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HYDRAULIC MODEL STUDIES OF UPPER STILLWATER DAM STEPPED SPILLWAY AND OUTLET WORKS

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16. ABSTRACT

Hydraulic model studies were made to aid in the design of a stepped spillway. Stepped spillways, economically constructed of slip-formed conventional concrete, may be used where the unit discharge is low and the stilling basin size must be limited. An outlet works stilling basin, designed for submerged operation of a 14-inch jet-flow gate, was also studied.

The results of the stepped spillway model study indicated that the crest shape is vital to efficient hydraulic operation and that the energy contained in the jet is minimal because of the tumbling action induced by the steps. The maximum velocity measured on the face of the 202-foot-high spillway near the toe was about 41 ft/s. Energy dissipation was approximately 75 percent greater than it would be for a smooth conventional spillway. This energy dissipation permitted the stilling basin length to be reduced from 200 to 30 feet. Impact and subatmospheric pressures on the steps of the spillway face were also investigated.

The outlet works stilling basin design was based on operation of the submerged 14-inch jet-flow gate under a maximum head of 207.5 feet and a discharge of 29 ft^3/s. The small, boxlike stilling basin resembles the type VI basin described in Bureau of Reclamation Monograph No. 25. The stilling basin operation is independent of the tailwater. Final dimensions of the basin were 17.5 feet long by 9 feet wide by 19 feet deep with a 7-foot-high end sill. Impact pressures, wave heights, and debris handling were investigated with the model.

17. KEY WORDS AND DOCUMENT ANALYSIS

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HYDRAULIC MODEL STUDIES OF UPPER STILLWATER DAM STEPPED SPILLWAY AND OUTLET WORKS

by

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October 1987

Hydraulics Branch
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Denver, Colorado

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ACKNOWLEDGMENTS

Marlene F. Young was the principal investigator of the hydraulic model studies. She performed or directly supervised the model design and testing and had responsibility for making model changes and final design recommendations. Marlene prepared three memorandums and an ASCE technical paper ("Feasibility Study of a Stepped Spillway") that were invaluable in the preparation of this report.

Eugene R. Zeigler performed the additional model studies discussed in the appendix. These studies were needed to augment the existing data because the probable maximum flood for Upper Stillwater Dam was so greatly increased in 1985.

The studies were accomplished through the cooperation of the Hydraulics Branch and the Concrete Dams Branch of the Engineering and Research Center. The feasibility designs were developed primarily by Alan T. Richardson, Robert J. Quint, Daniel D. Mares, Melissa S. Eckley, and Fred Lux III of the Concrete Dams Branch. Their continued input throughout the studies was greatly appreciated.

The model studies were conducted under the supervision of Thomas J. Rhone, Head Hydraulic Structures Section. Robert P. Woodby, rotation engineer, and Judith A. Kinkaid and Cheryl A. States, civil engineering technicians, assisted with the model testing. Photographs were taken by Wayne K. Lambert. Preliminary editing was performed by Barbara E. Prokop of the Hydraulics Branch.

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FIGURES – Continued

INTRODUCTION

Upper Stillwater Dam, an RCC (roller-compacted concrete) dam and part of the Bonneville Unit of the Central Utah Project, is located about 80 miles east of Salt Lake City, Utah (fig. 1). Upper Stillwater Reservoir will be used to regulate the flows of Rock Creek and South Fork of Rock Creek for release to the Strawberry Aqueduct. The reservoir water surface will be kept constant during the summer but will be lowered about 160 feet during fall and winter releases. The structural height of the dam is 285 feet. Its crest length is 2,800 feet at elevation 8175.5 feet with parapets to elevation 8180.0. The spillway, whose crest length is 600 feet at elevation 8172.0, must pass the design discharge of 15,000 ft^3/s at maximum reservoir elevation 8175.5. The maximum tailwater elevation is 7985.0. The outlet works is controlled by a 14-inch submerged jet-flow gate. The operating head ranges from 42 to 207.5 feet with a maximum discharge of 29 ft^3/s. The minimum tailwater height above the end sill of the outlet works stilling basin is 3 feet (El. 7975.0).

The model studies of the spillway and outlet works were conducted to study the hydraulic efficiency of the stepped spillway and to size the stilling basin for the spillway and the outlet works. The stepped spillway investigation included determining the crest shape, measuring velocities and pressures on the spillway face, and sizing the stilling basin. The outlet works study involved sizing the stilling basin, measuring wave heights and impact pressures, and testing the debris-handling capability of the basin.

The spillway model testing was conducted from April 1980 to March 1982, and the outlet works study was conducted from February 1982 to June 1982.

PURPOSE

The hydraulic model studies were conducted to determine parameters associated with the state-of-the-art designs of the spillway and outlet works for Upper Stillwater Dam of the Central Utah Project.

Using RCC at Upper Stillwater Dam required the development of new dam construction techniques. RCC was selected because of a forecasted significant reduction in cost and construction time. The construction methods associated with RCC enable a stepped downstream face to be easily produced on the dam. This stepped face is used as the spillway chute.

Hydraulic model studies were conducted to determine the crest shape and the ability of the spillway steps to dissipate energy. The spillway stilling basin dimensions were based on this energy dissipation.

A field-test section (fig. 2) completed in 1981 near the proposed damsite proved the success of the construction techniques and the need to determine an effective spillway design.

Results of the outlet works model study were used to develop stilling basin design parameters for a submerged jet-flow gate operating under high heads.

CONCLUSIONS

Studies were conducted for two different spillway geometries. Initial studies were based on a 15-foot top width and a constant 0.6:1 (horizontal: vertical) slope for the downstream face. The top width was then increased to 30 feet to facilitate construction, and the slope of the upper portion of the downstream face was increased to 0.32:1 so that it intersected the 0.60:1 slope at elevation 8100.0. An optimum crest shape was developed for both of these spillway geometries.

The following conclusions are based on the results of the spillway model study:

- A crest shape was developed for a spillway with a 15-foot top width and 0.60:1 sloped downstream face. This shape is shown by crest C on figure 3.
- The final crest slope developed for the 30-foot top width and 0.32:1 upper slope is shown on figure 4. The channel upstream of the crest was lowered to elevation 8165.0 to reduce approach velocities. The upper portion of the crest was designed to follow the underside of the theoretical nappe shape until meeting the 0.32:1 slope at elevation 8152.0.
- The discharge curve for the final spillway design is shown on figure 5. The maximum head of 3.5 feet at reservoir elevation 8175.5 produced a unit discharge of 25.7 ft^2/s, or a design discharge of 15,420 ft^3/s.
- Spillway training wall heights of 5 feet, perpendicular to the slope, will contain the flow for all discharges. Spray from the turbulent tumbling action down the steps may, however, exceed this wall height. To capture the spray, 20-foot-wide channels were constructed at elevation 8000.0 on both sides of the spillway.
- Without spillway walls the jet would spread as it progressed down the face and require the stilling basin to be widened by about 50 feet on both sides.

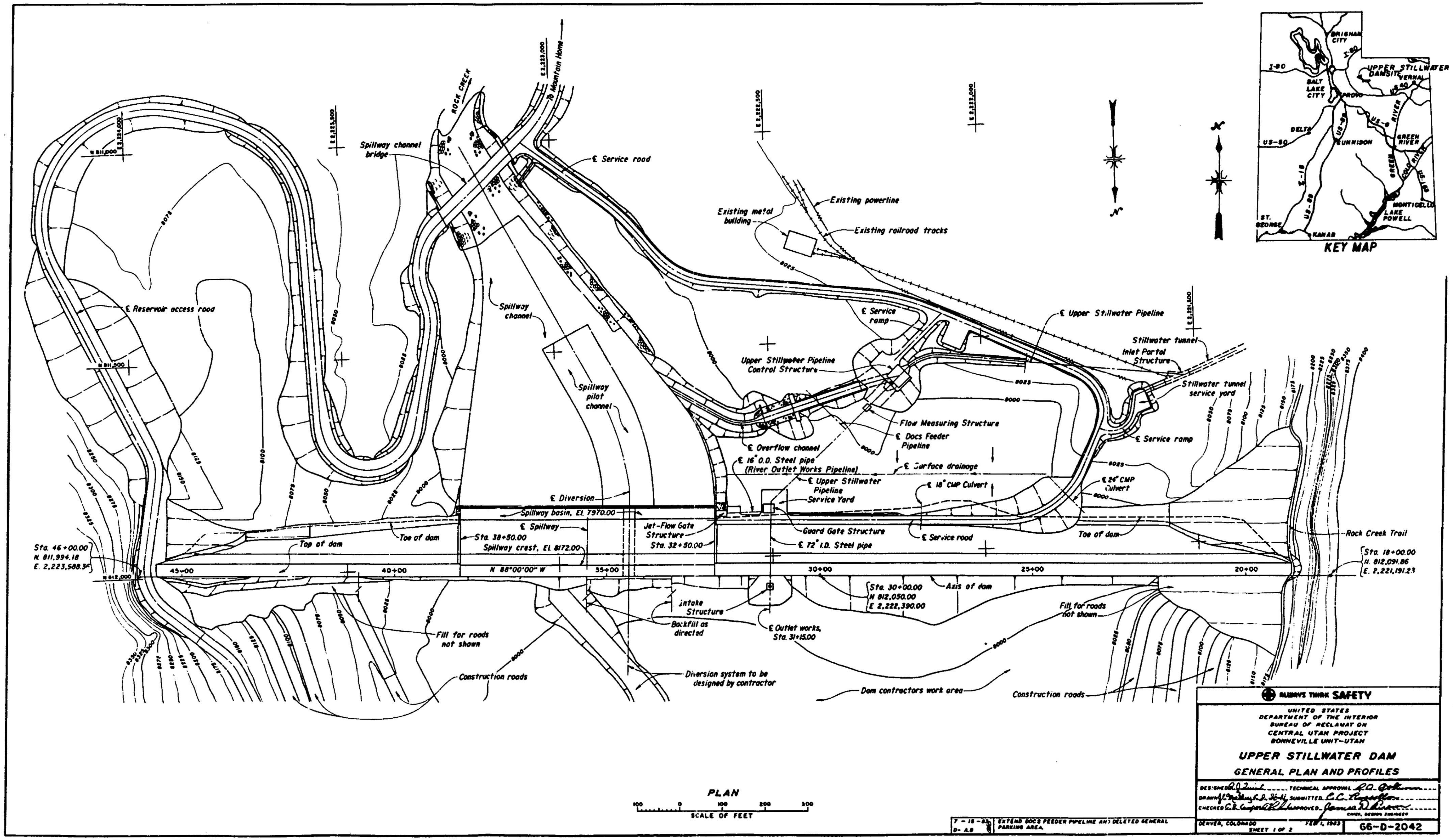

Figure 1. – General plan and location map of Upper Stillwater Dam.

Figure 2. – Completed field-test section of Upper Stillwater Dam. P–801–D81085.

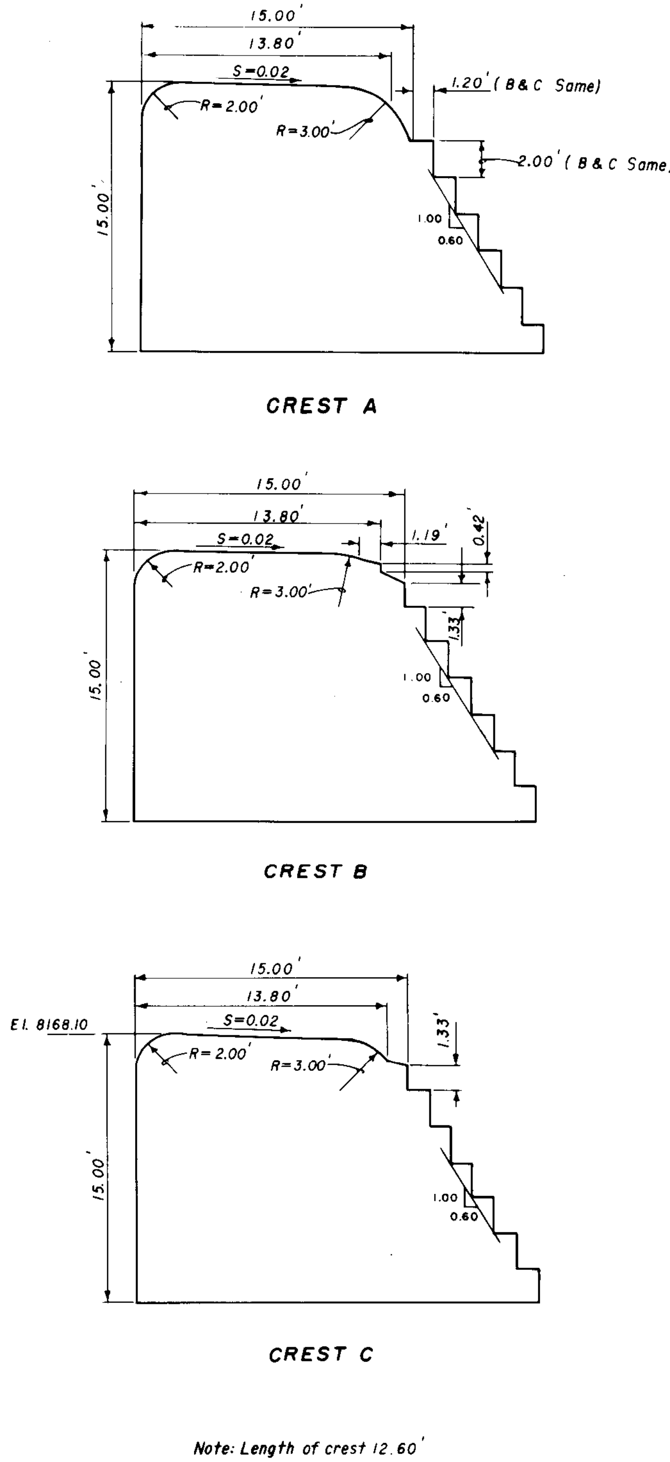

Figure 3. – Spillway crest shapes tested for preliminary design.

- Pressures measured at various locations down the spillway face were acceptable. The maximum and minimum pressures occurred at the abrupt 0.32:1 to 0.60:1 slope change. These pressures will not cause impact or cavitation damage.

- Velocities were measured along the stepped spillway face. A maximum velocity of 41 ft/s was attained about 25 feet downstream from the slope change. The velocity remained constant until the flow entered the stilling basin.

- The primary objective of the stepped spillway was to reduce the length of the stilling basin by dissipating energy down the spillway face. Compared with a conventional spillway of the same height, estimated velocities entering the basin were significantly lower, allowing the initial design for the stilling basin length to be reduced from 200 to 50 feet. The model study resulted in an additional 20-foot reduction producing a final stilling basin length of 30 feet.

The following conclusions are based on results of the outlet works model study:

- The final stilling basin design for the 14-inch jet-flow gate is shown on figures 6a, 6b, and 6c. The basin dimensions are 9 feet wide, 17.5 feet long, and 19 feet high. It has a 7-foot-high end sill that is 2 feet wide at the bottom and 5.5 feet wide at the top.

- Pressures were measured on the floor and at the end sill along the basin centerline. A maximum pressure of 16.2 feet was recorded at the base of the end sill under maximum discharge, 29 ft^3/s, at 207.5 feet of head. A minimum pressure of 0.36 foot was measured on top of the end sill for a discharge of 5 ft^3/s under 100, 140, and 207.5 feet of head. No pressures were excessive, confirming that the basin width is adequate.

- The stilling basin will self-clean, provided debris material is less than 2 inches in size and the

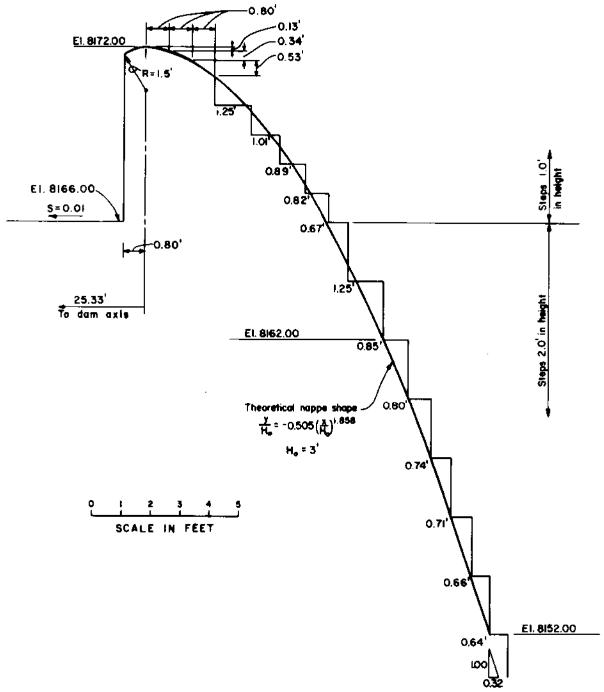

Figure 4. – Final design of the top 20 feet of spillway crest.

discharge occasionally reaches 29 ft³/s under a reservoir head of 207.5 feet.

THE MODELS

The model studies were performed using different spillway and outlet works models. The spillway was modeled with several sectional models, each representing a portion of the 600-foot crest length and 202-foot spillway height. Sectional models having 1:5 and 1:10 scales were used to determine the crest shape necessary to optimize the tumbling action of the flow down the steps on the spillway face. The optimum crest shape was then installed in a 1:15 scale model representing 60 feet of the 600-foot-long crest, all of the 202-foot-high spillway, and all of the 30-foot-long stilling basin.

The sectional spillway models were constructed in 2.5- and 4-foot-wide laboratory test flumes. The test flume facilities for the 1:5 scale sectional crest model and the 1:15 scale full-height spillway model are shown on figures 7 and 8, respectively. The spillway steps were made with sugar pine and placed on a sloping plywood face. Critical portions of the crest were modeled using sheet metal, high-density polyurethane foam, or sugar pine to allow easy modification.

The 14-inch jet-flow gate was modeled by a 3.53-inch gate previously used in an outlet works model study for Crystan Dam [1].* Using this valve determined the scale of 1:3.97 for the Upper Stillwater outlet works model. The initial design of the 17.5-foot-long by 9-foot-wide by 19-foot-deep stilling basin was modeled using plywood. Because the final dimensions for the basin were to be determined by the model, the model basin was designed for easy modification (fig. 9)

SIMILITUDE AND TEST DISCHARGES

The linear scales of the models were designed using Froude law relationships. The length ratios (scales) for the 2.5-foot-wide sectional spillway models used to develop the optimum crest shape were 1:5 or 1:10. The length ratio (scale) for the full-height model was 1:15.

For example, the length ratio L_r = 1:15 resulted in a discharge ratio of:

$$Q_r = (L_r)^{5/2} = (1:15)^{5/2} = 1:871.42$$

Therefore, spillway prototype discharge of 15,000 ft³/s equals a model discharge of:

$$\frac{15{,}000 \text{ ft}^3/\text{s}}{(15)^{5/2}} = 17.21 \text{ ft}^3/\text{s}$$

For a 600-foot prototype crest width, this total discharge equals a model unit discharge of:

$$\frac{17.21 \text{ ft}^3/\text{s}\ (15)}{600 \text{ ft}} = 0.43 \text{ ft}^2/\text{s}$$

The spillway crest length changed from 700 to 600 feet, and the maximum design reservoir elevation varied during the study; therefore, the unit discharges also changed. Initial crest shapes were tested based on a 700-foot crest length and unit discharges of 20.7 and 40.7 ft²/s. The final spillway design was developed for a 600-foot crest length and a maximum unit discharge of 25.7 ft²/s at reservoir elevation 8175.5. The maximum tailwater elevation was 7985.0, 15 feet above the stilling basin floor.

The outlet works was modeled with a length ratio L_r = 1:3.97. The prototype outlet works maximum discharge of 29 ft³/s converted to a model discharge of:

$$\frac{29 \text{ ft}^3/\text{s}}{(3.97)^{5/2}} = 0.92 \text{ ft}^3/\text{s}$$

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* Numbers in brackets refer to entries in the bibliography.

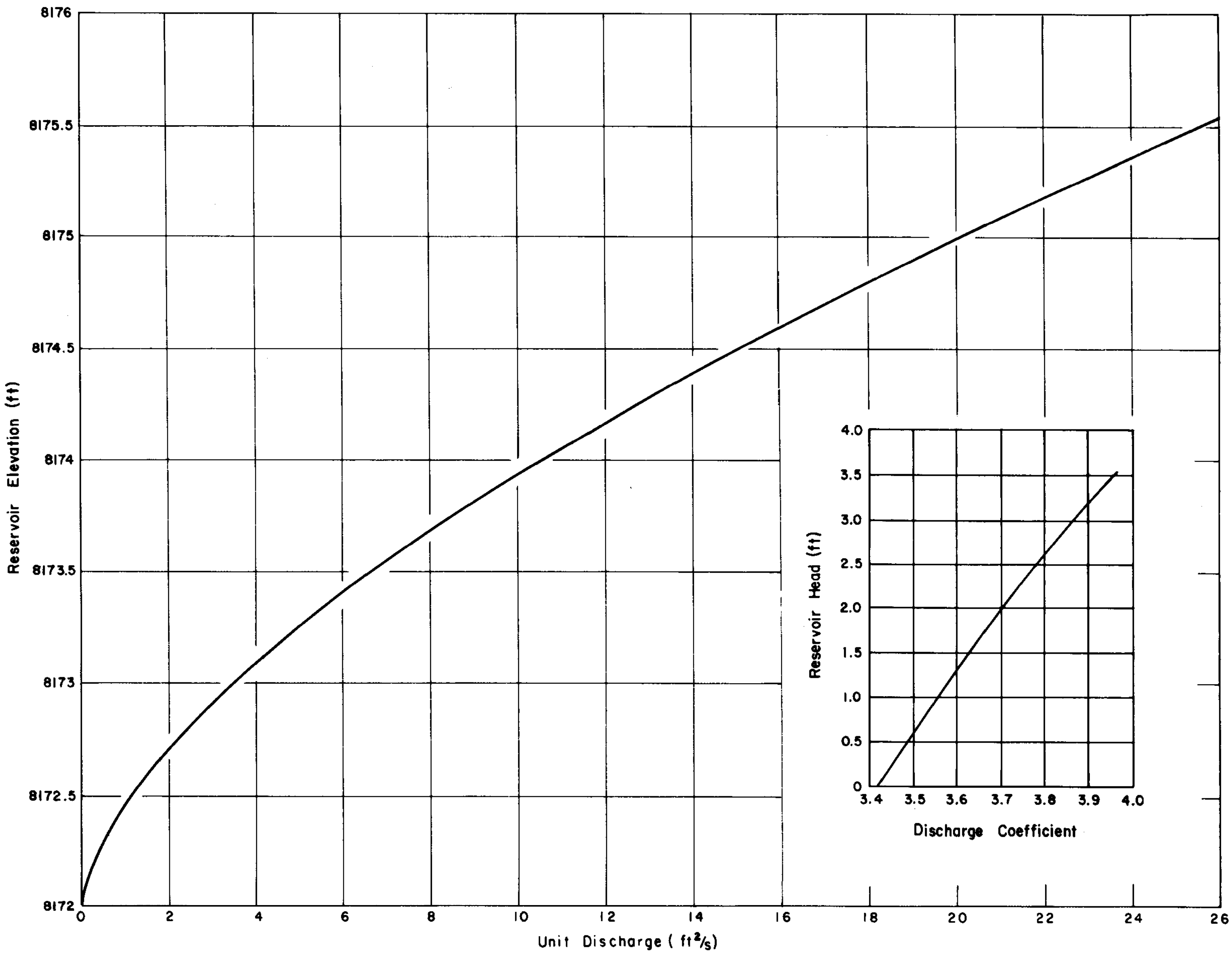


Figure 5. – Discharge and coefficient curves for the final crest design.

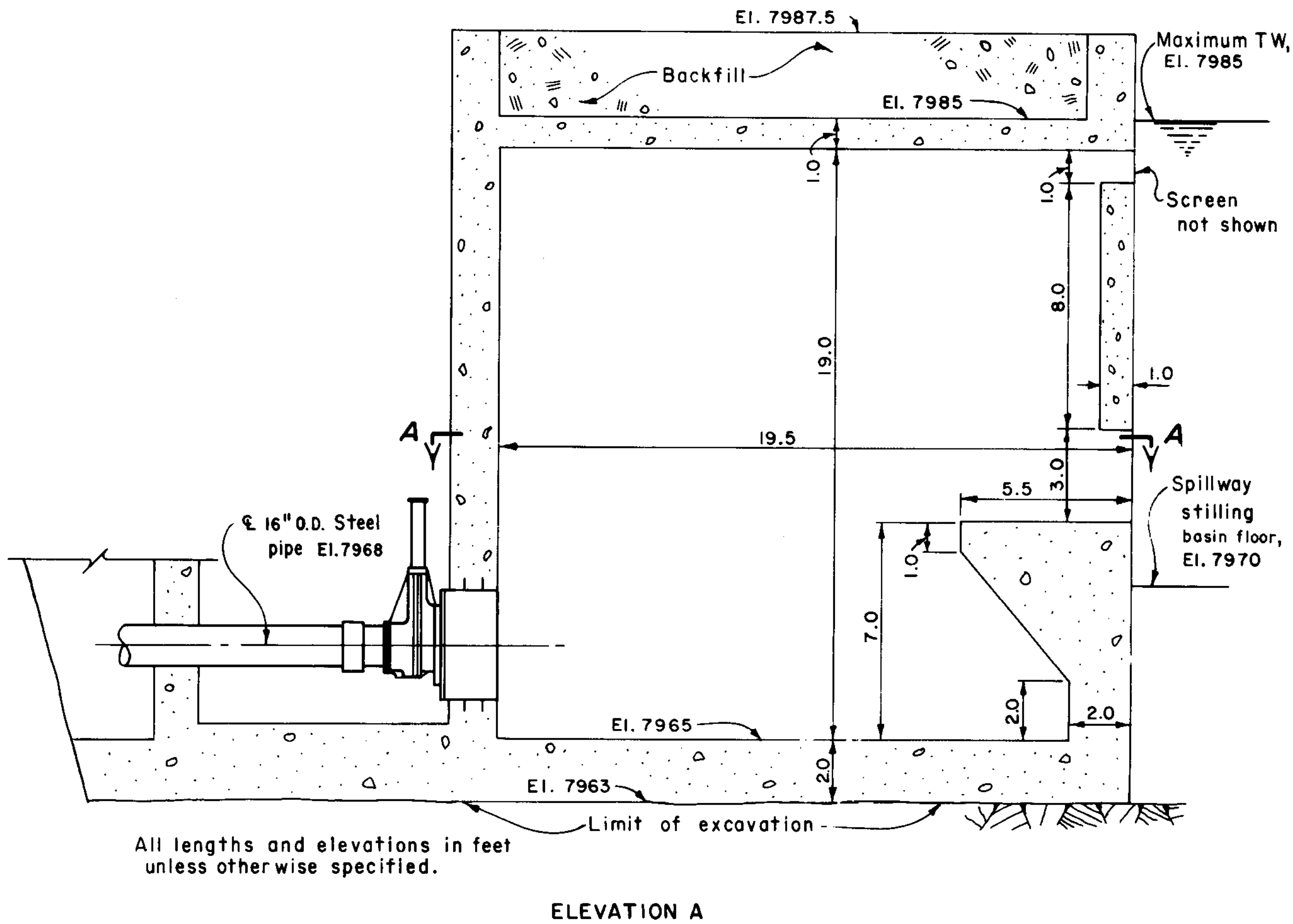


Figure 6a. – Elevation of outlet works jet-flow gate stilling basin.

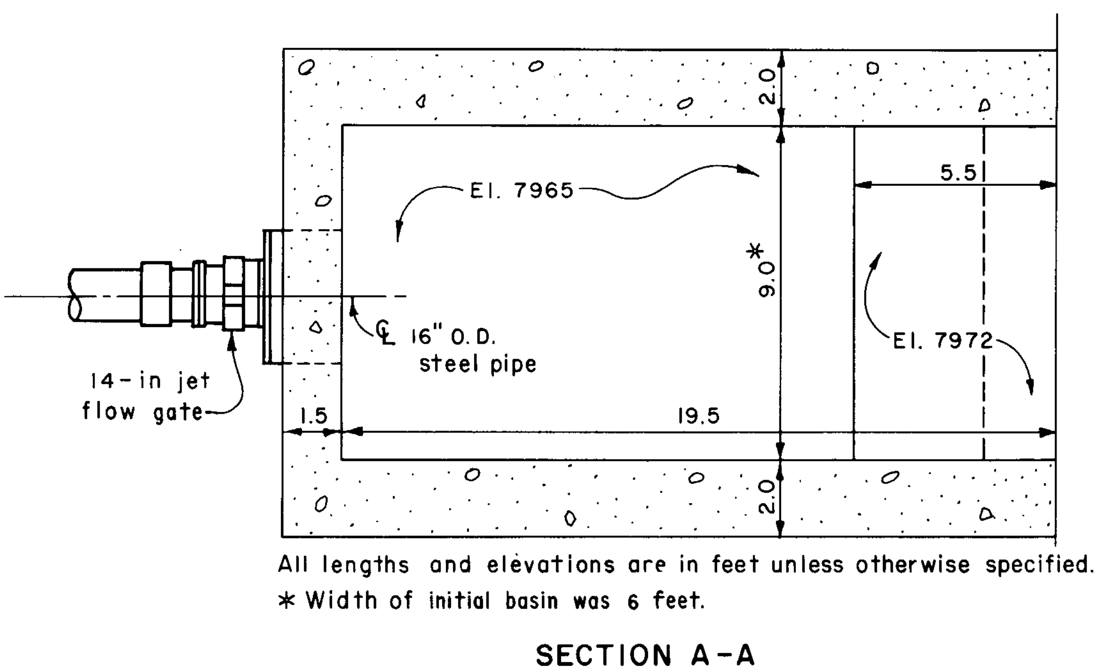


Figure 6b. – Section of outlet works jet-flow gate stilling basin.

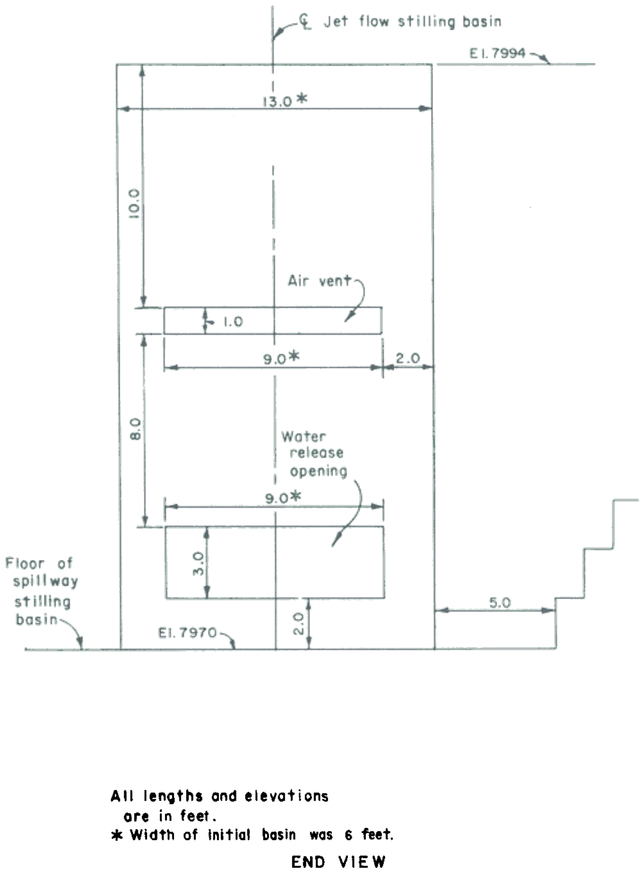


Figure 6c. – End view of outlet works jet-flow gate stilling basin.

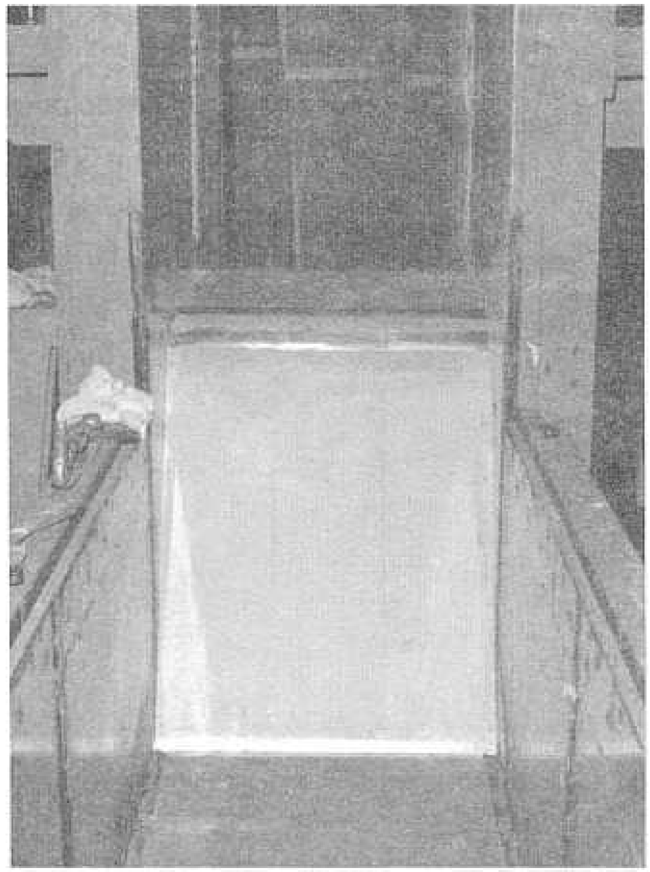


Figure 7. – 2.5-foot-wide flume test facility. P801–D–81086.

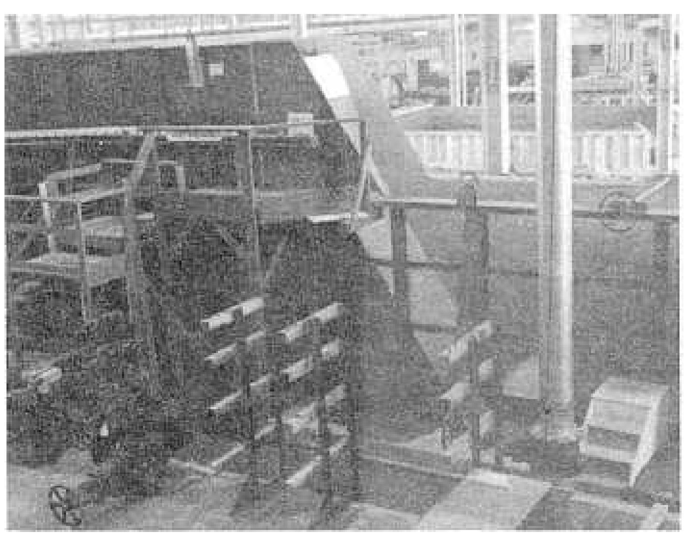


Figure 8. – 4.0-foot-wide flume test facility. P801–D–81087.

Most of the outlet works stilling basin testing was completed using representative discharges of 5, 15, and 29 ft^3/s under reservoir heads of 65.3, 100, 140, and 207.5 feet. The tailwater depths (based upon height above the end sill) ranged from 0 to 3 feet.

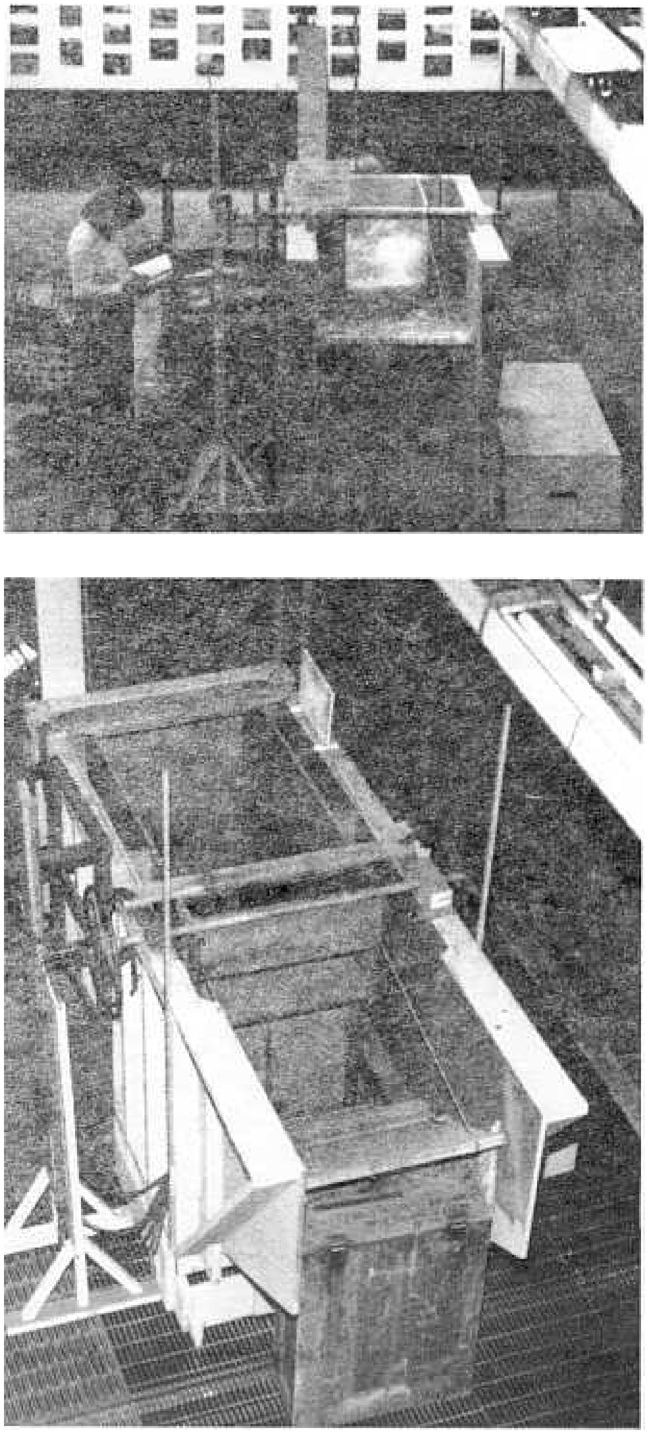


Figure 9. – Two views of the 1:3.97 outlet works model. P801–D–81088 and P801–D–81089.

SPILLWAY INVESTIGATION

Studies were conducted for two different spillway geometries: for a dam having a 15-foot top width and a 0.60:1 sloping downstream face, and for a 30-foot top width and a 0.32:1 sloping downstream face that changed to 0.60:1 at elevation 8100.0 and continued down to the stilling basin (see fig. 10).

The spillway investigation initially consisted of developing an effective crest shape. Three different crest shapes were investigated for the preliminary spillway geometry (fig. 3, crests A, B, and C), and six crest shapes for the final spillway geometry (fig. 15, crests D through G).

The optimum crest shape determined for each spillway geometry was then tested in the 4-foot-wide flume where the full spillway height and 60 feet of the crest length were modeled. These tests determined spillway and stilling basin velocities, water surface profiles and pressures along the spillway face, and stilling basin size.

Preliminary Crest Shapes

Initial design of the dam consisted of a 15-foot top width and a 0.60:1 constant slope on the stepped downstream face. The spillway crest was 700 feet long at elevation 8168.10. The maximum reservoir water surface elevation and discharge were changed

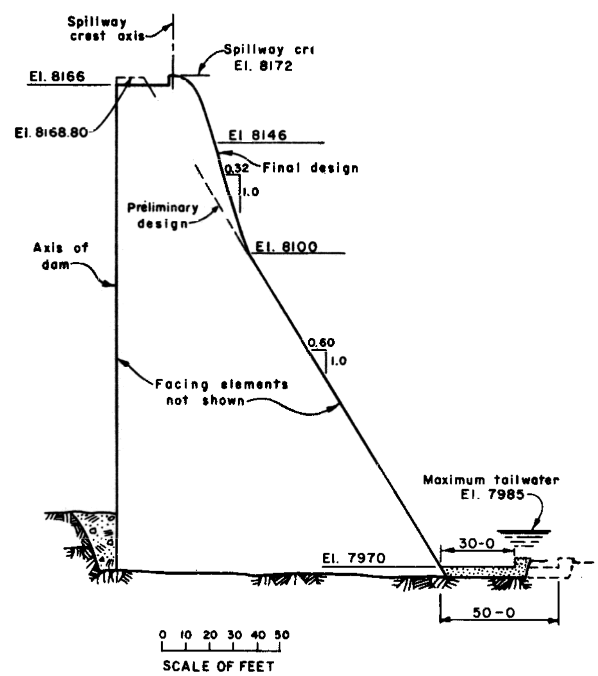


Figure 10. – Section of preliminary and final spillway designs.

during the study to investigate the possibility of decreasing the crest length by increasing the unit discharge. Reservoir elevations and discharges investigated for the initial spillway geometry are listed in table 1.

The 1:5 model scale produced a 12.5-foot crest length for each sectional model installed in the 2.5-foot-wide flume.

Initial testing of the crest A shape (fig. 3) immediately showed that the correct crest shape was critical to producing the desired tumbling action down the steps of the spillway. As for a broad-crested weir, the flow for crest A passed through critical depth near the upstream end of the crest and accelerated toward the downstream face. The jet then flowed over the downstream radius, and impinged on the first step of the spillway face. The jet sprang outward from this step, passing over, rather than tumbling down, the remaining steps (fig. 11). To prevent the jet from leaving the face of the spillway, the trajectory of the jet should be modified to produce a more favorable impingement angle on the stepped face. Figure 3 shows the two alternatives investigated: adding two sloping steps above the existing steps (crest B), and replacing these two steps with just one sloping step (crest C).

For the first modification, crest B, two angled steps were added above the top step of the initial design to change the jet trajectory. The jet still impinged on the first original step, sprang over the next few steps, and did not produce uniform tumbling (fig. 12).

The recommended design for a crest with a 15-foot top width and 0.60:1 sloped downstream stepped face is shown as crest C on figure 3. In this design the top two steps of crest B were replaced by one angled step. This produced uniform tumbling down the spillway steps over the full discharge range. Figure 13 shows the spillway operating at a unit discharge of 40.7 ft²/s. The unit discharge curve for this crest shape is shown on figure 14 and may be used to determine discharges of various crest lengths within the given reservoir head range.

Table 1. – Discharges and heads investigated for the initial spillway geometry.

Reservoir elevation, ft	Head, ft	Total discharge, ft³/s	Unit discharge, ft²/s
8171.84	3.74	14,490	20.70
8171.98	3.88	18,000	25.71
8173.3	5.20	28,490	40.70

Crest Shapes for Final Spillway Geometry. – Based on field observations during construction of the spillway test section, it was determined that the dam top width should be increased to 30 feet. To economically increase the top width, the slope of the dam on the downstream face was steepened to 0.32:1 for the upper 72 feet, intersecting the original 0.60:1 slope at elevation 8100.0. The spillway crest elevation was raised to 8172.0 feet, the crest length decreased to 600 feet, and the maximum reservoir elevation increased to 8176.0 feet. These major design changes required further investigation to determine the optimum crest shape. Various crest shapes were again modeled in the 2.5-foot-wide flume, but with a 1:10 scale to allow observation of flow over more steps. Preliminary designs, crests D through G, are shown on figure 15, and the final design is shown on figure 4.

The initial crest based on the new spillway geometry and discharge requirements is crest D on figure 15.

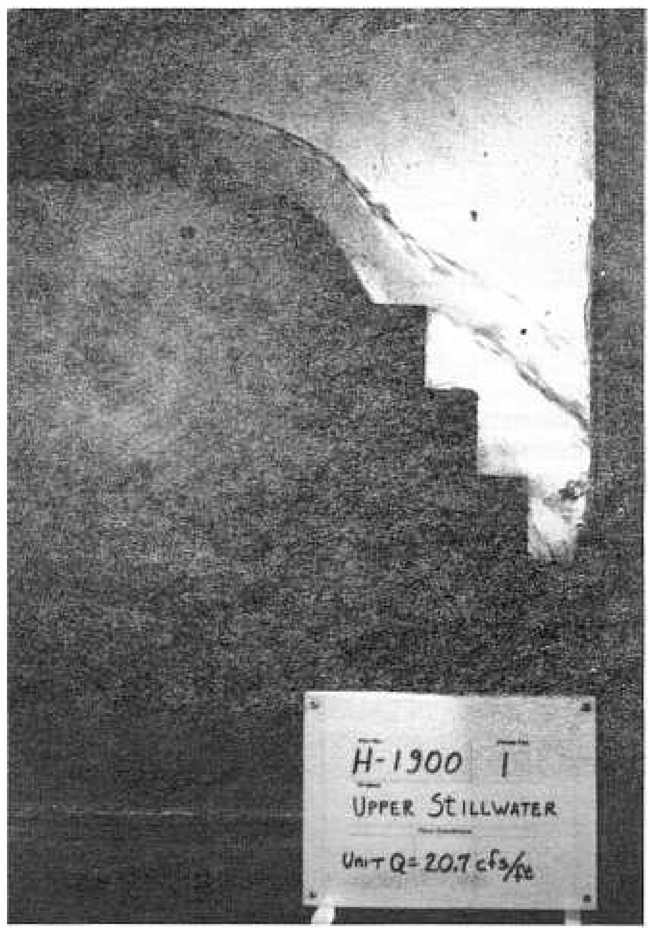


Figure 11. – Flow over crest A. The jet springs off the first step (q = 20.7 ft²/s). P801–D–81090.

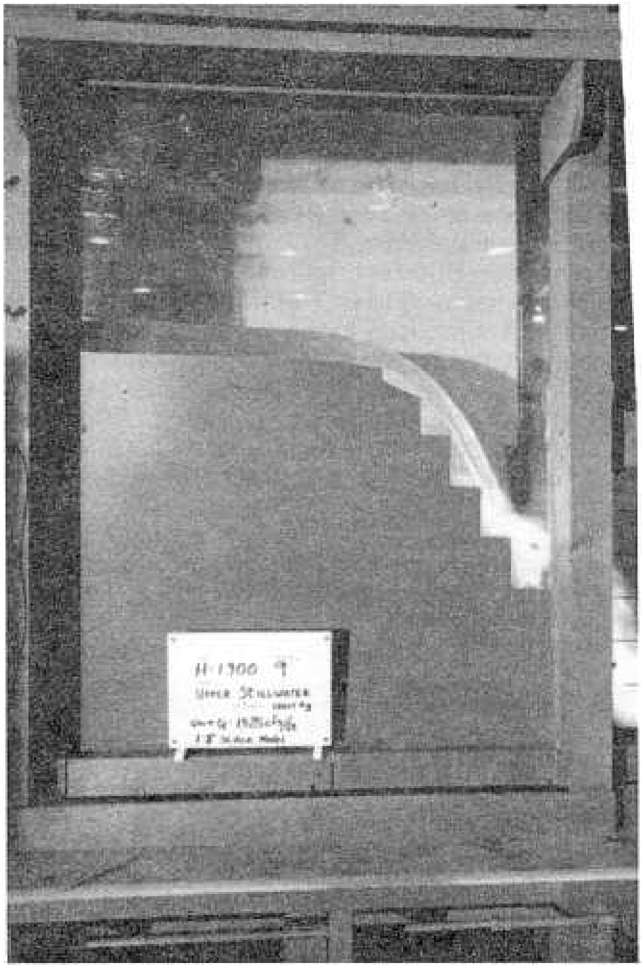


Figure 12. – Flow over crest B (q = 13.25 ft²/s). P801–D–81091.

The downstream end of the 0.01 sloping top width was formed by a radius of 3.88 feet approximated by three chords. Two feet below the downstream radius, the 0.32:1 sloping face began with 0.64-foot-wide by 2-foot-high steps.

The crest D design did not provide satisfactory flow conditions because the flow sprang free below the first crest chord (fig. 16). The design was altered by increasing the downstream crest radius to 5.21 feet and the number of chords to five (fig. 15, crest D). This change did not significantly improve the flow condition, and this design approach was abandoned.

Modified Approach to Crest Design. – With the greater top width (30 feet) and steeper downstream slope (0.32:1), the flow velocity was too great for the jet to cling to the stepped spillway face. Modifications were made to (1) lower the elevation of the approach channel, and (2) approximate the underside of the theoretical nappe shape with the spillway steps. It was thought that increasing the approach

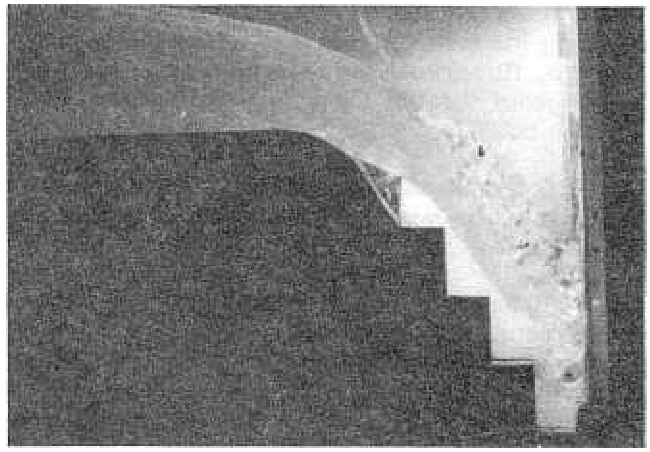


Figure 13. – Flow over preliminary design of crest C (q = 40.7 ft²/s). P801–D–81092.

depth would decrease the flow velocity and that reproducing the theoretical nappe shape with the steps would improve the jet impingement angle and the tumbling down the steps. It was hoped that these changes would provide satisfactory flow conditions down the critical upper portion of the spillway.

The equation for the theoretical nappe shape or crest profile from *Design of Small Dams* [2] is:

$$\frac{y}{H_o} = -K\left(\frac{x}{H_o}\right)^n \qquad (1)$$

where x and y designate points on the curve, H_o = design head = 4.0 feet, and K and n are constants based upon the approach velocity, inclination, and height of the upstream face of the crest and the design head (graphs defining these constants have been developed [2]).

The nappe shape continued down the face of the spillway until intersecting the 0.32:1 slope at elevation 8152.0. The approach channel and intersection points of the steps with the smooth theoretical nappe curve were installed in the 1:10 scale sectional model for continued investigation of crest shapes.

Further Testing of Crest Shapes. – The crest shapes shown on figure 15 were tested with a 4-foot approach channel depth and various step locations in relation to the theoretical nappe shape computed with a design head of 4 feet. The first three crest shapes tested are shown on figure 15 as crests E, E2, and E3.

For the crest E design, the smooth portion downstream from the spillway axis followed the nappe shape. The outside edge of the first step and all successive steps extended into the theoretical nappe

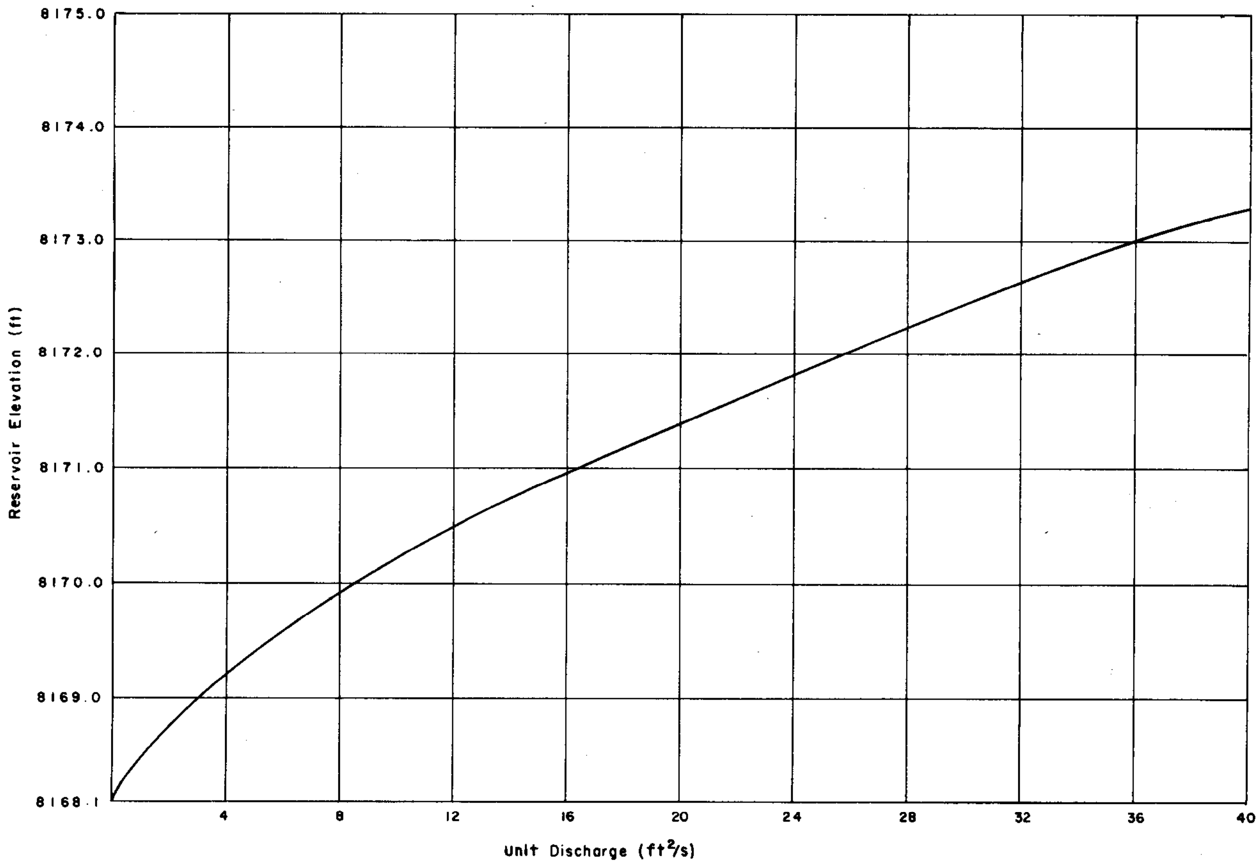


Figure 14. – Discharge curve for preliminary design of crest C.

shape. Flow over this crest was not satisfactory because the jet continued to spring off the first step.

Crest shape E was modified by serrating and angling the first step in 2-foot-wide sections (fig. 15, detail crest E2). Serrating the step improved the flow considerably; however, the jet still did not cling to the steps over the full discharge range (fig. 17). Moreover, the construction cost associated with this design would be prohibitive.

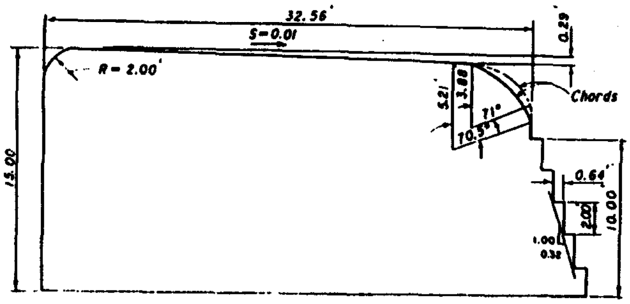
Crest E2 was then modified by removing the serrations from the first step leaving a chord from the top of the crest to the step below (fig. 15, crest E3). Flow over this crest was slightly better than that with the serrated crest. It did not spring free from the crest until about the sixth step, where the nappe-shaped design intersected the 0.32:1 slope.

Uniform tumbling down the steps was not achieved with any of the crest E designs. Therefore, the location of the steps with respect to the nappe shape was changed. The outside edge of the first step on crest F matched the nappe. The remaining steps gradually projected into the nappe shape down the spillway face until intersecting the 0:32:1 slope (fig. 15, crest F). This modification successfully produced uniform tumbling down the spillway face (fig. 18).

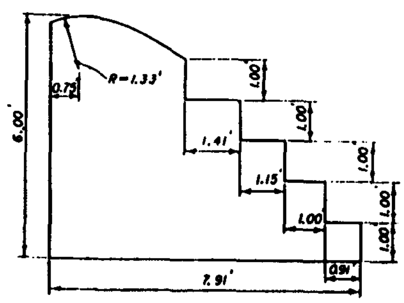
Crest G was tested to determine the feasibility of replacing the steps at the top of the spillway with a solid ogee crest profile. This was accomplished by filling in the area between the outside edges of the steps of crest F (fig. 15, crest G). The crest G shape produced good flow conditions at large flows, but considerable splashing developed at low discharges. This crest shape was rejected for hydraulic reasons – splashing at low discharges. Furthermore, this solid ogee crest would be more expensive to construct.

Final Crest Design

The discharge coefficient was increased by the steeper slope on the downstream spillway face and the lower approach velocities obtained by increasing the approach channel depth. Because of the increased coefficient, maximum discharge was passed at a lower head, allowing a decrease of the final design head to 3.5 feet and of the reservoir elevation to 8175.5. The maximum unit discharge remained at 25.7 ft^2/s. Because previous crest designs produced better flow conditions at higher discharges than low



CREST D

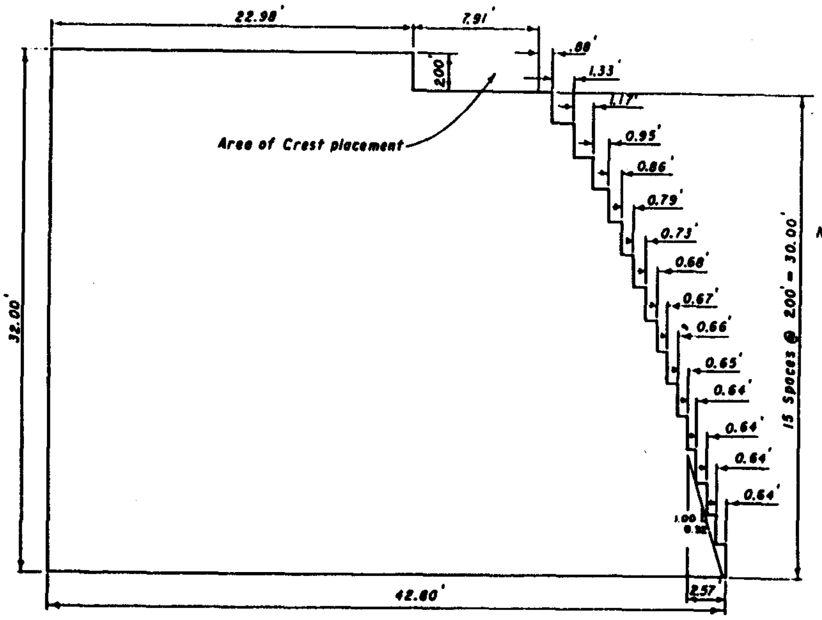


CREST F

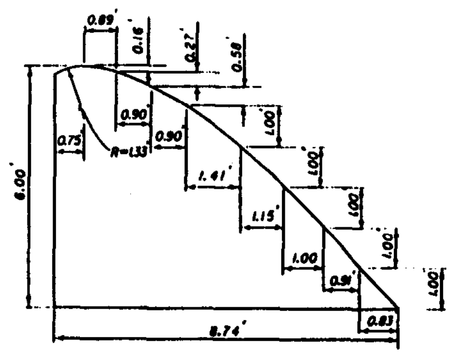
CURVE DATA
CREST F

X	Y
0.42	0.03
0.83	0.11
1.26	0.24
1.67	0.41
2.08	0.62
2.50	0.86
2.72	1.00

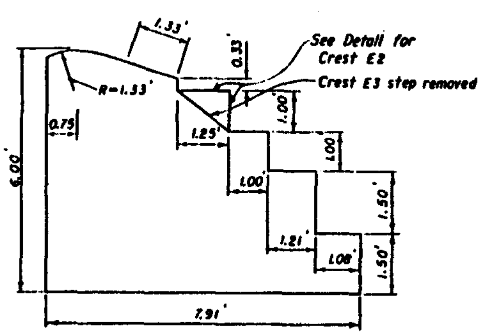
Note: Width of crest 25.0'



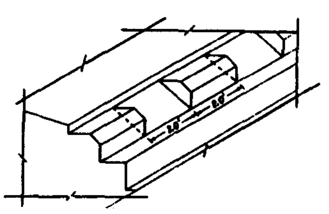
BASE FOR CRESTS E, F, AND G



CREST G



CREST E



DETAIL CREST E2

CURVE DATA
CREST E

X	Y
1.86	0.50
2.71	1.00
3.38	1.50
3.95	2.00
4.46	2.50
4.92	3.00
5.35	3.50
5.75	4.00
6.13	4.50
6.49	5.00
6.83	5.50
7.16	6.00

Figure 15. – Spillway crest shapes tested for final design.

Figure 16. – Flow over crest D. The flow leaves the crest surface below the first chord (q = 25.3 ft^2/s). P801–D–81093.

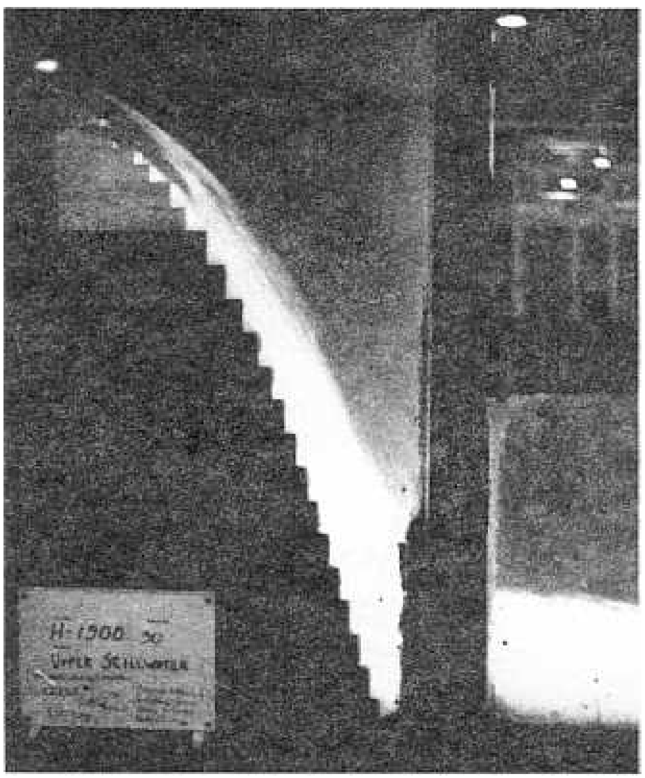


Figure 17. – Flow over crest E2. Serrated and angled step (q = 29.9 ft^2/s). P801–D–81094.

discharges, the theoretical jet trajectory was recomputed using H_o = 3 feet, in the hope of improving low-flow conditions. The approach channel was lowered to elevation 8166.0, 6 feet below the crest.

The final design of the upper portion of the spillway is shown on figure 4. The top of the crest is formed

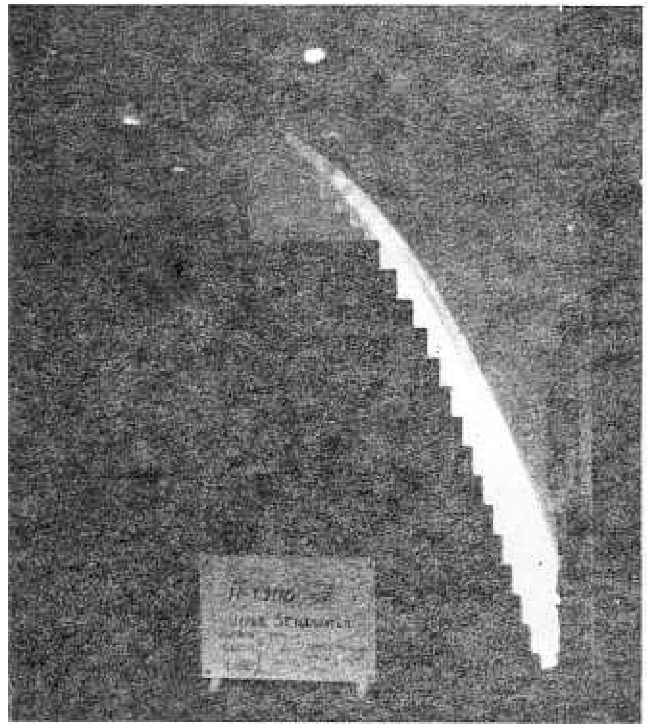


Figure 18. – Flow over Crest F. The steps gradually project into the theoretical nappe shape (q = 20 ft^2/s). P801–D–81095.

by three chords that approximate the nappe shape. The remainder of the crest is formed with 1- and 2-foot-high steps whose horizontal dimensions and locations vary with respect to the nappe shape. The outside edge of the top step matches the theoretical nappe shape. The next steps increasingly protrude into the theoretical nappe shape down to elevation 8162.0, below which the intersections of the risers and treads match the curve. The top six steps have 1-foot-risers, and the next seven have 2-foot-risers, all with varying widths. The slope is 0.32:1 from elevation 8152.0 to 8100.0. From elevation 8100.0 to the stilling basin floor at elevation 7970.0, the slope is 0.60:1 (figs. 4 and 10). This crest design produced uniform tumbling down the steps for all discharges with minor splashing at lower flow rates. The maximum head of 3.5 feet produced a unit discharge of 25.7 ft^2/s, or a total discharge of 15,420 ft^3/s, for the 600-foot crest length. This discharge is shown on the 1:10 scale sectional model of the final crest design (fig. 19). The unit discharge and coefficient curves for the final crest design are shown on figure 5.

Special care must be taken in constructing the top 20 feet of the prototype spillway crest because of the critical nature of the flow in this area. Construction tolerances must be within 1 inch of the specified

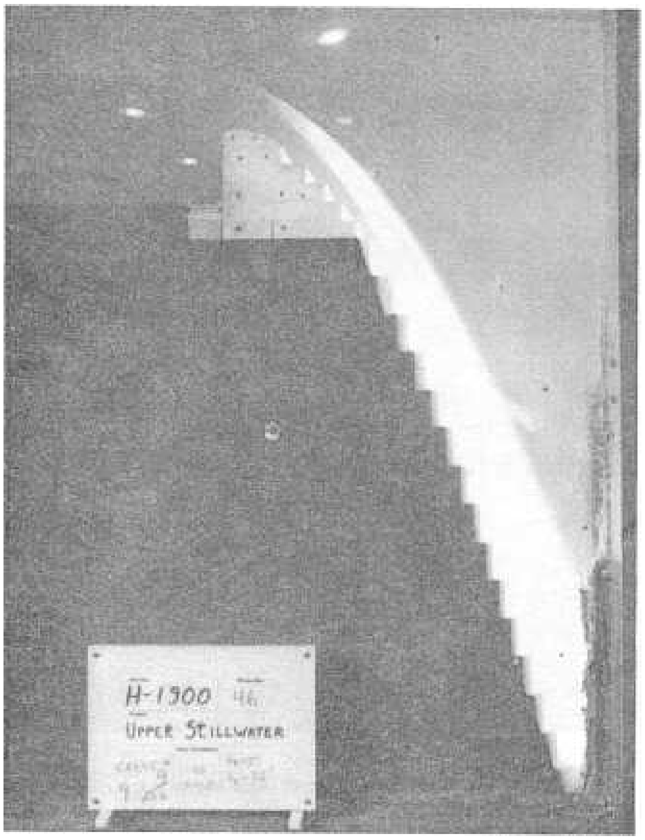


Figure 19. – 1:10 scale model of final crest design operating at maximum unit discharge of 25.7 ft²/s at reservoir elevation 8175.5 feet. P801–D–81096.

dimensions or the jet may spring away from the spillway face. No problems should occur if most of the 600-foot length of each step is within this tolerance.

Spillway Model – Full Height

The recommended crest shape developed by the flume testing was then installed as a 1:15 scale model of the full spillway height (fig. 8). This model included 60 feet of the 600-foot-long spillway crest, the 202-foot-high stepped spillway face, and the stilling basin. The model was used to study the flow down the sloping spillway face and in the stilling basin. Investigations included (1) measuring water surface profiles to determine training wall heights, (2) measuring pressures in impact areas and where subatmospheric pressures were suspected, (3) determining the energy dissipation in the flow caused by the tumbling action induced by the steps, and (4) evaluating the adequacy of the stilling basin. Other details relating to construction problems and public safety were also investigated.

Water Surface Profiles. – Water surface profiles were measured down the entire spillway face. The profiles provided information on the amount of splash from the flow tumbling down the steps and the effect of the abrupt change from 0.32:1 to 0.60:1 in the spillway slope. Tests covered the full range of reservoir operating heads from 0.5 to 3.5 feet. The profiles on figure 20 show that the maximum flow depth occurred at the change in slope. The recommended wall height is 5 feet, measured normal to the spillway slope. This wall height will contain the flow for all discharges except for spray that will occur in the prototype. Gutters should be installed at the downstream toe of the dam adjacent to the spillway to collect the spray runoff.

Spreading of Flow Down the Spillway Face. – The flow path down the spillway face was determined for flows not contained by training walls. The expense of spillway training walls could be avoided if the flow dropped vertically down the face and did not spread out during the fall. Tests were conducted with a 10- and 15-foot-long wall installed along the top of the crest to represent the right side of the spillway entrance (fig. 21). The flow spread from the end of the 10-foot-long wall and impinged on the flume wall at step 29, 52 feet from the top of the crest. The jet from the 15-foot-long wall impinged upon the flume wall at step 40, or 74 feet from the top of the crest. Over the full height of the spillway, elevation 8172.0

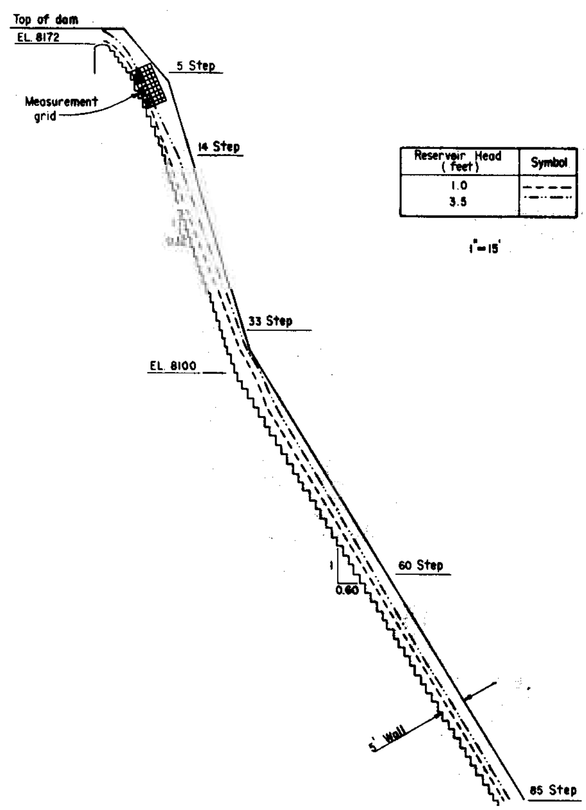


Figure 20. – Water surface profiles along spillway face.

Figure 21. – Flow spreading from parapet installed on top of crest. P801–D–81097.

to 7970.0, a conservative estimate of the spread of flow from each side of the spillway entrance would be 50 feet. Therefore, if flow down the spillway was not contained within training walls, the stilling basin would have to be widened about 50 feet on both sides.

Pressures Along Stepped Spillway Face. – Pressures were measured in both impact and nonimpact areas of the stepped spillway face. Piezometers were placed near the top of the spillway (El. 8170.0); about one-third of the way down the 0.32:1 slope (El. 8151.45); above, at, and below the change in slope (El. 8105.7, 8100.0, 8098.0, and 8094.0); about halfway down the 0.60:1 slope (El. 8048.0 and 8045.0); and at the bottom of the slope (El. 7990.0). These piezometers were numbered 1, 1A, 1B, 2, 3, 4, 5, 5A, and 6A, respectively (fig. 22). Transducers and a strip chart recorder were used to gather the pressure data.

Each piezometer was located in an impact area except No. 3, which was located on the riser (vertical face) of a step. The average pressures represent the median value from the strip chart recorder. For all discharges, the highest pressures were recorded at the abrupt change in spillway slope (El. 8100.0 piezometer, No. 2). The highest average pressure, 9 feet, occurred at maximum discharge.

Comparison of impact pressures down the full spillway height revealed low pressures near the top of the crest, the highest pressures at the change in slope, and a stabilized pressure profile below the change in slope as the flow became more uniformly turbulent and well-aerated. The average nonimpact pressure (piezometer No. 3) for all discharges was slightly above atmospheric with a maximum variance of ±4.5 feet that occurred at maximum discharge. The average pressure for each location is shown on figure 22.

Neither the impact nor the subatmospheric pressures were excessive. The maximum and minimum pressures occurred where the spillway slope changed abruptly from 0.32:1 to 0.60:1. Any damage from the jet impacting the steps would occur in this area; however, none is expected.

Spillway Flow Velocities. – The major benefit of the stepped spillway design is the reduction of the flow velocity, or increased energy dissipation, because of the flow tumbling down the steps. Lower flow velocities allow the stilling basin length to be shortened, thereby saving on construction costs. The velocities along the spillway were measured using two methods – a high-speed movie and a pitot tube.

Velocities at maximum discharge, 15,420 ft^3/s, were measured primarily with a high-speed movie camera. The pitot tube was used only as a spot check to verify the velocities predicted by the movie. Paper squares were inserted into the flow and photographed by a camera that indexed every $1/20$ second. A distance-time relationship that allowed calculation of the velocity was developed from the movie. Operating under low discharges, the steps did not allow the flow to accelerate down the spillway face. At maximum discharge, the jet fell about 10 feet, attaining a velocity of about 30 ft/s, before it became fully turbulent. A higher degree of turbulence was seen at the change in slope; this was also reflected by the pressure measurements. The average velocity down the spillway face was about 35 ft/s. The velocity 25 feet downstream from the slope change increased to about 41 ft/s, where it remained until the jet entered the stilling basin tailwater. [1]

These velocities indicate an energy reduction of about 75 percent over a conventional smooth spillway of the same height. Figure 23 shows the spillway discharging 25.7 ft^3/s. The turbulent flow begins below the crest and increases at the slope change (El. 8100.0). The velocities are site specific; that is, spillways with different unit discharges, fall distances, slopes, and step hights will have different velocities.

Spillway Stilling Basin. – The stilling basin was modeled to determine the velocities in the basin, its required length, and the training wall and end sill heights needed. Shortening the 600-foot-wide stilling basin was the primary objective. This objective

[1] These velocities are slightly higher than those previously reported in the preliminary results. Further analysis of the data gave these higher values.

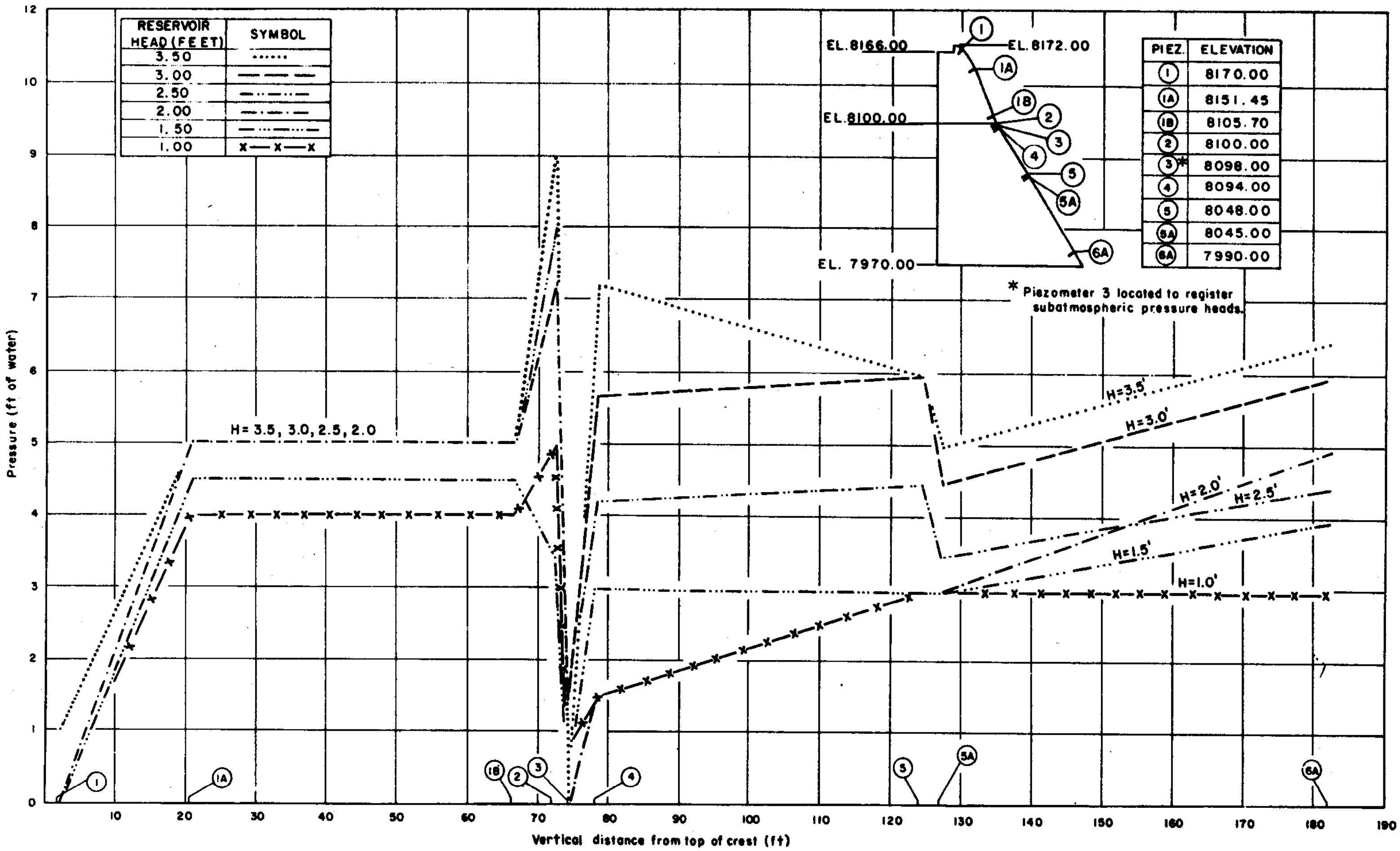


Figure 22. – Locations of piezometer taps along spillway face and average pressures.

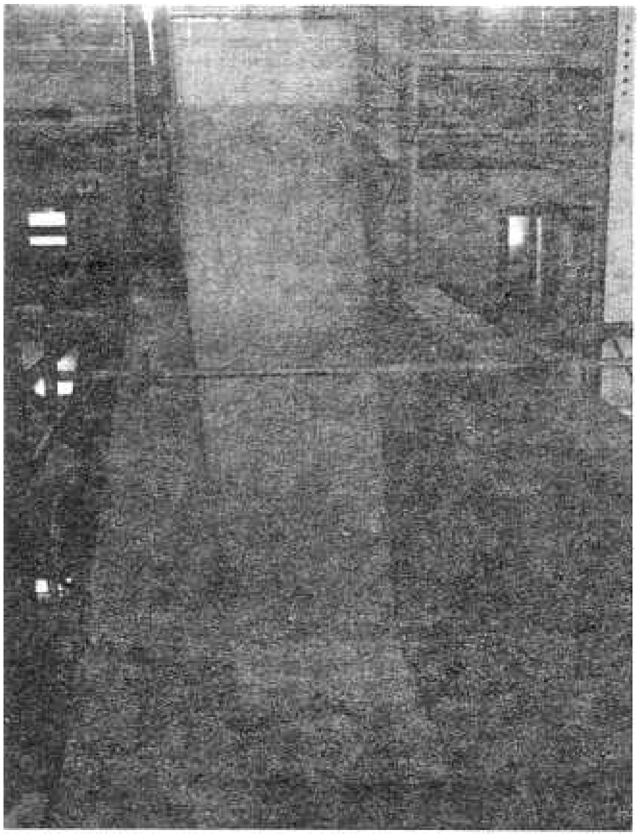


Figure 23. – Flow over full spillway height (q = 25.7 ft²/s). P801–D–81098.

was achieved as a result of the lower flow velocities produced by the stepped spillway design. The initial stilling basin design with invert elevation 7980.0 was 50 feet long with a 2-foot-high end sill. Operation showed that this basin could be shortened considerably because the hydraulic jump occurred in the upstream portion of the basin.

The length of the stilling basin was shortened to 25 feet with the invert at elevation 7970.0 and a 7-foot-high end sill. Tailwater elevations are listed in table 2.

Stilling basin velocities were measured using a pitot tube on the floor. Measurements were taken across the width of the upstream end of the stilling basin for reservoir heads of 0.5 to 3.5 feet at 0.5-foot increments. Velocities ranged from 8.8 to 16.7 ft/s over this head range.

Stilling basin wall heights were determined by the height of the boil formed by the hyudraulic jump. The maximum water surface elevation was 7990.0. The recommended 24-foot wall height, to elevation 7994.0, includes 20 percent additional height for air entrainment and freeboard.

Table 2. – Tailwater elevations for various discharges.

Spillway discharge, (ft^3/s)	Tailwater elevation, ft
0	7975.0
1,000	7976.0
2,000	7977.0
3,000	7977.8
5,000	7979.3
7,000	7980.5
10,000	7982.6
12,000	7983.7
15,000	7985.0

The natural riverbed below the stilling basin end sill will be quite erodible. Therefore, the stilling basin was lengthened to 30 feet even though the hydraulic jump was contained within the 25-foot stilling basin (fig. 24). The final design also included removing the bottom four steps to prevent people from climbing up the spillway face. This had no effect on the stilling basin efficiency. Large cost savings resulted from shortening the 600-foot-wide stilling basin by 20 feet. This 40-percent reduction in stilling basin length was the major benefit of the stepped spillway design.

OUTLET WORKS INVESTIGATION

Outlet Works Jet-Flow Gate and the Stilling Basin

The purpose of this portion of the Upper Stillwater model study was to determine the stilling basin size for submerged releases from a 14-inch jet-flow gate. The model scale, 1:3.97, was chosen to permit use of an existing 3.53-inch model jet-flow gate. The outlet works model was constructed to permit easy modification of the stilling basin width. The centerline of the jet flow gate was at elevation 7968.0.

The primary factors used to determine the basin size were visual observations of the stilling action, impact pressures on the floor and end sill, and water surface profiles. The discharges tested were 5, 15, and 29 ft³/s with reservoir heads of 65.3 (El. 8033.3), 100 (El. 8068.0), 140 (El. 8108.0), and 207.5 feet (El. 8175.5) above the gate centerline. The normal, and maximum, operating condition is a discharge of 29 ft³/s under 207.5 feet of head. Data were collected for tailwater depths to 3 feet above the end sill (El. 7975.0); however, data were frequently taken with only the natural tailwater produced by the end sill. Data taken in this manner produced a conservative evaluation of basin performance. (All tailwater depths are given in terms of the depth above the end sill, fig. 6a.) Other tests included the self-cleaning ability of the basin and its stilling action with the gate fully open. The model is shown on figure 9.

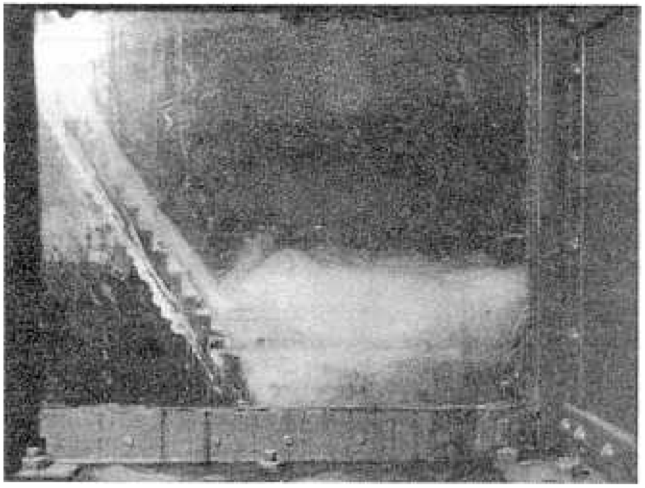


Figure 24. – Spillway stilling basin operation at q = 25.7 ft^2/s and tailwater elevation 7985.0 feet. P801–D–81099.

The model was operated by setting the discharge and closing the jet-flow gate until the pressure associated with the desired reservoir head was obtained. To operate in this manner, it was necessary to calculate the available head immediately upstream of the gate. To determine this operating head, all losses in the system from the outlet works intake to, but not including, the gate were calculated. The discharge equation for operation of a submerged jet-flow gate is:

$$Q = C_D A_o \sqrt{2g(H-h_2-h_L)} \qquad (2)$$

where:

C_D = discharge coefficient,
A_o = orifice area,
H = reservoir head above gate centerline,
h_2 = tailwater depth above gate centerline, and
h_L = head loss though the system down to the gate.

This equation was used to develop the discharge coefficient curve as a function of the percent gate opening [3]. The discharge coefficient for a fully open gate, 0.793, was used to determine the maximum discharge through the gate.

Initial Stilling Basin

The dimensions of the initial stilling basin are shown on figures 6a, 6b, and 6c. The basin was 6 feet wide, 17.5 feet long, and 19 feet high with a 7-foot-high end sill 5.5 feet wide at the top. (The model basin height approximated a prototype height of 13 feet for accessibility.) The centerline of the jet-flow gate was at elevation 7968.0, 3 feet above the basin floor. The tailwater elevations used during these tests were the natural tailwater produced by the end sill and a depth representing 2 feet above the end sill. (The outlet works will probably not be operated during spillway releases.)

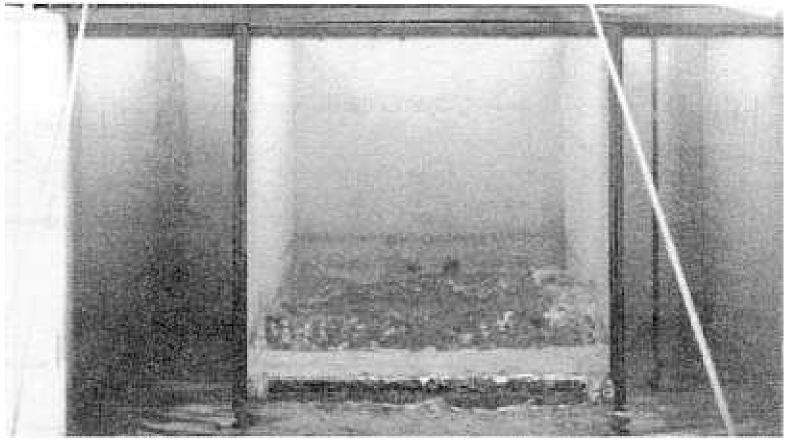
The basin operated with discharges up to 29 ft^3/s under a head of 207.5 feet. Operating conditions were observed over the full range of discharges. This basin configuration provided relatively calm flow downstream of the end sill; however, stilling action inside the basin produced a rough water surface. Stilling basin action is shown on figure 25 for discharges of 5, 15, and 29 ft^3/s under 207.5 feet of head and the tailwater produced by the end sill.

Pressure Measurements. – Pressure measurements were made to locate the impact area and the force of the jet. Pressures were primarily measured using water manometers; then tranducers were installed at locations of high fluctuation or impact. Pressures were measured on the gate centerline along the basin floor and on the impact face of the end sill over the full range of discharges and heads (fig. 26). The pressures were not excessively high, but showed that the jet impacted at the end of the basin, primarily at the base of the end sill. These pressure measurements were taken with the tailwater elevation produced by end sill control. The maximum and minimum pressures recorded were 26.2 and −7.1 feet of head at piezometers 6 and 7, respectively. The maximum pressure occurred with maximum discharge and head, the minimum with 15 ft^3/s and a head of 140 feet. Even though these pressures were not excessive, the basin was widened because of the turbulent water surface and height of the boils in the stilling basin.

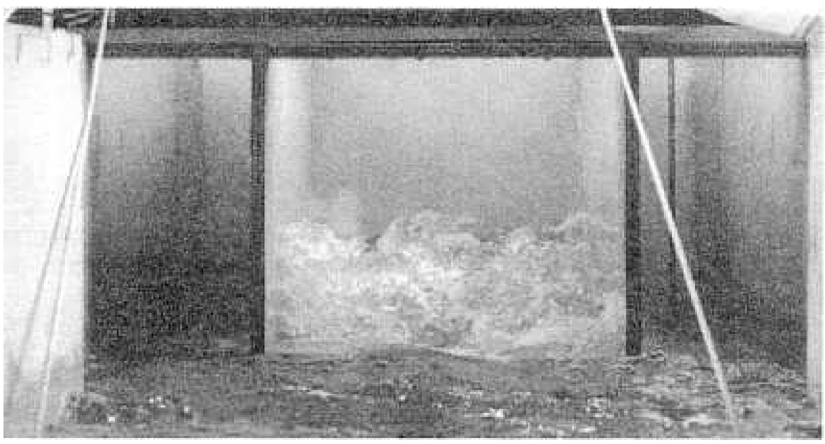
Stilling Basin Final Design

The recommended design of the stilling basin is shown on figure 6. The 9-foot basin width is the only dimension changed from the initial design. Evaluation of this design consisted of visual observation of the stilling basin operation, and pressure and water surface profile measurements. Also tested were the ability of the basin to self-clean (debris tests), and whether a special air vent would be necessary if the basin was entirely enclosed. Tests were made under the same operating criteria as previously outlined. Final testing also included observation of the basin with the jet-flow gate fully open under maximum reservoir elevation 8175.5. This condition produced a discharge of 64.6 ft^3/s with a head upstream of the gate of 59.4 feet. This gate operation could occur with malfunction of the remote control or during reservoir evacuation.

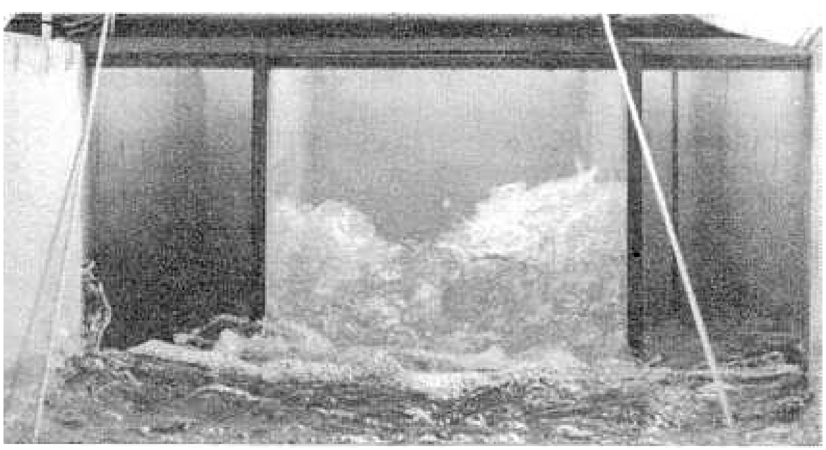
Figure 27 shows the recommended stilling basin operating under reservoir elevation 8175.5 and discharges of 5, 15, and 29 ft^3/s. Figure 28 shows the



(a) Q = 5 ft³/s. P801–D–81100.



(b) Q = 15 ft³/s. P801–D–81101.



(c) Q = 20 ft³/s. P801–D–81102.

Figure 25. – Initial 6-foot-wide jet-flow gate stilling basin at reservoir elevation 8175.5 feet.

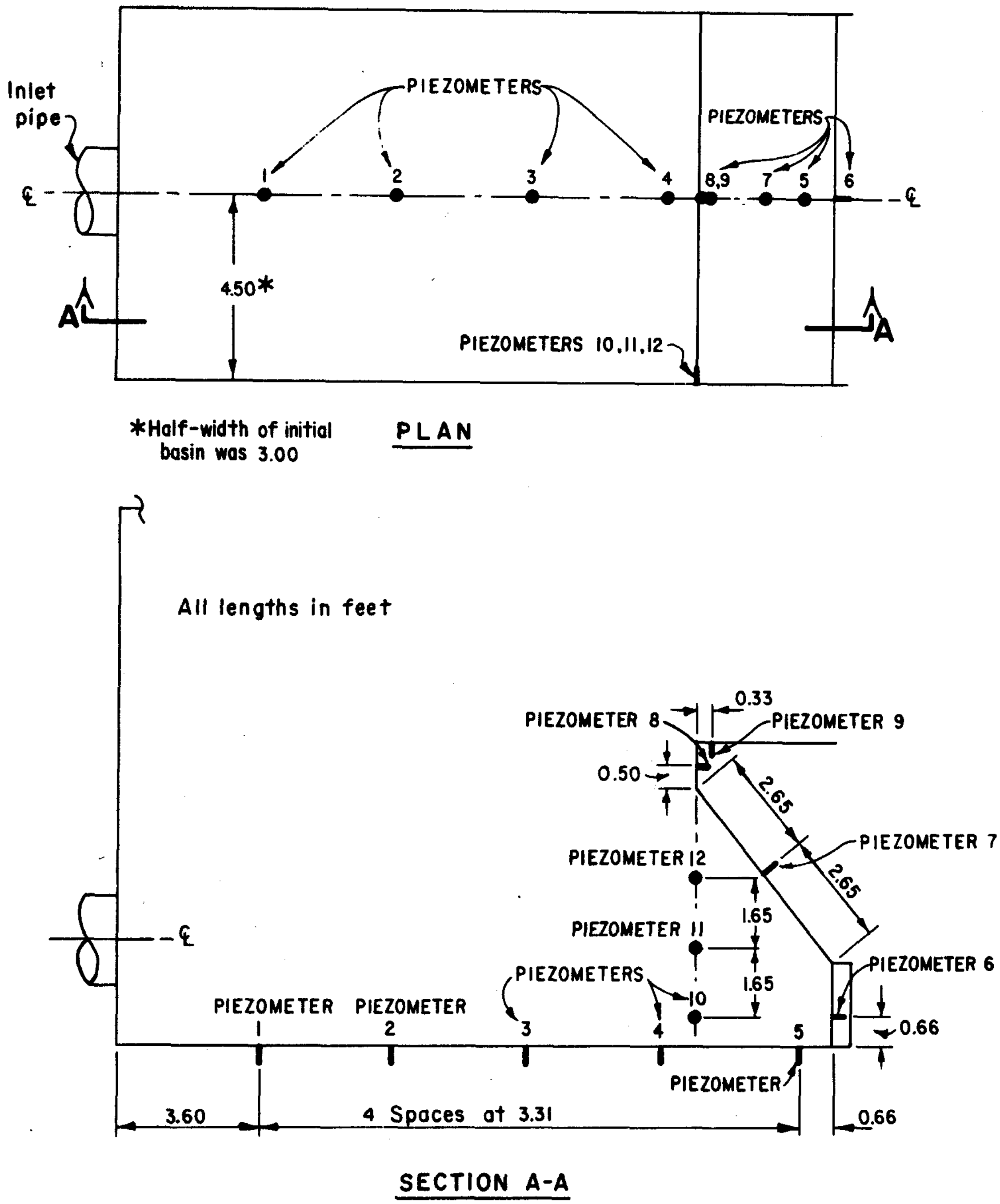
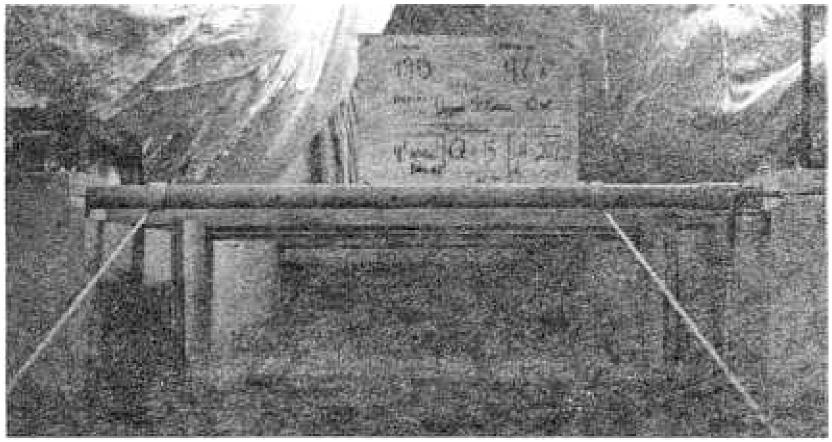


Figure 26. – Piezometer locations for the jet-flow gate stilling basin.

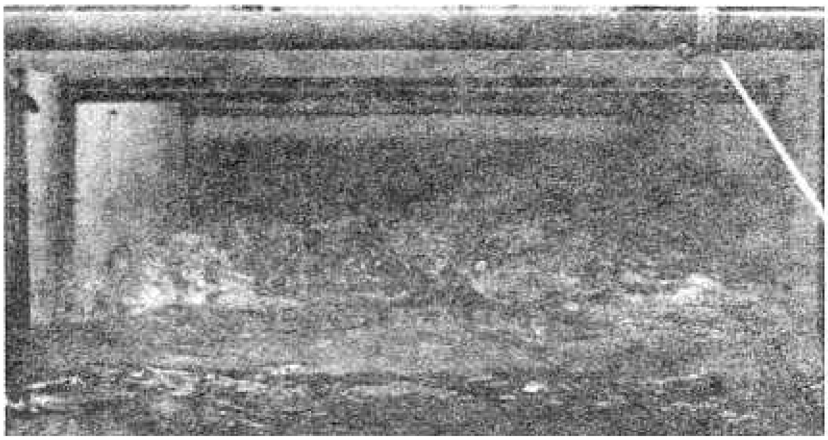
stilling basin flow condition produced by a discharge of 64.6 ft³/s during reservoir evacuation.

Visual Observations. – The water surface roughness in the basin improved considerably by widening the basin to 9 feet. The basin functioned adequately with the lower tailwater produced by end sill control or with a 3-foot tailwater depth. Occasional return flow into the basin occurred with the tailwater produced only by the end sill; with a 3-foot tailwater there was no evidence of return flow. A 3-foot tailwater produced uniform stilling action in the basin and very calm flow downstream of the end sill.

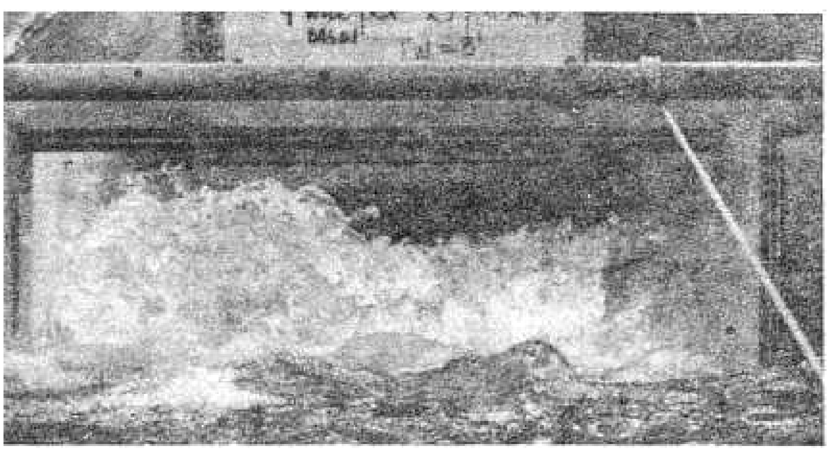
Pressure Measurements. – Pressures were measured at the same locations as for the 6-foot-wide basin (fig. 26) and only for the tailwater produced by end sill control (see table 3). The maximum pressure, 16.20 feet, was again recorded at the base of the end sill (piezometer No. 6) for a discharge of 29 ft³/s



(a) 9-foot-wide jet-flow gate stilling basin (Q = 5 ft³/s, tailwater = 3 ft). P801–D–81103.



(b) 9-foot-wide jet-flow gate stilling basin (Q = 15 ft³/s, tailwater = 3 ft).



(c) 9-foot-wide jet-flow gate stilling basin, (Q = 29 ft³/s, tailwater = 3 ft). P801–D–81105.

Figure 27. – Flow rates for the jet-flow gate stilling basin final design at reservoir elevation 8175.5 feet. P801–D–81104.

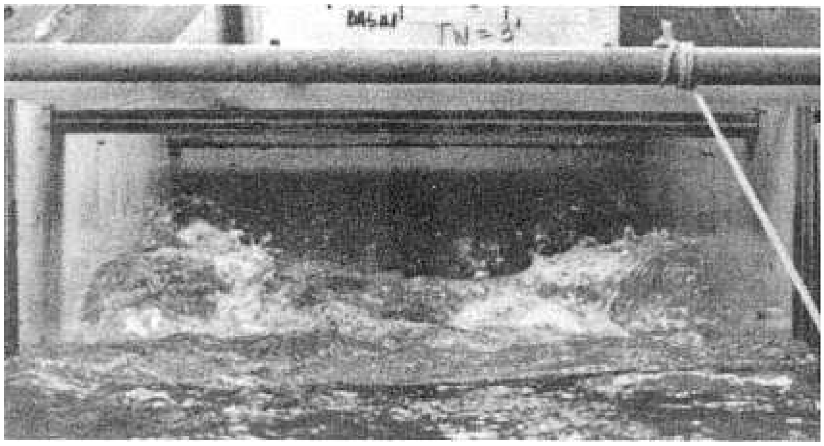


Figure 28. – Fully open gate operation at Q = 64.6 ft³/s. P801–D–81106.

at 207.5 feet of head. The minimum pressure, 0.36 foot, was recorded on top of the end sill (piezometer No. 9) for a discharge of 5 ft³/s.

All pressures increased as the discharge increased. The average pressures along the centerline of the basin floor (piezometers No. 1 to No. 5) ranged from 7.07 to 12.27 feet. The average pressures at the base of the end sill, piezometer No. 6, ranged from 6.55 to 14.21 feet. Piezometers No. 7, 8, and 9, along the sloped upstream face and top of the sill, read the lowest average pressures, ranging from 0.36 to 5.24 feet. Pressures measured on the stilling basin wall (piezometers No. 10, 11, and 12) primarily measured the tailwater elevation. Therefore, pressures measured on the wall near the floor averaged higher than those near the top of the wall and ranged from 3.30 to 8.17 feet.

Water Surface Profiles. – Water surface fluctuations downstream of the jet-flow gate were measured using wave probes located as shown by the 3 by 7 matrix on figure 29. Turbulence and water surface elevations increased with increases in discharge and head. The water surfaces, averaged across the basin and measured from the basin floor, ranged from 9.43 feet at 5 ft³/s and 65.3 feet of head to 10.93 feet at 29 ft³/s and 207.5 feet of head (fig. 30). The maximum difference in water surfaces, 1.63 feet, occurred 8.40 feet from the basin inlet. These data were taken with the tailwater 2 feet above the end sill, the original design tailwater. Subsequent backwater studies indicated the tailwater would be 3 feet (El. 7975.0) above the end sill under normal operating conditions. Increasing the tailwater depth by 1 foot would reduce the turbulence in the basin, but increase the static water level. Therefore, adding 1 foot to the data measured for 2 feet of tailwater would provide a conservative estimate of the water surface.

Debris Tests. – There was a possibility of rocks entering the jet-flow gate basin because of a diversion pipe that intersects the outlet works pipeline upstream. Because rocks in the basin could cause abrasion damage, tests were run to determine whether the basin would self-clean. These tests were done by introducing geometrically scaled rocks, representing ½- to 8-inch sizes, into the basin. Each test was run for 40 minutes, after which the number of rocks remaining in the basin were counted. The results are shown in table 4.

Table 4 shows that although the larger rocks will not be removed by normal operation, almost all of the smaller rocks will. A screened entrance to the diversion pipeline and a basin cover should prevent larger rocks from entering the basin. All small rocks entering the basin should be washed out under normal operating discharge (Q = 29 ft³/s) provided the reservoir head reaches 100 feet occasionally. The basin self-cleans well at higher heads provided the materials entering the basin are not larger than 2 inches. All materials should be removed from the basin after completion of construction.

Basin Aeration. – The basin is covered and has an 8-foot-high end wall located 3 feet above the end sill. The tailwater will close off the 3 feet between the end sill and the end wall and air will enter the basin only through a 1-foot opening between the top of the end wall and the basin cover (figs. 6a and 6c). When the basin was tested with the end wall and cover, no adverse flow conditions were seen. The water surface never reached the elevation of the cover except with occasional splashing, and the 1-foot opening provided adequate aeration.

Fully Open Gate Operation. – Operation with the jet-flow gate fully open at maximum reservoir elevation simulated the worst possible flow condition

Table 3. – Pressure measurements for the outlet works stilling basin.

Piezometer No.		Q = 5 ft³/s, Head, ft 65.3	100	140	207.5	Q = 15 ft³/s, Head, ft 65.3	100	140	207.5	Q = 29 ft³/s, Head, ft 65.3	100	140	207.5
	Min.												8.38
1	Avg.	7.34	7.27	7.23	7.15	8.14	8.14	8.18	8.38	8.34	8.30	9.21	8.97
	Max												10.92
	Min.												7.98
2	Avg.	7.23	7.15	7.11	7.11	7.94	8.06	8.10	8.18	8.18	8.42	8.61	8.61
	Max.												9.57
	Min.												7.46
3	Avg.	7.19	7.15	7.07	7.07	7.78	7.66	7.58	7.54	8.10	7.98	7.58	7.66
	Max.												7.98
	Min.												7.23
4	Avg.	7.19	7.30	7.15	7.15	7.86	7.78	7.70	7.58	6.62	7.94	7.70	7.50
	Max.												7.86
	Min.						8.61	8.46	8.85				10.88
5	Avg.	7.42	6.55	7.38	7.38	8.85	9.37	9.77	10.00	9.57	9.53	11.20	12.27
	Max.						10.08	10.68	11.00				14.53
	Min.						8.46		9.09				11.59
6	Avg.	6.67	6.55	6.55	6.63	8.50	9.21	9.81	10.40	9.61	10.80	12.27	14.21
	Max.						10.00	11.16	12.07				16.20
	Min.												3.93
7	Avg.	3.18	3.41	3.45	3.49	3.73	3.73	3.81	3.69	5.24	4.72	4.13	4.05
	Max.												4.29
	Min.												0.60
8	Avg.	0.87	0.87	0.83	0.83	1.39	1.39	1.31	1.11	1.31	1.23	0.99	0.79
	Max.												1.07
	Min.												0.44
9	Avg.	0.40	0.36	0.36	0.36	1.03	0.99	1.03	0.95	0.79	0.79	0.79	0.83
	Max.												1.19
	Min.												6.83
10	Avg.	6.75	6.75	6.79	6.79	7.54	7.50	7.54	7.66	8.18	7.98	7.86	7.86
	Max.												9.17
	Min.												5.20
11	Avg.	5.08	5.08	5.12	5.08	5.88	5.76	5.88	5.84	6.15	5.96	5.80	5.80
	Max.												6.91
	Min.												3.21
12	Avg.	3.33	3.30	3.33	3.33	4.05	3.77	3.85	3.89	4.37	4.25	3.89	3.65
	Max.												4.37

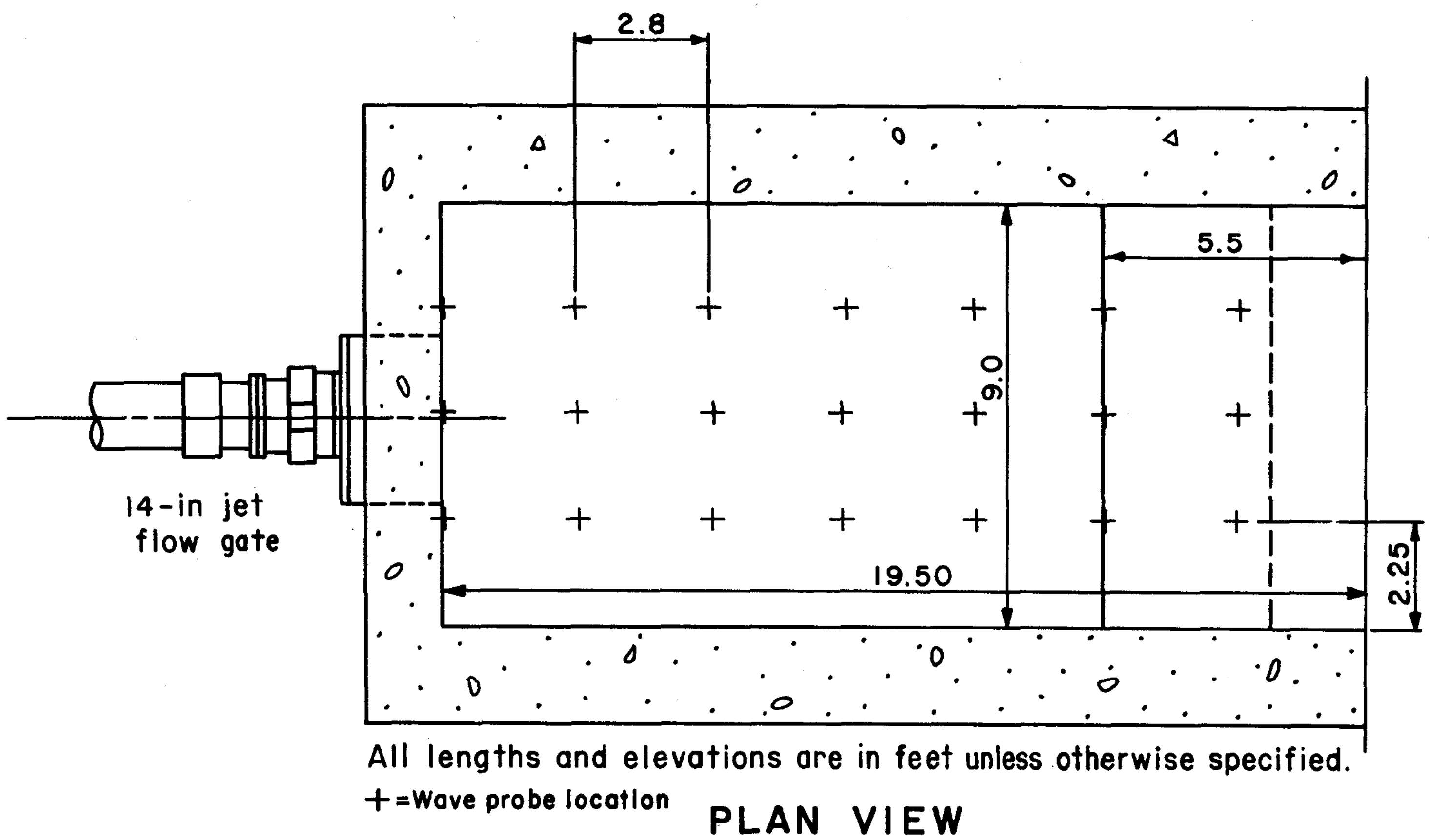


Figure 29. – Locations of wave probes in jet-flow gate stilling basin.

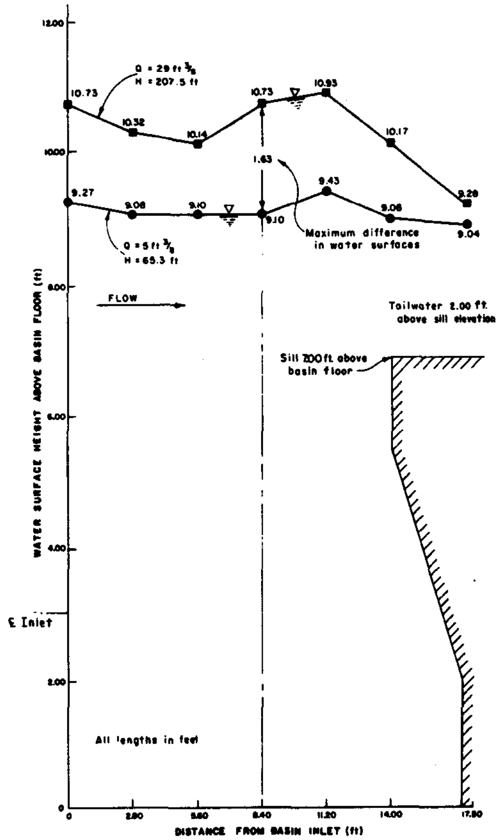


Figure 30. – Maximum and minimum water surface profiles averaged across the width of the jet-flow gate stilling basin.

for the basin. This condition was tested in case the remotely controlled gate should malfunction. With the gate fully open, the discharge was 64.6 ft³/s with the head at the gate 59.4 feet at maximum reservoir elevation. Tests showed that the basin provided the necessary stilling action under this flow condition (fig. 28). The pressure heads measured for fully open operation with a 3-foot tailwater ranged from 2.3 to 22.3 feet at the top and base of the end sill (piezometers 9 and 6, respectively). The maximum and minimum pressure heads occurred at the same locations as when operating under normal flow conditions.

Because these pressures were measured with the lowest possible tailwater, all values are conservative. An increase in tailwater depth should decrease pressure fluctuations, but average pressures may increase by the static head associated with such a higher tailwater.

Table 4. – Debris tests in jet-flow gate stilling basin.

Q, ft³/s	Head, ft	Rock size, inches: 6 to 8	4	2	½ to ¾
		Number of rocks placed in basin			
		5	5	5	10
		Number remaining after operation			
5	207.5	5	5	5	9
15	207.5	5	5	5	5
29	63.5	5	5	5	10
29	100	5	5	5	4
29	140	5	5	2	0
29	207.5	5	3	0	0

Pressures for the 9-foot-wide basin were consistently lower than those for the 6-foot-wide basin. The only exceptions were piezometers No. 6 and 7 for discharges of 5 and 15 ft³/s, where the average pressure heads were slightly higher for the 9-foot-wide basin. Average pressures for the normal operating discharge of 29 ft³/s were all below those for the 6-foot-wide basin. No excessive pressures were recorded. This confirmed the flow observations and indicated that the basin width was adequate and that no concrete erosion should occur as a result of the jet impact.

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[2] *Design of Small Dams,* Bureau of Reclamation, U.S. Government Printing Office, Washington, D.C., pp. 372-375, rev. reprint, 1977.

[3] Colgate, D., *Calibration of a 10-Inch Jet Flow Gate,* Bureau of Reclamation Report No. HYD–569, Denver, CO, February 1969.

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APPENDIX

HYDRAULIC MODEL STUDY OF UPPER STILLWATER DAM SPILLWAY FOR 74,000 ft^3/s DISCHARGE

(Based on the memorandum of May 30, 1986, from Eugene R. Zeigler to Chief, Hydraulics Branch)

APPENDIX CONTENTS

TABLE

FIGURES

ACKNOWLEDGMENTS

The model study was supervised by Thomas Rhone, Head of the Hydraulic Structures Section. Kathleen Houston designed the model and started model testing. The model study was done for the Concrete Dams Branch with coordination by the principal designer, Alan Richardson. Photographs were taken by Wayne Lambert.

INTRODUCTION

Previously, a hydraulic model study was made of the Upper Stillwater Dam spillway for a maximum discharge of 15,000 ft^3/s. A stepped spillway design was developed, whereby considerable energy was dissipated as the water cascaded down the spillway steps, resulting in an economical stilling basin. Construction of the dam with this spillway design started in 1982, and the placement of concrete began in 1985. However, the probable maximum flood has been revised upward and the maximum spillway discharge has been changed to 74,000 ft^3/s. Thus, another hydraulic model study was made to check the adequacy of the original spillway design and to determine whether modifications are necessary to safely pass the new 74,000-ft^3/s maximum discharge.

CONCLUSIONS

1. To pass the 74,000-ft^3/s discharge, 9.8 feet of head is needed above the spillway crest.

2. The spillway entrance corners should be streamlined to prevent flow separation and the springing free of flow from the spillway steps. An elliptical shape is recommended (6-ft minor axis aligned with the face of the dam and 12-ft major axis aligned with the spillway training wall).

3. Negative pressures occur on the downstream corner of the spillway steps, but the negative pressure is not great enough to cause cavitation.

4. The addition of two intermediate steps improved the spillway flow. One step at elevation 8170.5 inhibited flow from springing free at very low discharges. The second step at elevation 8165.0 prevented flow from springing free at high discharges during the model spillway entrance tests.

5. With the 74,000-ft^3/s discharge, the spillway training walls of the original design will be overtopped.

6. Action of the stilling basin at high discharges was radically different than for the original 15,000-ft^3/s discharge. The action was similar to a solid bucket energy dissipator. Flow came off the spillway, moved across the stilling basin floor, hit the end sill, and deflected upward in a turbulent boil. Although the basin action was violent, no changes are recommended in the basin geometry because the energy was effectively dissipated.

7. Flow from the turbulent boil acts downward on the channel downstream from the stilling basin. One hundred feet downstream from the end sill the velocity is relatively mild (4 ft/s, 3 ft above the bed). However, since the immediate channel downstream from the stilling basin is rock, no channel bed protection is required.

THE MODEL

Spillway dimensions were obtained from specification drawings 66–D–2091 and 66–D–2093, and a 1:15 scale sectional model was constructed in a 4-foot-wide flume. The model discharges were measured using Venturi meters of the permanent laboratory piping system. During the spillway discharge tests, the model water surface elevation was measured 4 feet upstream from the spillway crest. Water surface elevation downstream from the stilling basin was controlled by a flap gate on the flume floor and the basin tailwater set according to figure A-1.

SPILLWAY DISCHARGE

Tests were made to obtain the discharge rating curve for the spillway (fig. A-2). The graph ordinate of figure A-2 was given as total head above the crest instead of the usual reservoir elevation, in case the spillway crest elevation is changed. A total head of 9.8 feet above the crest is required to pass the new 74,000-ft^3/s discharge. This is 6.4 feet more than the 3.4 feet required for the initial design discharge of 15,000 ft^3/s.

FLOW DOWN THE SPILLWAY

The spillway handled flows up to the 75,000-ft^3/s discharge. However, at higher discharges the flow appearance suggested that the energy dissipation efficiency of the stepped spillway had decreased. With increased discharge, the water traveled farther down the spillway steps before breaking into a well-aerated turbulent flow (figs. A-3a to 3d). A closer view of the change to well-aerated flow is shown on figure A-4.

Pressure measurements were made on several of the spillway steps. The piezometer taps were located as near as possible to the corner of the step because of flow conditions observed relative to the step (fig. A-5). The intent was to locate piezometer taps in the areas of maximum and minimum pressures. Electronic instrumentation was used to record pressure fluctuations sensed by the piezometer taps (fig. A-6). Results of the measurements are given in table A-1 – positive pressure for the piezometer tap of the horizontal step surface and negative pressure for the piezometer tap of the vertical surface. The negative pressures are not great enough to induce cavitation.

Some characteristics about the spillway flow are implied by the variation of piezometric head (fig. A-7). The water flows down from the spillway crest increasing in velocity; positive head increases from the step at elevation 8164.0 to the step at 8130.0. From the step at elevation 8130.0 down to elevation 7992.0, there is not a significant increase of velocity – no appreciable increase of positive head. The highest positive head measured was at the step at elevation 8092.0, and part of this head was caused by the impact of flow on the flatter slope of the spillway. The spillway slope changes at elevation 8100.0 (fig. A-8).

Measuring the water surface profile along the spillway was difficult. The water surface was not smooth and steady, but had irregularities and spray (figs. A-3d and A-4d). Some judgement was used to obtain the water surface profiles shown on figure A-8. The intent was for the water surface profile to represent the higher surges but not the highest movement of spray. To contain the flow down the spillway from figure A-8, training wall heights would have to be a minimum of 6 feet on the 0.32:1 slope and 7 feet on the 0.60:1 slope.

The spillway crest shape was designed for a 3.0-foot head. Thus, with higher heads, negative pressures occurred along the surface downstream from the crest. During the first part of the model study, the spillway flow would occasionally spring free from the crest and impinge on the spillway about 100 feet (prototype distance) lower (figs. A-8 and A-9). Considerable splashing occurred at the point of impact (fig. A-9c). The pressure measured near the point of impact was not as high anticipated (table A-1 and fig. A-7).

Upon close inspection, air was observed entering the flow by the crest through the side of the model. When the areas of air leakage were plugged, the flow adhered to the spillway and did not spring free from the spillway crest.

Further observations were made of air in the negative pressure areas of the spillway at the 75,000-ft^3/s discharge. Air was introduced through a ¾-inch tube to various steps below the spillway. Air would fill the area of some steps (the area on fig. A-5 indicated by the note "Circulation of water within step") and spread laterally across the spillway. After the tube was removed, the air was flushed away by the flow. However, when air was introduced to the first step downstream from the spillway crest, the flow would immediately spring free from the spillway crest, and the reservoir water surface would rise 0.67 feet (prototype distance). Thus, it is crucial to prevent aeration near the spillway crest.

THE SPILLWAY ENTRANCE

A modification to simulate the spillway entrance was constructed in the sectional model (fig. A-10a). To simulate flow conditions, the width of the model dam and spillway were proportional to those of the prototype. When making tests, the model discharge was set by water depth above the crest (fig. A-2).

The initial entrance corner of the spillway had a 1.5-foot radius (fig. A-10b), and for the 15,000-ft^3/s discharge, the entrance corner had a negligible affect (fig. A-11a). However, for the 75,000-ft^3/s discharge, the 1.5-foot entrance corner produced considerable turbulence by the spillway side wall (left side of fig. A-11b). An intermittent vortex occurred near the side wall. Air would enter the vortex from 1 to 3 feet below the model crest, the air core would rapidly move up to the model crest, and then the vortex would dissipate. At times the vortex air core would supply air to the negative pressure zone of the spillway steps, and the spillway flow would spring free from the step at elevation 8164.0. Operation of the spillway would flush the air away in about a minute and the spillway flow would re-attach against the steps. Moreover, when air entered the vortex core, the vortex could expand, and centrifugal force propelled the flow away from the spillway (fig. A-12).

The undesirable turbulence and vortex action were caused by flow separation from the entrance corner (fig. A-13a). Streamlining the corner with an elliptical shape prevented excessive flow separation and produced better flow down the spillway (figs. A-13b and A-11c). The vortex action did not occur; air did not enter the spillway steps and allow the flow to spring free. Thus, an ellipse is recommended for the entrance corner, with the 12-foot major axis aligned with the spillway side and the 6-foot minor axis aligned with the face of the dam (fig. A-10b). The importance of the streamlining modification is to prevent air from entering immediately downstream of the spillway crest and causing the flow to spring free at the spillway crest.

ADDITIONAL SPILLWAY STEPS

During the spillway entrance tests, more attention was given to instances when the flow would spring free from the spillway steps. At 1,000- to 4,000-ft^3/s discharge, flow would spring free from the step at elevation 8170.0. An intermediate step 6 inches high and 8 inches wide was placed on the existing step at elevation 8170.0. This reduced the tendency for the flow to spring free. At high discharges and with the 1.5-foot radius entrance corner, the flow would spring free from the step at elevation 8164.0. An intermediate step 12 inches high and 7.5 inches wide placed on the step at elevation 8164.0 prevented the flow from springing free. Both intermediate steps (fig. A-14) were also tried with the 4-foot-wide sectional model and improved flow down the spillway steps.

THE STILLING BASIN

The stilling basin was tested over the full range of discharges (fig. A-15). For the original design discharge of 15,000 ft^3/s, the water entered the basin at the toe of the spillway and the energy was dissipated entirely within the basin (fig. A-15a). For higher discharges, the high-velocity flow came off the spillway, moved across the bottom of the basin to the end sill, and was deflected upward making a turbulent boil on the water surface (figs. A-15b, A-15c, and A-15d and figs. A-3b, A-3c, and A-3d). As the discharge increased, the turbulent boil was more pronounced. For the 75,000-ft^3/s discharge, the turbulent boil oscillated, sending waves downstream. The basin functioned somewhat like a solid-bucket stilling basin, where the water circulates in a roller type motion (fig. A-16). Energy of the entering flow is dissipated by the two rollers.

Pressure measurements were made where the flow impacts upon the stilling basin floor and end sill (fig. A-17 "Location of piezometer taps in stilling basin"). Results of the measurements are given as average, high pulses, and maximum pressures (figs. A-6 and A-17). The information can be used to review forces acting on the stilling basin.

Pressures were also measured downstream from the stilling basin, fig. A-18. The average pressure and pressure fluctuations (range of head) did not appear high enough to endanger the rock topography downstream from the stilling basin. However, intensity of the flow currents could remove erodible material downstream from the basin (fig. A-15d). Velocities were measured in the model with a propeller meter. Sixty feet downstream from the end sill, the velocity was 9 ft/s at 6 feet above the bed. One hundred feet downstream, the velocity varied from 4 ft/s at 3 feet above the bed to 5.8 ft/s at 23 feet above the bed. Stilling basin turbulence was nearly dissipated 100 feet downstream from the end sill (on fig. A-19 the right edge of right side glass panel is 110 ft downstream from end sill).

Table A-1. – Pressure measurements on the spillway steps, Q = 75,000 ft³/s.

Step elevation, ft	Average: Piezometric head, ft	Average: Pressure, lb/in²	High pulses: Piezometric head, ft	High pulses: Pressure, lb/in²
		Positive pressures		
7992.0	10.5	4.6	13.5	5.8
8022.0	10.5	4.6	13.5	5.8
8060.0	9.8	4.2	12.0	5.2
8064.0	9.0	3.9	12.0	5.2
8068.0	9.0	3.9	12.0	5.2
8092.0	15.0	6.5	22.5	9.8
8104.0	12.0	5.3	18.0	7.8
8130.0	12.0	5.3	15.0	6.5
8148.0	7.5	3.2	10.5	4.6
8158.0	6.0	2.6	9.8	4.2
8164.0	2.2	1.0	4.5	2.0
		Flow springing free from spillway crest and impinging on spillway steps		
8060.0	30.0	13.0	–	–
8064.0	33.0	14.3	55.0	24.0
8068.0	24.0	10.4	–	–
		Subatmospheric pressures		
7992.0	0	0	−0.5	−0.2
8022.0	−1.8	−0.8	−2.2	−1.0
8064.0	−1.5	−0.6	−1.8	−0.8
8092.0	−3.0	−1.3	−5.2	−2.2
8104.0	−3.0	−1.3	−7.5	−3.2
8130.0	−6.8	−3.0	−9.8	−4.2
8148.0	−3.8	−1.6	−6.8	−3.0
8158.0	−4.5	−2.0	−6.8	−3.0
8164.0	−9.0	−3.9	−12.0	−5.2

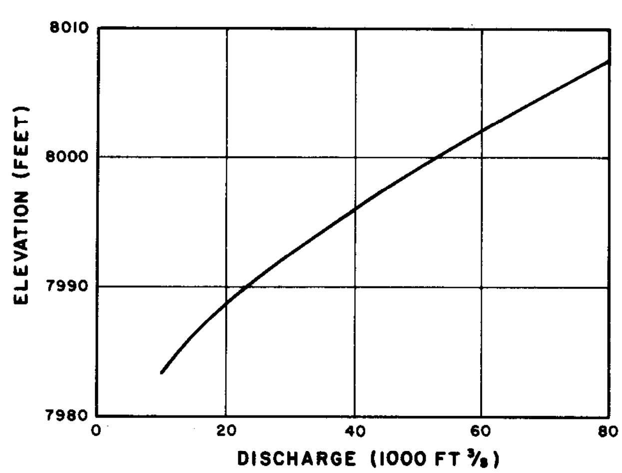


Figure A-1. – Tailwater elevation curve.

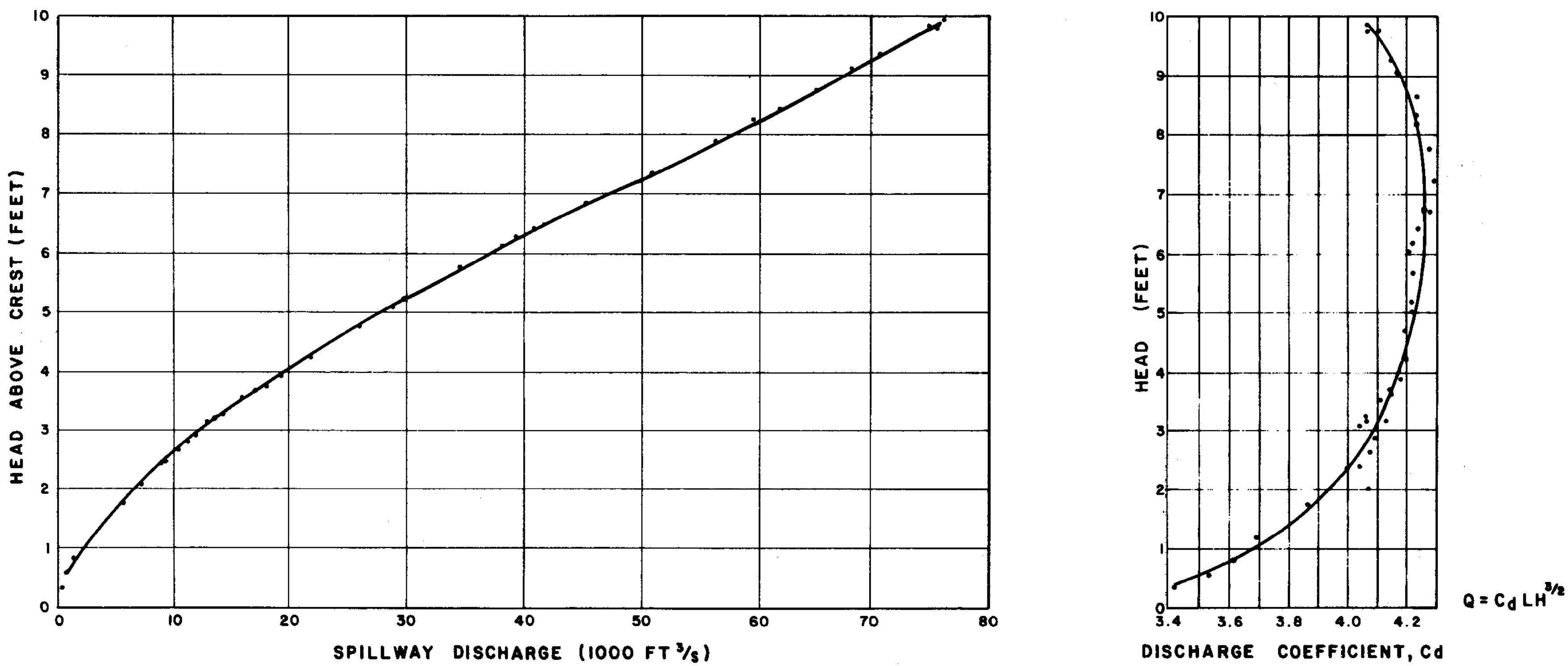
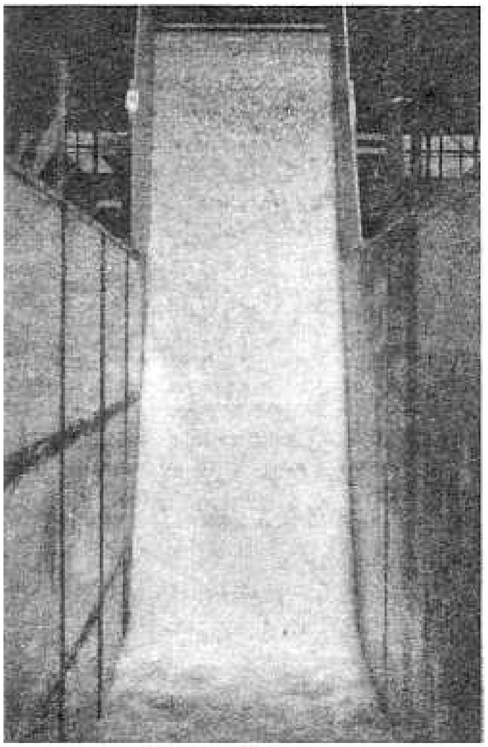
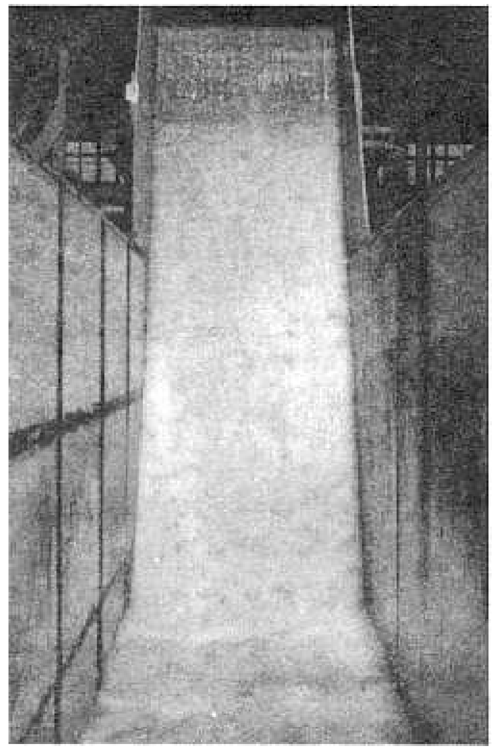


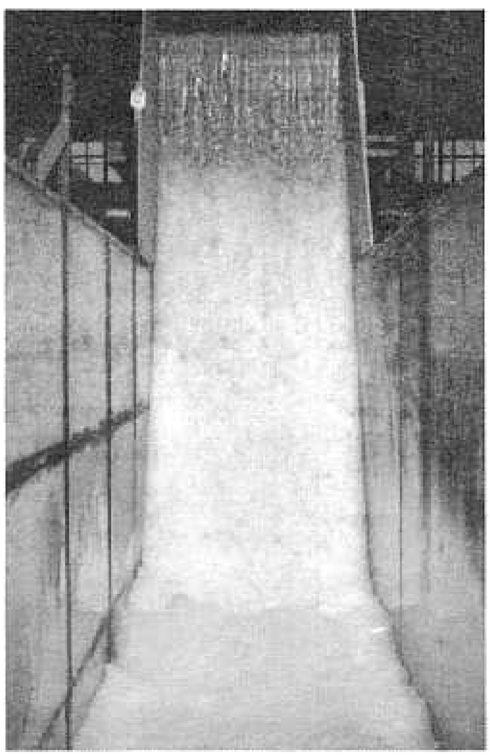
Figure A-2. – Spillway discharge rating curve.



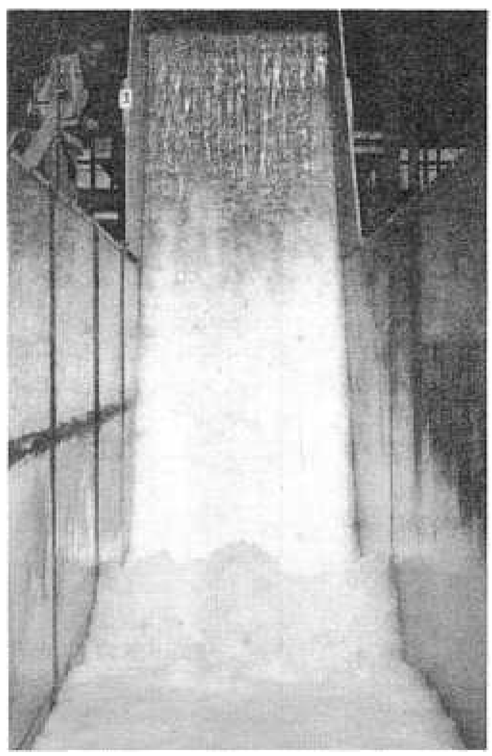
(a) 15,000 ft^3/s. P801–D–81107.



(b) 30,000 ft^3/s. P801–D–81108.

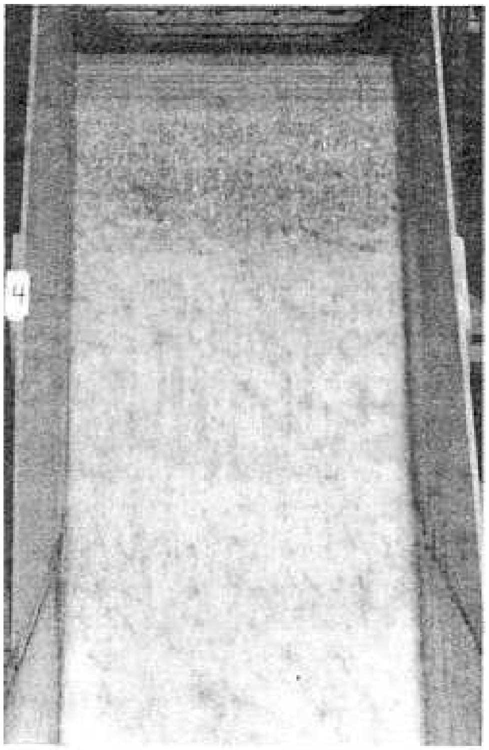


(c) 50,000 ft^3/s. P801–D–81109.

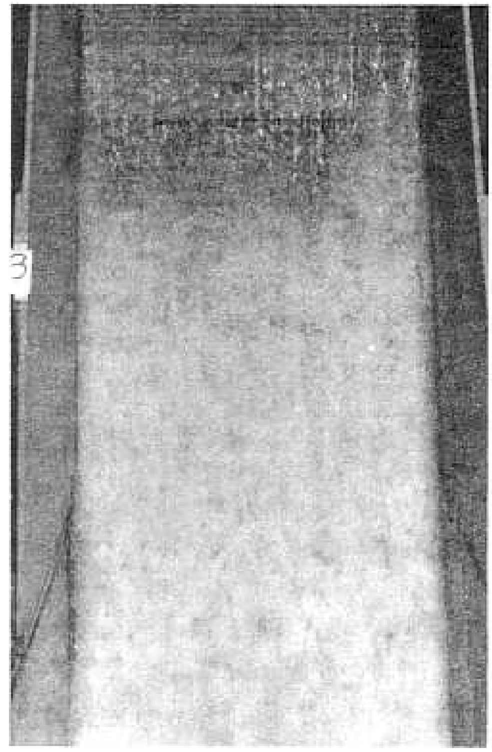


(d) 75,000 ft^3/s. P801–D–81110.

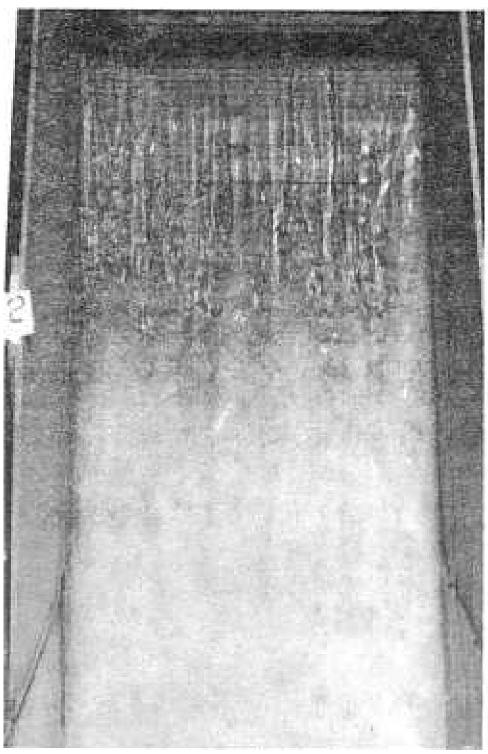
Figure A-3. – Flow down the spillway.



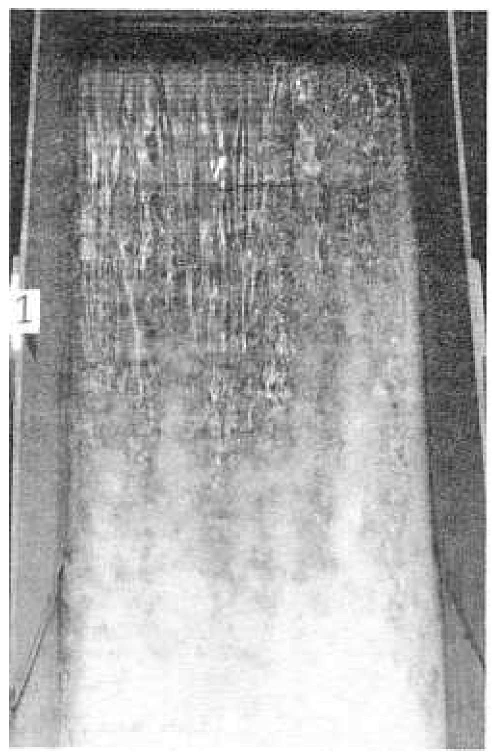
(a) 15,000 ft³/s. P801–D–81111.



(b) 30,000 ft³/s. P801–D–81112.

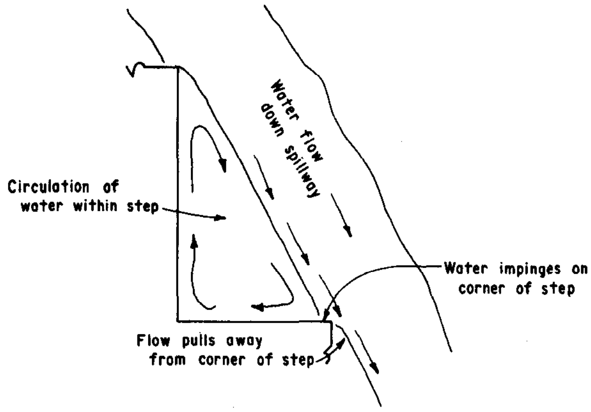


(c) 50,000 ft³/s. P801–D–81113.

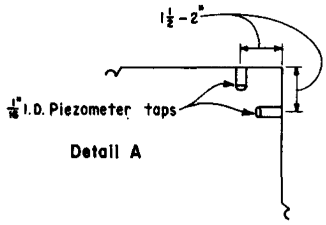


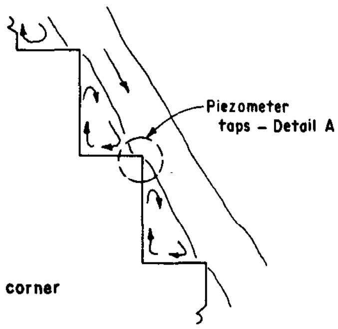
(d) 75,000 ft³/s. P801–D–81114.

Figure A-4. – Flow down from the spillway crest.



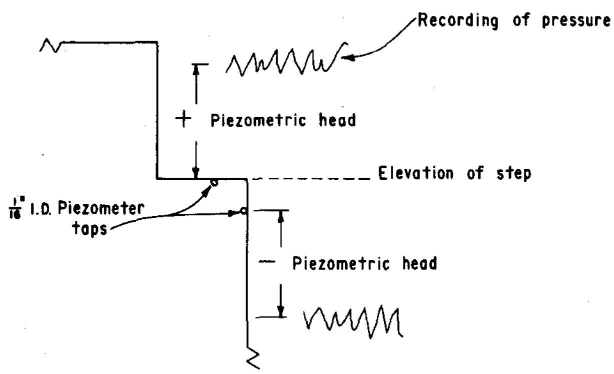
(a) View of flow over spillway step as seen through glass side wall of the 4-foot flume.



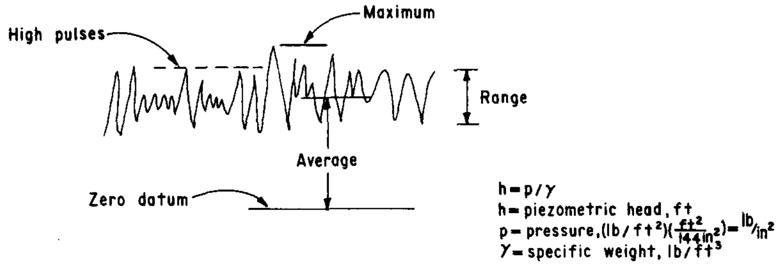


(b) Location of piezometer taps from corner of step (prototype distance).

Figure A-5. – Spillway flow with respect to piezometer taps.



(a) Piezometric head measurement with respect to step elevation.



(b) Manner of analyzing pressure recording.

Figure A-6. – Example of piezometric head measurement.

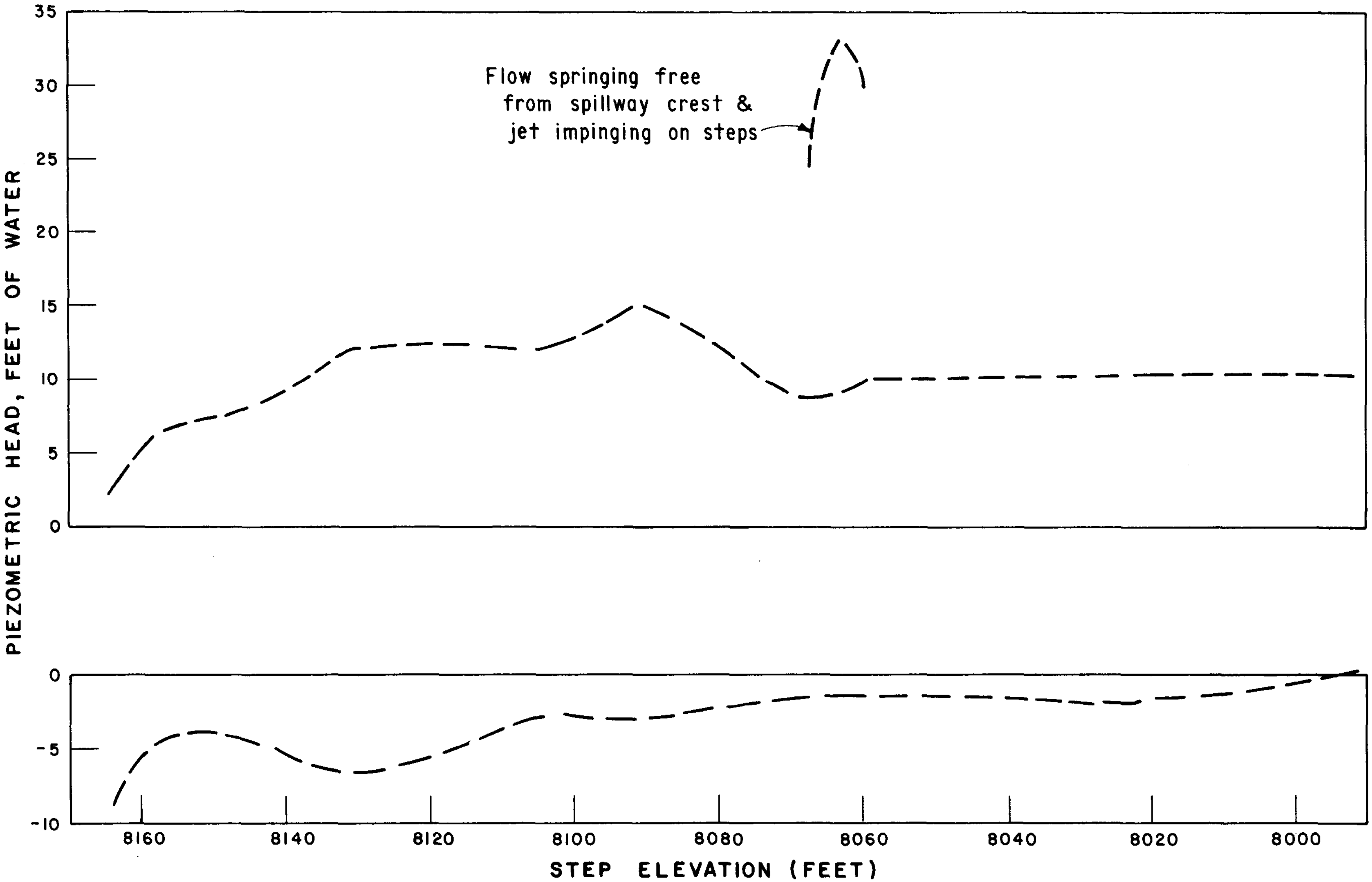


Figure A-7. – Piezometric head on spillway steps.

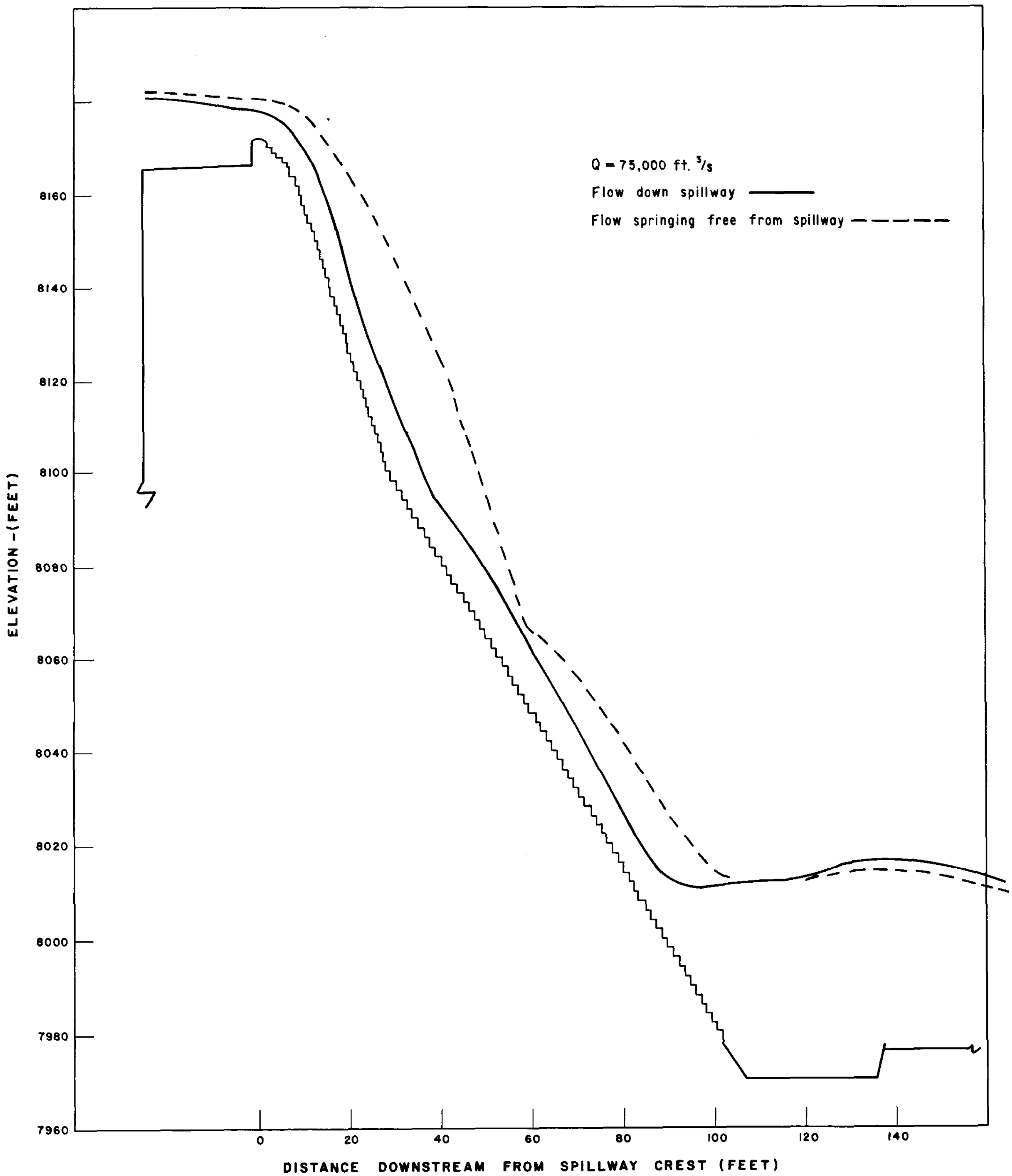
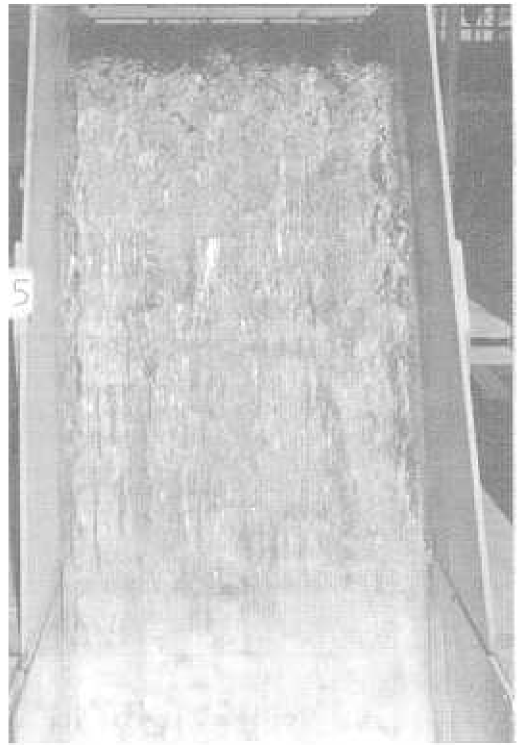
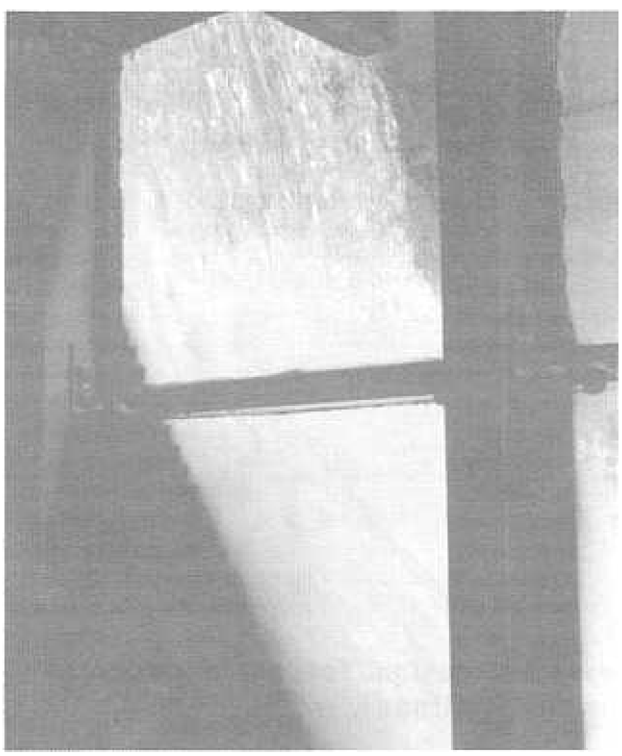


Figure A-8. – Water surface profile for spillway and stilling basin.

(a) Flow down spillway. P801–D–8115.

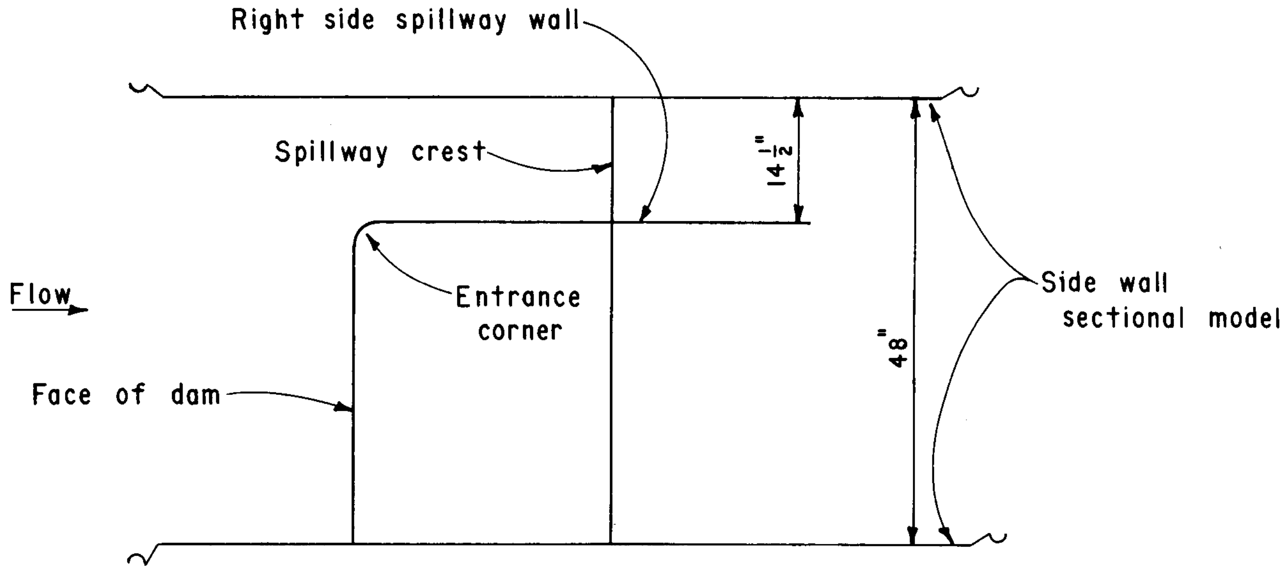


(b) Flow from spillway crest. P801–D–81116.

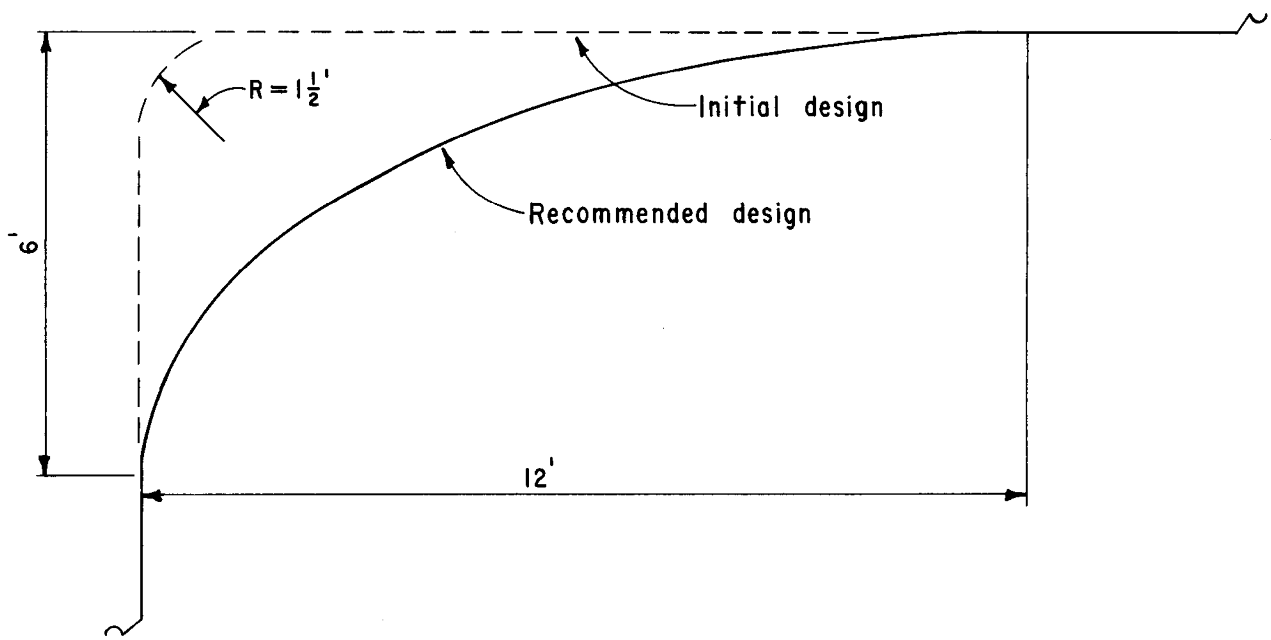


(c) Flow impinging upon spillway. P801–D–81117.

Figure A-9. – Flow springing free from spillway crest, Q = 75,000 ft^3/s.

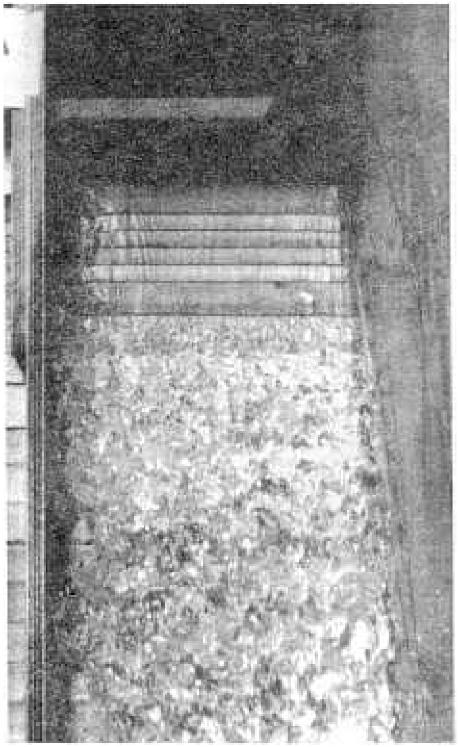


(a) Spillway entrance modification to sectional model. (model dimensions).

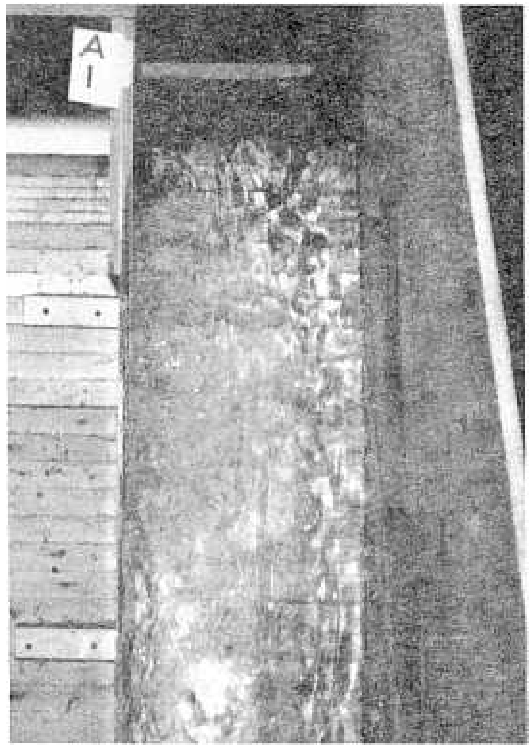


(b) Recommended design for entrance corner (prototype dimensions - ellipse).

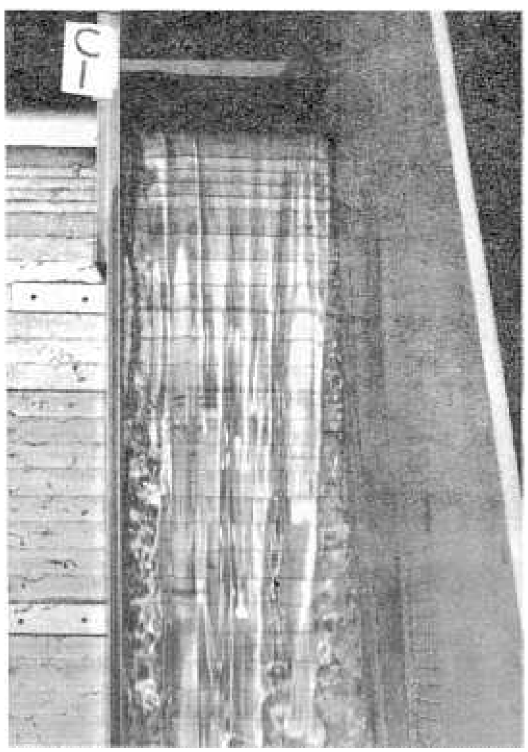
Figure A-10. – Entrance corner for the right side spillway wall.



(a) Q = 15,000 ft^3/s, entrance corner, 1½- foot radius. P801–D–81118.



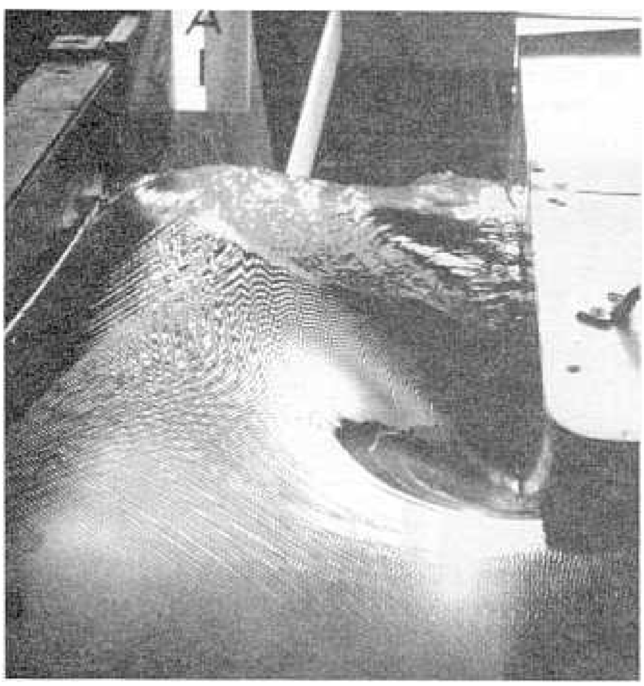
(b) Q = 75,000 ft^3/s, entrance corner, 1½-foot radius. P801–D–81119.



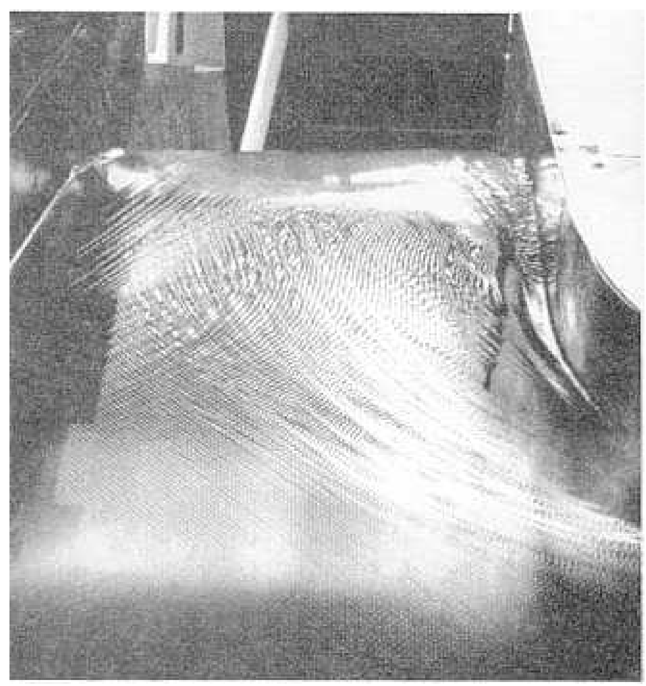
(c) Q = 75,000 ft^3/s, ellipse entrance corner, recommended design. P801–D–81120.

Figure A-11. – Flow affected by the spillway entrance.

Figure A-12. – Turbulence where water separated from spillway flow (1½-ft radius entrance corner, Q = 75,000 ft³/s). P801–D–81121.



(a) 1½-foot radius entrance corner. P801–D–81122.



(b) Recommended elliptical entrance corner. P801–D–81123.

Figure A-13. – Flow separation from entrance corner, Q = 75,000 ft³/s.

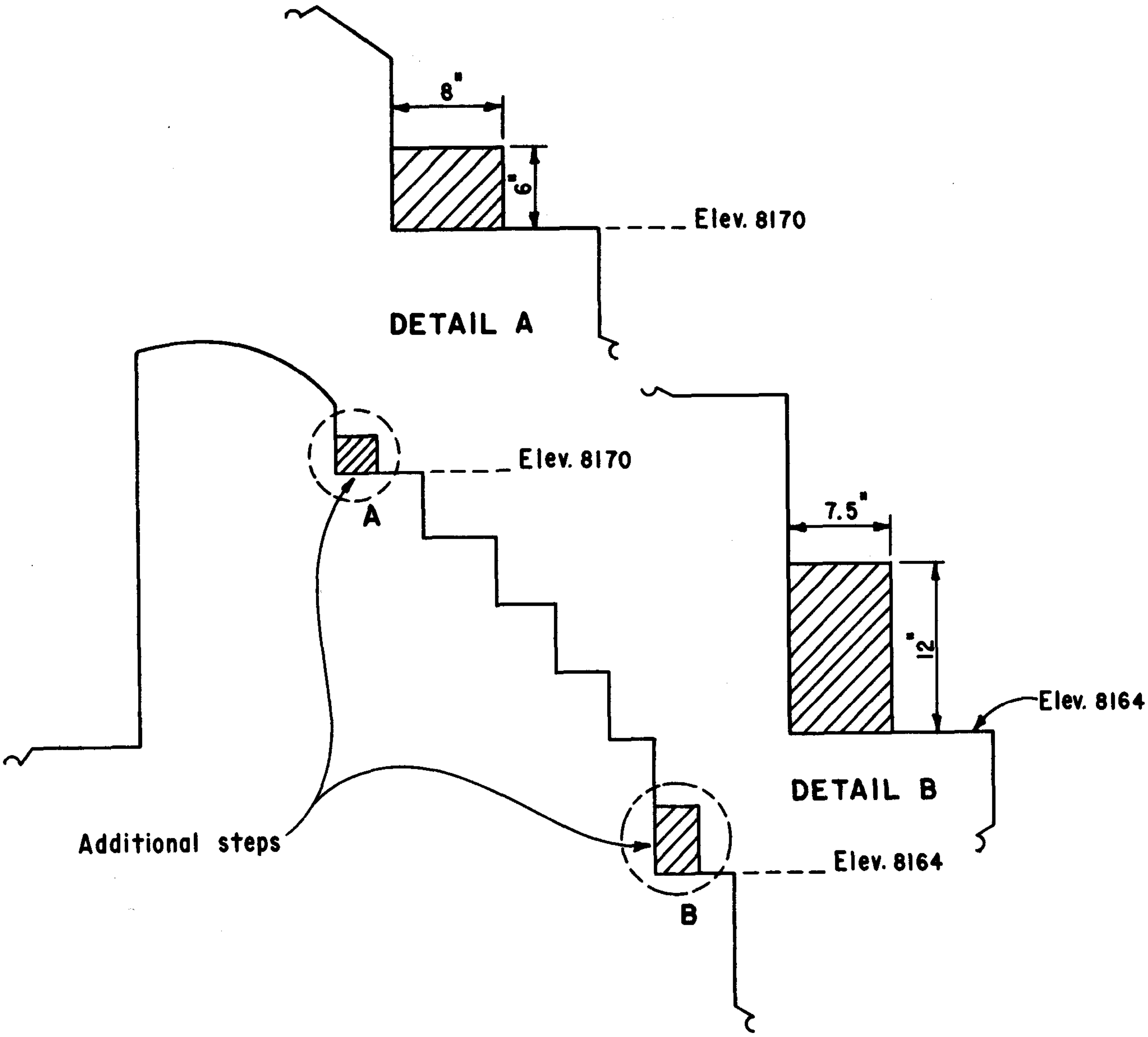
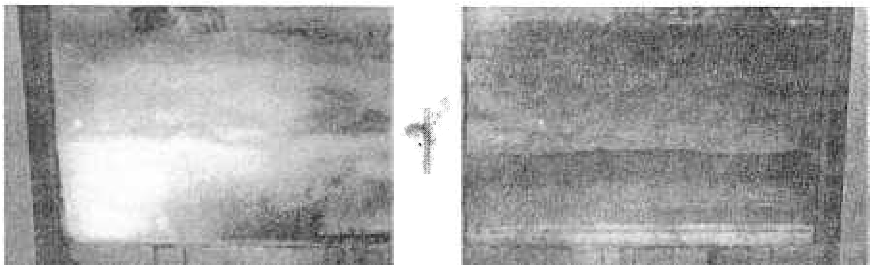
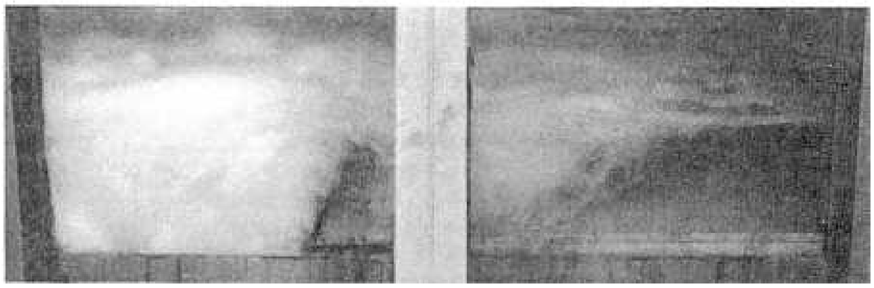


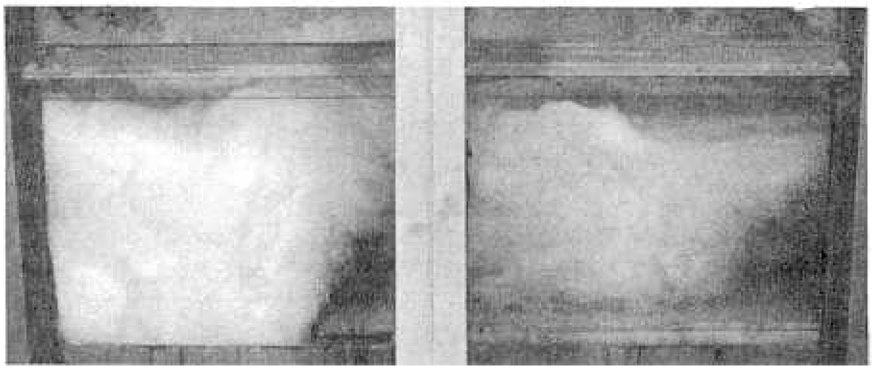
Figure A-14. – Locations and dimensions of additional spillway steps.



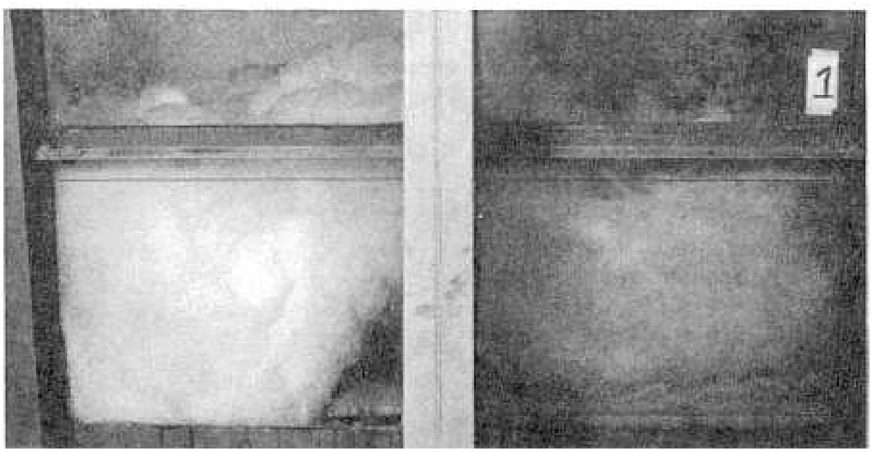
(a) ft³/s. P801–D–81124.



(b) 30, ft³ P801–D–8



(c) 50.000 ft³/s. P80 –D–81126



(d) 000 ft³/s. P80

Figure Stilling basin flows.

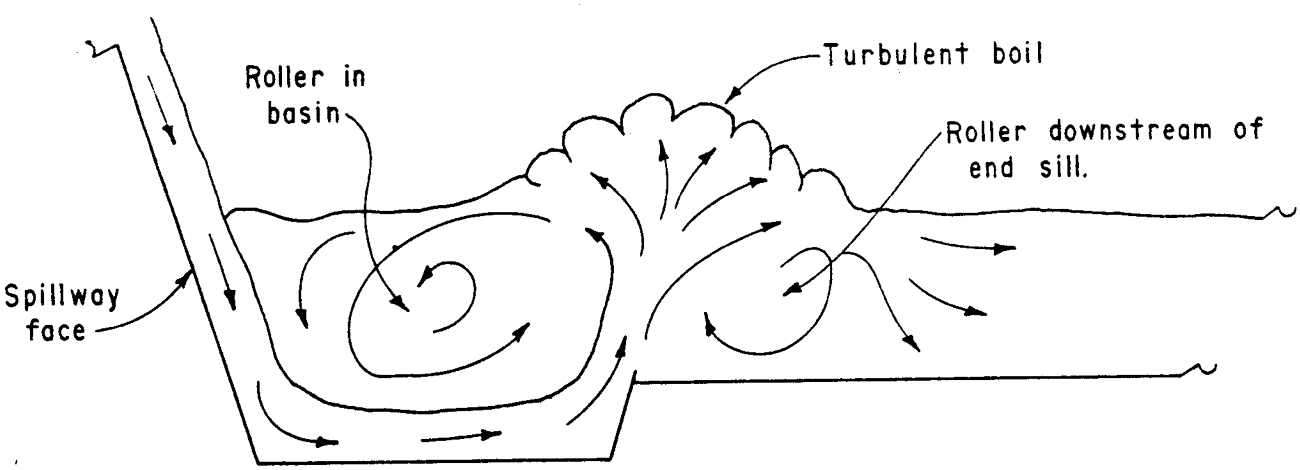


Figure A-16. – Stilling basin flow currents for Q = 30,000 to 75,000 ft³/s.

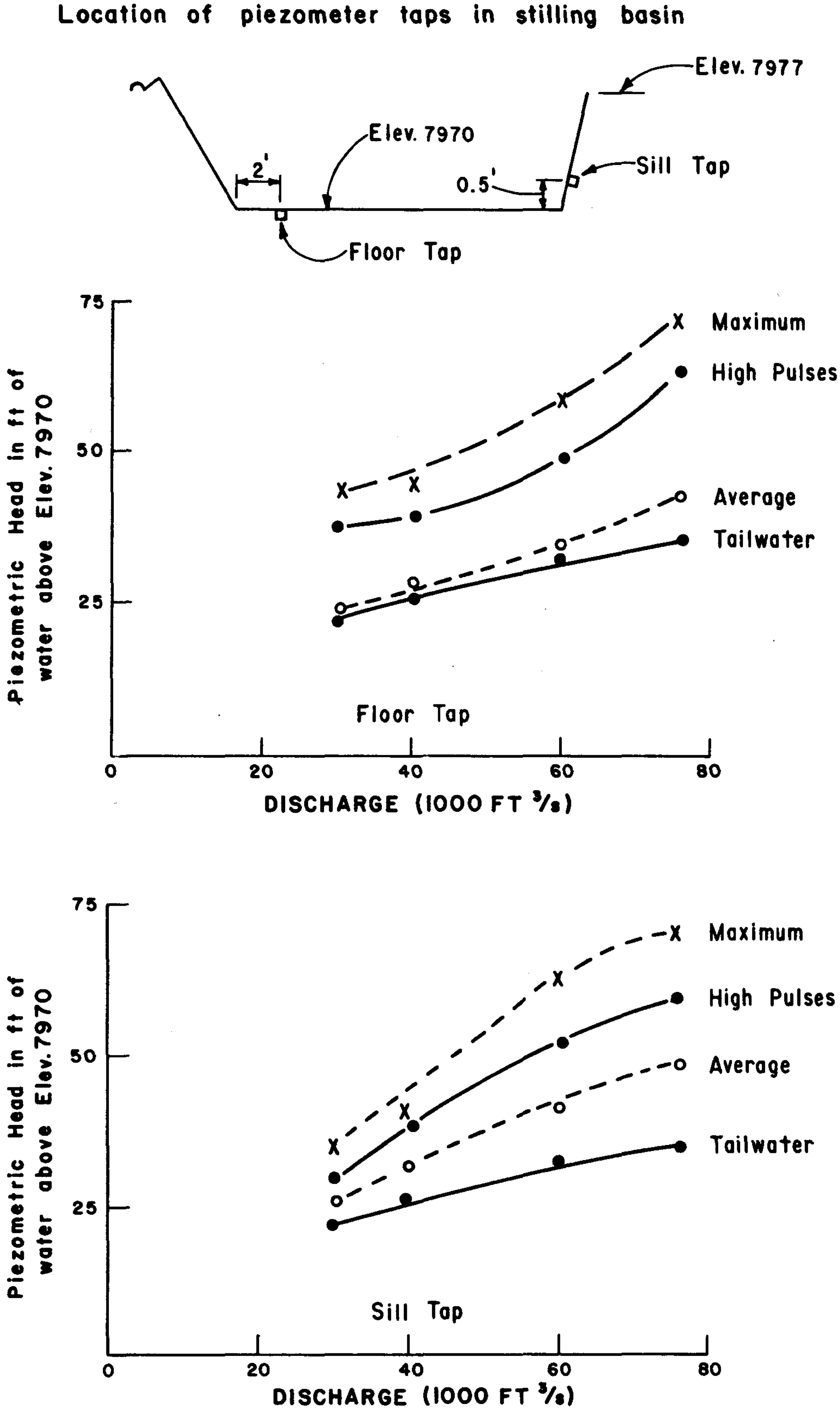
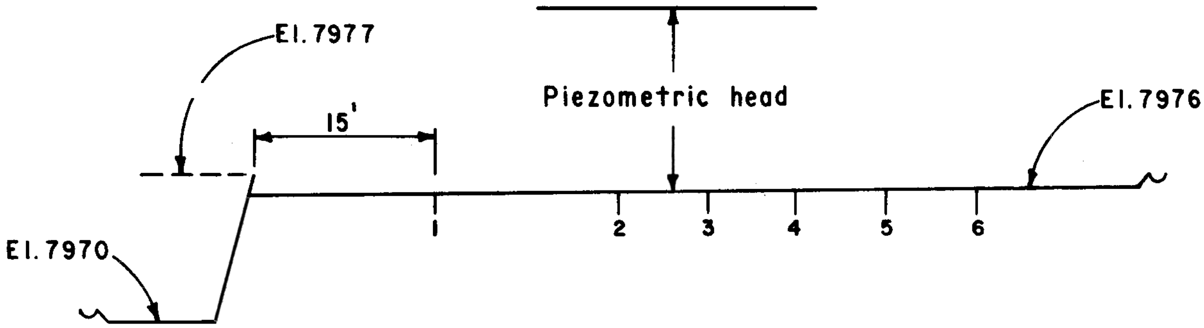


Figure A-17. – Pressure measurements in the stilling basin.



Piezometer tap No.	Distance downstream end sill, ft.	Average piezometric head, ft.	Range of piezometric head, ft.
1	15	25.5	24 – 28.5
2	30	25.5	22.5 – 30
3	37.5	27.0	24 – 30
4	45	28.5	24 – 33
5	52.5	28.5	24 – 31.5
6	60	28.5	24 – 31.5

Note – Piezometric head measured above El. 7976 datum.

Figure A-18. – Piezometric head measurements made downstream from stilling basin, Q = 75,0000 ft³/s, tailwater elevation 8006.0 feet.

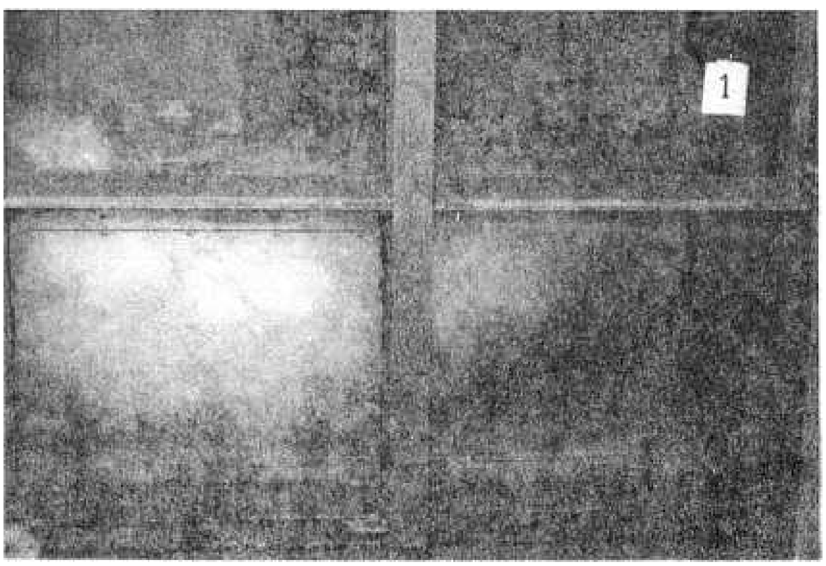


Figure A-19. – Flow downstream from the stilling basin, Q = 75,000 ft³/s, tailwater elevation 8006.0 feet. P801–D–81128.

GPO 854-847

Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.