THE HYDRAULIC DESIGN OF SLOTTED SPILLWAY BUCKET ENERGY DISSIPATORS

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SYNOPSIS

A slotted roller bucket for use as a submerged energy dissipator at the base of an overfall is developed from hydraulic model tests, and its performance is shown to be superior to that of a solid bucket. Charts are presented in dimensionless form so that a slotted bucket may be hydraulically designed for most combinations of discharge, height of fall, and tail water range. Sample problems are used to illustrate the use of the recommended general design procedures. The slotted bucket is self-cleaning, provides protection against excessive scour and undermining of the bucket structure, and is shown to be of minimum size consistent with good performance.

The tail water requirements for the slotted bucket are compared with those necessary for a hydraulic jump stilling basin, and the bucket is shown to be particularly suited to installations where the tail water is too deep for a hydraulic jump or where a short energy dissipator is preferred.

A simplified version of the seven steps required to design a bucket for any particular installation is given in the Summary of this paper.

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INTRODUCTION

The development of submerged buckets has been in progress for many years. Several types have been proposed, tested, and rejected for one reason or another. In 1933, with the aid of hydraulic models, the Bureau of Reclamation developed a solid bucket of the type shown in Figure 1A for use at Grand Coulee Dam.*

In 1945, a bucket-type energy dissipator was proposed for use at Angostura Dam** and hydraulic model tests were made in the Bureau laboratory to develop an improved bucket, the slotted bucket shown in Figure 1B. In these tests, the bucket dimensions were determined, tooth size and spacing were defined, and the proper vertical placement of the bucket established for the Angostura spillway.

In 1953 and 1954, extensive hydraulic model tests, covering a complete range of bucket sizes and tail water elevations, were conducted to verify the bucket dimensions and details obtained in 1945 and to establish general relations between bucket size, discharge capacity, and the maximum and minimum tail water depth limits. The 1945 and 1953-54 studies are the subject of this paper.

*Grand Coulee Dam is a major feature of the Columbia Basin Project, is located on the Columbia River in northeastern Washington, and is a concrete gravity-type dam having an overfall spillway 1,650 feet wide by 390 feet high from the bucket invert to crest elevation. The spillway is designed for 1 million second-feet.

**Angostura Dam is a principal structure of the Angostura Unit of the Missouri River Basin Project, is located on the Cheyenne River in southwestern South Dakota, and is an earthfill structure having a concrete overfall spillway 274 feet wide by 117.2 feet high from the bucket invert to crest elevation. The spillway is designed for 247,000 second-feet.

From the 1953-54 data, dimensionless curves were plotted which may be used to design hydraulically a slotted bucket for most combinations of spillway height and discharge capacity without the need for individual hydraulic model tests. In these generalization studies, every attempt was made to set limits so that the resulting structure will provide safe operation for the extreme limits and satisfactory or better performance throughout the usual operating range. Strict adherence to the charts and rules presented will therefore result in the smallest possible structure consistent with good performance and a moderate factor of safety. It is suggested, however, that confirming hydraulic model tests be performed whenever: (a) sustained operation near the limiting conditions is expected, (b) discharges per foot of width exceed 500 to 600 second-feet, (c) velocities entering the bucket are appreciably over 100 feet per second, (d) eddies appear to be possible at the ends of the spillway, and (e) waves in the downstream channel would be a problem.

PERFORMANCE OF SOLID AND SLOTTED BUCKETS

The solid and slotted roller or submerged buckets for spillways are shown operating in Figure 2.* Both types require more tail water depth than a hydraulic jump basin.

The hydraulic action and the resulting performance of the two buckets are quite different. In the solid bucket, all of the flow is directed upward by the bucket lip to create a boil on the water surface

*Figure 2 and other drawings showing flow currents have been traced from one or more photographs, similar to Figure 12, of the bucket performing under the conditions given. This method of presentation is used since a single photograph seldom portrayed typical action of the bucket.

and a violent ground roller on the riverbed. The upstream current in the ground roller moves bed material from downstream and deposits it at the bucket lip. Here, it is picked up, carried away, and dropped again. The constant motion of the loose material against the concrete lip and the fact that unsymmetrical spillway operation can cause eddies to sweep material into the bucket make this bucket undesirable in some installations. Trapped material can cause erosion damage in the bucket itself. With the slotted bucket, both the high boil and violent ground roller are reduced by the flow passing through the slots, resulting in improved performance. Very little motion of bed material occurs, and bed material will not stay in the bucket arc. Since only part of the flow is directed upward, the boil is less pronounced. The part of the flow directed downstream through the slots spreads laterally and is lifted away from the channel bottom by the apron extending downstream from the slots. Thus, the flow is dispersed and distributed over a greater area, providing less violent flow concentrations than occur with a solid bucket.

The usable tail water range is less with the slotted bucket than with the solid bucket. Sweepout occurs at a slightly higher tail water elevation with the slotted bucket, and if the tail water is too high, the flow dives from the apron lip to scour the channel bed, as shown in Figure 3. With the solid bucket, diving is impossible with the usual tail water elevations. In general, however, the slotted bucket is an improvement over the solid type and will operate satisfactorily over a wide range of tail water depths.

SLOTTED BUCKET DEVELOPMENT TESTS

General

The basic concept of the slotted bucket was the result of tests made to adapt the solid bucket for use at Angostura Dam. These tests, made on a 1:42 scale sectional model, are summarized in the following paragraphs.

Development from Solid Bucket

The first tests were undertaken to determine the minimum radius of bucket required to handle the maximum flow and to determine the required elevation of the bucket invert for the existing tail water conditions. Solid type buckets were used in the model to determine these approximate values since the slotted bucket had not yet been anticipated. The 42-foot radius bucket was found to be the smallest bucket which would provide satisfactory performance for 1,010 second-feet per foot of width and a velocity of 75 feet per second.

Best performance occurred when the bucket invert was 77 feet below tail water elevation. For all invert elevations tested, however, a ground roller, Figure 2A, moved bed material from downstream and deposited it against the bucket lip.

The second stage in the development was to modify the bucket to prevent the piling of bed material along the lip. Tubes were placed in the bucket lip through which jets of water flowed to sweep away the deposited material. Results were satisfactory at low discharges, but for the higher flows loose material piled deeply over the tube exits, virtually closing them.

Slots in the bucket lip were then used instead of larger tubes. The slots were found to not only keep the bucket lip free of loose material, but also provided exits for material that became trapped in the bucket during unsymmetrical operation of the spillway.

To maintain the effectiveness of the bucket action in dissipating energy, the slots were made just wide enough to prevent deposition at the bucket lip. The first slots tested were 1 foot 9 inches wide, spaced three times that distance apart. The slot bottoms were sloped upward on an 8° angle so that the emerging flow would not scour the channel bottom, and made tangent to the bucket radius to prevent discontinuities in the surfaces over which the flow passed. The spaces between the slots then became known as teeth. Three tooth designs, shown in Figure 4, were tested.

<u>Tooth Shape, Spacing, and Pressures</u>

With Tooth Design I, the energy dissipating action of the bucket and the elimination of piled material along the bucket lip were both satisfactory. However, small eddies, formed by the jets leaving the slots, lifted loose gravel to produce abrasive action on the downstream face of the teeth. Therefore, an upward sloping apron was installed downstream from the teeth to help spread the jets from the slots and also to keep loose material away from the teeth. The apron was sloped upward slightly steeper than the slope of the slots, to provide better contact with 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 investigated after the tooth shape and spacing were determined.

The profile of Tooth Design II, Figure 4, was made to conform to the radius of the bucket, eliminating the discontinuity in the flow passing over the teeth. A smoother water surface occurred downstream from the bucket. Pressure measurements showed the necessity of rounding of the edges of the teeth. Model radii ranging from 0.1 to 0.3 inch were investigated. The larger radius (12.6 inches prototype) was found to be the most desirable.

Tooth Design III, Figure 4, showed improved pressure conditions on the sides and downstream face of the teeth. The radius on the tooth edges was increased to 15 inches. Subatmospheric pressures occurred on the downstream face of the teeth at Piezometers 3, 4, and 5, but were above the critical cavitation range.

Preliminary tests had shown that pressures on the teeth varied according to the tooth spacing. The most favorable pressures consistent with good bucket performance occurred with Tooth Design III, tooth width 0.125R and spacing 0.05R at the downstream end. Table I shows the pressures in feet of water at the piezometers.

Table I

Pressures on Tooth Design III
0.125R Width, 0.05R Spacing
1,000 cfs per foot--TW depth, 77 feet

Piezometer No.	Pressure ft of water	Piezometer No.	Pressure ft of water
1	+1 to +16	9	+58
2	+5 to +13	10	+42
3	-2 to +15	11	+68
4	-13 to +16	12	+49
5	-9 to +11	13	+11
6	+8 to +16	14	+13
7	+22	15	+21
8	+62	16	+34
		17	+39

For 1,000 second-feet per foot of width in a 1:42 scale model having a 42-foot radius bucket, Piezometers 1 through 6 showed fluctuations between the limits shown. Piezometers 3, 4, and 5 showed subatmospheric values, but since these piezometers are on the downstream face of the teeth, it is unlikely that damage would occur as a result of cavitation. According to the pressure data, the teeth are safe against cavitation for velocities up to about 100 feet per second, i.e., velocity computed from the difference between headwater and tail water elevations.

Reducing the tooth spacing to 0.035R raised the pressures on Piezometers 3, 4, and 5 to positive values. Pressures on the tooth are shown in Table II for a discharge of 1,000 second-feet per foot of width in a 1:42 scale model having a 42-foot radius bucket.

Table II

Pressures on Tooth Design III
0.125R Width, 0.035R Spacing
1,000 cfs per foot--TW depth, 77 feet

Piezometer No.	Pressure ft of water	Piezometer No.	Pressure ft of water
1	+36	9	+62
2	+27	10	+57
3	+30	11	+71
4	+26	12	+63
5	+14	13	+21
6	+27	14	+28
7	+39	15	+40
8	+64	16	+47
		17	+58

With 0.035R spacing, the teeth should be safe against cavitation for velocities well over 100 feet per second. For small buckets, the spaces may be too small for convenient construction. In other respects, the 0.035R tooth spacing is satisfactory.

Apron Downstream from Teeth

The short apron downstream from the teeth serves to spread the jets from the slots and improve the stability of the flow leaving the bucket. A 16° upward sloping apron was found to be most satisfactory. With a 12° slope, the flow was unstable, intermittently diving from the end of the apron to scour the riverbed. With a 20° slope, the spreading action of the flow was counteracted to some degree by the directional effect of the steep apron.

Two apron lengths, one 10 feet and one 20 feet, were tested to determine the minimum length required for satisfactory operation. The longer apron, 0.5R in length, was found necessary to accomplish the spreading of the jets and produce a uniform flow leaving the apron. The 20-foot apron on a 16° slope was therefore adopted for use.

Slotted Bucket Performance

The slotted bucket thus developed, shown in Figure 1B, operated well over the entire range of discharge and tail water conditions in the sectional model, scale 1:42. The bucket was also tested at a scale of 1:72 on a wide spillway where end effects of the bucket could also be observed and evaluated.

In the 1:72 model, minor changes were made before the bucket was constructed and installed. The bucket radius was changed from 42 feet to an even 40 feet, and the maximum discharge was lowered from 277,000 to 247,000 second-feet. Figure 5 shows the 1:72 model in operation with 247,000 second-feet (900 second-feet per foot), erosion after 20 minutes of operation, and erosion after 1-1/2 hours of operation. Performance was excellent in all respects and was better than for any of the solid buckets or other slotted buckets investigated. For all discharges, the water surface was smoother and the erosion of the riverbed was less.

SLOTTED BUCKET VERIFICATION TESTS

Verification tests were made to investigate possible improvements in the size and location of the bucket teeth, Figure 7, to evaluate the performance of the slotted bucket with the teeth removed, and to compare the performance of the slotted and solid buckets. It was found, however, that the tooth size and arrangement developed for the Angostura bucket, shown in Figure 1B, in terms of the bucket radius, provided best hydraulic performance consistent with good structural practice.

Test Equipment

A testing flume and sectional model were constructed, as shown in Figure 6, and used in all subsequent tests. The test flume was 43 feet 6 inches long and 24 inches wide. The head bay was 14 feet deep and the tail bay was 6 feet 3 inches deep and had a 4- by 13-foot glass window on one side. The discharge end of the flume was equipped with a motor-driven tailgate geared to raise or lower the tail water slowly so that continuous observations could be made.

The sectional spillway model was constructed to fill the flume width with an ogee crest at the top of a 0.7 sloping spillway face. The bucket assembly was made detachable from the spillway face. Four interchangeable buckets having radii of 6, 9, 12, and 18 inches, constructed according to the dimension ratios shown in Figure 1B, were designed so that they could be installed with the bucket inverts located 5 feet below the spillway crest and about 6 inches above the floor of the flume. All flow surfaces were constructed of galvanized sheet metal with smooth joints. The downstream channel was a movable bed molded in pea gravel. The gravel 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

Flow was supplied to the test flume through a 12-inch centrifugal pump and was measured by one of a bank of Venturi meters permanently installed in the laboratory. Additional water, beyond the capacity of the 12-inch pump, was supplied by two vertical-type portable pumps equipped with two portable 8-inch orifice-Venturi meters. All Venturi meters were calibrated in the laboratory. Water surface elevations were measured with hook gages mounted in transparent plastic wells.

Bucket Modifications

To determine whether practical modifications to the bucket teeth could be made to improve the performance of the Angostura slotted bucket, the 12-inch radius bucket was used. The Angostura type of slotted bucket shown in Figure 1 and Figure 7 was tested first to establish a performance standard with which to compare the modified buckets. Each modification was subjected to a standard test of 3 second-feet per foot of bucket width, with the tail water 2.3 feet above the bucket invert, Figure 2B. The movable bed was molded level, just below the bucket apron lip, at the start of each test.

Much of the energy dissipation in a slotted bucket is the result of spreading action downstream rather than rolling action in the bucket. Very little bed erosion occurs. However, flow passes through and over the teeth to emerge at the water surface some 3 or 4 feet downstream from the bucket, Figure 2B, producing a boil and waves on the water surface downstream. It was apparent, therefore, that improvements in bucket performance should be directed toward reducing wave action in the downstream channel.

Four modifications of the bucket teeth were tested, the bucket with teeth removed was investigated, and a solid bucket was tested to indicate the relative advantages of the two types. To indicate the scope of the investigation, a brief summary of these tests is given; however, none of the modifications are recommended for general use.

Tooth Modification I. The teeth were extended in height along the arc of the bucket radius from 45° to 60°, as shown in Figure 7. For the standard test, the bucket performed much the same as the original. However, a boil occurred about 6 inches farther upstream and was slightly higher. Waves were also slightly higher.

Tooth Modification II. The teeth were extended in height along the arc of the bucket radius to an angle of 90°, as shown in Figure 7. It was realized that the teeth would be too tall to be structurally stable in any but a small bucket, but the trend in performance was the primary purpose in making the test.

Performance was excellent for the standard test. A large portion of the flow was turned directly upward to the water surface where it rolled back into the bucket. The tail water depth in the bucket was about the same as the depth downstream. Only a slight boil could be detected over the teeth. The flow passing between the teeth provided uniform distribution of velocity from the channel bed to the water surface in the channel downstream. The downstream water surface was smooth and the channel bed was not disturbed. The bucket also performed well for high and low tail water elevations. In fact, the range of tail water depths for which the bucket operated satisfactorily was greater than for any other slotted bucket tested. The teeth are suggested for possible use in small buckets.

Tooth Modification III. In the third modification, a radius, half that of the bucket radius, was used as shown in Figure 7 to extend the teeth to a height of 90°. This modification was made to determine whether the height of the teeth, or the 90° curvature of the teeth, provided the improved performance.

Tests showed that the shorter teeth were not effective in lifting flow to the surface. Flow passed over and through the teeth to form a high boil downstream similar to the first modification.

Tooth Modification IV. The teeth from Modification III were placed on the apron at the downstream end of the bucket, as shown in Figure 7. Performance tests showed that the teeth turned some of the flow upward but the performance was no better than for the Angostura design.

Slotted bucket with teeth removed. Tests were made to indicate the value of the teeth and slots in dissipating the energy of the spillway flow. The bucket without teeth is shown in Figure 7. Operation was satisfactory for flows of 3 and 4 second-feet but performance was poor for 6 second-feet. For flows of 5 to 6 second-feet, the flow leaving the bucket was unstable and the water surface was rough. For a few seconds, the boil would be quite high then suddenly would become quite low. However, erosion of the riverbed was negligible for all flows.

The tests indicated that the primary function of the teeth is to stabilize the flow and reduce water surface fluctuations in the channel downstream. The tests also suggested that should the teeth in a prototype slotted bucket deteriorate over a period of time, the degree of deterioration could be evaluated from the appearance of the surface flow. Discharges up to about half maximum would be satisfactory if the teeth were entirely gone.

Solid bucket. The solid bucket, shown in Figure 7, was tested to compare the action with that of a slotted bucket. The performance was similar to that shown in Figure 2A and described previously. These tests confirmed the conclusion that a solid bucket is not desirable when loose material may be carried into the bucket or when the high boil would create objectionable waves. Also, a deep erosion hole occurs from 1R to 3R downstream from the bucket lip.

SLOTTED BUCKET GENERALIZATION TESTS

General

The investigation to determine the minimum bucket size and tail water limits for a range of structure sizes, discharges, and overfall height was accomplished by the testing of 6-, 9-, 12-, and 18-inch radius buckets. Each bucket was tested over a range of discharges and tail water elevations in the test flume used for the verification tests, Figure 6.

For each test, the head on the spillway was measured and recorded. The relationship between head and discharge on the spillway is shown in Figure 8. For each discharge, the tail water depth was lowered slowly until the flow swept out of the bucket, as shown in Figure 9A. The sweepout depth considered to be too low for proper bucket performance was a limiting value and was recorded in Tables III to VI (line 2) and plotted in Figure 10. Tail water depth is the difference in elevation between the bucket invert and the tail water surface measured at the tail water gage shown in Figure 6. Figure 9B shows the 6-inch bucket operating with tail water depth just safely above sweepout. The tail water depth just safely above the depth required for the sweepout will, henceforth in this paper, be called the lower or minimum tail water limit.

For each discharge, the upper tail water limit was also investigated. The tail water was raised slowly until the flow dived from the apron lip, as shown in Figures 3 and 9C. When diving occurred, a deep hole was scoured in the channel bed near the bucket. The tail water depth for diving, considered to be too high for proper performance of the bucket, was also recorded in Tables III to V (line 12) and plotted in Figure 10. The tail water depth just safely below the depth required for diving will, henceforth, be called the upper or maximum tail water limit.

Six-inch Radius Bucket

Lower tail water limit. At the sweepout depth, the flow left the bucket in the form of a jet, Figure 9A. The jet scoured the channel bed at the point of contact but did not cause excessive water surface roughness downstream. However, a more undesirable flow pattern occurred just before sweepout. An unstable condition developed in the bucket causing excessive erosion and water surface roughness. It is therefore undesirable to design a bucket for both submerged and flip action in this transition region.

The lower tail water limit was estimated to be from 0.05 to 0.15 foot above the sweepout depth. Only the sweepout depth was actually measured since it was a more definite point than the lower tail water limit. A safe lower limit, T_{min}, was established at the conclusion of all model testing by adding 0.2 foot to the sweepout tail water depth.

Upper tail water limit. At the tail water depth required for diving to occur, Figure 9C, it was noted that after 3 or 4 minutes (model time) diving suddenly ceased and the flow rose to the surface as shown in Figure 9D. The changeover occurred only after the movable bed had become sufficiently scoured to allow a ground roller to form beneath the jet and lift the flow from the apron lip to the water surface. The ground roller then moved the deposited gravel upstream into the scoured hole until the riverbed was nearly level with the apron lip. At the same time, the strength of the ground roller was reduced until it was no longer capable of lifting the flow to the water surface and the flow dived again to start another cycle which was repeated over and over. Very little bed material was moved downstream out of reach of the ground roller even after several cycles. Five or six minutes were required for one cycle.

When the flow was diving, the water surface was very smooth; but, when the flow was directed toward the surface, a boil formed and a rough downstream water surface was in evidence. In the former case, part of the energy was dissipated on the channel bed; in the latter case, energy was dissipated on the surface.

In approaching the upper tail water limit, diving occurred in spurts not sufficiently long 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 III and plotted in Figure 10, the tail water depth required to cause sustained diving was used because it was a definite point. At the conclusion of all model testing, the upper tail water limit, T_{max}, was established by subtracting 0.5 foot from the tail water depth at which sustained diving occurred. This margin of safety was sufficient to prevent momentary diving in all cases.

It was difficult to obtain consistent results for the tail water depth at which diving occurred because the upper tail water limit was also dependent upon the shape and elevation of the channel bed. Since it was difficult to maintain the same bed shape between one test run and another, the gravel was removed from the model in anticipation that the upper tail water limit could be determined from observations of the flow pattern.

The gravel was removed completely so that the floor of the test flume was the channel bed. This arrangement proved unsuccessful since diving did not occur. However, this test showed that excellent performance occurred, Figure 11A, when the tail water depth above the bucket invert was less than the bucket radius. With deeper tail water, the performance was not as good but was still satisfactory.

The channel bed represented by a wood floor at the elevation of the apron lip produced flow currents that followed along the floor for quite some distance before rising to the surface, Figure 11C. The flow followed along the floor for a greater distance with higher tail water. No other changes in flow pattern occurred at high tail water elevations, and again no upper limit could be found.

Testing was continued with the gravel bed molded level slightly below the apron lip. It was necessary to reshape the bed before each test to obtain consistent upper limit results; even then it was difficult. Testing showed that it was important that the channel bed be below the apron lip elevation to prevent the diving flow pattern from occurring at a much lower tail water elevation. Therefore, the bed was maintained at approximately 0.05R, or 0.3 of an inch, below the apron lip of the bucket at the beginning of each test. However, in testing the larger radius buckets, a sloping bed was included in the investigation.

Maximum capacity. As the discharge capacity of the bucket was approached, the difference between the upper and lower tail water limits became smaller. The maximum capacity of the bucket was judged from its general performance and by the range of useful tail water elevations between the upper and lower tail water limits, Figure 10. The maximum capacity of the 6-inch bucket was found to be 3 to 3.5 second-feet or 1.5 to 1.75 second-feet per foot of bucket width. The performance of the bucket for 1.75 second-feet with normal tail water elevation is shown in Figure 9B.

Nine-inch Radius Bucket

The 9-inch bucket was tested in the same manner as the 6-inch bucket. The bucket in operation, before and after diving occurred, is shown in Figure 12. The maximum capacity of the 9-inch bucket was determined to be between 2 to 2.5 second-feet per foot of width. Discharges of 1.5 to 3 second-feet with a normal tail water depth of 1.85 feet are shown in Figure 13. For 3 second-feet, the tail water range for satisfactory performance was quite narrow since a depth of 1.65 feet was too little and 2.3 feet was too great.

The tail water sweepout depth and the depth at which diving occurred are recorded in Table IV and plotted in Figure 10 for a range of flows tested with bed elevation approximately 0.05R, or 0.5 inch, below the apron lip. For a given discharge, the tail water sweepout depth was not as low as for the 6-inch bucket but the diving depth was higher.

The upper tail water limit was again difficult to determine. However, a safe upper limit appeared to be approximately 0.5 of a foot below the average depth for diving to occur. The safe lower tail water limit appeared to be from 0.05 to 0.15 of a foot above the sweepout depth.

Upper and lower tail water limits were also determined with the channel bed sloping 16° upward from the apron lip to approximately 6 inches above the lip. Tests on this arrangement showed that sweepout occurred at the same depth but diving occurred at a much lower tail water depth. Diving occurred at about the same tail water depth as for the 6-inch bucket with the level bed just below the lip. The maximum capacity of the bucket did not change with bed arrangement. Thus, the effect of the sloping bed was to reduce the operating range between minimum and maximum tail water depth limits by lowering the upper tail water limit.

To aid in defining water surface profiles, measurements were made for a range of flows with the tail water at about halfway between the upper and lower limits, Figure 14.

Twelve-inch Radius Bucket

The performance of the 12-inch bucket was similar to the 6- and 9-inch buckets. Figure 15 shows the performance for unit flows ranging from 2.5 to 4 second-feet with normal tail water depth of 2.3 feet. Figure 14 shows water surface characteristics for the 9- and 12-inch buckets. The maximum capacity of the bucket was estimated to be from 3.25 to 3.5 second-feet per foot of width.

Tail water depths for sweepout and diving with the bed level at approximately 0.05R, or 0.6 inch, below the apron lip are recorded in Table V and plotted in Figure 10. Again, it was difficult to get consistent data for diving and to determine the exact margin of safety required for establishing the upper and lower tail water depth limits. However, the safe margins were about the same as for the smaller buckets.

The tests were repeated with the bed sloping upward at 16° to about 6 inches above the lip; again, the results were comparable to those for the 9-inch bucket. The safe maximum limit was about the same as the upper limit for the 9-inch bucket with the bed molded level below lip elevation. These data are given in Table V and plotted in Figure 10. The capacity of the 12-inch bucket did not change with the upward sloping bed.

Eighteen-inch Radius Bucket

The performance of the 18-inch bucket is shown in Figure 16 for unit discharges ranging from 3 to 5.5 second-feet with normal tail water depths. The capacity of the bucket was determined to be 5 to 5.5 second-feet per foot of width.

With the movable bed molded level, approximately 0.05R or 0.9 inch below the apron lip, tests for sweepout were made and the data obtained are recorded in Table VI and plotted in Figure 10. Depths for sweepout and diving were even more difficult to determine precisely than for the smaller buckets. In fact, the sustained 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.

The minimum tail water depth at which the bucket operated satisfactorily was found to be 0.1 foot above the sweepout depth; however, 0.2 foot was used, as for the other buckets, to provide a factor of safety.

The sloping bed tests could not be made because of difficulties in maintaining the bed shape while starting a test run. Performance with the bed sloping was, therefore, assumed to be consistent with the sloping bed test results on the 9- and 12-inch radius buckets.

Larger and Smaller Buckets

Increasing difficulties in measuring bucket capacity and tail water depth limits for near capacity flows made it inadvisable to test larger buckets on the 5-foot spillway. In addition, maximum tail water depths would either submerge the crest or closely approach that condition. It was not intended at this time to investigate a bucket with a submerged crest.

It was unnecessary to test smaller buckets because very few, if any, prototype structures would use a bucket radius smaller than one-tenth the height of the spillway. A short radius bend is usually avoided on high structures where velocities are also high. Therefore, the available data were analyzed and, with some extrapolation, found to be sufficient.

Data Analysis

Safety factor. At the conclusion of the testing, the data for the four buckets were surveyed and the margins of safety, between sweepout depth and minimum tail water depth and between maximum tail water depth and the diving depth, were definitely established. An ample margin of safety for the lower limit was 0.2 foot and for the upper limit 0.5 foot. These values were sufficient for both the level and sloping movable beds previously described and are included in items T_{min} and T_{max} of Tables III, IV, V, and VI.

Evaluation of variables. To generalize the design of a bucket from the available data, it is necessary to determine the relation of the variables shown in Figure 17. The available data are shown in Tables III through VI and are plotted in Figure 10.

Figure 10 shows that, for a given height of structure having a particular overfall shape and spillway surface roughness, the sweepout depth and minimum tail water depth are functions of the radius of the bucket R and the head on the crest H. The height of structure may be expressed as the height of fall h from the spillway crest to the tail water elevation. H and the overfall crest shape, which determines the discharge coefficient, may be expressed as q. Since the spillway surface roughness and the spillway slope had negligible effect on flow in the model, they were not considered in the analysis of model data. Prototype effects, however, are discussed in a subsequent section of this paper. By actual test, it was found that the elevation or shape of the movable bed did not affect the minimum tail water limits.

Therefore,

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

Similarily, the maximum tail water depth limit is a function of the same variables but since the slope and elevation of the movable bed with respect to the apron lip does affect the tail water at which diving occurs

$$T_{max} = f \text{ (h, R, q and channel bed)}$$

The maximum capacity of a bucket is slightly greater for intermediate tail water depths than for the extremes. But, since the bucket is expected to operate over a range of tail water depths, the minimum bucket radius is a function of only h and q.

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

The Froude number, a dimensionless parameter, is a function of velocity and depth of flow and may be expressed

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

in which V_1 and D_1 are at tail water elevatión, as shown in Figure 17. Since V_1 and D_1 are functions of h and q, they may be replaced by the Froude number F.

Substituting, then

$$T_{min}, T_{max} \text{ and } T_s = f\ (R, F)$$

and

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

Numerical values for the Froude number were computed from the available test data in the tables for points on the spillway face at the tail water elevation. At these points, all necessary information for computing velocity and depth of flow can be determined from the available test data which include headwater elevation, discharge, and tail water elevation. Since the Froude number expresses a ratio of velocity to depth and is dimensionless, a numerical value represents a prototype as well as a model flow condition.

To express T_{min}, T_{max}, and R as dimensionless numbers so that they may also represent prototype flow conditions, T_{min} and T_{max} were divided by D_1; 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, computed from test data, are shown in Tables III, IV, V, and VI. In computing the tabular values, frictional resistance in the 5-foot model was considered to be negligible.

In Figure 18, the dimensionless ratio for the bucket radius is plotted against the Froude number, using only the test points bracketing the estimated maximum bucket capacity. Values were plotted for both the sweepout and diving tail water elevations since the Froude number and $\frac{R}{D_1 + \frac{V_1^2}{2g}}$ both vary with tail water elevation. For example, the maximum capacity of the 6-inch bucket is q = 1.5 to 1.75 in Columns 7 and 8 of Table III; data from lines 8 and 11 and lines 17 and 20 were plotted in Figure 18. The two points thus obtained for each discharge were connected by a dashed line to indicate the trend for constant discharge. Eight dashed lines were thereby obtained for the four buckets. A single envelope curve was then drawn, shown as the solid line to the right of the preliminary lines, to indicate the minimum radius bucket. Values taken from the solid line, therefore, include a factor of safety indicated by the distance between the solid line and the test points.

Since both the upper and lower depth limits are functions of the bucket radius and the Froude number, $\frac{T_{min}}{D_1}$ and $\frac{T_{max}}{D_1}$ for each test point in Tables III through VI were plotted versus the Froude number in Figure 19, and each point and curve was labeled with the computed value of $\frac{R}{D_1 + \frac{V_1^2}{2g}}$. The upper four curves are for the minimum tail water limit and apply to any bed arrangement. The 10 lower curves apply to the maximum tail water limitation and have 2 sets of labels, 1 for the sloping bed and 1 for the level bed. Two curves are shown for each value of $\frac{R}{D_1 + \frac{V_1^2}{2g}}$;

the upper or solid line curves have an extra factor of safety included because of the difficulty in obtaining consistent upper tail water limit values. The lower or dashed line curves are a strict interpretation of the values in Tables III through VI.

The curves of Figure 19 may be used directly to determine minimum and maximum tail water limits for a given Froude number and bucket ratio. However, a simpler and easier to use version of the same data is given in Figures 20 and 21, which were obtained by cross-plotting the curves of Figure 19. Figure 20 contains a family of curves to determine $\frac{T_{min}}{D_1}$ values in terms of the Froude number and $\frac{R}{D_1 + \frac{V_1^2}{2g}}$. Figure 21 contains similar curves to determine $\frac{T_{max}}{D_1}$ and includes the extra factor of safety discussed for Figure 19. The two abscissa scales in Figure 21 differentiate between the sloping bed and the level bed used in the tests.

The tail water sweepout depth T in Tables III through VI was also expressed as a dimensionless ratio $\frac{T_s}{D_1}$ and plotted versus the Froude number in Figure 22, and a curve for each bucket size was drawn. These curves were then cross-plotted in Figure 23 to provide means for determining the sweepout depth for any installation. The difference between sweepout depth indicated by the curves and the depth to be expected in the prototype indicates the margin of safety.

To aid in determining approximate water surface profiles in and downstream from the bucket, the data of Figure 14 and values scaled from photographs of other bucket tests were analyzed and plotted. Refinement of the curves obtained resulted in the curves of Figure 24. The height of the boil above the tail water may be determined from the Froude number and the ratio $\frac{R}{X}$, where R is the bucket radius and X is the height of the spillway from crest to bucket invert. The depth of the water in the bucket, dimension B in Figures 14 and 24, was found to remain fairly constant over most of the design operating range, about 80 to 85 percent of the dimension T. For minimum recommended tail water, the percentage dropped to 70 percent, while with high tail water the value increased to 90 percent, approximately.

Practical Applications

To illustrate the use of the methods and charts given in this paper, a step-by-step procedure for designing a slotted bucket is presented. Discharge data, height of fall, etc., from Grand Coulee Dam spillway will be used in the example so that the resulting slotted bucket may be compared with the solid bucket individually determined from model tests and now in use at Grand Coulee Dam. The calculations are summarized in Table VII.

For maximum reservoir elevation 1291.65, the spillway discharge is 1,000,000 second-feet. Since the spillway crest is at elevation 1260, the head is 31.65 feet. The width of the bucket is 1,650 feet, making the discharge per foot 606 second-feet. The tail water in the river is expected to be at elevation 1011 for the maximum flow. The velocity head of the flow entering the basin is the difference between tail water elevation and reservoir elevation or 280.65 feet. Then, theoretically, the velocity entering the tail water is 134.4 feet per second; $V_1 = \sqrt{2g(H + h)}$. See Figure 17.

The actual velocity is less than theoretical at this point, however, due to frictional resistance on the spillway face. Using Figure 25, the actual velocity is found to be 91 percent of theoretical. Figure 25 may be used to reduce the computation work on the preliminary design of overfall spillways and is believed to be reasonably accurate. However, only a limited amount of prototype data were available to develop the chart so that the information obtained should be used with caution. Entering Figure 25 with the height of fall 280.65 feet as the ordinate and intersecting the curve for 31.65 feet of head on the crest, the abscissa is found to be 0.91. Therefore, the actual velocity in this example is 91 percent of 134.4, or 122.4 feet per second. The corresponding depth of flow D_1 on the spillway face is $\frac{q}{V_1}$ or 4.95 feet. Having determined D_1 and V_1, the Froude number, $\frac{V_1}{\sqrt{gD_1}}$, is computed to be 9.7.

Entering Figure 18 with Froude number 9.7, the dimensionless ratio for the minimum allowable bucket radius is found to be 0.12 from the solid line curve. The minimum bucket radius is then computed to be 28.5 feet. In round numbers, a 30-foot bucket radius would probably be used. For the 30-foot radius, the dimensionless ratio would be 0.13. Entering Figure 20 with the dimensionless ratio and the Froude number, $\frac{T_{min}}{D_1}$ is found to be 14.7. The minimum tail water depth limit is then 73 feet, measured from the bucket invert to the tail water surface elevation. Similarly, $\frac{T_{max}}{D_1}$ for the bed elevation below the apron lip is found to be 23 from Figure 21. The maximum tail water depth limit is then 114 feet.

To determine the sweepout depth, enter Figure 23 with the Froude number and the bucket radius dimensionless ratio; the sweepout depth dimensionless ratio is 12.6. The sweepout depth then is approximately 63 feet. Thus, the minimum tail water depth limit of 73 feet provides 10 feet of margin against flow sweeping out of the bucket at the maximum discharge.

The riverbed at Grand Coulee Dam is at elevation 900, approximately. If the bucket invert is placed at riverbed elevation, the tail water depth would be 111 feet, which is close to the upper limit of 114 feet. No diving would occur. On the other hand, if the tail water depth was greater than the upper tail water limit, diving still would not occur because the lip of the bucket is considerably more than 0.05R above the channel bed. With the bucket invert at riverbed elevation, the appearance of the flow would be similar to that shown in Figure 11B and would be satisfactory, provided the water surface profile computed from Figure 24 is satisfactory. However, to obtain a smoother water surface, the bucket invert should be set well above the riverbed so that the tail water depth above the bucket invert is less than sweepout depth plus bucket radius (93 feet) but more than the minimum depth of 73 feet. The performance would then appear as shown in Figure 11A.

The data in Figure 14 and the curves of Figure 24 may be used to obtain an approximate water surface profile if the bucket invert is placed near channel bed elevation 900. For $F = 9.7$ and $\frac{R}{X} = \frac{30}{360} = 0.083$; $\frac{A}{T} = 1.3$. The maximum height of boil A is then 1.3×111, or 144 feet above the bucket invert and 33 feet above the tail water. In the bucket, the depth of water B would be 90 percent of 111 feet or approximately 100 feet. The maximum difference (A-B) would be about 44 feet for the design tail water. The length and location of the boil may be estimated from the data in Figure 14.

If a larger usable range of tail water is desired, a bucket radius larger than 30 feet could be used. With a 50-foot radius, the bucket dimensionless ratio, $\frac{R}{D_1 + V_1^2/2g}$, would be 0.21. From Figures 20 and 21, the minimum and maximum tail water depth limit ratios are 15.8 and 7, respectively. The corresponding tail water depths are then 78 and 183 feet. From Figure 23, the sweepout depth is determined to be 67 feet. With the bucket placed to provide 111 feet of tail water $\frac{R}{X} = 0.14$ and $\frac{A}{T} = 1.1$. The height of the boil then would be about 122 feet above the bucket invert or 11 feet above tail water. The water in the bucket, 80 percent of 111, would be 89 feet deep. The 50-foot bucket would provide a smoother water surface profile.

If the invert of the 50-foot radius bucket is placed below riverbed elevation and the bed is sloped upward from the apron lip, the ratio $T(max)/D_1$ is approximately 20.5 as found in Figure 21. The upper depth limit, therefore, would be only 101 feet. In this case, the flow from the apron might scour the channel bed because the tail water depth above the bucket invert is greater than the maximum limit.

Before adopting either of the bucket sizes discussed for the design discharge, consideration should be given to the fact that the bucket might be required to operate with tail water corresponding to the discharge just before it was increased to maximum. Other factors which might affect the tail water elevation for a particular spillway discharge such as powerplant, outlet works, or other discharges, should also be investigated. Spillway discharges less than the design flow may also be investigated; however, it is seldom that a discharge less than design flow governs the bucket requirements because the tail water limits increase quite rapidly as the discharge decreases in a given installation. After the bucket radius has been determined, the bucket design may be completed from the data in Figure 1.

Discharges less than maximum were investigated for the Angostura installation in Table VII, using the methods presented in this paper. These computations show that the bucket design obtained for the maximum flow is larger than necessary for the smaller flows and that the tail water depth range for satisfactory performance is greater for smaller flows than for the maximum flow.

The Angostura analysis in Table VII shows, too, that the bucket radius determined from the Angostura model study is less than the radius shown in the table, indicating that the methods presented in this paper provide a factor of safety. This is a desirable feature when hydraulic model studies are not contemplated. On the other hand, hydraulic model studies make it possible to explore regions of uncertainty in particular cases and help to provide the absolute minimum bucket size consistent with acceptable performance.

Other examples in Table VII include an analysis using the data from Trenton Dam spillway. This spillway utilizes a long flat chute upstream from the energy dissipator. Friction losses are considerably higher than would occur on the steep spillways for which Figure 25 was drawn. Other means must therefore be used to obtain V_1 and D_1 for the bucket design. In this example, actual velocity measurements taken from a model were used. If frictional resistance is neglected in the velocity computations, the minimum tail water limit would be higher, providing a greater factor of safety against sweepout. But the maximum tail water limit would also be higher which reduces the factor of safety against flow diving.

Tail water requirements for bucket versus hydraulic jump. In general, a bucket-type dissipator requires a greater depth of tail water than a stilling basin utilizing the hydraulic jump. This is illustrated in Table VIII where pertinent data from Table VII are summarized to compare the minimum tail water depth necessary for a minimum radius bucket with the computed conjugate tail water depth for a hydraulic jump. Line 6 shows T_{min} for the buckets worked out in the section Practical Applications. Line 7 shows the conjugate tail water depth required for a hydraulic jump for the same Froude number and D_1 determined from the equation $\frac{D_2}{D_1} = 1/2 \sqrt{1 + 8F^2} - 1$.

Table VIII

COMPARISON OF TAIL WATER DEPTHS REQUIRED FOR BUCKET AND HYDRAULIC JUMP

		Angostura Dam	Angostura Dam	Angostura Dam	Angostura Dam	Grand Coulee Dam	Grand Coulee Dam	Trenton Dam	Missouri Diversion Dam (Not built)
1	Q in thousands cfs	247	180	100	40	1,000	1,000	133	90
2	V_1 ft/sec	72	72	73	70	122.4	122.4	66	39
3	D_1 ft	12.5	9.1	5.0	2.1	5.0	5.0	7.6	3.6
4	F	3.6	4.3	5.7	8.5	9.7	9.7	4.2	3.7
5	T_{max} ft	71	72	89	210	114	183	98	32
6	T_{min} ft	67	59	46	32	73	78	49	20
7	T_{conj} ft	57	52	38	24	66	66	40	16
8	Bucket radius	47	39	26	12	30	50	35	12.5

Note: If a larger than minimum bucket radius is used, the required minimum tail water depth becomes greater, as shown for the two Grand Coulee bucket radii.

SUMMARY

The Angostura-type slotted bucket, Figure 1B, is well adapted for general use as an energy dissipator at the base of an overfall. Tests showed the slotted bucket to be superior to the solid bucket in all respects. Wherever practicable, the higher teeth recommended in Design Modification II, Figure 7, should be used.

A simplified version of the seven steps required to design a bucket is given below. The letter symbols refer to Figure 17.

1. Determine Q, q (per foot of bucket width), V_1, D_1; compute Froude number from $F = \frac{V_1}{\sqrt{gD_1}}$ for maximum flow and intermediate flows. In some cases V_1 may be estimated from Figure 25.

2. Enter Figure 18 with F to find bucket radius ratio

$\frac{R}{D_1 + \frac{V_1^2}{2g}}$ from which minimum allowable bucket radius R may be computed.

3. Enter Figure 20 with $\frac{R}{D_1 + \frac{V_1^2}{2g}}$ and F to find $\frac{T_{min}}{D_1}$ from which minimum tail water depth limit may be computed.

4. Enter Figure 21 as in Step 3 above to find maximum tail water depth limit, T_{max}.

5. Set bucket invert elevation so that tail water curve elevations are between tail water depth limits determined by T_{min} and T_{max}. Keep apron lip and bucket invert above riverbed, if possible. For best performance, set bucket so that the tail water depth is near T_{min}. Check setting and determine factor of safety against sweepout from Figure 23 using methods of Step 3.

6. Complete design of bucket using Figure 1 to obtain tooth size, spacing, dimensions, etc.

7. Use Figures 14 and 24 to estimate the probable water surface profile in and downstream from the bucket.

The procedures outlined above summarize the main considerations in the hydraulic design of a slotted bucket. The sample calculations in Table VII may prove helpful in analyzing a particular problem. However, other considerations are discussed in the paper, and the entire paper should be read before attempting to use the procedures given above. The procedures and data may also be used (with caution) to determine the radius and lower tail water limit for a solid-type bucket. Figures 18 and 22 might prove helpful in determining the radius and upper tail water limit for a flip-type bucket.

ACKNOWLEDGEMENTS

The bucket tests described in this paper are of recent origin although bucket tests in general have been made since about 1933. Some of the early tests were valuable in this study in that they helped to point the way for the later tests and eliminated certain bucket schemes from further consideration. These early tests were conducted by J. H. Douma, C. W. Thomas, J. W. Ball, and J. N. Bradley. Later tests were made by R. C. Besel, E. J. Rusho, and J. N. Bradley under the laboratory direction of J. E. Warnock. The final tests to develop the slotted bucket and generalize the design were made by G. L. Beichley under the supervision of A. J. Peterka and J. N. Bradley and laboratory direction of H. M. Martin. Some of the material contained in this paper was submitted by G. L. Beichley, as a thesis for the degree of Master of Science, University of Colorado. All tests and analyses were conducted in the Bureau of Reclamation Hydraulic Laboratory, Denver, Colorado.

Table III

DATA AND CALCULATED VALUES FOR 6-INCH RADIUS BUCKET

	Bed was approx 0.05R below apron lip at beginning of each run								
	1	2	3	4	5	6	7	8	9
				Sweepout Conditions					
1: H	0.198	0.274	0.352	0.413	0.480	0.481	0.526	0.581	0.678
2: T (swpout) (depth)	0.767	0.765	0.826	0.943	1.023	1.081	1.139	1.203	1.403
3: q	0.31	0.54	0.81	1.03	1.30	1.30	1.50	1.75	2.25
4: T_{min}	0.967	0.965	1.026	1.143	1.223	1.281	1.339	1.403	1.603
5: $\frac{V_1^2}{2g}$	4.231	4.309	4.326	4.270	4.257	4.200	4.187	4.178	4.075
6: V_1	16.50	16.65	16.70	16.58	16.56	16.45	16.42	16.41	16.20
7: D_1	0.019	0.032	0.048	0.062	0.078	0.079	0.091	0.107	0.139
8: $F = \frac{V_1}{\sqrt{gD_1}}$	21.2	16.31	13.36	11.72	10.42	10.31	9.50	8.85	7.65
9: $\frac{T_{min}}{D_1}$	51.43	29.78	21.10	18.40	15.57	16.21	14.66	13.16	11.54
10: $D_1 + \frac{V_1^2}{2g}$	4.245	4.341	4.374	4.332	4.335	4.279	4.278	4.285	4.214
11: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.12	0.12
				Diving Flow Conditions					
12: T (diving) (depth)	2.565	2.576	2.435	2.464	2.439	2.397	2.043	2.200	2.213
13: T_{max}	2.065	2.076	1.935	1.964	1.939	1.897	1.543	1.700	1.713
14: $\frac{V_1^2}{2g}$	2.133	2.198	2.417	2.449	2.541	2.584	2.983	2.881	2.965
15: V_1	11.72	11.89	12.47	12.55	12.78	12.90	13.86	13.62	13.81
16: D_1	0.026	0.045	0.065	0.089	0.102	0.101	0.108	0.128	0.163
17: $F = \frac{V_1}{\sqrt{gD_1}}$	12.67	9.84	8.62	7.40	7.06	7.20	7.42	6.70	6.02
18: $\frac{T_{max}}{D_1}$	77.92	45.72	29.76	21.62	19.06	18.82	14.26	13.23	10.51
19: $D_1 + \frac{V_1^2}{2g}$	2.159	2.243	2.486	2.538	2.643	2.685	2.983	3.009	3.128
20: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.23	0.22	0.20	0.20	0.19	0.19	0.17	0.17	0.16

R = bucket radius (ft)
H = ht. of reservoir above the crest (ft)
T = depth of TW above the bucket invert (ft)
T_{min} = min TW depth for good performance (ft) = sweepout depth + 0.2 ft
T_{max} = max TW depth for good performance (ft) = diving depth - 0.5 ft
q = discharge per ft of model crest length (cfs)
X = ht. of crest above bucket invert = 5 ft
V_1 = velocity of flow entering the bucket computed at TW el (ft/sec)
D_1 = depth of flow entering the bucket computed at TW el (ft)
F = Froude number of flow entering bucket computed at TW el

Maximum capacity of bucket estimated to be 1.5 to 1.75 second-feet per ft of width.

Table IV

DATA AND CALCULATED VALUES FOR 9-INCH RADIUS BUCKET

		Bed approx 0.05R below apron lip at beginning of each run					
	Run No.	1	2	3	4	5	6
		Sweepout Conditions					
1	H	0.419	0.476	0.531	0.642	0.682	0.722
2	T (swpout) (depth)	1.02	1.11	1.19	1.33	1.41	1.45
3	q	1.05	1.28	1.52	2.05	2.28	2.50
4	T_{min}	1.22	1.31	1.39	1.53	1.61	1.65
5	$\frac{V_1^2}{2g}$	4.199	4.166	4.141	4.112	4.072	4.072
6	V_1	16.45	16.38	16.33	16.28	16.20	16.20
7	D_1	0.064	0.078	0.093	0.126	0.141	0.154
8	$F = \frac{V_1}{\sqrt{gD_1}}$	11.49	10.34	9.44	8.09	7.62	7.27
9	$\frac{T_{min}}{D_1}$	19.12	16.77	14.93	12.15	11.44	10.69
10	$D_1 + \frac{V_1^2}{2g}$	4.262	4.244	4.234	4.238	4.212	4.226
11	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.18	0.18	0.18	0.18	0.18	0.18
		Diving Flow Conditions					
12	T (diving) (depth)	3.40	3.03	3.01	2.46	2.38	2.44
13	T_{max}	2.90	2.53	2.51	1.96	1.88	1.94
14	$\frac{V_1^2}{2g}$	1.519	1.946	2.021	2.682	2.802	2.782
15	V_1	9.89	11.20	11.40	13.14	13.43	13.40
16	D_1	0.106	0.114	0.133	0.156	0.170	0.187
17	$F = \frac{V_1}{\sqrt{gD_1}}$	5.34	5.84	5.49	5.85	5.72	5.46
18	$\frac{T_{max}}{D_1}$	2.733	22.13	18.82	12.56	11.07	10.39
19	$D_1 + \frac{V_1^2}{2g}$	1.625	2.060	2.154	2.838	2.972	2.969
20	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.46	0.36	0.35	0.26	0.25	0.25

Note: See Table III for definition of symbols.

Maximum capacity of bucket estimated to be 2.0 to 2.5 second-feet per ft of width.

Table IV--Continued

Run No.	7	8	9	10	11	12	13
	Bed approx 0.05R below apron lip at beginning of each run						
	Sweepout Conditions						
1: H	0.764	0.805	0.852	0.884	0.534	0.578	0.585
2: T (swpout) (depth)	1.51	1.60	1.67	1.70			
3: q	2.74	3.00	3.30	3.52	1.53	1.73	1.78
4: T_{min}	1.71	1.80	1.87	1.90			
5: $\frac{V_1^2}{2g}$	4.054	4.005	3.982	3.984			
6: V_1	16.16	16.06	16.02	16.02			
7: D_1	0.170	0.187	0.206	0.220			
8: $F = \frac{V_1}{\sqrt{gD_1}}$	6.92	6.56	6.22	6.03			
9: $\frac{T_{min}}{D_1}$	10.08	9.63	9.07	8.64			
10: $D_1 + \frac{V_1^2}{2g}$	4.224	4.192	4.188	4.204			
11: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.18	0.18	0.18	0.18			
	Diving Flow Conditions						
12: T (diving) (depth)	2.44	2.32	2.46	2.37	2.68	2.39	2.37
13: T_{max}	1.94	1.82	1.96	1.87	2.18	1.89	1.87
14: $\frac{V_1^2}{2g}$	2.824	2.985	2.892	2.014	2.354	2.688	2.715
15: V_1	13.48	13.87	13.65	13.94	12.31	13.16	13.22
16: D_1	0.203	0.216	0.242	0.252	0.126	0.131	0.135
17: $F = \frac{V_1}{\sqrt{gD_1}}$	5.26	5.25	4.89	4.89	6.11	6.41	6.38
18: $\frac{T_{max}}{D_1}$	9.54	8.54	8.10	7.40	17.28	14.38	13.89
19: $D_1 + \frac{V_1^2}{2g}$	2.077	3.201	3.134	3.266	2.480	2.819	2.850
20: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.25	0.23	0.24	0.23	0.30	0.27	0.26

Table IV--Continued

Run No.	14	15	16	17	18	19	20
				Bed slopes up from apron lip			
				Sweepout Conditions			
1: H	0.633	0.54	0.433	0.485	0.527	0.634	0.723
2: T (swpout) (depth)							
3: q	2.02	1.56	1.12	1.32	1.50	2.01	2.50
4: T_{min}							
5: $\frac{V_1^2}{2g}$							
6: V_1							
7: D_1							
8: $F = \frac{V_1}{\sqrt{gD_1}}$							
9: $\frac{T_{min}}{D_1}$							
10: $D_1 + \frac{V_1^2}{2g}$							
11: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$							
				Diving Flow Conditions			
12: T (diving) (depth)	2.42	3.07	1.96	1.86	2.23	2.69	2.43
13: T_{max}	1.92	2.57	1.46	1.36	1.73	2.19	1.93
14: $\frac{V_1^2}{2g}$	2.713	1.970	2.790	3.125	2.797	2.444	2.793
15: V_1	13.21	11.26	13.84	14.18	13.42	12.55	13.40
16: D_1	0.153	0.138	0.081	0.093	0.112	0.160	0.187
17: $F = \frac{V_1}{\sqrt{gD_1}}$	5.95	4.15	8.59	8.19	7.08	5.53	5.46
18: $\frac{T_{max}}{D_1}$	12.55	18.55	18.00	14.60	15.47	13.67	10.34
19: $D_1 + \frac{V_1^2}{2g}$	2.866	2.108	3.054	3.218	2.909	2.604	2.980
20: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.26	0.35	0.25	0.23	0.26	0.29	0.25

Table V

DATA AND CALCULATED VALUES FOR 12-INCH RADIUS BUCKET

	Bed was approx 0.05R below apron lip at beginning of each run							
Run No.	1	2	3	4	5	6	7	8
				Sweepout Conditions				
1: H	0.543	0.592	0.637	0.679	0.729	0.765	0.811	0.850
2: T (swpout) (depth)	1.27	1.33	1.40	1.45	1.52	1.56	1.68	1.72
3: q	1.58	1,82	2.03	2.25	2.53	2.75	3.05	3.28
4: T_{min}	1.47	1.53	1.60	1.65	1.72	1.76	1.88	1.92
5: $\frac{V_1^2}{2g}$	4.073	4.062	4.037	4.029	4.009	4.005	3.931	3.930
6: V_1	16.20	16.17	16.12	16.11	16.07	16.06	15.92	15.91
7: D_1	0.099	0.112	0.126	0.140	0.157	0.171	0.192	0.206
8: $F = \frac{V_1}{\sqrt{gD_1}}$	9.10	8.51	8.01	7.60	7.14	6.84	6.41	6.18
9: $\frac{T_{min}}{D_1}$	14.91	13.60	12.71	11.81	10.93	10.28	9.81	9.31
10: $D_1 + \frac{V_1^2}{2g}$	4.172	4.175	4.163	4.169	4.166	4.176	4.123	4.136
11: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
				Diving Flow Conditions				
12: T (diving) (depth)	3.90	4.00	3.95	3.95	3.95	3.95	--	2.91
13: T_{max}	3.45	3.50	3.40	3.45	3.45	3.45	--	2.41
14: $\frac{V_1^2}{2g}$	1.093	1.092	1.237	1.229	1.279	1.315	--	2.440
15: V_1	8.39	8.39	8.92	8.90	9.07	9.20	--	12.54
16: D_1	0.188	0.217	0.228	0.253	0.279	0.299	--	0.262
17: $F = \frac{V_1}{\sqrt{gD_1}}$	3.42	3.17	3.29	3.11	3.02	2.96	--	4.31
18: $\frac{T_{max}}{D_1}$	18.35	16.12	14.91	14.63	12.36	11.53	--	9.19
19: $D_1 + \frac{V_1^2}{2g}$	1.281	1.309	1.465	1.482	1.558	1.614	--	2.702
20: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.78	0.72	0.68	0.67	0.64	0.62		0.37

Note: See Table III for definition of symbols.

Maximum capacity of bucket estimated to be 3.25 to 3.50 second-feet per ft of width.

Table V--Continued

Run No.	9	10	11	12	Bed slopes up from apron lip 13	14	15	16
				Sweepout Conditions				
1: H	0.887	0.961	1.02	1.221	0.565	0.651	0.723	0.839
2: T (swpout) (depth)	1.78	1.89	1.96	2.23				
3: q	3.54	4.06	4.48	6.08	1.67	2.00	2.50	3.21
4: T_{min}	1.98	2.09	2.16	2.43				
5: $\frac{V_1^2}{2g}$	3.907	3.871	3.860	3.791				
6: V_1	15.86	15.79	15.77	15.63				
7: D_1	0.223	0.257	0.284	0.389				
8: $F = \frac{V_1}{\sqrt{gD_1}}$	5.93	5.49	5.22	4.42				
9: $\frac{T_{min}}{D_1}$	8.87	8.13	7.60	6.25				
10: $D_1 + \frac{V_1^2}{2g}$	4.133	4.128	4.144	4.180				
11: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.24	0.24	0.24	0.24				
				Diving Flow Conditions				
12: T (diving) (depth)	2.87	3.22	3.17	3.00	3.25	3.00	2.45	2.35
13: T_{max}	2.37	2.72	2.67	2.50	2.75	2.50	1.95	1.85
14: $\frac{V_1^2}{2g}$	2.517	2.241	2.35	2.721	1.815	2.131	2.773	2.889
15: V_1	12.72	12.01	12.30	12.23	10.81	11.71	13.36	13.64
16: D_1	0.278	0.338	0.364	0.460	0.154	0.171	0.187	0.235
17: $F = \frac{V_1}{\sqrt{gD_1}}$	4.25	3.64	3.41	3.44	4.86	4.98	5.54	4.96
18: $\frac{T_{max}}{D_1}$	8.52	8.04	7.33	5.54	17.85	14.61	10.42	7.87
19: $D_1 + \frac{V_1^2}{2g}$	2.795	2.579	2.714	3.181	1.969	2.302	2.960	3.124
20: $\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.36	0.39	0.37	0.31	0.51	0.43	0.34	0.32

Table VI

DATA AND CALCULATED VALUES FOR 18-INCH RADIUS BUCKET

		Bed was approx 0.05R below apron lip at beginning of each run							
	Run No.	1	2	3	4	5	6	7	8
					Sweepout Conditions				
1	H	0.631	0.734	0.804	0.898	0.926	1.001	1.083	1.150
2	T (swpout) (depth)	1.45		1.78					
3	q	2.00	2.56	2.99	3.61	3.80	4.35	4.98	5.48
4	T_{min}	1.65	1.85	1.98	2.07	2.15	2.23	2.32	2.45
5	$\frac{V_1^2}{2g}$	3.981	3.884	3.824	3.828	3.776	3.771	3.763	3.700
6	V_1	16.02	15.86	15.70	15.70	15.27	15.68	15.67	15.44
7	D_1	0.125	0.161	0.190	0.230	0.249	0.277	0.318	0.355
8	$F = \frac{V_1}{\sqrt{gD_1}}$	7.98	6.94	6.33	6.76	5.39	5.24	4.88	4.56
9	$\frac{T_{min}}{D_1}$	13.22	11.46	10.39	9.00	8.64	8.03	7.30	6.70
10	$D_1 + \frac{V_1^2}{2g}$	4.106	4.045	4.014	4.058	4.025	4.043	4.081	4.055
11	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
					Diving Flow Conditions				
12	T (diving) (depth)								
13	T_{max}								
14	$\frac{V_1^2}{2g}$								
15	V_1								
16	D_1								
17	$F = \frac{V_1}{\sqrt{gD_1}}$				No Data Taken				
18	$\frac{T_{max}}{D_1}$								
19	$D_1 + \frac{V_1^2}{2g}$								
20	$\frac{R}{D_1 + \frac{V_1^2}{2g}}$								

Note: See Table III for definition of symbols.

Maximum capacity of bucket estimated to be 5.0 to 5.5 second-feet per ft of width.

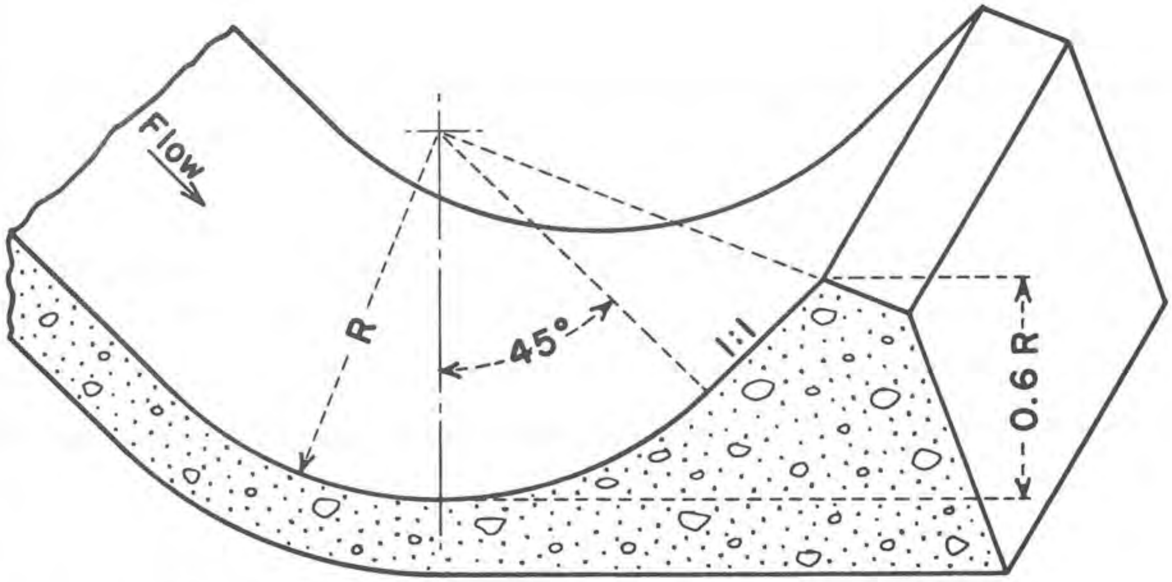
Table VII

EXAMPLES OF BUCKET DESIGN PROCEDURES

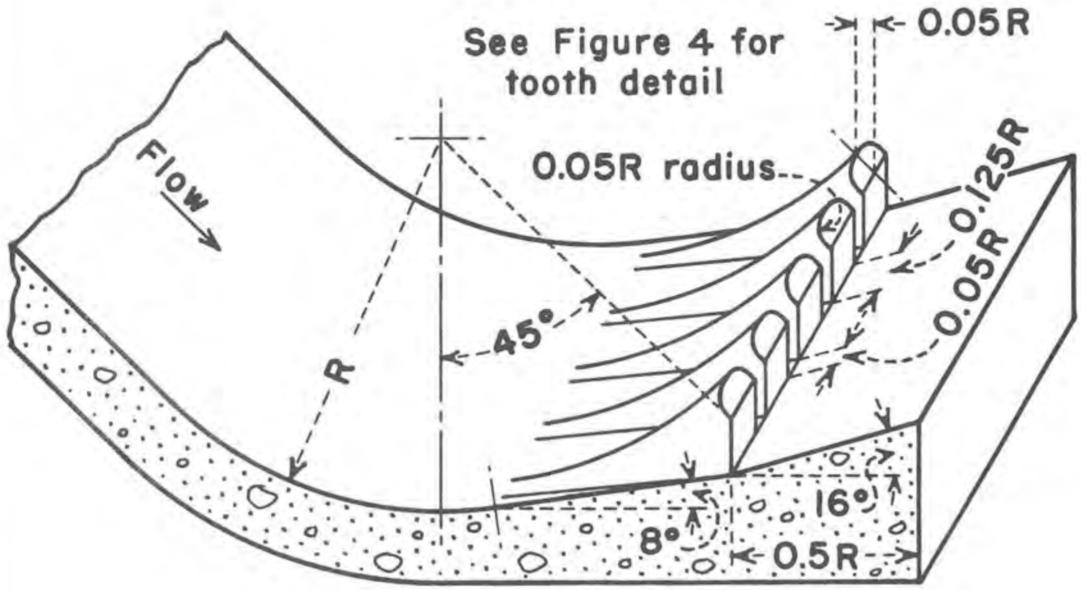
	Angostura Dam				Grand Coulee Dam	Trenton Dam	Missouri Diversion Dam
Q (1,000) (cfs)	247	180	100	40	1000	133	90
HW el	3198.1	3191.0	3181.5	3170.4	1291.65	2785	2043.4
Crest el	3157.2	3157.2	3157.2	3157.2	1260	2743	2032
H	40.9	33.8	24.3	13.2	31.65	42	11.4
L	274	274	274	274	1650	266	644
q	901	657	365	146	606	500	140
TW el	3114	3106	3095	3084	1011	2700.6	2018.3
$*\frac{V_1^2}{2g}$	84.1	85.0	86.5	86.4	280.65	84.4	25.1
$*V_1$	73.6	74	74.6	74.5	134.4	73.7	40.2
$\frac{**V_1}{*V_1}$	0.98	0.98	0.97	0.93	0.91		0.98
$**V_1$	72.2	72.5	72.4	69.3	122.4	66.3	39.4
$**\frac{V_1^2}{2g}$	80.9	81.6	81.4	74.6	233.0	68.3	24.1
D_1	12.48	9.06	5.04	2.11	4.95	7.54	3.55
$\sqrt{D_1}$	3.53	3.01	2.24	1.45	2.23	2.75	1.88
$F = \frac{V_1}{\sqrt{gD_1}}$	3.61	4.25	5.68	8.42	9.70	4.25	3.70
$D_1 + \frac{V_1^2}{2g}$	93.38	90.66	86.44	76.71	237.95	75.84	27.65
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.50	0.43	0.30	0.16	0.12	0.43	0.49
R	47	39	26	12	28.5	33	14
R (used)	40	40	40	40			
R (rec)					30	35	12.5
$\frac{R}{D_1 + \frac{V_1^2}{2g}}$	0.43	0.44	0.46	0.52	0.13	0.46	0.45
$\frac{T_{min}}{D_1}$	5.4	6.5	9.1	15.3	14.7	6.5	5.6
T_{min}	67	59	46	32.5	73	49	20
$\frac{T_{max}}{D_1}$	5.7	7.9	17.6	100	23	13.0	8.9
T_{max}	71	72	89	210	114	98	32
$\frac{T_s}{D_1}$	5.0	6.0	8.2	14.4	12.6	6.0	5.2
T_s	62	54	41	30	63	45	18

Note: See Table III for definition of symbols.

*Theoretical velocity.
**Actual velocity.

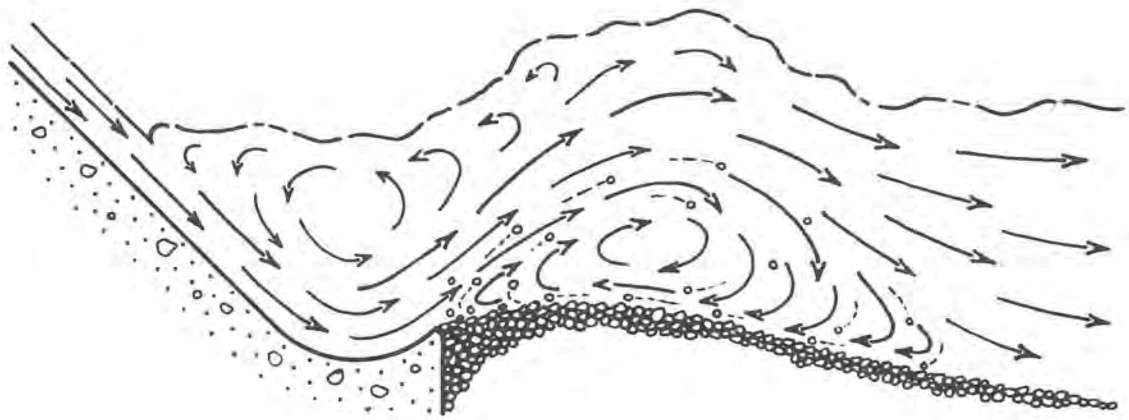


A. GRAND COULEE TYPE SOLID BUCKET

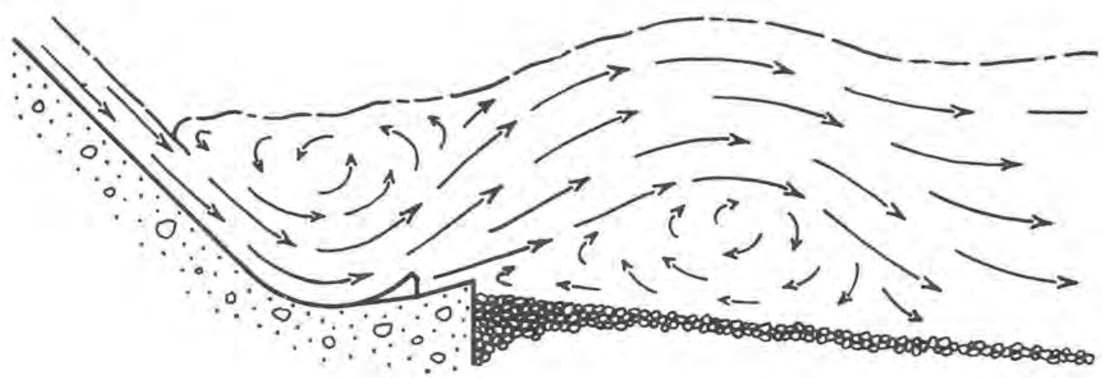


B. ANGOSTURA TYPE SLOTTED BUCKET

SUBMERGED BUCKETS



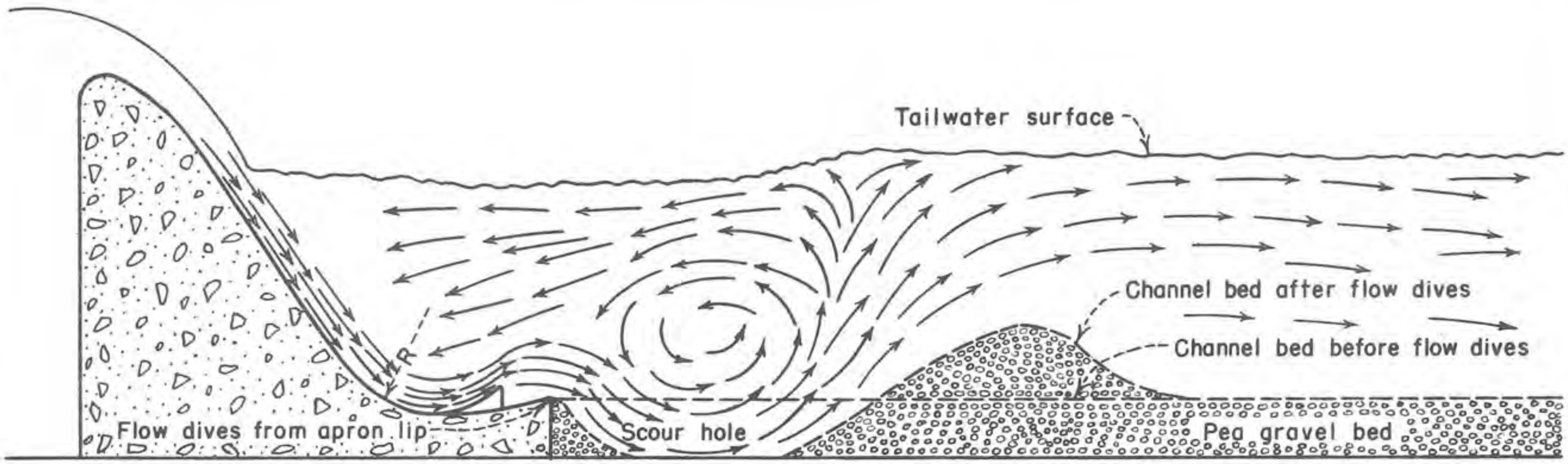
A. SOLID TYPE BUCKET



B. ANGOSTURA TYPE SLOTTED BUCKET

Bucket radius = 12", Discharge (q) = 3 c.f.s.,
Tailwater depth = 2.3'
Crest elevation to Bucket invert = 5.0'

PERFORMANCE OF SOLID AND SLOTTED BUCKETS



Note: The diving flow condition occurs with the slotted bucket only when the tailwater depth becomes too great.

DIVING FLOW CONDITION
SLOTTED BUCKET

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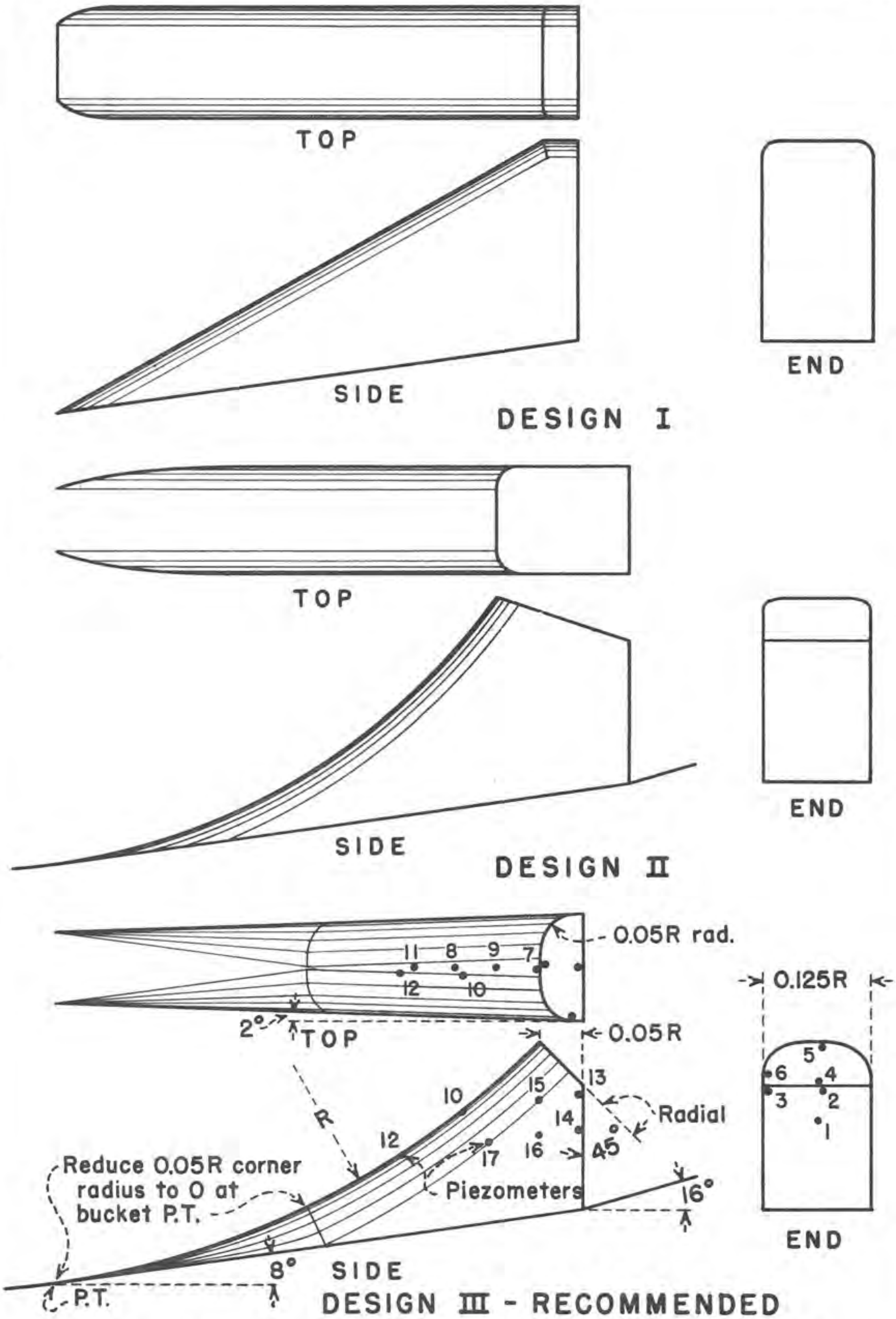
FIGURE 3

FIGURE 4



TOOTH SHAPES TESTED FOR SLOTTED BUCKET

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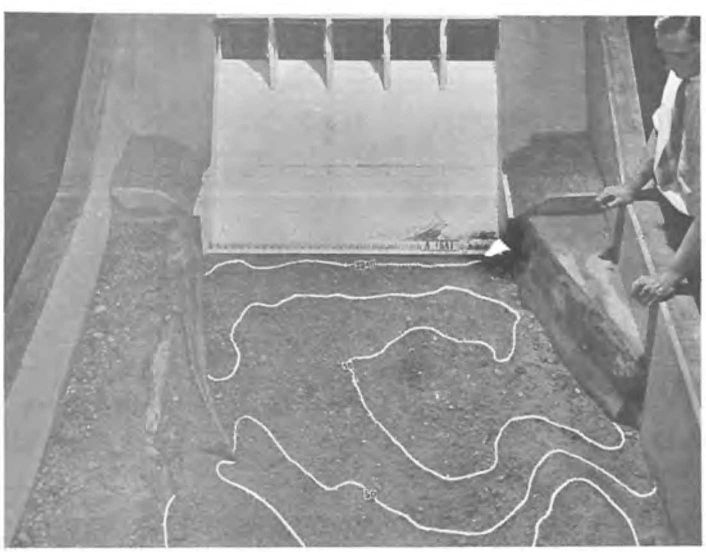
igure 5

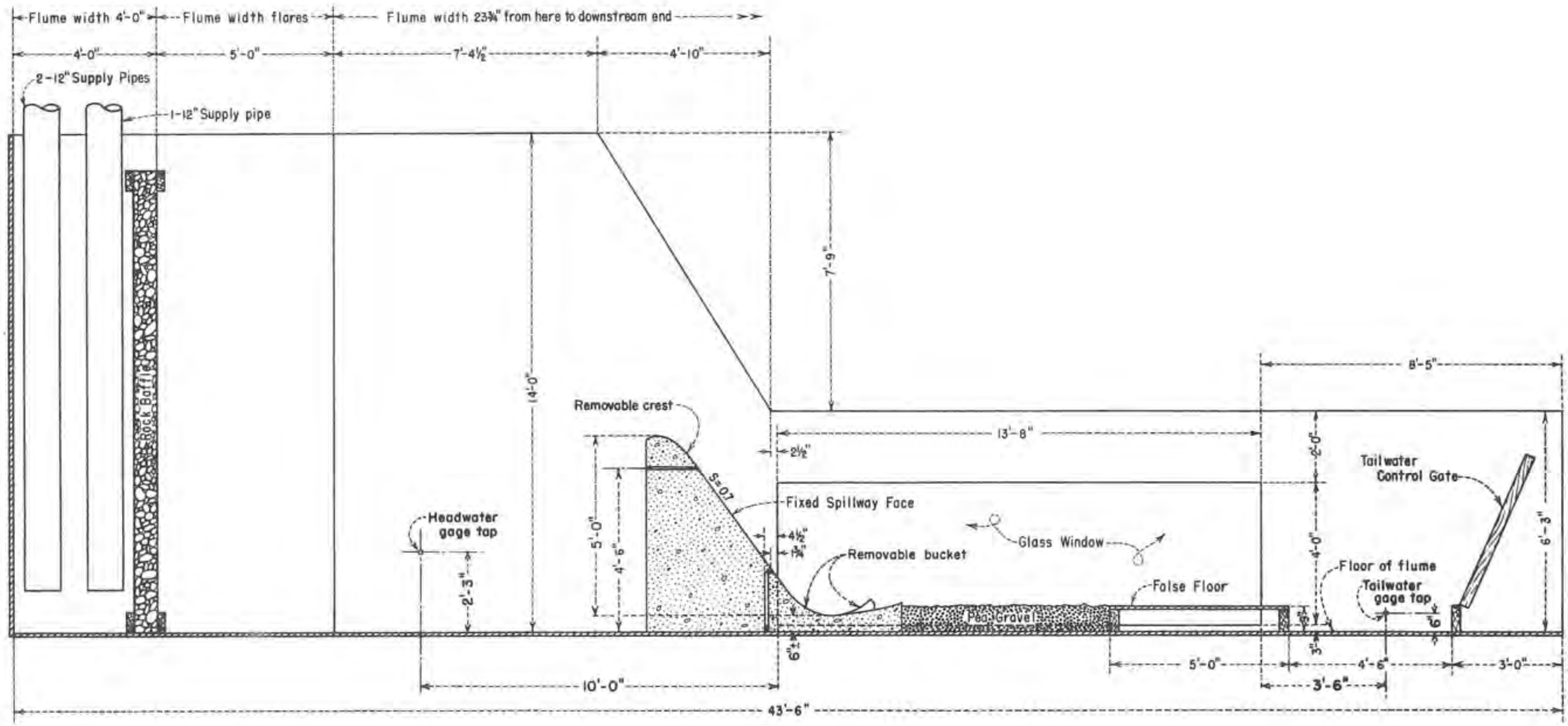
Maximum discharge
900 second feet
per foot of width
Bucket Invert Elevation 3040
T. W. Elevation 3114

Erosion after
20 minutes



Erosion after
90 minutes

Erosion Test
on Angostura Dam Spillway
1:72 Scale Model
Recommended Slotted Bucket



SECTION ON ℄ OF TEST FLUME

TEST FLUME AND SECTIONAL SPILLWAY

FIGURE 6

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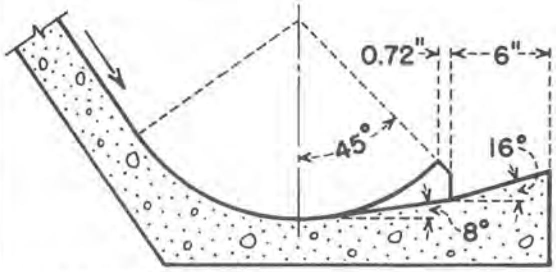
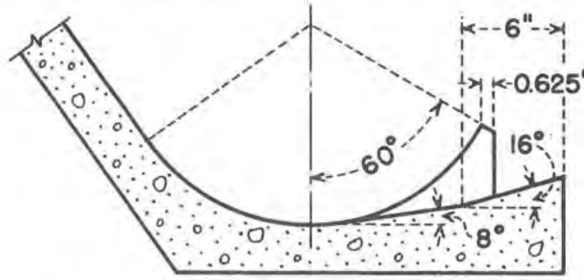
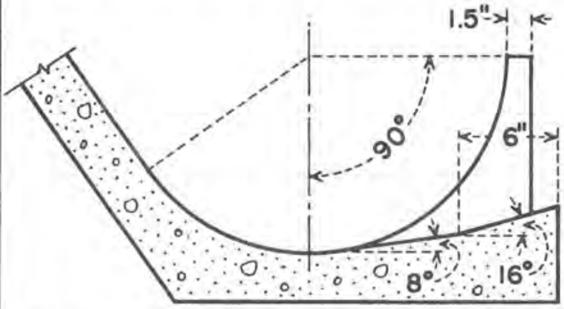


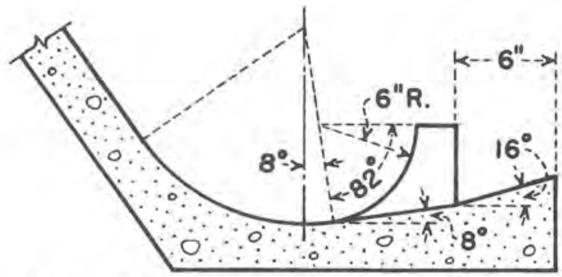
ANGOSTURA TYPE SLOTTED BUCKET



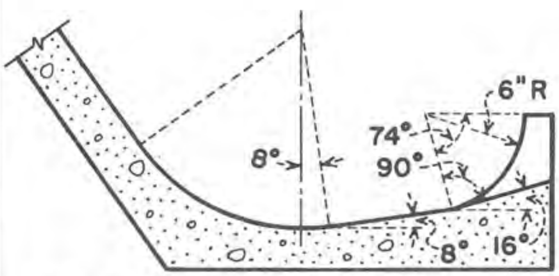
SLOTTED BUCKET MODIFICATION I



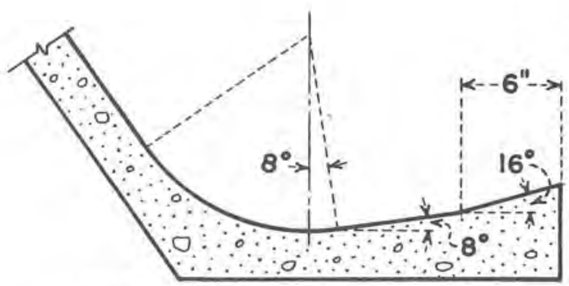
SLOTTED BUCKET MODIFICATION II



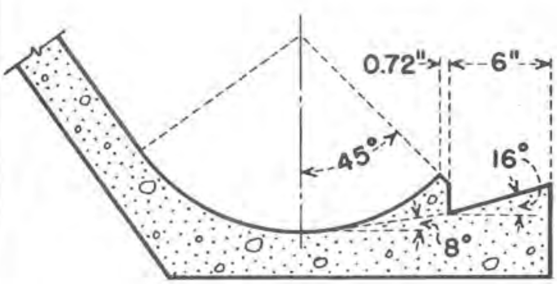
SLOTTED BUCKET MODIFICATION III



SLOTTED BUCKET MODIFICATION IV



ANGOSTURA TYPE BUCKET
WITHOUT TEETH



SOLID BUCKET

Dimensions applicable to all designs–
Bucket invert to downstream edge of structure = 15.21".
Approach chute slope = 7:10.
Bucket radius = 12".
Where shown,
tooth width = 1.5" and
space between teeth = 0.72".

SLOTTED BUCKET MODIFICATIONS TESTED

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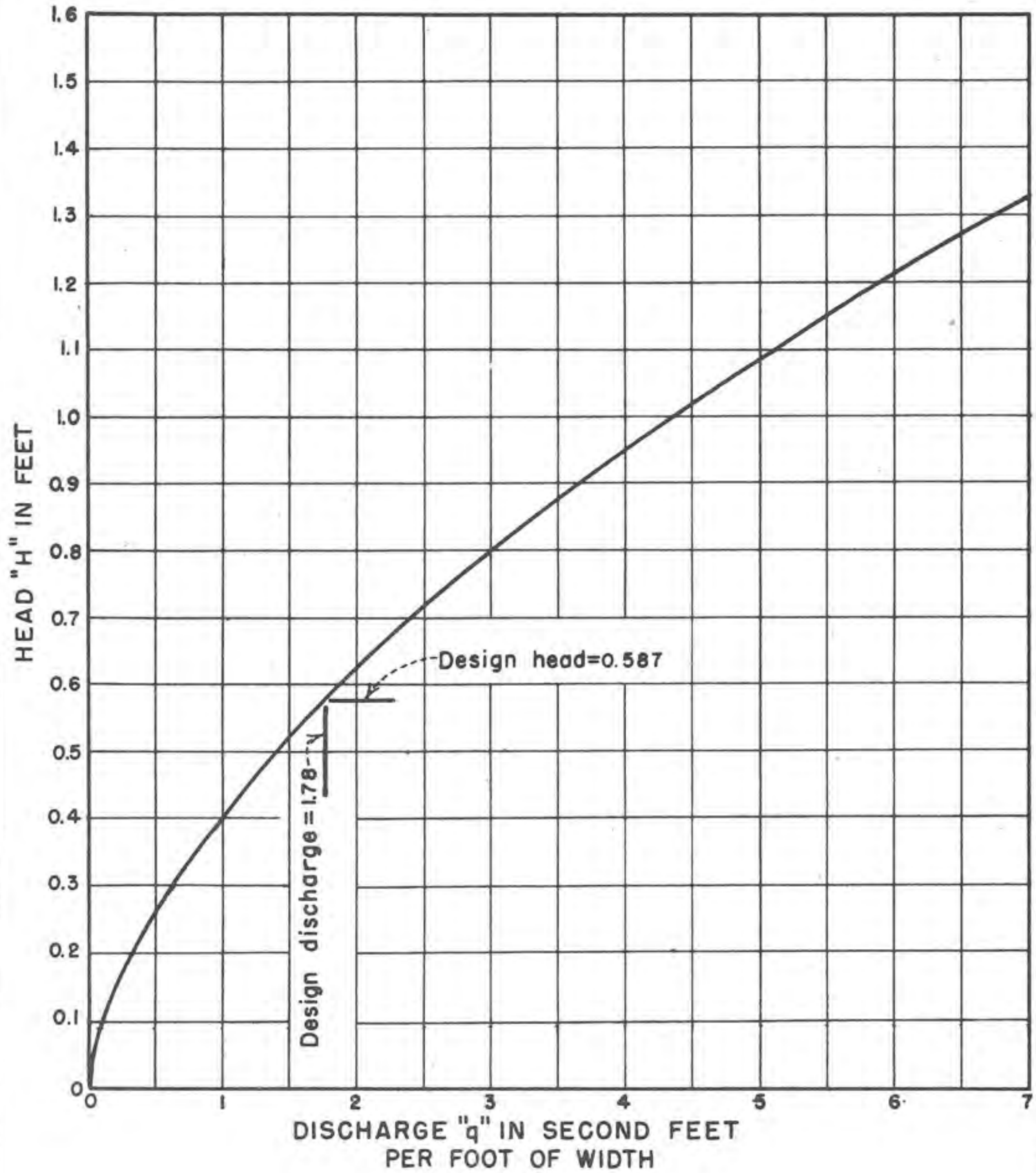
FIGURE 8



DISCHARGE CALIBRATION OF
THE 5-FOOT MODEL SPILLWAY

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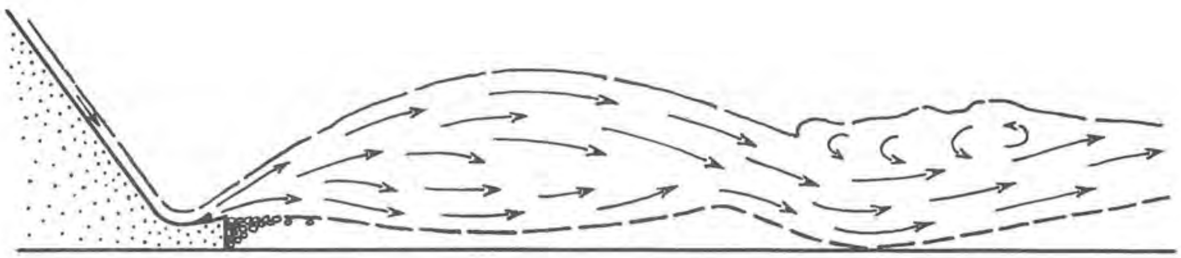
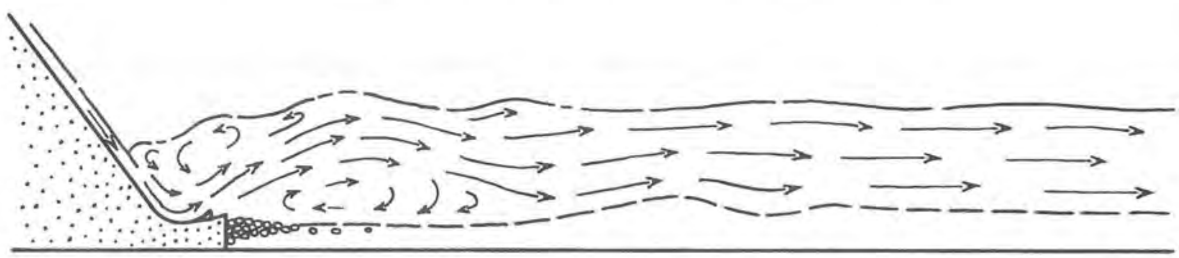
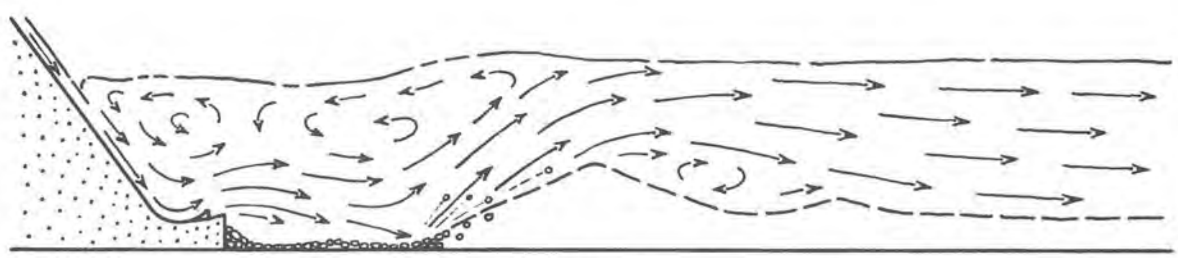
FIGURE 9



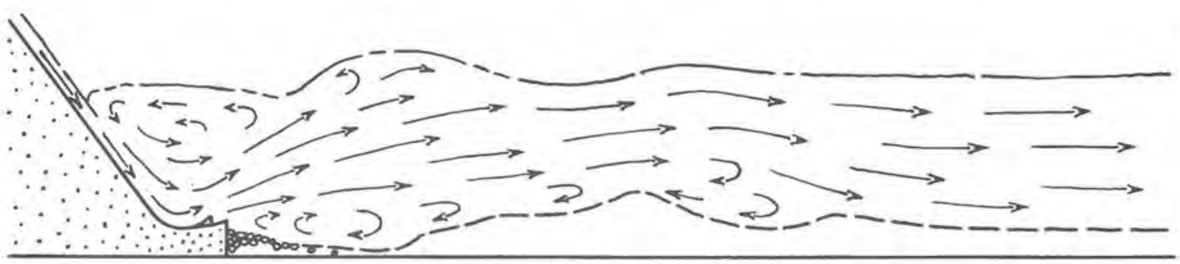
A. Tailwater below minimum. Flow sweeps out.



B. Tailwater below average but above minimum.
Within normal operating range.



C. Tailwater above maximum. Flow diving from
apron scours channel



D. Tailwater same as in C. Diving jet is lifted by ground
roller. Scour hole backfills similar to B. Cycle repeats.

(Bed level 0.3-inch below apron lip at start of test)

6-INCH BUCKET - DISCHARGE (q) = 1.75 C.F.S.
(DESIGN CAPACITY)

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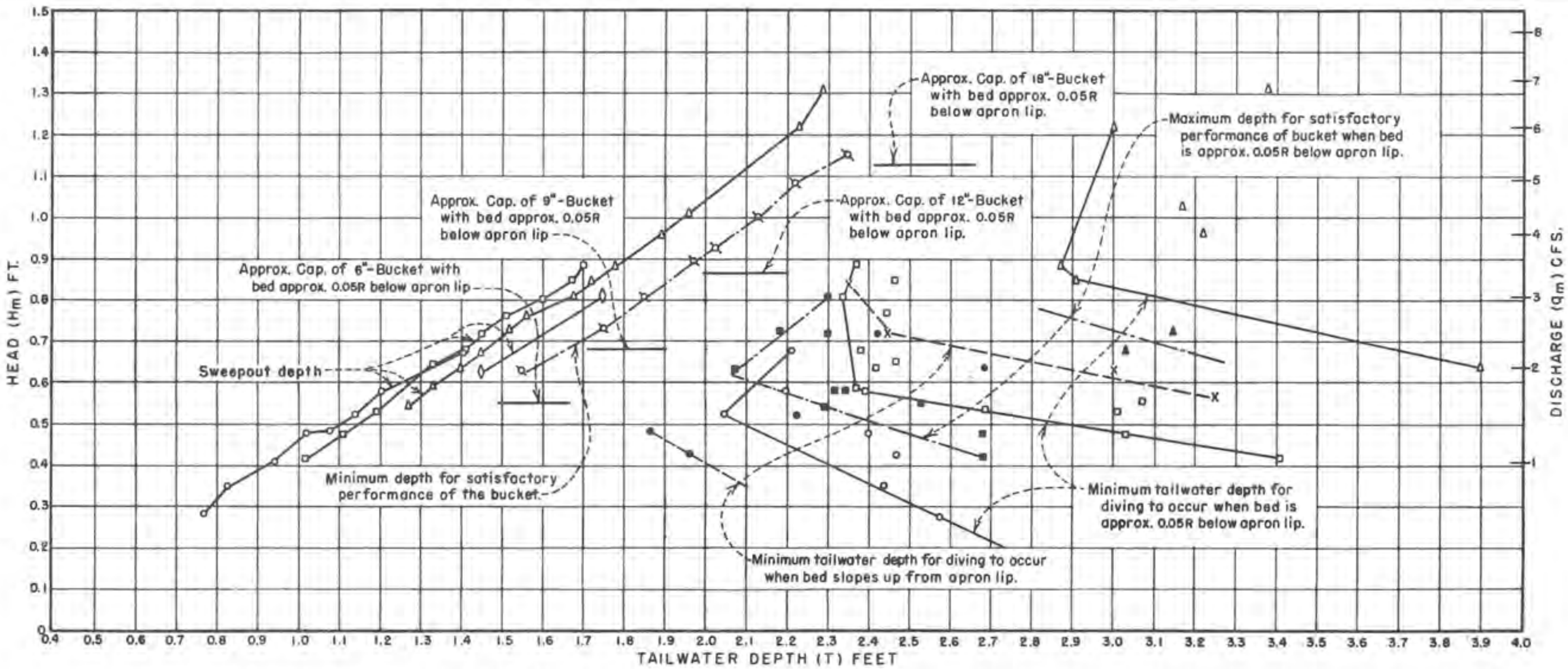

BUCKET RADIUS (R) INCHES	BUCKET CAPACITY IN C.F.S. PER FT. OF WIDTH	
	BED APPROX. 0.05R BELOW APRON LIP	BED SLOPES UP FROM APRON LIP
6	1.5 TO 1.75	—
9	2.0 TO 2.5	1.5
12	3.25 TO 3.5	2.0 TO 2.5
18	5.0 TO 5.5	—

TABLE NO	TEST DATA SYMBOLS	BUCKET RADIUS (R) INCHES	BED ARRANGEMENT	DESCRIPTION OF TEST DATA SYMBOLS
III	○	6	Bed approx. 0.05R below apron lip.	Tailwater sweepout depth and Min. tailwater depth at which diving occured
IV	□	9	Bed approx. 0.05R below apron lip.	Tailwater sweepout depth and Min. tailwater depth at which diving occured
V	△	12	Bed approx. 0.05R below apron lip.	Tailwater sweepout depth and Min. tailwater depth at which diving occured.
VI	◊	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.
IV	●	9	Bed sloped up from apron lip.	Min. tailwater depth at which diving occured.
V	X	12	Bed sloped up from apron lip.	Min. tailwater depth at which diving occured.

TAILWATER LIMITS AND BUCKET CAPACITIES

FIGURE 10

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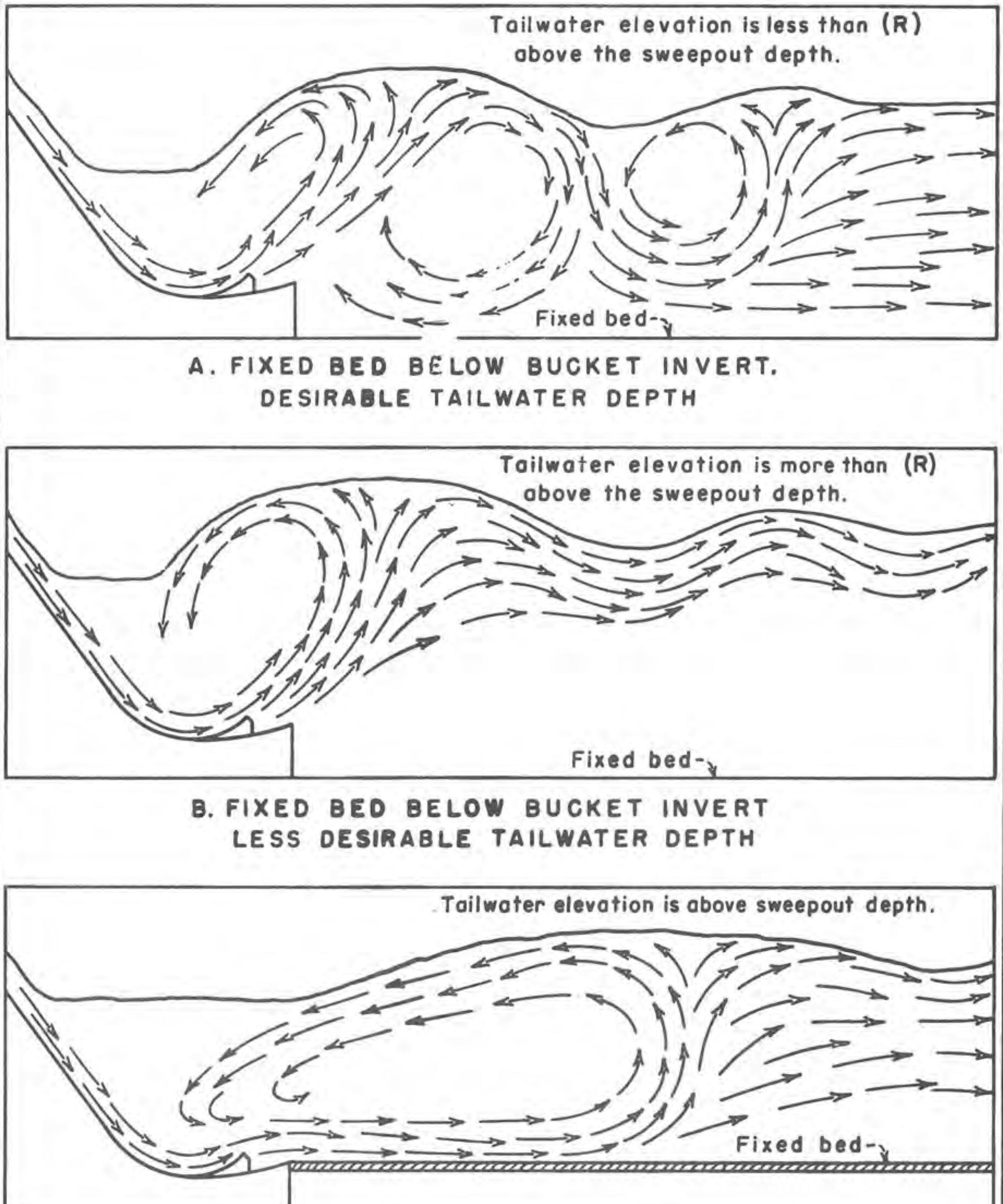
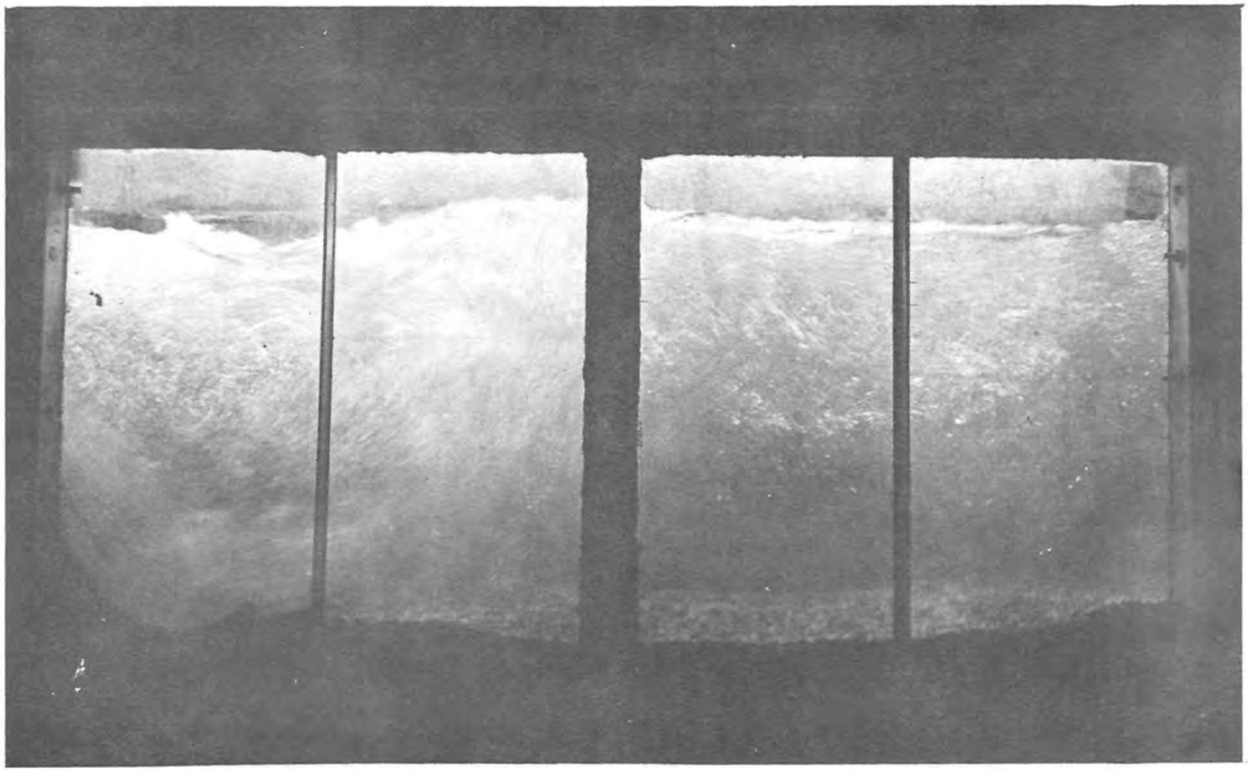


Note:

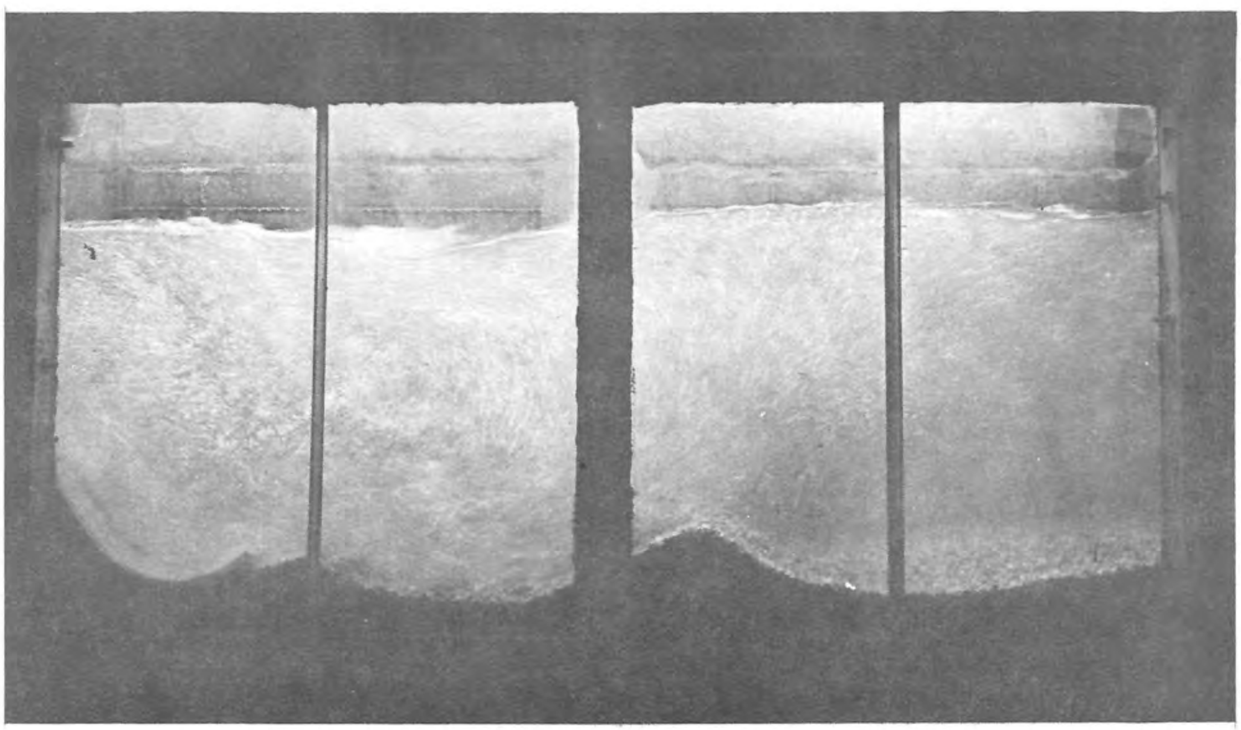
Bucket radius (R) is 6 inches.

Design discharge - 1.75 second feet per unit foot of width.

FLOW CURRENTS FOR VARIOUS ARRANGEMENTS OF FIXED BEDS



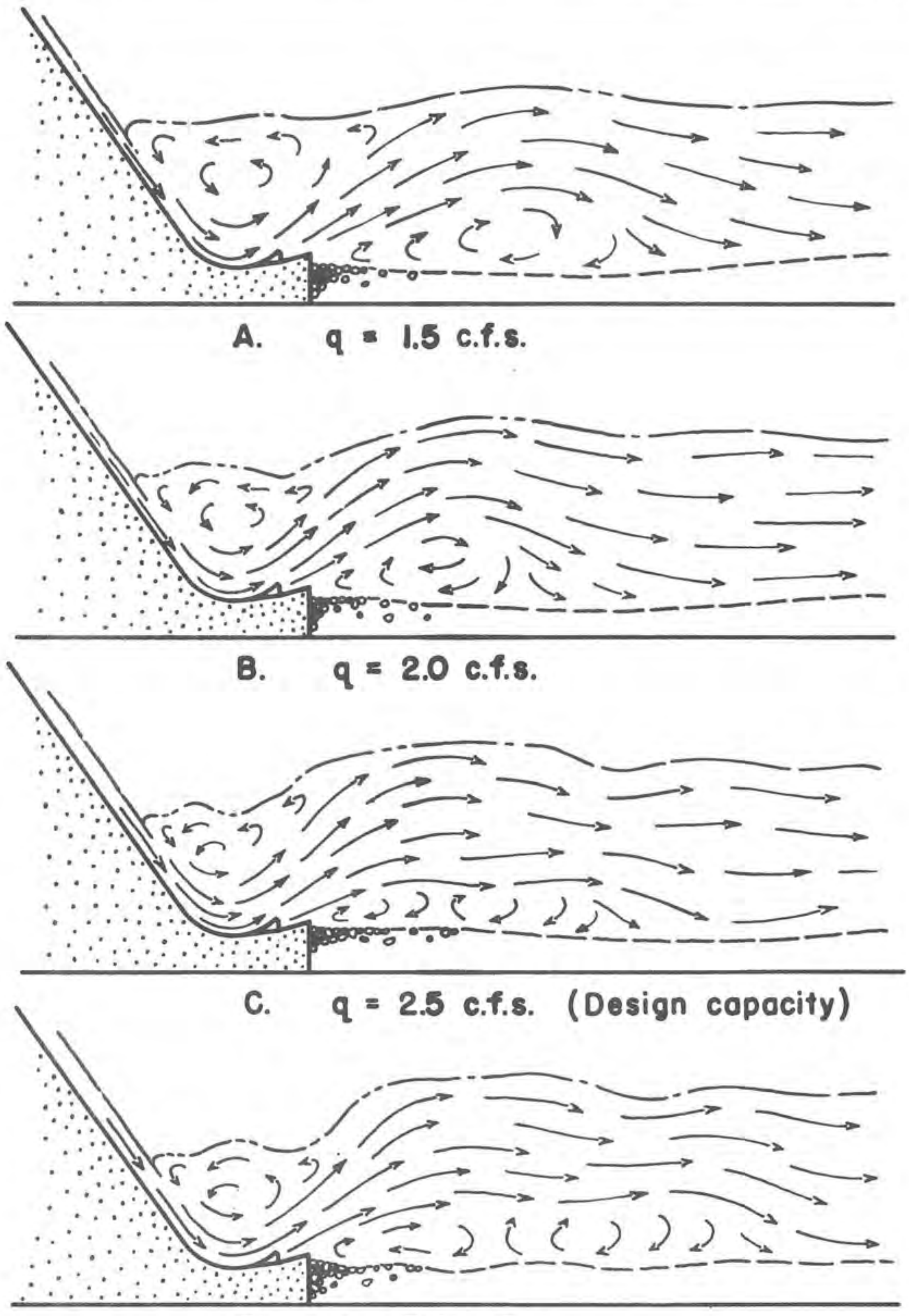
A. Flow is about to dive from apron lip--maximum tailwater depth limit has been reached.



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

Nine-Inch Bucket--Discharge (q) = 1.5 c.f.s.

FIGURE 13



(Bed level 0.5-inch below apron lip at start of test.)

9-INCH BUCKET — TAILWATER DEPTH = 1.85 FEET

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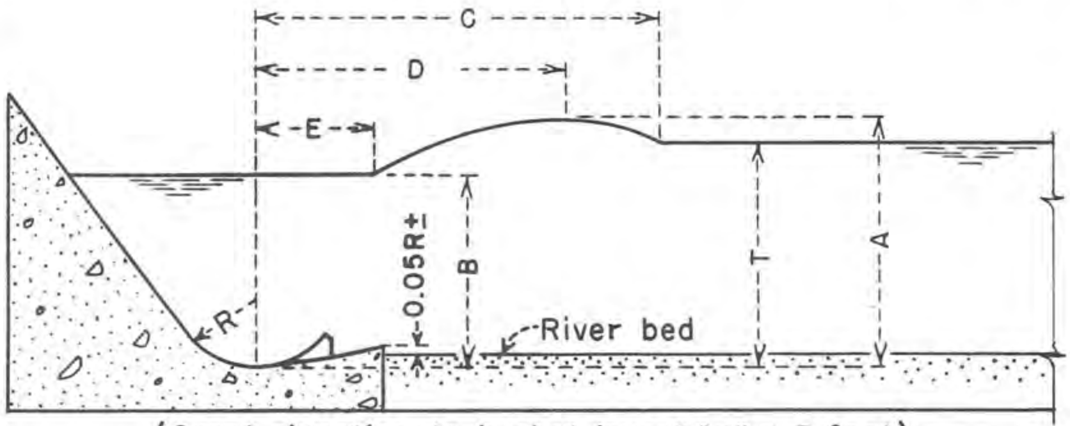


(Crest elevation to bucket invert "x" = 5 feet)

9-INCH BUCKET (R)

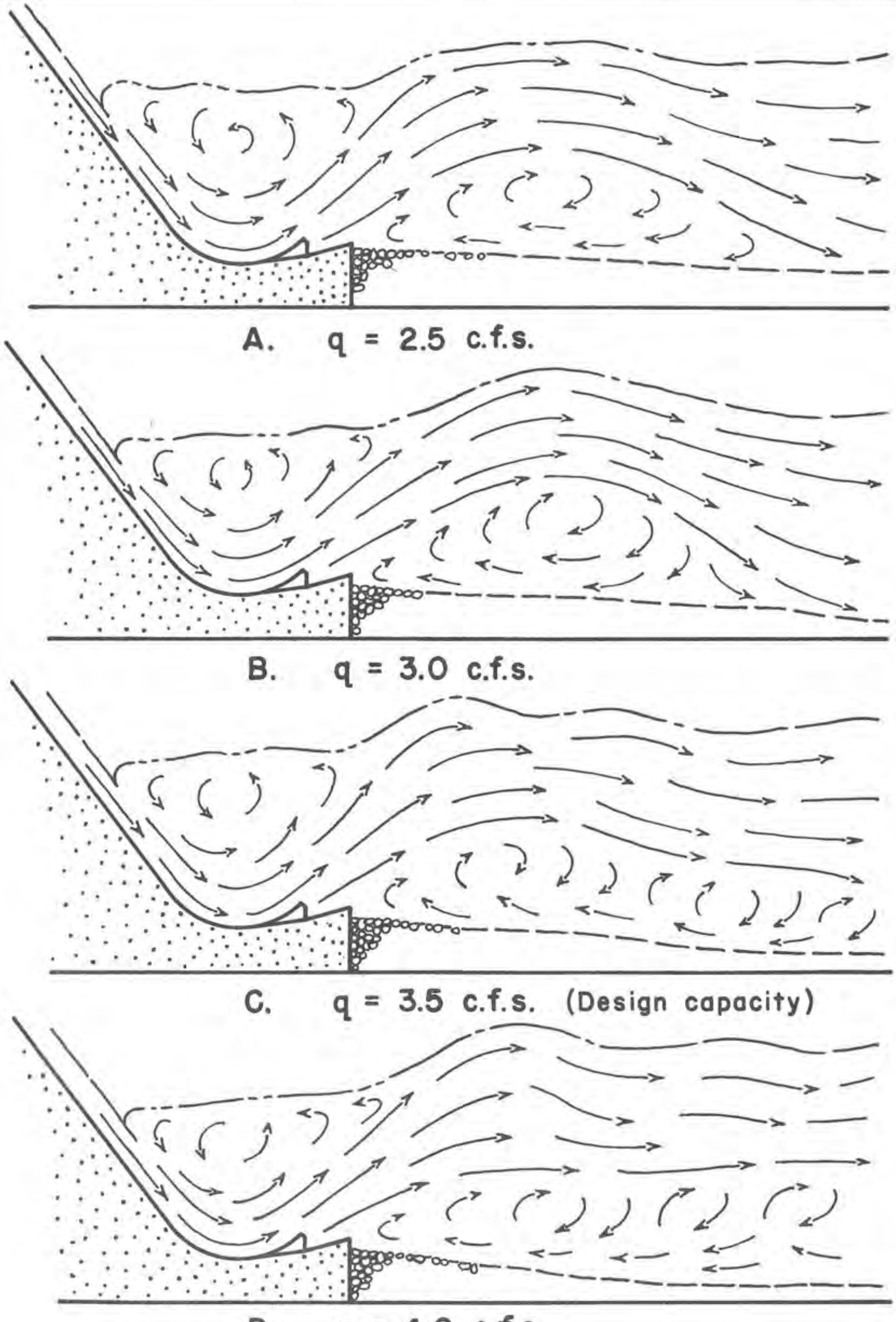
Q-cfs	q-cfs	T-ft.	A	B	C	D	E
3.0	1.50	1.85	25	19	45	25	5
3.0	1.50	2.40	32	26	46	27	1
3.50	1.75	1.85	26	19	45	25	5
4.00	2.00	1.85	27	19	46	25	5
4.50	2.25	1.85	28	19	48	28	6
5.00*	2.50	1.85	28	18	50	32	6
5.50	2.75	1.85	29	17	51	31	6
6.00	3.00	1.85	30	16	52	32	6

12-INCH BUCKET (R)

Q-cfs	q-cfs	T-ft.	A	B	C	D	E
5.0	2.5	2.30	32	23	52	35	14
6.0	3.0	2.30	33	22	62	37	11
7.0 *	3.5	2.30	33	21	68	37	9
8.0	4.0	2.30	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
* Design capacity

AVERAGE WATER SURFACE MEASUREMENTS



A. q = 2.5 c.f.s.

B. q = 3.0 c.f.s.

C. q = 3.5 c.f.s. (Design capacity)

D. q = 4.0 c.f.s.

(Bed level 0.6-inch below apron lip at start of test.)

12-INCH BUCKET — TAILWATER DEPTH = 2.30 FEET

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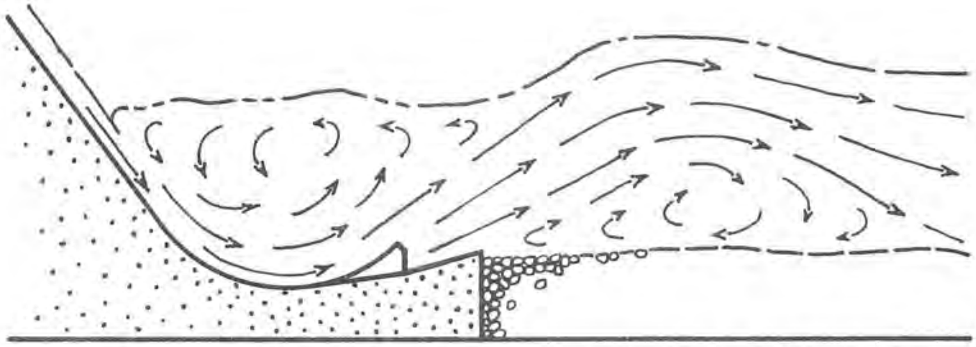
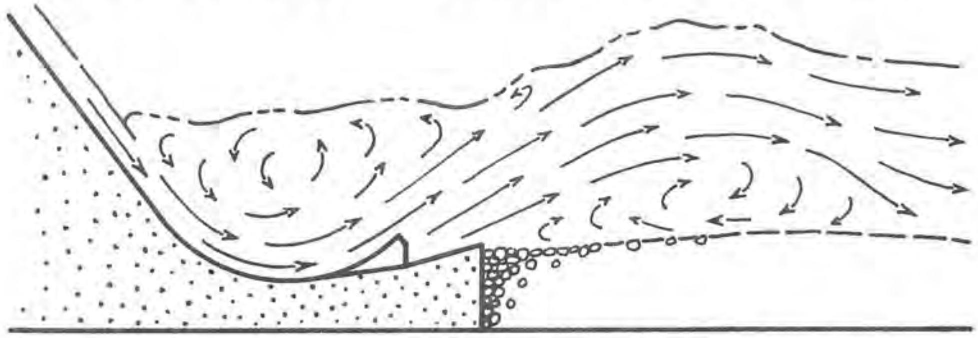
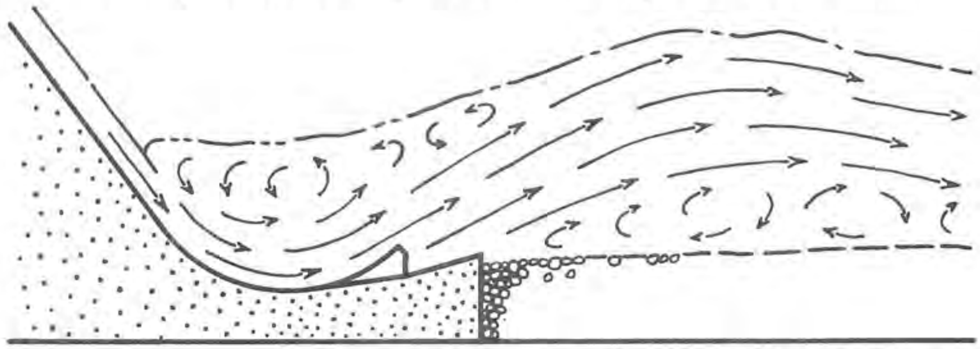


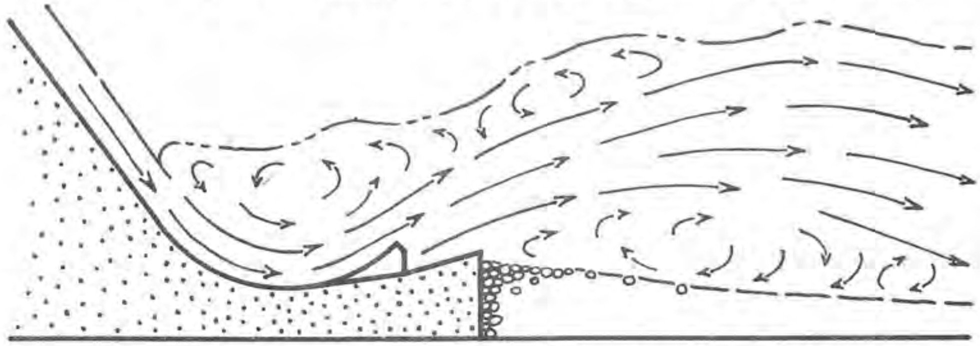
A. q = 3 c.f.s., Tailwater depth = 2.30 feet.



B. q = 3.5 c.f.s., Tailwater depth = 2.30 feet.



C. q = 4 c.f.s., Tailwater depth = 2.30 feet.

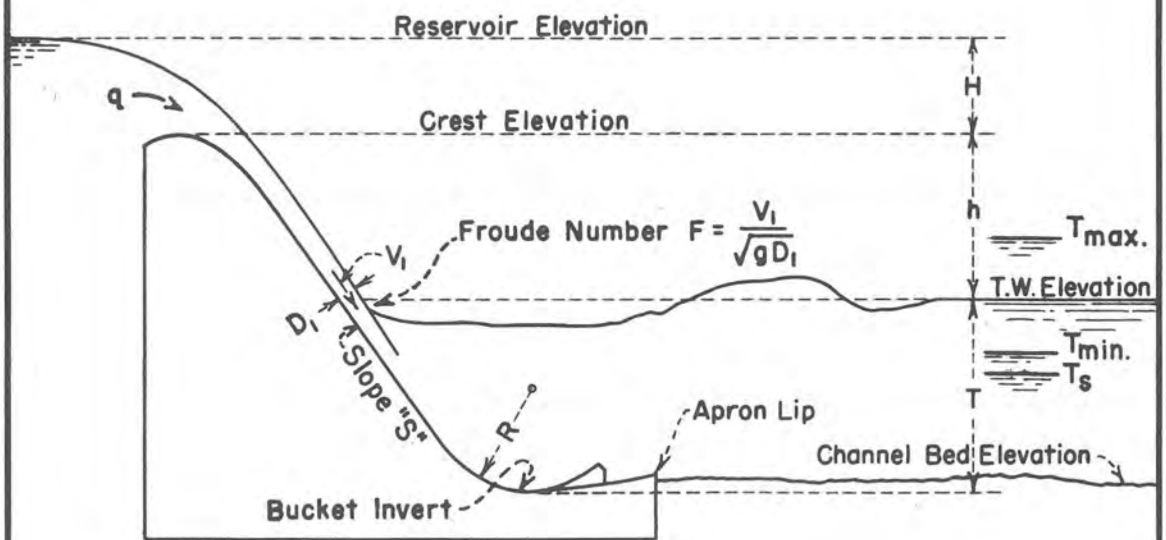


D. q = 5.5 c.f.s., Tailwater depth = 2.45 feet
(Design capacity)

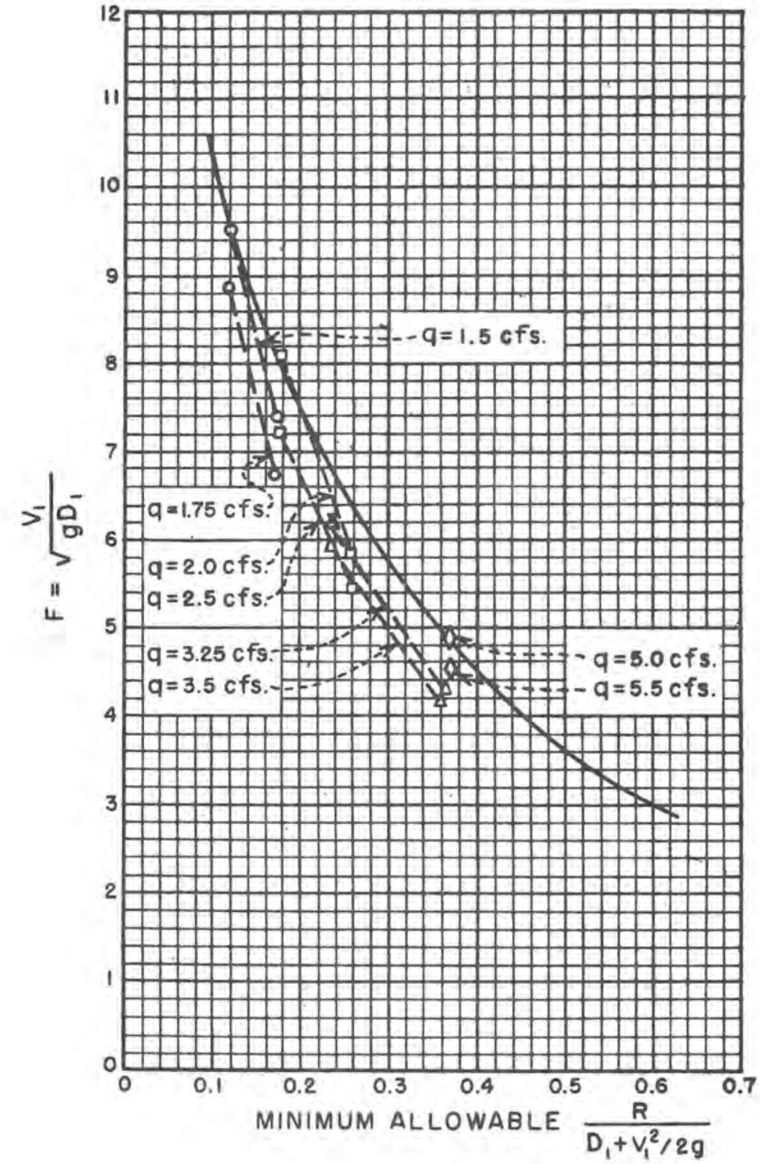
(Bed level 0.9-inch below apron lip at start of test.)

18-INCH BUCKET PERFORMANCE

FIGURE 17



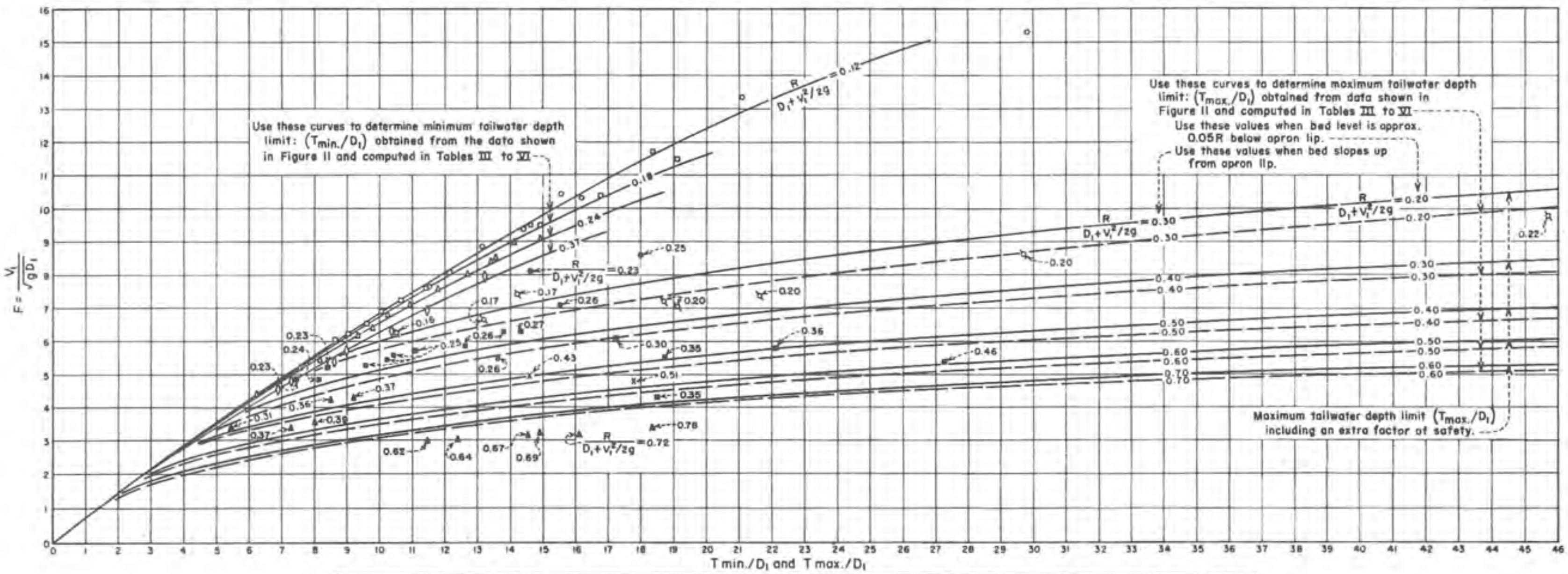
DEFINITION OF SYMBOLS



EXPLANATION

○ For bucket radius (R) = 6 inches
□ For bucket radius (R) = 9 inches
△ For bucket radius (R) = 12 inches
◊ For bucket radius (R) = 18 inches
Bed level approximately 0.05R below lip of apron.

MINIMUM ALLOWABLE BUCKET RADIUS



DATA SYMBOL	BUCKET RADIUS (R) INCHES	$\frac{R}{D_1+V_1^2/2g}$	BED ARRANGEMENT	DESCRIPTION OF DATA POINT	FROM TABLE
○	6	0.12	For any position of the bed	Min. tailwater depth limit	III
□	9	0.18	For any position of the bed	Min. tailwater depth limit	IV
△	12	0.24	For any position of the bed	Min. tailwater depth limit	V
◊	18	0.37	For any position of the bed	Min. tailwater depth limit	VI
○ (flagged)	6	0.16 to 0.23	For bed level approx. 0.05R below apron lip	Max. tailwater depth limit	III
■	9	0.23 to 0.46	For bed level approx. 0.05R below apron lip	Max. tailwater depth limit	IV
▲	12	0.31 to 0.68	For bed level approx. 0.05R below apron lip	Max. tailwater depth limit	V
■ (flagged)	9	0.25	For bed sloping up from apron lip	Max. tailwater depth limit	IV
x	12	0.43 to 0.51	For bed sloping up from apron lip	Max. tailwater depth limit	V

DIMENSIONLESS PLOT OF MAXIMUM AND MINIMUM TAILWATER DEPTH LIMITS

FIGURE 19

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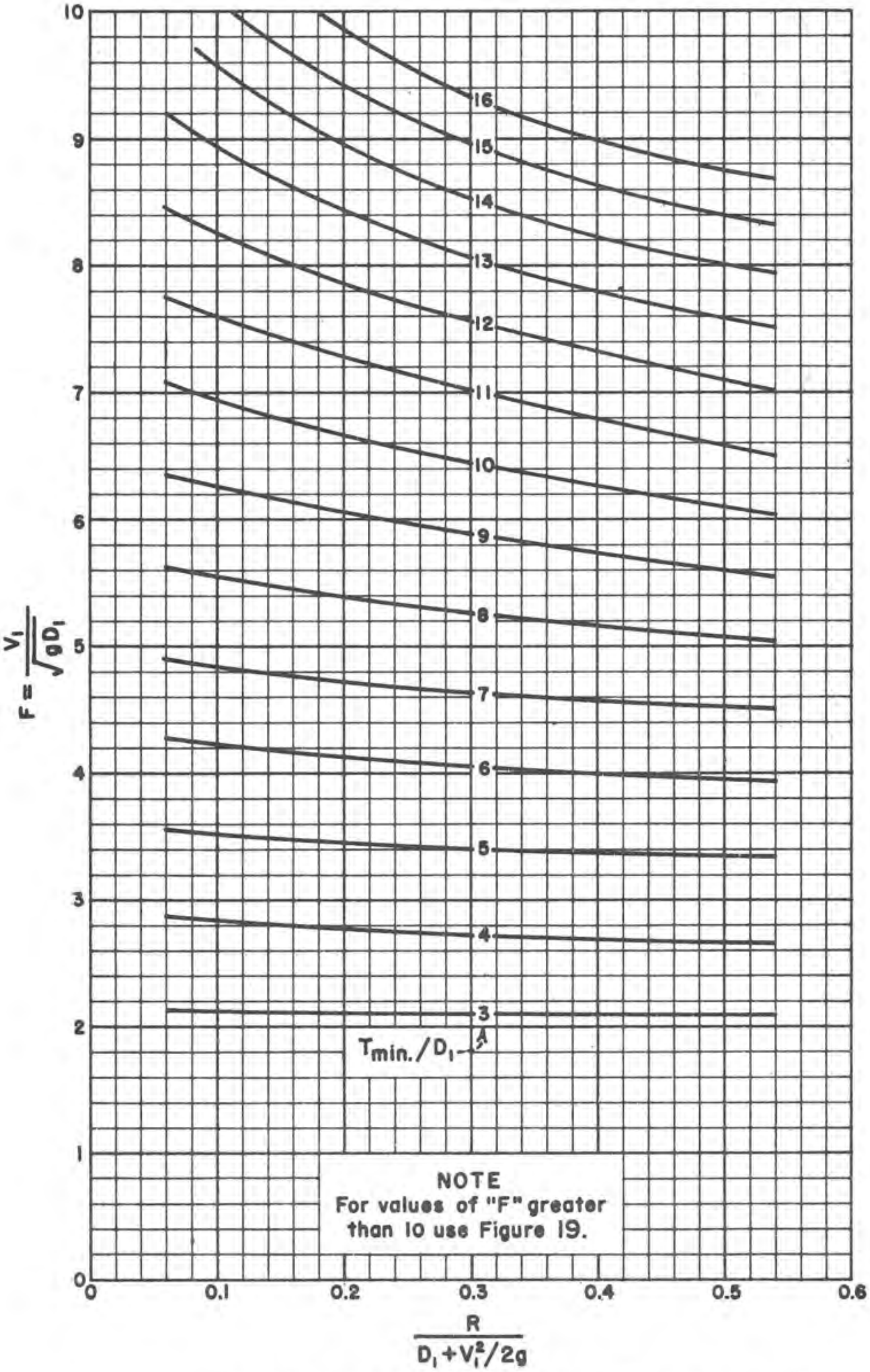
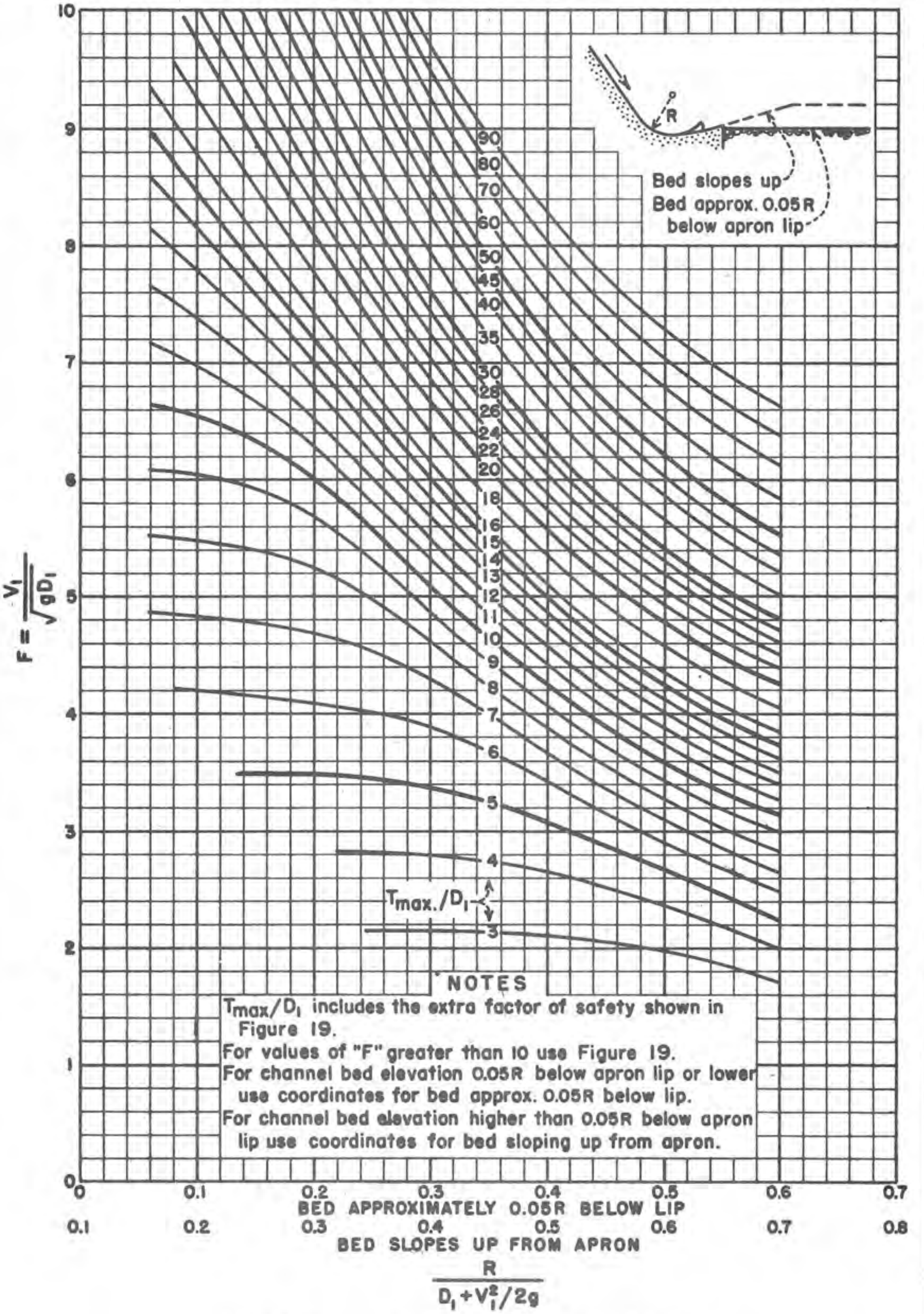
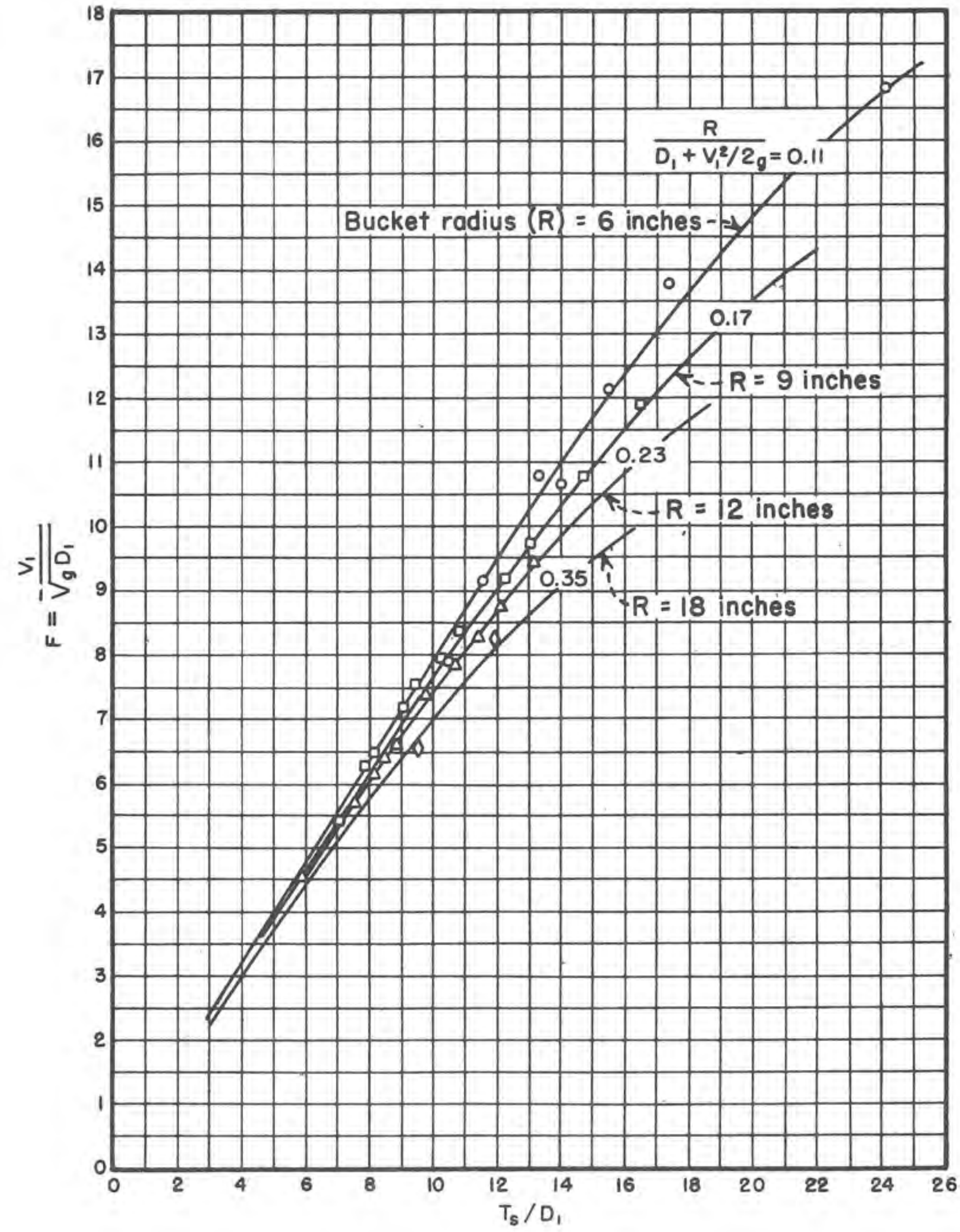


MINIMUM TAILWATER LIMIT

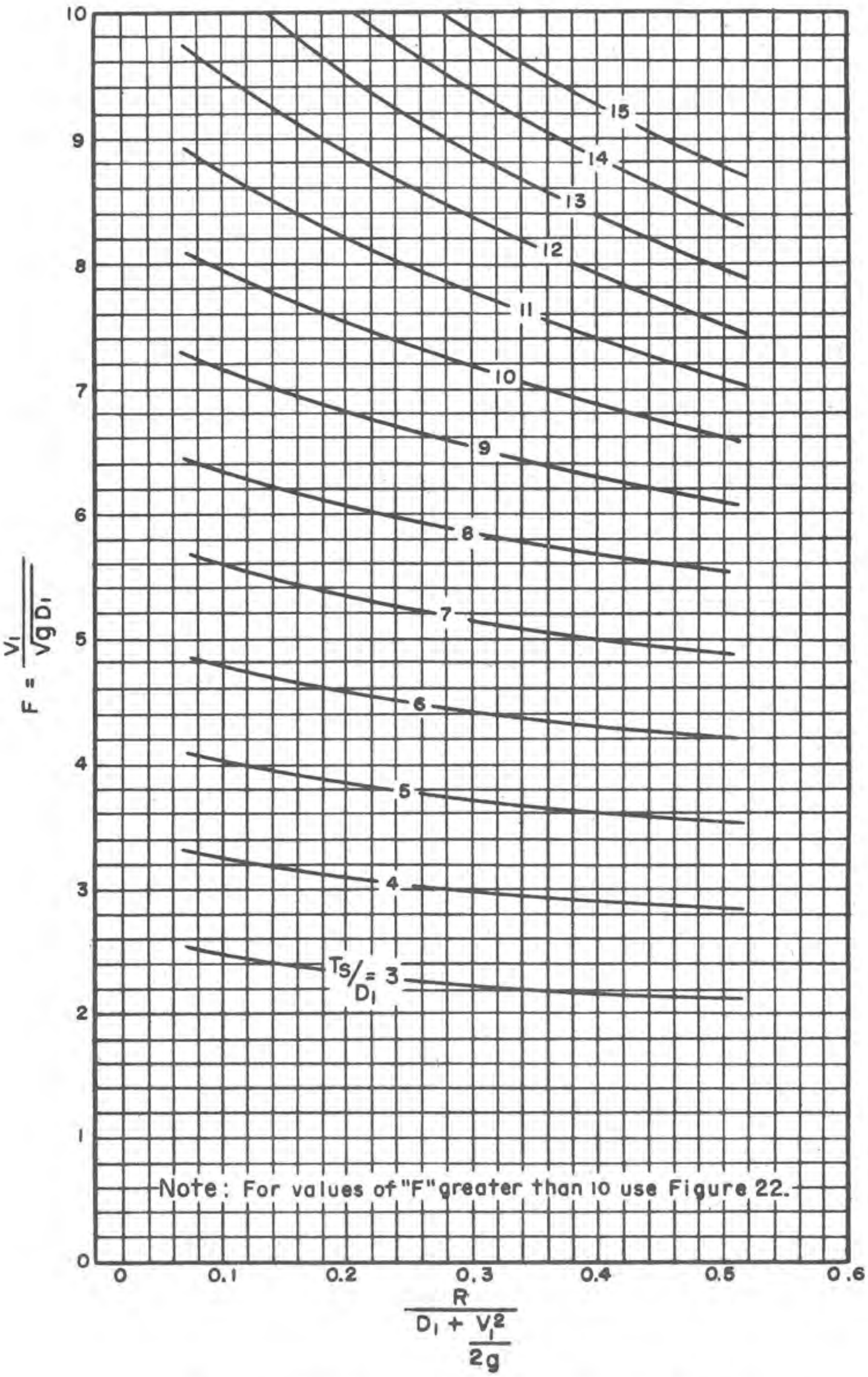


MAXIMUM TAILWATER LIMIT

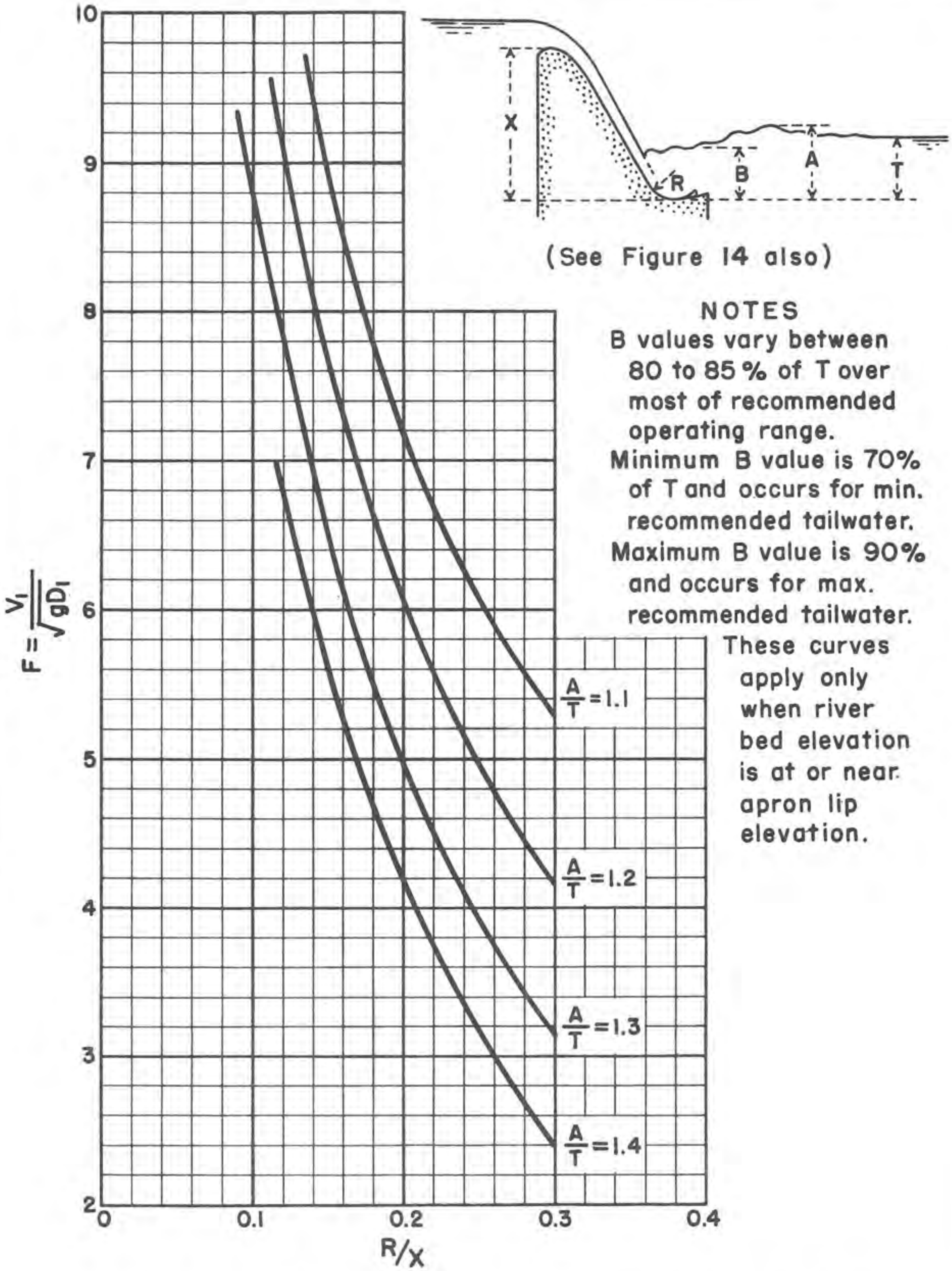


Note: Bed arrangement not critical for sweepout condition

TAILWATER DEPTH AT SWEEPOUT



TAILWATER SWEEPOUT DEPTH



NOTES

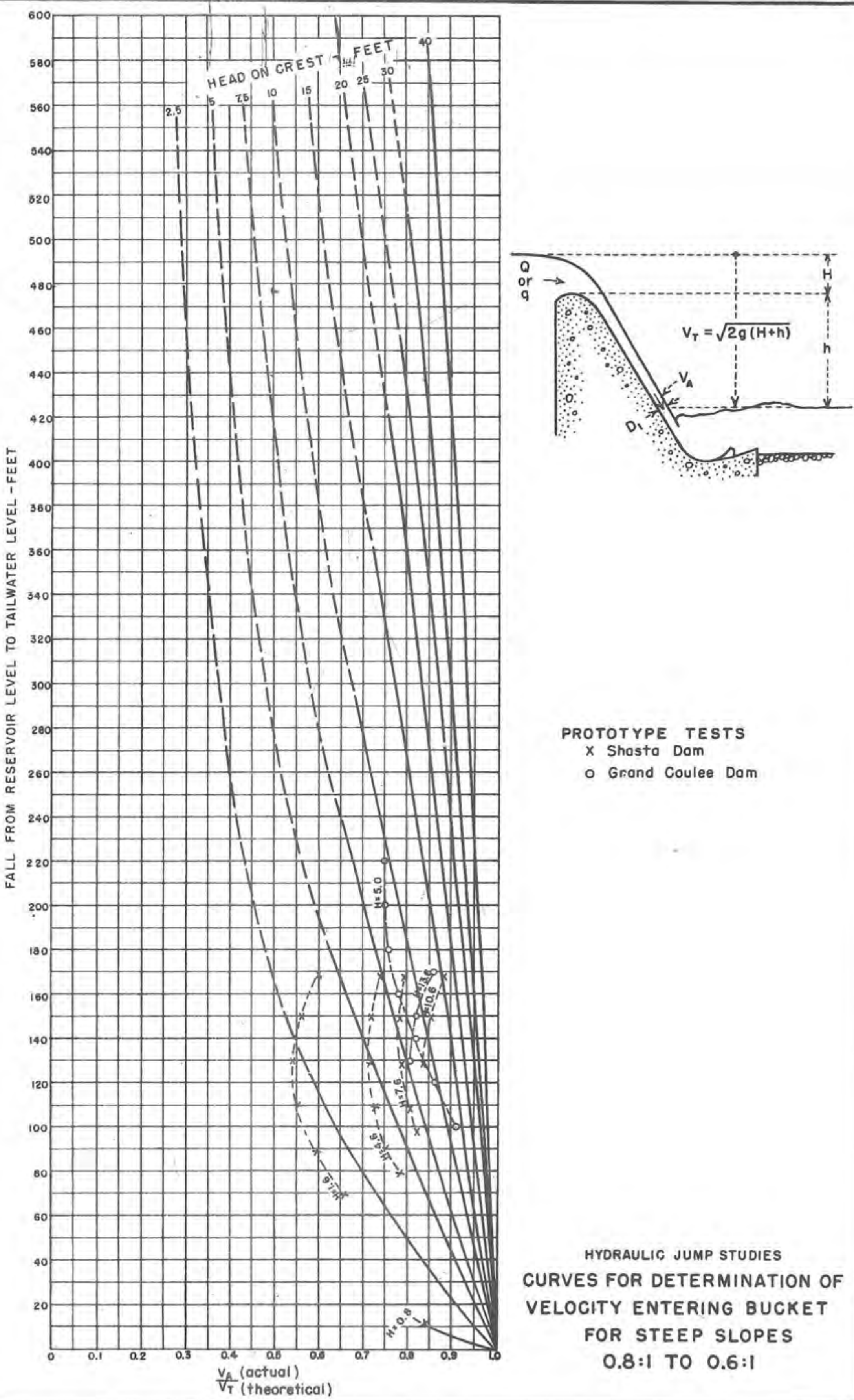
B values vary between 80 to 85 % of T over most of recommended operating range.

Minimum B value is 70% of T and occurs for min. recommended tailwater.

Maximum B value is 90% and occurs for max. recommended tailwater.

These curves apply only when river bed elevation is at or near apron lip elevation.

WATER SURFACE PROFILE CHARACTERISTICS
FOR SLOTTED BUCKETS ONLY



HYDRAULIC JUMP STUDIES

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

GPO 856949