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DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MEMORANDUM TO DIRECTOR DIVISION OF RECLAMATION
SUBJECT: PROTECTION AGAINST BURGAR AT THE TOWN OF THE
MOUNTAINS AND NO. 2 BANKS OF THE YANKEE TRAILER AUTHORITY

BY R. W. LANE, RECLAMATION DIVISION

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Denver, Colorado,
December 9, 1935.

MEMORANDUM TO THE CHIEF DESIGNING ENGINEER
(E. W. Lane).

Subject: Protection against Scour at the Toe of the Norris and No. 3 Dams of the Tennessee Valley Authority.

1. The determination of the best form of protection against scour at the toes of the Norris and No. 3 Dams on the Tennessee river is an important factor in the design of these structures because of the magnitude of the energy contained in the water falling over their spillways, and the destructive action to the foundation of the dam which is possible if this energy is not properly controlled. So far as known the Norris dam will be higher than any other dam, over the crest of which large quantities of water are passed. The water will have a fall of 248 feet and should the flow reach 260,000 second feet, for which the protection is designed, the energy involved would be 4,530,000 h.p. In the case of Dam No. 3, the fall is much less, being only about 50 feet, but the quantity is much larger than at the Norris dam, and should a flood ever come which would reach a 450,000 second foot discharge, the energy of the over-falling water would be 3,430,000 h. p. The design of these dams so that these immense potentially destructive forces are rendered harmless is therefore vital to the safety of the structures.

Principles of Scour Protection.

2. Until recently the principles of protection against scour below dams has not been very completely understood. A determination for each individual case by means of model testing has rapidly grown into use, but the principles involved were not in all cases well considered and the results of these tests were therefore not as reliable as otherwise might have been the case. As a result of the studies of the Bureau of Reclamation in connection with the Madden, Cle Elum, and other dams, the principles governing the design of scour protection have been worked out and the principles applicable to conditions at various dams have been classified. Model studies are still necessary to determine of the several forms that are applicable to the condition given damsite is the best, but the classification of given damsite in the field which is necessary to study and insure satisfactory conditions are not overlooked.

3. The principles governing scour protection are outlined in U. S. Bureau of Reclamation, Technical Memorandum No. 323, entitled "Protection Against Scour below Overfall Dams," a copy of which is attached hereto as Appendix I. Briefly stated, the type of scour protection depends upon the relation throughout the entire range of discharge, of the elevation of the tailwater below the dam to the elevation necessary to cause a hydraulic jump to form on a level apron at the elevation of the stream bed, or in other words, to the relative position of the tailwater rating curve and a jump-forming height curve, for an apron at stream bed level. This is true whether or not the hydraulic jump is used for the scour protection. The types applicable to the various relations of the elevation of the tailwater rating curve and jump forming height curve are given in Appendix I.

Conditions at Morris Dam.

4. The conditions at Morris dam are very favorable to the protection from scour by simple means. The tailwater rating curve for the tailwater below the dam is shown on Figure 1. It was determined by Mr. Frank Campbell, under the direction of Mr. E. B. Debler according to the methods suggested by Prof. J. M. Woodward. The height of water necessary to form the jump on an apron at the stream bed level for the various discharges is also shown on Figure 1. This curve is based on the assumption that all the gates are held at the same elevation.

As will be seen from Figure 1, the jump height curve for the apron at stream bed level is considerably above the tailwater rating curve for all discharges. This dam therefore falls into the Class 1, described in the attached memorandum (Appendix I). For this condition, the possible solutions are (1) shaping the bucket to throw the overfalling stream far from the base of the dam, (2) raising the tailwater level by a secondary dam, (3) deepening the pool below the dam, and (4) various forms of baffles. The first one of these solutions with the stratified rock bottom and very high heads acting at the Morris Dam would produce severe scour in the river bed downstream from the dam and pile up debris in the stream channel below the dam which would probably obstruct the flow from the power house. Since a very good solution is possible by another one of the four methods, this method, which would be sure to have undesirable results, was not given serious consideration. Satisfactory protection from the hydraulic standpoint could

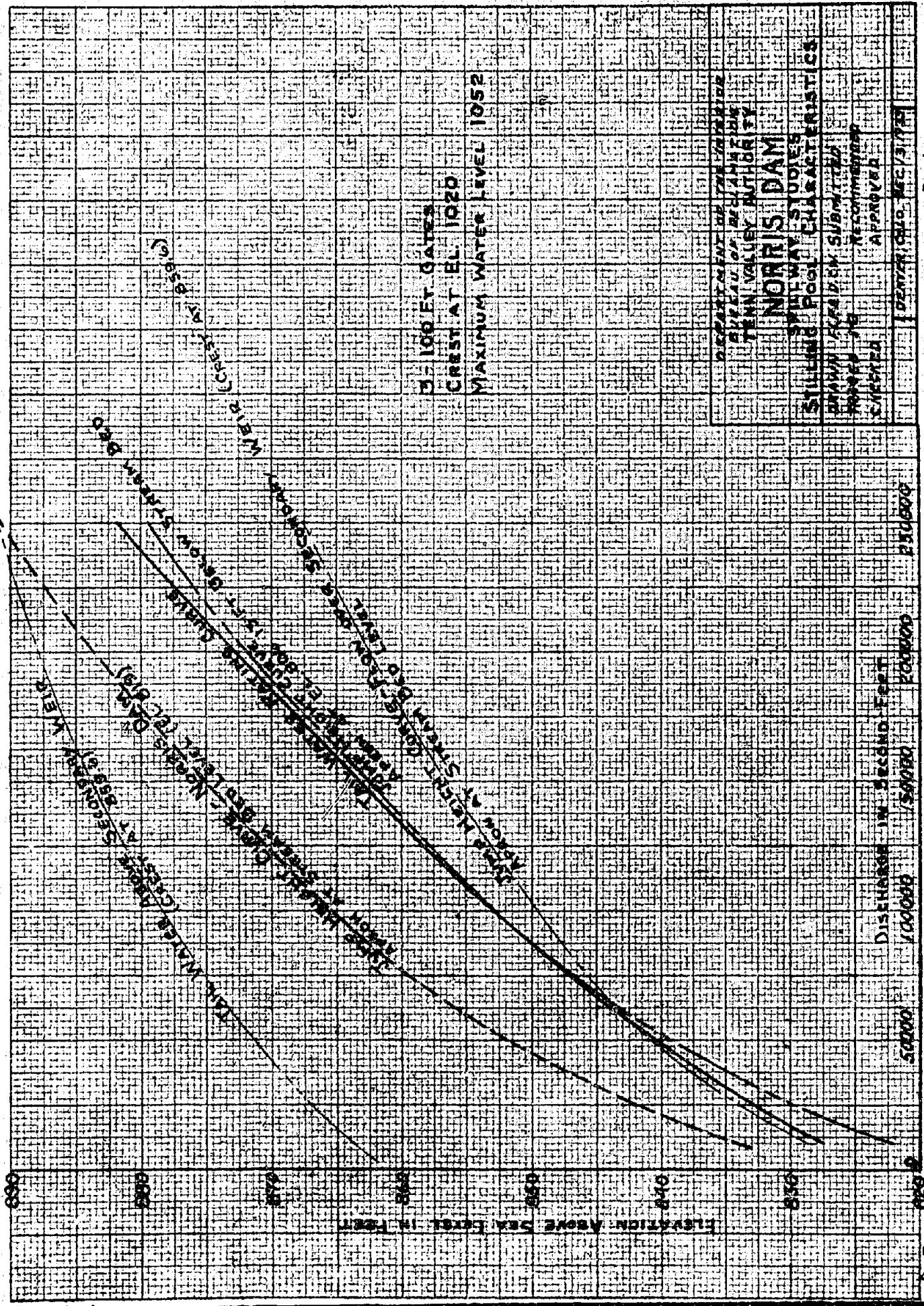
undoubtedly be secured by means of the tailwater weir mentioned as the second solution. The secondary weir must be high enough to produce the required tailwater level for all discharges. Figure 1 shows that a weir with crest at Elevation 859.6 would be required to hold the water to the height required for a discharge of 250,000 sec. ft. Such a dam would be about 40' high and would require retaining walls 70' high along both sides of the pool. Moreover, the pool would have to be of considerable length 4.5 to 5.0 times the height of the jump as this is the length which is required to produce satisfactory conditions when the height of the secondary weir is an appreciable part of the pool depth. Some protection against scour would also be required below the secondary weir but since, (as shown on Figure 1) the natural tailwater curve is nearly high enough to produce a jump below the secondary weir on an apron at stream bed level, little in addition to a horizontal apron below the secondary weir would be required. The cost of the 40 ft. tailwater weir with its apron and the 70 ft. retaining walls however is so great that this form of protection, although undoubtedly satisfactory from the hydraulic standpoint would be entirely too expensive.

The use of baffles of the ordinary forms to dissipate the energy of the water passing over the Morris Dam is not favored because of the unprecedented velocities which would act on them and the difficulty of building them strong enough to resist the blows to which they might be subjected by logs. The large difference in height between the tailwater rating curve and the curve for height of jump on an apron at stream bed level indicates that the energy which would have to be dissipated by any form of baffles would be large, and therefore they would be subjected to large impacts. The excellent results secured with the depressed pool type as described in the following paragraphs make it unnecessary to resort to baffles.

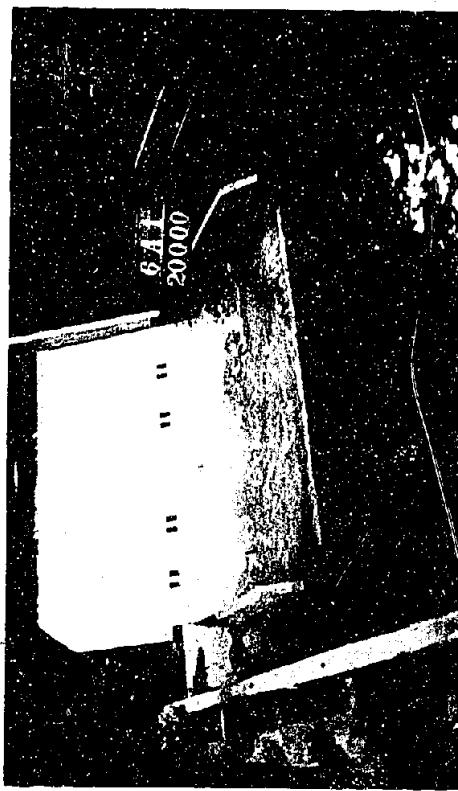
A form of baffle suggested by Mr. Hornsby which does not sustain any direct impact of the water on the baffle was tested but is not recommended, for reasons which will be described later.

FORMS OF PROTECTION RECOMMENDED

The best form of protection is secured by deepening the pool by excavation, placing the pool bottom at Elevation 855, or 15 feet below the stream bed level. For this condition the depth of the pool is sufficient to form a jump at all flows. The



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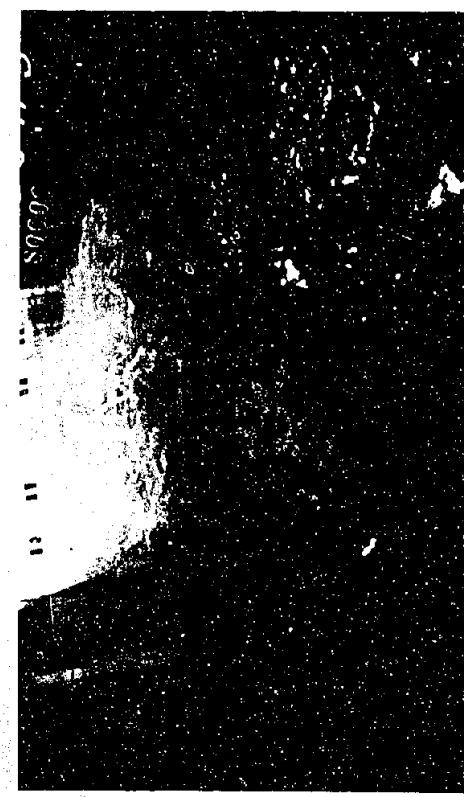


A. Completed Model No flow

B. Discharge 20,000 Sec. Feet



C. Discharge 40,000 Sec. Feet

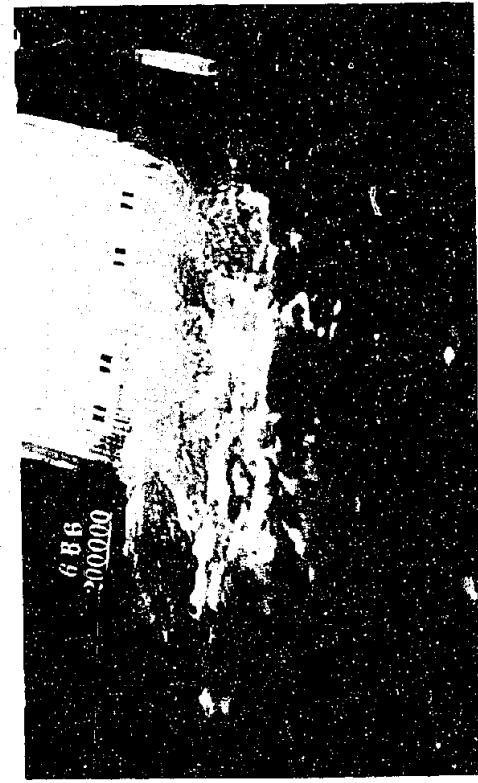


D. Discharge 80,000 Sec. Feet

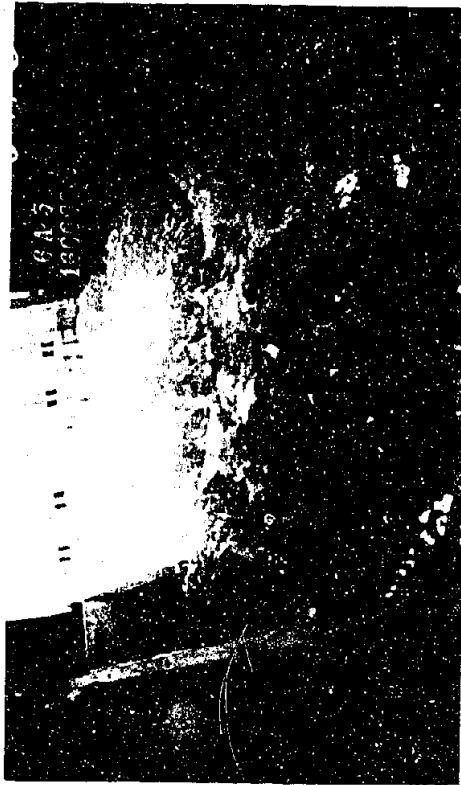
NORRIS DAM TENNESSEE VALLEY AUTHORITY
TESTS WITH DEPRESSED LEVEL APRON



A. Discharge 130,000 sec. Foot



C. Discharge 200,000 sec. Foot



B. Discharge 160,000 sec. Foot



D. Condition of River Bottom
after Tests

HOLDING THE TERRACE WHILE AGRICULTURE
WILL DEPEND UPON IT

close agreement between the jump height curve and the tailwater curve indicates that a nearly perfect hydraulic jump would be formed, in which the energy would be very efficiently dissipated.

The jump height curve is computed on the assumption that no friction exists to retard the velocity of the water passing over the dam. This of course is not true, but as the amount of this friction would be uncertain, it is best to make the action sure whatever its magnitude. The existence of the friction will provide a factor of safety in case the actual tailwater level proves to be somewhat lower than predicted. An additional factor of safety is provided by the slope up from the pool to river bottom level, which tends to deflect the currents upward and raise the water surface at that point, producing the same effect as a higher tailwater level. If the velocity approaching this sill at the end of the pool increases the rise of the water surface over it is also increased, and therefore the tendency of the pool to be swept out by the inflowing water is more strongly opposed.

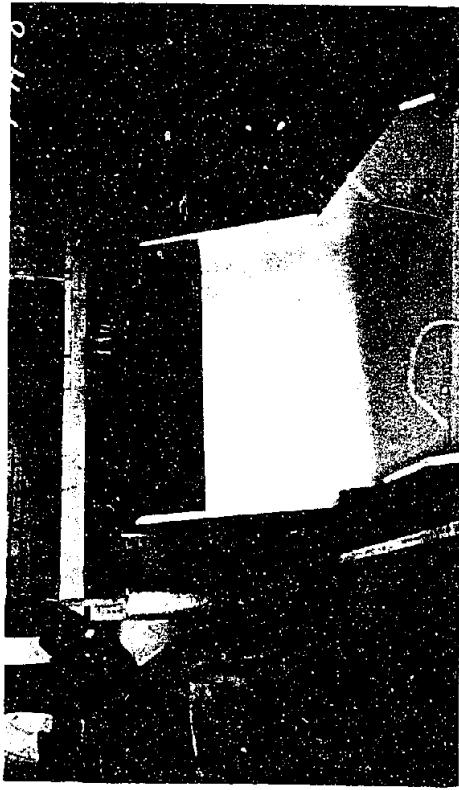
The action of the pool is shown on Figure 1 which is based on the assumption that the gates are kept at the same elevation. For the lower discharges this is not so important, since the pool is deeper than necessary for this condition and some unbalancing of the gate discharges would be permissible.

RESULTS OF TESTS ON NORRIS DAM MODEL

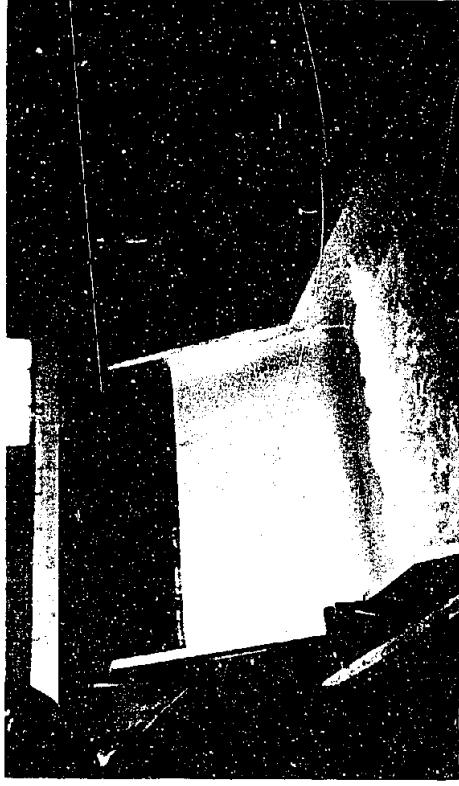
The model experiments for the design of the Norris Dam spillway were performed on a 1:72 model shown on Plates 1 and 2, at the hydraulic laboratory of the Colorado Agricultural College, which was very kindly loaned for this purpose. The tests on the model with the depressed level apron were confirmation of the results predicted by means of Figure 1. The condition of flow for the various discharges are shown on Plates 3 and 4. For all discharges except the low ones a very effective jump was formed, as would be indicated by the agreement of the jump height and tailwater curves of Figure 1. Very little scour of the bottom downstream for the end of the apron was produced, even at the highest discharges (Plate 4-D).

The action of this pool was very satisfactory and this form is recommended for the final design.

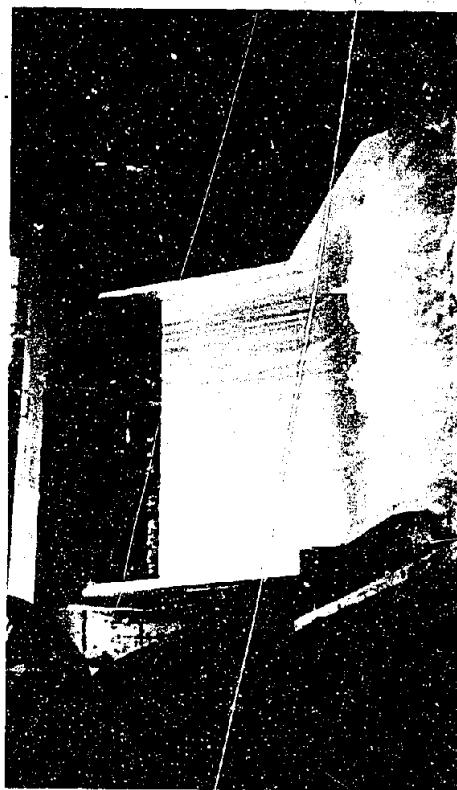
Although the depressed level apron performed satisfactorily, it was hoped that the excavation necessary for the pool might be decreased by using a sloping portion at its upper end. The



A. No Discharge



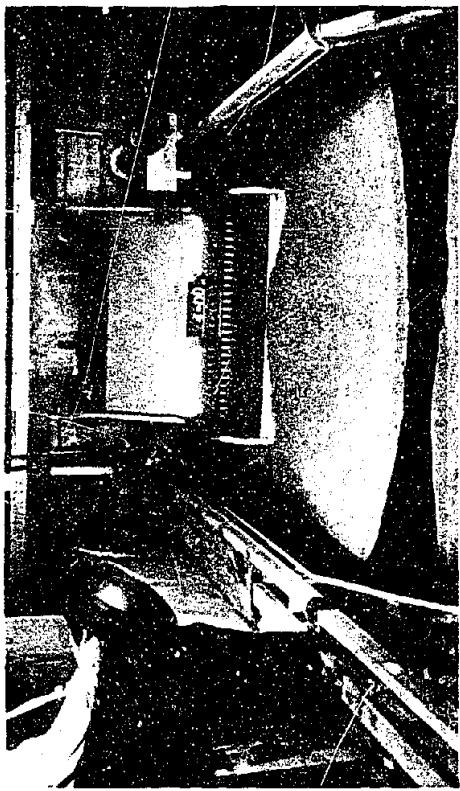
B. Discharge 40,000 Sec. Feet



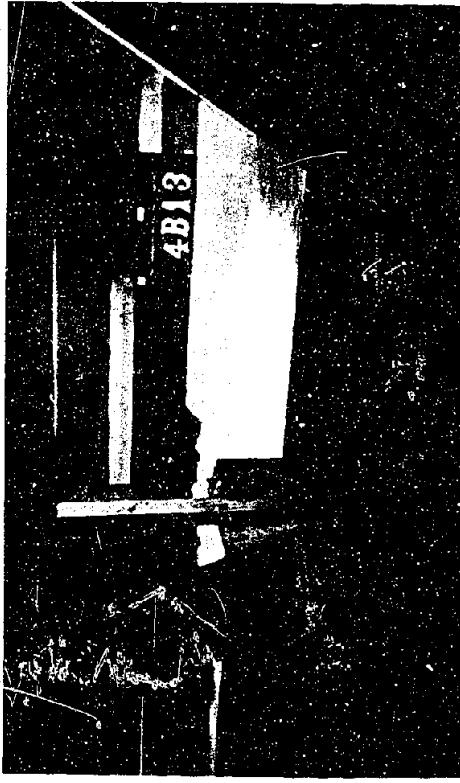
C. Discharge 120,000 Sec. Feet

D. Discharge 200,000 Sec. Feet

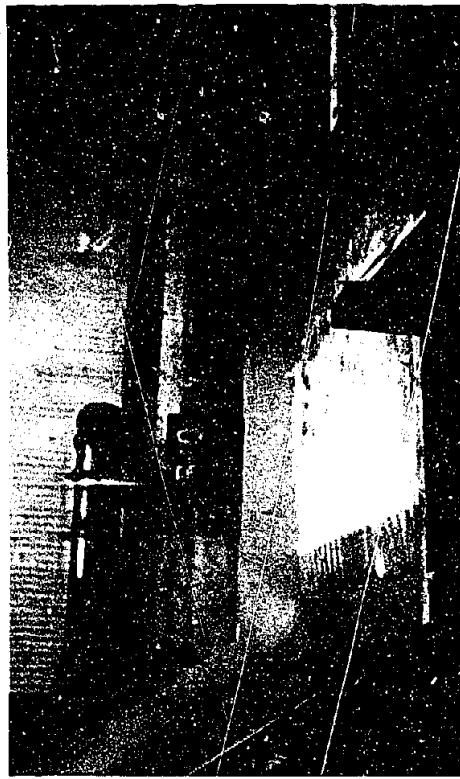
MORRIS DAM TENNESSEE VALLEY AUTHORITY
TESTS WITH DEPRESSED, SLOPING APRON



A. No Flow



A. No Flow



B. Mischarge 30,000 Sec. Ft.



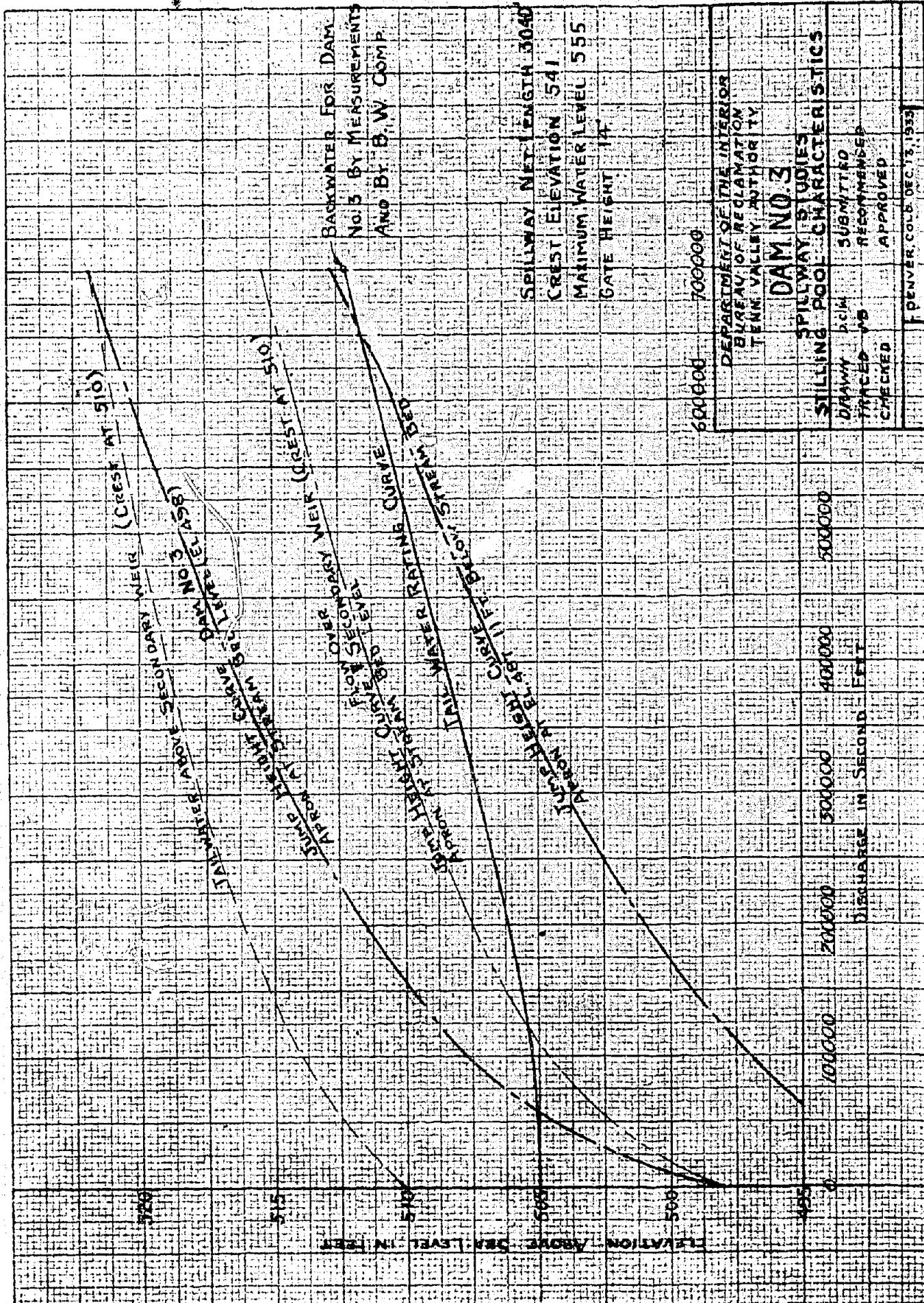
B. Mischarge 30,000 Sec. Ft.

C. Discharge 120,000 Sec. Ft.

PROBLEMS WITH VALVE SPURTS
PROBLEMS WITH BOTTLES CROWNED BY MR. BOTLEY

D. Discharge 300,000 Sec. Ft.

MR. BOTLEY



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slope was made to conform to the natural dip of the rock. It was found however that such an arrangement did not give a sufficient length of deep pool for the formation of the jump at low discharges as shown on Plate 5-B and C although the action was more satisfactory at higher discharges. It will thus be seen that the depressed sloping apron is of no particular advantage where the jump height and tailwater rating curves for the level depressed apron agree as closely as they do in the case of the Morris Dam. Where the jump height curve for the level depressed apron is considerably below the tailwater rating curve for part of the discharge range, the sloping apron is an advantage as was shown by the tests for the Dam No. 5 apron.

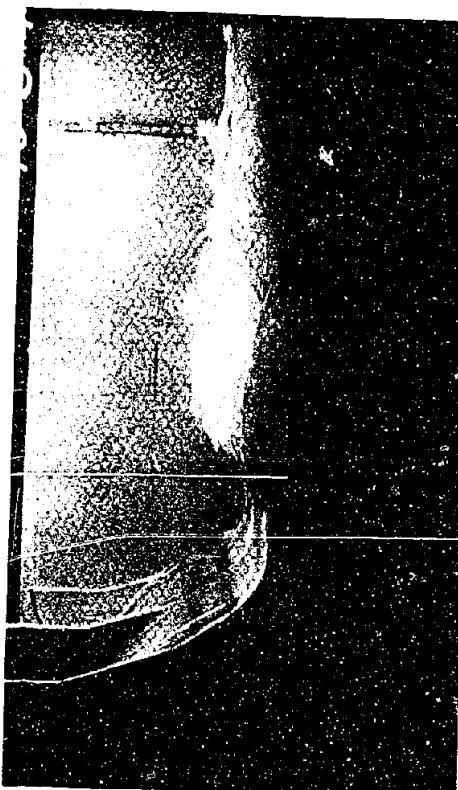
A form of baffle suggested by Mr. Hornsby was also tested. This baffle has the advantage over most other forms that have been proposed in that there is no direct impact of the water on the baffle. The form is shown on Plates 5-A and B. The action of this baffle is not sufficiently effective to permit the elimination of the depression of the apron, but it would make possible some reduction in its length for the flow over the spillway. The total length of pool as originally designed however is needed to receive the discharge through the sluice gates, and therefore on this dam this form of baffle would not be an advantage.

CONDITIONS AT DAM NO. 3

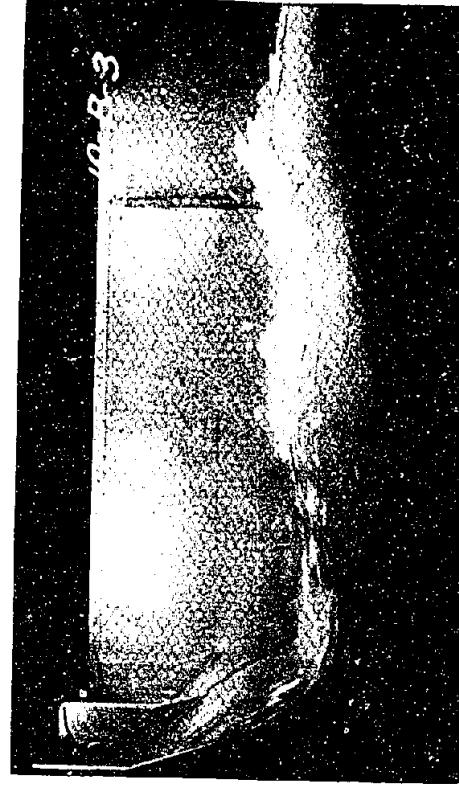
The characteristics of the Dam No. 3 site, from the standpoint of scour protection are shown on Figure 2. The conditions at this site are especially severe because the river below the dam is steep and wide, and the tailwater depth is therefore low. The jump height curve for an apron at streambed level (Figure 2) falls considerably above the tailwater curve and this dam therefore is in Case I (Appendix I) which is the same case as the Morris Dam.

The same four types of protection are therefore applicable. The principal dimensions required for certain forms of protection may be predicted from Figure 2. This shows that in order to produce a sufficient depth with a secondary weir to maintain the jump on an apron at stream bed level for all discharges up to 700,000 sec. ft. a weir with crest at Elevation 510 would be required. Below this secondary weir there would be another problem of protection, since the jump height curve for the flow over the secondary weir is also higher than the natural tailwater rating.

PLATE 7



B. Mechanical 350,000 second foot



C. Mechanical 730,000 second foot



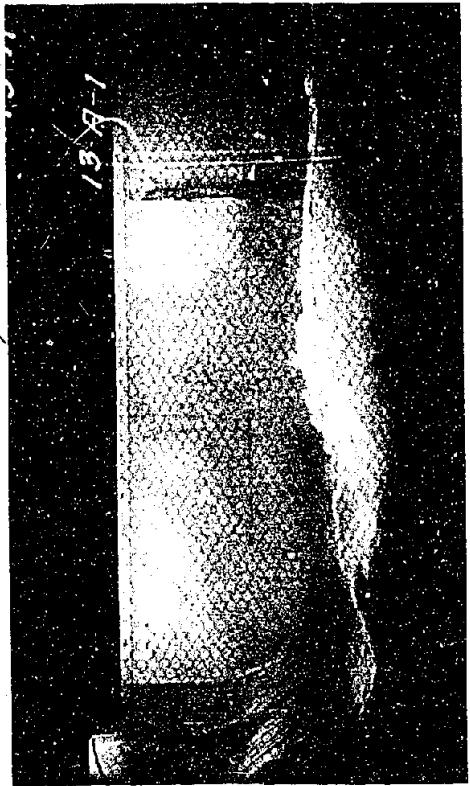
D. Mechanical 1,000,000 second foot



E. Mechanical 1,000,000 second foot

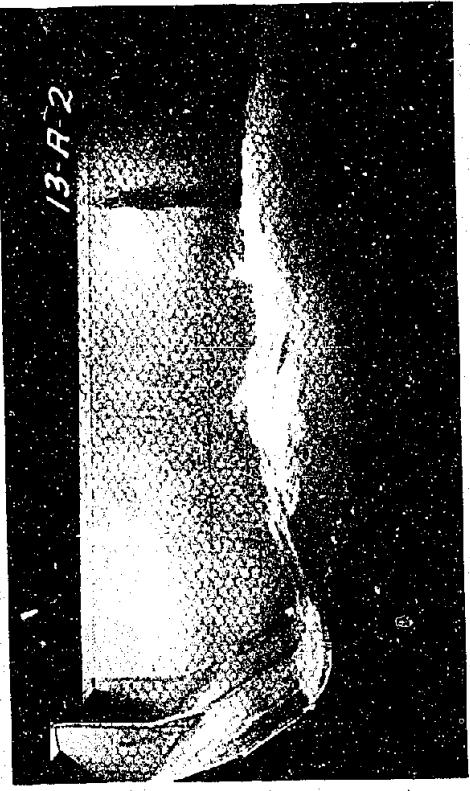
DIA NO. 3 DIA 1/4 INCH
DIA NO. 3 DIA 1/4 INCH
TIME OF EXPOSURE 10 SECONDS
TIME OF EXPOSURE 10 SECONDS

F. Mechanical 1,000,000 second foot



A. Discharge 350,000 Second Feet

ASPMN LIP AT PL. \$20.0

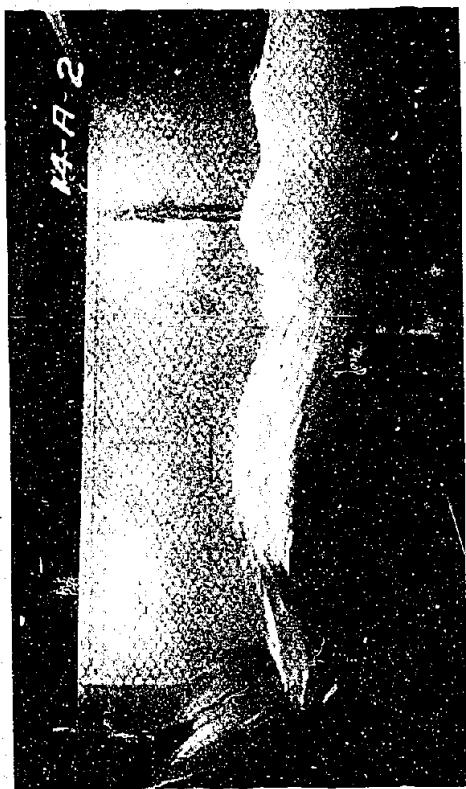


B. Discharge 700,000 Second Feet



C. Discharge 350,000 Second Feet

ASPMN LIP AT PL. \$20.0
ONE NO. 4 TUBING PER VOLUME OF CAPACITY
TUBE OF SECTION ONE INCH DIA. LENGTH FIVE FEET



D. Discharge 700,000 Second Feet

ASPMN LIP AT PL. \$20.0
ONE NO. 4 TUBING PER VOLUME OF CAPACITY
TUBE OF SECTION ONE INCH DIA. LENGTH FIVE FEET

PL. 28, B

curve. Figure 2 also shows that a depressed pool formed by excavating to place the apron at Elevation 487, would produce a jump for all discharges up to 700,000.

In the tailwater rating curve is important in determining the action of the stilling pool, it was determined as accurately as possible. Up to 318,000 the elevation of the tailwater has been determined by observation on actual floods. The value of roughness of the river channel was computed from this observed discharge and the channel size, as determined from surveys. The stages which would be reached for discharges of 500,000 and 700,000 were computed using these roughness values. It is believed that this method gives results which are sufficiently accurate for the purpose.

It was originally expected to use gates 20 ft. high on the crest, but with such gates the jump height curve was even higher than shown on Figure 2. A better agreement of jump height and tailwater curve was obtained by using 14 ft. gates. Estimates showed that although the lower gates required a longer spillway section and therefore a greater length of protection, the decrease in cost of protection per foot for the lower gates almost entirely offset the increased length and resulted in practically the same total cost on account of the less severe scour conditions resulting from the 14 ft. gates and the smaller depth of pool which would be required, it was believed that the 14 ft. gates were preferable.

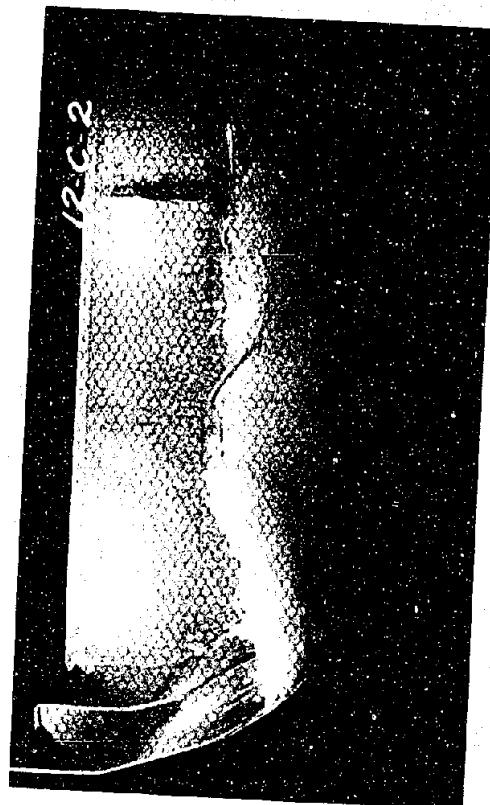
RESULTS OF MODEL TESTS ON THE SPILLWAY OF DAM NO. 3

The four types of protection suitable for Case I conditions were all tested in the hydraulic laboratory of the Colorado Agricultural College, on a 1:36 model (Plate 13-C). Ten major forms were experimented upon several of which were tested with a number of different shapes. In all thirty different forms of protection were tried.

TESTS ON DEFLECTING BUCKET TYPE

For testing the type in which the bucket is designed to throw the overflowing sheet as far from the base of the dam as possible, a flexible bucket was used on the model, which could easily be adjusted to a variety of shapes. For convenience this type will be called the "Deflecting Bucket." The results of these tests are shown on Plates 7 and 8. Buckets with lips at Elevations 495.5, 497.8, 499.0, and 504.0 were tested. The upward slope of the bucket increased with increasing lip elevation. The effect of raising the lip was to move the point of scour further from the base of the dam, but it also produced deeper scour. The scour below the dam if any of these types of protection was used would probably not endanger the dam, but a piling up of the rock would occur similar to that at Wilson Dam, and since much better results could be secured with another form of protection, the deflecting bucket is not recommended.

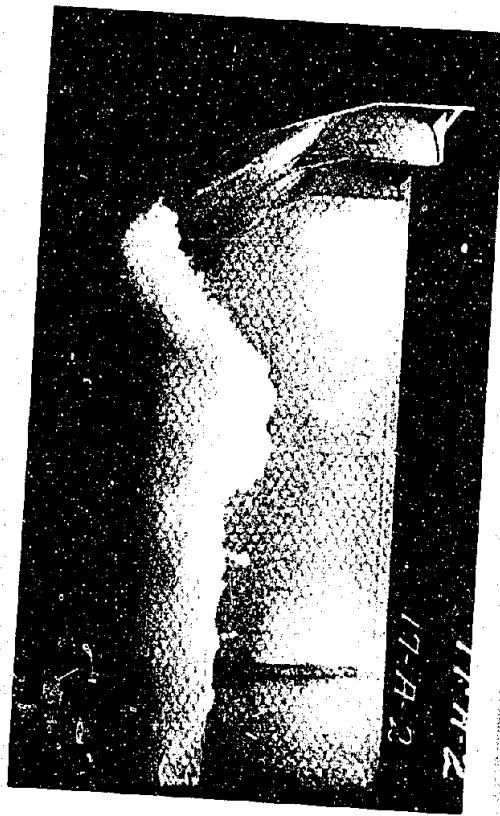
PLATE 9



A. Deflecting Bucket Type with High Tailwater.
Discharge 700,000 Sec. Ft. Tailwater 5 sec. 1



B. Dikeprostoy Bucket with Apron
Discharge 700,000 Second Feet



C. Discharge 350,000 Second Feet

D. Discharge 700,000 Second Feet
DIKEPROSTOY BUCKET AT LOW ELEVATION
DM NO. 3 TENNESSEE VALLEY AUTHORITY
TESTS OF DIKEPROSTOY TYPE BUCKET

PLATE 10



A. Discharge 350,000 Second Feet

TESTS WITH SECONDARY WEIR



B. Discharge 700,000 Second Feet



C. Discharge 350,000 Second Feet



D. Discharge 700,000 Second Feet

DAM NO. 3 TENNESSEE VALLEY AUTHORITY
TESTS WITH REINFORCED SILLS ON APRON AT STREAM BED LEVEL

DNIEPROSTROY TYPE BUCKET

When the tailwater is raised on the model with deflecting bucket, much higher than it would be at the dam site, another form of action takes place, as shown on Plates 9-A. The action on this case is somewhat like a hydraulic jump on a bottom sloping upward. Most of the energy is dissipated in turbulence, and high velocities exist only near the upper part of the tailwater. This action is described on pages 12 to 14 of Appendix I. It can be secured with the tailwater levels which would exist at the site of Dam No. 5 by placing the bucket at a low enough level. The up-sloping portion was given a steep slope, as this produced a better action. For convenience this form of apron will be called the Dnieprostroy type, as it was used on that dam. The action of an apron of this type is shown on Plates 9-C and D. This type is efficient in reducing scour below the dam and is inexpensive, but the excavation of a large hole at the toe of the dam is believed to be undesirable. This type of protection is better adapted to conditions where the tailwater rating curve is above the jump height curve, since in this case the bucket can be placed above the stream bed level.

SECONDARY WEIR

The use of a secondary weir to raise the tailwater level to a height sufficient to form a jump on an apron at stream bed level was also tested. The results are shown on Plate 10-A and B. They show a satisfactory action below the main weir, but confirm the predictions from Figure 2 as stated on Page 5 that the depth of tailwater would be insufficient to form a jump below the secondary weir. As the velocities from the overall of this weir might reach 35 ft. per second, some form of protection would be necessary below this dam. A depression of the apron to about 3 ft. below stream bed level, or some form of baffles would probably accomplish this result. The secondary weir form of protection is undesirable however from a construction standpoint, as it necessitates a wide cofferdam, and prevents a compact construction plant. It also would interfere somewhat with diversion during construction. For these reasons it is not believed to be as desirable as other forms of protection.

VARIOUS TYPES OF BAFFLES

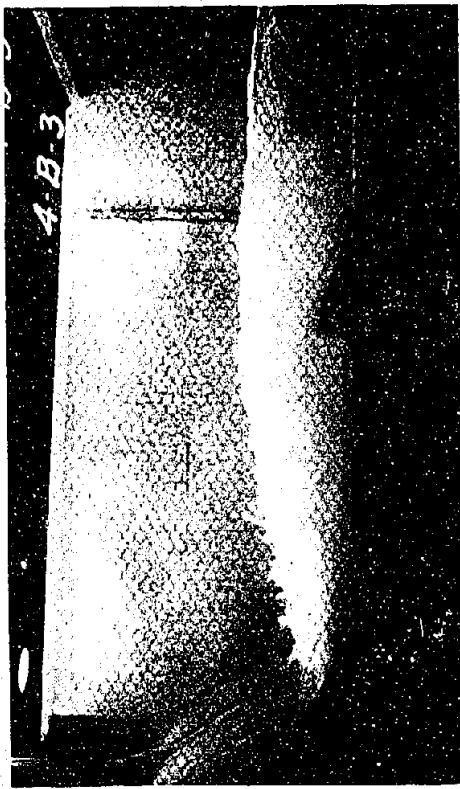
Three types of baffles were tested. One of these was the dentated sill invented and patented by Dr. Rohrbeck. With these sills on an apron at streambed level, a hydraulic jump is not formed upstream from the sills and they are subjected to a high impact, as shown on Plate 10-C and D. The nearness of the sills to the weir

PLATE 11



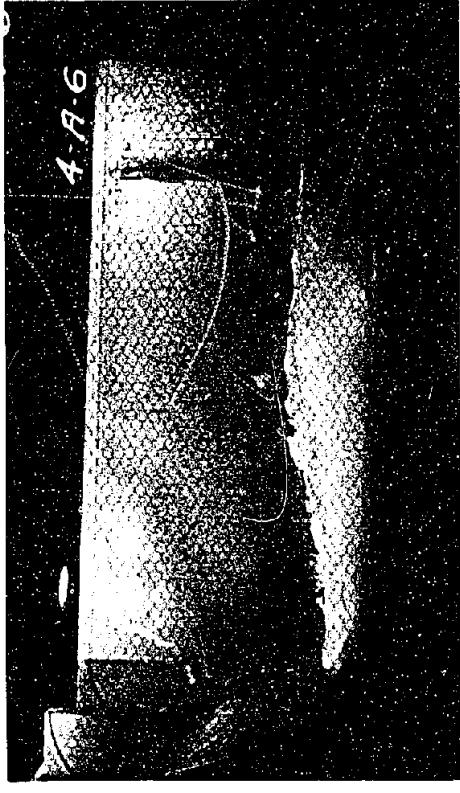
A. Discharge 350,000 Second Feet

SILLS 60 FEET FROM TOE OF DAM



B. Discharge 700,000 Second Feet

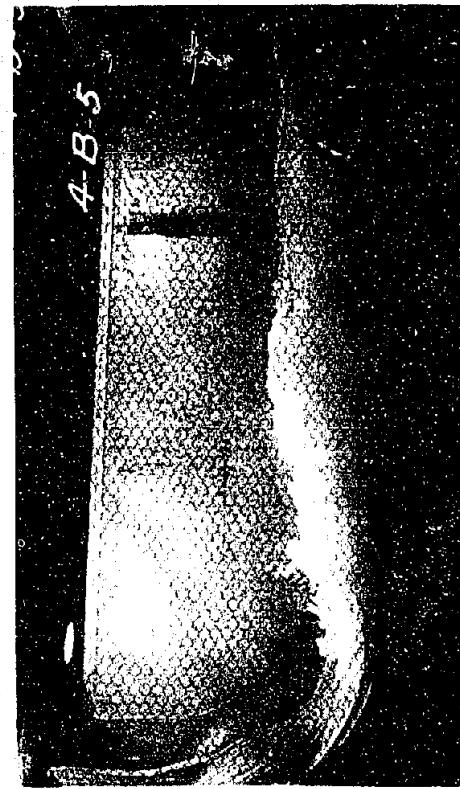
SILLS 60 FEET FROM TOE OF DAM



C. Discharge 350,000 Second Feet

SILLS 78 FEET FROM TOE OF DAM

DAM NO. 3 TENNESSEE VALLEY AUTHORITY
WEST OF REHBACK SILLS ON APRON 8 FEET BELOW STREAMBED LEVEL



D. Discharge 700,000 Second Feet

SILLS 78 FEET FROM TOE OF DAM

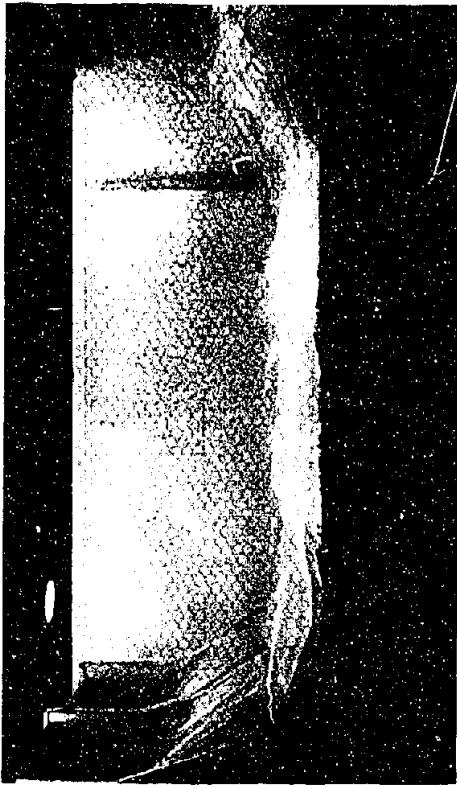
DAM NO. 3 TENNESSEE VALLEY AUTHORITY

PLATE 12

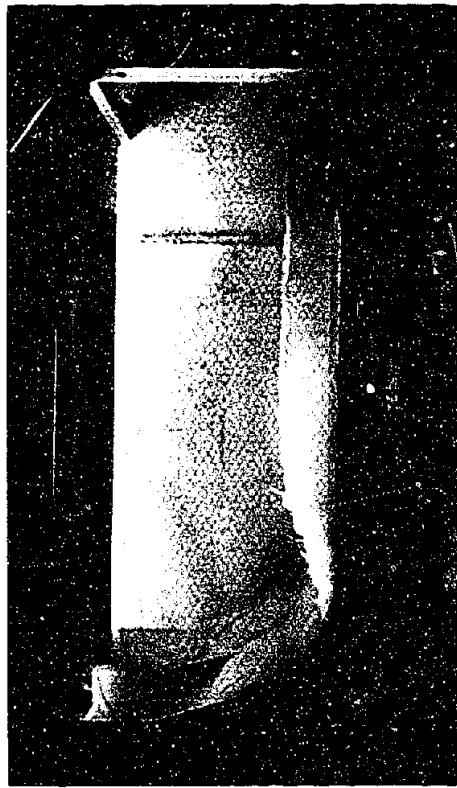


A. Discharge 350,000

APRON AT RIVER BED LEVEL

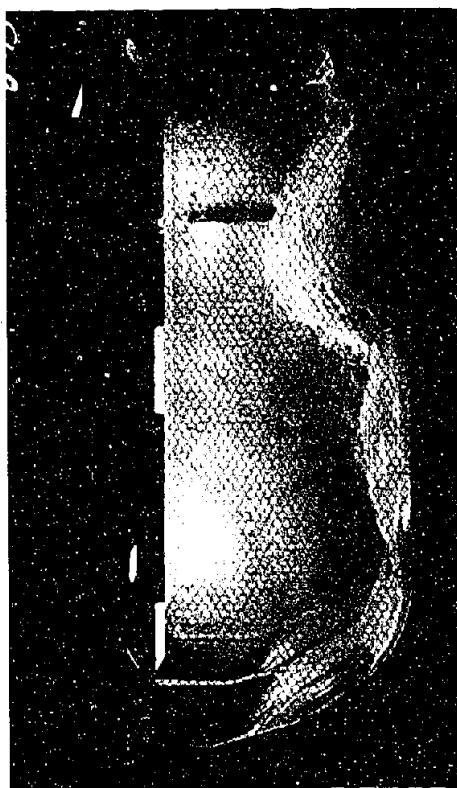


B. Discharge 700,000

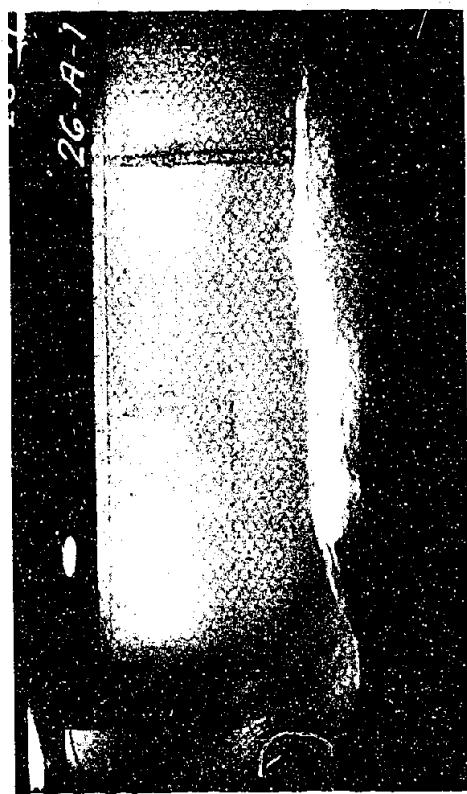


C. Discharge 350,000

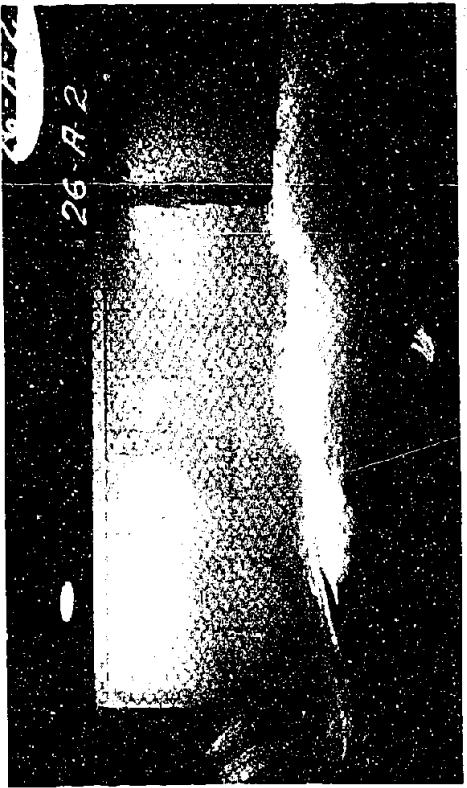
APRON 8 FEET BELOW RIVER BED LEVEL
DAM NO. 3 TENNESSEE VALLEY AUTHORITY
TEST WITH SMALL TRIANGULAR SILLS



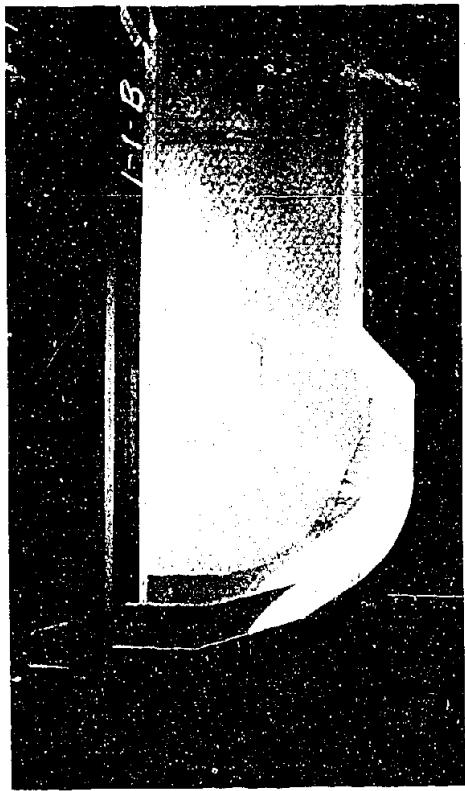
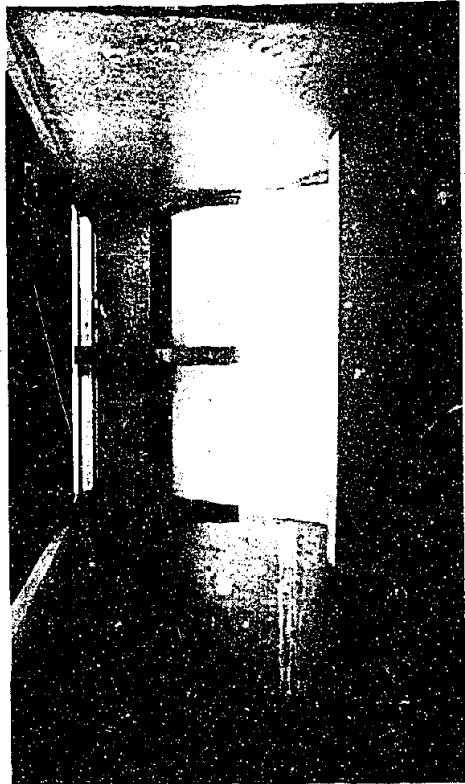
D. Discharge 700,000



A. Discharge 350,000 Second Feet



B. Discharge 700,000 Second Feet



C. Dam Number 3 Model Looking Upstream

DAM NO. 3, TENNESSEE VALLEY AUTHORITY
TESTS WITH LEVEL, DEPRESSED APRON

D. Level Depressed Apron
24 Ft. Length No Flow

was not found to exercise much effect on this action. This is true because the retarding effect of a longer distance would result only because of the friction to flow over the apron, which would be relatively small. Better results were secured by placing the demister sills on a depressed apron, as shown on Plate 11. To construct a depressed apron would greatly increase the cost of the protection. The hydraulic jump must form, in more or less perfect condition, upstream from the sill to make its action satisfactory. With the sill, the jump will form with somewhat less pool depth than is required to form the jump without it. The cost of the sill can therefore be balanced against the cost of slightly deeper pool. A cheaper and equally satisfactory solution can be obtained however than either the sills with depressed aprons, or deeper depressed apron alone, and therefore their use is not recommended.

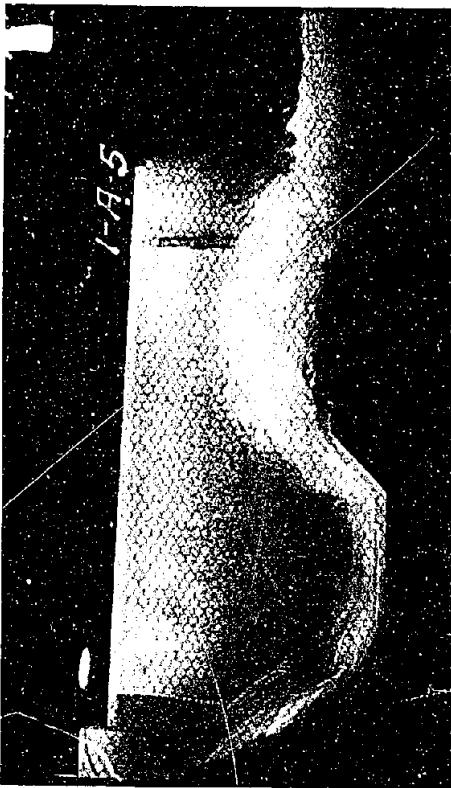
Sets of small triangular sills, suggested by Mr. Savage were also tried. When these were placed on an apron at streambed level, Plate 12-A and B, the water swept across them at high velocity to the end of the apron. If placed on an apron depressed 8 feet below streambed level, a satisfactory condition was produced for a flow of 350,000 sec. ft. (Plate 12-C) but for 700,000 sec. ft. the result was unsatisfactory (Plate 12-D). Since practically as good results were secured with no sills at all with apron 8 feet below streambed level, it may be concluded that these sills had little beneficial effect. Several other sizes and shapes of these small triangular sills were experimented upon with the same result as those mentioned above.

Tests were also made with the form of baffle suggested by Mr. Hornsby, described on Page 5. The dissipating effect of this form was not sufficiently great to enable the depression of the apron to be dispensed with. The action on an apron at stream bed level is shown on Plate 13-A and B.

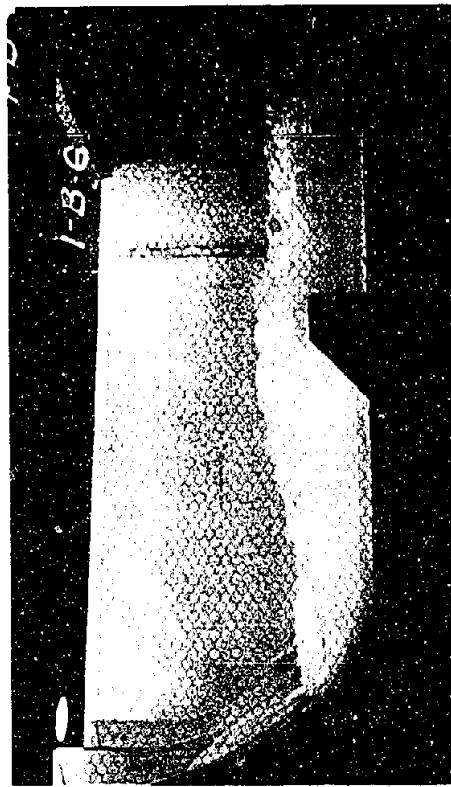
LEVEL DEPRESSED APRON

The fourth general type of protection tested was the depressed apron. There were two principal sub-divisions of this type, the level and the sloping aprons. Figure 2 shows that to have the jump form for all discharges, the apron for the 14 ft. gate must be depressed 11 ft. below the river bed level, or to Elevation 487.

The principal question in designing a level depressed apron is the length required to form the jump satisfactorily. If the pool



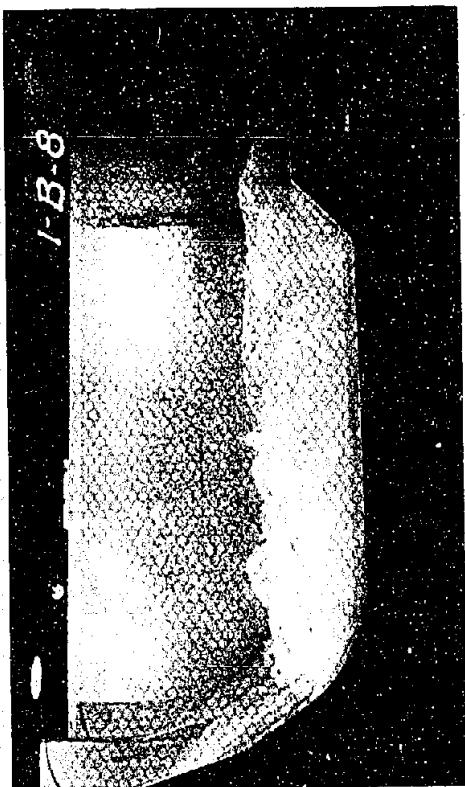
A. Pool Length 24 Ft.



B. Pool Length 42 Ft.



C. Pool Length 60 Ft.

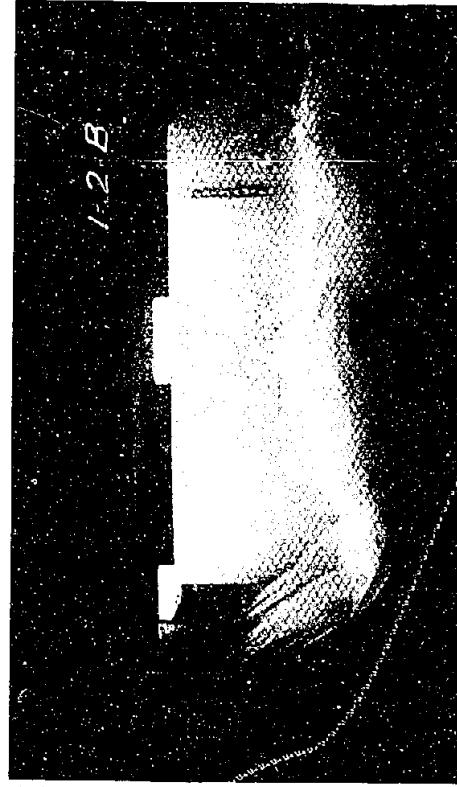


D. Pool Length 78 Ft.

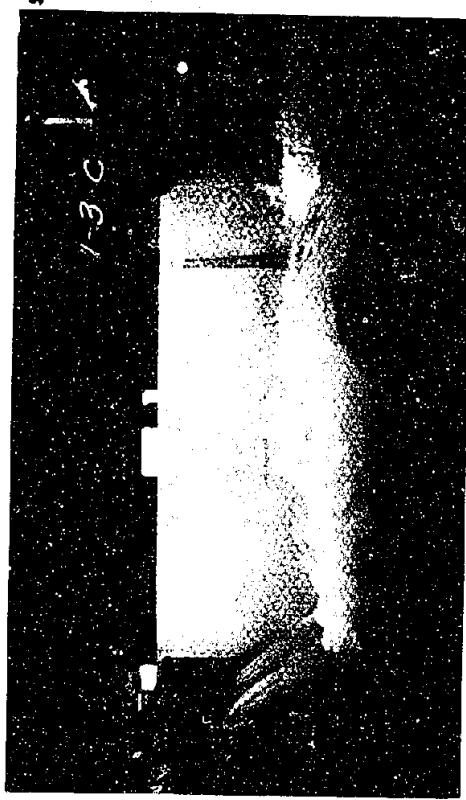
DAM NO. 3, TENNESSEE VALLEY AUTHORITY
ACTION OF LEVEL, DEPRESSED APRON WITH 300,000 SEC. FT. DISCHARGE



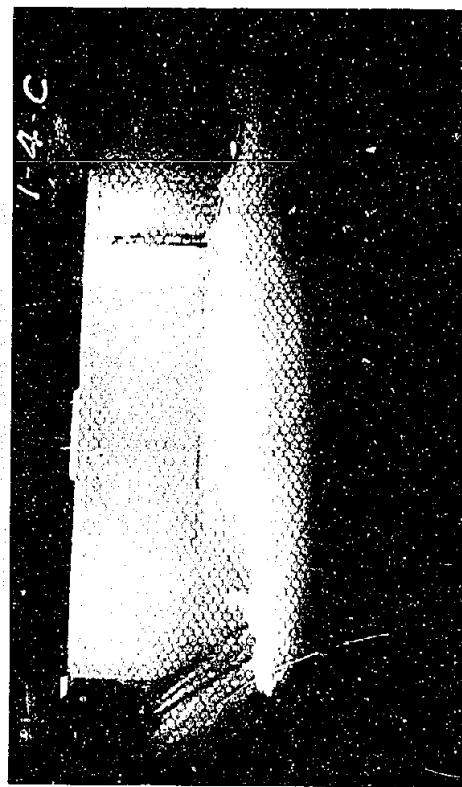
A. Pool Length 24 ft.



B. Pool Length 42 ft.

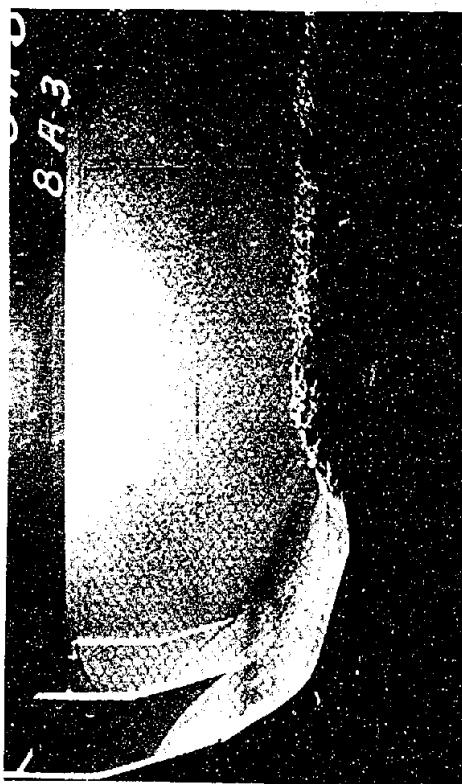


C. Pool Length 60 ft.

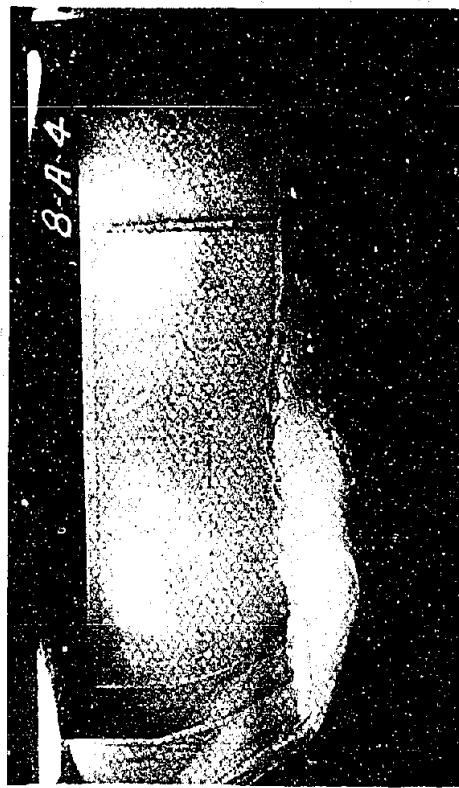


D. Pool Length 78 ft.

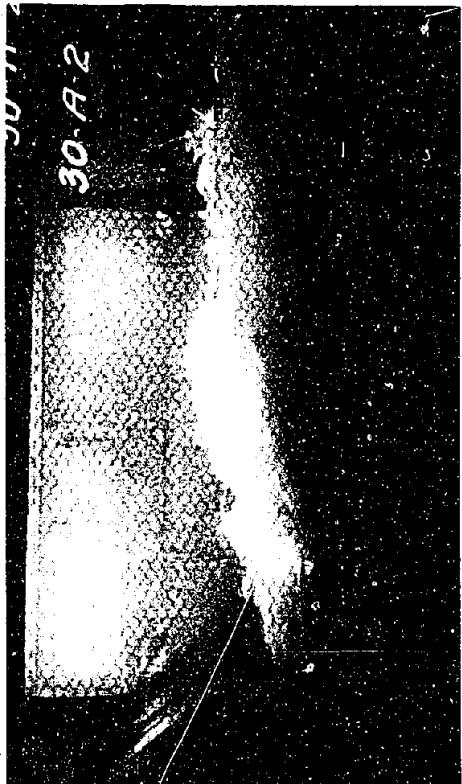
DAM NO. 3, TENNESSEE VALLEY AUTHORITY
ACTION OF LEVEL, DEPRESSED APRON WITH 700,000 SEC. FT. DISCHARGE



A. No Flow



B. Discharge 350,000 Second Feet



C. Discharge 733,000 Second Feet
Pond Level 557'



D. Discharge 733,000 Second Feet
Pond Level 557'. Lowered Tailwater

DAM NO. 3, TENNESSEE VALLEY AUTHORITY
THE RECOMMENDED DESIGN, DEPRESSED SLOPING APRON

is too short, it will be swept out as shown on Plate 14-A, even if the tailwater depth is sufficient to form a normal jump. In other words, for the formation of a jump, a certain minimum length is required as well as a minimum depth. Plates 14 and 15 show that as the length of the pool is increased the effectiveness of the stilling action is greater. This form of pool would undoubtedly have been satisfactory from the hydraulic standpoint. The principal disadvantages of it are high cost and the deep hole which it necessitates right at the toe of the dam. The depressed sloping apron is an improvement from both of these standpoints.

THE DEPRESSED SLOPING APRON - THE RECOMMENDED DESIGN

The best results, considering both hydraulic action and cost, of any of the forms of scour protection was secured by the use of the depressed sloping apron. This form combines the advantages of the depressed pool, and the sloping apron. The sloping apron alone, built above the river bed level, as discussed in Appendix I, would not have been satisfactory, as it would not have caused a jump to form on the apron. When the sloping apron is depressed however, so that it bears the proper relation to the tailwater level, the action is the same as that discussed in the appendix.

The action of this form of spillway is shown on Plate 16. For a discharge of 550,000 sec. ft. (Plate 16-B) or a flood for which the average frequency would be once in ten years. There would be practically no movement of the bedrock below the dam, if it were excavated on a 3:1 slope below the apron. Should a flood occur which would require the entire capacity of the spillway with the 2 ft. surcharge giving a discharge of 753,000 sec. ft. although some material would be moved from the bed, the scour would not be serious. Plate 16-C shows the results with the tailwater computed for this discharge, but even should the tailwater prove to be materially lower, although the action of the jump will not be so effective, the scour will not be serious, as shown on Plate 16-D. The tailwater level is more likely to be higher than estimated, on account of the obstructing effect of the portions of the cofferdam and excavated rock which will probably be left on the river bottom downstream from the spillway, and because the spillway occupies only a portion of the width of the river and some drop will be necessary to cause this flow to spread to the full river width, which is the condition assumed in computing the tailwater level. If this higher tailwater exists, the results will be even better than the model experiments indicate. The action of this form of spillway will therefore, it is believed, be entirely satisfactory, from the hydraulic standpoint, and since its cost is below any other form giving equally satisfactory results it is recommended for use on the spillway of Dam No. 3.

