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# HYDRAULIC MODEL STUDIES OF NAVAJO DAM AUXILIARY OUTLET WORKS AND HOLLOW-JET VALVE BYPASS - MODIFICATIONS TO REDUCE DISSOLVED GAS SUPERSATURATION

Engineering and Research Center
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16. ABSTRACT

It has been observed that operation of the auxiliary outlet works and the 762-mm (30-inch) hollow-jet valve bypass at Navajo Dam result in high levels of dissolved gas supersaturation in released waters. These high dissolved gas levels, which are caused by the deep penetration of the flow into the spillway stilling basin pool, have had adverse effects on the fishery. Structural modifications were considered which included a flattening of the trajectory of the jet from the 762-mm (30-inch) bypass and the addition of a deflector or flip lip to the auxiliary outlet works. A 1:48 scale hydraulic model was used to refine and evaluate these modifications. Depth of jet penetration, degree of energy dissipation, strength of back eddies returning into the stilling basin, potential for cavitation development below the flip lip, and simplicity of design were factors considered in the evaluation.


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by

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Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION

## ACKNOWLEDGMENT

The final plans that evolved from this study were developed through the cooperation of the staffs of the Spillways, Outlets, and Experimental Analysis Section, Dams Branch, Division of Design, and the Hydraulics Branch, Division of General Research, during the period March through July 1975. The hydraulic model study was conducted by the author and reviewed by T. J. Rhone, Head, Applied Hydraulics Section, under the general supervision of D. L. King, Chief, Hydraulics Branch.

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## PURPOSE

These studies were made to aid in developing satisfactory modifications for the auxiliary outlet works and the 762-mm (30-in) hollow-jet valve bypass at Navajo Dam, N. Mex. The modifications would reduce dissolved gas supersaturation levels created by the operating prototype structures (fig. 1).[1]

## RESULTS

1. Reducing the downward angle of the 762-mm (30-in) hollow-jet valve from 24° to 15° (fig. 2) should reduce the expected maximum dissolved gas supersaturation level from 123 percent to 112 percent.

2. The 762-mm hollow-jet valve, directed downward at an angle of 15°, was found to operate satisfactorily in all aspects. The maximum wave height at downstream riprapped surfaces was 305 mm (12 in), the maximum velocity in back eddies returning into the stilling basin was 229 mm/s (9 in/s), and the maximum depth of jet penetration was 5.8 meters (19 feet).

3. A flip lip placed on the auxiliary outlet works (fig. 3) at elevation 1742.15 m (5715.72 ft) should reduce expected maximum dissolved gas supersaturation levels from 150 percent to 104 percent. Included in the flip lip design was an expanding section (upstream of the lip) which spread the flow and thus eliminated a concentrated surface jet.

4. The flip lip produced satisfactory auxiliary outlet works operation in all respects. The maximum observed wave height on downstream riprap was 671 mm (2.2 ft), the maximum depth of flow penetration was 4.3 m (14 ft), the maximum velocity in back eddies returning into the basin was 640 mm/s (2.1 ft/s), and the structure is expected to be cavitation-free.

5. Spillway operation over the flip lip was satisfactory. However, because only a portion of the spillway flow is affected by the flip, the flip will not greatly reduce dissolved gas supersaturation levels created by spillway operation. The maximum observed wave heights at downstream riprapped surfaces were 762 mm (2.5 ft) at a discharge of 283.2 $m^3/s$ (10,000 $ft^3/s$), 1372 mm (4.5 ft) at 566.3 $m^3/s$ (20,000 $ft^3/s$), and 1829 mm (6.0 ft) at 962.8 $m^3/s$ (34,000 $ft^3/s$). Maximum observed velocities in back eddies were very small and in many cases there were no back eddies. Although negative pressures[2] were observed below the flip lip, no pressures were noted that were severe enough to indicate a potential for cavitation damage.

6. The expanding section (upstream from the flip lip) was initially tested with a crown down the center of its invert (fig. 2). The crown, which was to aid in spreading the flow, actually overspread the flow and created concentrations at the outside limits. An expanding section with a flat invert (fig. 3) was tested and found to adequately spread the flow. Because the structure with the flat invert was also simpler to construct, it was selected for the final design.

## APPLICATIONS

Application of the specific results of these studies is limited to structures that are very similar to those observed. Resulting dissolved gas levels, wave heights, back eddies, and pressures on surfaces are not only a function of structure configuration but are also affected by stilling basin depth, discharge, and flow velocity. Thus, unless all of these factors are quite similar to those studied, it would be difficult to apply the results of these tests to another structure. However, the design concepts presented may provide initial direction for studies of structures with similar problems.

## INTRODUCTION

It has been observed that some hydraulic structures may create supersaturated dissolved gas levels in the waters they release. Dissolved gas supersaturation is a condition in which the water holds more dissolved gases (mainly oxygen and nitrogen) than it would naturally hold. Generally, supersaturated conditions result at hydraulic structures because of the phenomenon that water can hold more dissolved gas when under pressure. At many structures, air bubbles carried by the flow will penetrate to the bottom of deep pools where the pressure is high. Under these conditions, relatively large amounts of air are dissolved. The pressure is reduced as the water slowly rises and leaves the pool, yet large amounts of dissolved gas remain in solution. Dissolved gas supersaturation therefore develops. Such supersaturation is not a stable condition and, with time, the gas will tend to come out of solution and reduce the supersaturation levels. Significant reduction may take minutes or days, depending on the amount of water turbulence. The reason for

[1] Dimensions used in this report refer to the prototype structure, unless otherwise stated.

[2] All pressures in this report are gage values.

concern with this problem is that the blood of fish swimming in the supersaturated water will also become supersaturated. If the dissolved gas level is sufficiently high, bubbles may form in the blood and the fish would get a disease similar to the bends experienced by human divers. The disease may result in permanent damage and can even be fatal.

Two structures where supersaturation has been of particular concern are the auxiliary outlet works and 762-mm (30-in) hollow-jet valve bypass at Navajo Dam in northwestern New Mexico (fig. 1). Relatively high supersaturation levels have been observed at both structures. On two occasions, fish kills have been observed.

The auxiliary outlet works (figs. 1 and 4) consists of a submerged intake which leads to a 533-m (1750-ft) long, nearly horizontal tunnel, which exits at the spillway stilling basin (the deep pool). The flow is controlled by 1219- by 1219-mm (4- by 4-ft) tandem outlet gates located approximately halfway through the tunnel. There is free flow between the control gates and the stilling basin. The flow enters the stilling basin through a slot in the spillway chute floor. The maximum discharge capacity of the auxiliary outlet works is 45.3 $m^3/s$ (1,600 $ft^3/s$).

The 762-mm (30-in) hollow-jet valve bypass (figs. 1 and 5) receives water from the pressure tunnel which also supplies the 1829-mm (72-in) hollow-jet valves. The 1829-mm (72-in) hollow-jet valve tunnel, as with the auxiliary outlet works tunnel, has a submerged intake from the reservoir. The hollow-jet valve bypass is located at the top of the left spillway stilling basin sidewall, approximately 4.6 m (15 ft) above the tailwater surface. The valve is directed downward at an angle of 24°. The valve's maximum discharge capacity is 11.3 $m^3/s$ (400 $ft^3/s$).

Flows leaving both structures penetrate the tailwater to the floor of the spillway stilling basin, thus exposing the air-water mixtures from the structures to pressures equal to approximately 12.2 m (40 ft) of water. It was proposed that the auxiliary outlet works entrance to the stilling basin pool be redesigned (fig. 3) so that the flow will be deflected across the tailwater surface thus reducing penetration. This structure is referred to as a flip lip. Likewise, it was proposed that the downward angle of the bypass be reduced from 24° to 15° (fig. 3) which also would reduce penetration. Both modifications would reduce resulting supersaturation by reducing flow penetration levels.

A hydraulic model study was initiated to observe the performance of the modifications and to optimize the design. The study had five basic objectives.

- Determine wave heights along riprap surfaces downstream from the stilling basin. – Wave heights were a concern because rough surface action was expected to develop with the more shallow penetration. The deep penetration was included in the original design because it caused a high degree of energy dissipation. This level of energy dissipation resulted in a smooth water surface and therefore a minimum threat of erosion to riprap surfaces. Skimming the flow from the structures across the surface develops the maximum wave potential, thus creating the possibility of erosion damage in the downstream channel. Therefore, observing wave heights along model riprap surfaces helped to evaluate the likelihood of erosion damage and determine the need for additional riprap protection.

- Determine the strength of back eddies that may return to the stilling basin underneath the outgoing surface flows. – Back eddies flowing into the stilling basin, below-surface flows leaving the basin, have been observed at many structures. These eddies may have sufficient velocity to carry rock and sediment into the basin. This material may then be moved around in the basin by currents and cause erosion damage to the concrete. Velocities in the back eddies were measured in the model to insure that bed material movement and the resulting erosion would not occur. The velocities were measured at the bottom just downstream of the end sill of the stilling basin. The flow at this location is important because it supplies the force to carry the material into the basin.

- Determine pressures just downstream of the lip of the auxiliary outlet works flip structure to assure cavitation-free operation. – Pressures just downstream of the flip lip were a concern because of the close proximity of the lip to the tailwater surface. It is possible that the region under the flow coming off the lip would be submerged, and therefore the underside of the flow would not be vented. If this was the case, the potential exists for the development of strong negative pressures between the jet and the spillway face, which could result in cavitation.

- Determine and try to minimize the depth of penetration of the flows from the two structures into the spillway stilling basin. — Because depth of flow penetration directly controls the level of supersaturation, resulting penetration depths were of concern throughout the study. A predictive analysis developed by Johnson [1] * allowed the conversion of these penetration depths into resulting supersaturation levels. Decisions could then be made on the acceptability of these levels.

- Minimize size, complexity, and cost of the structural modifications. — The last of the five objectives was to reduce the cost of the modifications. This includes reducing the size of the structure, simplifying the design of the structure, and using the simplest construction methods.

## THE MODEL

The hydraulic model (fig. 6) was constructed to a scale of 1:48 to allow use of an existing head box At this scale, very little work was required on the head box and thus a major expense was eliminated. Included in the model were:

- Head box. — Heads ranging from zero to the full reservoir head (119 m (390 ft)) could be developed.

- Lower half of the spillway. — This was sufficient to allow correct modeling of the spillway flow over the flip lip structure. The spillway was supplied through a slide gate, which allowed the development of the full reservoir head and correct velocities on the spillway.

- Auxiliary outlet works entrance to the stilling basin, supplied through a valved conduit from the head box. — Included with the conduit were a gate valve and a slide gate which allowed independent operation of the auxiliary outlet works. A 15.2-m (50-ft) length of the tunnel upstream from the flip lip structure was also modeled. The flip lip section was constructed to allow quick modification. A portion of the spillway face could be removed for access to a box which contained removable ribs. The ribs could be cut to the shape of the structural cross sections. The areas between the ribs were filled with modeling clay to yield the desired contour.

- Stilling basin and downstream topography. — Included in the model were all of the spillway stilling basin and all topography within 61 m (200 ft) on either side of the spillway centerline to a point 76 m (250 ft) downstream from the end sill of the stilling basin.

- The 762-mm (30-in) hollow-jet valve bypass. — The hollow-jet valve bypass was fed by a valved conduit from the head box The valve was modeled with the valve needle fixed at full open.

The 119-m (390-ft) maximum drop from the reservoir water surface to the tailwater surface was modeled as 2.5 m (8.1 ft). The 59.4-m (195-ft) stilling basin width was modeled as 1250-mm (4.1-ft). The 962.8-$m^3$/s (34,000-$ft^3$/s) maximum spillway discharge was modeled as 60.3 $\ell$/s (2.13 $ft^3$/s). The 45.3-$m^3$/s (1,600-$ft^3$/s) maximum auxiliary outlet works discharge was modeled as 2.8 $\ell$/s (0.10 $ft^3$/s) and the 11.3-$m^3$/s (400-$ft^3$/s) maximum bypass discharge was modeled as 0.708 $\ell$/s (43.2 $in^3$/s).

It was possible to independently operate the spillway, bypass, and auxiliary outlet works. Discharges were measured with venturi and venturi-orifice meters.

## THE INVESTIGATION

Initially, the model was studied to verify that the created flow conditions were representative of true prototype conditions. Of main concern was the spillway where the configuration of the upper portion of the structure had been modified to simplify model construction. Water surface profiles in the chute and photographs of the stilling basin action that had been obtained by Beichley [2] in the original model study were used as a guide. The flow distribution on the chute was then manipulated until a satisfactory duplication was obtained. Manipulation was primarily done with guide vanes and with a canvas tarp that was laid on the water surface. In addition, observation of the operating bypass indicated that the valve needle support vanes (which had been simplified in the model) required streamlining to obtain satisfactory flow representation. The vanes were streamlined and satisfactory flow conditions were obtained. All other flow characteristics were found to be satisfactory.

With the completion of the model verification, the investigation was started. For each structural and operational condition observed, wave height, back eddy strength, flip lip pressures, and penetration depth were measured. The wave height data collected were crest-to-trough amplitude for the largest waves observed. The wave height data were collected on the

*Numbers in brackets refer to references at end of the report.

right bank (looking in the direction of flow) approximately 61 m (200 ft) downstream from the end of the stilling basin.

This location (fig. 1) was selected because the wave action was representative of typical conditions. The back eddy velocity data were taken just above the bottom and just downstream of the end sill. The velocity data were collected with a small propeller meter at quarter points across the channel. Average velocities over 1-minute (prototype) intervals were measured. Since the velocity fluctuates, the short time interval was selected because it yielded values closer to the instantaneous maximum values that occur. Five velocity readings were taken at each position for each flow condition. The highest of the five comprise the velocities presented in this report. The flip lip pressures were measured with three piezometers placed just downstream of the lip (fig. 3). This region is the least likely to be vented and the most likely to develop critically low pressures. The piezometers were attached to electronic pressure transducers which allowed monitoring of instantaneous pressures. Output from the transducers was recorded on a strip chart. Representative portions of these strip chart recordings are presented in the report for significant conditions. The data are also presented as average maximum pressures (an average of instantaneous maximum pressures), average minimum pressure (an average of instantaneous minimum pressures), and average pressures. Finally, portions of the walls of the model stilling basin were constructed of clear plastic to allow visual evaluation and measurement of penetration depth of discharge. Data collection began with the initially proposed auxiliary outlet works flip lip installed (figs. 2 and 7). The spillway was operated at discharges of 283.2, 566.3, and 962.8 $m^3/s$ (10,000, 20,000, and 34,000 $ft^3/s$) (fig. 8). The auxiliary outlet works were operated at 11.3 (fig. 9), 28.3 (fig. 10), and 45.2 $m^3/s$ (fig. 11) (400, 1,000 and 1,600 $ft^3/s$) The bypass was operated at 11.3 $m^3/s$ (400 $ft^3/s$), which is its maximum discharge rate (fig. 12). For each structure and discharge setting, data were collected at several tailwater elevations. A wide range of tailwater elevations required study because the powerplant and river outlet works may operate separately from the spillway stilling basin structures and their operation affects the tailwater elevation. The tailwater elevation range considered was determined from figure 13 (where the discharge used was the combined total of all possible discharges for the condition being studied).

The data obtained from the initial flip lip design are summarized in table 1.

It can be seen that the spillway releases tended to create the largest waves along the downstream riprapped surfaces. Waves as high as 1.8 m (6 ft) (trough to crest) occurred with the spillway operating at maximum discharge. At a spillway discharge of 283.2 $m^3/s$ (10,000 $ft^3/s$), the observed waves were less than 610 mm (2 ft) high. The largest waves observed, when only the auxiliary outlet works was operating, were approximately 610 mm (2 ft) high. Generally, for auxiliary outlet works operation and for bypass operation, the observed wave heights along the riprap surfaces were less than 305 mm (12 in). It was concluded that the modifications did not create excessive wave action and that the existing riprap should be more than adequate for all conditions except possibly when spillway discharges are above 566.3 $m^3/s$ (20,000 $ft^3/s$).

The inward velocities in the back eddies (table 1) indicate that with only the auxiliary outlet works operating, the highest velocities were measured and that the greater the discharge from the auxiliary outlet works, the greater the velocities. By studying flow patterns in the model, it was found that the auxiliary outlet works created a strong surface current which in turn resulted in the back eddy formation (fig. 14). As the discharge increased, so did the strength of the surface current, which strengthened the back eddies. The maximum bottom velocities observed were approximately 610 mm/s (2 ft/s). Somewhat similar flow conditions were observed with the bypass except that only one large eddy was created which had flow exiting the basin on the right side (looking in the direction of flow) and reentering the basin on the left (fig. 15). The maximum inward velocities observed were less than 305 mm/s (1 ft/s). Conversely, spillway operation showed very little back eddy formation. Although some of the spillway flow was deflected by the flip lip, the majority of the flow penetrated to the bottom of the basin and then moved downstream. This flow negated the tendency for back eddy formation created by the flip.

Because the bottom of the channel downstream of the basin is riprap lined, movement of material into the basin was considered unlikely and the back eddy velocities were accepted.

The pressures below the auxiliary outlet works flip lip were found to be generally acceptable. As can be seen in table 1, the lowest average pressures occurred when the spillway was operating at 283.2 or 566.3 $m^3/s$ (10,000 or 20,000 $ft^3/s$). When the spillway was operated at 962.8 $m^3/s$ (34,000 $ft^3/s$), the tailwater

Table 1. — *Data summary — Initial modification design*

| OPERATING STRUCTURE | DISCHARGE RATE: $m^3/s$ ($ft^3/s$) † | TAILWATER ELEVATION: METERS (FEET) | MAXIMUM INWARD VELOCITY IN BACK EDDIES: mm/s (ft/s) | MAXIMUM DEPTH OF PENETRATION: METERS (FEET) | WAVE HEIGHTS: METERS (FEET) | PREDICTED RESULTING % OF DISSOLVED GAS | PIEZOMETER 1 * | | | PIEZOMETER 2 * | | | PIEZOMETER 3 * | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | AVG. PRESSURE METERS HEAD (FT OF WATER) | AVERAGE MAXIMUM | AVERAGE MINIMUM | AVG. PRESSURE METERS HEAD (FT OF WATER) | AVERAGE MAXIMUM | AVERAGE MINIMUM | AVG. PRESSURE METERS HEAD (FT OF WATER) | AVERAGE MAXIMUM | AVERAGE MINIMUM |
| Spillway (with initial aux outlet modification) | 283.2 (10,000) | 1742.24 (5716) | 131 (0.43) | 12.5 (41) | 0.43 (1.4) | | -1.04(-3.4) | 0 | -3.66(-12.0) | -0.58(-1.9) | 0 | -1.16(-3.8) | -0.43(-1.4) | 0.58(1.9) | -1.16(-3.8) |
| | | 1742.54 (5717) | | 12.8 (42) | 0.52 (1.7) | | -0.88(-2.9) | 0.30(1.0) | -4.39(-14.4) | -0.15(-0.5) | -1.04(3.4) | -0.88(-2.9) | 0 | 0.58(1.9) | -1.04(-3.4) |
| | | 1742.85 (5718) | 219 (0.72) | 13.1 (43) | 0.61 (2.0) | | -1.31(-4.3) | 0 | -4.08(-13.4) | 0 | 0.88(2.9) | -0.73(-2.4) | 0 | 1.31(4.3) | -1.04(-3.4) |
| | 566.3 (20,000) | 1742.69 (5717.5) | All outward | 13.0 (42.5) | 1.16 (3.8) | | -1.46(-4.8) | 0 | -3.23(-10.6) | -0.43(-1.4) | -0.30(-1.0) | -0.73(-2.4) | 0 | 0.30(1.0) | -0.58(-1.9) |
| | | 1743.00 (5718.5) | | 13.3 (43.5) | 1.22 (4.0) | | -1.46(-4.8) | -0.30(-1.0) | -3.66(-12.0) | -0.43(-1.4) | -0.15(-0.5) | -0.88(-2.9) | 0.15(0.5) | 0.43(1.4) | -0.88(-2.9) |
| | | 1743.30 (5719.5) | All outward | 13.6 (44.5) | 0.91 (3.0) | | -1.46(-4.8) | -0.15(-0.5) | -4.08(-13.4) | -0.43(-1.4) | 0 | -1.04(-3.4) | 0.15(0.5) | 0.58(1.9) | -1.16(-3.8) |
| | 962.8 (34,000) | 1743.15 (5719) | All outward | 13.4 (44) | 1.52 (5.0) | | -0.73(-2.4) | 0 | -1.77(-5.8) | 0.73(2.4) | 0.73(2.4) | 0.73(2.4) | 0.30(1.0) | 0.58(1.9) | -0.15(-0.5) |
| | | 1743.46 (5720) | All outward | 13.7 (45) | 1.83 (6.0) | | -0.73(-2.4) | -0.15(-0.5) | -1.77(-5.8) | 1.04(3.4) | 1.04(3.4) | 1.04(3.4) | 0.30(1.0) | 0.43(1.4) | -0.15(-0.5) |
| | | | | | | | | | | | | | | | |
| Auxiliary outlet (initial modification) | 45.3 (1,600) | 1741.63 (5714) | 582 (1.91) | 4.3 (14) | 0.67 (2.2) | 106% $N_2$ | 0 | 0.15(0.5) | -0.30(-1.0) | 0 | 0.30(1.0) | -0.43(-1.4) | 0 | 0.15(0.5) | -1.16(-3.8) |
| | | 1741.93 (5715) | | 4.0 (13) | 0.43 (1.4) | 97% $O_2$ | 0 | 0.15(0.5) | -2.50(-8.2) | 0.30(1.0) | 0.58(1.9) | 0 | 0.15(0.5) | 0.30(1.0) | -0.30(-1.0) |
| | | 1742.54 (5717) | 634 (2.08) | 2.7 (9) | 0.21 (0.7) | | -0.43(-1.4) | 0.15(0.5) | -1.31(-4.3) | 1.04(3.4) | 1.31(4.3) | 0.73(2.4) | 0.58(1.9) | 0.88(2.9) | 0.30(1.0) |
| | 28.3 (1,000) | 1741.47 (5713.5) | 396 (1.30) | 2.9 (9.5) | 0.27 (0.9) | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 1741.93 (5715) | | 3.0 (10) | 0.21 (0.7) | | -0.43(-1.4) | 0.15(0.5) | -1.77(-5.8) | -0.15(-0.5) | 0 | -0.30(-1.0) | 0.15(0.5) | 0.30(1.0) | -0.15(-0.5) |
| | | 1742.54 (5717) | 360 (1.18) | 4.3 (14) | 0.21 (0.7) | | 0.15(0.5) | 0.88(2.9) | -1.04(-3.4) | 0.88(2.9) | 1.16(3.8) | 0.58(1.9) | 0.73(2.4) | 0.88(2.9) | 0.58(1.9) |
| | 11.3 (400) | 1741.93 (5715) | 290 (0.95) | 1.2 (4) | 0.15 (0.5) | | -0.43(-1.4) | 0.30(1.0) | -1.04(-3.4) | -0.43(-1.4) | -0.30(-1.0) | -0.58(-1.9) | -0.15(-0.5) | 0.30(1.0) | -0.43(-1.4) |
| | | 1741.78 (5714.5) | | 1.4 (4.5) | 0.15 (0.5) | | -0.15(-0.5) | 0.15(0.5) | -1.04(-3.4) | -0.58(-1.9) | -0.30(-1.0) | -1.04(-3.4) | 0.15(0.5) | 0.30(1.0) | -0.43(-1.4) |
| | | 1741.63 (5714) | | 1.8 (6) | 0.15 (0.5) | | 0 | 0.15(0.5) | -0.15(-0.5) | -0.30(-1.0) | 0 | -0.73(-2.4) | 0 | 0.15(0.5) | -0.30(-1.0) |
| | | 1741.02 (5712) | 247 (0.81) | 3.7 (12) | 0.15 (0.5) | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | | | | | | | | | |
| 762-mm bypass (directed downward at 15°) | 11.3 (400) | 1742.08 (5715.5) | 216 (0.71) | 4.7 (15.5) | | | | | | | | | | | |
| | | 1741.32 (5713) | 168 (0.55) | 5.8 (19) | | 114% $N_2$ 108% $O_2$ | | | | | | | | | |

* All pressures are gage values.

† Numbers in parenthesis are English equivalents of the metric values next to them, as indicated in the heading.

surface was drawn down by the penetrating flow, which allowed partial venting of the underside of the jet leaving the lip. This partial venting reduced the magnitude of the negative pressure under the lip. Strip chart pressure data collected for spillway operation are shown in figure 16. Table 1 shows that changes in the tailwater elevation do not significantly affect the pressures that result from spillway operation.

Although average and average minimum pressures observed for auxiliary outlet works operation were higher than those observed for spillway operation, the largest magnitude instantaneous negative pressures occurred when only the auxiliary outlet works was operating. These large-magnitude negative pressure peaks occurred when the structure was operating in a make-and-break condition. A make-and-break condition occurred when the tailwater was at such elevation that wave action on the tailwater surface caused the region under the jet leaving the flip lip to be alternately free to the atmosphere or filled with water. The critical period of this make-and-break condition, with respect to negative pressure development, is when the break is occurring. As the water vacates the region, a short-duration partial vacuum results. Under such conditions, prototype pressures as low as 7.3 m (24 ft) or water below atmospheric were observed. A strip chart recording of this condition is shown in figure 17. The magnitude of these subatmospheric pressures might cause concern that cavitation would develop. However, because of the short duration of these pressures and because the pressures in the region are near atmospheric most of the time, these low pressures were considered to be acceptable.

From table 1, it can also be seen that the observed depths of penetration ranged from 1219 mm (4 ft) to the full basin depth of 13.7 m (45 ft). All spillway flows penetrated to the floor of the basin. For spillway flows, it was not possible to observe the depth of penetration of that portion of the flow affected by the auxiliary outlet works flip, but observation of surface flows did indicate that the penetration was significantly reduced. Penetration depths resulting from only the operation of the auxiliary outlet works ranged from 1.2 to 4.3 m (4 to 14 ft). Generally, the greater the discharge, the greater the penetration. In the existing prototype, these flows would penetrate to the stilling basin floor, a depth of 12.2 to 13.7 m (40 to 45 ft). For the discharge and tailwater elevation ranges observed, tailwater elevation again seemed to have no distinct effect on penetration depth. Application of a predictive analysis [1] indicates athat maximum supersaturation levels created by auxiliary outlet works operation should be reduced from 158 percent nitrogen and 135 percent oxygen to 106 percent nitrogen and 97 percent oxygen.

Flow from the modified bypass penetrated to depths of 4.6 to 5.8 m (15 to 19 ft). This is fairly deep, but still shallower than the 12.2 to 13.7 m (40 to 45 ft) which appeared to occur in the prototype. Calculations using the predictive analysis [1] indicate that the reduced penetration should result in dissolved nitrogen levels being reduced from 125 percent to 114 percent and dissolved oxygen levels being reduced from 120 percent to 108 percent. Further, it was believed that the 15° angle of penetration was approaching the flattest angle that could be used without having high velocity flow impinge the opposite stilling basin wall. Also, the bypass should be used infrequently. Thus, it was concluded that the modification to the bypass was satisfactory and that no further model testing was needed. The bypass operation is shown in figure 12.

The next step in the investigation was an attempt to simplify the initial flip lip design to reduce the cost of the modification. There were two factors considered in the simplification. First, the crown or ridge in the invert of the structure might be removed. The crown was initially included in the design to spread the flow to allow quicker energy dissipation and to minimize penetration. Observation of the model operating with the crown in place indicated that the crown was overspreading the flow and creating flow concentrations to the outside. Construction of the crown would add significantly to the cost of the structure.

Secondly, the elevation of the flip lip might be raised to simplify dewatering of the construction area. Raising the lip would put the modification work above the tailwater surface which would reduce the cost of the modification.

Initially, just the crown was removed (fig. 18) and the model was tested as before. In general, the flow at the lip was spread quite uniformly, although there was some flow concentration in the center of the structure. The flow concentration was no greater than had been observed along the outside walls of the structure with the crown in place. For all conditions, the structure appeared to perform satisfactorily. Data collected during the testing are summarized in table 2. As can be seen, wave heights, velocities in back eddies, and penetration depths were all approximately the same as had been observed with the crown in place (table 1). Pressures below the lip were also of similar magnitude. Pressures observed when the auxiliary outlet works were operating indicate that the lowest average pressures occur at the smaller discharges. This tendency

Table 2. — *Data summary — Final modification design*

| OPERATING STRUCTURE | DISCHARGE RATE m³/s (ft³/s)† | TAILWATER ELEVATION: METERS (FEET) | MAXIMUM INWARD VELOCITY IN BACK EDDIES: mm/s (ft /s) | MAXIMUM DEPTH OF PENETRATION: METERS (FEET) | WAVE HEIGHTS: METERS (FEET) | PREDICTED RESULTING % OF DISSOLVED GAS | PIEZOMETER 1 * | | | PIEZOMETER 2 * | | | PIEZOMETER 3 * | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | AVG. PRESSURE METERS HEAD (FT OF WATER) | AVERAGE MAXIMUM | AVERAGE MINIMUM | AVG. PRESSURE METERS HEAD (FT OF WATER) | AVERAGE MAXIMUM | AVERAGE MINIMUM | AVG. PRESSURE METERS HEAD (FT OF WATER) | AVERAGE MAXIMUM | AVERAGE MINIMUM |
| Spillway (with final aux. outlet modification) | 283.2 (10,000) | 1742.85 (5718) | Small | 13.1 (43) | 0.69 (2.25) | | | | | | | | | | |
| | | 1742.54 (5717) | | 12.8 (42) | 0.76 (2.5) | | | | | | | | | | |
| | | 1742.24 (5716) | Small | 12.5 (41) | 0.69 (2.25) | | | | | | | | | | |
| | 566.3 (20,000) | 1743.15 (5719) | Small | 13.4 (44) | 1.22 (4) | | | | | | | | | | |
| | | 1743.0 (5718.5) | | 13.3 (43.5) | 1.37 (4.5) | | | | | | | | | | |
| | 962.8 (34,000) | 1743.46 (5720) | All outward | 13.7 (45) | 1.52 (5) | | | | | | | | | | |
| | | 1743.30 (5719.5) | All outward | 13.6 (44.5) | 1.52 (5) | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| Auxiliary outlet (final modification) | 11.3 (400) | 1742.08 (5715.5) | 98 (0.32) | 1.4 (4.5) | Min | | -1.62 (-5.3) | -0.73 (-2.4) | -2.62 (-8.6) | -1.16 (-3.8) | -1.01 (-3.3) | -1.31 (-4.3) | -1.62 (-5.3) | -0.88 (-2.9) | -1.89 (-6.2) |
| | | 1741.78 (5714.5) | | 1.5 (5) | Min | | -1.31 (-4.3) | -0.58 (-1.9) | -1.68 (-5.5) | -1.16 (-3.8) | -0.85 (-2.8) | -1.46 (-4.8) | -1.31 (-4.3) | -0.88 (-2.9) | -2.04 (-6.7) |
| | | 1741.47 (5713.5) | | 1.7 (5.5) | Min | | -0.73 (-2.4) | -0.43 (-1.4) | -1.31 (-4.3) | -0.88 (-2.9) | -0.73 (-2.4) | -1.19 (-3.9) | -0.88 (-2.9) | -0.58 (-1.9) | -1.19 (-3.9) |
| | | 1741.32 (5713) | 201 (0.66) | 2.1 (7) | 0.15 (0.5) | | -0.58 (-1.9) | -0.43 (-1.4) | -0.73 (-2.4) | -1.46 (-4.8) | -1.46 (-4.8) | -1.46 (-4.8) | -1.16 (-3.8) | -1.10 (-3.6) | -1.22 (-4.0) |
| | 28.3 (1,000) | 1742.08 (5715.5) | 475 (1.56) | 3.4 (11) | 0.23 (0.75) | | 0.15 (0.5) | 0.43 (1.4) | -0.27 (-0.9) | 1.46 (4.8) | 1.46 (4.8) | 1.46 (4.8) | 0.30 (1.0) | 0.30 (1.0) | 0.30 (1.0) |
| | | 1741.78 (5714.5) | | 3.0 (10) | 0.27 (0.9) | | 0.30 (1.0) | -0.18 (-0.6) | 0.46 (1.5) | 1.16 (3.8) | 1.10 (3.6) | 1.22 (4.0) | 0 | 0.30 (1.0) | -0.43 (-1.4) |
| | | 1741.47 (5713.5) | 369 (1.21) | 3.0 (10) | 0.30 (1.0) | | -0.30 (-1.0) | 0.15 (0.5) | -0.88 (-2.9) | -0.15 (-0.5) | 0 | -1.04 (-3.4) | 0.06 (0.2) | 0.52 (1.7) | -0.21 (-0.7) |
| | 45.3 (1,600) | 1742.24 (5716) | 661 (2.17) | 3.0 (10) | 0.30 (1.0) | | -1.16 (-3.8) | 0 | -3.20 (-10.5) | 0.43 (1.4) | 0.79 (2.6) | 0.06 (0.2) | 0.15 (0.5) | 0.46 (1.5) | -0.15 (-0.5) |
| | | 1741.93 (5715) | | 3.7 (12) | 0.38 (1.25) | | -0.15 (-0.5) | 0.30 (1.0) | -0.88 (-2.9) | 0 | -0.15 (-0.5) | 0.15 (0.5) | -0.06 (-0.2) | 0.24 (0.8) | -0.37 (-1.2) |
| | | 1741.63 (5714) | 564 (1.85) | 4.6 (15) | 0.53 (1.75) | | 0 | 0.30 (1.0) | -0.58 (-1.9) | -0.15 (-0.5) | 0 | -0.58 (-1.9) | -0.21 (-0.7) | 0 | -1.04 (-3.4) |
| | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |

* All pressures are gage values
† Numbers in parenthesis are English equivalents of the metric values next to them, as indicated in the heading.

was also observed with the crown in place, but it was much more prevalent with the crown removed. Peaks of reduced pressure were again observed with the make-and-break action, but no peaks as great as those from the initial design were noted. Typical strip chart data are shown in figure 19. Again it is believed that all pressures observed were within acceptable limits. Operation of the structure without the crown was acceptable and the crown was removed from the final design.

As a final test, the relative position of the flip lip with respect to the tailwater surface was evaluated to determine how the structure's performance was affected. It was found that make-and-break action can exist over a range of tailwater elevations from 152 mm (6 in) above the lip to 610 mm (2 ft) below the lip. Thus, if the lip is at elevation 1741.6 m (5714 ft) (initial design), make-and-break conditions can occur between elevations 1741.8 and 1741.0 m (5714.5 and 5712 ft). A tailwater elevation of 1741.8 m (5714.5 ft) would result if the total release from the dam was 56.6 $m^3/s$ (2,000 $ft^3/s$). A tailwater elevation of 1741 m (5712 ft) is lower than any possible tailwater elevation. Since a discharge of 14.2 $m^3/s$ (500 $ft^3/s$) with a tailwater elevation of 1741.4 m (5713.4 ft) will be the most common release and as the great majority of the releases from the dam will be less than 56.6 $m^3s$ (2,000 $ft^3/s$), the auxiliary outlet works would almost always operate in the make-and-break range. Although considered satisfactory, this operating condition created the lowest negative pressure at the lip and resulted in larger wave formation. For these reasons, it was considered desirable to eliminate the make-and-break action from the most common operating situations. If the lip was raised to elevation 1742.1 m (5715.7 ft), the make-and-break action would occur between tailwater elevations of 1742.3 and 1741.5 m (5716.2 and 4713.7 ft). These tailwater elevations correspond to total discharges of 175.6 $m^3/s$ (6,200 $ft^3/s$) and 19.8 $m^3/s$ (700 $ft^3/s$), respectively. An auxiliary outlet works discharge of 14.2 $m^3/s$ (500 $ft^3/s$) would therefore not be in the make-and-break range. Placing the lip at elevation 1742.1 m (5715.7 ft) would also allow the simplified dewatering of the construction site. It was found that higher lip elevations resulted in greater flow penetration. For these reasons, a flip lip elevation of 1742.1 m (5715.7 ft) was selected for the final design (fig. 3).

## REFERENCES

[1] Johnson, P. L., "Prediction of Dissolved Gas at Hydraulic Structures," Report No. GR-8-75, U. S. Department of the Interior, Bureau of Reclamation, July 1975

[2] Beichley, G. L., "Hydraulic Model Studies of Navajo Dam Spillway and Auxiliary Outlet Works Junction with Spillway," Report No. HYD 458, U. S. Department of the Interior, Bureau of Reclamation, November 14, 1961

# FIGURES

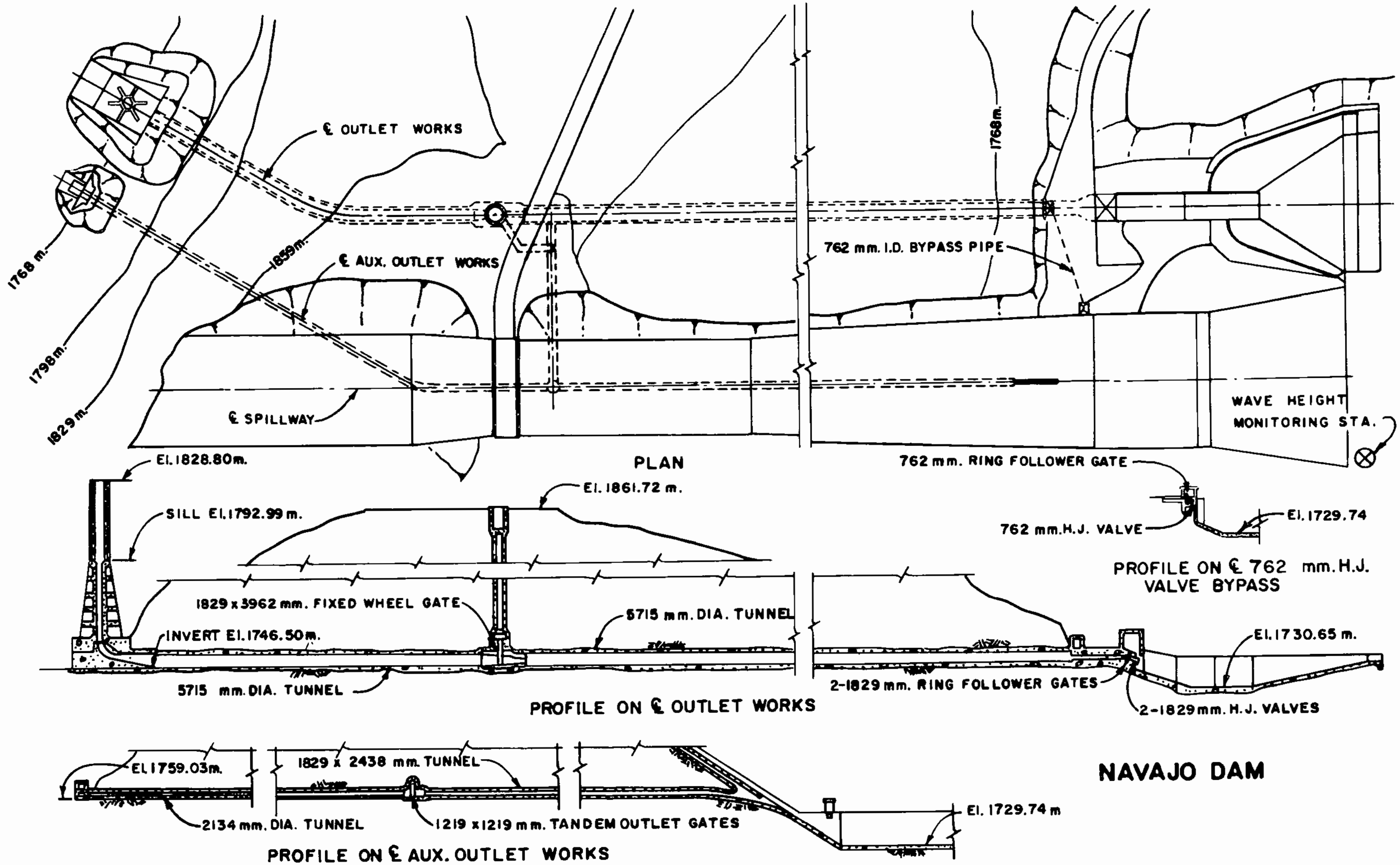



Figure 1. — Original prototype design — Metric.

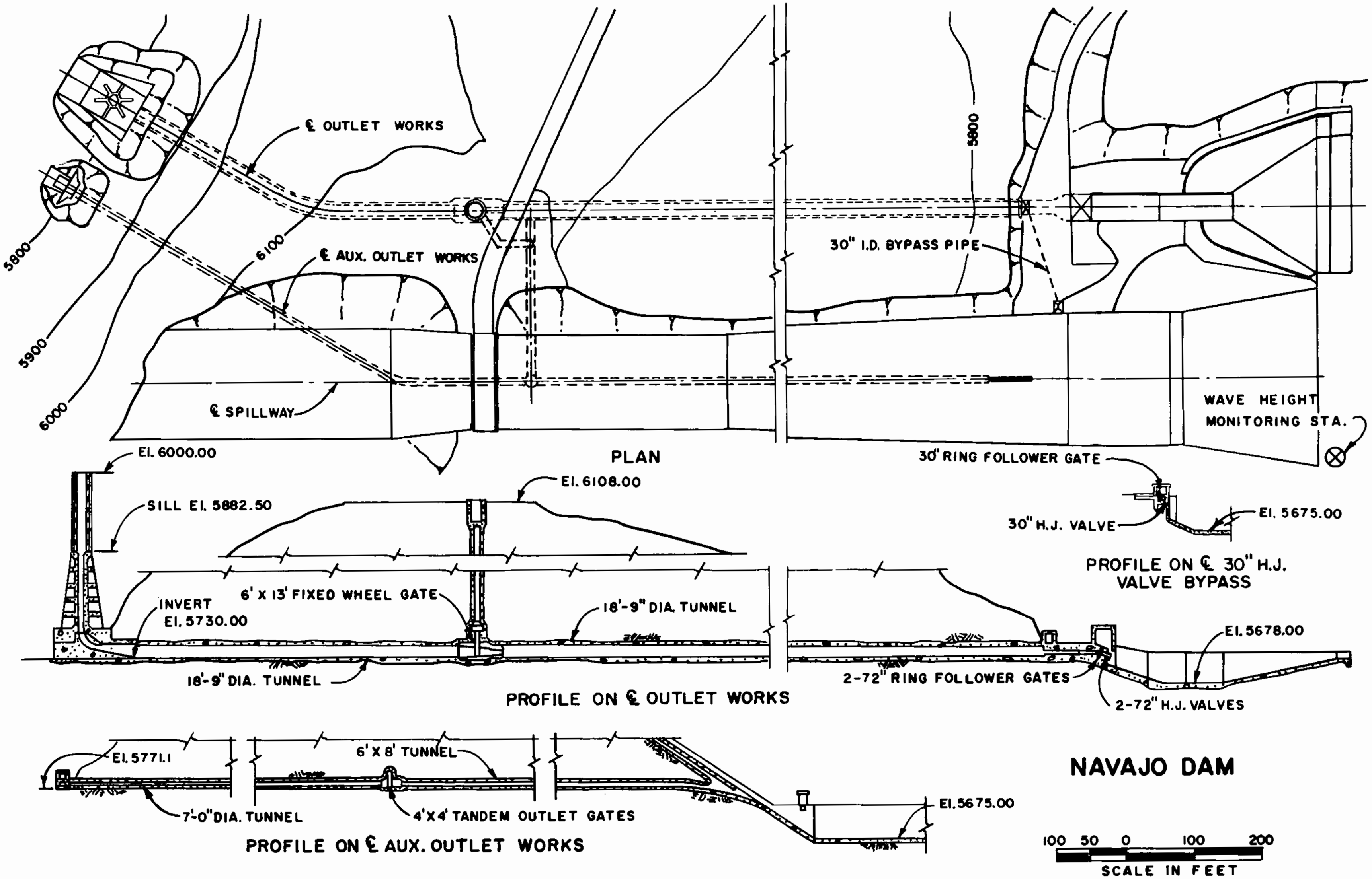



Figure 1. — Original prototype design — English.

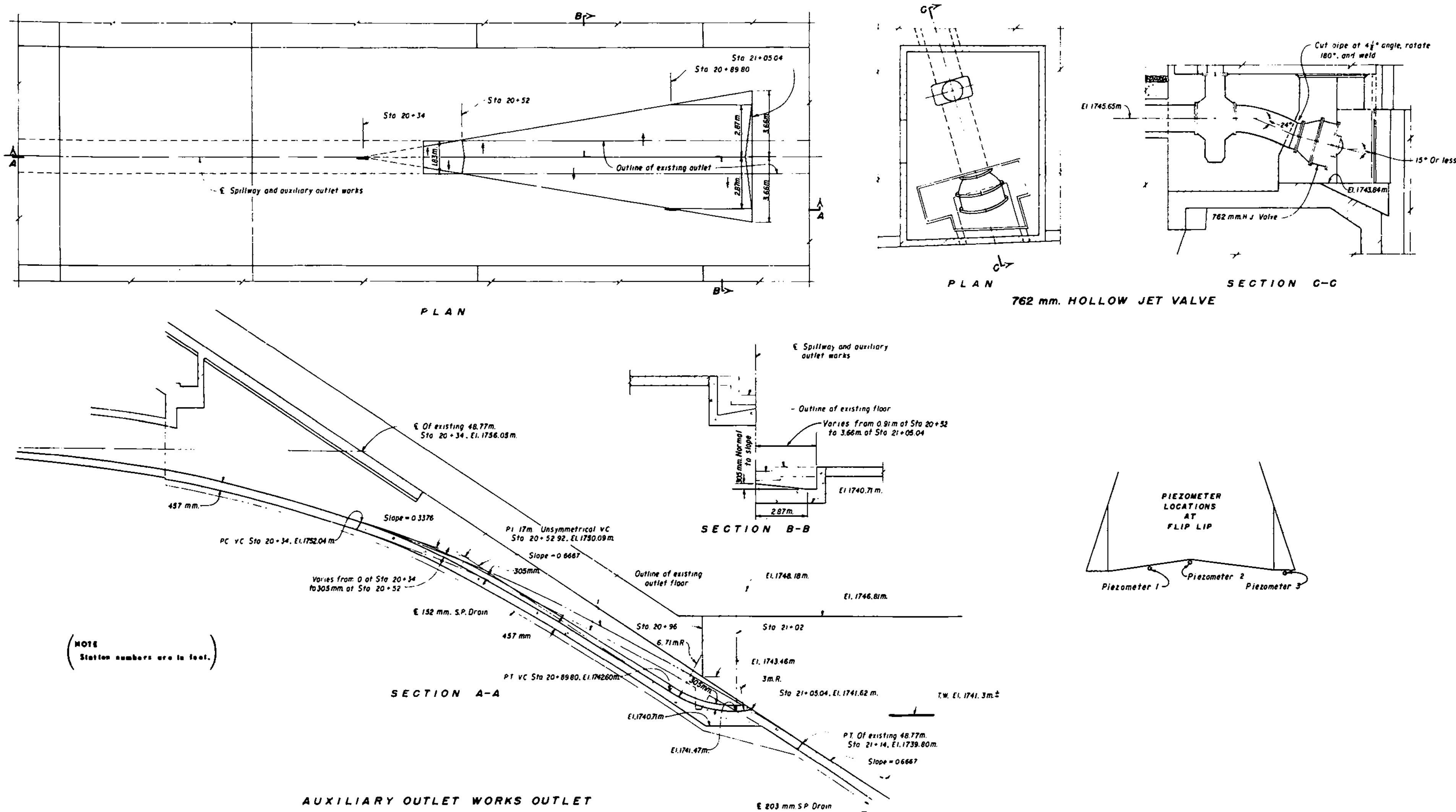



Figure 2. — Initial modification design —Metric — With crown.

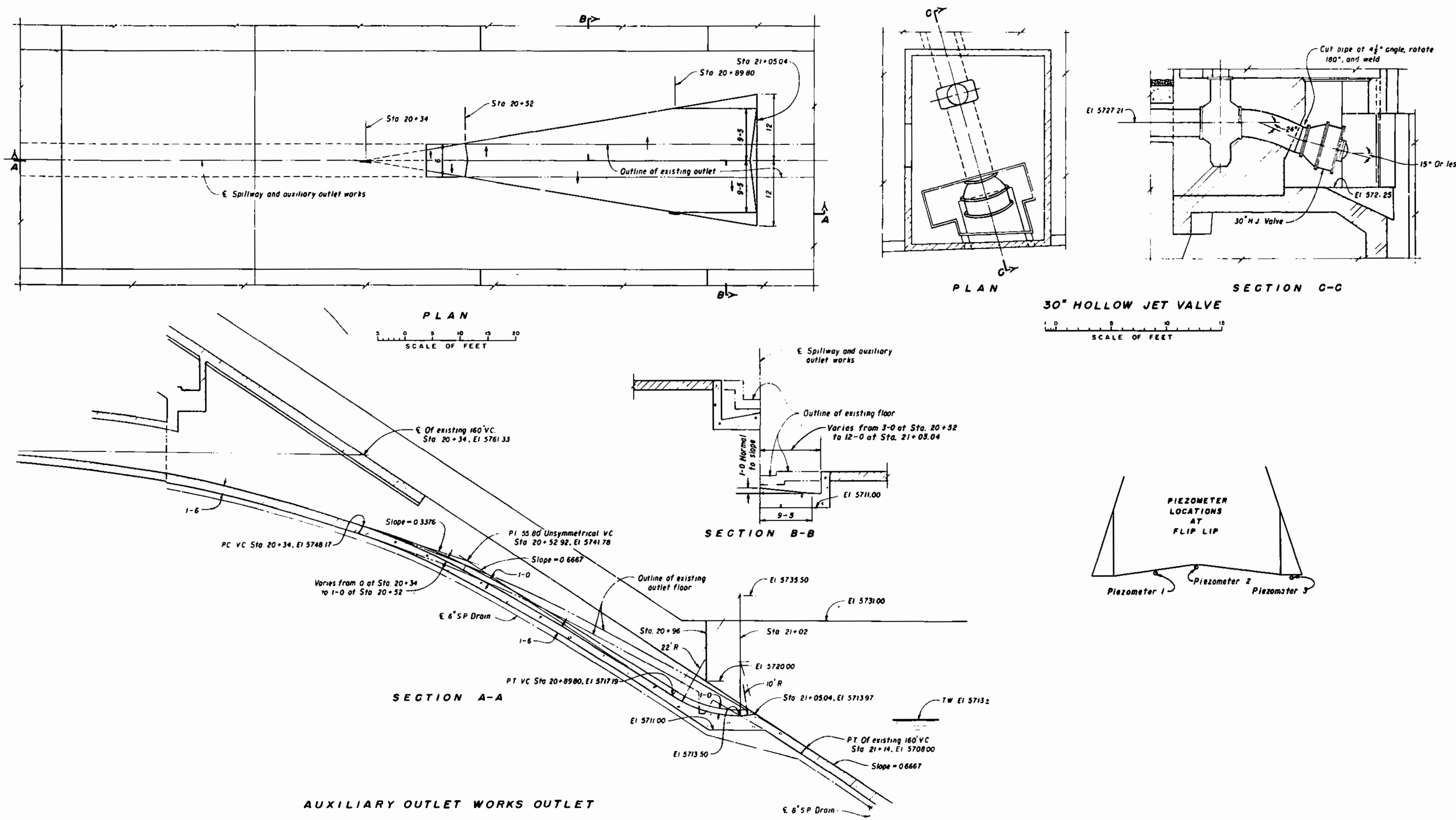



Figure 2. — Initial modification design — English — With crown.

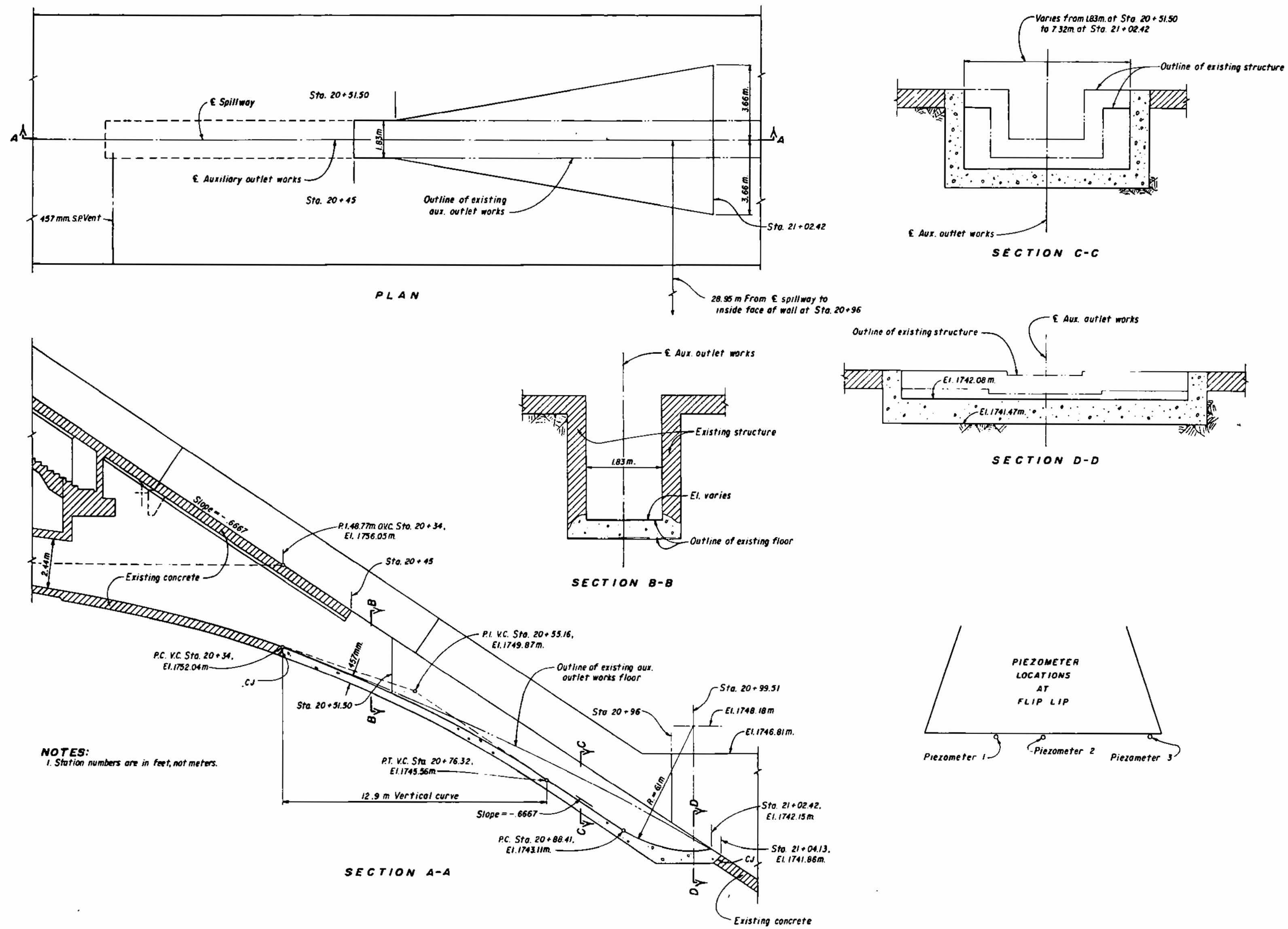



Figure 3. — Final modification design — Metric.

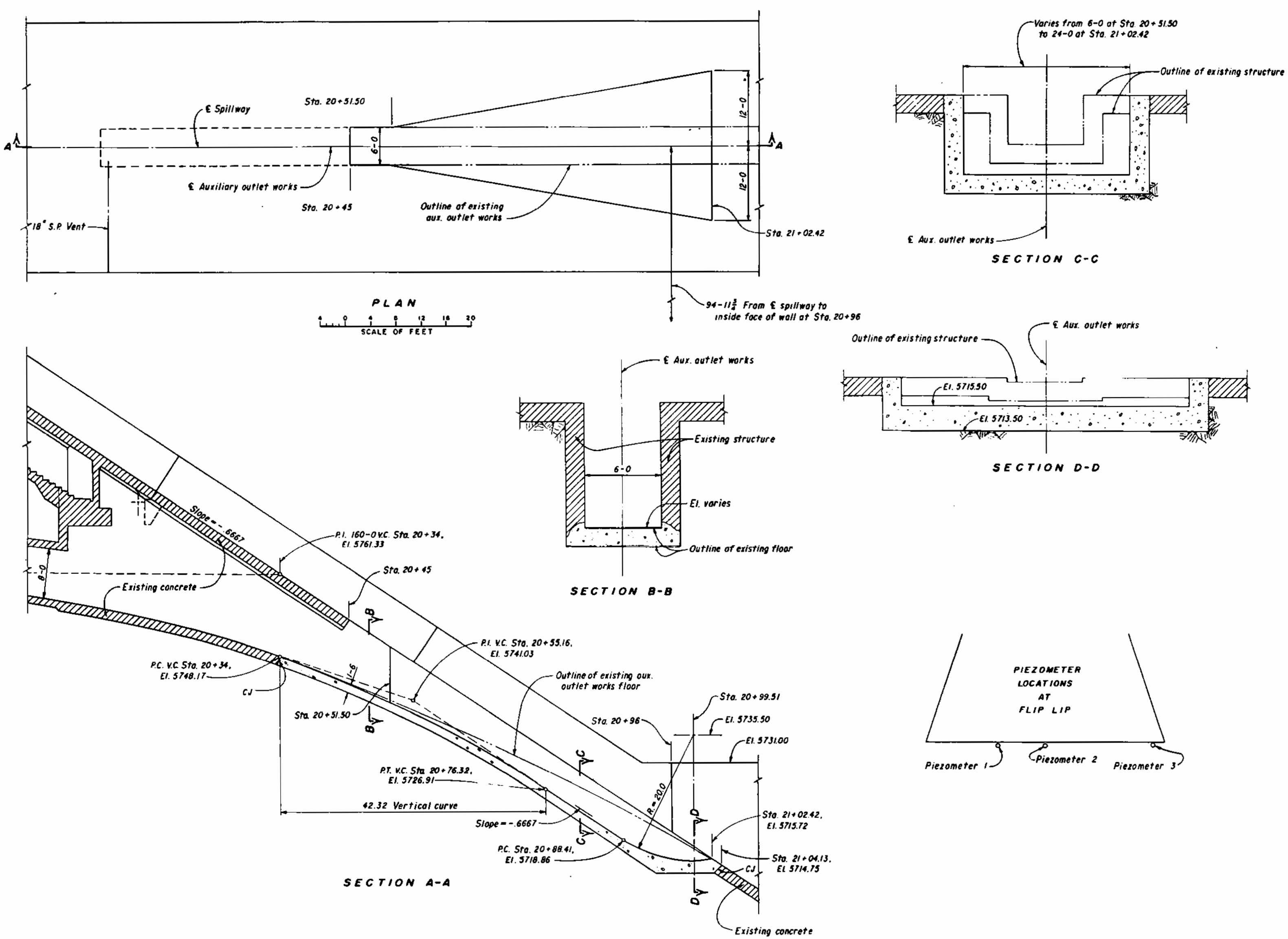



Figure 3. — Final modification design — English.

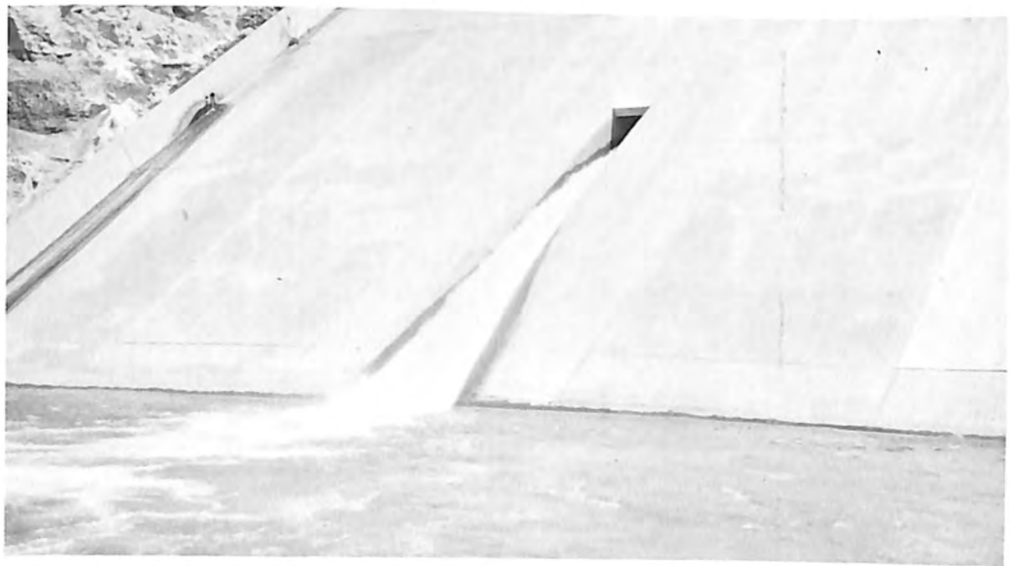
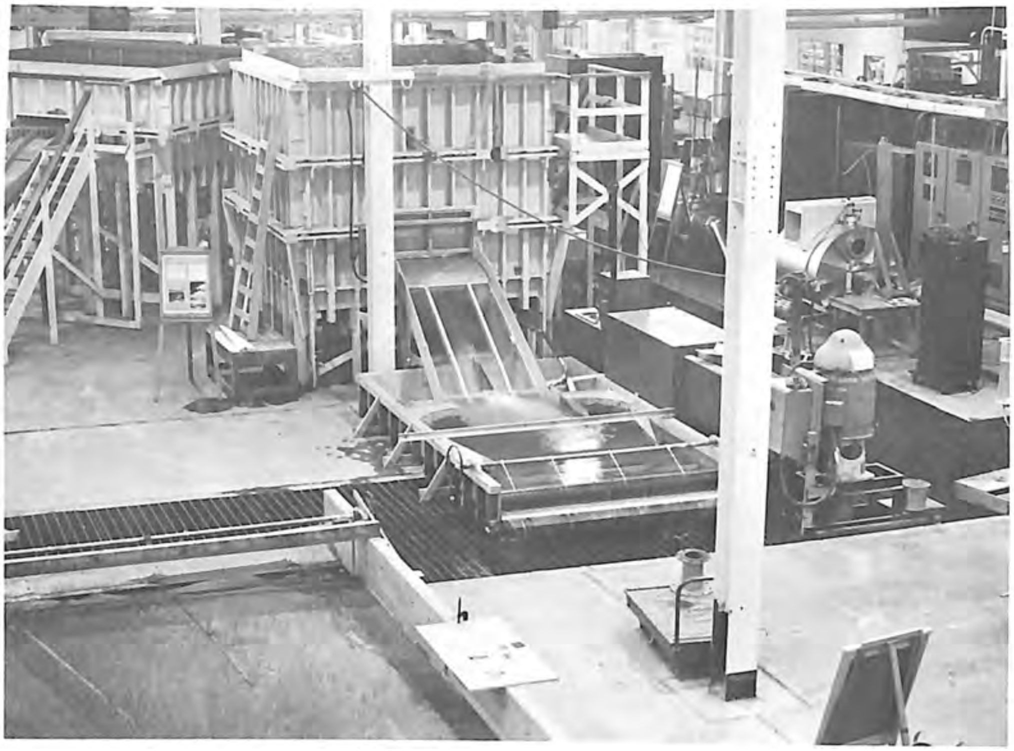


Figure 4. — Original auxiliary outlet works.

Figure 5. — Original 762-mm (30-in) hollow-jet valve bypass.



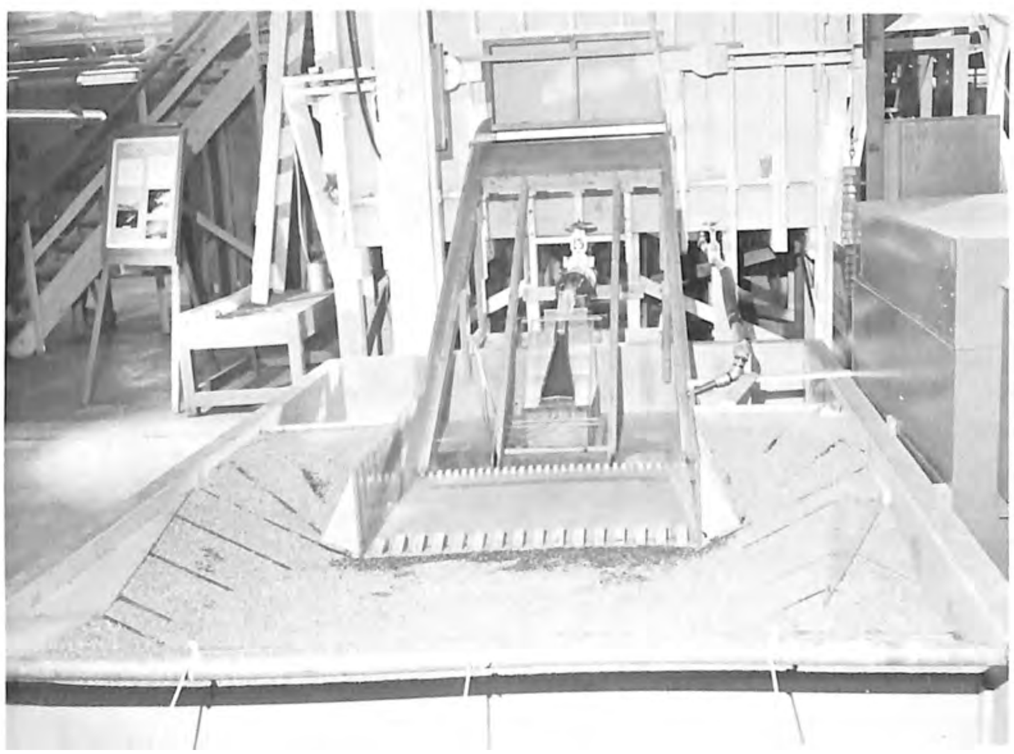


Figure 6. — Hydraulic model.

Figure 7. — Modeled initial modification.

283.2 $m^3/s$ (10,000 $ft^3/s$)

566.3 $m^3/s$ (20,000 $ft^3/s$)

962.8 $m^3/s$ (34,000 $ft^3/s$)

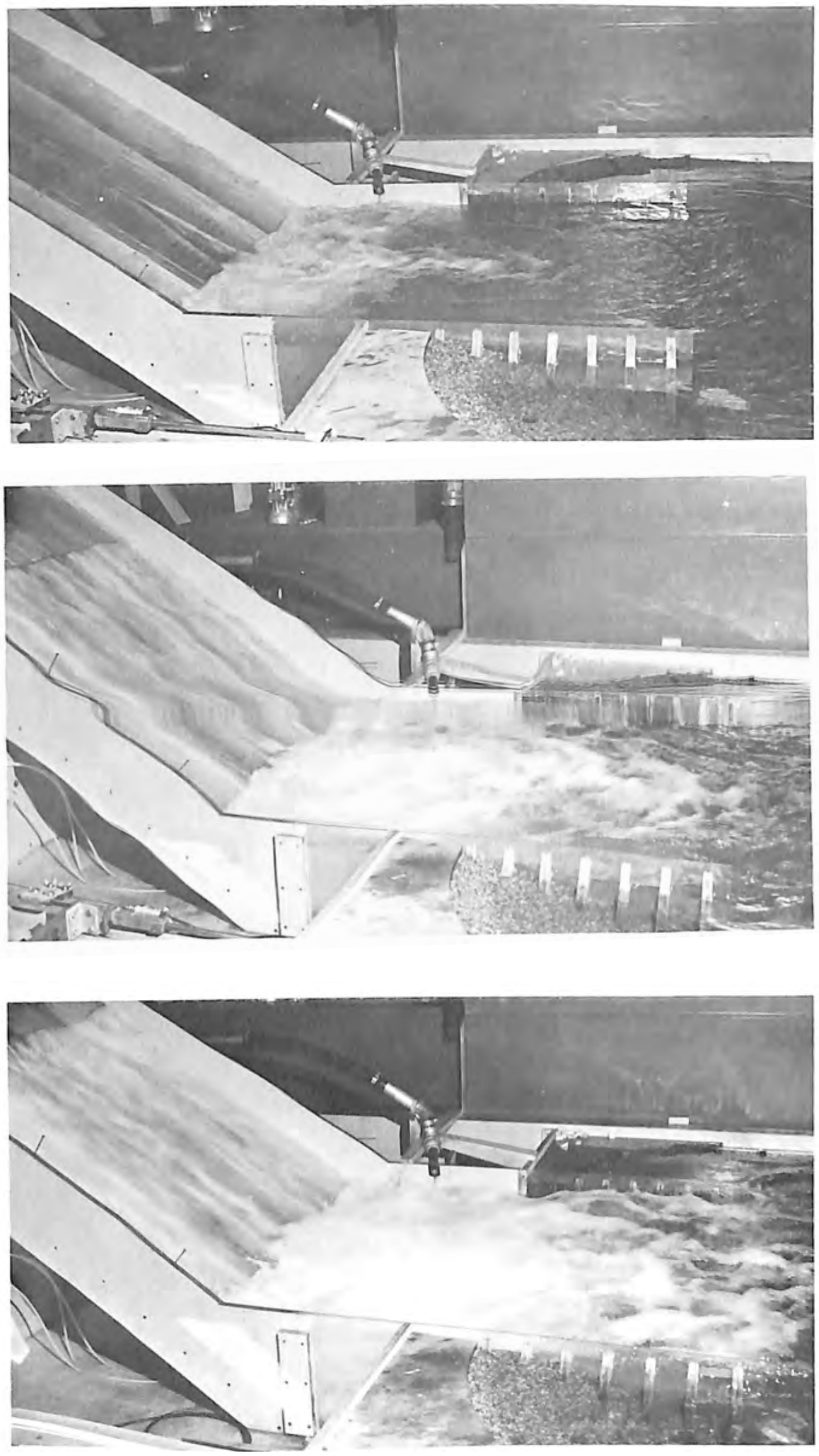
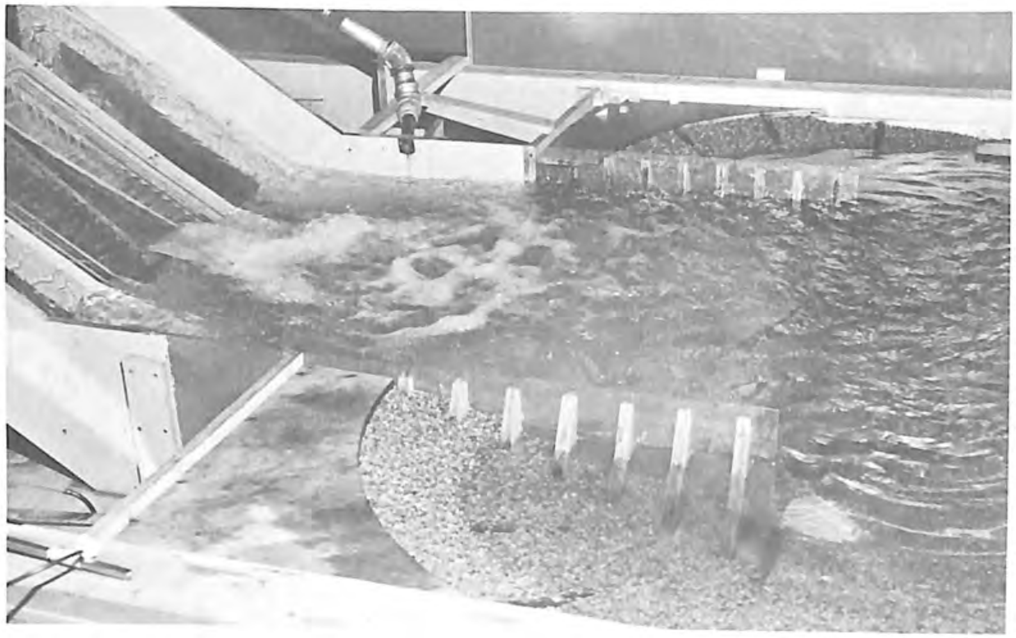


Figure 8. — Operating model spillway.

LOW TAILWATER–
FREE RELEASE JET



HIGH TAILWATER–
SUBMERGED LIP

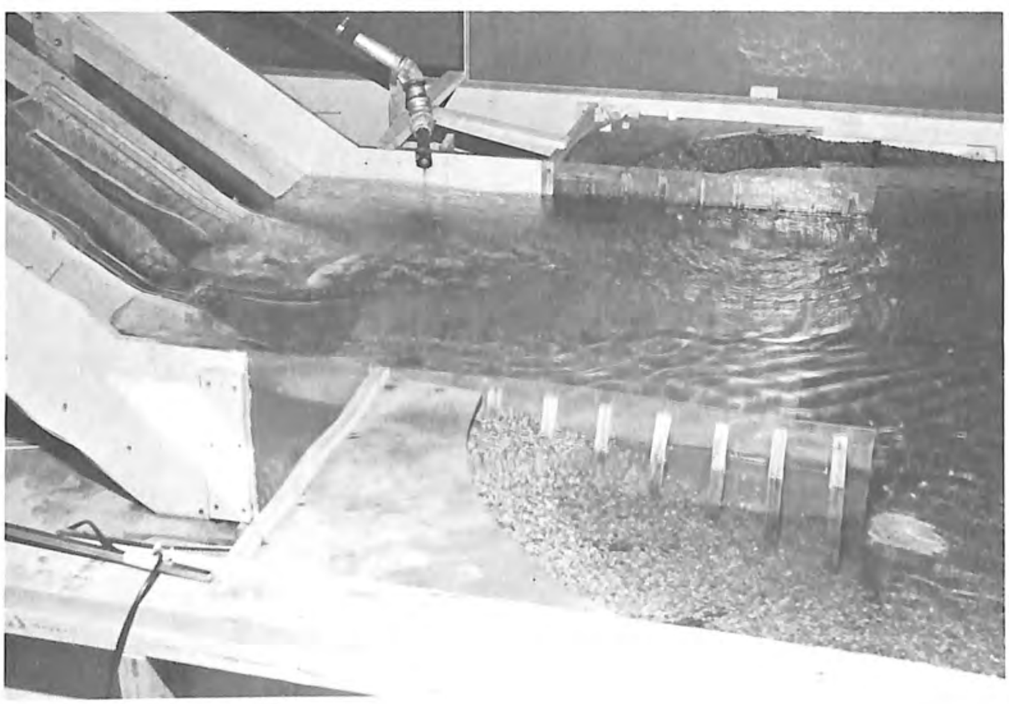
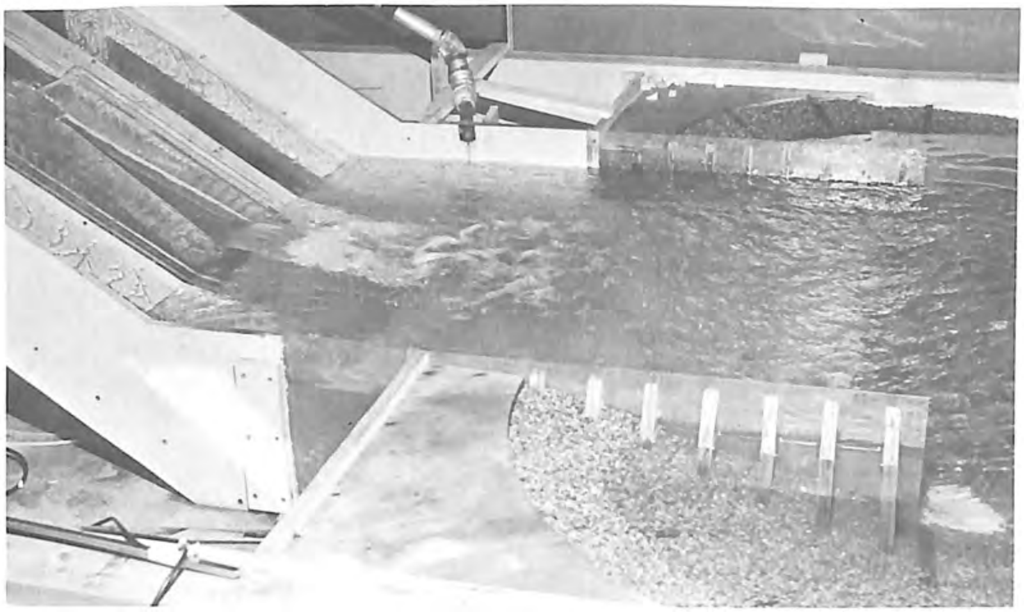


Figure 9. — Operating model of flip lip 11.3 $m^3/s$ (400 $ft^3/s$) discharge.

LOW TAILWATER–
FREE RELEASE JET



HIGH TAILWATER–
SUBMERGED LIP

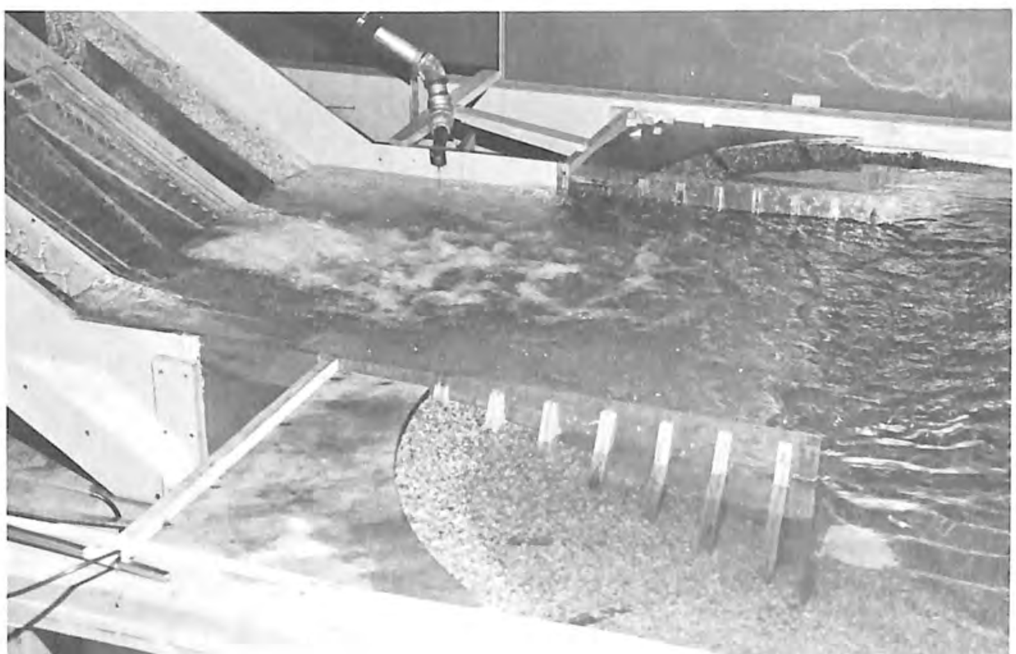


Figure 10. – Operating model of flip lip 28.3 $m^3/s$ (1000 $ft^3/s$) discharge.

LOW TAILWATER–
FREE RELEASE JET

HIGH TAILWATER–
SUBMERGED LIP

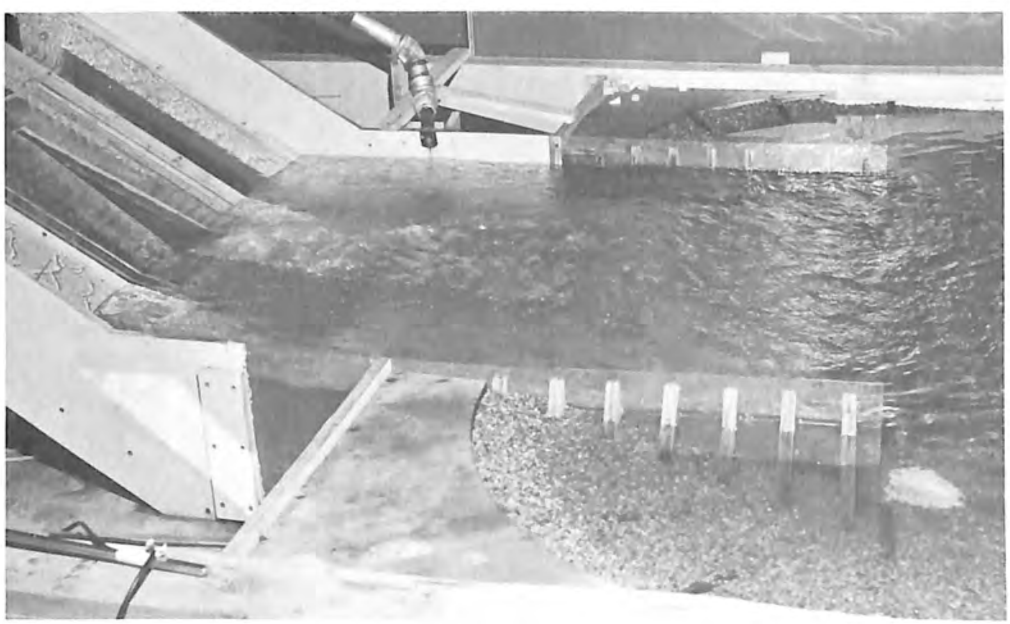


Figure 11. – Operating model of flip lip 45.3 $m^3/s$ (1600 $ft^3/s$) discharge.

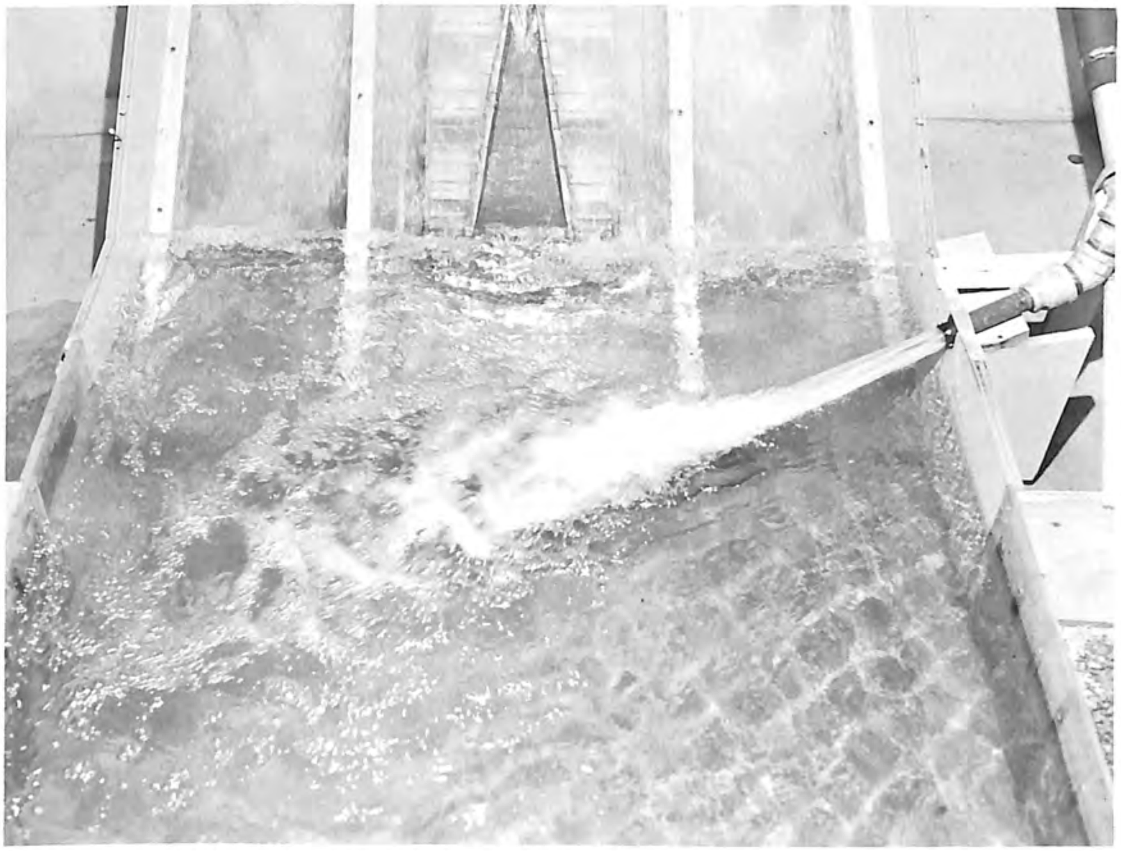


Figure 12. — Operating model of 762-mm (30-in) bypass.

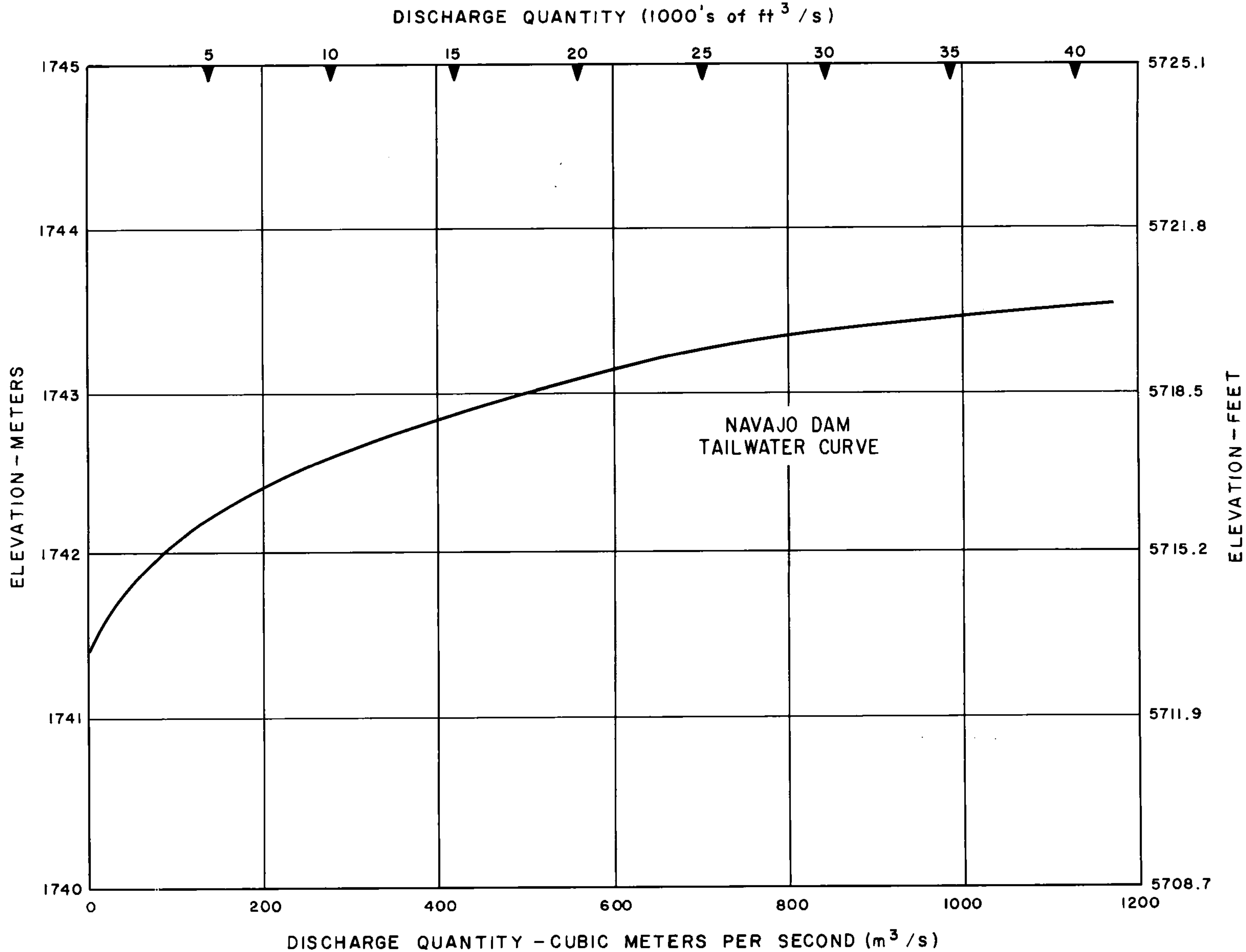



Figure 13. — Tailwater curve.

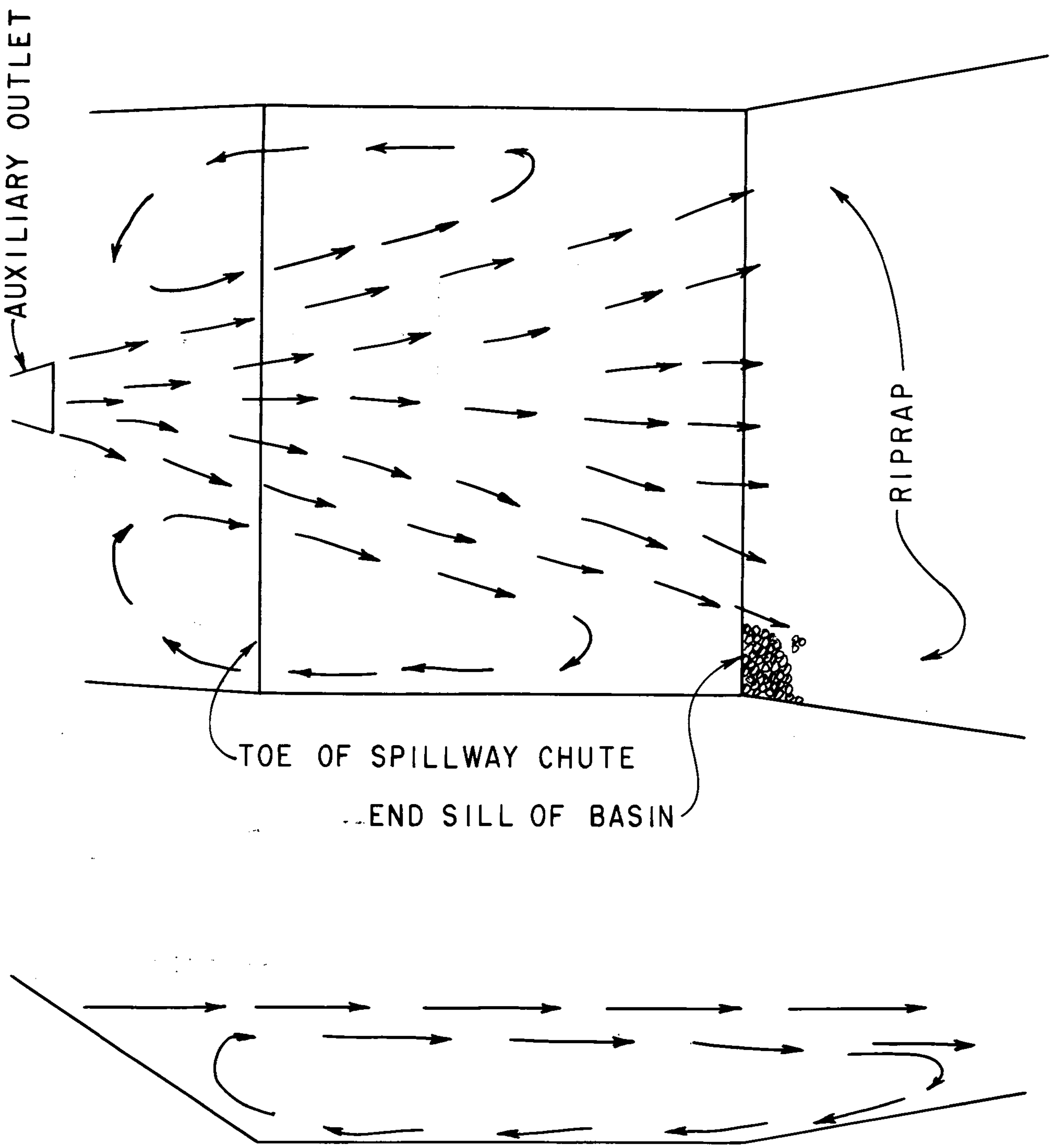



Figure 14. — Eddy patterns for flip lip operation.

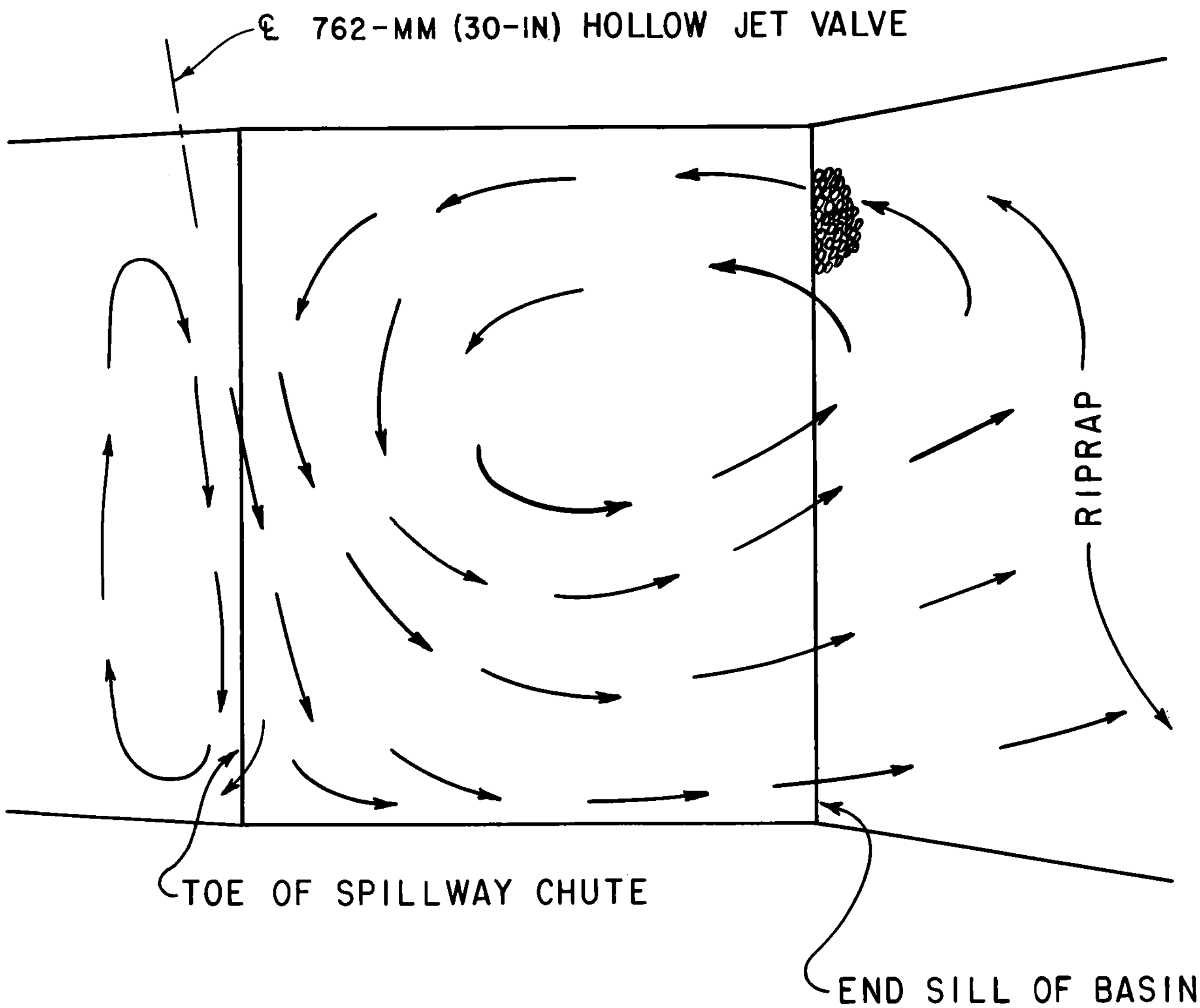



Figure 15. – Eddy patterns for 762-mm (30-in) bypass operation.

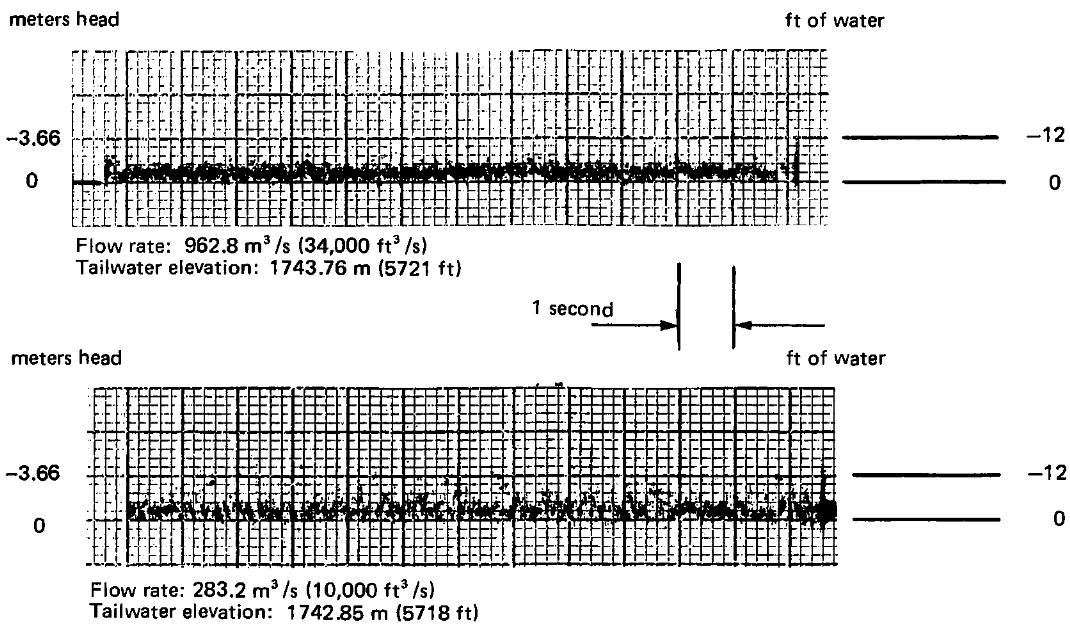



Figure 16. — Strip chart pressure recording for spillway operation.

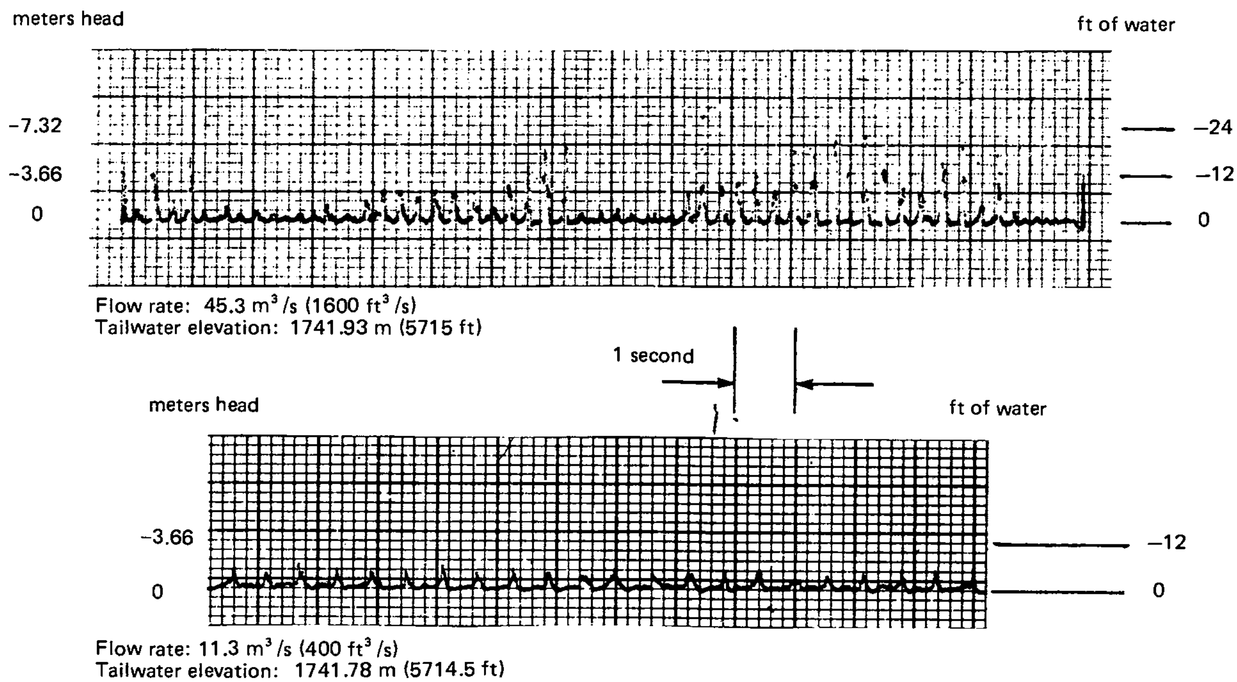



Figure 17. — Strip chart pressure recording for flip lip make-and-break operation.

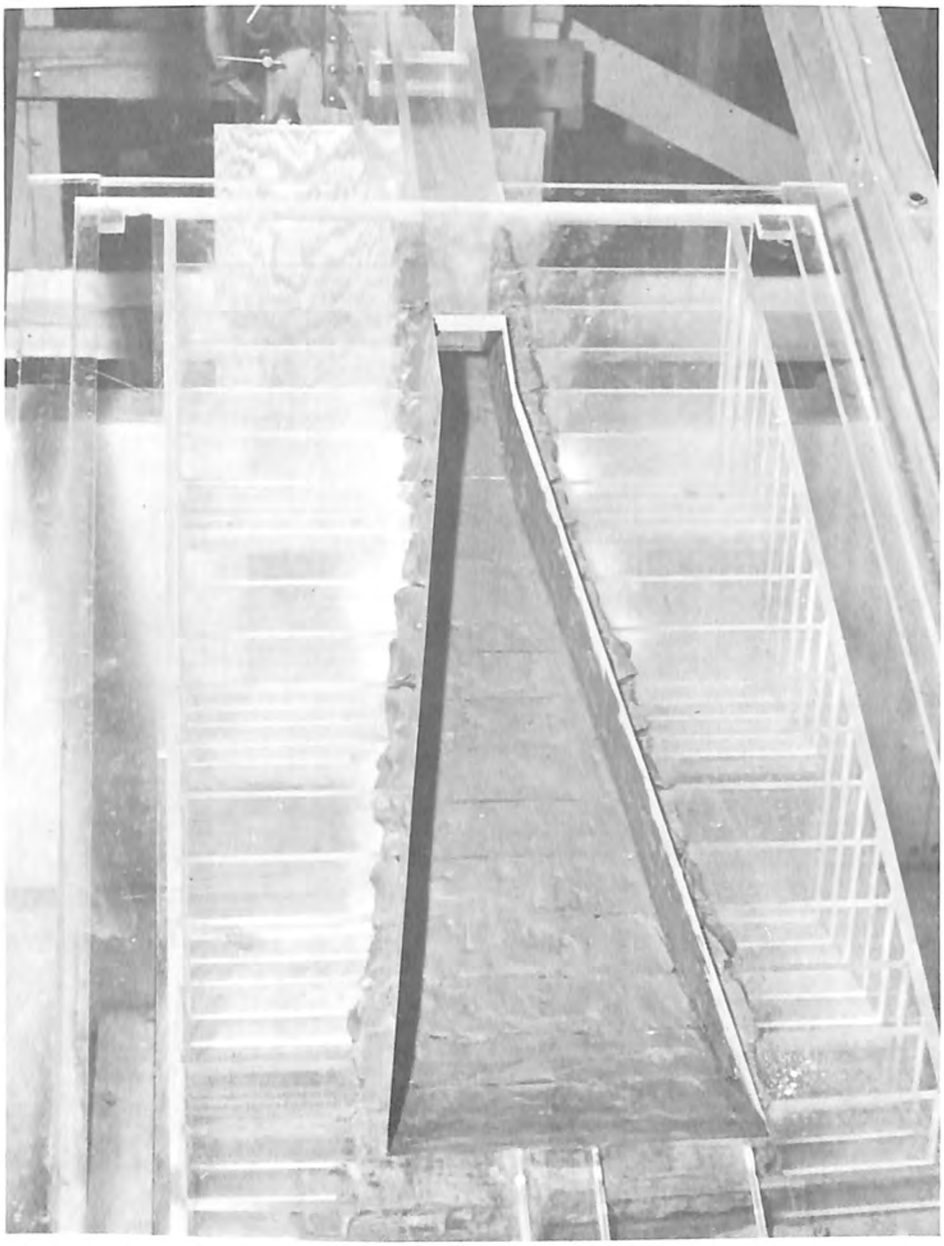


Figure 18. – Modeled final flip lip design.

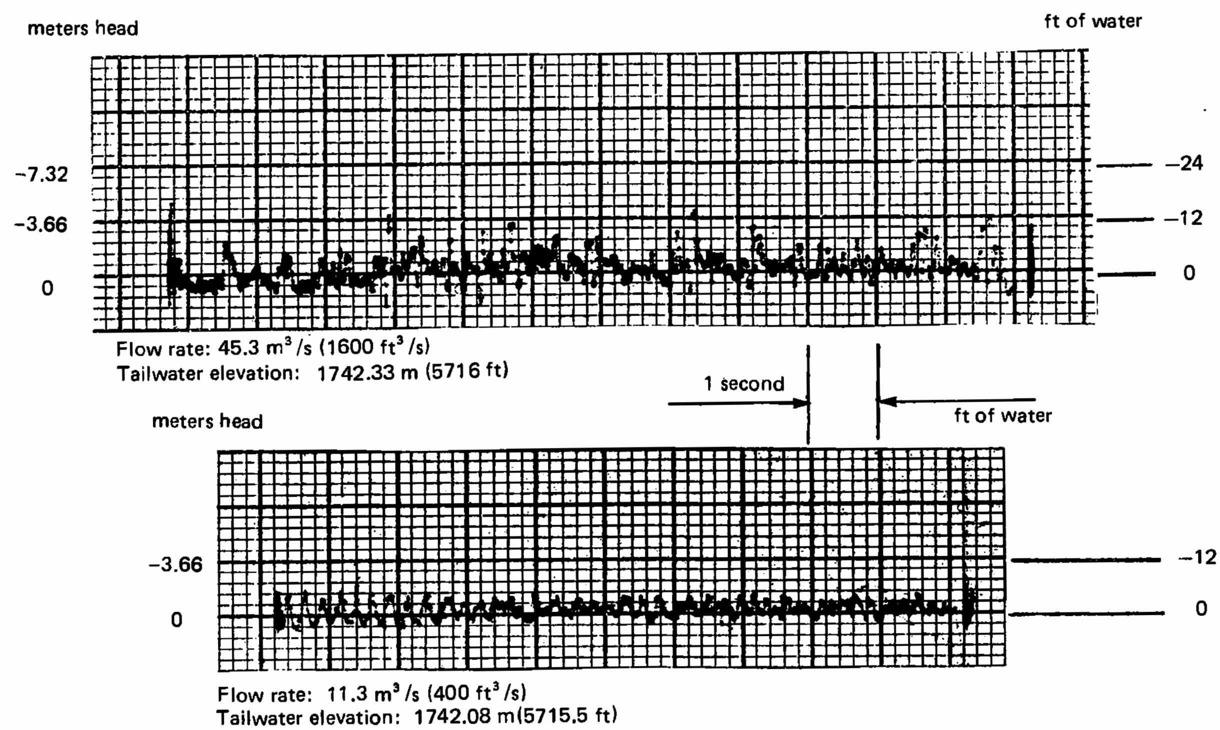



Figure 19. — Strip chart pressure recording for final flip lip design.

## ABSTRACT

It has been observed that operation of the auxiliary outlet works and the 762-mm (30-inch) hollow-jet valve bypass at Navajo Dam result in high levels of dissolved gas supersaturation in released waters. These high dissolved gas levels, which are caused by the deep penetration of the flow into the spillway stilling basin pool, have had adverse effects on the fishery. Structural modifications were considered which included a flattening of the trajectory of the jet from the 762-mm (30-inch) bypass and the addition of a deflector or flip lip to the auxiliary outlet works. A 1:48 scale hydraulic model was used to refine and evaluate these modifications. Depth of jet penetration, degree of energy dissipation, strength of back eddies returning into the stilling basin, potential for cavitation development below the flip lip, and simplicity of design were factors considered in the evaluation.



## ABSTRACT

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REC-ERC-76-5
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Bur Reclam Rep REC-ERC-76-5, Div Gen Res, Apr 1976. Bureau of Reclamation, Denver, 30 p, 19 fig, 2 tab, 2 ref
DESCRIPTORS—/ *supersaturation/ dissolved gases/ *outlet works/ cavitation/ energy dissipation/ erosion/ *hydraulic models/ design modifications
IDENTIFIERS—/ Navajo Dam, N. Mex.

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