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# HYDRAULIC DESIGN OF HOLLOW-JET VALVE STILLING BASINS

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## SYNOPSIS

Hydraulic model and prototype tests made to generalize and prove the hydraulic design of a new type of stilling basin which utilizes the hollow-jet valve for discharge control are described. Dimensionless curves are derived from model data and are used to define the important dimensions of the basin for the usual combinations of valve size, operating head, and discharge. Sample problems are presented to illustrate the use of the design curves and the general hydraulic design procedures. Prototype tests on the Boysen and Falcon Dam stilling basins are described and analyzed to help establish the reliability of the recommended basins. Basin dimensions obtained from individual model tests on six stilling basins are shown to compare favorably with the dimensions obtained from the dimensionless curves and methods given in this paper.

## INTRODUCTION

The hollow-jet valve stilling basin described in this paper is of a new type and is used to dissipate hydraulic energy at the downstream end of an outlet works control structure. To reduce cost and save space, the stilling basin is usually constructed within or adjacent to the powerhouse structure as shown in Figs. 1 and 2. The hollow-jet valve, Fig. 3, controls and regulates the flow.

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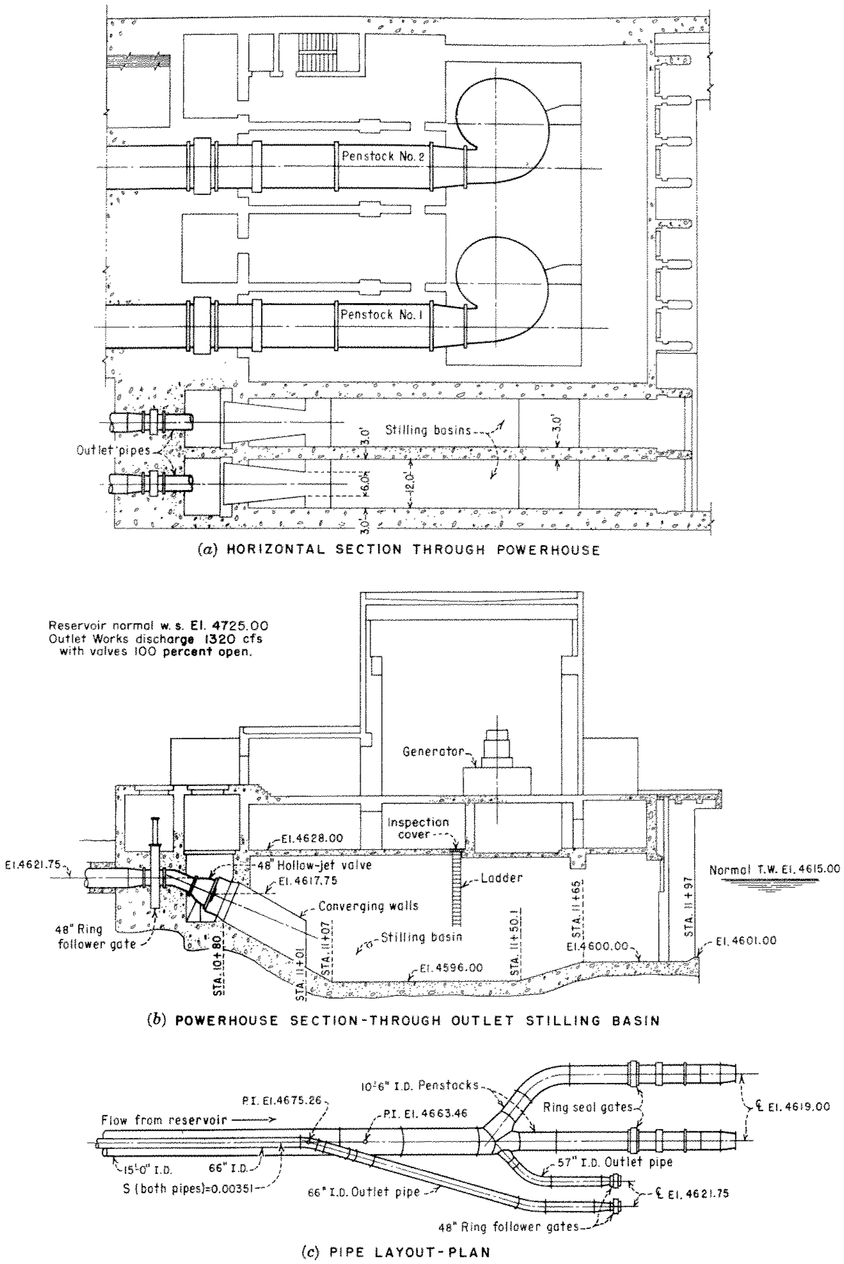



FIG. 1.—BOYSEN DAM OUTLET WORKS STILLING BASIN AND POWER PLANT



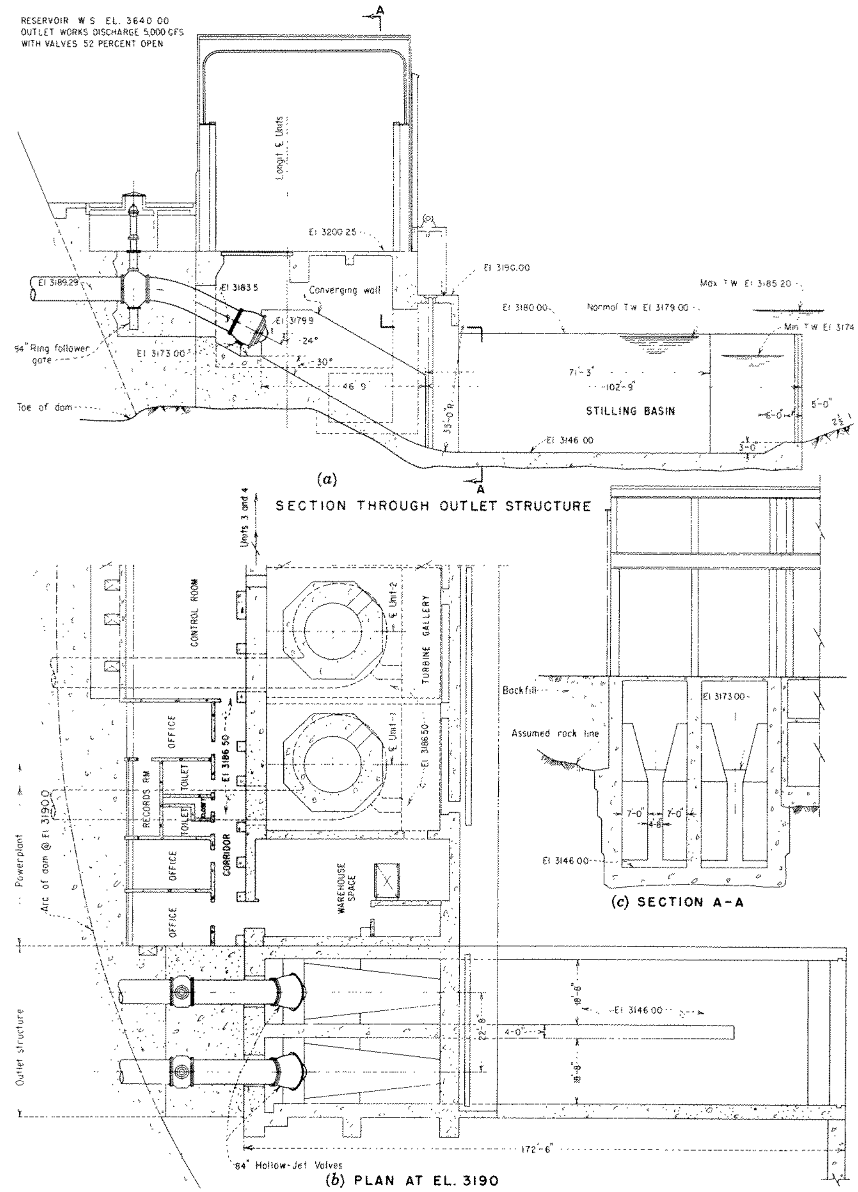



FIG. 2.—YELLOWTAIL DAM PROPOSED OUTLET WORKS STILLING BASIN AND POWERPLANT

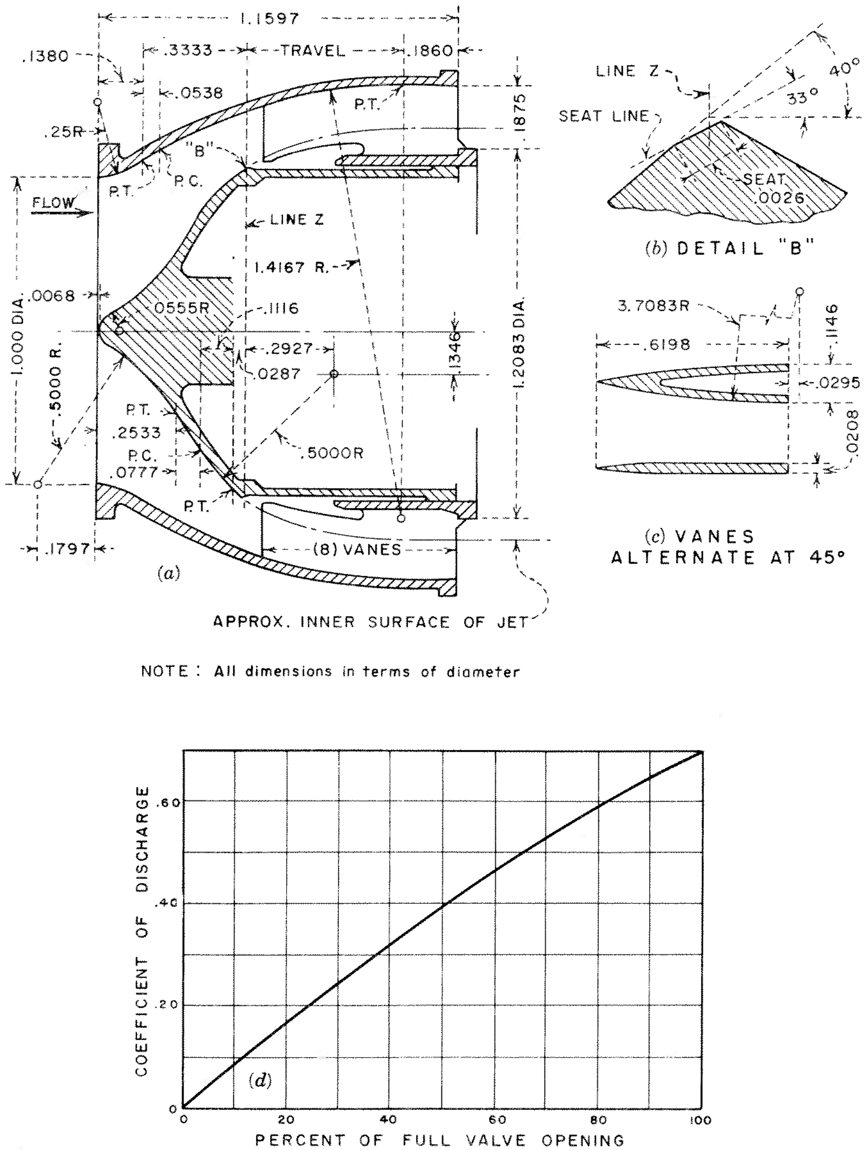
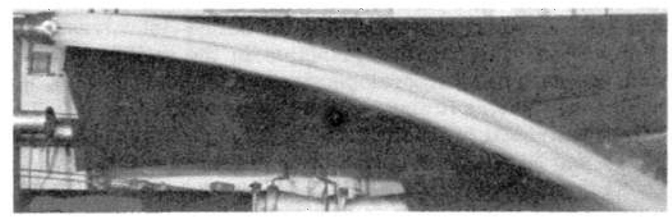



FIG. 3.—HOLLOW-JET VALVE DIMENSIONS AND DISCHARGE COEFFICIENTS

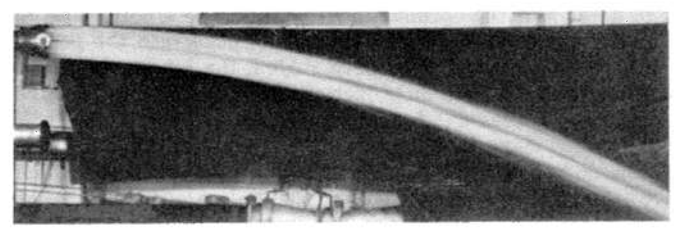


Regardless of the valve opening or head, the outflow has the same pattern, an annular or hollow jet of water of practically uniform diameter throughout its length, Fig. 4. The stilling basin is designed to take advantage of the hollow-jet shape; solid jets cannot be used in this basin.

The hollow-jet valve was developed by the Bureau of Reclamation in the early 1940's to fill a need for a dependable regulating valve. The design was accomplished with the aid of a complete 6-in.-diameter hydraulic model and a sectional 12-in.-diameter air model. These models were tested in the Bureau of Reclamation Hydraulic Laboratory. To evaluate the valve characteristics at greater than scale heads, a 24-in.-diameter valve was tested at Hoover Dam under heads ranging from 197 ft to 349 ft.



(*a*) Valve fully open



(*b*) Valve 50 percent open

FIG. 4.—SIX-INCH HOLLOW-JET VALVE DISCHARGING

Piezometer pressure measurements, thrust determinations on the valve needle, and rates of discharge were studied in both field and laboratory tests. It was found that the hydraulic characteristics of the larger valves could be predicted from the performance of the smaller model valves. From these tests and investigations of prototype valves up to 96 in. in diameter, the valve has been proved to be a satisfactory control device.

Cavitation damage, found on a few of the many prototype valves in use, was minor in nature and was caused by local irregularities in the body casting and by misalinement of the valve with the pipe. These difficulties have been eliminated by careful foundry and installation practices. On one installation, damage that occurred on the cast iron valve support vanes may have been caused by abrasive sediment in the water. The design itself is cavitation free.

Because a large valve operating at high heads can discharge flows having an energy content of up to 150,000 hp, a stilling basin is usually required downstream from the valve. In early designs, the valve was discharged horizontally onto a trajectory curved floor which was sufficiently long to provide a uniformly distributed jet entering the hydraulic jump stilling pool. This resulted in an extremely long structure, twice or more the length of the basin recommended herein. When two valves were used side by side, a long, costly dividing wall was also required. Hydraulic model tests showed that the basin length could be reduced more than 50% by turning the hollow-jet valves downward and using a different energy dissipating principle in the stilling basin. The first stilling basin of this type was developed for use at Boysen Dam, a relatively low-head structure. Basins for larger discharges and higher heads were later developed from individual hydraulic models of the outlet works at Falcon, Yellowtail, Trinity, and Navajo Dams. It became apparent at this time that generalized design curves could be determined to cover a wide range of operating heads and discharges. Therefore, a testing program was initiated to provide the necessary data. A brief description of the individual model tests made to develop the basin type is given in the following section. Table 1 gives a summary of basin dimensions, valve sizes, test heads, and discharges for these structures.

## DEVELOPMENT OF BASIN FEATURES

*Boysen Dam.*—In the Boysen Dam model studies, a series of basic tests was made to determine the optimum angle of entry of a hollow-jet into the tail water. For flat angles of entry, the jet did not penetrate the pool but skipped along the tail water surface. For steep angles, the jet penetrated the pool but rose almost vertically to form an objectionable boil on the water surface. When the valves were depressed 24° from the horizontal, Fig. 1, and a 30° sloping floor was placed downstream from the valve to protect the underside of the jet from turbulent eddies, optimum performance resulted. The submerged path of the valve jet was then sufficiently long that only a minimum boil rose to the surface. The size and intensity of the boil were further reduced when converging walls were placed on the 30° sloping floor to protect the sides of the jet until it was fully submerged. The converging walls have another function, however; they compress the hollow-jet between them to give the resulting thin jet greater ability to penetrate the tail water pool. Sudden expansion of the jet as it leaves the converging walls plus the creation of fine grain turbulence in the basin account for most of the energy losses in the flow. Thorough breaking-up of the valve jet within the basin and good velocity distribution over the entire flow cross section account for the low velocities leaving the basin. Fig. 5 shows the performance of a hollow-jet basin both with and without the converging walls.

Pressures on the inside face and downstream end of the converging walls were measured to determine whether low pressures which might induce cavitation were present. The lowest pressure, measured on the end of the wall,



was 3 ft of water above atmospheric; therefore, cavitation should not occur. Pressures measured on the sloping floor, and under and near the impinging jet, were all above atmospheric. Maximum pressures did not exceed one-fourth of the total head at the valve.

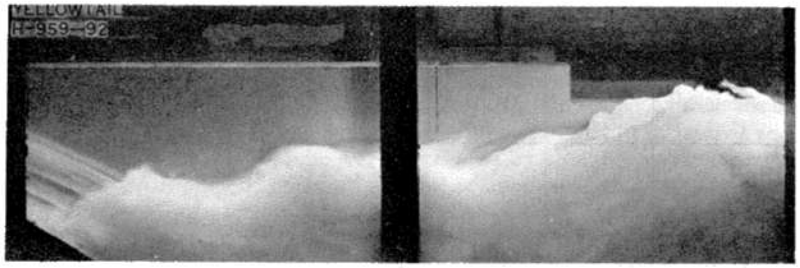
TABLE 1.—COMPARISON OF BASIN DIMENSIONS[a, b, c]

| Basin Dimensions (1) | Boysen (2) | Falcon, U. S. (3) | Falcon, Mexico (4) | Yellowtail (5) | Trinity (6) | Navajo (7) |
|---|---|---|---|---|---|---|
| Valve diameter, in ft | 4 | 6 | 7.5 | 7 | 7 | 6 |
| Head at valve, in ft | 86 | 81.5 | 81.9 | 380 | 315 | 217 |
| Design Q, in cfs | 660 | 1,460 | 2,285 | 2,500 | 3,835 | 2,340 |
| Coefficient C | 0.70 | 0.70 | 0.70 | 0.41 | 0.70 | 0.70 |
| Percentage valve open | 100 | 100 | 100 | 52 | 100 | 100 |
| Depth D, in ft | 16.2<br>19 | 21.0<br>22.5 | 24.7<br>25.2 | 31.5<br>32.6 | 38.5<br>38 | 30.0<br>35[e] |
| Depth $D_s$, in ft | 13.6<br>14 | 17.4<br>17.5 | 20.2<br>19.5 | 25.9<br>25.6 | 31.5<br>31.8 | 24.6<br>24 |
| Length L, in ft | 60.4<br>58 | 74.4<br>73.9 | 86.2<br>94 | 104<br>102.8 | 129<br>123 | 103<br>110[e] |
| Width W, in ft | 10.2<br>12 | 14.7<br>16.2 | 18<br>16.2 | 19.2<br>18.7 | 19.6<br>18.9 | 16.2<br>18.0[e] |
| End sill height | 3<br>4 | 3<br>3 | 3.1<br>3 | 3.9<br>3 | 4.8<br>5 | . . .[e]<br>. . .[e] |
| End sill slope | 3.3:1[d] | 2:1 | 2:1 | 2:1 | 2:1 | . . .[e] |
| Converg wall height | 3.0 d | 4.5 d | 3.9 d | 3.1 d | 3.5 d | 3.4 d |
| Converg wall gap | 0.50 W | 0.52 W | 0.65 W | 0.25 W | 0.25 W | 0.23 W |
| Center wall length | 1.5 L[d] | 0.5 L | 0.4 L | 0.7 L | 0.3 L | 0.5 L |
| Channel slope | . . .[d] | 4:1 | 4:1 | 2.5:1 | 2:1 | 6:1[e] |

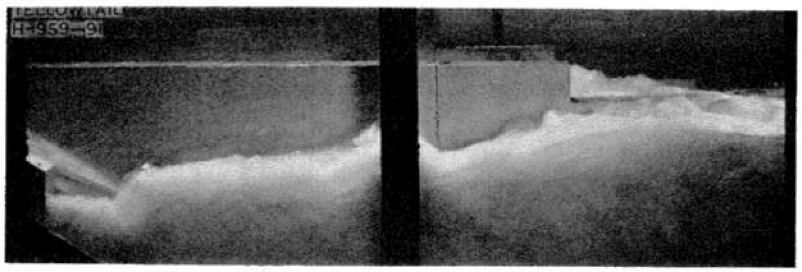
[a] Upper values in each box were calculated from Figs. 11 through 15; lower values in each box were developed from individual model studies.
[b] Valve tilt 24°; inclined floor 30° in all cases.
[c] See Figs. 1, 2, 6, 7, 8, 9, and 11.
[d] Special case, for structural reasons.
[e] Special case, for diversion flow requirements (dentated sill used and basin size increased).

Scour downstream from the end sill was mild and prototype wave heights were only 0.5 ft in the river channel. A vertical traverse taken near the end sill showed surface velocities to be about 5 fps, decreasing uniformly to about 2 fps near the floor.

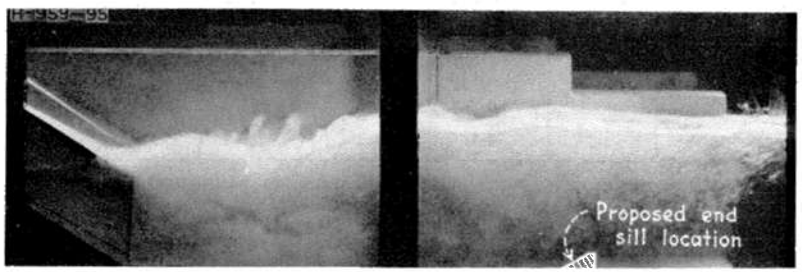
*Falcon Dam.*—In the Falcon Dam tests, two separate basins were developed, one for the United States outlet works and one for the Mexican outlet works, Figs. 6 and 7. In these tests, the basic concepts of the Boysen design were proved to be satisfactory for greater discharges. In addition, it was confirmed




(*a*) Stilling action without converging walls




(*b*) Stilling action with short converging walls




(*c*) Stilling action with recommended converging walls

FIG. 5.—HOLLOW-JET VALVE STILLING BASIN WITH AND WITHOUT CONVERGING WALLS

that dentils on the end sill were not necessary and that the center dividing wall need not extend the full length of the basin. A low 2:1 sloping end sill was sufficient to provide minimum scour and wave heights. Maximum pressures on



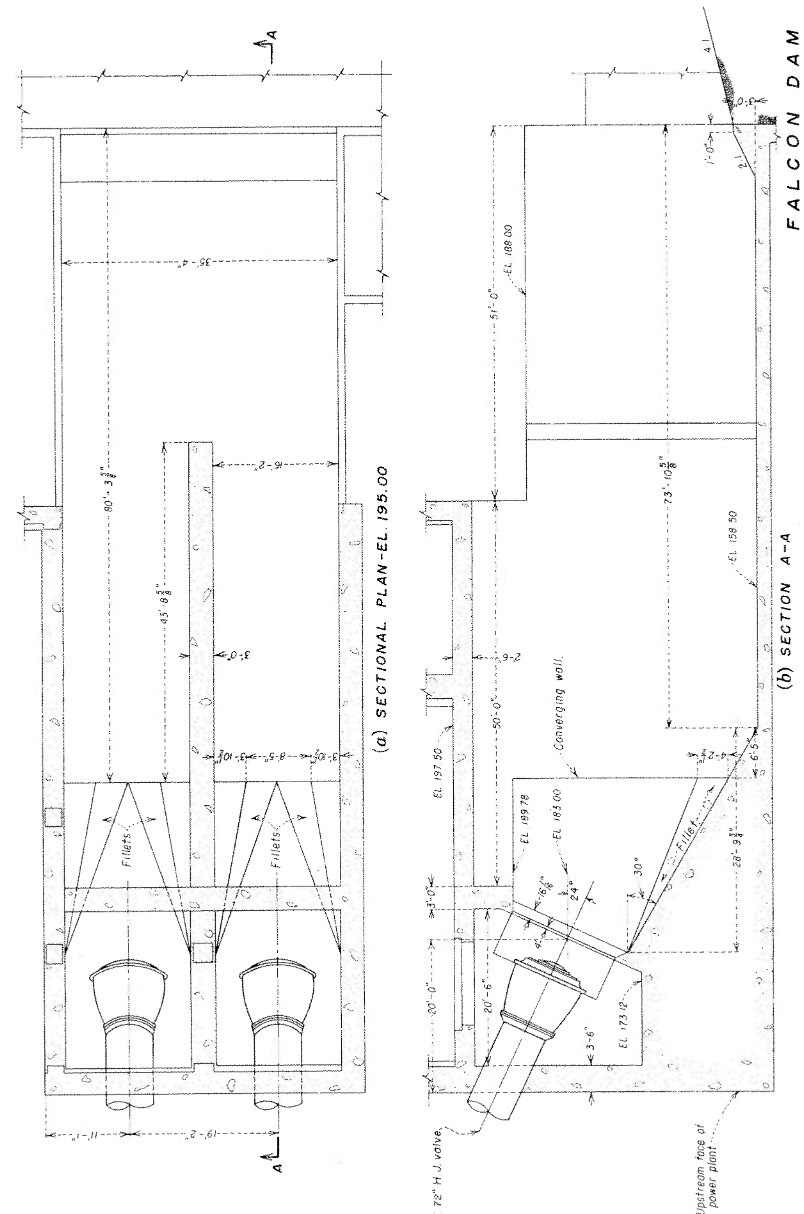



FIG. 6.—UNITED STATES OUTLET WORKS

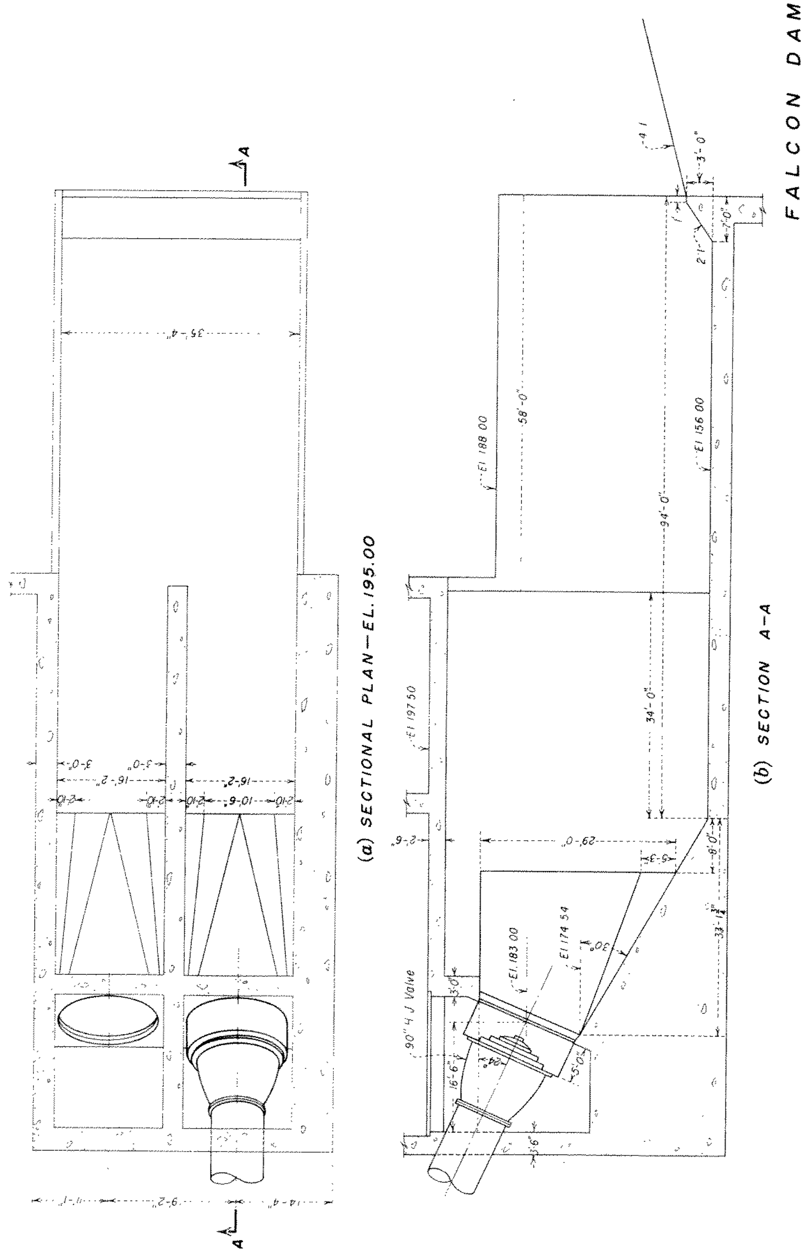



FIG. 7.—MEXICAN OUTLET WORKS



the floor beneath the impinging jet were found to be about one-third of the total head at the valve, somewhat greater than found in the Boysen tests, but still not excessive.

*Yellowtail Dam.*—In the Yellowtail Dam model studies, the head and discharge were both considerably higher than in the Boysen and Falcon tests. Because of the high velocity flow from the valves, it was found necessary to extend the converging walls to the downstream end of the sloping floor, Fig. 2, and to reduce the wall gap to about one-quarter of the basin width. These refinements improved the stilling action within the basin, Fig. 5 (c), and made it possible to further reduce the basin length. Scour was not excessive, and the water surface in the downstream channel was relatively smooth. Pressures on the converging walls and other critical areas in the basin were found to be above atmospheric.

*Trinity Dam.*—The Trinity Dam outlet works utilized a head almost 4 times greater and a discharge 5 times greater than at Boysen Dam. In the development tests, it was found that the performance of this type of basin would be satisfactory for extremely high heads and discharges. Although several variations in the basin arrangement were investigated, no new features were incorporated in the design. Fig. 8 shows the developed design.

*Navajo Dam.*—The experimental work on the Navajo outlet works was complicated by the fact that the hollow-jet valve basin, Fig. 9, had to first serve as a temporary diversion works stilling basin. Since the diversion works basin was larger than required for the outlet works basin, it was possible to insert the proper appurtenances in the temporary basin to convert it to a permanent outlet works basin. The development tests indicated that a larger than necessary basin does not in itself guarantee satisfactory performance of the hollow-jet valve basin. Best outlet works performance was obtained when the temporary basin was reduced in size to conform to the optimum size required for the permanent structure. Since the Navajo Dam outlet works model was available both during and after the generalization tests, the model was used both to aid in obtaining the generalized data and to prove that the design curves obtained were correct.

## GENERALIZATION STUDY

Because development work on individual basins had reached a point where the general arrangement of the basin features was consistent, and because the basin had been proved satisfactory for a wide range of operating conditions, a testing program was inaugurated to provide data for use in generalizing the basin design. The purpose of these tests was to provide basin dimensions and hydraulic design procedures for any usual combinations of valve size, discharge, and operating head. The main purpose of this paper is to describe these tests, to explain the dimensionless curves which are derived from the test data, and to show, by means of sample problems, the procedures which may be used to hydraulically design a hollow-jet valve stilling basin. Prototype tests on the Boysen and Falcon basins are included to demonstrate that hollow-jet valve basins, that fit the dimensionless curves derived in the general study, will perform as well in the field as predicted from the model tests.

*Test Equipment.*—The outlet works stilling basin model shown in Fig. 10 was used for the generalization tests. The glass-walled testing flume contained two stilling basins separated by a dividing wall. The right-hand basin

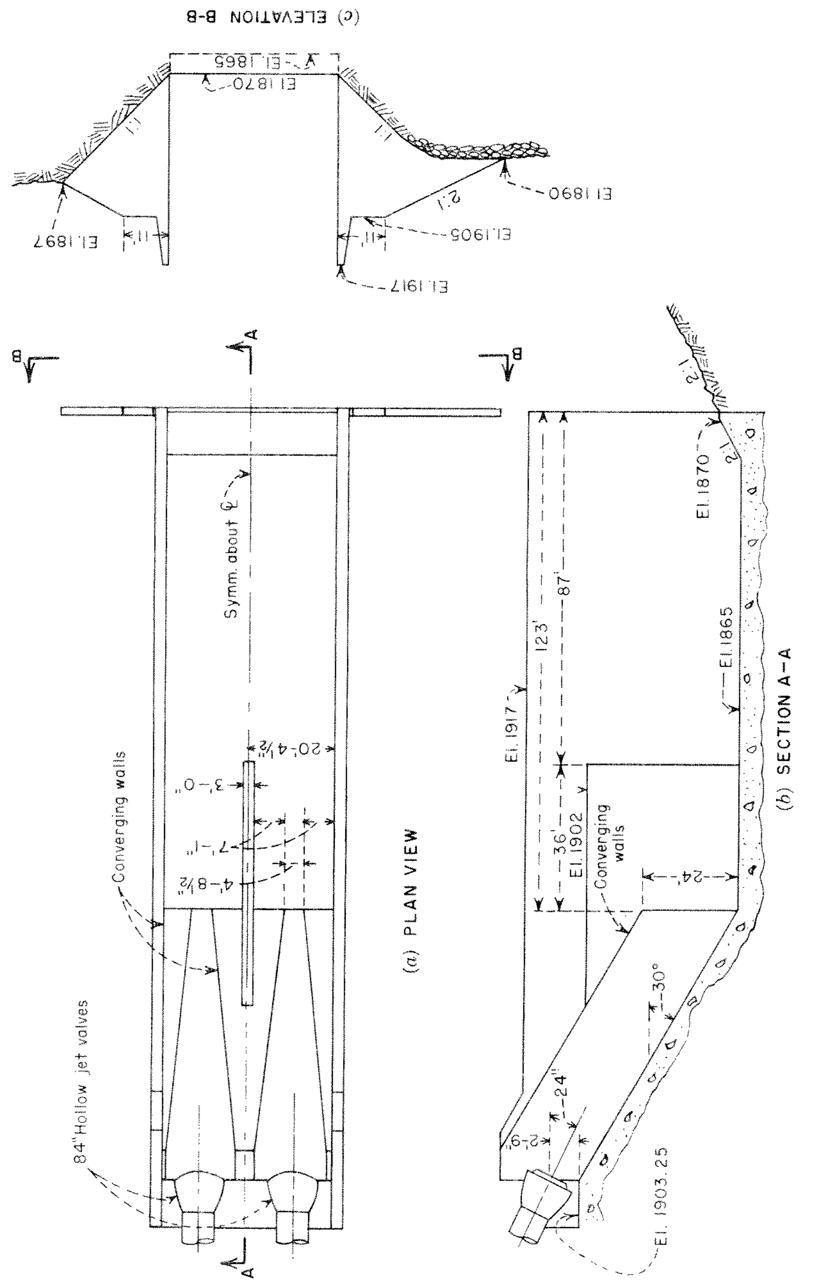



FIG. 8.—TRINITY DAM OUTLET WORKS



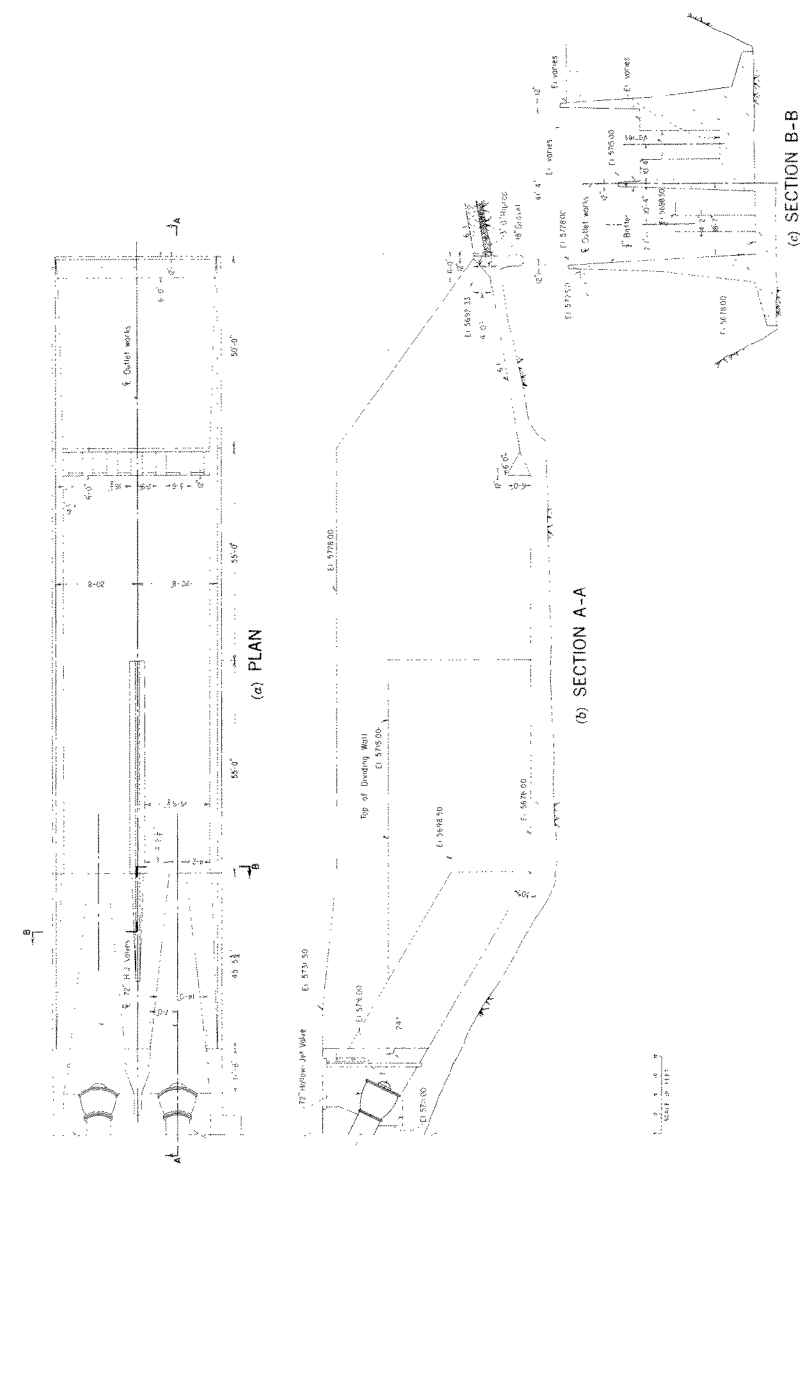



FIG. 9.—NAVAJO DAM OUTLET WORKS STILLING BASIN

having the glass panel as one wall was operated singly to determine the basin length, width, and depth requiremetns; both basins were used to study the performance with and without flow in an adjacent basin.

The glass panel permitted observation of the stilling action and the flow currents within and downstream from the basin. The length, width, and depth of the basin were varied by inserting false walls or by moving the basin within the test box. The tail box contained an erodible sand bed to represent the discharge channel bed.

The test valves were exact models of a prototype valve in that the flow surfaces were exactly reproduced, and could be opened and closed to any partial opening. The models were 3-in. valves machined from bronze castings.

The pressure head at each model valve was measured using a piezometer located in the 3-in. supply pipe 1 diameter upstream from the valve flange.

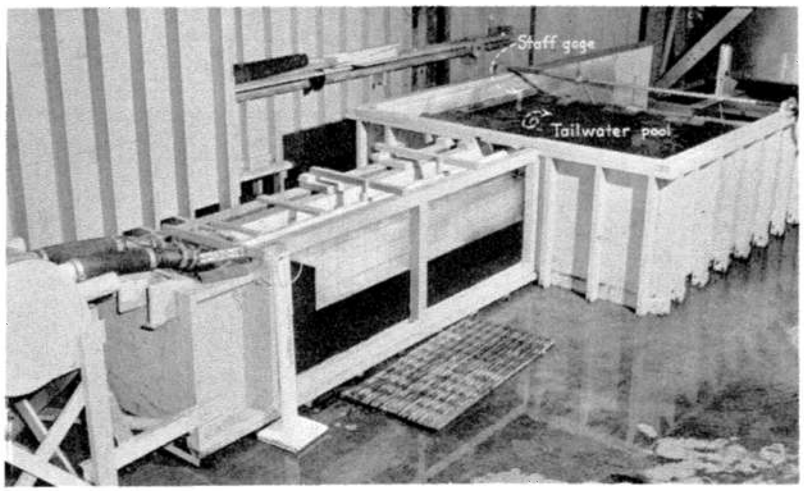



FIG. 10.—HOLLOW-JET VALVE STILLING BASIN MODEL USED FOR GENERALIZATION TESTS

Discharges were measured using calibrated venturi meters permanently installed in the laboratory. The tail water elevation in the discharge channel was controlled with a hinged tailgate in the tail box. Tail water elevations were determined visually from a staff gage on the tail box wall located approximately 62 valve diameters downstream from the valves.

*Preliminary Procedures.*—The investigation was begun by tabulating the important dimensions of the Boysen, Falcon, Yellowtail, and Trinity outlet works basins and expressing them in dimensionless form, as shown in Table 1. Based on these dimensions, a model was constructed as shown in Fig. 11, using the 3-in. valve dimension to establish the absolute model size. More weight was given to the Yellowtail and Trinity basins because they were developed for higher heads and contained refinements in the converging wall design which improved the basin performance at high heads. Also, the latter basins had



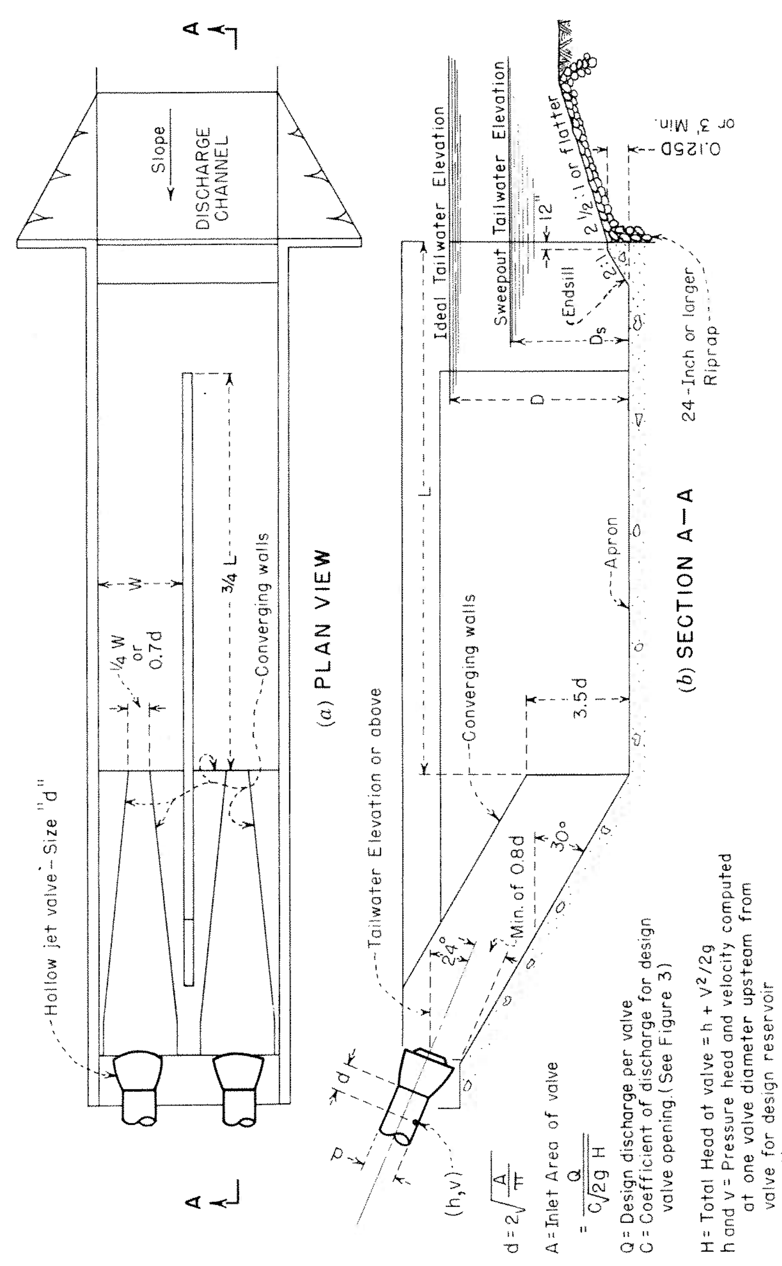



FIG. 11.—GENERALIZED DESIGN

been model tested over a greater operating range than were the earlier low-head basins.

To provide practical dishcarge limits for the tests, the 3-in. model was assumed to represent an 84-in. prototype valve, making the model scale 1:28. Discharges of 2,000 sec-ft to 4,000 sec-ft with one valve open 100% were considered to be the usual design discharges for a valve of this size. To produce these discharges, heads of 100 ft to 345 ft of water at the valve would be required.

Initial tests were made with the stilling basin apron longer than necessary and with no end sill in place. For a given discharge, the ideal depth of tail water was determined from visual inspection of the stilling action as it occurred over a range of tail water elevations. For each ideal tail water determination, the minimum length of concrete apron was estimated after an inspection of the flow currents in the model had indicated where an end sill should be placed in the prototype. Confirming tests were then conducted successively on a representative group of basins having the apron lengths previously determined and having an end sill at the end of the apron. Adjustments were then made as necessary to the preliminary values to obtain final ideal tail water depths and apron lengths. In the latter tests, the height of the valve above the maximum tail water elevation was adjusted to simulate a typical prototype installation. Similar tests were then made with the valve open 75% and 50%. Finally, a series of tests was made to determine the ideal width of stilling basin and the range of widths over which satisfactory performance could be expected.

*Preliminary Tests.*—In a typical test, the desired discharge was set by means of the laboratory venturi meters and passed through the hollow-jet valve or valves opened 100%. The tail water elevation was adjusted to provide the best energy dissipating action in the basin. The optimum value, tail water depth D in Fig. 11, was judged by the appearance and quality of the stilling action in the basin and on the smoothness of the tail water surface.

For discharges of 2,000 sec-ft to 4,000 sec-ft, it was found that the tail water could be raised or lowered about 3 ft (0.1 ft in model) from the ideal tail water elevation without adversely affecting the basin performance. Increasing the tail water depth beyond this margin reduced the efficiency of the stilling action and allowed the jet to flow along the bottom of the basin for a greater distance before being dissipated. This also produced surges in the basin and increased the wave heights in the discharge channel. Decreasing the tail water depth below the 3-ft margin moved the stilling action downstream in the basin and uncovered the valve jets at the end of the converging walls. This increased the flow velocity entering the discharge channel and increased the tendency to produce bed scour. Uncovering of the stilling action also produced objectionable splashing at the upstream end of the basin. If the tail water depth was decreased further, the flow swept through the basin with no stilling action having occurred. The latter tail water depth was measured and recorded as the sweep-out depth $D_s$. These tests were made with the dividing wall extended to the end of the basin, since this provided the least factor of safety against jump sweep out. With a shorter dividing wall, sweep out occurs at a tail water elevation slightly less than $D_s$.

With the ideal tail water depth set for a desired flow, the action in the basin was examined to determine the ideal length, L, of the basin apron, Fig. 11. The apron length was taken to the point where the bottom flow currents began to rise from the basin floor of their own accord, without assistance from an end sill, Fig. 5 (c). The water surface directly above and downstream from this point was fairly smooth, indicating that the stilling action had been completed and that the paved apron and training walls need not extend farther. In the preceding individual model studies, it had been found that when the basin was appreciably longer than ideal, the ground roller at the end sill carried bed material from the discharge channel over the end sill and into the basin. If this action occurred in a prototype structure the deposited material would swirl around in the downstream end of the basin and cause abrasive damage to the concrete apron and end sill. It had also been found that scour tendencies in the discharge channel were materially increased if the basin was appreciably shorter than ideal. Therefore, the point at which the currents turned upward from the apron, plus the additional length required for an end sill, was determined to be the optimum length of apron. At this point, the scouring velocities were a minimum and any scouring tendencies would be reduced by the sloping end sill to be added later.



Practical difficulties were experienced in determining the exact length of apron required, however. Surges in the currents flowing along the basin floor caused the point of upturn to move upstream and downstream a distance of 1/4 to 1/2 D in a period of 15 sec to 20 sec in the model. An average apron length was therefore selected in the preliminary tests. For this reason, too, the end sill would help to neutralize the scouring tendencies which increased as the bottom currents surged downstream.

The depth D, sweep-out depth $D_s$, and length L were then determined for the range of discharges possible with the hollow-jet valve open 75%, and finally 50%, using the testing methods described in the preceding paragraphs. Partial openings were investigated because the valve size is often determined for the minimum operating head and maximum design discharge. When the same quantity is discharged at higher heads, the valve opening must be reduced. It may be necessary, therefore, to design the basin for maximum discharge with the valves opened less than 100%. When the relation between head and velocity in the valve is changed materially, the minimum required basin dimensions will be affected. The data for the partially opened valves are also useful in indicating the basin size requirements for discharges greater or less than the design flow conditions.

*Final Tests and Procedures.*—The final tests were made to correct or verify the dimensions obtained in the preliminary tests and to investigate the effect of varying the basin width. Scour tendencies were also observed to help evaluate the basin performance. D, $D_s$, and L for the three valve openings are functions of the energy in the flow at the valve. The energy may be represented by the total head, H, at the valve, Fig. 11. Therefore, to provide dimensionless data which may be used to design a basin for any size hollow-jet valve, D, $D_s$, and L values from the preliminary tests were divided by the valve diameter d, and each variable was plotted against H/d. The resulting curves, similar to those in Figs. 12, 13, and 14, were used to obtain dimensions for a group of model basins which were tested with the end sill at the end of the apron and with the valves placed to give the proper vertical distance between the valve and the tail water. For each model basin, a 3:1 upward sloping erodible bed, composed of fine sand, was installed downstream from the end sill. The bed was kept sufficiently low that it did not interfere with tail water manipulation, even when the tail water was lowered for the sweep-out tests. Test procedure was essentially as described for the preliminary tests.

*Basin Depth and Length.*—The preliminary depth curves for both ideal tail water depth and sweep-out tail water depth needed but little adjustment. The preliminary basin lengths were found to be too long for the high heads and too short for the lower heads, although both adjustments were relatively minor. The adjusted and final curves are shown in Figs. 12, 13, and 14.

It was observed that a longer apron than indicated by Fig. 14 was necessary when the tail water depth exceeded the tail water depth limit in Fig. 12. As the stilling action became drowned, the action in the basin changed from fine-grain turbulence to larger and slower moving vertical eddies. The bottom flow currents were not dissipated as thoroughly or as quickly and were visible on the apron for a greater distance, thereby increasing the necessary length of basin. The action is similar to that observed in hydraulic jumps which are drowned by excessive tail water depths. A moderate amount of drowning is tolerable, but it is important that the ideal tail water depth be maintained within stated limits if the best performance is desired. The tail water depth limits, 0.1 ft above and below the ideal depth, expressed in dimensionless form is 0.4 d. If this limit is exceeded, a model study is recommended.

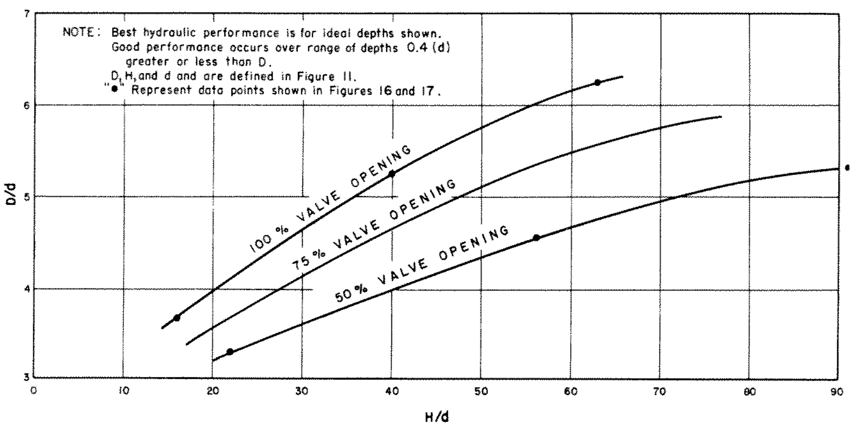



FIG. 12.—IDEAL TAIL WATER DEPTH

*Basin Width.*—To determine the effect of basin width, tests on several basins were made in which only the basin width was varied. It was found that the width could be increased to 3.0 times the valve diameter before the action became unstable. The width could be decreased to 2.5 times the valve diameter before the stilling action extended beyond the ideal length of basin. However, the H/d ratio and the valve opening were found to affect the required basin width as shown for 100%, 75%, and 50% valve openings in Fig. 15.

Basin width is not a critical dimension but certain precautions should be taken when selecting a minimum value. If the tail water is never to be lower than ideal, as shown by the curves in Fig. 12, the basin width may be reduced to 2.5 d. If the tail water elevation is to be below ideal, however, the curve values for width in Fig. 15 should be used. In other words, the lower limits for both tail water and basin width should not be used in the same structure. The combined minimums tend to reduce the safety factor against jump sweep-out and poor overall performance results. The basin width should not be increased above 3.0 d to substitute for some of the required length or depth of



the basin. If unusual combinations of width, depth, and length are needed to fit a particular space requirement, a model study is recommended.

*Basin Performance.*—The six model basins shown operating in Figs. 16 and 17 illustrate the performance to be expected from the recommended structures. The operating conditions in Figs. 16 and 17 correspond to points shown in Figs. 12, 14, and 15. Fig. 16 shows the operation for 100% valve opening; Fig. 17 shows the operation for 50% opening. The photographs may be used to determine the model appearance of the prototype basin and may help to provide a visual appraisal of the prototype structure. Wave heights, boil heights, or other visible dimensions may be scaled from the photographs (using the scale shown in the photographs) and converted to prototype dimensions by multiplying the scaled distances by the model scale. To determine the model scale, the prototype valve diameter in inches should be divided by 3 (the model valve diameter). To determine which of the six photographs represents the prototype in question, the H/d ratio should be used to select the photograph which most nearly represents the design problem. It is permissible to interpolate between photographs when necessary.

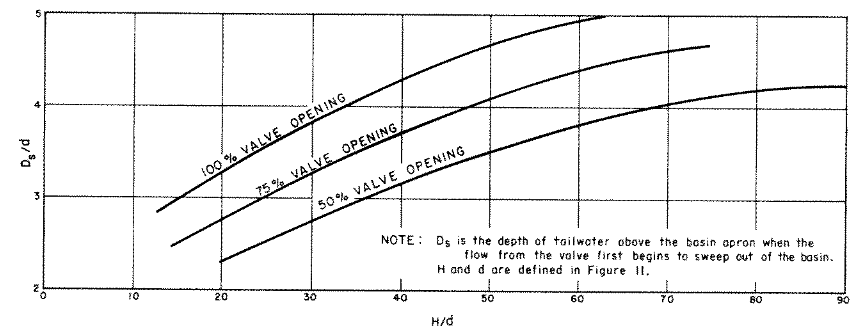



FIG. 13.—TAIL WATER SWEEPOUT DEPTH

*Center Dividing Wall.*—Prototype stilling basins usually have two valves placed a minimum distance apart, and alined to discharge parallel jets. It is necessary, without exception, to provide dividing walls between the valves for satisfactory hydraulic performance. When both valves are discharging without a dividing wall, the flow in the double basin sways from side to side to produce longitudinal surges in the tail water pool. This action occurs because the surging downstream from each valve does not have a fixed period, and the resulting harmonic motion at times becomes intense. When only one valve is discharging, conditions are worse. The depressed water surface downstream from the operating valve induces flow from the higher water level on the non-operating side. Violent eddies carry bed material from the discharge channel into the basin and swirl it around. This action in the prototype would damage the basin as well as the discharge channel. In addition, the stilling action on the operating side is impaired.

To provide acceptable operation with one valve operating, the dividing wall should extend to three-fourths of the basin length or more. However, if the two adjacent valves discharge equal quantities of flow at all times, the length

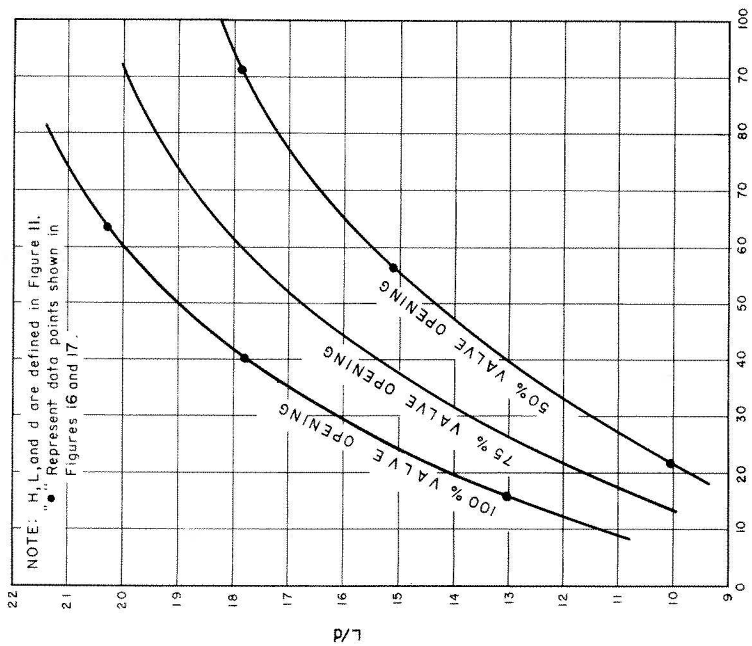



FIG. 14.—STILLING BASIN LENGTH

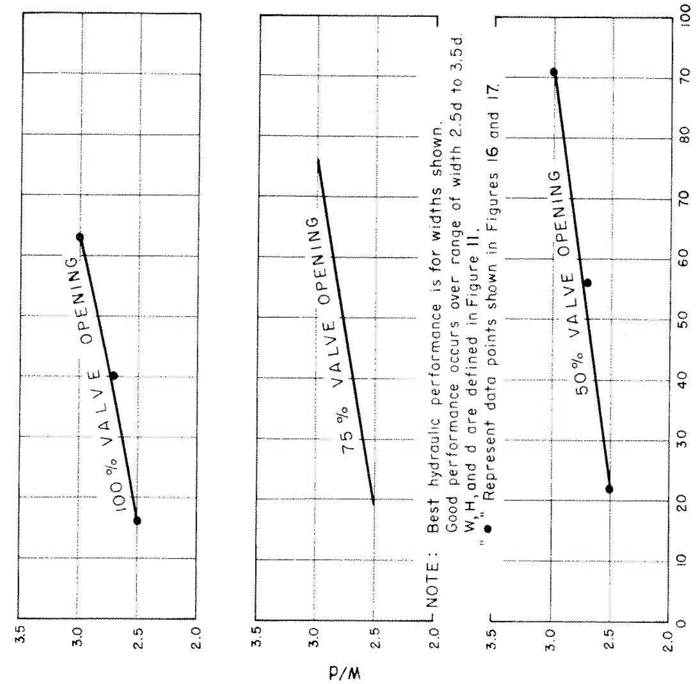
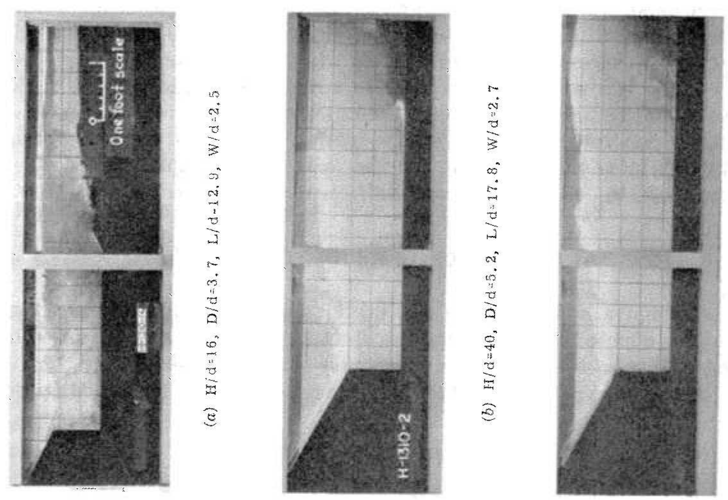



FIG. 15.—BASIN WIDTH PER VALVE



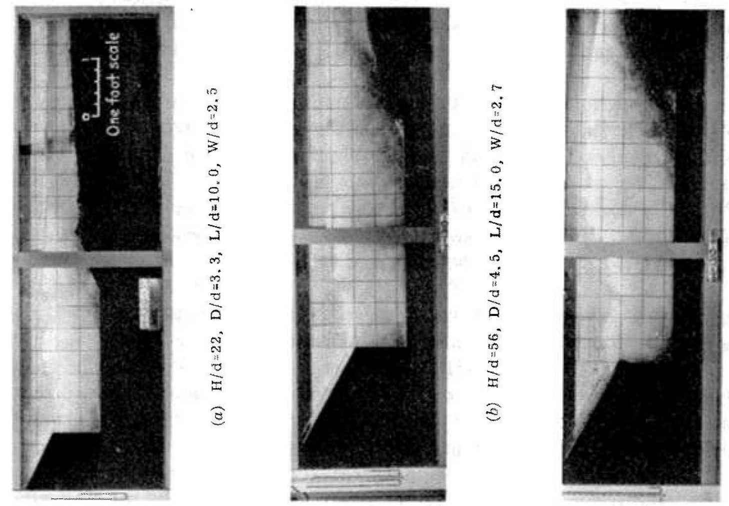



(a) H/d=16, D/d=3.7, L/d=12.9, W/d=2.5

(b) H/d=40, D/d=5.2, L/d=17.8, W/d=2.7

(c) H/d=63, D/d=6.2, L/d=20.3, W/d=3.0

FIG. 16.—HOLLOW-JET VALVE STILLING BASIN PERFORMANCE, VALVE 100% OPEN




(a) H/d=22, D/d=3.3, L/d=10.0, W/d=2.5

(b) H/d=56, D/d=4.5, L/d=15.0, W/d=2.7

(c) H/d=91, D/d=5.3, L/d=17.8, W/d=3.0

FIG. 17.—HOLLOW-JET VALVE STILLING BASIN PERFORMANCE VALVE 50% OPEN

of the center dividing wall may be reduced to one-half of the basin length. The margin against sweep out is increased, but the stability of the flow pattern is decreased as the dividing wall is shortened. In some installations, a full-length wall may be desirable to help support the upper levels of a powerplant, Fig. 1. If other arrangements of the center wall are required a model study is recommended.

*Valve Placement.*—A hollow-jet valve should not operate submerged because of the possibility of cavitation occurring within the valve. However, the valve may be set with the valve top at maximum tail water elevation, and the valve will not be underwater at maximum discharge. The valve jet sweeps the tail water away from the downstream face of the valve sufficiently to allow usual ventilation of the valve. However, as a general rule, it is recommended that the valve be placed with its center (downstream end) no lower than tail water elevation.

*Riprap Size.*—A prototype basin is usually designed for maximum discharge, but will often be used for lesser flows at partial and full valve openings. For these lesser discharges, the basin will be larger than necessary, and in most respects, the hydraulic performance will be improved. However, at less than design discharge, particularly those close to the design discharge, the ground roller will tend to carry some bed material upstream and over the end sill into the basin. The intensity of this action is relatively mild over most of the discharge range, and movement of material may be prevented by placing riprap downstream from the end sill. Riprap, having 50% or more of the individual stones 24 in. to 30 in. or larger in diameter, should provide a stable channel downstream from the end sill. The riprap should extend a distance D, or more, from the end sill. If the channel is excavated and slopes upward to the natural river channel, the riprap should extend from the end sill to the top of the slope, or more. The riprap should not be terminated on the slope.

The justification for choosing riprap as described is as follows: Because of the fixed relationships between depth and width of basin, the average velocity leaving the basin will seldom exceed 5 fps, regardless of structure size. Surface velocities will therefore seldom exceed 7 fps to 8 fps and bottom velocities 3 fps to 4 fps. To protect against these velocities, stones 10 in. to 12 in. in diameter would be ample. However, the critical velocity for riprap stability is the upstream velocity of the ground roller which has a curved path and tends to lift the stones out of place. Model tests showed that graded riprap up to 24 in. to 30 in. in diameter was sufficient to provide bed stability.

## APPLICATION OF RESULTS

*Problems.*—Design a stilling basin for (a) 1 hollow-jet valve discharging 1,300 cfs, and (b) a double basin for 2 valves discharging 650 cfs each. In both problems, the reservoir is 108 ft above maximum tail water elevation.

*One-valve Stilling Basin Design.*—The valve size should be determined from the equation:

$$Q = C A \sqrt{2 g H} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

in which Q is the design discharge, C is the coefficient of discharge, A is the inlet area to the valve, g is the acceleration of gravity, and H is the usable or total head at the valve with the valve center placed at maximum tail water elevation. In this example, the usable head at the valve is estimated to be 80% of the total head of 108 ft, or 86 ft.



From Fig. 3, for 100% valve opening:

$$C = 0.7$$

Then, from Eq. 1

$$A = 25 \text{ sq ft}$$

and

$$d = 5.67 \text{ ft}$$

in which d is the inlet diameter of the valve and also the nominal valve size. Since nominal valve sizes are usually graduated in 6-in. increments,

$$d = 6 \text{ ft}$$

would be selected. Because the selected valve is larger than required, it would not be necessary to open the valve fully to pass the design flow at the maximum head.

Having determined the valve size and therefore the diameter of the supply conduit, the probable head losses in the system from reservoir to valve may be computed. In this example, the computed losses are assumed to be 20 ft, which leaves 88 ft of head at the valve. Using Eq. 1, C is computed to be 0.61; from Fig. 3, the valve opening necessary to pass the design discharge at the design head is 83%.

The basin depth, length, and width may be determined from Figs. 12, 13, 14, and 15 using the head ratio

$$\frac{H}{d} = \frac{88}{6} = 14.67$$

For 83% valve opening, Fig. 12 shows the depth ratio

$$\frac{D}{d} = 3.4$$

The depth of the basin is

$$D = 20.4 \text{ ft}$$

therefore, the apron is placed 20.4 ft below the maximum tail water elevation.

For 83% valve opening, Fig. 14 shows the length ratio

$$\frac{L}{d} = 11.2$$

The length of the basin is

$$L = 67 \text{ ft}$$

For 83% valve opening, Fig. 15 shows the width ratio

$$\frac{W}{d} = 2.5$$

The width of the basin is

$$W = 15 \text{ ft}$$

The dimensions of other components of the basin may be determined from Fig. 11.

The tail water depth at which the flow will sweep from the basin may be determined from Fig. 13. For 83% valve opening, the depth sweep-out ratio

$$\frac{D_s}{d} = 2.7$$

The sweep-out depth is

$$D_s = 16.2 \text{ ft}$$

Since 20.4 ft of depth is provided, the basin has a safety factor against sweep-out of 4.2 ft of tail water depth. In most installations this is sufficient, but if a greater margin of safety is desired, the apron elevation may be lowered

$$0.4 \text{ (d)} = 2.4 \text{ ft}$$

If greater economy and less margin of safety are desired, the basin floor may be placed 2.4 ft higher to provide only 18 ft of depth

If the tail water depth from Fig. 12 is adopted, the water surface profile will be similar to that shown in Fig. 16 (a), since the H/d value of 16 in Fig. 16 (a) is comparable to 14.67 in this example. If tail water depth 2 ft greater or less than the ideal is adopted for the prototype, the water surface profile will be moved up or down accordingly. Water surfaces may be estimated by multiplying the variations shown in Fig. 16 (a) by the quotient obtained by dividing the prototype valve diameter of 72 in. by the mdoel valve diameter of 3 in. Wave heights in the downstream channel will be considerably less as indicated in other photographs showing downstream conditions.

*Two-valve Stilling Basin Design.*—If two valves are to be used to discharge the design flow of 1,300 sec-ft, a double basin with a dividing wall is required. The discharge per valve is 650 cfs, and at 100% valve opening the valve coefficient is 0.7, Fig. 3. The head on the valve is estimated to be 86 ft as in the first example. From Eq. 1, the inlet area of the valve is found to be 12.48 sq ft. A 48-in. valve provides practically the exact area required.

For this example, it is assumed that the computations to determine head losses have been made and that the estimated head of 86 ft at the valves is correct. Therefore, 100% valve opening will be necessary to pass the design flow.

Using the methods given in detail in the first example:

$$\frac{H}{d} = 21.5$$

$$\frac{D}{d} = 4.06, \text{ from Fig. 12}$$

and

$$D = 16.2 \text{ ft}$$

$$\frac{D_s}{d} = 3.3, \text{ from Fig. 13}$$

then

$$D_s = 13.2 \text{ ft}$$



The tail water depth for sweep out is therefore 3.0 ft below the ideal tail water depth. If more or less insurance against the possibility of sweep out is desired, the apron may be set lower or higher by the amount

$$0.4 \text{ (d)} = 1.6 \text{ ft}$$

To aid in determining the apron elevation, the effect of spillway, turbine, or other discharges on the tail water range may need to be considered.

$$\frac{L}{d} = 14.4, \text{ from Fig. 14}$$

then

$$L = 58 \text{ ft}$$

$$\frac{W}{d} = 2.6, \text{ from Fig. 15}$$

then

$$W = 10.4 \text{ ft}$$

Since two valves are to be used, the total width of the basin will be 2(W) plus the thickness of the center dividing wall. The length of the center dividing wall should be three-fourths of the apron length or 43.5 ft long, Fig. 11. If it is certain that both valves will always discharge equally, the wall need be only one-half the apron length or 29 ft long. The hydraulic design of the basin may be completed using Fig. 11.

If the tail water depth determined from Fig. 12 is adopted, the water surface profile for determining wall heights may be estimated by interpolating between Fig. 16 (a) and (b). Water surface variations may be predicted by multiplying values scaled from the photographs by the ratio 48/3.

## PROTOTYPE PERFORMANCE

The Boysen Dam and Falcon Dam outlet works stilling basins, Figs. 1, 6, and 7, fit the design curves derived from the generalized study quite well, and have been field tested and found to perform in an excellent manner. Table 1 shows the important dimensions of these basins and indicates that the values computed from the design curves of this paper are in good agreement with those obtained from the individual model tests.

*Boysen Dam.*—The outlet works basin at Boysen Dam is designed for 1,320 cfs from two 48-in. hollow-jet valves 100% open at reservoir elevation 4725.00. Design tail water elevation at the basin is 4616.00. The model performance of this basin is shown in Figs. 18 and 19.

The prototype tests, Figs. 20, 21, and 22, were conducted with the reservoir at elevation 4723.5 and with the powerplant both operating and shut down. The spillway was not operating. The outlet works discharge was measured at a temporary gaging station located about 1/2 mile downstream from the dam using a current meter to determine the discharge. Tail water elevations were read on the gage located in the powerhouse.

The prototype performed as well as predicted by the model and was considered satisfactory in all respects. However, the field structure entrained more air within the flow than did the model. This caused the prototype flow to appear more bulky, and "white water" extended farther into the downstream channel than was indicated in the model. A comparison of the model and prototype photographs, Figs. 19 and 22, illustrates this difference. Greater air

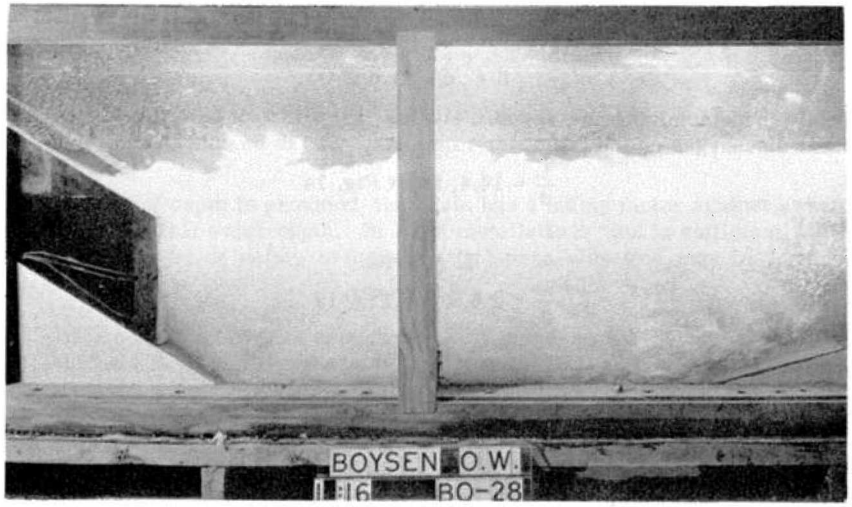



FIG. 18.—BOYSEN DAM, LEFT VALVE OF OUTLET WORKS BASIN, DISCHARGING 660 CFS 1:16 SCALE MODEL

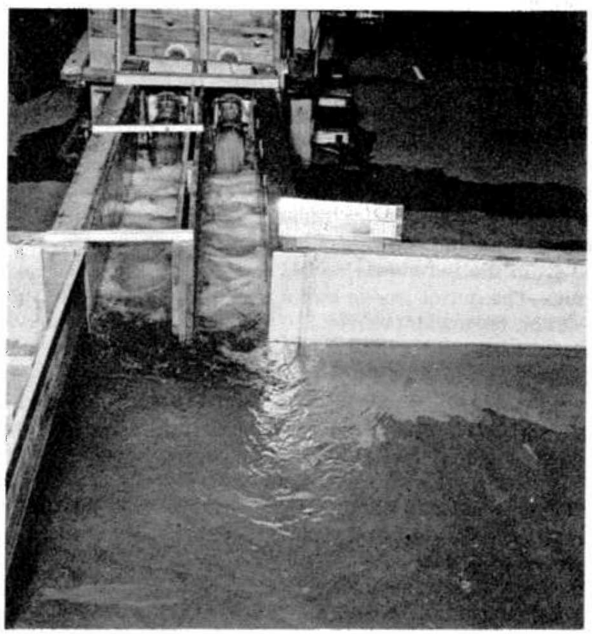


FIG. 19.—BOYSEN DAM, OUTLET WORKS DISCHARGING 1320 CFS 1:16 SCALE MODEL



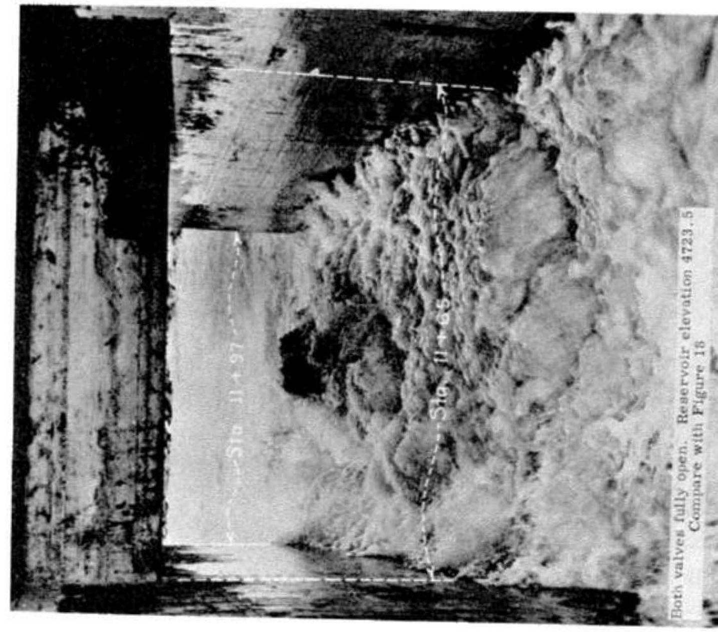



FIG. 21.—BOYSEN DAM, LEFT VALVE OF OUTLET WORKS BASIN DISCHARGING 732 CFS LOOKING DOWNSTREAM

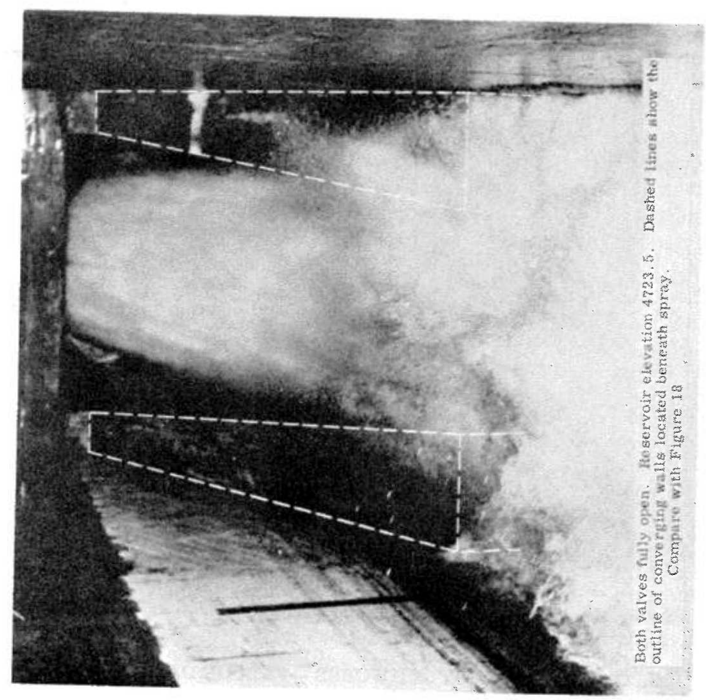



FIG. 20.—BOYSEN DAM, LEFT VALVE OF OUTLET WORKS BASIN DISCHARGING 732 CFS LOOKING UPSTREAM

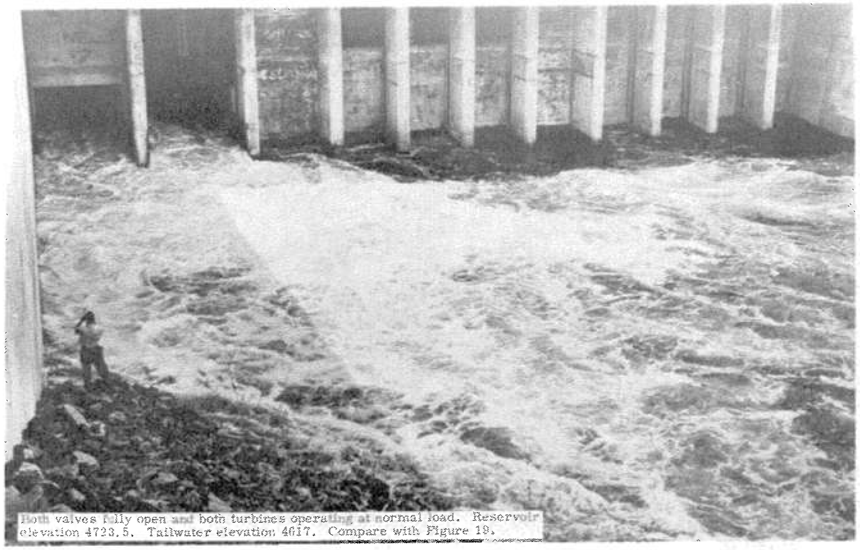



FIG. 22.—BOYSEN DAM OUTLET WORKS DISCHARGING 1344 CFS

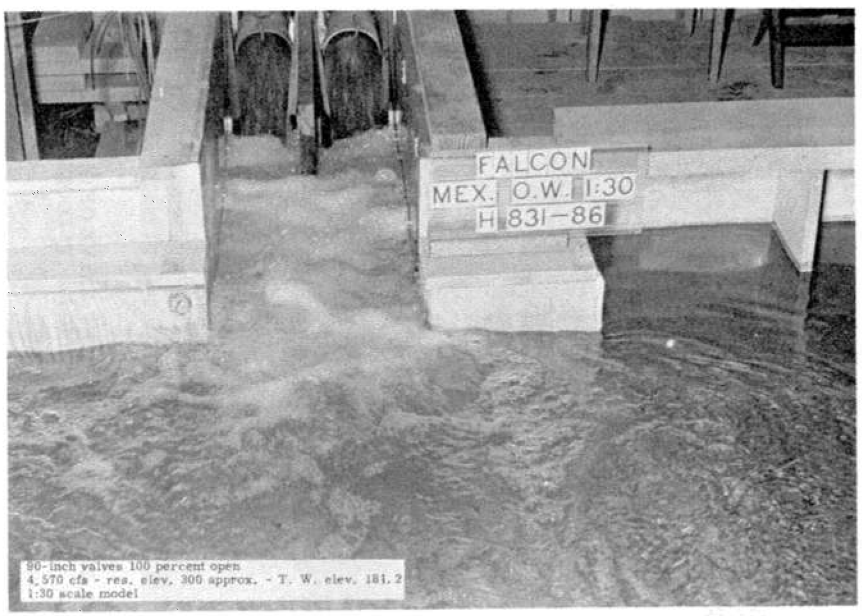



FIG. 23.—MEXICAN OUTLET WORKS - FALCON DAM



entrainment in the prototype is usually found when making model prototype comparisons, particularly when the difference between model and prototype velocities is appreciable. In other respects, however, the prototype basin was as good or better than predicted from the model tests.

For the initial prototype test, only the left outlet valve was operated; the powerhouse was not operating. At the gaging station, the discharge was measured to be 732 cfs after the tail water stabilized at elevation 4614.5. (This is a greater discharge than can be accounted for by calculations. It is presumed that valve overtravel caused the valve opening to exceed 100% even though the indicator showed 100% open.) It was possible to descend the steel ladder, Fig. 1, to closely observe and photograph the flow in the stilling basin, Figs. 20 and 21. The basin was remarkably free of surges and spray; the energy dissipating action was excellent. There was no noticeable vibration at the valves or in the basin. The flow leaving the structure caused only slightly more disturbance in the tailrace than the flow from the draft tubes when the turbines were operating at normal load.

Operation of the prototype provided an opportunity to check the air requirements of the structure, which could not be done on the model. With the inspection cover removed, Fig. 1, the basin was open to the rooms above. Air movements through the inspection opening and in the powerplant structure were negligible, which indicated that ample air could circulate from the partially open end of the stilling basin, Fig. 21.

When both valves were discharging fully open, the tail water stabilized at elevation 4615. A discharge measurement at the gaging station disclosed that both valves were discharging 1,344 cfs. Since the left valve had been found to discharge 732 cfs, the right valve was discharging 612 cfs.

The reason for the difference in discharge is that the 57-inch-inside-diameter outlet pipe to the left valve is short and is connected to the 15-foot-diameter header which supplies water to the turbines, Fig. 1. The right valve is supplied by a separate 66-inch-diameter pipe extending to the reservoir. Therefore, greater hydraulic head losses occur in the right valve supply line, which accounts for the lesser discharge through the right valve. Although it was apparent by visual observation that the left valve was discharging more than the right valve, Fig. 22, no adverse effect on the performance of the outlet works stilling basin or on flow conditions in the powerhouse tailrace could be found.

The outlet works basin performance was also observed with the turbines operating and the tail water at about elevation 4617. No adverse effects of the outlet works discharge on powerplant performance could be detected. Flow conditions in the tailrace area were entirely satisfactory, Fig. 22. Since the tests were made at normal reservoir level and maximum discharge, the stilling basin was subjected to a severe test.

*Falcon Dam.*—The outlet works basin on the Mexico side at Falcon Dam is designed to accommodate 4,570 cfs from two 90-in. valves or 2,400 cfs from one valve, with the valves 100% open and the reservoir at elevation 300. The tail water elevation is 181.2 when the powerplant is discharging 5,400 cfs in conjunction with both valves. The model performance of this basin is shown in Figs. 23 and 24.

The outlet works basin on the United States side at Falcon Dam is designed to discharge 2,920 cfs from two 72-in. valves, or 1,600 cfs from one valve, with the valves 100% open and the reservoir at elevation 310. Tail water is at

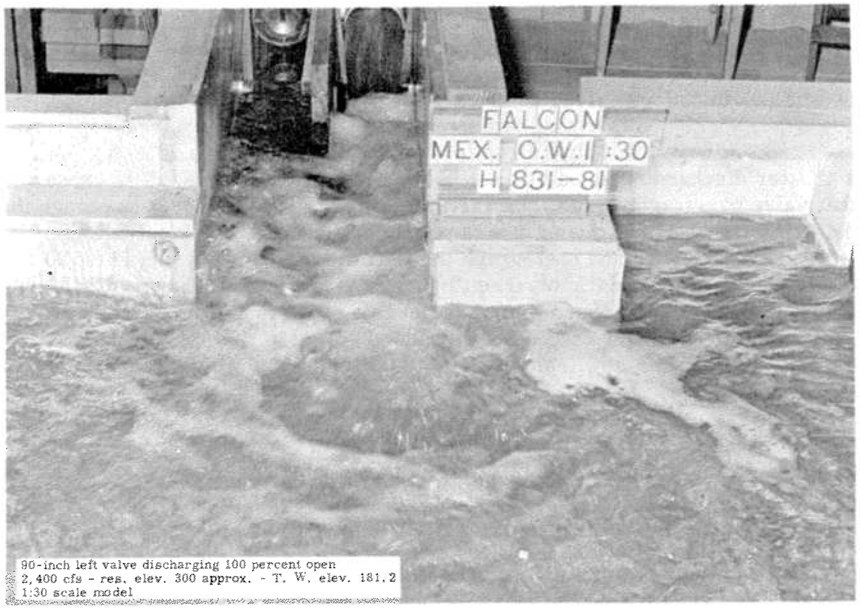



FIG. 24.—MEXICAN OUTLET WORKS - FALCON DAM

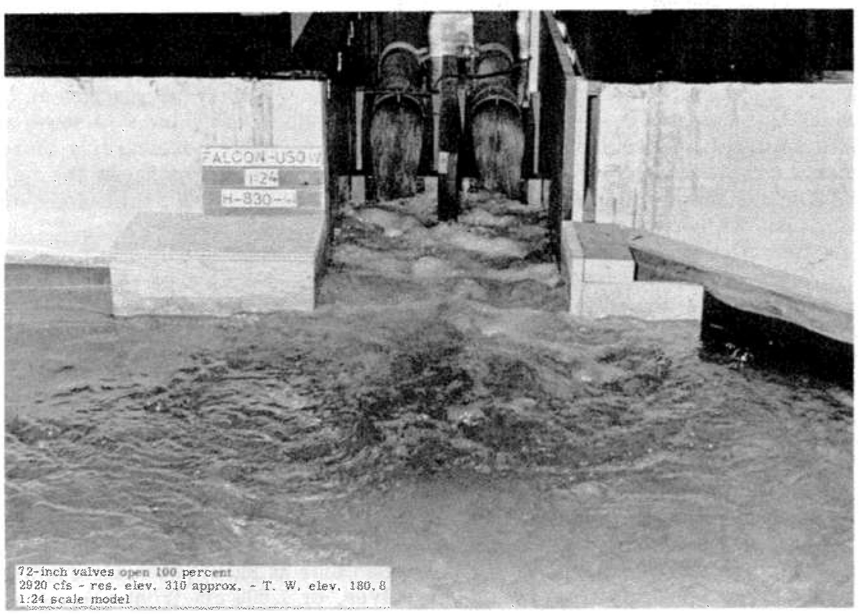



FIG. 25.—UNITED STATES OUTLET WORKS - FALCON DAM



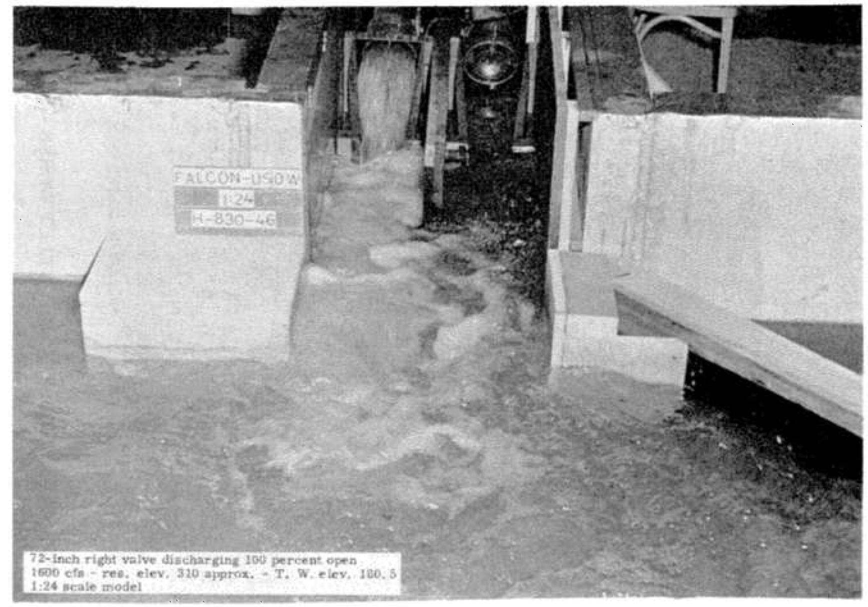



FIG. 26.—UNITED STATES OUTLET WORKS - FALCON DAM

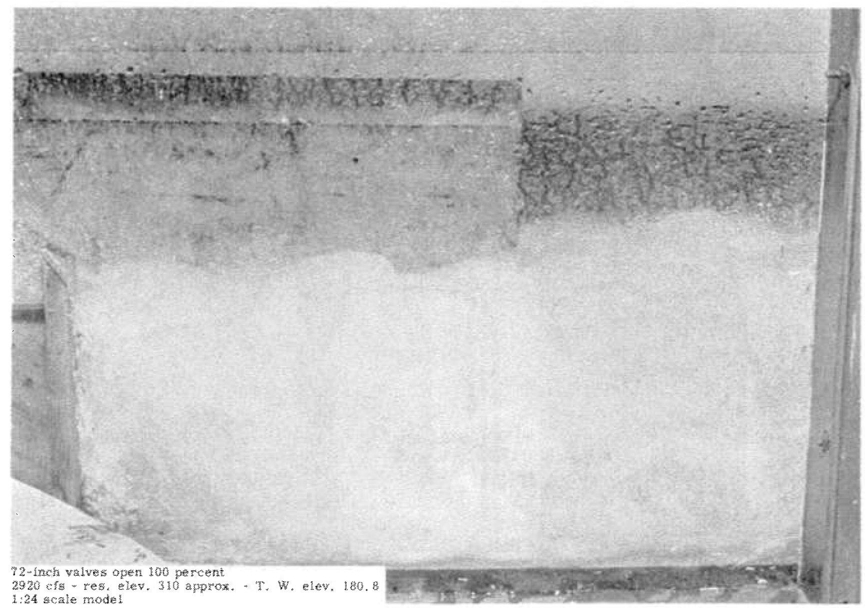
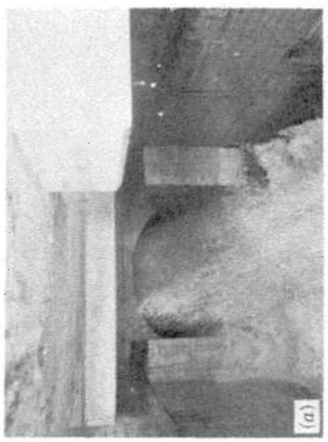



FIG. 27.—UNITED STATES OUTLET WORKS - FALCON DAM



90-inch left valve discharging - 100 percent open
2,300 cfs approx. - res. elev. 301.83. - T. W. elev. 183.0
Compare with Figure 24

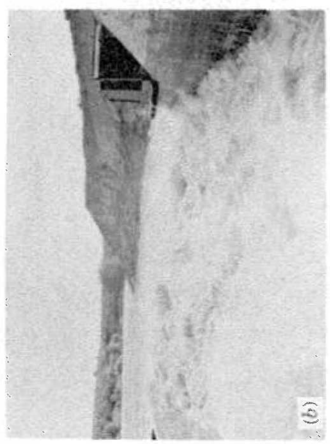
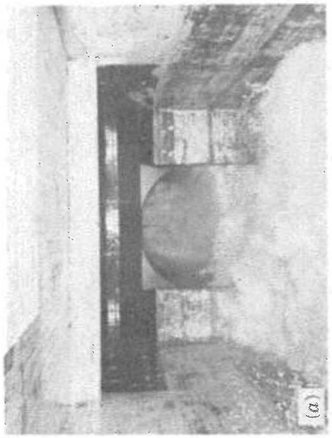


FIG. 28.—MEXICAN OUTLET WORKS - FALCON DAM



72-inch left valve discharging 100 percent open
1,750 cfs approx. - res. elev. 301.83 - T. W. elev. 182.7
Compare with Figures 26 & 27

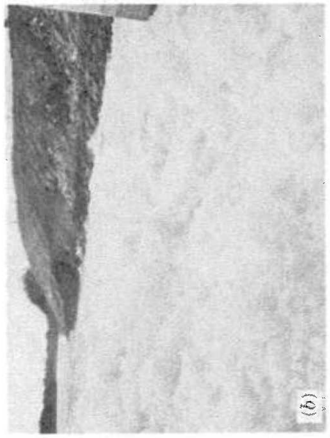
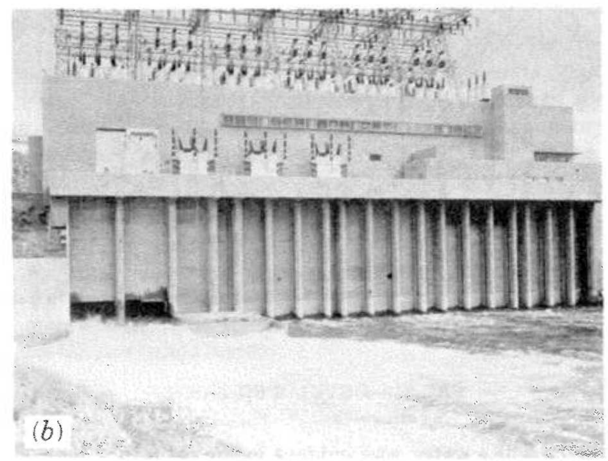


FIG. 29.—UNITED STATES OUTLET WORKS - FALCON DAM



90-inch outlet works valves open 100 percent discharging
4,500 cfs approx. - T. W. elev. 183.6.
Turbine gates 72 percent open - 100 percent load.



72-inch outlet works valves open 100 percent discharging
3,000 cfs approx. - T. W. elev. 184.1.
Turbine gates 72 percent open - 100 percent load.

FIG. 30.—FALCON DAM MEXICAN & UNITED STATES POWER-PLANTS & OUTLET WORKS DISCHARGING AT RESERVOIR ELEVATION 301.83.

elevation 180.8 when two valves are operating and 180.5 when one valve is operating. The model performance of this basin is shown in Figs. 25, 26, and 27.

The prototype tests at Falcon, Figs. 28, 29, and 30, were conducted at near maximum conditions; the reservoir was at elevation 301.83, and the valves were 100% open. In each outlet works, the valves were operated together and individually. Single-valve operation represents an emergency condition and subjects the stilling basin to the severest test, Figs. 28 and 29. All turbines at both powerplants were operating at 72% gate and 100% load during all tests. The prototype valve discharges were determined from discharge curves based on model test data.

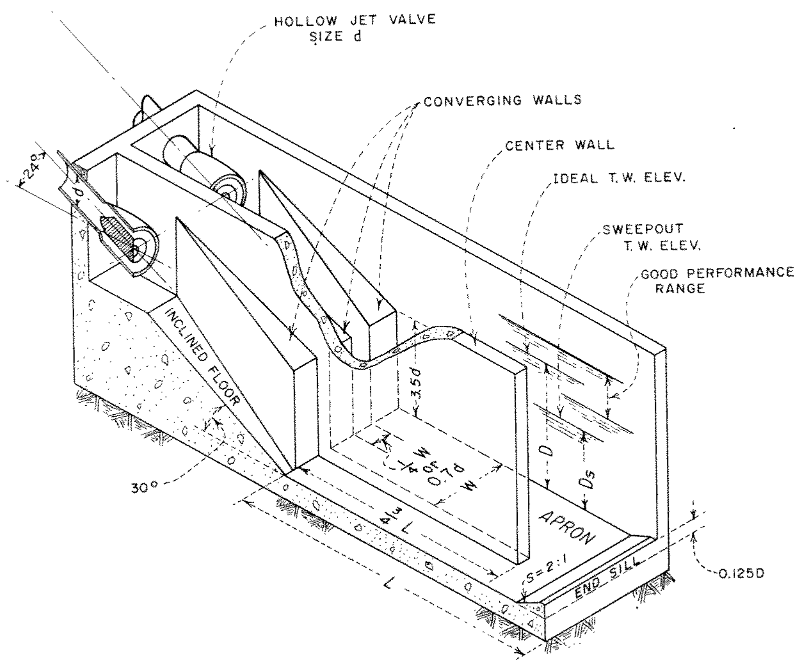



FIG. 31.—DEVELOPED BASIN

Here, too, more white water was evident in the prototype than in the model. The greater amount of air entrainment in the prototype, evident in the photographs, caused bulking of the flow at the end of the stilling basin and a higher water surface than was observed in the model. However, the prototype tail water is 3 ft to 4 ft higher than shown in the model photograph, and this probably helps to produce a higher water surface boil at the downstream end of the basin by reducing the efficiency of the stilling action. In other respects, the prototype basin performed as predicted by the model.



## CONCLUSIONS

The schematic drawing, Fig. 31, shows the developed basin and the relationships between important dimensions.

A brief description of the seven steps required to design a stilling basin is given below:

1. Using the design discharge Q, the total head at the valve H, and the hollow-jet valve discharge coefficient C from Fig. 3, solve the equation $Q = C\,A\,\sqrt{2\,g\,H}$ for the valve inlet area A and compute the corresponding diameter d which is also the nominal valve size.
2. Use H/d in Fig. 12 to find D/d and thus D, the ideal depth of tail water in the basin. Determine the elevation of the basin floor, tail water elevation minus D. It is permissible to increase or decrease D by as much as 0.4 (d).
3. Use H/d in Fig. 14 to find L/d and thus L, the length of the horizontal apron.
4. Use H/d in Fig. 15 to find W/d and thus W, the width of the basin for one valve.
5. Use H/d in Fig. 13 to find $D_S/d$ and thus $D_S$, the tail water depth at which the action is swept out of the basin. D minus $D_S$ gives the margin of safety against sweep out.
6. Complete the hydraulic design of the basin from the relationships given in Fig. 11.
7. Use the H/d ratio to select the proper photograph in Figs. 16 and 17 to see the model and help visualize the prototype performance of the design. The water surface profile may be scaled from the photograph using the scale on the photograph. To convert to prototype dimensions, multiply the scaled values by the ratio d (in.)/3.

Stilling basin dimensions calculated as indicated above are in close agreement with the dimensions obtained from individual model tests of the basins for Boysen, Falcon, Yellowtail, Trinity, and Navajo Dams, Table 1. Since the Boysen and Falcon basins performed satisfactorily during prototype tests, it is believed that satisfactory future projects may be hydraulically designed from the material presented herein.

## ACKNOWLEDGMENTS

Data and material used in this paper were obtained through cooperation of individuals too numerous to acknowledge singly, yet their wholehearted interest aided materially in providing a complete analysis of the problem. Their assistance is gratefully acknowledged.

The hollow-jet valve stilling basin was developed in the Hydraulic Laboratory, Division of Engineering Laboratories, through close coordination with the Mechanical Branch and the Dams Branch of the Divsioni of Design, all of the Bureau of Reclamation, Assistant Commissioner and Chief Engineer's Office, Denver, Colorado.

The prototype tests at Boysen Dam were made with the cooperation of the Bureau's Region 6 office in Billings, Montana, and the Yellowstone-Bighorn Projects Office, Cody, Wyoming. Bureau personnel at Boysen Dam operated the hydraulic structures and assisted in obtaining data. United States Geological Survey personnel at Riverton, Wyoming, made the river gagings, and State of Wyoming personnel made downstream river adjustments to permit above-normal discharges.

The prototype tests at Falcon Dam, which included tests on both the United States and Mexico outlet works and powerplants, were conducted by personnel at Falcon Dam through arrangements with the International Boundary and Water Commission, El Paso, Texas.