of the investigation, Part II, was to determine the size of the slotted bucket and the tail water depth at which the bucket performed best for any given combination of ~~of~~ discharge and spillway height. Several sizes of buckets were tested each with a range of discharges and tail water depths.

Test Equipment

The United States Bureau of Reclamation Hydraulic Laboratory in Denver, Colorado, Figure 12, was used in conducting the investigations. A test flume, Figure 13, was used for installing a sectional spillway model, Figure 14.

The flume, Figure 13, is a semi-permanent structure in the laboratory, constructed of wood, and lined with sheet metal to provide watertightness. The flume is approximately 24 inches wide by 43 feet 6 inches long. The upstream end is 14 feet high to accommodate high model reservoir water surfaces while the downstream end is 6 feet 3 inches deep to accommodate deep tail water depths. The upstream end is baffled to provide smooth reservoir water surfaces. The downstream end is equipped with a hinged gate for controlling the elevation of the tail water. The tail water control gate is operated by a 1/20-horsepower motor through a set of speed-reducing gears so that the tail water elevation raises or lowers slowly. The downstream portion of the flume is provided with a 4- by 13-foot 8-inch glass window on one side for observing and photographing flow characteristics in the tail water area.

The sectional spillway model, Figure 14, in the flume was constructed in three sections: the crest section, the spillway face, and the energy dissipator. The spillway face was constructed permanently into the flume while the crest section and energy dissipator were both removable, thus it was a small task to vary the size and height of the crest sections and the size and type of energy dissipator. All three portions of the spillway were constructed with sheet metal surfaces over which the flow passed. The crest was an ogee design placed 5 feet above the invert of the bucket for this investigation. The spillway face was on a slope of 10 vertical to 7 horizontal and the inverts of all of the energy dissipators tested were approximately 6 inches above the floor of the flume. A movable river bed material was used to indicate erosion characteristics downstream from the bucket. The material chosen for use was pea gravel with sizes shown by the following sample sieve analysis:

Retained on 3/4-inch screen	6 percent
Retained on 3/8-inch screen	66 percent
Retained on No. 4 screen	25 percent
Retained on pan	3 percent

Water was supplied to the test flume from the reservoir in the laboratory shown in Figure 12. One of the 12-inch pumps at either end of the laboratory could be used to pump water from the reservoir through the main supply line to the flume. Two portable vertical pumps were used to supply additional water to the flume when needed. The water flowed through the flume and discharged back into the reservoir.

The quantity of flow from the 12-inch pump was measured by use of a Venturi meter permanently installed in the supply line previously calibrated in place. The quantity of flow from the vertical pumps was measured by two portable 8-inch orifice Venturi meters previously calibrated in the laboratory. The elevation of the reservoir water surface was measured with a hook gage in a transparent plastic well. The tail water elevation was measured in a similar way.

PART I

Investigation of Solid and Slotted Buckets

Angostura Slotted Bucket

The slotted bucket, as developed for Angostura Dam, was tested first for comparison of hydraulic performance with other types of buckets and with other modifications of the Angostura slotted bucket. The proposed bucket designs tested are shown in Figures 15 and 16.

For comparison purposes it was more convenient that all model buckets tested be of the same radius and that the spillway height be held constant. Five feet was chosen as the height of the model spillway from bucket invert to crest elevation, and 12 inches was chosen as the radius of the model buckets to be tested and compared.

In establishing standard operating conditions for use in testing all of the bucket modification, it was observed that the 12-inch Angostura bucket was capable of dissipating the energy of about 6 second feet and that energy dissipation for 6 second feet was best with a tail water depth of approximately 2.3 feet above the bucket invert, Figure 2B. If the tail water depth was too shallow, the flow would sweep out of the bucket; and if the tail water depth was too great, the flow would dive from the apron lip as shown in Figure 3. In the latter case a deep hole was scoured in the channel bed near the bucket. Therefore, an intermediate tail water depth of 2.3 feet was used with a discharge of 6 second feet for testing all buckets to be compared. The river bed was also standardized for the comparative tests. A horizontal movable pea gravel bed at slightly below lip level was used as this remained fairly stable for the above operating conditions.

In testing the 12-inch Angostura bucket it was noted that much of the dissipation was a spreading action rather than a roller action which confirms the observations made in the earlier model development of the Angostura bucket. The flow passed through and over the teeth to emerge at the water surface some 3 or 4 feet downstream from the bucket, Figure 2B. A boil occurred at this point which produced waves on the water surface downstream. The boil and waves, at some installations, may cause bank erosion and under some circumstances be objectionable to powerhouse operation. Therefore, tests were conducted with modified designs of the Angostura type slotted bucket in an attempt to reduce the surface roughness. However, the bucket appeared to be very effective in dissipating the energy of the flow and in protecting the river bed from erosion.

Slotted Bucket Modification I

In the initial development of the Angostura bucket it was found undesirable to increase or decrease the slope of the apron or to change the spacing of the teeth; therefore, modifications of this kind were not considered here. Instead, for the first modification, the teeth were extended in height to a 60° angle as shown in Figures 15 and 16.

The performance of this bucket, Figure 17A, closely resembled the performance of the Angostura bucket. In this case, the boil occurred about 6 inches farther upstream and was somewhat higher than for the Angostura bucket. The roughness of the water surface was no smoother than before. The higher teeth kept the flow from sweeping out of the bucket for a slightly lower tail water elevation than before, but the difference was too small to be considered an advantage.

Slotted Bucket Modification II

The first modified design indicated that if the teeth were extended even higher, perhaps the boil would be moved upstream over the bucket. Thus far the water surface over the bucket was relatively less than the tail water elevation so it was desirable to move the boil upstream if possible. Therefore, the teeth were extended to an angle of 90° as shown in Figures 15 and 16. Teeth this high are probably impractical for prototype construction on large buckets; but, nevertheless it was thought desirable to model test this design for possible use on small structures.

The performance of this modified bucket was excellent, as shown in Figure 17B for 6 second feet. The teeth turned a large portion of the flow directly upward to the water surface where it rolled back into the bucket. The tail water depth directly over the bucket invert was about the same as the depth downstream. A slight boil could be detected over the teeth, but it was not nearly as great as for the two previous slotted buckets tested. The flow passing through the teeth also provided fairly uniform distribution of velocity from the channel bed to the water surface in the channel downstream. The water surface was quite smooth and the channel bed was not disturbed.

The bucket also performed well for high and low tail water elevations as shown in Figure 18. The tail water could be raised to a higher elevation than for the two previous buckets before the flow pattern changed to scour the channel bed; and it could be lowered to a lower elevation before the flow would sweep from bucket. Thus, the range of tail water depths for which the bucket operated satisfactorily was increased.

The performance of this bucket was very good in every respect; however, cavitation was possible on the top and end surfaces of the teeth. Subatmospheric pressures on the sides of the teeth were not likely because the slots between them tapered the same as for the Angostura teeth. The possibility of cavitation pressure or the possibility of eliminating such pressures were not investigated because the teeth were considered too high for practical use on large structures. Therefore, this slotted bucket modification is merely recorded and suggested for possible use with small buckets.

Slotted Bucket Modification III

In the third modification of the slotted bucket a tooth radius half that of the bucket radius was used as shown in Figures 15 and 16. The half radius was used to curve the teeth to a 90° angle from the bucket invert the same as in Modification II without extending the teeth so high as was necessary in that case. It was anticipated that the 90° curvature of the teeth would give similar satisfactory results as obtained with Modification II.

The performance of this modified bucket, Figure 17C, was not as satisfactory as was anticipated. Teeth were not effective in lifting flow to the surface over the bucket, instead the flow passed over and through the teeth to form a high boil downstream in a manner similar to that occurring in the first modified bucket. In addition, observation of the flow currents over the top ends of the teeth, Figure 17C, showed cavitation pressures to be a likely possibility. Pressures were not investigated, since the performance of the bucket was not as good as for the Angostura slotted bucket.

Slotted Bucket Modification IV

Slotted bucket Modification IV utilized the same tooth as in Modification III, but the teeth were placed on the apron at the downstream end of the bucket, as shown in Figures 15 and 16. It was anticipated that the teeth, at this farther point downstream and at this slightly higher elevation, would turn a portion of the flow directly upward to the water surface as was the case in Modification II.

Performance tests, Figure 19A, showed that the teeth turned the flow upward better than in Modification III, but the performance was still no better than for the Angostura design.

Angostura Bucket with Teeth and Slots Removed

The Angostura bucket without teeth is shown in Figure 15. This design was not expected to perform as well as the slotted Angostura bucket, but was tested merely to indicate the value of the teeth and slots in dissipating the energy of the spillway flow.

The performance of this bucket with teeth removed is shown in Figure 19B. This bucket, without teeth, operated quite satisfactorily for smaller flows of 3 and 4 second feet but was not satisfactory for 6 second feet. The flow leaving the bucket was more unstable than when teeth were used because the water surface fluctuated more. For a few seconds the boil would be quite high and then for the next few seconds quite low. The water surface was rougher than with the teeth; however, erosion of the river bed was negligible in either case. This test indicated that it is desirable to use the Angostura type teeth in a prototype structure; but should the teeth deteriorate over a period of years, immediate repairs may not be necessary providing increased roughness of the water surface would not be objectionable.

Solid Bucket

The solid bucket design, shown in Figure 15, was tested merely to observe the type of action expected as compared to a slotted bucket. The performance of the bucket as compared to the Angostura slotted bucket is shown in Figure 2. All of the flow is directed to the water surface a short distance downstream from the bucket resulting in a very high boil. Part of the flow then rolls back into the bucket while part continues on downstream. Since there are no slots to provide flow currents in a downstream direction under the boil, a violent undercurrent flowing upstream existed. This undercurrent is also known as a ground roller that moves gravel toward the bucket lip where it is deposited. This is the same flow action experienced when solid buckets were initially used in the Angostura model study and the same as experienced with the solid bucket at Grand Coulee Dam. The deposit of bed material at the bucket lip is not unfavorable except when it is allowed to move into the bucket. Side eddies, resulting from unsymmetrical operation of the outlets or spillway gates, might wash this material into the bucket. Once the material is in the bucket, it is trapped and causes erosion of the concrete surfaces as it is moved about both laterally and longitudinally inside the bucket arc.

Therefore, a solid bucket, without slots, is not recommended for prototype construction where loose material may be carried into the bucket, or where the high boil might be objectionable.

Some advantages, however, were found for use of a solid bucket. A lower tail water elevation was required for the flow to sweep out of the bucket. The flow would not dive from the steep 45° bucket lip to scour the channel bed. Diving might have been possible on a higher spillway model with a high enough tail water elevation, or with this spillway using a smaller bucket and high tail water. The water surface downstream from the boil was smoother than for the slotted buckets except for the design of Modification II. However, in general, the slotted bucket appeared to perform better than the solid bucket.

Black Canyon Bucket

During the course of the investigation, an opportunity arose to investigate for the Bureau of Reclamation the proposed bucket for rehabilitation of the Black Canyon Dam spillway. It is shown in Figure 15 reduced to the scale of the 5-foot-high model spillway section. This bucket actually amounts to only a half bucket plus a short apron sloping upward in a downstream direction from the invert.

For the Black Canyon installation, in which case the river bed elevation was 40 feet below the invert of the bucket, the bucket performed very well in dissipating the energy at the maximum design model discharge of 3.36 second feet as shown in Figure 19C. The complete study is reported in the United States Bureau of Reclamation Hydraulic Laboratory Memorandum Report No. 347(2). When the discharge was increased to 6 second feet for comparison with the preceding designs, the action resembled that of the Angostura bucket without teeth but was more erratic. The performance was very unfavorable when the river bed material was placed near the level of the lip. When the river bed was near lip level or above, the flow dived scouring a deep hole near the lip. This diving and scouring also occurred for shallow tail water depths and for small discharges. It is not recommended that this bucket be used, except for river bed conditions similar to those at Black Canyon Dam.

Summary

The Angostura bucket performed better than any of the modifications of the bucket except for Modification II which was very satisfactory. However, Modification II was considered to be impractical for prototype construction of a large bucket since the teeth would need to be tremendously high. For small dams the relatively high teeth might be practical in which case the use of Modification II should be considered.

The Angostura slotted bucket with or without modifications, in general, is considered to be superior in performance to the solid bucket. The Angostura slotted bucket also provided more stable energy dissipation than did the Angostura bucket with teeth removed; however, the bucket with teeth removed did provide dissipation without disturbing the channel bed. The Angostura slotted bucket without modification is, therefore, recommended for most spillway structures where tail water depths are within the limits required for use of a bucket type energy dissipator.

PART II

Angostura Type Slotted Bucket--Radius and Tail Water Depth Limitations

Preliminary Preparations

The test flume, Figures 13 and 14, would accommodate a spillway height of approximately 10 feet and a maximum model discharge of approximately 12 second feet. Therefore, it was originally decided to test bucket sizes of 6-, 9-, 12-, 18-, and 24-inch radii with spillway heights ranging from 5 feet to 10 feet, measured from bucket invert to crest.

The crest of the 10-foot spillway was to be designed for 10 second feet; therefore, to maintain hydraulic similitude, the 5-foot spillway crest, which was to be used first in the investigation, would need to be designed for a discharge of 3.535 second feet. The use of the same set of buckets with the various spillway heights would then increase the range of the investigation and overlap in some cases to permit checking similitude. However, after the investigation was completed using the 5-foot spillway height, other spillway model heights were not investigated at this time since the range of the ratio of bucket radius to spillway height was fairly well covered by use of the 5-foot spillway alone. By extrapolation of test data, the bucket radius and tail water depth requirement could be determined for any prototype combination of spillway height and discharge, except where the spillway crest was submerged by the tail water.

The crest of the 5-foot spillway was an ogee shape. It was designed for 3.535 second feet in accordance with the procedure outlined in United States Bureau of Reclamation's Boulder Canyon Project Final reports[3]. It was installed in the model and calibrated in place.

The head and discharge relationship was determined from the calibration data and plotted in Figure 20. The coefficient of discharge for the design discharge in the equation, $q = CH^{3/2}$, where q is the discharge per foot of crest length and H is the height of the reservoir elevation above crest elevation, was determined to be 3.97 which is very close to the anticipated design value.

<u>Six-inch Bucket Radius</u>

The investigation for determining bucket size and tail water depth requirements began with the testing of the 6-inch radius bucket. The 9-, 12-, and 18-inch radius buckets followed in that order. For each bucket installation, a range of discharges was passed over the spillway. For each discharge, the tail water depth was lowered slowly until the flow swept out of the bucket as shown in Figure 21. This tail water depth is too low for proper performance of the bucket and it was recorded in Table 1 and plotted in Figure 22. Figure 23A shows the bucket operating with a tail water depth which is safely above the depth required for sweepout. The minimum tail water depth that is safely above the depth required for the sweepout will, henceforth, be called the lower or minimum limit in this report. The performance of the bucket was investigated for several discharges with higher tail water depths by increasing the depth slowly until the flow dove from the apron lip as shown in Figures 3 and 23B. When diving occurred a deep hole was scoured in the channel bed near the bucket. This tail water depth was too high for proper performance of the bucket and was recorded in Table 1 and plotted in Figure 22. It was, therefore, evident that a maximum tail water depth exists also. The maximum tail water depth that is safely below the depth required for diving will, henceforth, be called the upper or maximum tail water limit.

At the sweepout depth, the flow swept from the bucket like a jet as shown in Figure 21. The channel bed was quiet and undisturbed from the bucket downstream to the point at which the jet landed. The jet scoured the channel bed at point of contact, but did not cause much water surface roughness downstream. However, if a powerhouse, training wall, or other structure was to be located near this point, the scour might be dangerous to its foundation. Also, the material from the eroded hole would most likely form a bar downstream that would raise the tail water elevation in the powerhouse tailrace; and, thereby, reduce the efficiency of the powerplant. Spray from the jetlike projection of the flow would most likely be undesirable too.

At the lower tail water limit, which allowed for a margin of safety to guard against sweepout occurring, the gravel in the model channel bed began to move considerably. The gravel did not move away from the bucket, but instead was agitated in place; that is, it was merely lifted and dropped by numerous small eddies that occurred between the main flow leaving the bucket and the channel bed. This action was not considered desirable nor particularly objectionable.

The lower limit appeared to be from 0.05 to 0.15 of a foot (model) above the sweepout depth. Only the sweepout depth was recorded in the data shown in Table 1 since it was a more definite point than the minimum low tail water limit. A safe lower limit was established at the conclusion of all model testing by adding 0.2 of a foot to the sweepout tail water depth.

At the tail water depth required for diving to occur, as shown in Figure 23B, it was noted that by maintaining the tail water at this depth for 3 or 4 minutes in the model, the flow from the bucket would suddenly cease diving and rise to the surface as shown in Figure 23C. The flow from the bucket apparently rose to the surface only after the river bed became scoured sufficiently to allow upstream undercurrents to lift the flow from the apron lip to the water surface. The undercurrents moved the previously deposited pea gravel upstream into the scoured hole until the river bed became nearly level with the lip at which time the strength of the undercurrent was reduced until it was no longer capable of lifting the flow to the water surface. Then, the deep tail water again forced the flow to dive, and the cycle was repeated over and over again while the tail water depth remained constant. Five or six minutes were required for one cycle.

When the flow from the bucket was diving, the water surface was very smooth; but, when the flow was not diving, it created a boil and a rough water surface downstream. In the former case, part of the energy was dissipated on the channel bed, while in the latter case, the energy was directed to the surface for dissipation. It was more desirable to dissipate energy at the water surface as long as the waves did not become sufficiently forceful to cause serious erosion to channel banks or to cause damage to nearby structures.

Near the upper tail water limit diving spurts momentarily occurred but were not sustained long enough to move bed material. As the depth approached that required for sustained periods of diving, the momentary spurts occurred more often. In the test data recorded in Table 1 and plotted in Figure 22, the upper limit was not recorded; instead, the tail water depth that caused diving was recorded because that was a definite point. At the conclusion of all model testing, the approximate upper limit was thus established by subtracting 0.5 foot from the tail water depth at which diving occurred to allow for a margin of safety.

Preliminary model runs showed that it was difficult to get consistent results for the tail water depth at which diving occurred. It was determined that the upper tail water limit was dependent also upon the characteristics of the channel bed, especially upon its elevation downstream from the bucket. Since with the movable bed it was difficult to maintain the same channel bed characteristics between one test run and another, the gravel was removed from the model completely in anticipation that the upper tail water limit could be determined by merely observing the flow pattern.

The gravel was removed completely so that the floor of the model, which was 6 inches below the bucket invert, was the channel bed. With this arrangement the lower limit could still be determined, but the upper limit could not because the flow currents would not dive from the end of the bucket. However, there was a tail water depth limit not far above the sweepout depth at which the flow pattern changed instantly if exceeded. To cite an example for a particular discharge of 1.75 second feet per unit foot of bucket width, this upper tail water depth limit occurred about 7 inches above the sweepout depth. For a tail water depth below this point, Figure 24A, there was an upstream undercurrent similar to that which occurs for the solid bucket; however, material that might deposit along lip of the apron would not fall into the bucket because of the slots and because the bucket was relatively high above the channel bed. The water surface was very smooth and the velocity of the flow in the channel was quite uniformly distributed from the channel bed to the water surface. If the tail water depth for 1.75 second feet per foot in the model was more than 7 inches above the sweepout depth, Figure 24B, the flow pattern was entirely different and not so desirable. In this case, the bulk of the flow continued downstream along the water surface causing wave action. Therefore, this arrangement of the bed in the model could not be used to determine the upper diving depth for a channel bed at lip level, but this arrangement of the bed elevation with relation to the apron lip would be desirable for prototype construction wherever possible.

It was then decided to try to determine the upper and lower limit by using a solid floor at the elevation of the apron lip, to represent the channel bed. For this arrangement, flow from the bucket followed along the solid bed, then rose to the surface downstream, as shown in Figure 24C. For deep tail water depths, the flow followed the solid floor farther downstream than for shallow depths before turning upward to the surface. Such a current would definitely scour an erodible bed. It was found that the lower limit could be determined for this model bed arrangement, but again the upper limit could not.

It was decided to return to the use of the erodible pea gravel bed for determining the minimum and maximum tail water depth limits. It was necessary to reshape the gravel bed at the end of each test run for the start of the next to get more consistent upper limit results. Even then it was difficult. Testing showed that it was important that the channel bed be slightly below the apron lip elevation. If the bed was at lip elevation, the diving flow pattern occurred at a much lower tail water elevation. Therefore, the bed was maintained at approximately 0.05 of the radius or 0.3 of an inch below the apron lip of the bucket at the beginning of each test for determining the upper and lower tail water limits for the 6-inch bucket.

As the head on the crest was increased, the capacity of the bucket for good performance was approached and the upper and lower tail water limits approached each other. The capacity of the bucket was judged by the observed performance and by the nearness of the upper tail water limit to the lower limit, Figure 22. The maximum capacity of the 6-inch bucket with bed level below lip was judged to be approximately 3 to 3.5 second feet, total model discharge, or 1.5 to 1.75 second feet per foot of bucket width. The performance of the bucket for 3.5 second feet of flow with a normal tail water elevation is shown in Figure 23 . Water surface is relatively rough at this discharge.

Data were not recorded for other bed arrangements with the 6-inch bucket such as a movable bed sloping up from the apron lip since it was not contemplated investigating this bed arrangement in detail at this time. Later though, with the larger buckets to follow, it was decided also to include this sloping bed arrangement in the investigation.

Nine-inch Bucket Radius

The 9-inch bucket performed in about the same manner as the 6-inch bucket. When the tail water depth was insufficient, the flow swept out of the bucket as shown in Figure 25. If the tail water depth was too high, the flow dived from the apron lip as shown in Figure 26.

The 9-inch bucket used with a 5-foot high spillway is the same as a one and a half times larger model of a 6-inch bucket used with a 3.33-foot high spillway except for the shape of the spillway crest. Therefore, the capacity of the 9-inch bucket on a 5-foot spillway was a little greater than for the 6-inch bucket on the same spillway. Judged by the difference between the upper and lower tail water depth limits and by the relative surface roughness in the downstream channel, the capacity of the 9-inch bucket was determined to be somewhere between 4 and 5 second feet with bed level slightly below apron lip. Discharges of 3, 4, 5, and 6 second feet with a normal tail water depth of 1.85 feet are shown in Figures 27 and 28. For 6 second feet, the tail water range for satisfactory performance was quite narrow since a depth of 1.65 feet was too low and 2.3 feet was too high as shown in Figure 29. Therefore, the limiting capacity of the 9-inch bucket was determined not to exceed 5 second feet.

Water surface roughness for the limiting discharge of the 9-inch bucket was greater than for the limiting discharge of the 6-inch bucket, since the 9-inch bucket actually represented a one and one-half times larger scale model than the 6-inch bucket. Water surface measurements that may be of value to designers were made for a range of flows with a tail water depth about halfway between the upper and lower limits, Figure 30.

The tail water sweepout depth and the depth at which diving occurred are recorded in Table 2 and plotted in Figure 22 for a range of flows tested with bed elevation at approximately 0.05 of the radius or 0.5 inch below the apron lip. For a given discharge the sweepout depth was not as low for the 9-inch bucket as for the 6-inch but the diving depth was higher for the 9-inch size than for the 6 inch.

The minimum and maximum tail water depth limits for satisfactory performance of the bucket were also estimated by observing the flow in each test run above. The maximum limit as observed for the 9-inch bucket is plotted in Figure 22. It was quite indefinite since the depth at which diving occurred was not very consistent, but a reasonably safe upper limit appeared to be approximately 0.5 of a foot below the average depth for diving to occur. This margin of safety was determined after completion of all bucket tests.

The minimum limit appeared to be from 0.05 to 0.15 of a foot above the sweepout depth. After completion of all bucket tests, it was decided that a safe lower limit should be at least 0.2 of a foot above the sweepout depth to provide for an ample margin of safety.

The minimum and maximum limits were also recorded with a channel bed sloping 16° upward in a downstream direction from the apron lip to approximately 6 inches above elevation of the lip, since this position of the bucket below the channel bed would be quite common for many installations. Sweepout occurred at approximately the same depth above bucket invert as with the bed elevation below lip level, but diving occurred at a much lower tail water depth than for the lower bed. The diving occurred at about the same tail water depth as for the 6-inch bucket with bed elevation below lip level. At the depth required for diving, the cycle of scouring and filling was repeated over and over while the discharge and tail water depth remained constant in the same manner as occurred for the lower bed, Figure 31. The maximum capacity of the bucket with the bed sloping upward was considered to be the same as with the lower bed level, but the operating range between minimum and maximum tail water depth limits was greatly reduced.

Twelve-inch Bucket Radius

The performance of the 12-inch bucket was similar to that of the 6- and 9-inch buckets. It is shown in Figures 32, 33, and 34 for flows ranging from 5 to 12 second feet with normal tail water depth. The water surface waves were greater than for the 6- and 9-inch buckets, but here again the model represented a lower height of dam and, therefore, was a larger scale model than the two smaller buckets. The maximum capacity of the bucket was estimated to be from 6.5 to 7 second feet. Average water surface measurements, which might be useful to designers are shown in Figure 30 for a range of flows with tail water depth about halfway between the upper and lower limits.

Tail water depths for sweepout and diving are recorded in Table 3 and plotted in Figure 22 for a bed level approximately 0.05 of the radius or 0.6 of an inch below the apron lip. Again, as for the smaller buckets, it was difficult to get consistent data at which diving occurred and again it was difficult to determine the exact margin of safety required for establishing the upper and lower tail water depth limits. However, the margins appeared to be about the same as required for the smaller buckets previously tested.

The test was repeated with the bed sloping upward in a downstream direction from the apron to about 6 inches above the lip; and, again, the results were comparable to the results from the 9-inch bucket. The safe maximum limit appeared to be about the same as the upper limit for the 9-inch bucket with bed below lip elevation. The data are given in Table 3 and plotted in Figure 22. As for the 9-inch bucket, the maximum capacity of the 12-inch bucket was considered to be the same with the upward sloping bed as with the lower bed.

Eighteen-inch Bucket Radius

The performance of the 18-inch bucket is shown in Figures 35 through 39 inclusive, for discharges ranging from 6 second feet to 12 second feet with high, low, and normal tail water depths. The capacity of the bucket appeared to be from 10 to 11 second feet. The 5-foot high model spillway with the 18-inch bucket represented a relatively lower spillway than when smaller buckets were used. The use of the 18-inch bucket in the 5-foot model resembled a low diversion dam spillway while the use of the 6-inch bucket typifies a high dam overflow spillway. If the size of the bucket was increased further, then the necessary tail water depth for good performance would more nearly submerge the crest.

For bed level approximately 0.05 of the radius or 0.9 of an inch below the apron lip, the tail water depths for sweepout and diving are recorded in Table 4 and plotted in Figure 22 for a range of discharges. The minimum and maximum tail water depth limits and the actual depths for sweepout and diving were even more difficult to determine precisely than for the smaller buckets. In fact, the diving condition could not be reached by raising the tail water as high as possible in the model for any discharge. However, the tendency to dive was present and momentary diving occurred, but in no case was it sustained. Data for obtaining the maximum depth limit was not recorded.

The minimum tail water depth at which the bucket operated satisfactorily was observed and plotted in Figure 22. The minimum observed tail water depth for satisfactory performance appeared to be at least 0.1 of a foot above the sweepout depth.

The maximum tail water limit was not determined for a bed at higher than lip level because of difficulties in maintaining the bed at this elevation while starting a test run. It was, therefore, assumed to be in line with test results from the smaller buckets. The capacity of the bucket with the higher bed was not tested for the same reason, but it is probably the same as that with the bed level below the apron lip.

Larger and Smaller Buckets

Larger buckets were not tested with this 5-foot spillway because of the increasing difficulties in measuring bucket capacity and tail water depth limits for these greater flows; and, because a larger bucket operating at near maximum tail water depth limit would either submerge the crest or, closely, approach that condition. It was not intended here to investigate the use of a bucket with a submerged crest. A limited number of studies made previously by the Bureau of Reclamation has shown the use of a bucket with a crest that is much more than 50 percent submerged by the tail water to be undesirable. With such an arrangement, the flow does not enter the bucket, but, instead, passes over the bucket.

Smaller buckets were not tested because very few prototype structures would be represented by a smaller bucket with a 5-foot high dam. Therefore, the available data were analyzed and found to be sufficient with some extrapolation.

Data Analysis

At this stage of the investigation the margin of safety between sweepout depth and minimum tail water depth, and also the margin of safety between the maximum tail water depth and the depth required for diving were definitely established. For all four bucket radii tested, 0.2 of a foot model appeared to be an ample margin of safety for the lower limit while 0.5 of a foot appeared to be an ample margin for the upper limit with either of the two bed elevations tested. Perhaps the margins of safety for the upper and lower limits should have been increased for each increase in bucket radius, but it appeared that these limits were ample for the largest bucket tested; and, therefore, safe margins for the smaller buckets. The values for the upper and lower limits thus determined were entered in Tables 1 through 4.

To relate the data in such a way that it will be useful in determining minimum allowable bucket radius "R," the safe minimum tail water depth "T_{min}" and the safe maximum tail water depth "T_{max}" for any prototype overflow spillway, where the crest is not submerged by the tail water, it was necessary to first consider the variables, shown in Figure 40, that affect the unknown requirements. Figure 22 shows the sweepout depth and, therefore, the minimum tail water depth limit for a given height of model spillway above tail water elevation "h," with a given slope "S," to depend upon the radius of bucket "R" and the head on the crest "H". The latter in turn depends upon the discharge "q" per foot of spillway width and the discharge coefficient "c".

$$q = cH^{\frac{3}{2}}$$

Therefore:

$$T_{min} = f(h,\ S,\ R,\ H \text{ and } q)$$

Figure 22 shows the tail water depth for diving, and, therefore, the maximum tail water depth limit, to depend upon the elevation of the channel bed with respect to the apron lip in addition to the bucket radius and head on the crest. Therefore:

$$T_{max} = f(h,\ S,\ R,\ H,\ q \text{ and elevation of channel bed in relation to elevation of bucket apron lip})$$

Actually, the prototype bed will tend to level out with time if the bucket operates near the diving depth. Figure 22 also shows the minimum allowable bucket radius for a given height of model spillway, above tail water elevation, with given slope to be a function only of the head on the crest. Therefore, the minimum allowable bucket radius:

$$R_{min} = f(h,\ S,\ H \text{ and } q)$$

The maximum capacity of a given radius bucket may be increased slightly when the tail water depth is an intermediate value between the minimum or maximum tail water depths, but for practical purposes it does not depend upon tail water depth.

The elevation of the bed with respect to the apron lip does not, within limits, affect the sweepout depth or the required size of bucket radius, appreciably; therefore, it can be neglected in determining the sweepout depth, minimum tail water depth limit, and the bucket radius.

The slope of the spillway face within limits will also not, appreciably, affect the minimum or maximum tail water depth limits or the minimum allowable bucket radius; therefore, this can be neglected for spillway slopes that are approximately the same as that of the model tested. The slope of the spillway model tested was 0.7. In the prototype, frictional resistance on the spillway face would also affect the minimum depth limit, the maximum depth limit, and the minimum allowable bucket radius since frictional resistance in effect would reduce the effective height of fall. However, frictional resistance is, primarily, a function of head, discharge, and height of spillway, above tail water elevation; therefore, it need not be considered as a separate variable.

The velocity of the flow entering the bucket "V_1" and depth "D_1" are functions of head, discharge, height of spillway above tail water elevation, and spillway slope, and the Froude number "F" is a function of the velocity and depth of flow.

$$V_1 \text{ and } D_1 = f(h, S, H, \text{and } q)$$

$$F = \frac{V_1}{\sqrt{gD_1}}$$

Therefore:

$$T_{min} = f(R, F)$$

$$T_{max} = f(R, F, \text{and elevation of channel bed with respect to apron lip.})$$

$$R_{min} = f(F)$$

It was chosen to compute "F" on the spillway face at tail water elevation since all necessary variables for computing the velocity and depth of flow at that point could be predetermined from given values of reservoir elevation, discharge, tail water elevation, and frictional resistance on the spillway face.

The value of "F" then is a fixed value for any given prototype condition and all similar models of the prototype.

In relating the tail water depth limits and the bucket radius with the Froude number, it is desirable to express "T_{min}," "T_{max}," and "R" as dimensionless numbers. Therefore, "T_{min}" and "T_{max}" were divided by "D_1"; and "R" was divided by "$D_1 + V_1^2/2g$" the depth of flow plus the velocity head at tail water elevation on the spillway face. These dimensionless ratios and the Froude number are shown computed for the test data in Tables 1, 2, 3, and 4. In computing these the frictional resistance in the 5-foot model is negligible. The bucket radius dimensionless ratio and the Froude number for each of the test runs which represent the maximum estimated capacity of each bucket was plotted in Figure 41. A curve to the right of these plotted points represents the minimum allowable bucket radius for a given Froude number and allows for a safety factor.

Since the tail water depth limits depended upon both the bucket radius and the Froude number, the dimensionless ratios for the tail water depth limits and the bucket radius were plotted in Figure 42 versus the Froude number for the test data shown in Figure 22 and recorded in Tables 1 to 4, inclusive. Since the upper tail water depth limit also depended upon the elevation of the channel bed with respect to apron lip, two sets of upper tail water depth dimensionless ratios were plotted for each of the two bed elevations tested. Curves were drawn through these points in Figure 42, so that, for any given Froude number and bucket radius as determined in Figure 41 the minimum and maximum tail water depth limits could be determined. The curves in Figure 42 were cross plotted in Figures 43 and 44 for easier use in determining tail water depth limits.

The tail water sweepout depth "T_s" data was also divided by "D_1" to form a dimensionless ratio and then plotted versus the Froude number in Figure 45 for each of the four bucket sizes tested. Figure 45 is cross plotted in Figure 46 for use in determining sweepout depth at a prototype installation. The difference between sweepout depth and actual depth anticipated will indicate the margin of safety.

Application

Practical application of the test data is illustrated in Table 5 for the following dams: Angostura, Grand Coulee, Missouri Diversion, and Trenton. The tail water depth requirement should be determined for the maximum discharge condition and for smaller discharges such as one-fourth, one-half, and three-fourths maximum, as shown for Angostura Dam in Table 5.

The Angostura illustration, incidentally, serves as a means of checking the design that was initially developed for Angostura Dam. The Angostura design was found to be underdesigned for the maximum discharge, but about right for three-fourths maximum and overdesigned for smaller discharges.

An independent partial investigation on this subject, made in 1949 by E. J. Rusho, formerly of the Bureau of Reclamation, provides a means of checking the sweepout depth as determined here. The curves that Rusho developed and the application of their use in determining the sweepout depth are illustrated in Figure 47. However, his method does not take into account the efficiency of the crest as represented by the coefficient of discharge nor does it take into account the frictional resistance on the spillway. Mr. Rusho's investigation also does not provide for determining the minimum allowable bucket radius or the maximum allowable tail water depth.

The example shown in Figure 47 is illustrated in Table 5 for checking one method with the other. Neglecting frictional resistance, the sweepout depth of 11.1 feet computed in Table 5 checks closely the 12.3 figure computed in Figure 47. To check further for a low dam with a smaller Froude number, the data from Angostura Dam was used in Figure 47 to compute the sweepout tail water depth. In Figure 47 the sweepout depth for a 40-foot radius bucket at Angostura Dam is 62 feet. Using the method presented here, the sweepout depth is also 62 feet.

The step by step procedure in designing a slotted bucket using method presented here is outlined in the following paragraphs. The prototype data for Grand Coulee Dam (see Table 5) is used as an example. For maximum design reservoir elevation 1290, the design spillway discharge is 935,000 second feet. Spillway crest is at elevation 1260; the design head is, therefore, 30 feet. Length of the crest is 1,485 feet; therefore, the discharge per foot of bucket width is 630 second feet. Tail water in the channel below the dam is expected to be at elevation 1009 for the design flow. The theoretical velocity head of the flow entering the basin at tail water elevation on the spillway face is the difference between tail water elevation and reservoir elevation or 281 feet. Then, theoretically the velocity at this point "V_1" is, 130.5 feet per second. The actual velocity and velocity head is less than the theoretical at this point due to frictional resistance on the spillway face. The ratio of the actual velocity to the theoretical is estimated to be 91 percent in Figure 48. Figure 48 was prepared by J. N. Bradley of the Bureau of Reclamation from a limited amount of data and should not be used indiscriminately for other purposes than presented here. It was prepared principally to reduce the computation work on preliminary design of overfall spillways. The actual velocity in this example is, therefore, 91 percent of 130.5 or 118.8 feet per second and the actual velocity head is, then, 219.2 feet, and the depth of flow "D_1" on the spillway at this point then is q/V_1 or 5.3 feet. Having now determined D_1 and V_1, the Froude number is readily computed to be 9.11.

Entering Figure 41 with this Froude number, the dimensionless ratio of the minimum usable bucket radius is found to be 0.13. The minimum allowable bucket radius is then computed to be 29 feet. It would, therefore, be recommended that at least a 30-foot bucket radius be used. Suppose that it is decided to use a 30-foot radius bucket then the bucket radius parameter would still be 0.13. Entering Figure 43 with the bucket radius dimensionless ratio and the Froude number, the dimensionless ratio of the minimum tail water depth limit "T_{min}/D_1" is found to be 13.8. Then the minimum tail water depth limit is 73 feet as measured from the bucket invert to tail water surface elevation. Entering Figure 44 with the dimensionless ratio of the bucket radius and the Froude number, the dimensionless ratio of the maximum tail water depth limit for a channel bed elevation below the apron lip is found to be 18.8, and the maximum tail water depth limit is then, 100 feet, as measured from bucket invert to tail water elevation. The channel bed at the foot of Grand Coulee is at approximately average elevation 900. If invert of bucket is placed at channel bed elevation then the tail water depth would be 109 feet, which exceeds the upper limit of 100 feet. Therefore, a bucket of this size should be set above the channel bed so that the tail water depth from the bucket invert would be between 73 and 100 feet.

The bucket would then perform as shown in Figures 24A or B. The performance of 24A would be preferred but 24B would most likely be acceptable. The bucket would perform as shown in Figure 24A if the bucket invert is placed high enough that the tail water depth above is close to the lower limit. A tail water depth of between 75 and 80 feet would probably be most satisfactory.

The sweepout depth can also be determined if so desired. Enter Figure 46 with the Froude number and the bucket radius dimensionless ratio to find the sweepout depth dimensionless ratio of 11.8. The sweepout depth then is approximately 63 feet. Thus, the minimum tail water depth limit of 73 feet provides approximately 10 feet safety factor. Therefore, a tail water depth above bucket invert of 75 feet would probably be suitable.

Using the Grand Coulee data with Figure 47, the sweepout depth for a 30-foot radius bucket is approximately 76 feet. Using the method presented here, but neglecting the frictional resistance, the approximate sweepout depth for a 30-foot radius bucket is 64 feet, which is only 1 foot more than the 63 feet computed above when frictional resistance was not neglected. The disagreement is most likely due to the fact that Mr. Rusho's test data which he used to obtain the curves in Figure 47 are quite limited for values of "$h_d^{3/2}/q$" above 4 and below 0.8. It is suggested, however, that dams as large as Grand Coulee be model tested for verification of the design derived by this method.

Another solution for the Grand Coulee example presented here would be to use a larger bucket radius, rather than raise the elevation of the bucket invert. For example, suppose, instead of using the minimum allowable bucket radius of 30 feet, it is decided to use a 50-foot radius bucket. The bucket radius dimensionless ratio then would have a value of 0.23 which in Figure 43 shows the minimum tail water depth dimensionless ratio limit to be 15 and in Figure 44 shows the maximum tail water depth dimensionless ratio to be 33. The lower tail water depth limit then would be 80 feet and the upper limit would be 175 feet. If the invert of the bucket was now placed at the approximate bed elevation 900, the tail water depth would be 109 feet which is well within the two limits. However, if the bucket invert was placed below the bed so that the channel bed sloped up from the apron, then the dimensionless ratio of the maximum tail water depth limit would be approximately 19 as found in Figure 44, and the upper depth limit would be only 100 feet. The tail water depth would be something greater than 109, therefore, river bed scouring might occur as shown in Figure 31. To complete the slotted bucket design, Figure 1 should be used to determine the length of apron, size of teeth, spacing, etc.

For dams such as Trenton that have a long spillway chute, other means than Figure 48 must be used for determining the actual velocity entering the bucket at tail water elevation. If frictional resistance was neglected in the design computation, then the minimum tail water limit would be higher; and, therefore, on the safe side, but the maximum tail water limit would be higher too, which is not on the safe side.

<u>Summary</u>

The Angostura type slotted bucket, Figure 1B, is well adapted for general use as an energy dissipator at the base of an overfall spillway. However, wherever practical the higher teeth recommended in design Modification II, Figures 16, 17B, and 18, should be used. Also, wherever possible the elevation of the bucket invert should be placed above the channel bed, as in Figure 24A, for best performance.

Design curves, Figures 41 through 44, inclusive, were developed from the experimental data, Tables 1 through 4, inclusive, and Figure 22, for use in designing an Angostura type slotted bucket. From the curves the minimum bucket radius, the required tail water depth, and the maximum permissible tail water depth can be determined as illustrated in Table 5. In addition, the tail water sweepout depth can be determined in either of Figures 45 or 46 and checked approximately in Figure 47. Caution should be used in designing buckets for large structures such as 200-foot high spillways with discharges of 500 second feet per foot of width without model verification. Model verification is desirable in all cases, however.

The design curves presented here may also be used for determining the radius and tail water depth requirements for a solid bucket if for some reason it was desirable to use one. It is probable that the minimum and maximum tail water depth limits provided here would be more than safe for use of solid buckets.

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BIBLIOGRAPHY

1. United States Bureau of Reclamation, Hydraulic Laboratory Report No. 192, "Hydraulic Model Studies on the Spillway for the Angostura Dam, Angostura Unit--Missouri River Basin Project," by R. C. Besel.

2. United States Bureau of Reclamation, Hydraulic Laboratory Memorandum Report No. 347, "Model demonstration of bucket proposed for rehabilitation of Black Canyon Dam Spillway--Boise Project, Idaho," by J. N. Bradley.

3. United States Bureau of Reclamation, Boulder Canyon Project Final Reports, Part VI Hydraulic Investigations, Bulletin 3, "Studies of Crests for Overfall Dams," Chapter III, Section 21, page 45.

Table 1

DATA COMPUTATION FOR 6-INCH RADIUS BUCKET

Run No.	1	2	3	4	5	6	7	8	9
	Bed was approximately 0.05R below apron lip at beginning of each run								
H	0.198	0.274	0.352	0.413	0.480	0.481	0.526	0.581	0.678
T (sweep out depth)	0.767	0.765	0.826	0.943	1.023	1.081	1.139	1.203	1.403
q	0.31	0.54	0.81	1.03	1.30	1.30	1.50	1.75	2.25
T_{min}	0.967	0.965	1.026	1.143	1.223	1.281	1.339	1.403	1.603
$\frac{V_1^2}{2g} = X + H - T_{min}$	4.231	4.309	4.326	4.270	4.257	4.200	4.187	4.178	4.075
V_1	16.50	16.65	16.70	16.58	16.56	16.45	16.42	16.41	16.20
D_1	0.019	0.032	0.048	0.062	0.078	0.079	0.091	0.107	0.139
$F = \frac{V_1}{\sqrt{gD_1}}$	21.2	16.31	13.36	11.72	10.42	10.31	9.50	8.85	7.65
$\frac{T_{min}}{D_1}$	51.43	29.78	21.10	18.40	15.57	16.21	14.66	13.16	11.54
$D_1 + \frac{V_1^2}{2g}$	4.245	4.341	4.374	4.332	4.335	4.279	4.278	4.285	4.214
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12
T (diving depth)	2.565	2.576	2.435	2.464	2.439	2.397	2.043	2.200	2.213
T_{max}	2.065	2.076	1.935	1.964	1.939	1.897	1.543	1.700	1.713
$\frac{V_1^2}{2g} = X + H - T_{max}$	2.133	2.198	2.417	2.449	2.541	2.584	2.983	2.881	2.965
V_1	11.72	11.89	12.47	12.55	12.78	12.90	13.86	13.62	13.81
D_1	0.026	0.045	0.065	0.089	0.102	0.101	0.108	0.128	0.163
$F = \frac{V_1}{\sqrt{gD_1}}$	12.67	9.84	8.62	7.40	7.06	7.20	7.42	6.70	6.02
$\frac{T_{max}}{D_1}$	77.92	45.72	29.76	21.62	19.06	18.82	14.26	13.23	10.51
$D_1 + \frac{V_1^2}{2g}$	2.159	2.243	2.486	2.538	2.643	2.685	2.983	3.009	3.128
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.23	0.22	0.20	0.20	0.19	0.19	0.17	0.17	0.16

R = bucket radius (ft)
H = height of reservoir above the crest (ft)
T = depth of tail water above the bucket invert (ft)
T_{min} = minimum tail water depth for good performance (ft) = sweep out depth + 0.2 ft
T_{max} = maximum tail water depth for good performance (ft) = diving depth - 0.5 ft
q = discharge per foot of model crest length (cfs)
X = height of crest above bucket invert = 5 feet
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation

Table 2

DATA COMPUTATION FOR 9-INCH RADIUS BUCKET

Run No.	Bed was approximately 0.05R below apron lip at beginning of each run															Bed slopes up from apron lip				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
H	0.419	0.476	0.531	0.642	0.682	0.722	0.764	0.805	0.852	0.884	0.534	0.578	0.585	0.633	0.54	0.433	0.485	0.527	0.634	0.723
T (sweep out depth)	1.02	1.11	1.19	1.33	1.41	1.45	1.51	1.60	1.67	1.70										
q	1.05	1.28	1.52	2.05	2.28	2.50	2.74	3.00	3.30	3.52	1.53	1.73	1.78	2.02	1.56	1.12	1.32	1.50	2.01	2.50
T_{min}	1.22	1.31	1.39	1.53	1.61	1.65	1.71	1.80	1.87	1.90										
$\frac{V_1^2}{2g} = X + H - T_{min}$	4.199	4.166	4.141	4.112	4.072	4.072	4.054	4.005	3.982	3.984										
V_1	16.45	16.38	16.33	16.28	16.20	16.20	16.16	16.06	16.02	16.02										
D_1	0.064	0.078	0.093	0.126	0.141	0.154	0.170	0.187	0.206	0.220										
$F = \frac{V_1}{\sqrt{gD_1}}$	11.49	10.34	9.44	8.09	7.62	7.27	6.92	6.56	6.22	6.03										
$\frac{T_{min}}{D_1}$	19.12	16.77	14.93	12.15	11.44	10.69	10.08	9.63	9.07	8.64										
$D_1 + \frac{V_1^2}{2g}$	4.262	4.244	4.234	4.238	4.212	4.226	4.224	4.192	4.188	4.204										
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18										
T (diving depth)	3.40	3.03	3.01	2.46	2.38	2.44	2.44	2.32	2.46	2.37	2.68	2.39	2.37	2.42	3.07	1.96	1.86	2.23	2.69	2.43
T_{max}	2.90	2.53	2.51	1.96	1.88	1.94	1.94	1.82	1.96	1.87	2.18	1.89	1.87	1.92	2.57	1.46	1.36	1.73	2.19	1.93
$\frac{V_1^2}{2g} = X + H - T_{max}$	1.519	1.946	2.021	2.682	2.802	2.782	2.824	2.985	2.892	2.014	2.354	2.688	2.715	2.713	1.970	2.970	3.125	2.797	2.444	2.793
V_1	9.89	11.20	11.40	13.14	13.43	13.40	13.48	13.87	13.65	13.94	12.31	13.16	13.22	13.21	11.26	13.84	14.18	13.42	12.55	13.40
D_1	0.106	0.114	0.133	0.156	0.170	0.187	0.203	0.216	0.242	0.252	0.126	0.131	0.135	0.153	0.138	0.081	0.093	0.112	0.160	0.187
$F = \frac{V_1}{\sqrt{gD_1}}$	5.34	5.84	5.49	5.85	5.72	5.46	5.26	5.25	4.89	4.89	6.11	6.41	6.38	5.95	4.15	8.59	8.19	7.08	5.53	5.46
$\frac{T_{max}}{D_1}$	2.733	22.13	18.82	12.56	11.07	10.39	9.54	8.54	8.10	7.40	17.28	14.38	13.89	12.55	18.55	18.00	14.60	15.47	13.67	10.34
$D_1 + \frac{V_1^2}{2g}$	1.625	2.060	2.154	2.838	2.972	2.969	2.077	3.201	3.134	3.266	2.480	2.819	2.850	2.866	2.108	3.054	3.218	2.909	2.604	2.980
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.46	0.36	0.35	0.26	0.25	0.25	0.25	0.23	0.24	0.23	0.30	0.27	0.26	0.26	0.35	0.25	0.23	0.26	0.29	0.25

R = bucket radius (ft)
H = height of reservoir above the crest (ft)
T = depth of tail water above the bucket invert (ft)
T_{min} = minimum tail water depth for good performance (ft) = sweep out depth + 0.2 ft
T_{max} = maximum tail water depth for good performance (ft) = diving depth - 0.5 ft
q = discharge per foot of model crest length (cfs)
X = height of crest above bucket invert = 5 feet
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation

Table 3

DATA COMPUTATION FOR 12-INCH RADIUS BUCKET

Run No.	Bed was approximately 0.05R below apron lip at beginning or each run												Bed slopes up from apron lip			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
H	0.543	0.592	0.637	0.679	0.729	0.765	0.811	0.850	0.887	0.961	1.02	1.221	0.565	0.651	0.723	0.839
T (sweep out depth)	1.27	1.33	1.40	1.45	1.52	1.56	1.68	1.72	1.78	1.89	1.96	2.23				
q	1.58	1.82	2.03	2.25	2.53	2.75	3.05	3.28	3.54	4.06	4.48	6.08	1.67	2.00	2.50	3.21
T_{min}	1.47	1.53	1.60	1.65	1.72	1.76	1.88	1.92	1.98	2.09	2.16	2.43				
$\frac{V_1^2}{2g} = X + H - T_{min}$	4.073	4.062	4.037	4.029	4.009	4.005	3.931	3.930	3.907	3.871	3.860	3.791				
V_1	16.20	16.17	16.12	16.11	16.07	16.06	15.92	15.91	15.86	15.79	15.77	15.63				
D_1	0.099	0.112	0.126	0.140	0.157	0.171	0.192	0.206	0.223	0.257	0.284	0.389				
$F = \frac{V_1}{\sqrt{gD_1}}$	9.10	8.51	8.01	7.60	7.14	6.84	6.41	6.18	5.93	5.49	5.22	4.42				
$\frac{T_{min}}{D_1}$	14.91	13.60	12.71	11.81	10.93	10.28	9.81	9.31	8.87	8.13	7.60	6.25				
$D_1 + \frac{V_1^2}{2g}$	4.172	4.175	4.163	4.169	4.166	4.176	4.123	4.136	4.133	4.128	4.144	4.180				
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24				
T (diving depth)	3.95	4.00	3.90	3.95	3.95	3.95	--	2.91	2.87	3.22	3.17	3.00	3.25	3.00	2.45	2.35
T_{max}	3.45	3.50	3.40	3.45	3.45	3.45	--	2.41	2.37	2.72	2.67	2.50	2.75	2.50	1.95	1.85
$\frac{V_1^2}{2g} = X + H - T_{max}$	1.093	1.092	1.237	1.229	1.279	1.315	--	2.440	2.517	2.241	2.35	2.721	1.815	2.131	2.773	2.889
V_1	8.39	8.39	8.92	8.90	9.07	9.20	--	12.54	12.72	12.01	12.30	12.23	10.81	11.71	13.36	13.64
D_1	0.188	0.217	0.228	0.253	0.279	0.299	--	0.262	0.278	0.338	0.364	0.460	0.154	0.171	0.187	0.235
$F = \frac{V_1}{\sqrt{gD_1}}$	3.42	3.17	3.29	3.11	3.02	2.96	--	4.31	4.25	3.64	3.41	3.44	4.86	4.98	5.54	4.96
$\frac{T_{max}}{D_1}$	18.35	16.12	14.91	14.63	12.36	11.53	--	9.19	8.52	8.04	7.33	5.54	17.85	14.61	10.42	7.87
$D_1 + \frac{V_1^2}{2g}$	1.281	1.309	1.465	1.482	1.558	1.614	--	2.702	2.795	2.579	2.714	3.181	1.969	2.302	2.960	3.124
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.78	0.72	0.68	0.67	0.64	0.62		0.37	0.36	0.39	0.37	0.31	0.51	0.43	0.34	0.32

R = bucket radius (ft)
H = height of reservoir above the crest (ft)
T = depth of tail water above the bucket invert (ft)
T_{min} = minimum tail water depth for good performance (ft) = sweep out depth + 0.2 ft
T_{max} = maximum tail water depth for good performance (ft) = diving depth - 0.5 ft
q = discharge per foot of model crest length (cfs)
X = height of crest above bucket invert = 5 feet
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation

Table 4

DATA COMPUTATION FOR 18-INCH RADIUS BUCKET

	Bed was approximately 0.05R below apron lip at beginning of each run							
Run No.	1	2	3	4	5	6	7	8
H	0.631	0.734	0.804	0.898	0.926	1.001	1.083	1.150
T (sweep out depth)	1.45		1.78					
q	2.00	2.56	2.99	3.61	3.80	4.35	4.98	5.48
T_{min}	1.65	1.85	1.98	2.07	2.15	2.23	2.32	2.45
$\frac{V_1^2}{2g} = X + H - T_{min}$	3.981	3.884	3.824	3.828	3.776	3.771	3.763	3.700
V_1	16.02	15.86	15.70	15.70	15.27	15.68	15.67	15.44
D_1	0.125	0.161	0.190	0.230	0.249	0.277	0.318	0.355
$F = \frac{V_1}{\sqrt{gD_1}}$	7.98	6.94	6.33	6.76	5.39	5.24	4.88	4.56
$\frac{T_{min}}{D_1}$	13.22	11.46	10.39	9.00	8.64	8.03	7.30	6.70
$D_1 + \frac{V_1^2}{2g}$	4.106	4.045	4.014	4.058	4.025	4.043	4.081	4.055
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
T (diving depth)								
T_{max}								
$\frac{V_1^2}{2g} = X + H - T_{max}$								
V_1								
D_1								
$F = \frac{V_1}{\sqrt{gD_1}}$								
$\frac{T_{max}}{D_1}$								
$D_1 + \frac{V_1^2}{2g}$								
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$								

R = bucket radius (ft)
H = height of reservoir above the crest (ft)
T = depth of tail water above the bucket invert (ft)
T_{min} = minimum tail water depth for good performance (ft) = sweep out depth + 0.2 ft
T_{max} = maximum tail water depth for good performance (ft) = diving depth - 0.5 ft
q = discharge per foot of model crest length (cfs)
X = height of crest above bucket invert = 5 feet
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation

Table 5

EXAMPLE APPLICATIONS

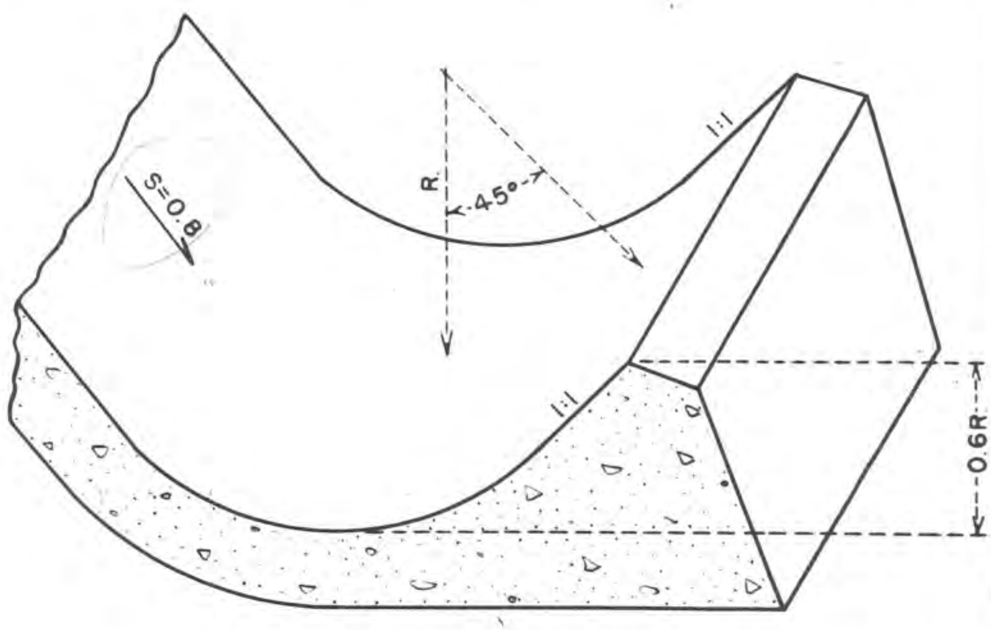
		Angostura Dam	Angostura Dam	Angostura Dam	Angostura Dam	Grand Coulee Dam	Trenton Dam	Missouri Diversion Dam	Example given in Figure 47
1	Q	247,000	180,000	100,000	40,000	935,000	133,000	90,000	
2	Reservoir elevation	3198.1	3191.0	3181.5	3170.4	1290	2785	2043.4	
3	Crest elevation	3157.2	3157.2	3157.2	3157.2	1260	2743	2032	
4	H	40.9	33.8	24.3	13.2	30	42	17.4	5
5	L	274	274	274	274	1485	266	644	
6	q	901	657	365	146	630	500	140	42
7	Tail water elevation	3114	3106	3095	3084	1009	2700.6	2018.3	
8	$\frac{V_1^2}{2g}$ (theoretical) = (2) - (7)	84.1	85.0	86.5	86.4	281	84.4	25.1	40
9	V_1 (theoretical)	73.6	74	75	75	130.5	73.7	40.2	50.8
10	$\frac{V_1 \text{ (actual)}}{V_1 \text{ (theoretical)}}$	0.98	0.98	0.97	0.93	0.91	0.90	0.98	
11	V_1 (actual)	72.2	72.5	72.8	69.8	118.8	66.0	39.4	
12	$\frac{V_1^2}{2g}$ (actual)	80.9	81.6	82.3	75.6	219.2	67.6	24.1	
13	D_1	12.48	9.06	5.01	2.09	5.30	7.58	3.55	0.83
14	$\sqrt{D_1}$	3.53	3.00	2.24	1.45	2.30	2.75	1.88	0.91
15	$F = \frac{V_1}{\sqrt{gD_1}}$	3.61	4.26	5.73	8.49	9.11	4.23	3.70	9.85
16	$D_1 + \frac{V_1^2}{2g}$	93.38	90.66	87.31	77.69	224.50	75.18	27.65	40.83
17	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$ (minimum)	0.50	0.43	0.30	0.15	0.13	0.43	0.48	0.11
18	R (minimum)	47	39	26	12	29	33	13	4.5
19	R (actually used)	40	40	40	40	30	35	12.5	7.4
20	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$ (actual)	0.43	0.44	0.46	0.51	0.13	0.47	0.45	0.18
21	$\frac{T_{min}}{D_1}$	5.4	6.6	9.3	16.4	13.8	6.6	5.5	15.9
22	T_{min}	67	60	46	34	73	50	20	13.2
23	$\frac{T_{max}}{D_1}$	5.6	7.9	17.6	60.0	18.8	13.0	8.8	
24	T_{max}	70	72	88	125	100.7	99	31	
25	$\frac{T_s}{D_1}$	5.0	6.0	8.0	14.4	11.8	5.7	5.0	13.4
26	T_s	62	54	40	30	63	44	18	11.1

not actually used

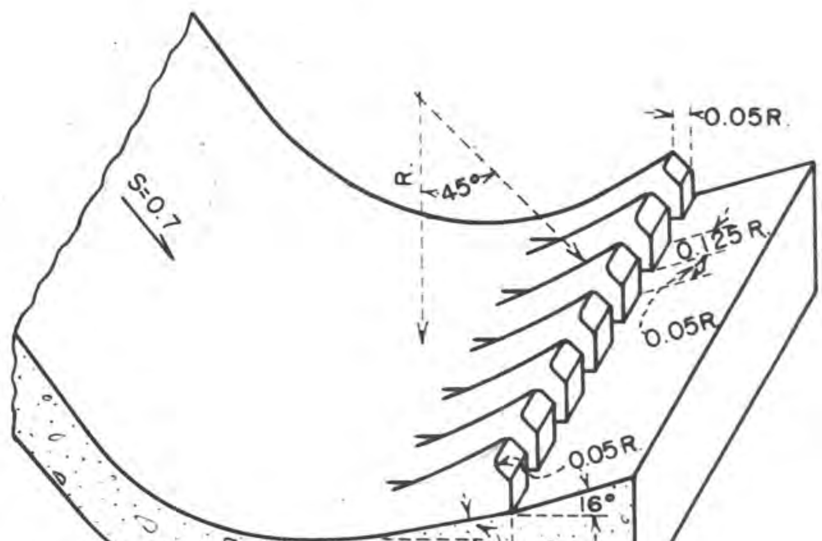
Q = total discharge (cfs)
L = bucket width (ft)
q = discharge per foot of bucket width (cfs)
H = height of reservoir above crest (ft)
V_1 = velocity of flow entering the bucket computed at tail water elevation (ft/sec)
D_1 = depth of flow entering the bucket computed at tail water elevation (ft)
F = Froude number of flow entering bucket computed at tail water elevation
R = bucket radius (ft)
T_{min} = minimum tail water depth limit (ft)
T_{max} = maximum tail water depth limit (ft)
T_s = tail water sweep out depth (ft)

Line 10 from Figure 48
Line 17 from Figure 41
Line 21 from Figure 43
Line 23 from Figure 44
Line 25 from Figure 46

FIGURE 1

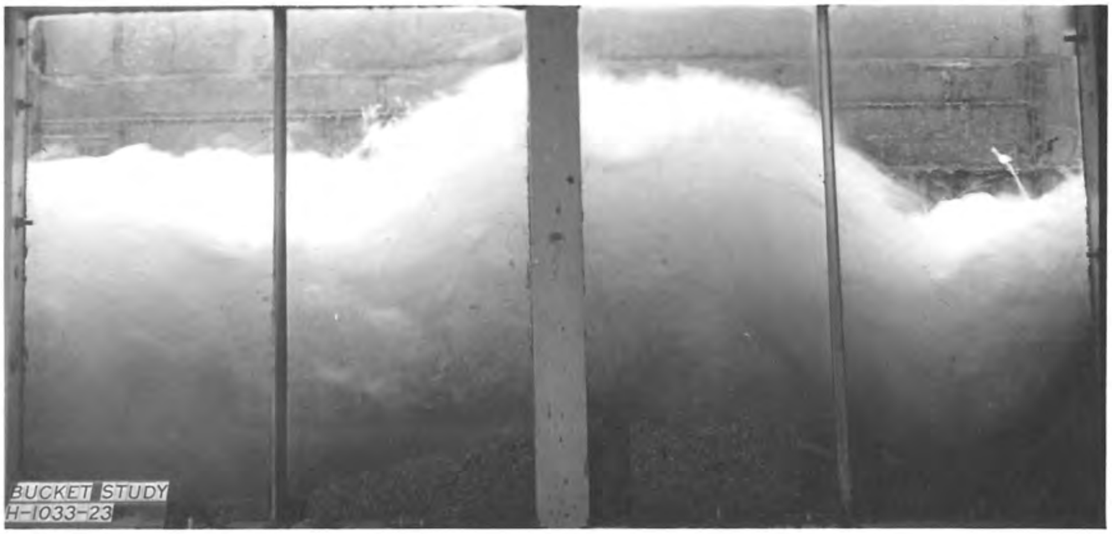


A- GRANDE COULEE TYPE SOLID BUCKET



B- ANGOSTURA TYPE SLOTTED BUCKET

BUCKET ENERGY DISSIPATORS



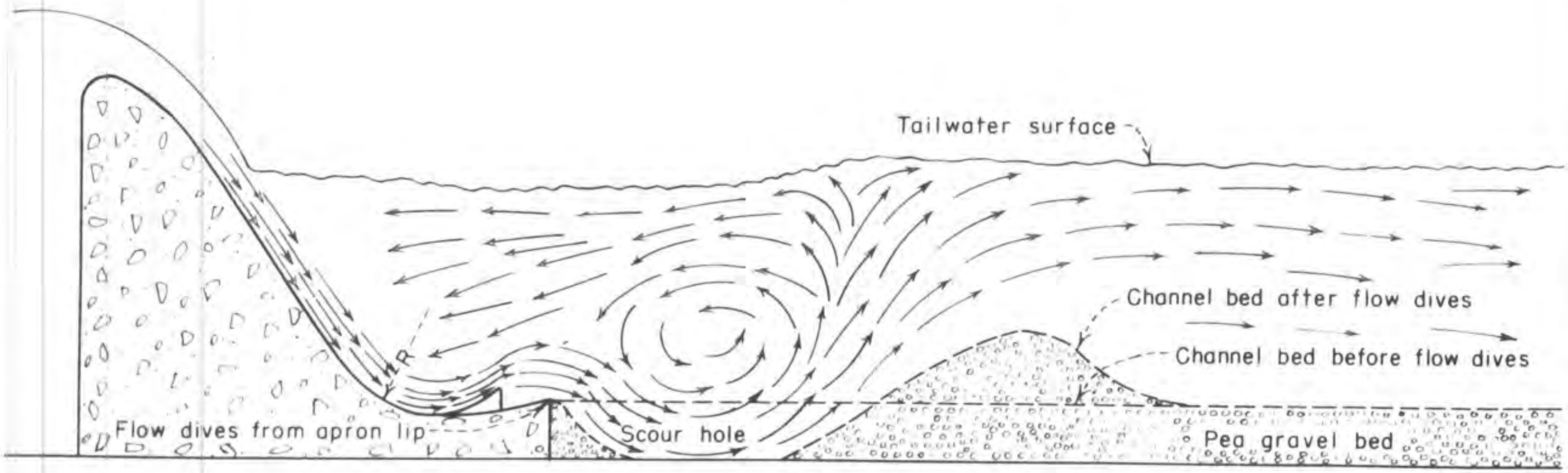
A. Solid type bucket

B. Angostura slotted type bucket

Bucket radius 12 inches, discharge 6 cfs, tail-water depth 2.3 feet

F = 4.4

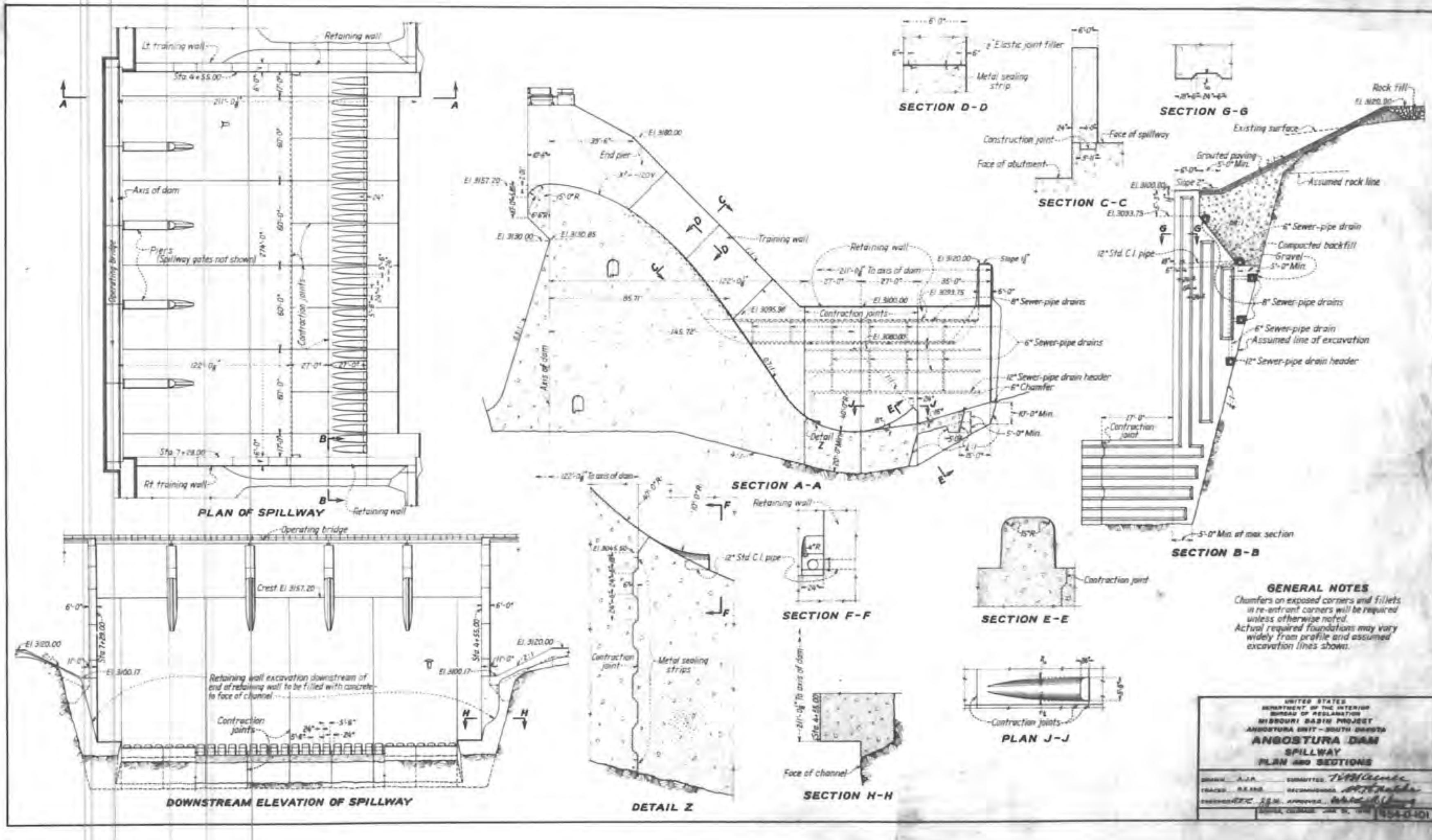
PERFORMANCE OF THE SLOTTED AND SOLID BUCKETS



Note: The diving flow condition occurs with the use of the Angostura-type bucket only when the tailwater depth becomes too great.

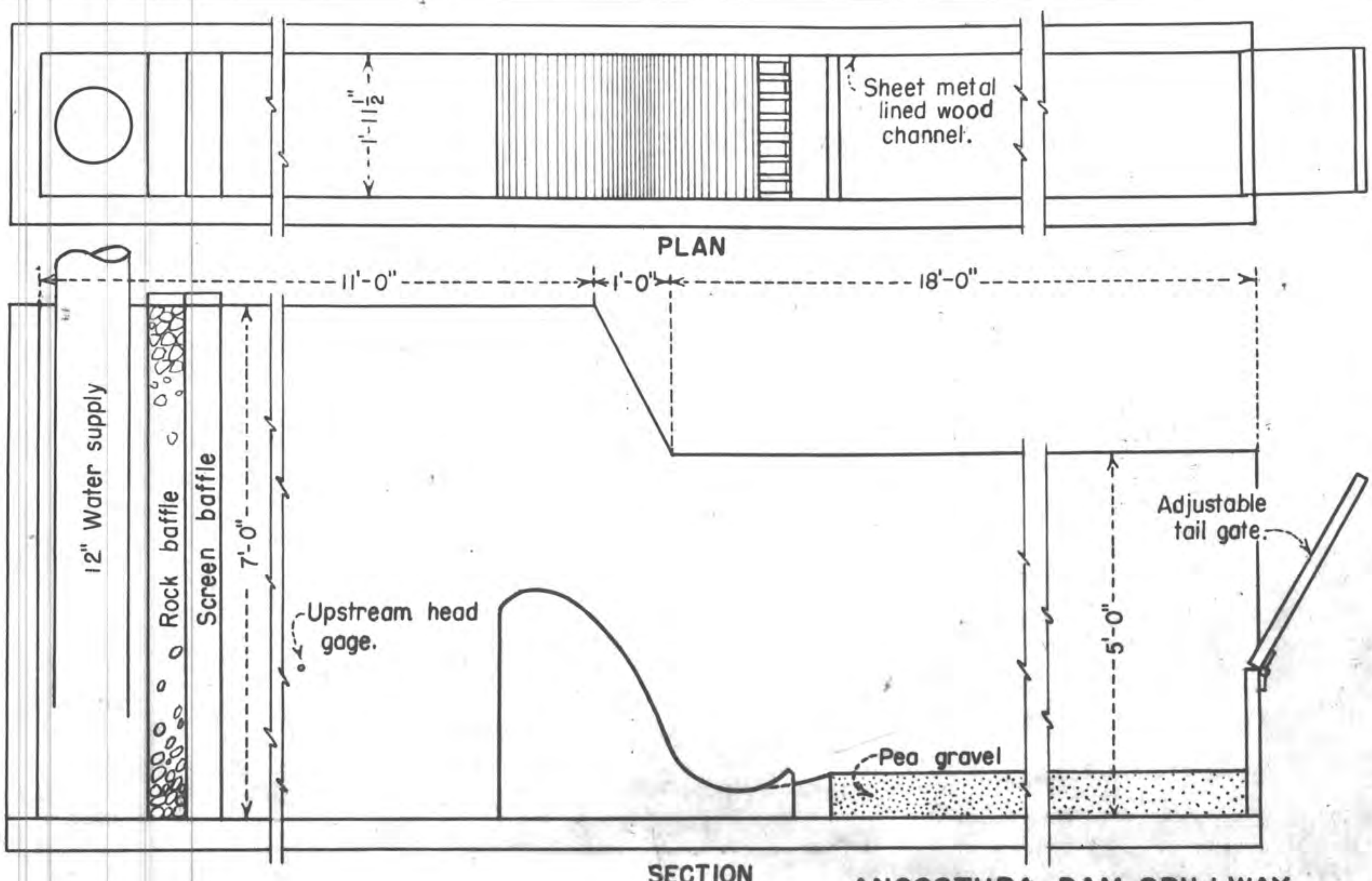
DIVING FLOW CONDITION

FIGURE 3



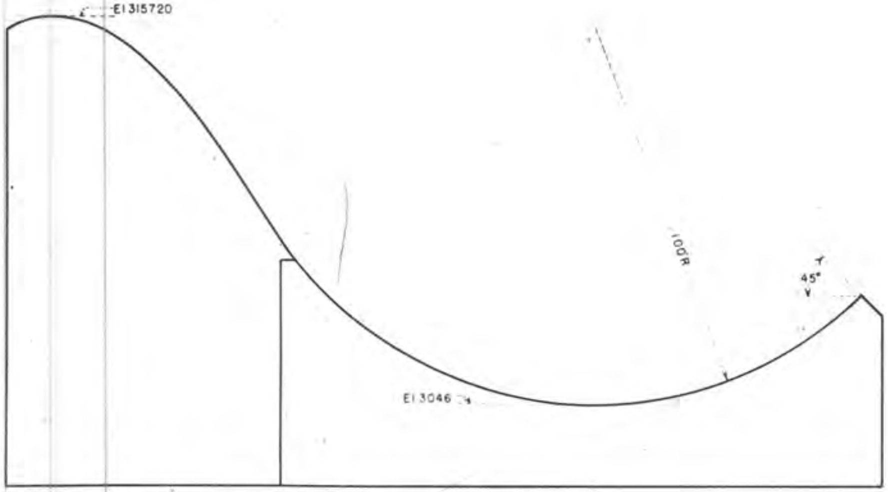
PLAN OF SPILLWAY
Lt training wall
Retaining wall
Sta 4+55.00
Axis of dam
Piers (Spillway gates not shown)
Operating bridge
Contraction joints
Sta 7+28.00
Rt training wall
SECTION A-A
End pier
Training wall
Retaining wall
Contraction joints
8" Sewer-pipe drains
6" Sewer-pipe drains
12" Sewer-pipe drain header
6" Chamfer
Detail Z
SECTION D-D
Elastic joint filler
Metal sealing strip
SECTION C-C
Construction joint
Face of spillway
Face of abutment
SECTION G-G
SECTION B-B
Rock fill
Existing surface
Grouted paving
Assumed rock line
6" Sewer-pipe drain
Compacted backfill
Gravel
8" Sewer-pipe drains
Assumed line of excavation
12" Sewer-pipe drain header
12" Std C.I. pipe
Contraction joint
5'-0" Min at max section
DOWNSTREAM ELEVATION OF SPILLWAY
Operating bridge
Crest El 3157.20
Retaining wall excavation downstream of end of retaining wall to be filled with concrete to face of channel
Contraction joints
DETAIL Z
Contraction joint
Metal sealing strips
SECTION F-F
12" Std C.I. pipe
SECTION H-H
Face of channel
SECTION E-E
Contraction joint
PLAN J-J
Contraction joints
GENERAL NOTES
Chamfers on exposed corners and fillets in re-entrant corners will be required unless otherwise noted.
Actual required foundations may vary widely from profile and assumed excavation lines shown.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI BASIN PROJECT
ANGOSTURA UNIT—SOUTH DAKOTA
ANGOSTURA DAM
SPILLWAY
PLAN AND SECTIONS

FIGURE 4



ANGOSTURA DAM SPILLWAY
HYDRAULIC MODEL STUDIES
SCALE 1:42 SECTIONAL MODEL

FIGURE 5

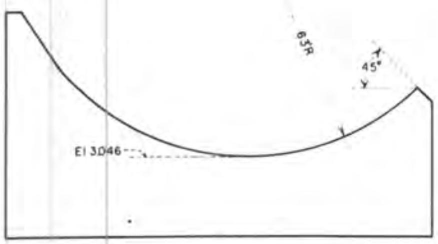


CREST AND 100' RADIUS BUCKET

DESIGN 1

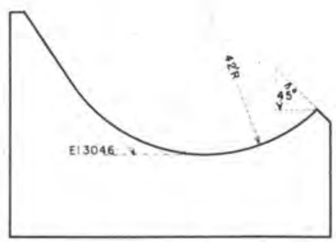
42' RADIUS BUCKET-15° LIP

DESIGN 4



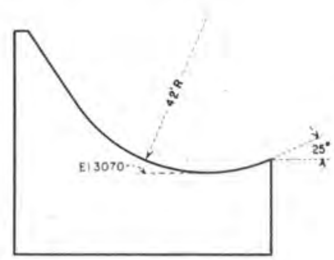
63' RADIUS BUCKET

DESIGN 2



42' RADIUS BUCKET

DESIGN 3



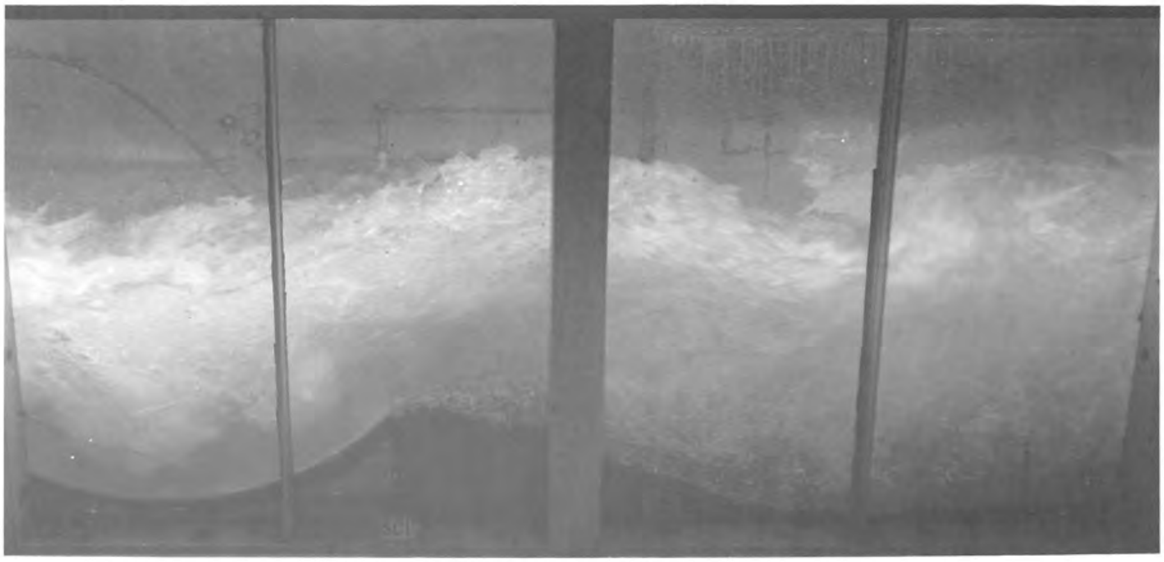
42' RADIUS BUCKET-25° LIP

DESIGN 5

MISSOURI BASIN PROJECT
ANGOSTURA UNIT-SOUTH DAKOTA
ANGOSTURA DAM SPILLWAY
HYDRAULIC MODEL STUDIES
PRELIMINARY SOLID BUCKETS

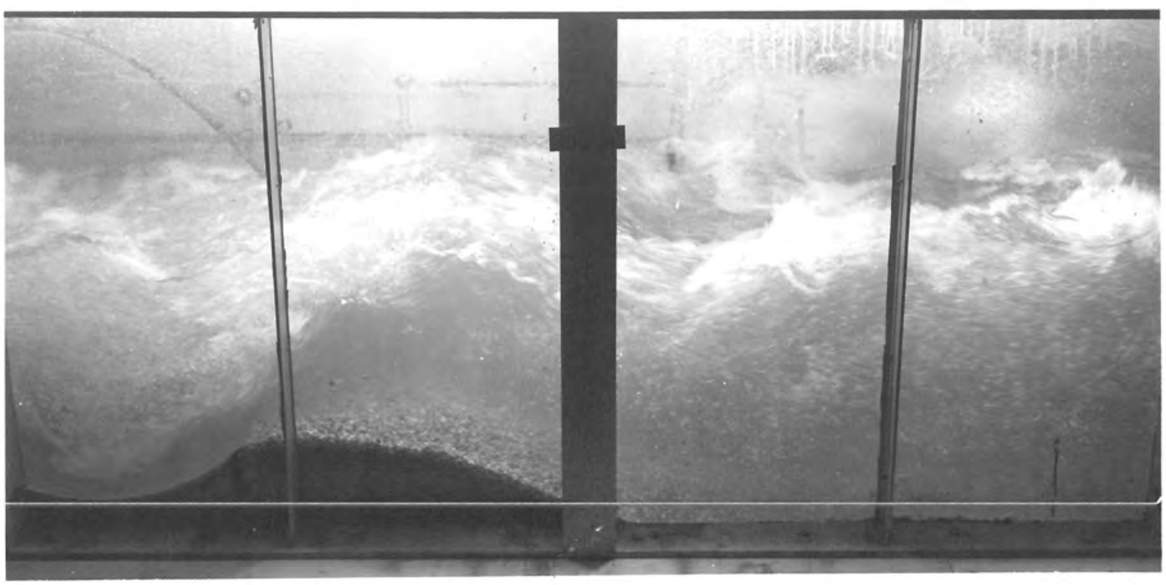
FIGURE 6

FIGURE 7



A - Flow of 277,000 second-feet.

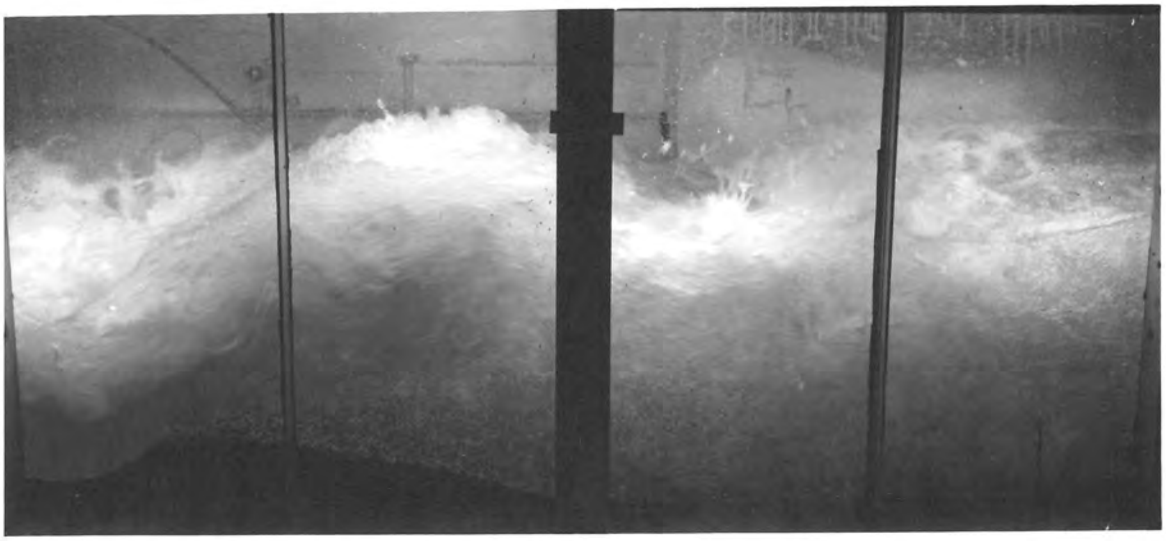
100 FOOT RADIUS BUCKET WITH DOWNSTREAM
LIP ON 45° TANGENT



B - Flow of 277,000 second-feet

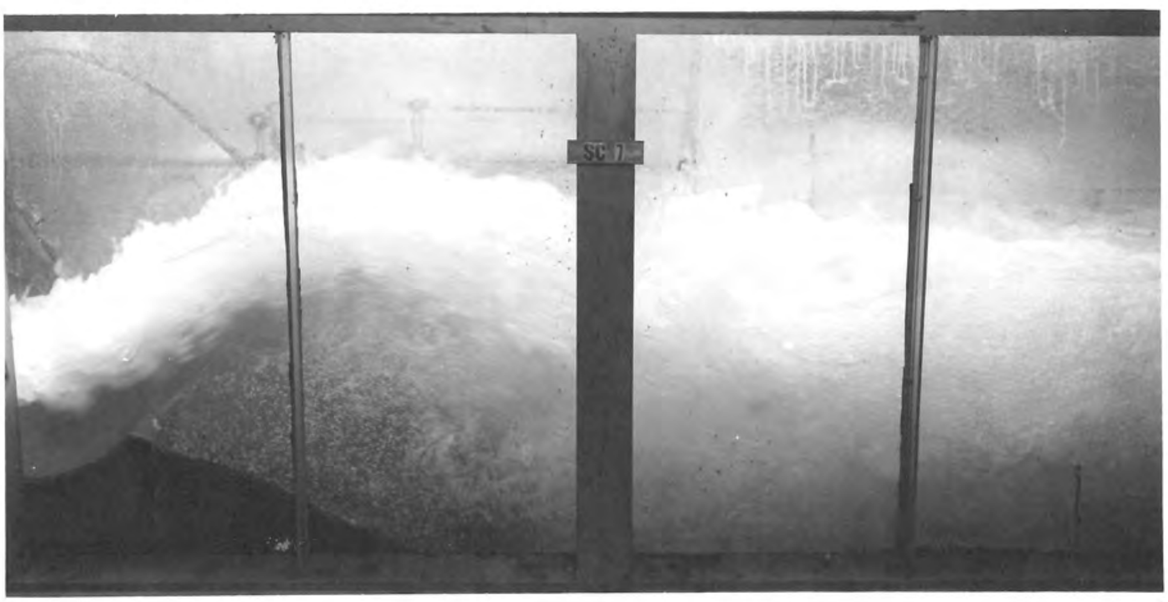
63 FOOT RADIUS BUCKET WITH DOWNSTREAM
LIP ON 45° TANGENT

ANGOSTURA DAM SPILLWAY
SECTIONAL MODEL ON 1:42 SCALE
PERFORMANCE OF SOLID BUCKETS



A - Flow of 277,000 second-feet 42 foot radius bucket.

42 FOOT RADIUS BUCKETS WITH DOWNSTREAM
LIP ON 45° TANGENT

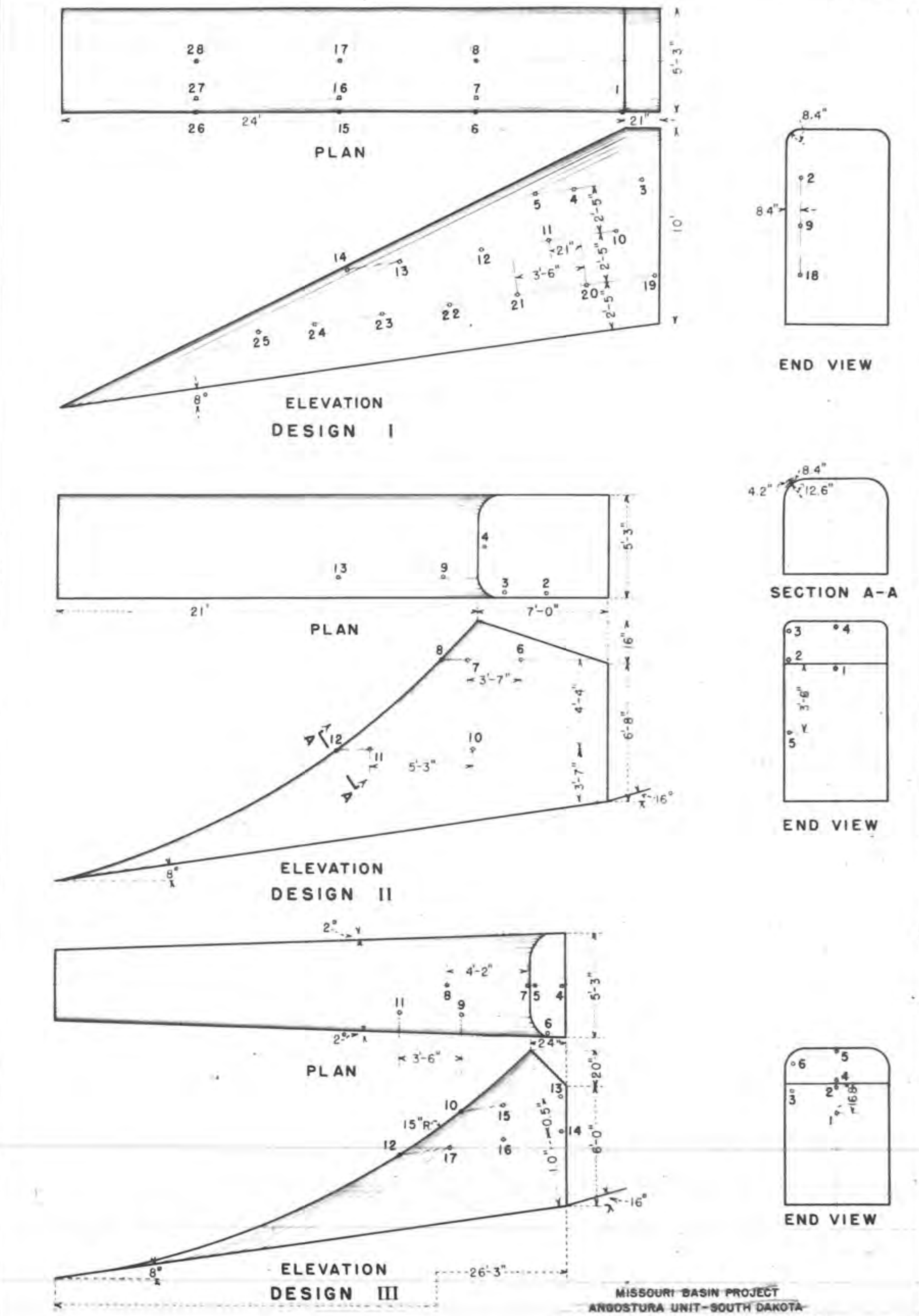


B - Flow of 277,000 second-feet.

42 FOOT RADIUS BUCKET WITH DOWNSTREAM LIP
ON 15° TANGENT

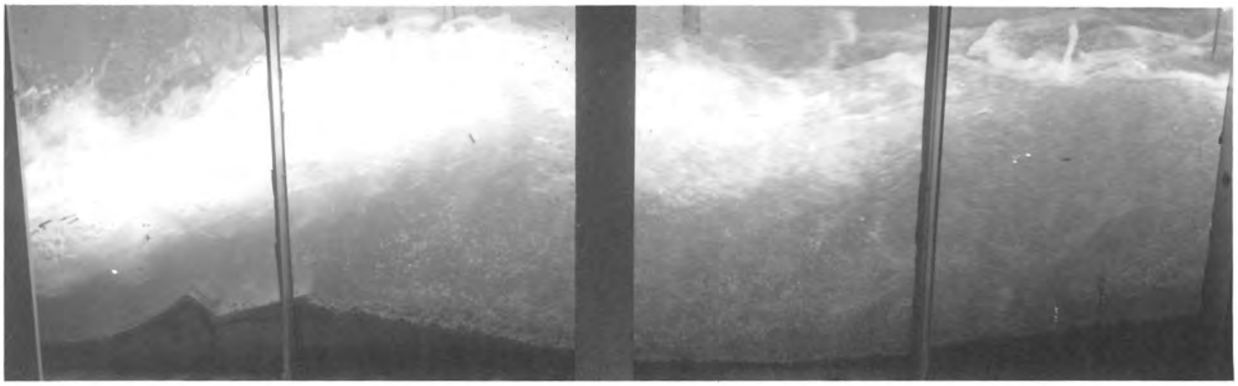
ANGOSTURA DAM SPILLWAY
SECTIONAL MODEL ON 1:42 SCALE
PERFORMANCE OF SOLID BUCKETS

FIGURE 9



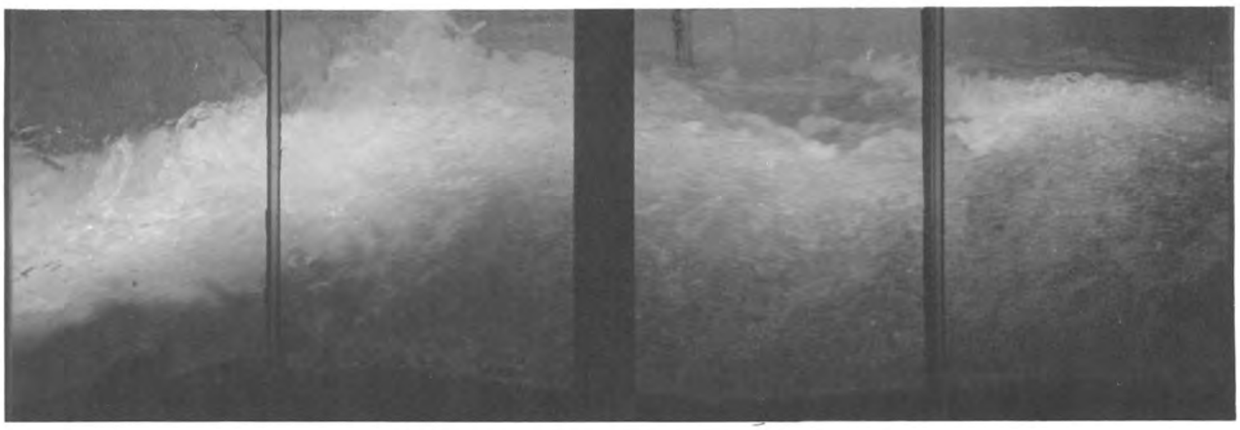
MISSOURI BASIN PROJECT
ANGOSTURA UNIT-SOUTH DAKOTA
ANGOSTURA DAM SPILLWAY
SHAPE OF TEETH AND LOCATION OF PIEZOMETERS

Figure 10



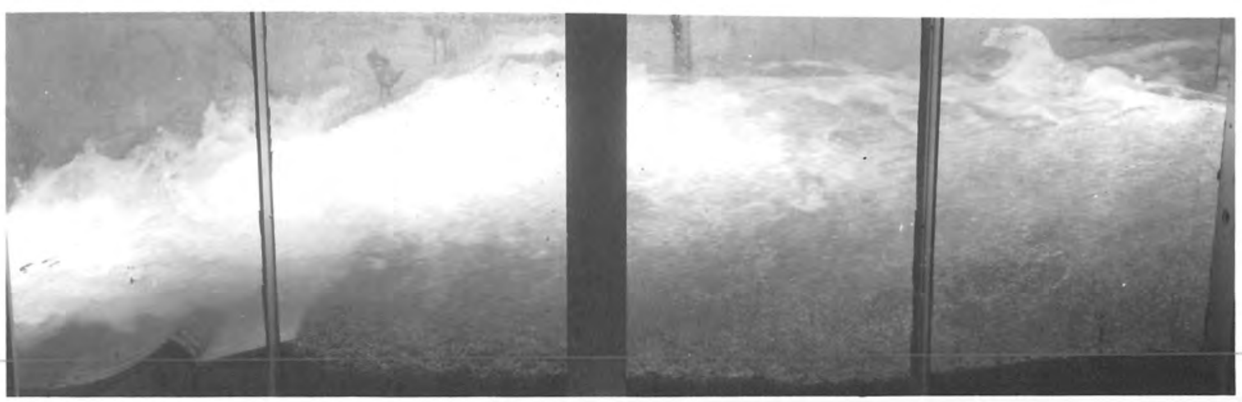
A - Flow of 277,000 second-feet.

3 TO 1 TOOTH SPACING



B - Flow of 277,000 second-feet.

2 TO 1 TOOTH SPACING



C - Flow of 277,000 second-feet.

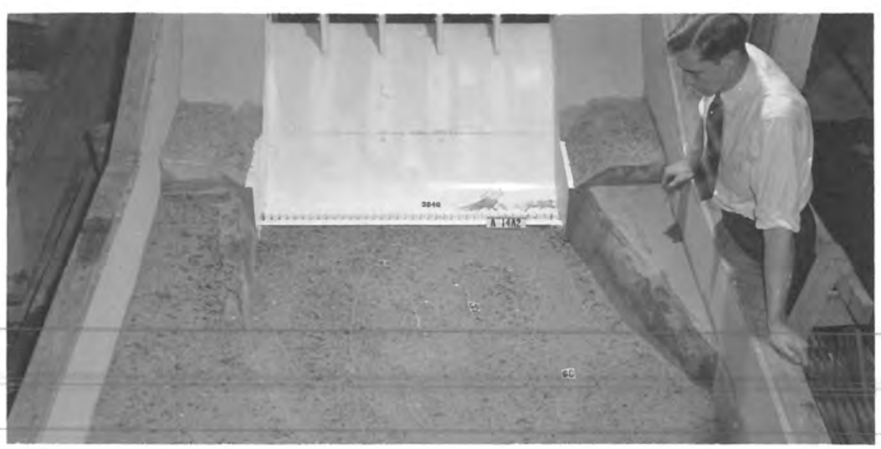
1 TO 1 TOOTH SPACING

ANGOSTURA DAM SPILLWAY
SECTIONAL MODEL ON 1.42 SCALE
TOOTH SPACING TEST

Figure 11

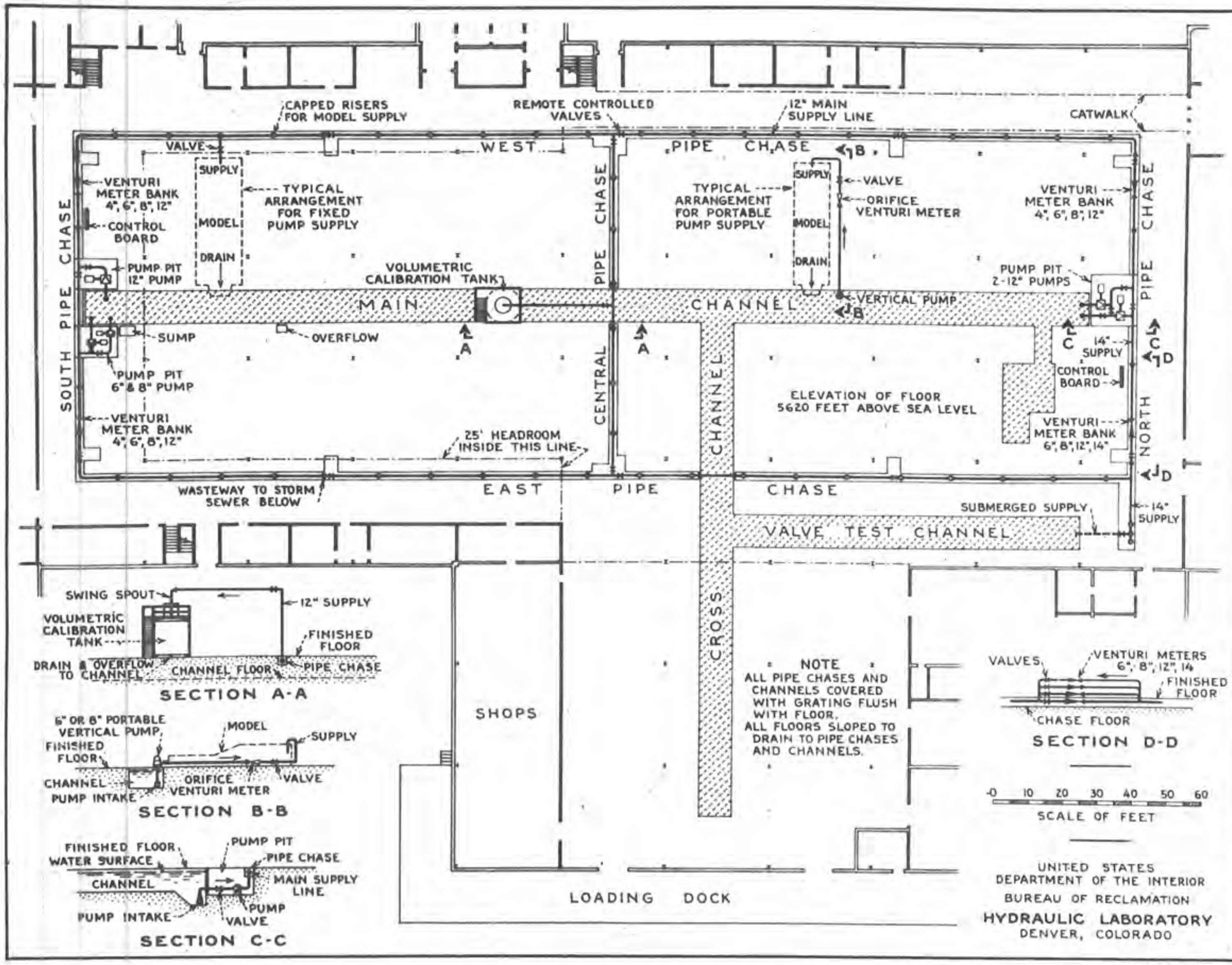
A - Flow of 277,000 second-feet over spillway.

B - Erosion after flow of 277,000 second-feet for 20 minutes.



C - Erosion after flow of 277,000 second-feet for 1.5 hours.

ANGOSTURA DAM SPILLWAY MODEL (scale 1:72)
EROSION TEST - RECOMMENDED DESIGN

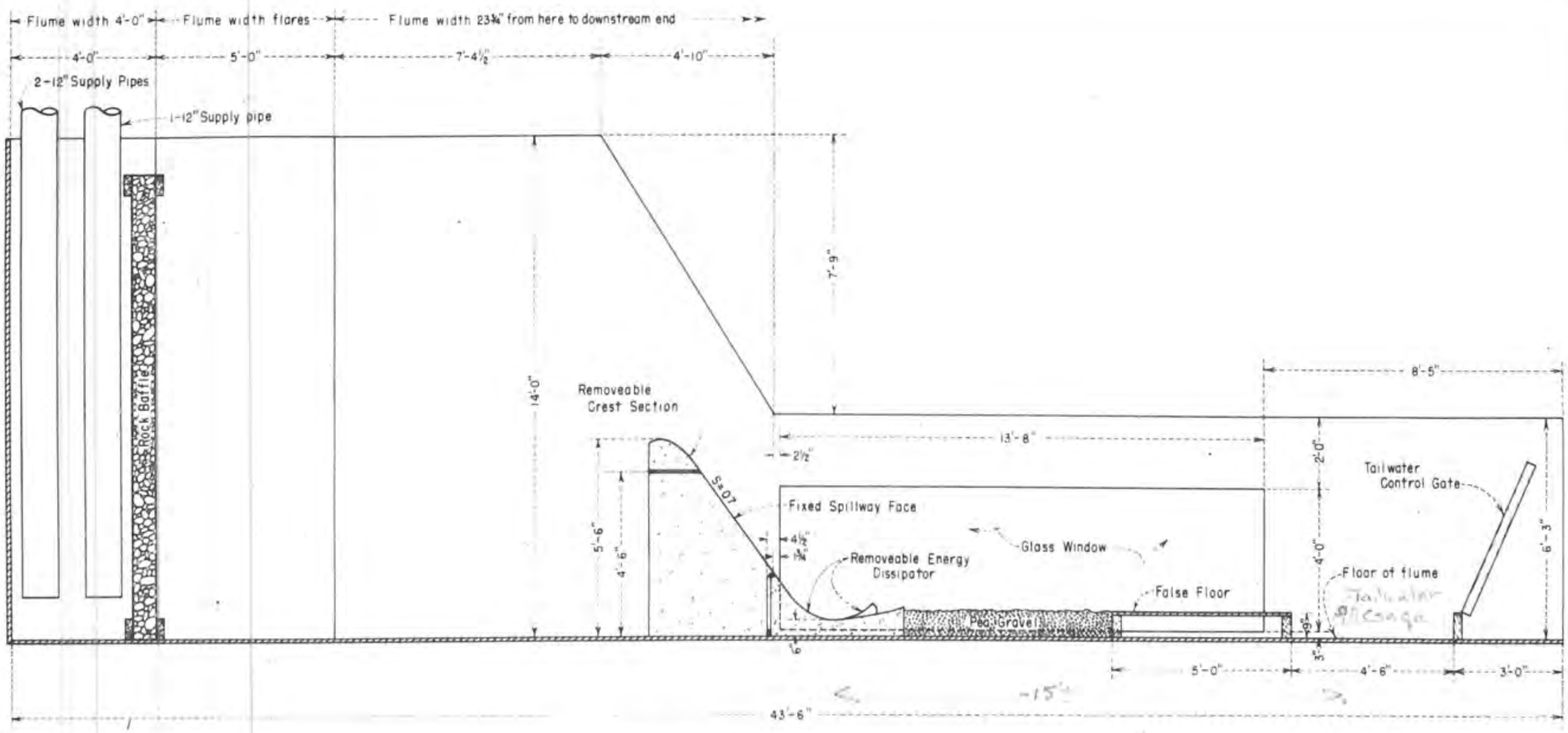


CAPPED RISERS FOR MODEL SUPPLY
REMOTE CONTROLLED VALVES
12" MAIN SUPPLY LINE
CATWALK
VALVE
WEST PIPE CHASE
SUPPLY
MODEL
DRAIN
TYPICAL ARRANGEMENT FOR FIXED PUMP SUPPLY
TYPICAL ARRANGEMENT FOR PORTABLE PUMP SUPPLY
VALVE
ORIFICE VENTURI METER
VENTURI METER BANK 4", 6", 8", 12"
CONTROL BOARD
PUMP PIT 12" PUMP
VOLUMETRIC CALIBRATION TANK
MAIN CHANNEL
VERTICAL PUMP
PUMP PIT 2-12" PUMPS
SUMP
OVERFLOW
PUMP PIT 6" & 8" PUMP
SOUTH PIPE CHASE
CENTRAL PIPE CHASE
NORTH PIPE CHASE
CROSS CHANNEL
14" SUPPLY
CONTROL BOARD
ELEVATION OF FLOOR 5620 FEET ABOVE SEA LEVEL
VENTURI METER BANK 4", 6", 8", 12"
VENTURI METER BANK 6", 8", 12", 14"
25' HEADROOM INSIDE THIS LINE
WASTEWAY TO STORM SEWER BELOW
EAST PIPE CHASE
SUBMERGED SUPPLY
14" SUPPLY
VALVE TEST CHANNEL
SWING SPOUT
12" SUPPLY
VOLUMETRIC CALIBRATION TANK
FINISHED FLOOR
DRAIN & OVERFLOW TO CHANNEL
CHANNEL FLOOR
PIPE CHASE
SECTION A-A
6" OR 8" PORTABLE VERTICAL PUMP
MODEL
SUPPLY
FINISHED FLOOR
CHANNEL
ORIFICE VENTURI METER
VALVE
PUMP INTAKE
SECTION B-B
FINISHED FLOOR
WATER SURFACE
PUMP PIT
PIPE CHASE
CHANNEL
MAIN SUPPLY LINE
PUMP
PUMP INTAKE
VALVE
SECTION C-C
SHOPS
NOTE
ALL PIPE CHASES AND CHANNELS COVERED WITH GRATING FLUSH WITH FLOOR.
ALL FLOORS SLOPED TO DRAIN TO PIPE CHASES AND CHANNELS.
VALVES
VENTURI METERS 6", 8", 12", 14
FINISHED FLOOR
CHASE FLOOR
SECTION D-D
0 10 20 30 40 50 60
SCALE OF FEET
LOADING DOCK
UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
HYDRAULIC LABORATORY
DENVER, COLORADO

FIGURE 12


Head-water gage.
Tail-water control
gate switch.
Tail-water gage.

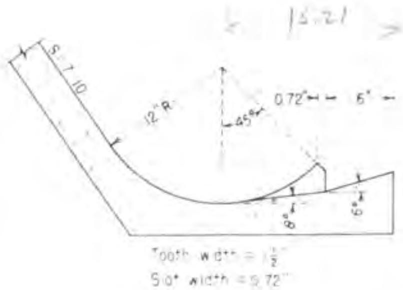
TEST FLUME



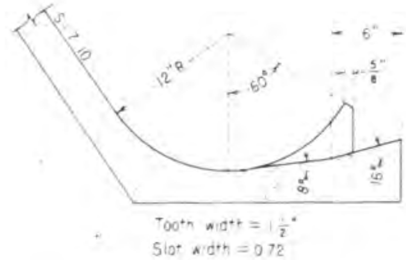
SECTION ON ℄ OF TEST FLUME

SECTIONAL MODEL SPILLWAY

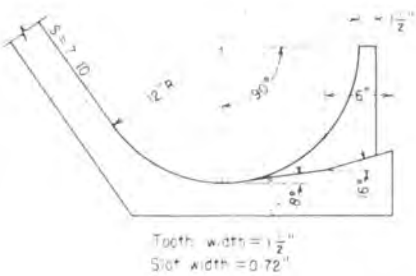
FIGURE 14



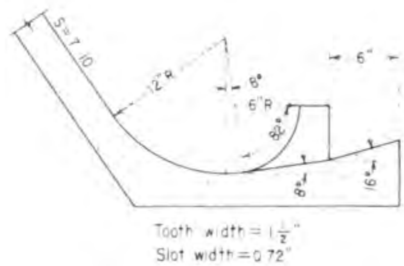
ANGOSTURA TYPE SLOTTED BUCKET



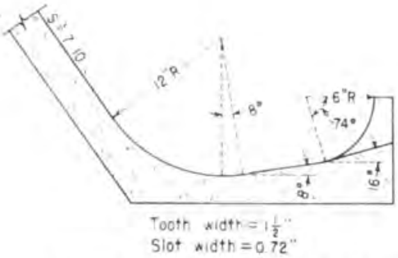
SLOTTED BUCKET MODIFICATION I



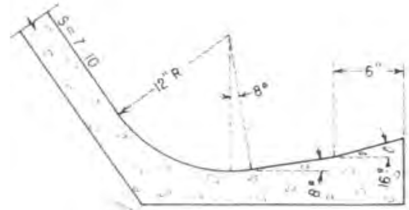
SLOTTED BUCKET MODIFICATION II



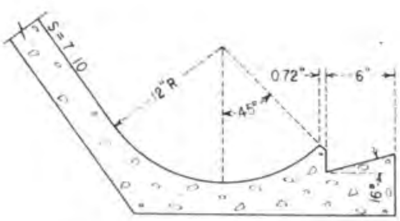
SLOTTED BUCKET MODIFICATION III



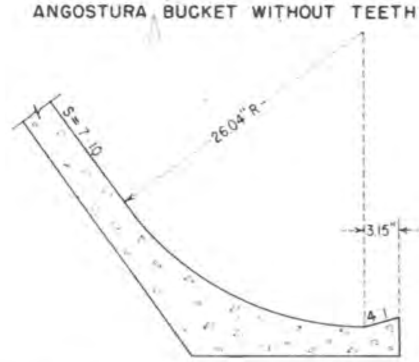
SLOTTED BUCKET MODIFICATION IV



ANGOSTURA BUCKET WITHOUT TEETH



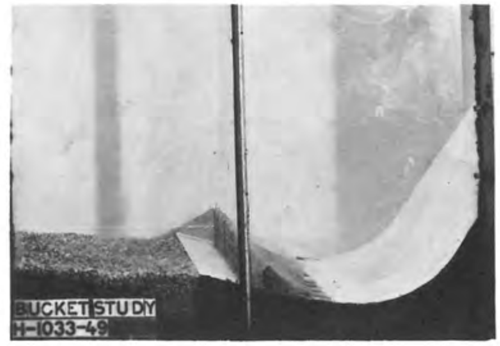
SOLID BUCKET WITHOUT SLOTS



BLACK CANYON TYPE BUCKET

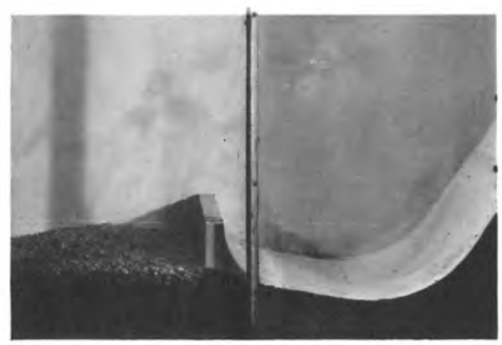
BUCKET DESIGNS TESTED

Angostura type slotted bucket



Slotted bucket Modification I

Slotted bucket Modification II

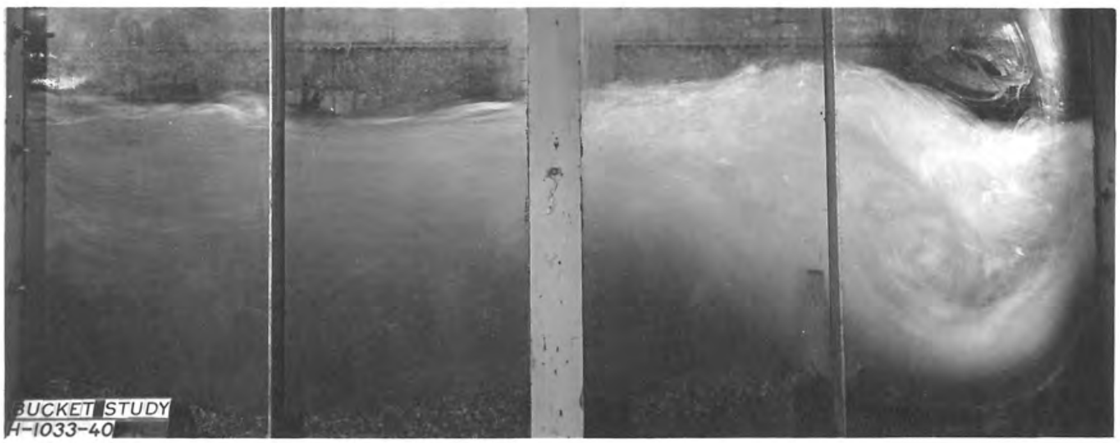


Slotted bucket Modification ~~III~~ IV

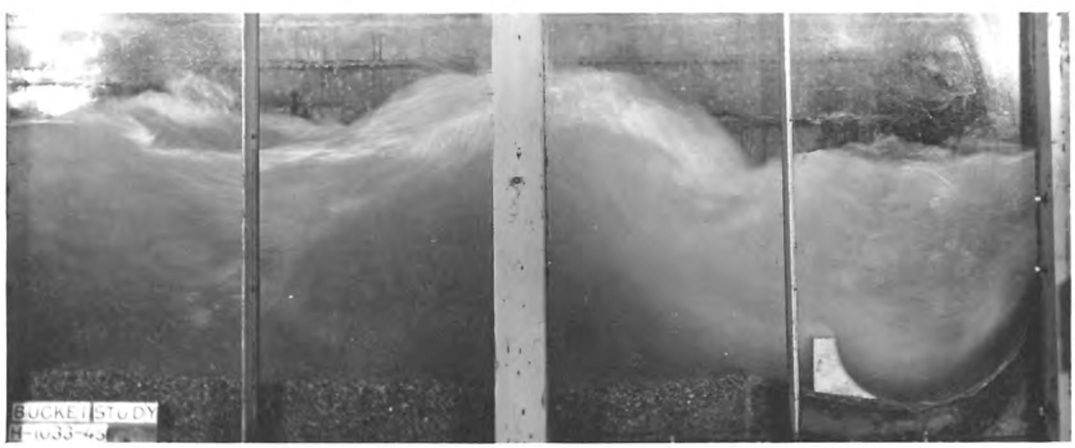
Slotted bucket Modification ~~IV~~ III

SLOTTED BUCKET MODIFICATIONS TESTED

A. Slotted bucket Modification I



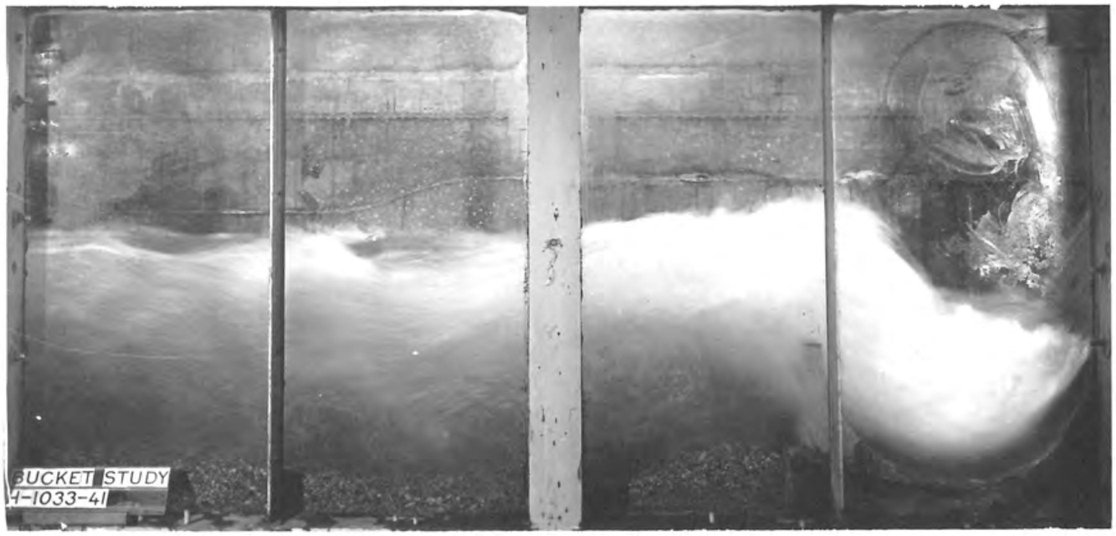
B. Slotted bucket Modification II



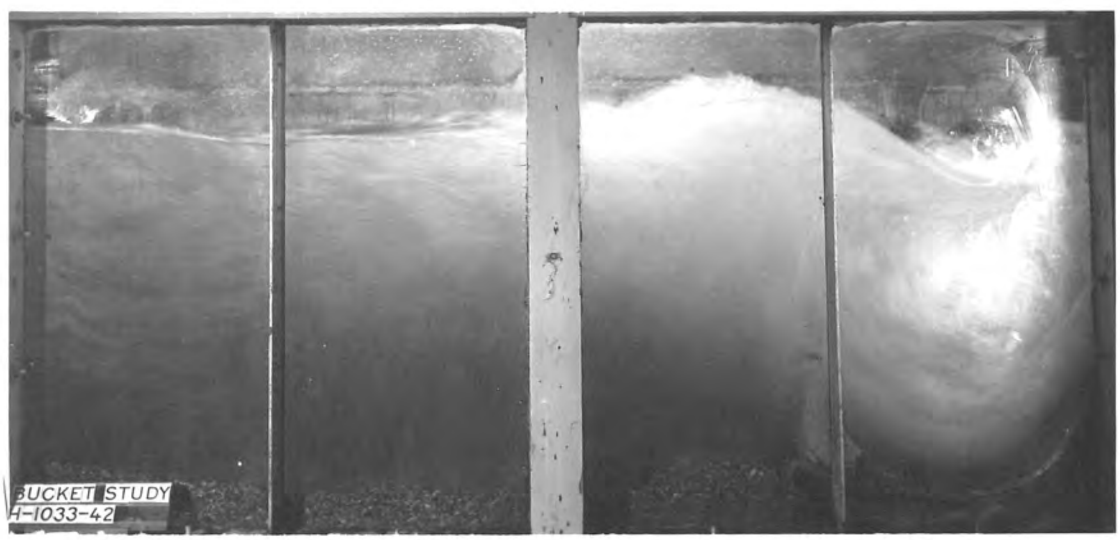
C. Slotted bucket Modification III

Bucket radius 12 inches, discharge 6 cfs, tail-water depth 2.3 feet

PERFORMANCE OF MODIFIED SLOTTED BUCKETS

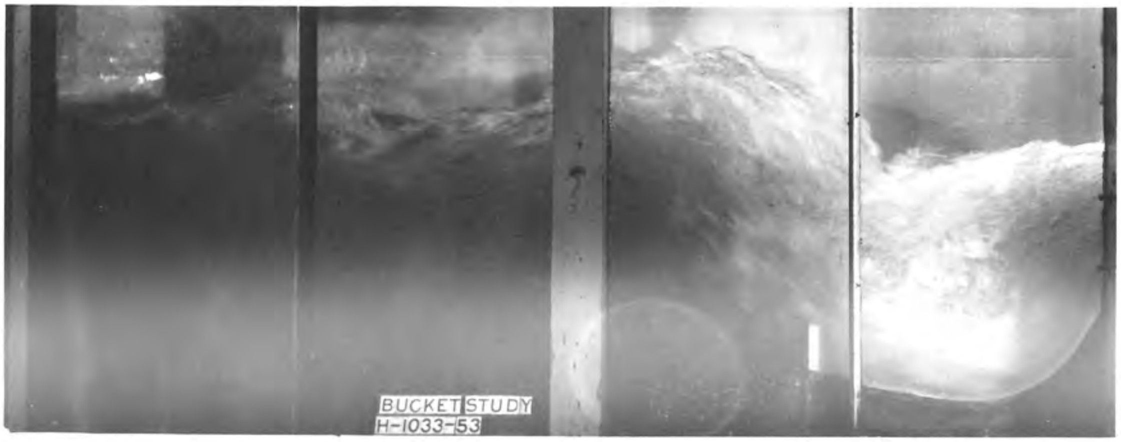


A. Discharge 6 cfs, tail-water depth 1.65 feet

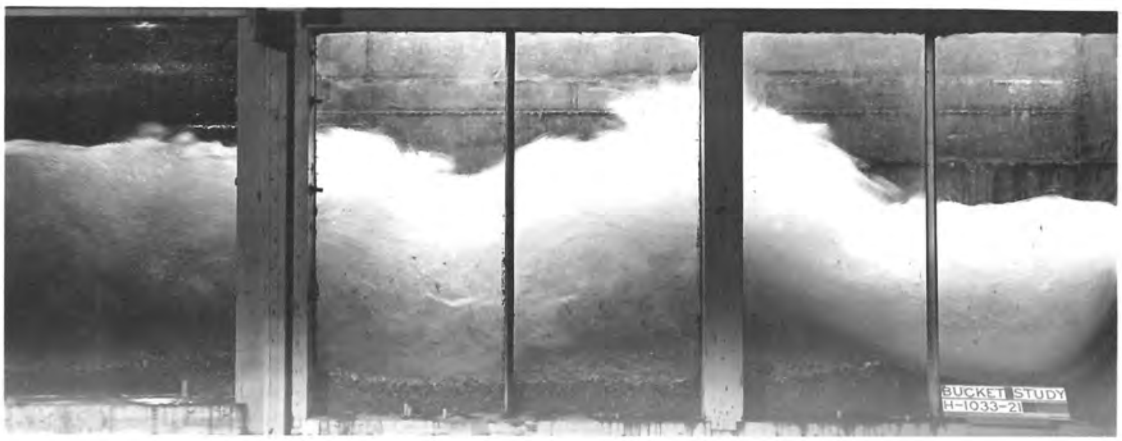


B. Discharge 6 cfs, tail-water depth 2.8 feet

PERFORMANCE OF 12-INCH SLOTTED BUCKET MODIFICATION II



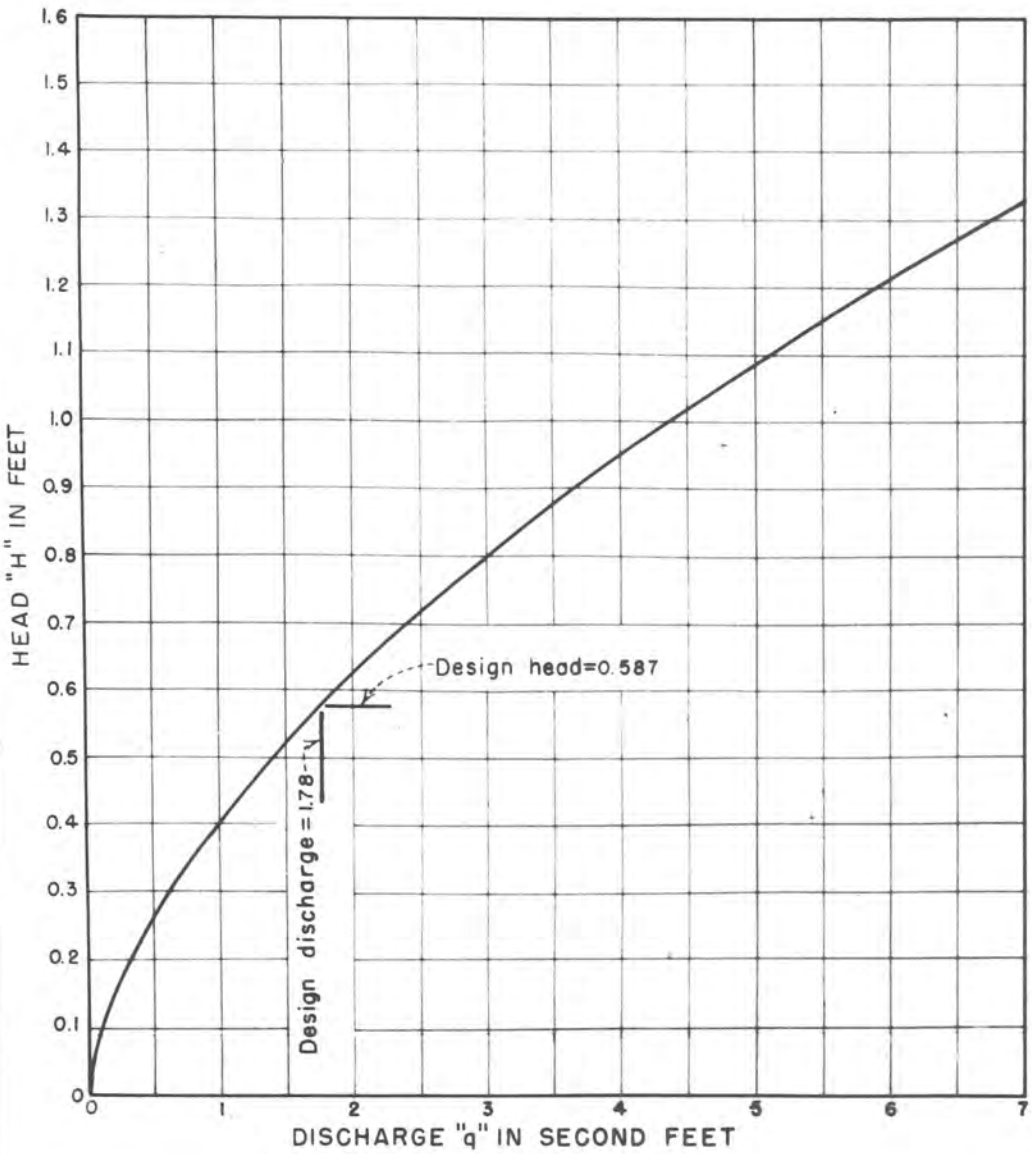
A. Slotted bucket Modification IV
Bucket radius 12 inches, discharge 6 cfs, tail-water depth 2.3 feet



B. Angostura type bucket without slots and teeth
Bucket radius 12 inches, discharge 6 cfs, tail-water depth 2.3 feet

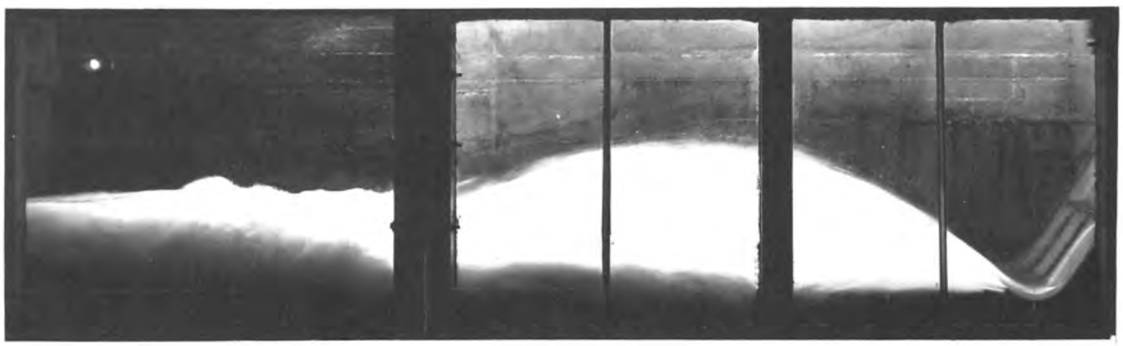
C. Black Canyon type bucket
Bucket radius 26.04 inches, discharge 3.36 cfs, tail-water depth 2.22 feet

PERFORMANCE OF MODIFIED ANGOSTURA BUCKETS AND THE BLACK CANYON BUCKET

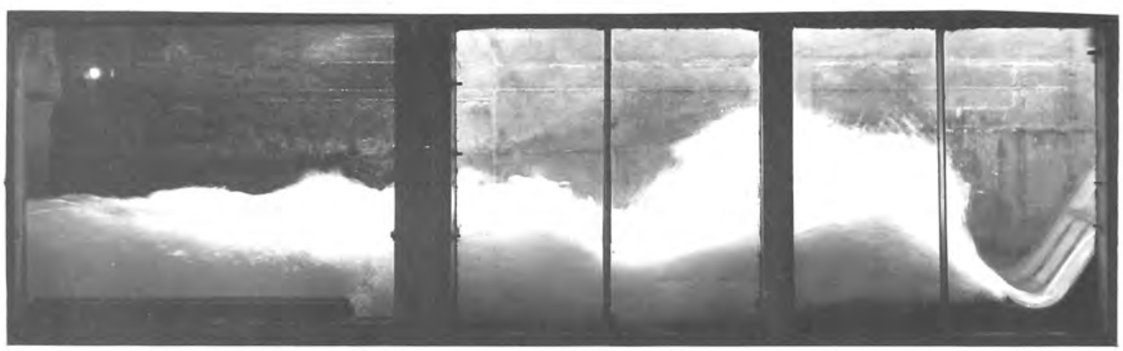


DISCHARGE CALIBRATION OF THE 5-FOOT MODEL SPILLWAY

A. Flow is about to sweepout of bucket as tail-water depth is decreasing



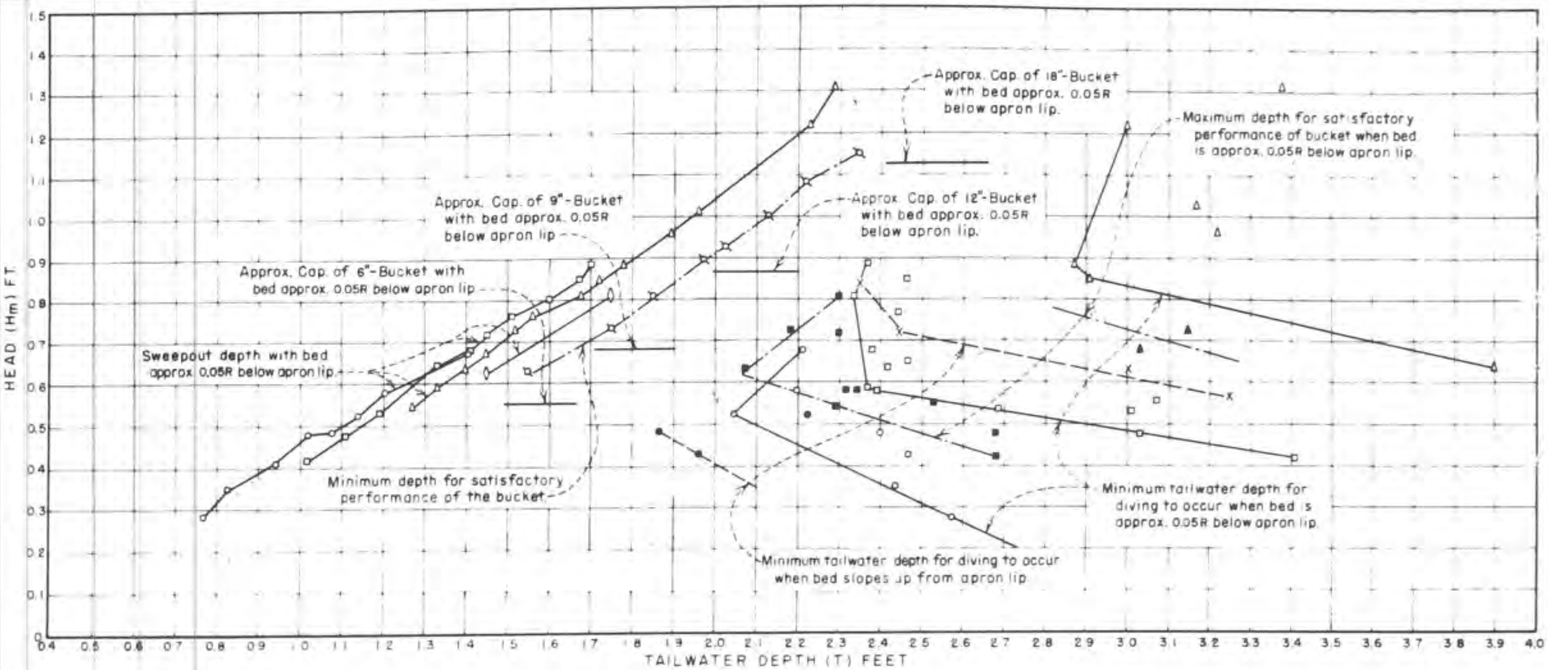
B. Flow is sweeping out as tail-water elevation is below sweepout depth.



C. Flow is about to fall back into bucket as tail-water depth is decreasing.

Note: Bed elevation at beginning of test run was approximately 0.3 inch below apron lip.

6-INCH BUCKET DISCHARGING 3.5 SECOND-FEET



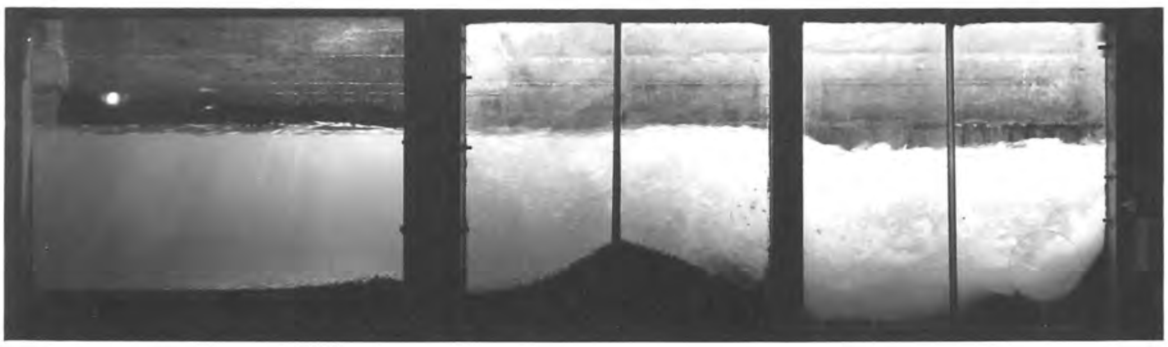
BUCKET RADIUS (R) INCHES	APPROX. CAPACITY OF BUCKET (q_m) CFS.	
	BED APPROX. 0.05R BELOW APRON LIP	
6	1.5 TO 1.75	
9	2.0 TO 2.5	
12	3.25 TO 3.5	
18	5.0 TO 5.5	

TEST DATA SYMBOLS	BUCKET RADIUS (R) INCHES	BED ARRANGEMENT	DESCRIPTION OF TEST DATA SYMBOLS
○	6	Bed approx 0.05R below apron lip	Tailwater sweepout depth and Min. tailwater depth at which diving occured
□	9	Bed approx 0.05R below apron lip	Tailwater sweepout depth and Min tailwater depth at which diving occured
△	12	Bed approx 0.05R below apron lip	Tailwater sweepout depth and Min tailwater depth at which diving occured
◊	18	Bed approx 0.05R below apron lip	Tailwater sweepout depth
⌑	18	Bed approx 0.05R below apron lip	Est Min tailwater depth for satisfactory performance of the bucket
■	9	Bed approx 0.05R below apron lip	Est Max tailwater depth for satisfactory performance of the bucket.
▲	12	Bed approx 0.05R below apron lip	Est Max tailwater depth for satisfactory performance of the bucket.
●	9	Bed sloped up from apron lip.	Min tailwater depth at which diving occured
x	12	Bed sloped up from apron lip.	Min tailwater depth at which diving occured

TAILWATER LIMITS AND BUCKET CAPACITIES

FIGURE 22

A. Normal operating conditions - tail-water depth between maximum and minimum limits being closer to the minimum



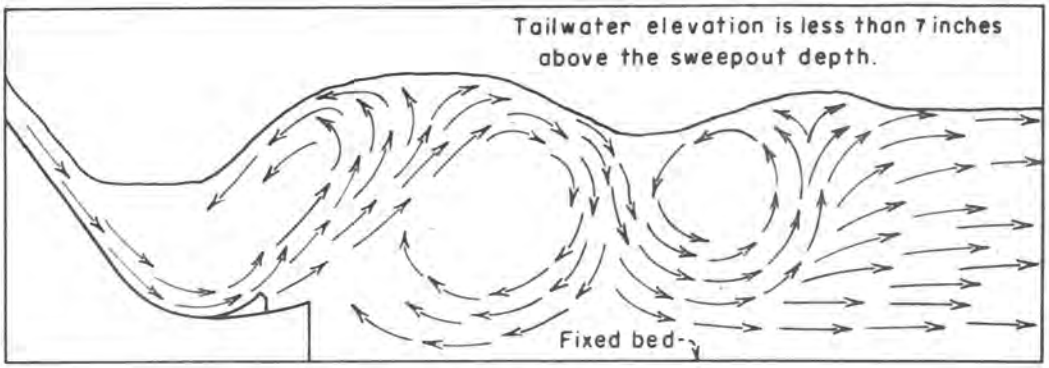
B. Flow is diving from the apron to scour the channel bed because tail-water depth exceeds maximum limit

C. Tail-water depth exceeds the maximum limit but flow from the apron is lifted to the surface by a ground roller flow pattern which develops after the channel bed has been scoured sufficiently deep and the ground roller back fills the erosion hole

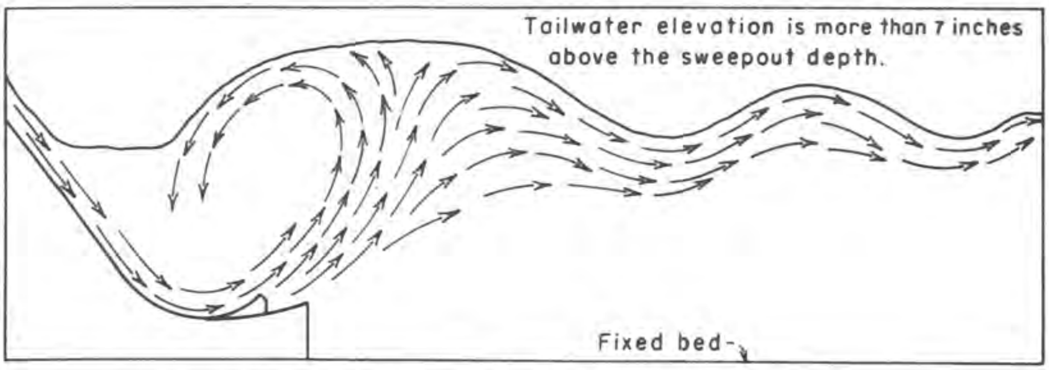
Note: Bed elevation at beginning of test run was approximately 0.3 inch below apron lip.

6-INCH BUCKET DISCHARGING 3.5 SECOND-FEET

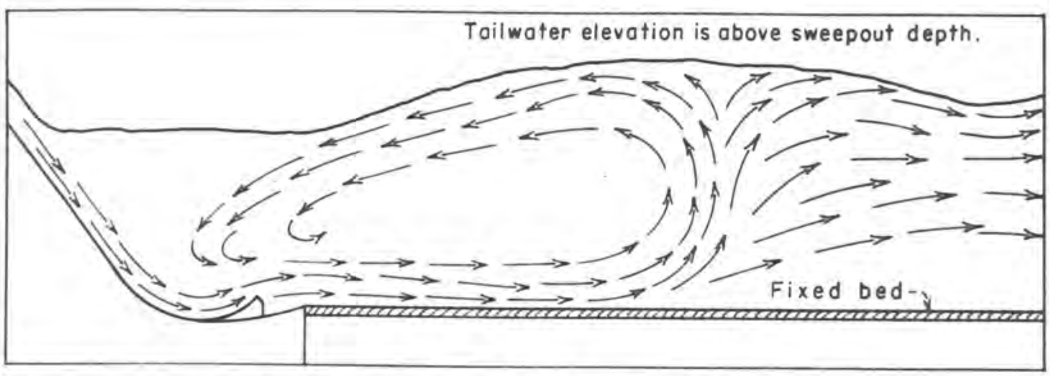
FIGURE 24



A. FIXED BED 6 INCHES BELOW BUCKET INVERT. DESIRABLE TAILWATER DEPTH



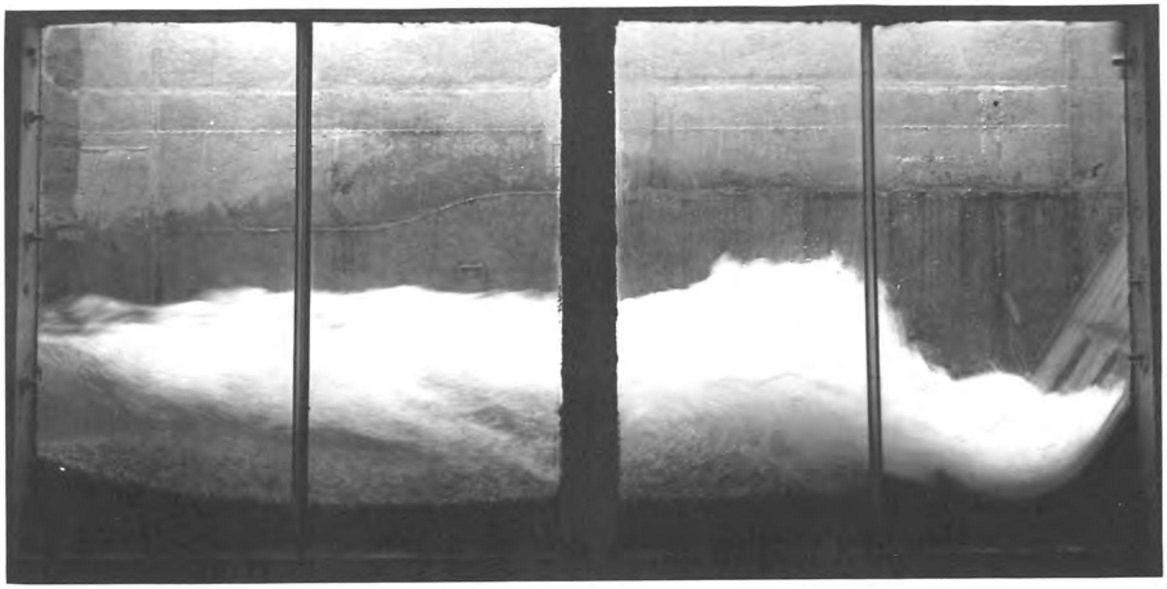
B. FIXED BED 6 INCHES BELOW BUCKET INVERT. LESS DESIRABLE TAILWATER DEPTH



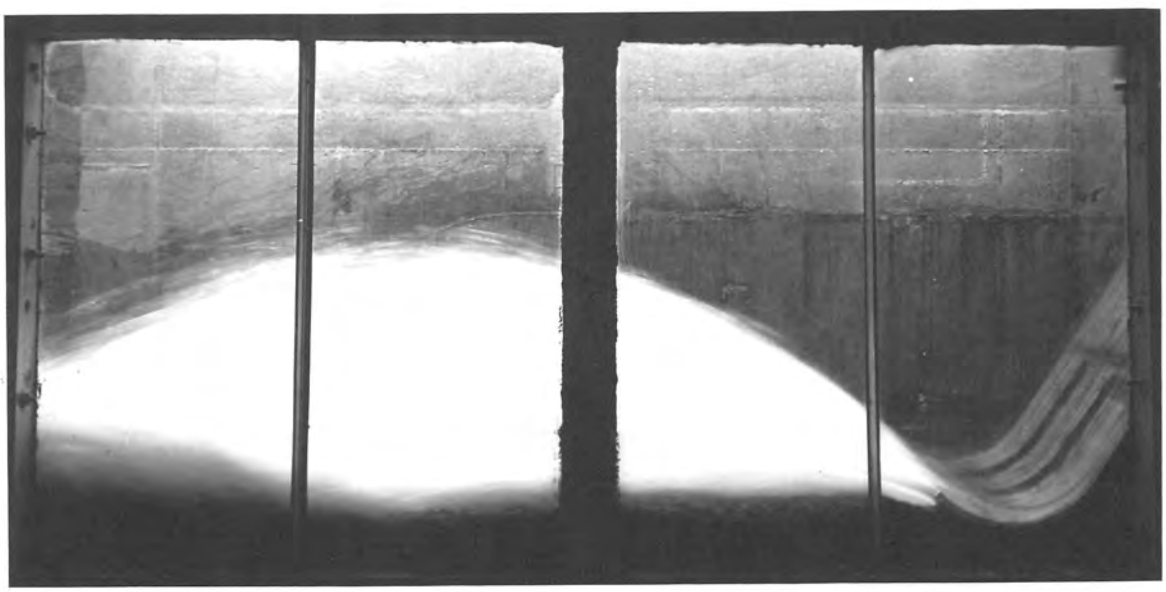
C. FIXED BED AT APRON LIP LEVEL

Note:
Bucket radius is 6 inches.
Discharge is 1.75 second feet per unit foot of width.

FLOW CURRENTS FOR VARIOUS ELEVATIONS OF THE BUCKET WITH RESPECT TO BED AND TAILWATER ELEVATIONS



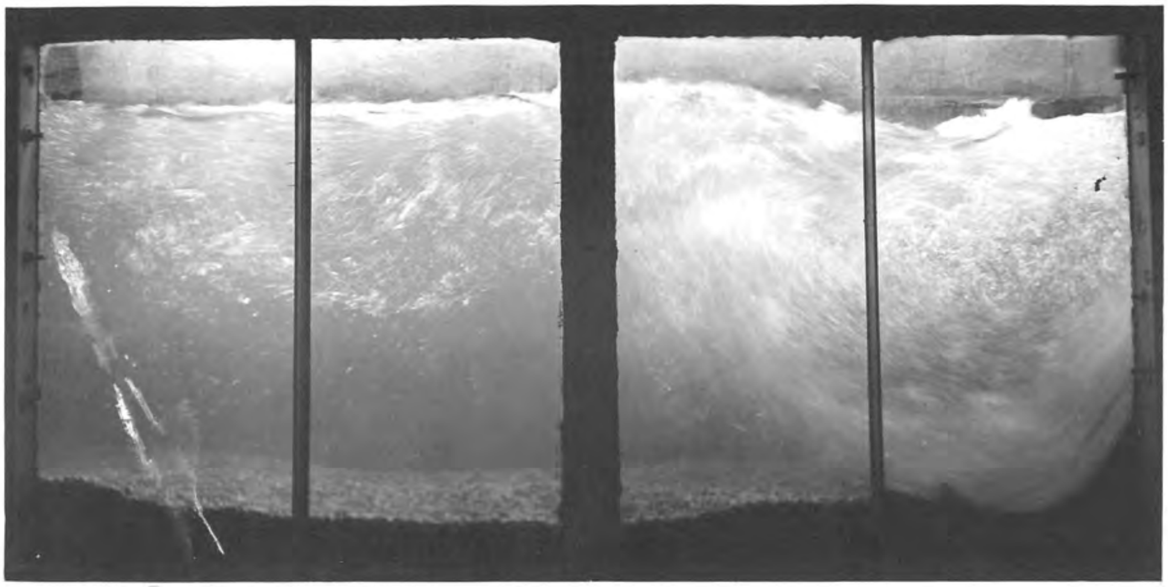
A. Tail-water elevation near sweepout depth



B. Tail-water elevation below the sweepout depth

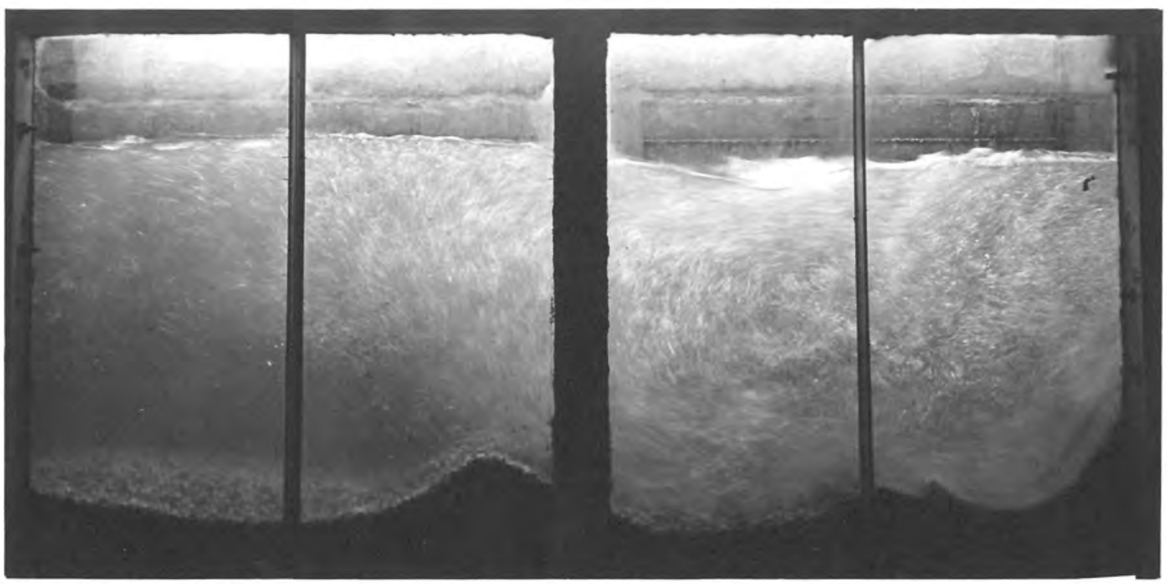
Note: Bed elevation at beginning of test run was approximately 0.5 inch below apron lip.

9-INCH BUCKET DISCHARGING 3 SECOND-FEET



H-1033-15

A. Flow is about to dive from the apron lip - maximum tail-water depth limit has been exceeded

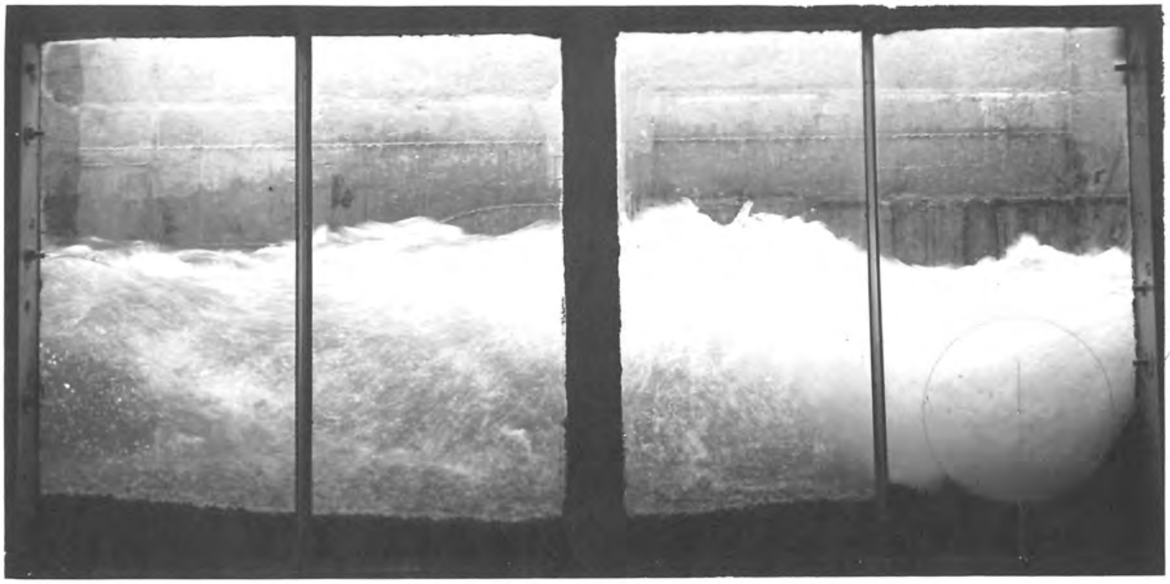


H-1033-14

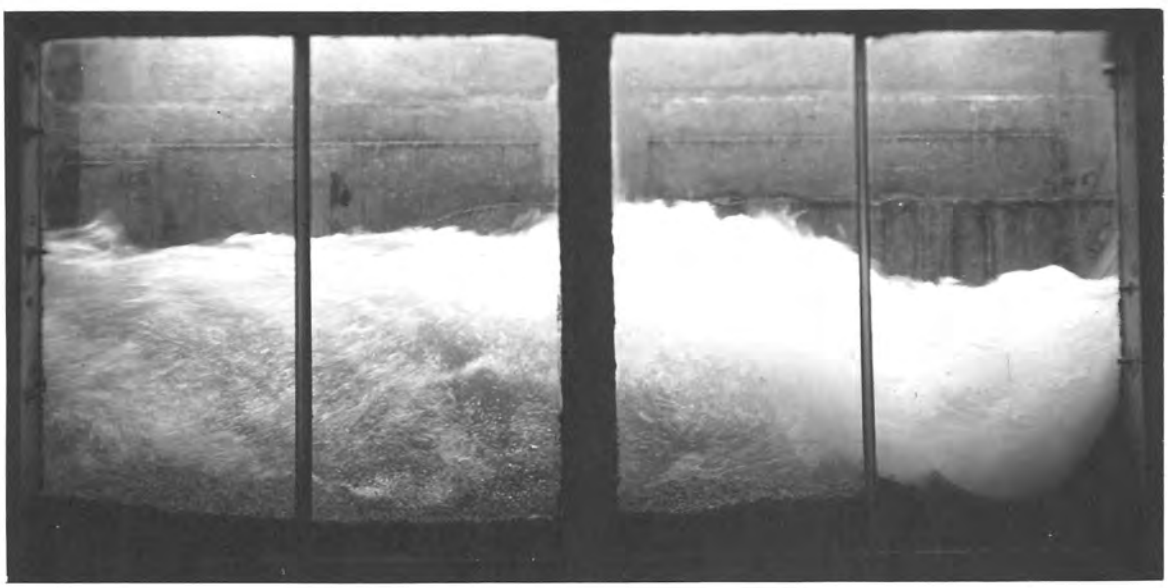
B. Flow is diving from the apron lip - maximum tail-water depth limit has been exceeded

Note: Bed elevation at beginning of test run was approximately 0.5 inch below apron lip.

9-INCH BUCKET DISCHARGING 3 SECOND-FEET



A. 3 second-feet



B. 4 second-feet

Note: Bed elevation at beginning of test was approximately 0.5 inch below apron lip.

9-INCH BUCKET DISCHARGING TAIL-WATER DEPTH = 1.85 FEET

A. 5 second-feet

B. 6 second-feet

Note: Bed elevation at beginning of test was approximately 0.5 inch below apron lip.

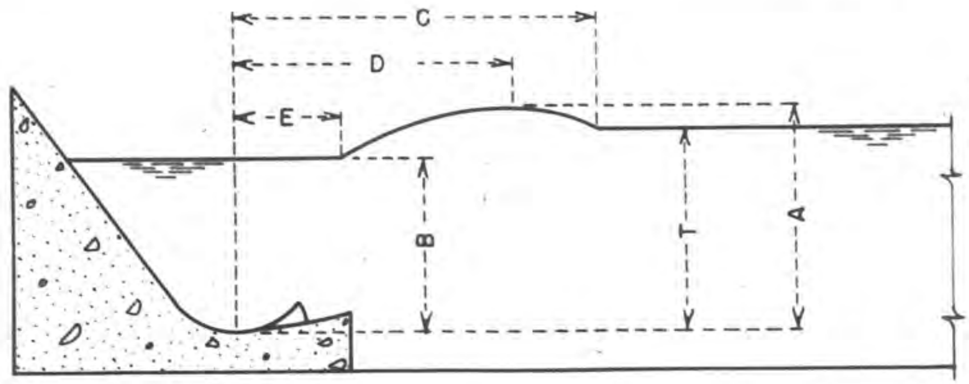
9-INCH BUCKET DISCHARGING
TAIL-WATER DEPTH = 1.85 FEET

A. Tail-water depth (1.65 feet) is below the minimum limit

B. Tail-water depth (2.30 feet) exceeds the maximum limit

Note: Bed elevation at beginning of test was approximately 0.5 inch below apron lip.

9-INCH BUCKET DISCHARGING 6 SECOND-FEET



9-INCH BUCKET

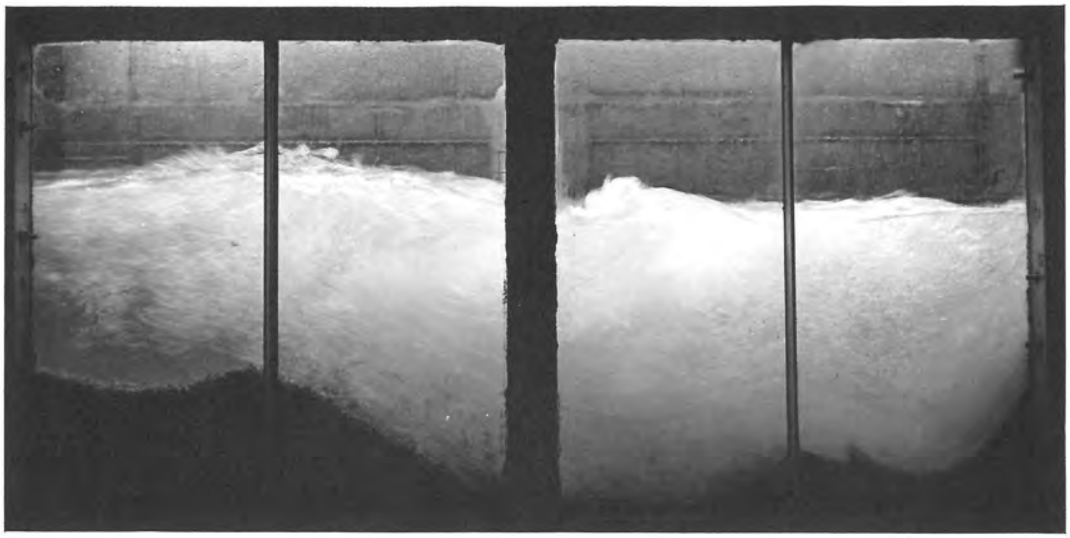
Q-cfs	q-cfs	T-ft.	A	B	C	D	E
3.0	1.50	1.85	25	19	45	25	5
3.0	1.50	2.40	32	26	46	27	1
3.50	1.75	1.85	26	19	45	25	5
4.00	2.00	1.85	27	19	46	25	5
4.50	2.25	1.85	28	19	48	28	6
5.00	2.50	1.85	28	18	50	32	6
5.50	2.75	1.85	29	17	51	31	6
6.00	3.00	1.85	30	16	52	32	6

12-INCH BUCKET

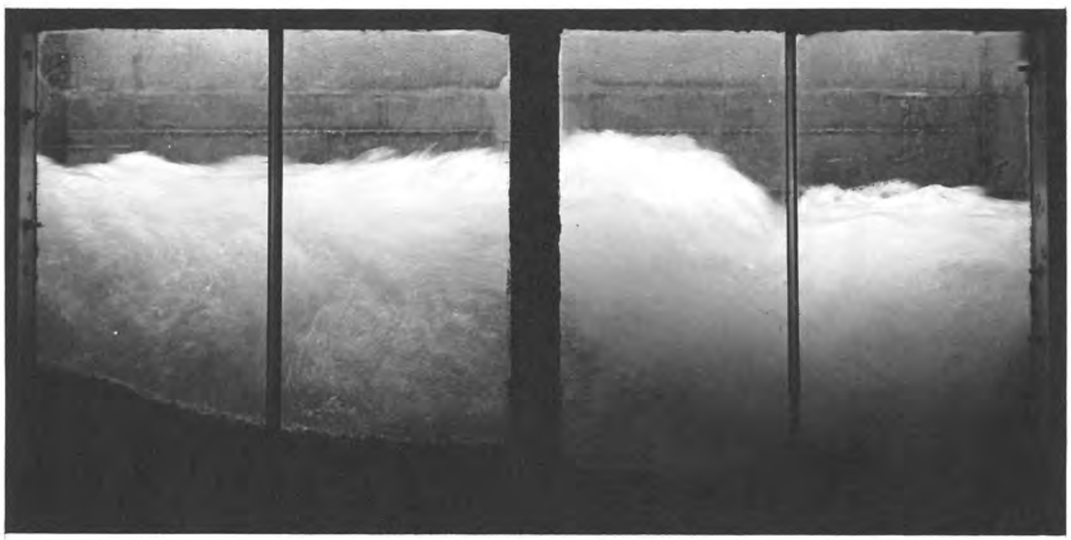
Q-cfs	q-cfs	T-ft.	A	B	C	D	E
5.0	2.5	1.65	32	23	52	35	14
6.0	3.0	1.65	33	22	62	37	11
7.0	3.5	1.65	33	21	68	37	9
8.0	4.0	1.65	35	19	70	37	6
12.0	6,0	—	36	7	90	40	1

NOTE: Dimensions A, B, C, D, and E are in inches

AVERAGE WATER SURFACE MEASUREMENTS



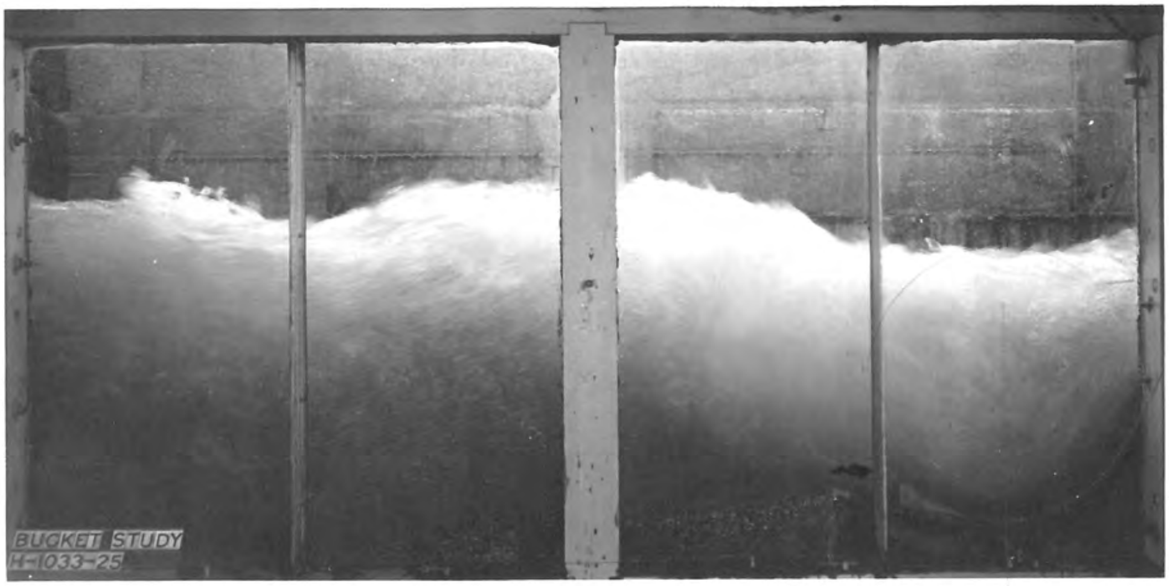
A. Flow is diving from apron to scour channel bed



B. Flow is rising from apron and the ground roller is backfilling the hole that was scoured in (A) above

Note: Bed elevation at beginning of test sloped up from apron lip to approximately 6 inches above lip elevation.

9-INCH BUCKET DISCHARGING 5 SECOND-FEET
TAIL-WATER DEPTH (2.43 FEET) EXCEEDS MAXIMUM LIMIT

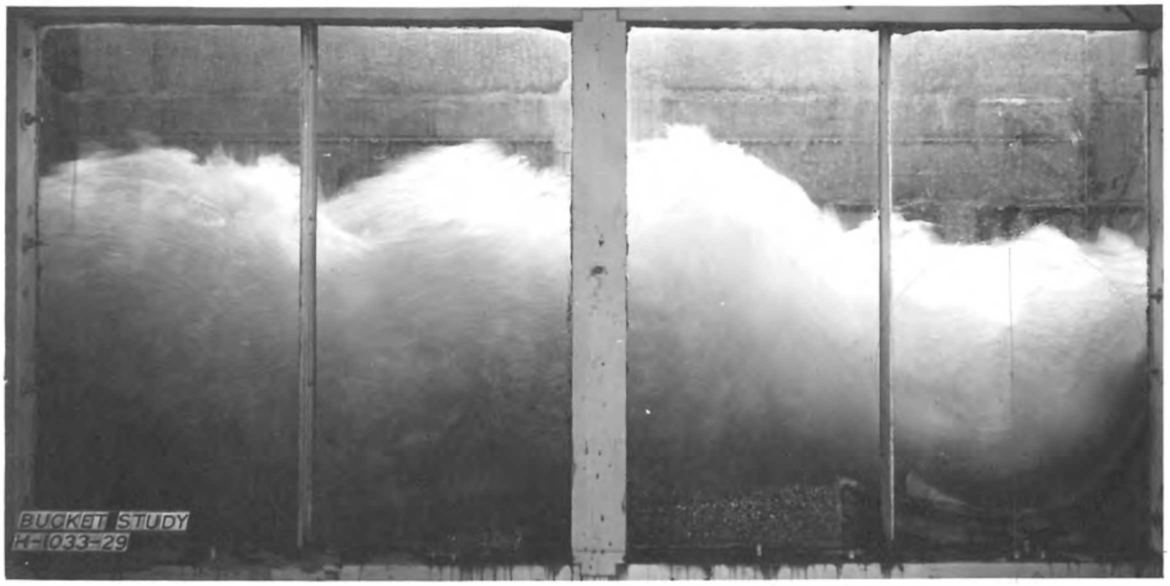


A. 5 second-feet

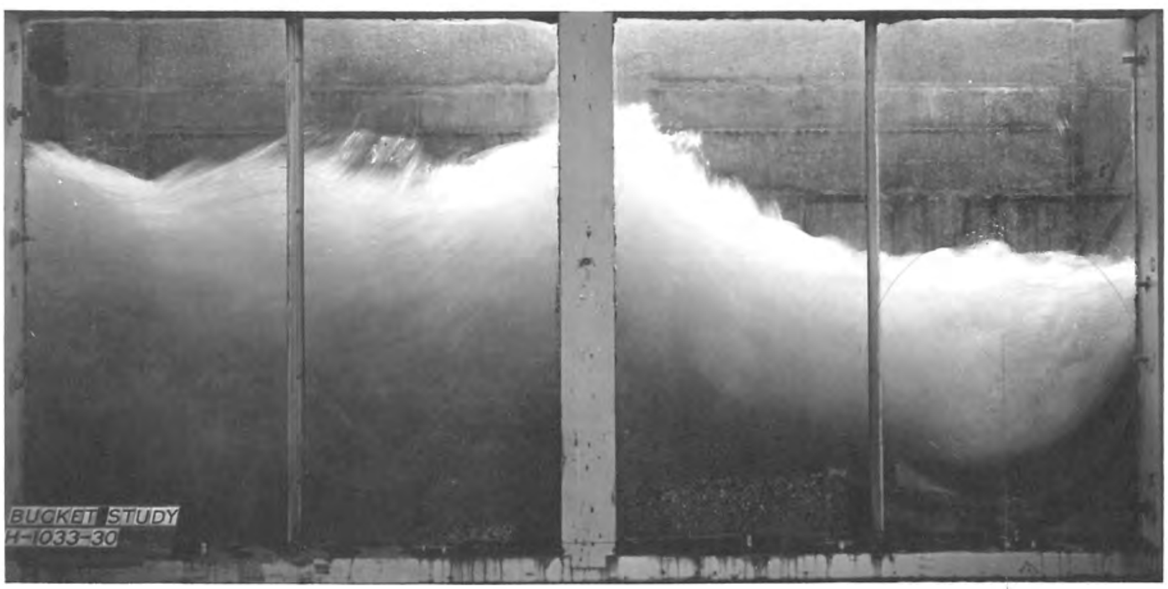
B. 6 second-feet

Note: Bed elevation at beginning of test was approximately 0.6 inch below apron lip.

12-INCH BUCKET DISCHARGING
TAIL-WATER DEPTH = 2.3 FEET



A. 7 Second-feet



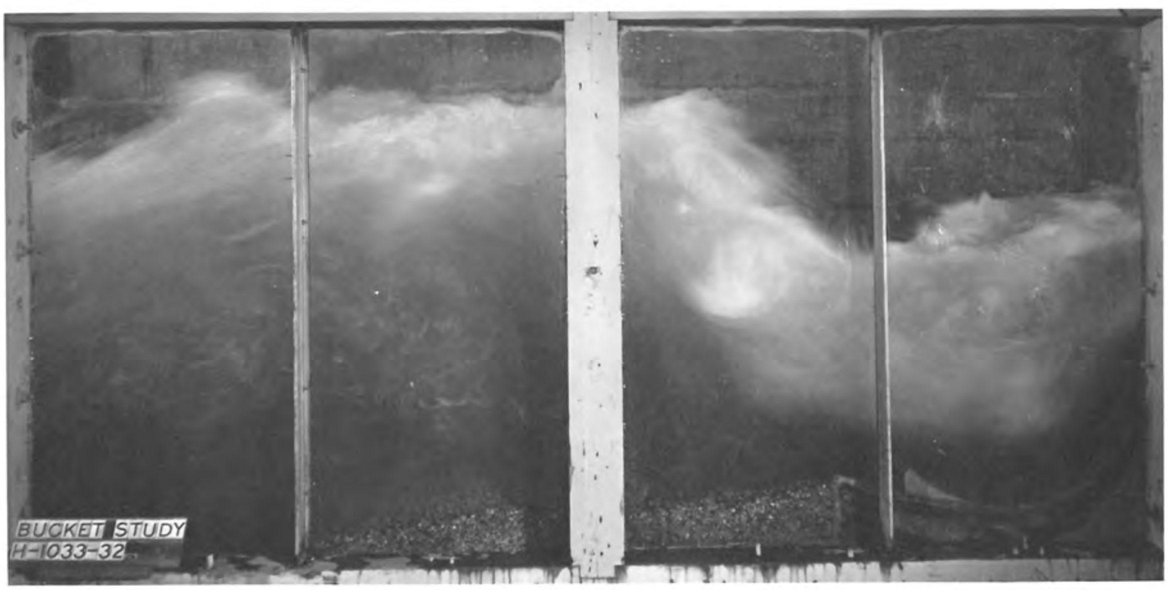
B. 8 Second-feet

Note: Bed elevation at beginning of test was approximately 0.6 inch below apron lip.

~~ARGING~~
~~8 FEET~~

12-INCH BUCKET DISCHARGING
TAIL-WATER DEPTH = 2.3 FEET

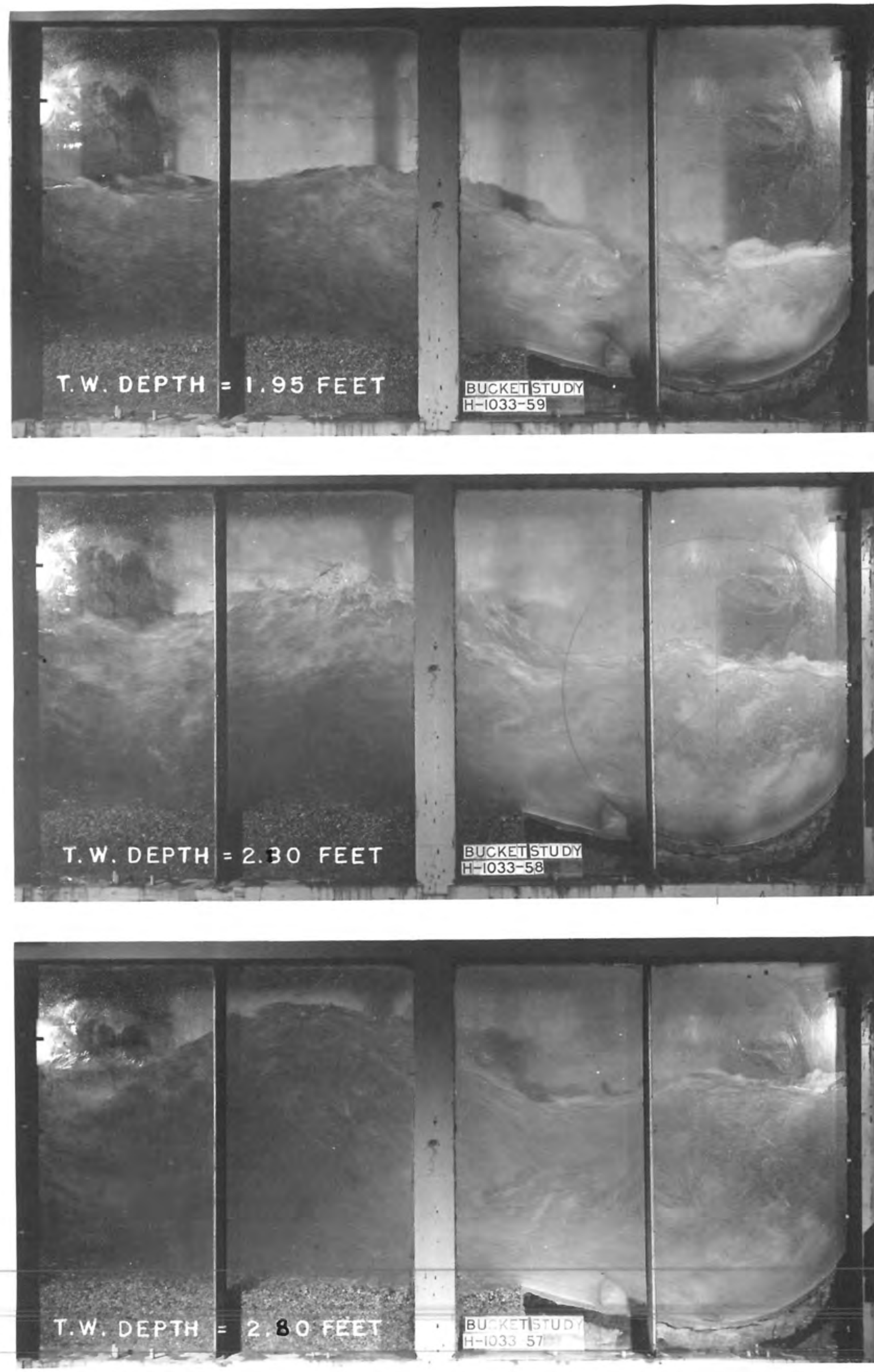
Tail-water depth = 2.30 feet



Tail-water depth = 2.80 feet

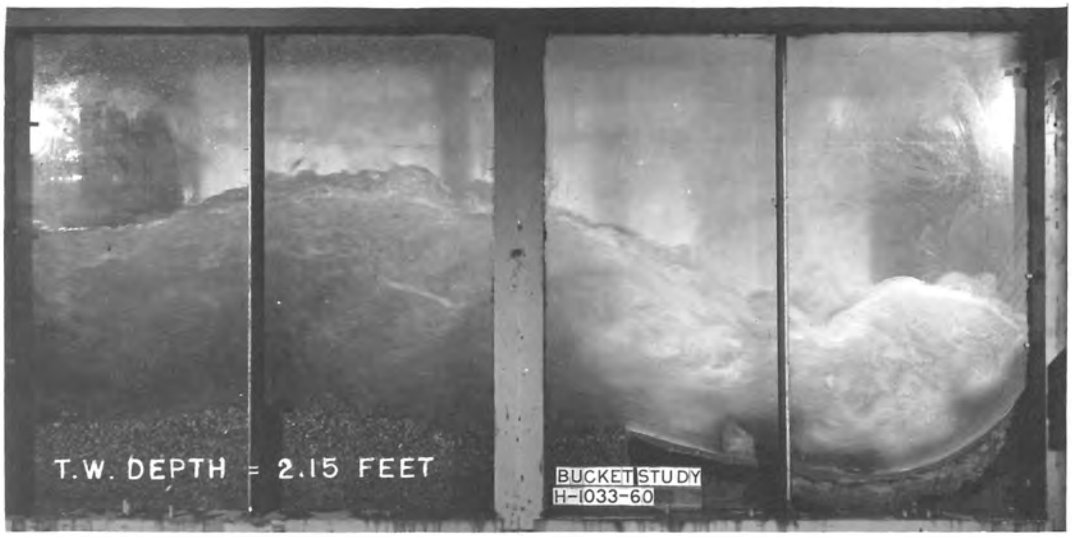
Note: Bed elevation at beginning of test was approximately 0.6 inch below apron lip.

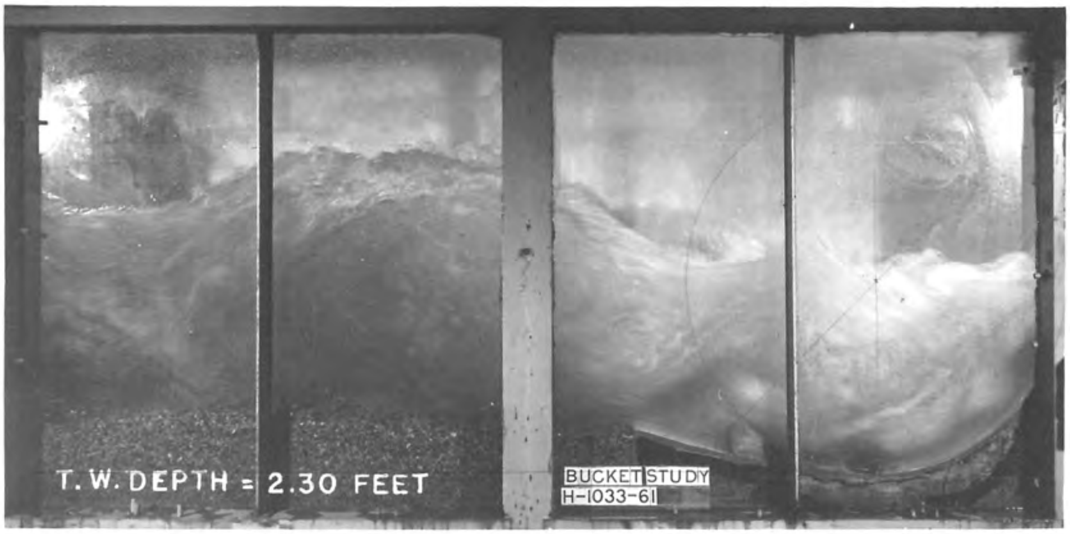
12-INCH BUCKET DISCHARGING 12 SECOND-FEET



Note: Bed elevation at beginning of test was approximately 0.9 inch below apron lip.

18-INCH BUCKET DISCHARGING 6 SECOND-FEET

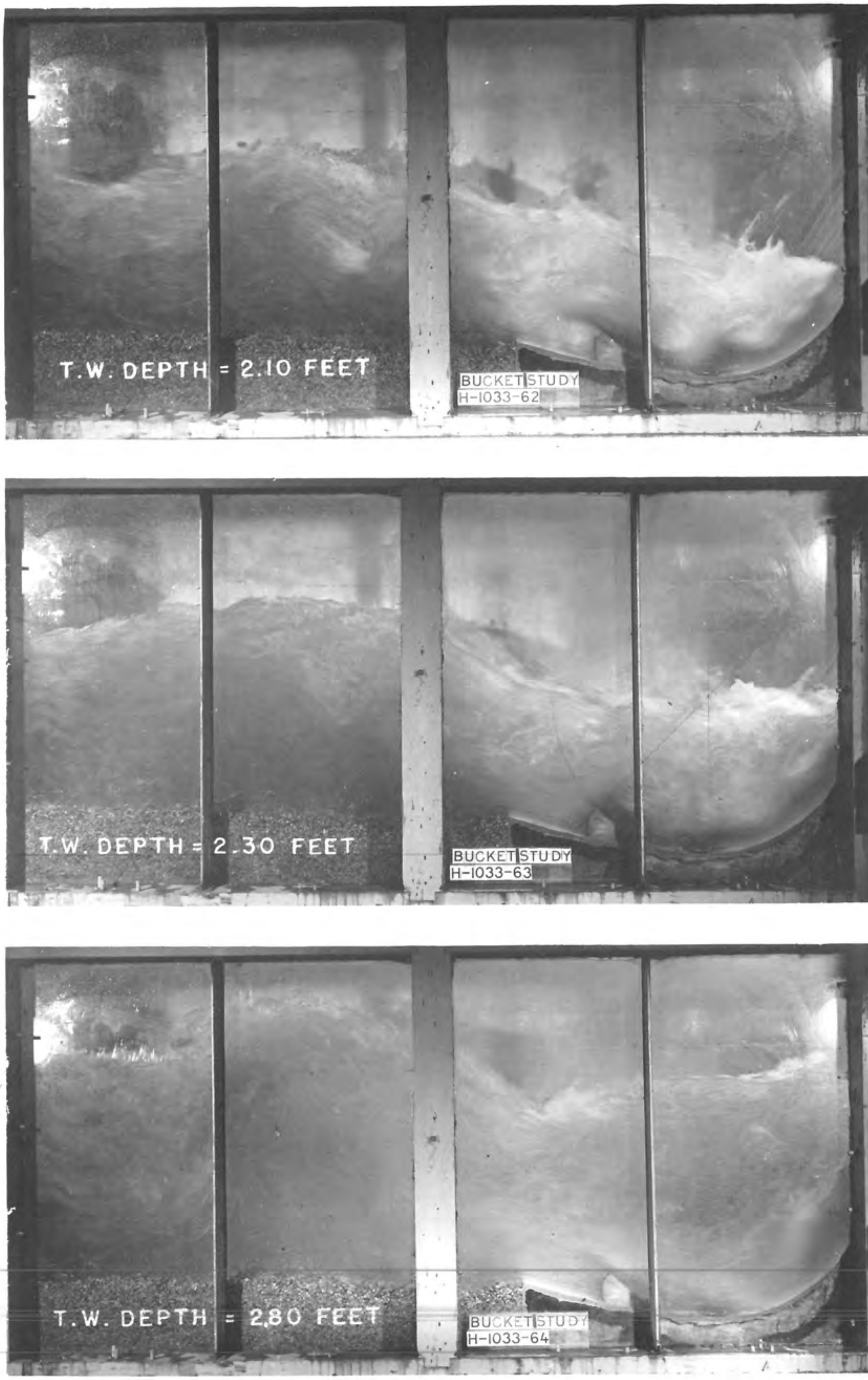




Note: Bed elevation at beginning of test was approximately 0.9 inch below lip.

18-INCH BUCKET DISCHARGING 7 SECOND-FEET

Figure 37

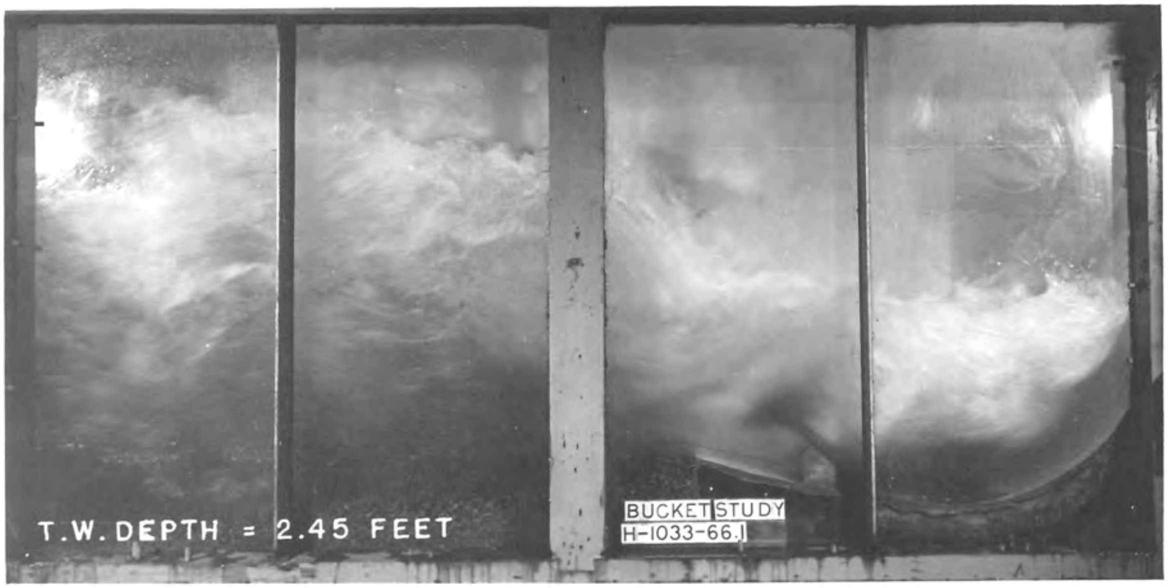


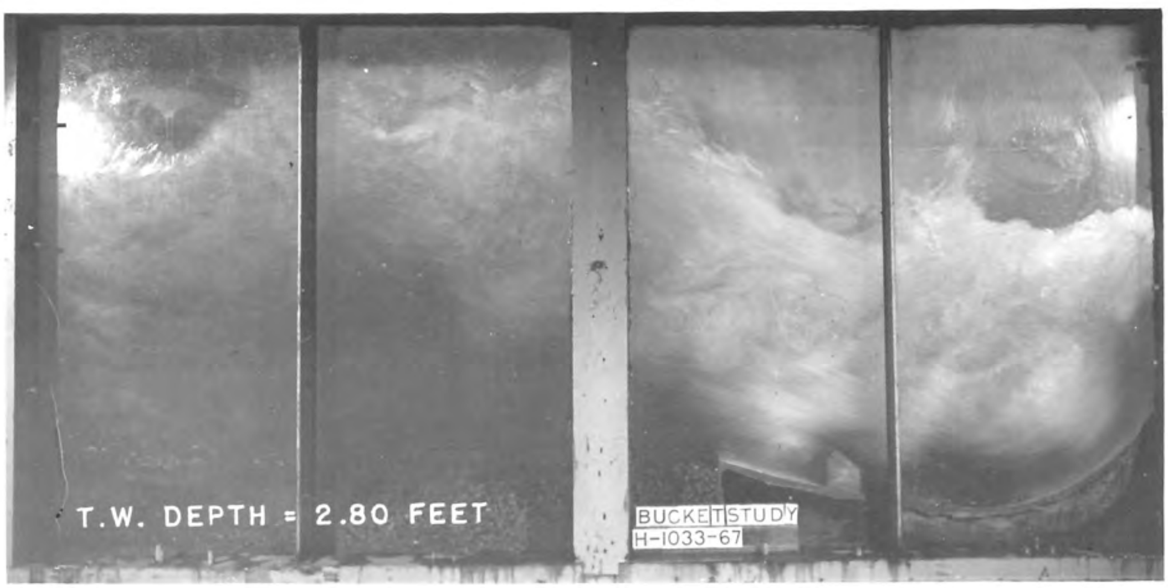
Note: Bed elevation at beginning of test was approximately 0.9 inch below apron lip.

18-INCH BUCKET DISCHARGING 8 SECOND-FEET

Note: Bed elevation at beginning of test was approximately 0.9 inch below apron lip.

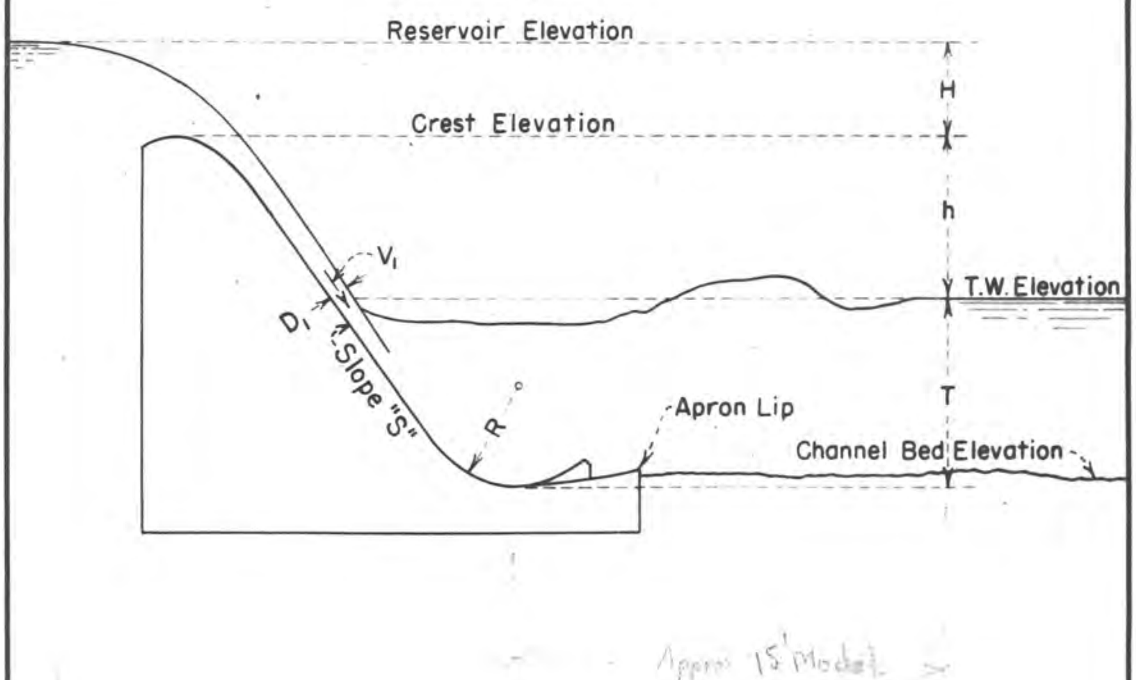
18-INCH BUCKET DISCHARGING 11 SECOND-FEET



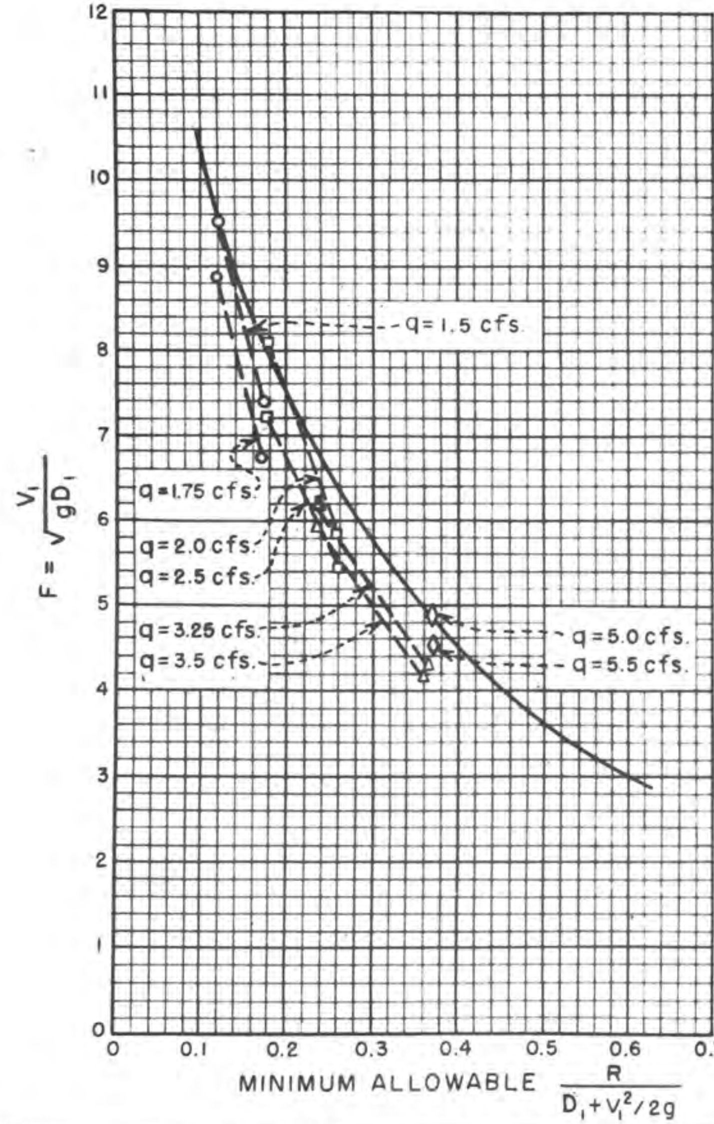


Note: Bed elevation at beginning of test was approximately 0.9 inch below apron lip.

18-INCH BUCKET DISCHARGING 12 SECOND-FEET

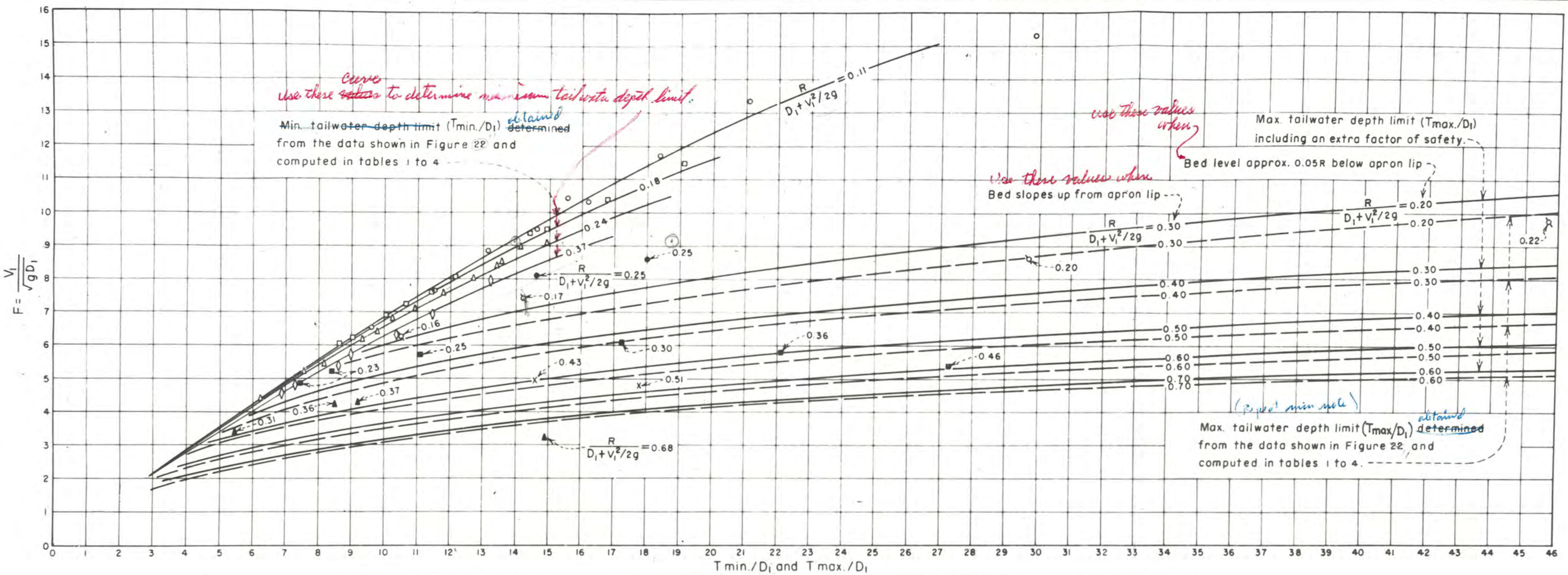


VARIABLES UPON WHICH BUCKET RADIUS AND TAIL WATER DEPTH DEPEND



DATA SYMBOLS	BUCKET RADIUS (R) INCHES	BED ARRANGEMENT
○	6	Bed level approx. 0.05R below apron lip.
□	9	Bed level approx. 0.05R below apron lip.
△	12	Bed level approx. 0.05R below apron lip.
◊	18	Bed level approx. 0.05R below apron lip.

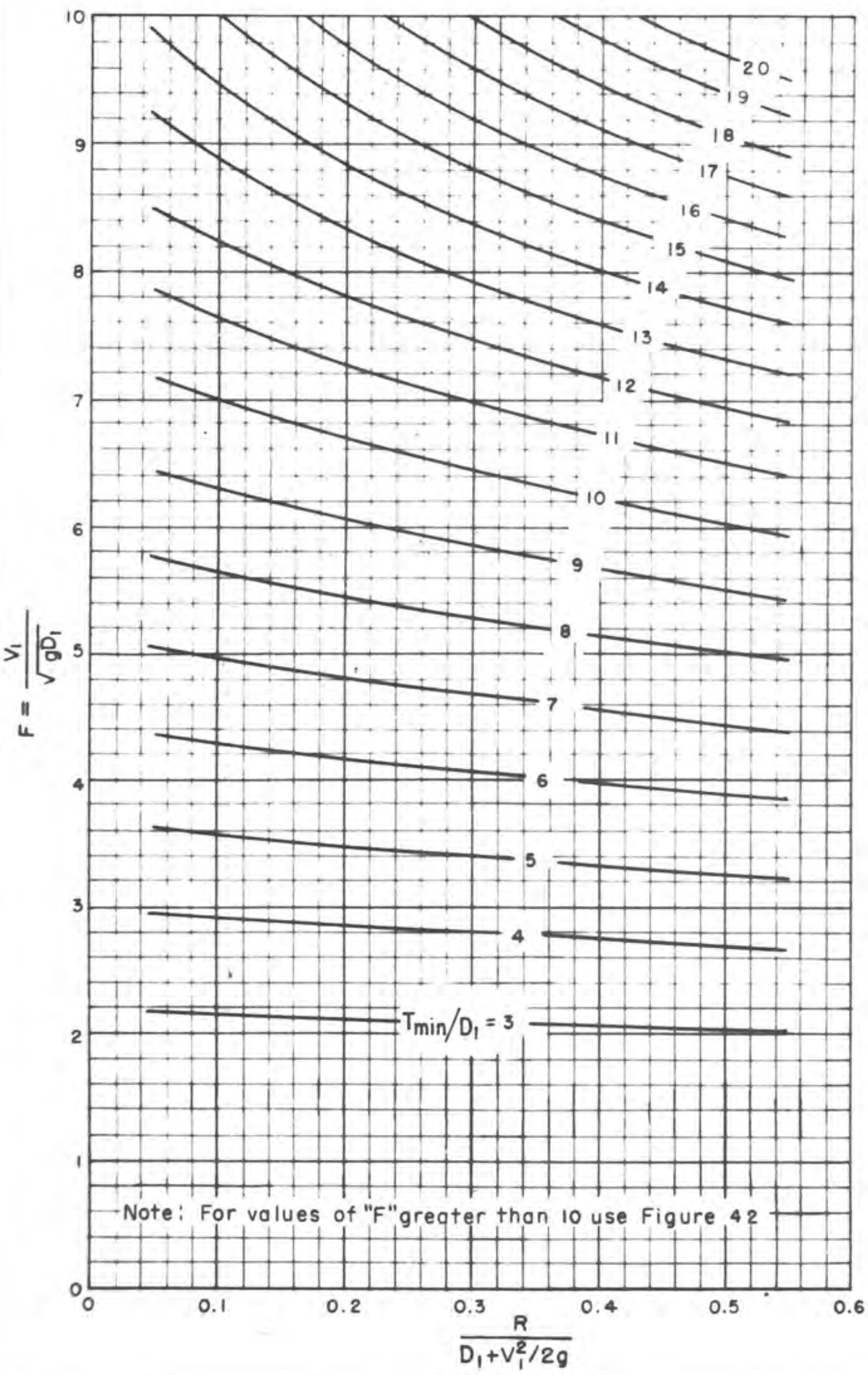
MINIMUM ALLOWABLE BUCKET RADIUS



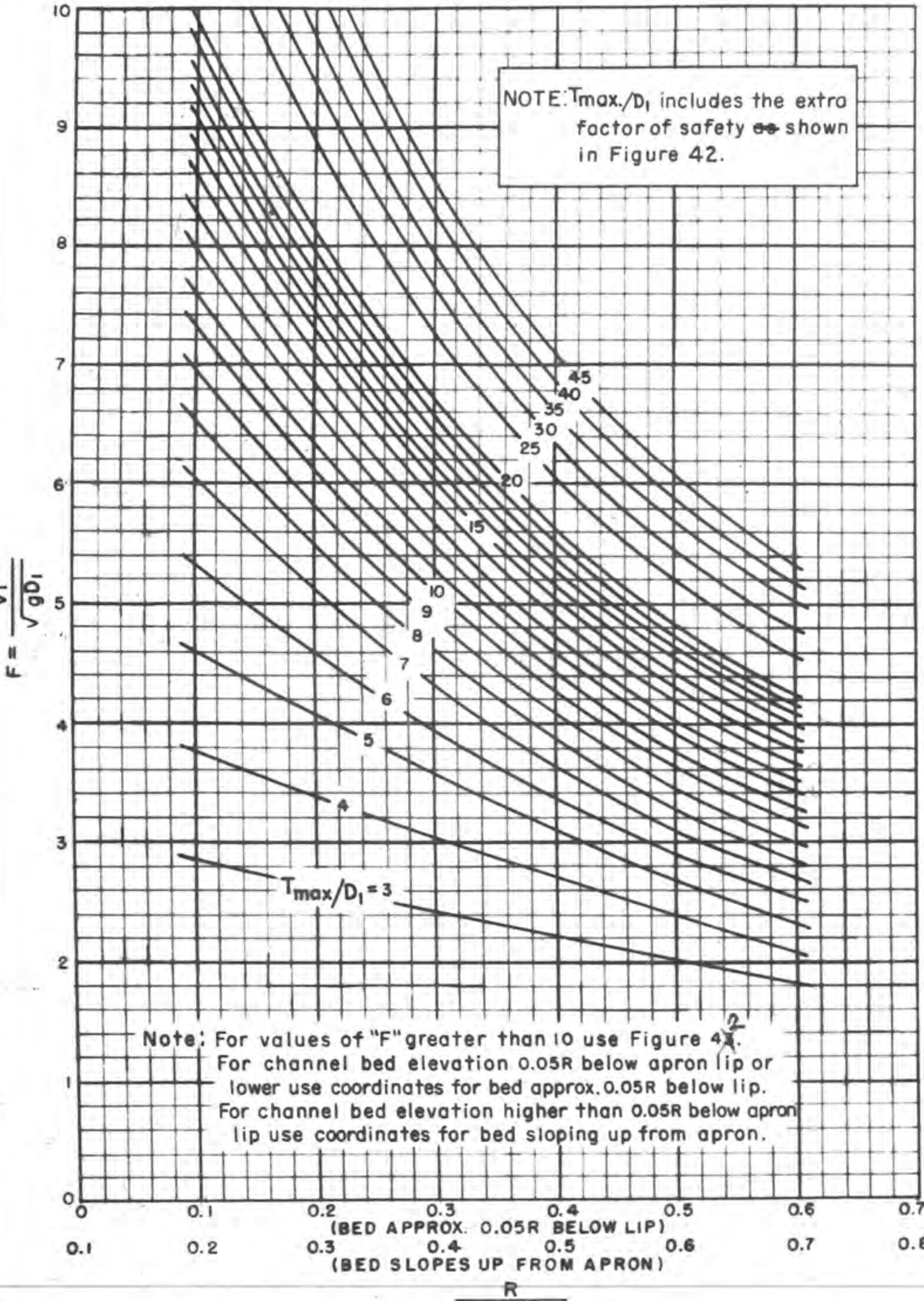
DATA SYMBOL	BUCKET RADIUS (R) INCHES	$\frac{R}{D_1+V_1^2/2g}$	BED ARRANGEMENT	DESCRIPTION OF DATA POINT
○	6	0.11	For any position of the bed	Min. tailwater depth limit
□	9	0.18	For any position of the bed	Min. tailwater depth limit
△	12	0.24	For any position of the bed	Min. tailwater depth limit
◊	18	0.37	For any position of the bed	Min. tailwater depth limit
ǫ	6	0.16 to 0.22	For bed level approx. 0.05R below apron lip	Max. tailwater depth limit
■	9	0.23 to 0.46	For bed level approx. 0.05R below apron lip	Max. tailwater depth limit
▲	12	0.31 to 0.68	For bed level approx. 0.05R below apron lip	Max. tailwater depth limit
●	9	0.25	For bed sloping up from apron lip	Max. tailwater depth limit
x	12	0.43 to 0.51	For bed sloping up from apron lip	Max. tailwater depth limit

DIMENSIONLESS PLOT OF MAXIMUM AND MINIMUM TAILWATER DEPTH LIMITS

FIGURE 43

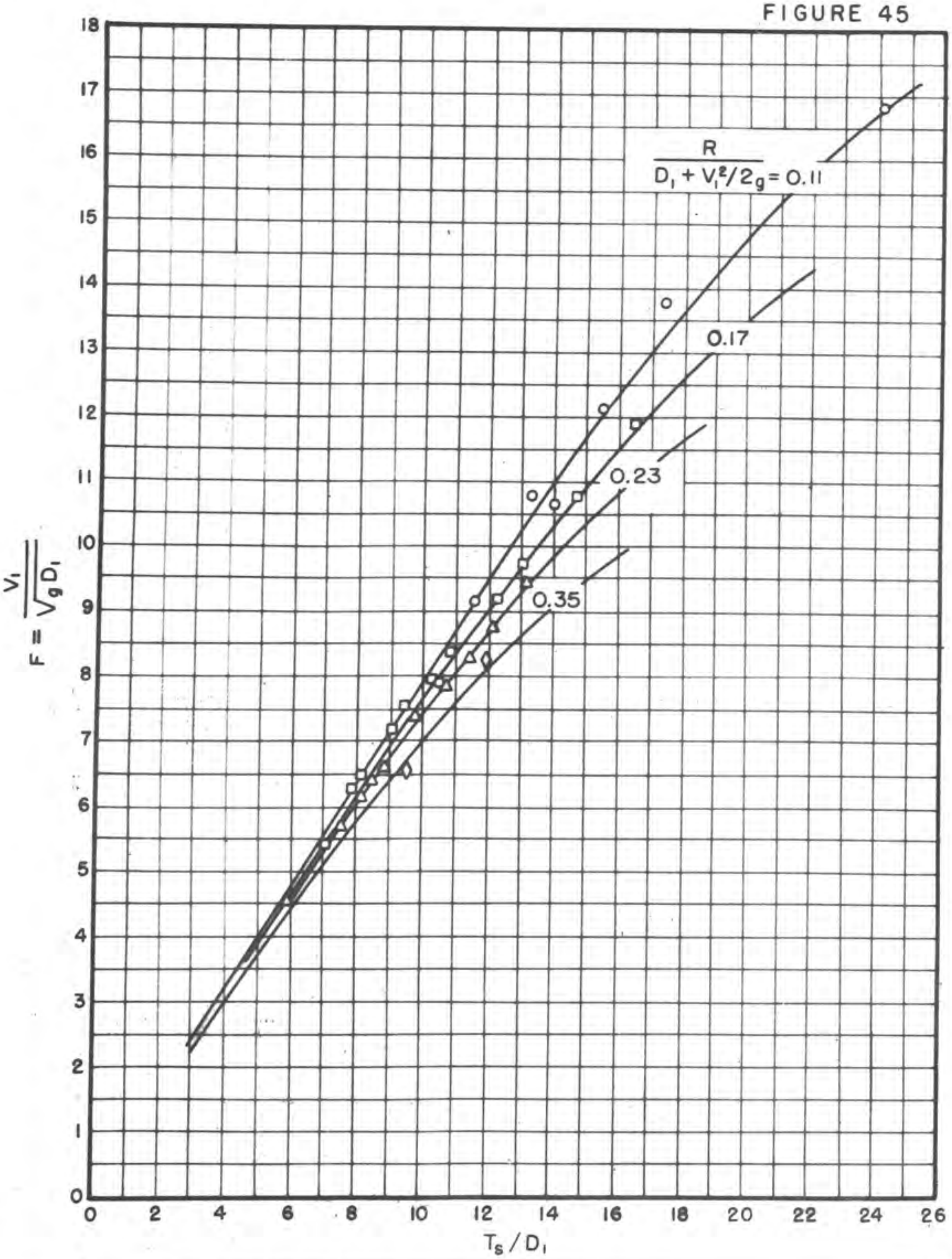


MINIMUM TAILWATER LIMIT



MAXIMUM TAILWATER LIMIT

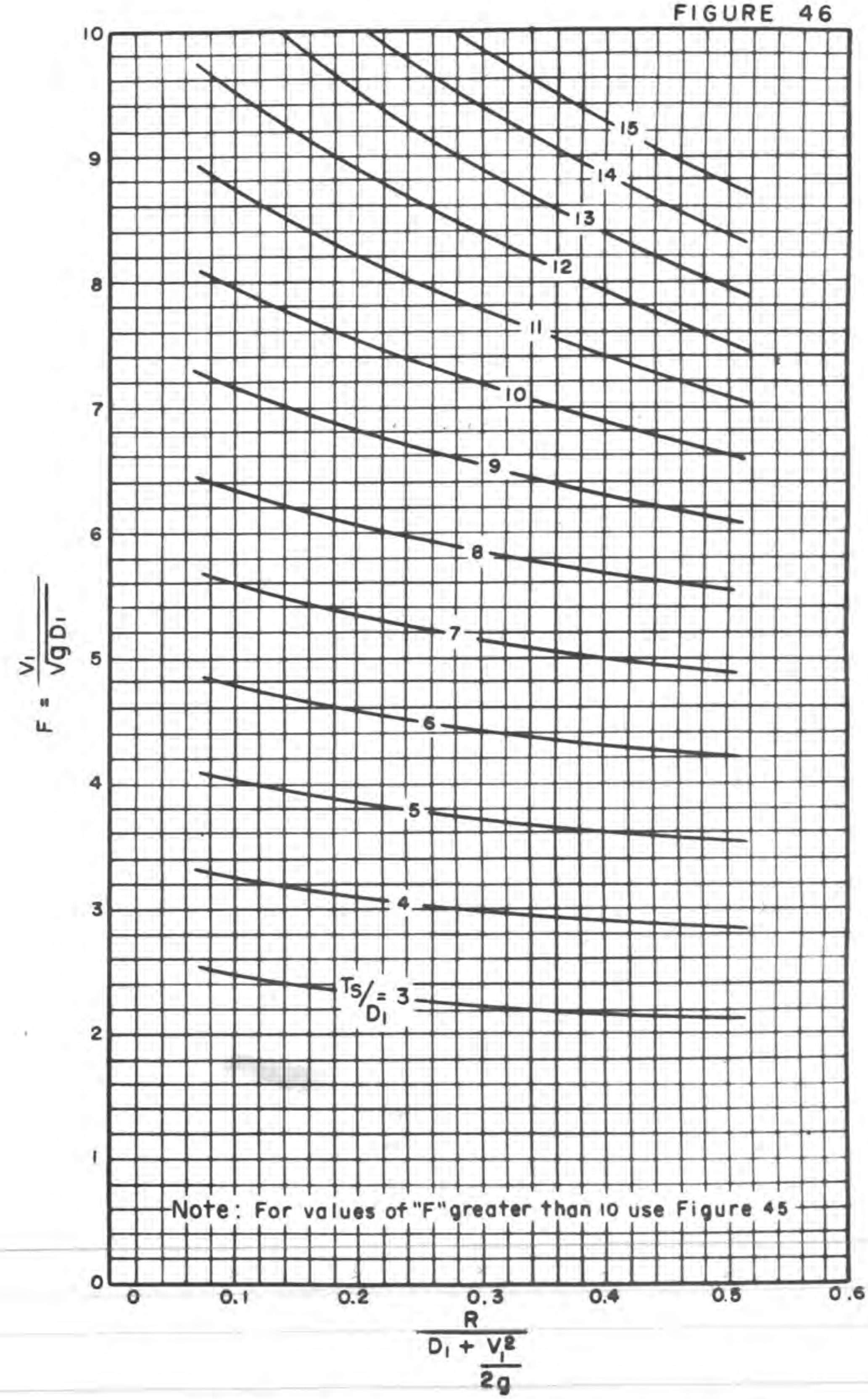
FIGURE 45



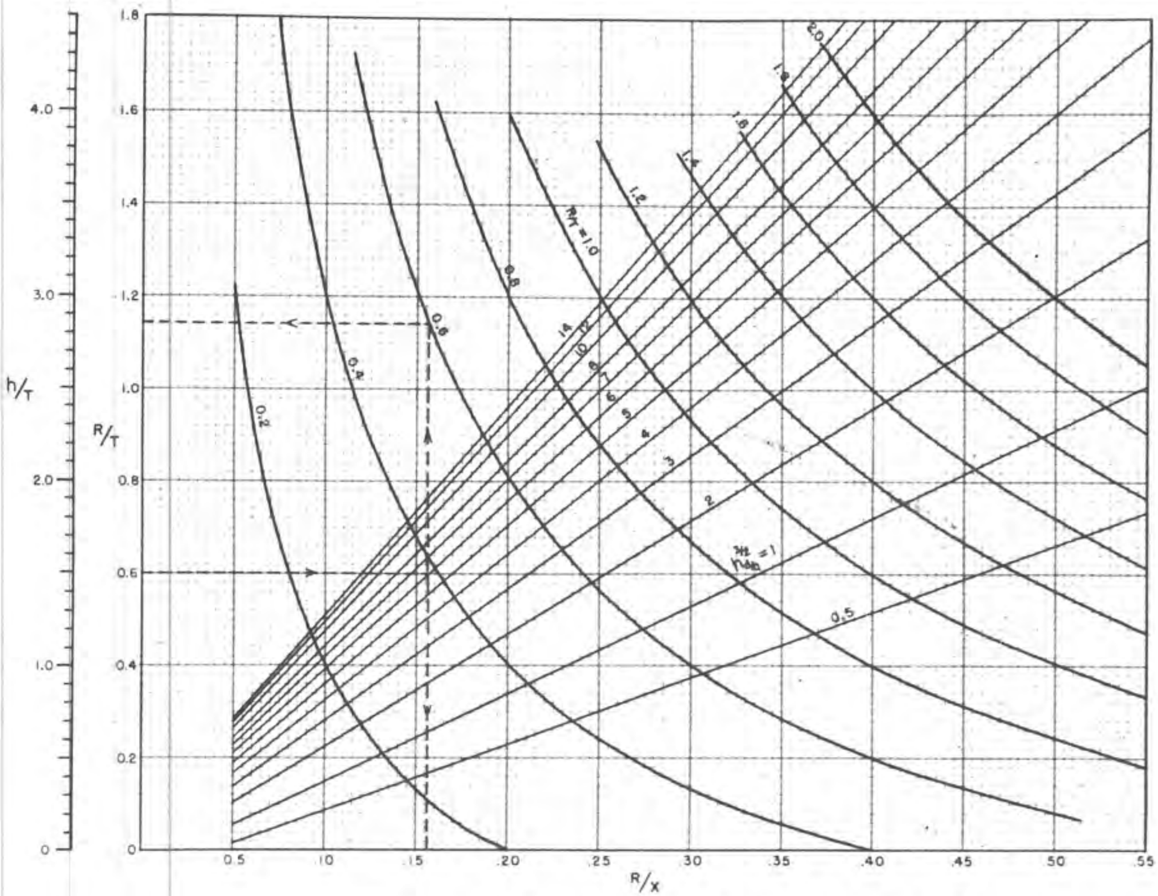
DATA SYMBOLS	BUCKET RADIUS R (INCHES)	$\frac{R}{D_1 + V_1^2/2g}$	BED ARRANGEMENT
○	6	0.11	Bed position not critical
□	9	0.18	Bed position not critical
△	12	0.24	Bed position not critical
◊	18	0.37	Bed position not critical

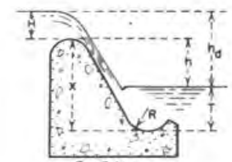
DIMENSIONLESS PLOT OF SWEEPOUT DEPTH

FIGURE 46



TAILWATER SWEEPOUT DEPTH





EQUATIONS OF CURVES

$$R/T = m\left(R/X + \frac{1}{23}\right) - \frac{1}{9}$$

Where

$$m = \sqrt{2\left(\frac{h_d^{3/2}}{q}\right) - \frac{1}{16}\left(\frac{h_d^{3/2}}{q}\right)^2} + \frac{1}{2}$$

$$h/T = X/R\left(R/T - R/X\right)$$

EXAMPLE

Given

$h_d = 40$, $H = 5$, $h = 35$

and $q = 42$

Then

$\frac{h_d^{3/2}}{q} = 6$

Assume

$R/T = .6$

From Curves

$R/X = .156$, $h/T = 2.85$

So $T = 12.3$, $R = 7.4$

$X = 47.3$

$X + H = 52.3$ } Check

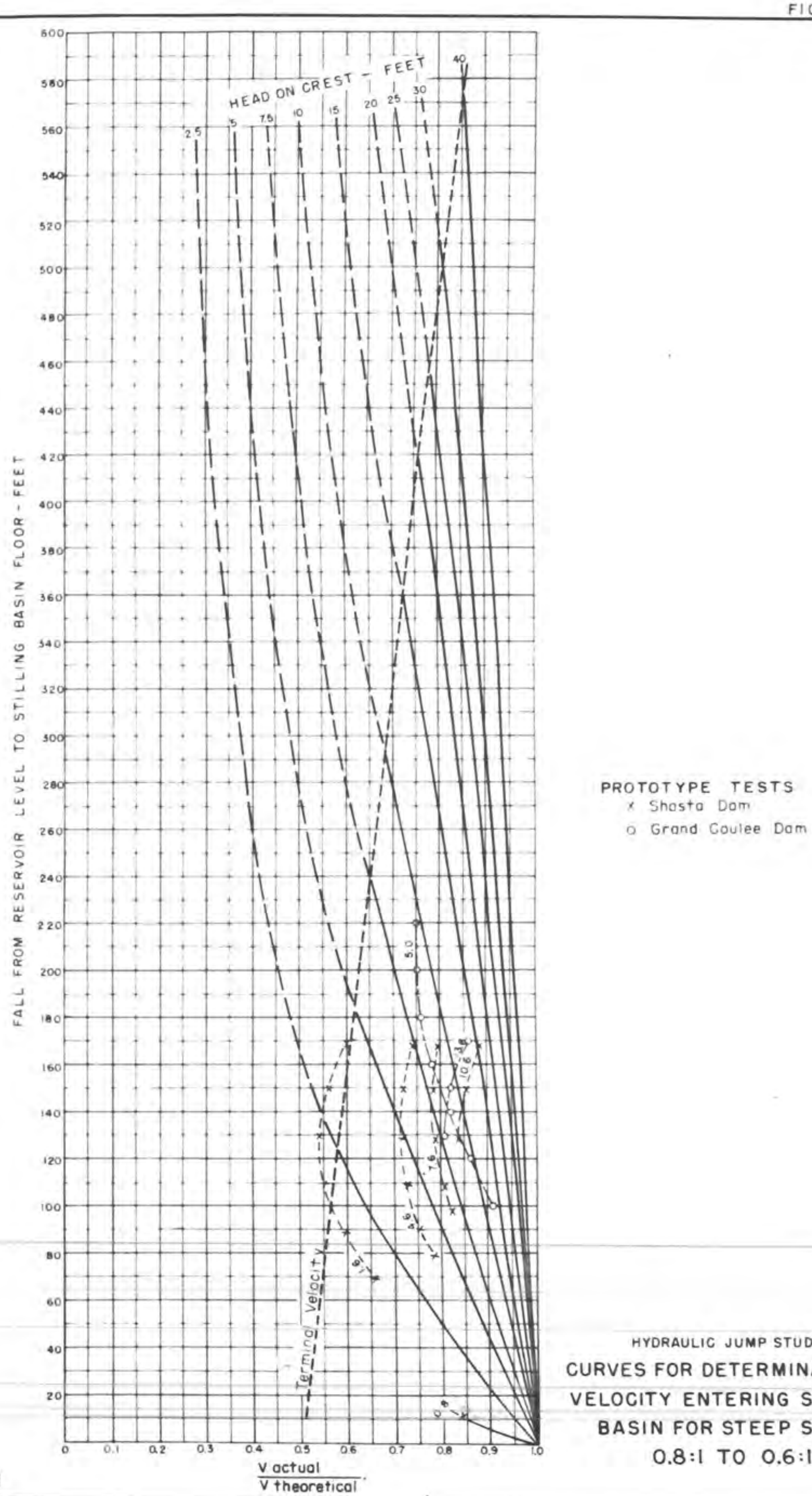
$h_d + T = 52.3$ }

ANGOSTURA TYPE BUCKET SWEEPOUT CURVES

3-23-49 E. J. RUSHO

FIGURE 47

17 x 22



HYDRAULIC JUMP STUDIES

CURVES FOR DETERMINATION OF VELOCITY ENTERING STILLING BASIN FOR STEEP SLOPES 0.8:1 TO 0.6:1