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GRAND COULEE PUMPING-GENERATING PLANT MODEL STUDIES CONDUIT ENTRANCES P/G7 & P/G8

Hydraulics Branch
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16. ABSTRACT

Hydraulic model studies were performed to develop modifications of pump penstock exits at Grand Coulee Dam, Washington, for use as inlets, when the penstocks supply water for new pump-turbines. Six of twelve penstocks are in service to convey water through siphon elbows to a canal discharging into Banks Lake; however, six others are to function with flows in either direction in the pump-turbine mode. The studies concern revising the structure in the Feeder Canal to attain efficient and safe operation as an inlet and outlet. Five conduit entrance shapes are described. Twelve headwall designs were investigated for flow patterns occurring with operation of six penstocks as turbine conduits. Several guide pier and entrance shapes were studied. Conduit wall pressures and pressures in the siphon elbow were measured. Includes 56 figures, 1 table, and 80 pages.

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Division of Research
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UNITED STATES DEPARTMENT OF THE INTERIOR ★ WATER AND POWER RESOURCES SERVICE

As the Nation's principal conservation agency, the Department of the Interior has the responsibility for most of our nationally owned and public lands and natural resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

On November 6, 1979, the Bureau of Reclamation was renamed the Water and Power Resources Service in the U.S. Department of the Interior.

Frontispiece — Grand Coulee Dam and Franklin D. Roosevelt Lake on the Columbia River in Washington. Banks Lake is in the background. The pumping-generating plant and 12 conduits are near the center. Photo CD30527

CONTENTS

CONTENTS—Continued

TABLE

Figure FIGURES

Figure | *Page*

PURPOSE

Modifications were considered necessary to the discharge ends of six penstocks (conduits) servicing the Feeder Canal from Banks Lake when the pump discharge ends serve as intakes for new pump-turbine units to be used in the turbine mode. Conduits P/G7 through P/G12, in a pump discharge outlet (fig. 5) structure of 12, were studied in a model to determine the extent of the modifications required in the pumping-generating plant siphon elbows and outlets leading to the Feeder Canal. The overall scheme was to be hydraulically efficient as both inlet and outlet when mode of operation changed from pumping water to generating power.

RESULTS OF THE STUDY

1. To accept turbine flow, the pump discharge conduit entrances at the Feeder Canal headwall should be modified as follows:

   a. For turbine flow, the roof of the conduit entrance should be streamlined by shaping and lowering the roof between the entrance and the circular conduit as shown on figure 21.

   b. Trashrack slots should be provided for entrances PG/7 through P/G12. Air-entraining vortices will form in the slots when trashracks are not in place because the slot acts as an air passage, but with the racks in place vortices do not form.

   c. A curved vortex-suppressing large-radius center wingwall should be installed upstream from — but attached to — the underdrain well, as shown on figure 43.

2. Each siphon elbow operates satisfactorily as-built with a turbine discharge of 2,300 ft^3/s, and at a Feeder Canal water surface elevation 1562 or higher at the canal headwall.

3. The present Feeder Canal, with Banks Lake at or above elevation 1564.2, will convey water satisfactorily for two turbines discharging 2,300 ft^3/s each (Banks Lake maximum El. is 1570.0).

Satisfactory operation for three turbines requires a Banks Lake minimum elevation 1566.7; and with five turbines, elevation 1569.0. The present (1967) Feeder Canal does not have adequate capacity for simultaneous operation of six turbines.

INTRODUCTION

Water and Power Resources Service modified 2 of the 12 conduits leading from Franklin D. Roosevelt Lake to Banks Lake — the storage reservoir for Columbia Basin Project lands. The pumping plant was constructed to house 12 pump units, and all entrances, conduits, and appurtenant facilities when completed. Initially, only six pumps were installed and began service in May 1951. By installing pump-turbines rather than single-duty pumps in the remaining six installations, Banks Lake can be used as the upper reservoir in a pumped-storage scheme, as well as an equalizing reservoir for irrigation. Modifications are necessary to allow proper operation of the new pump-turbine and generator-motor units for generation (peaking power).

The pumping range between Franklin D. Roosevelt Lake and Banks Lake has a vertical lift from 267 to 363 feet, figure 1. The same head range is available for power generation when the units are reversed. In the turbine mode, the units will generate 50 000 kW of (peaking) power per unit.

Final details for necessary changes to the conduits at the Banks Lake canal headwall were determined from hydraulic model studies. The model included two outlet siphon elbows, entrance transitions (turbine) for pump-turbines P/G7 through P/G12 conduits, and the canal-side configuration to ensure proper flow in both the pump and turbine modes. When the pump mode is being discussed in this report, the operation is noted as P6, P7, etc. When the turbine mode is the topic, the designation is P/G7, P/G8, etc.

Model studies reported herein were conducted in 1967-70[1] and construction of the recommended design was completed in 1973. The report was not completed until 1980 because of more urgent work.

THE MODEL

The first model (scale 1:18.65) included a portion of the Feeder Canal, canal headwall, and siphon elbows P/G7 and P/G8 (figs. 2 and 3). For comparison with the prototype, see also figure 4. Details of the prototype siphon bends and canal headwall are shown on figure 5.

Figure 6 shows the prototype headwall. The model did not include conduit units P1 through P6, to the left of the underdrain well near the center of the figure. Conduits P1 through P6 serve the six pumps installed originally and, except for the addition of stop-log slots, will not be changed. The final expanded model (fig. 23) included conduits for P/G7 through P/G12, but none for P1 through P6.

COMPUTED LIMITING VALUES

Siphon Crown Pressure

The highest point in each conduit is the siphon-elbow crown and at the location where the vapor pressure would occur most readily. The average barometric pressure at the elevation of the Grand Coulee siphons is 28.3 inches of mercury. The appropriate maximum vacuum which the vacuum pumps on the siphons will develop is minus 24.5 inches of mercury, figure 7. The minus 24.5-inch value was determined to be the limiting negative pressure (at the siphon crown). At this

[1] In the interim, P/G7 and P/G8 were furnished under Bureau of Reclamation solicitation DS-6638, 1968. Unit P/G7 has been tested: A. E. Rickett and A. B. Lewey, Report HM-22, *Pump-Turbine Performance Test — Flow Measurement by the Salt Velocity Method,* presently under preparation (May 1981). Currently, units P/G9 through P/G12 are being furnished and installed under solicitation DS-7189, 1976.

pressure, the presently installed vacuum pumps should be capable of removing air pockets from the siphon crowns.

Canal Headwall Water Surface

The water surface elevation at the Feeder Canal headwall will affect directly the pressure at the siphon crown. Hydraulic losses, between Banks Lake and station 3 + 12.12 (the canal throat near the headwall), for turbine flow are shown in a family of curves, figure 8. A similar set of curves was made for pump flow with a weir near Banks Lake as a choking feature in the system, figure 9. Figures 7, 8, and 9 were used to ensure that prototype conditions were duplicated properly in the model. The model studies were concerned primarily with turbine flow. Therefore, *upstream* in this report denotes the canal side from the canal headwall.

INITIAL TESTS AND OBSERVATIONS

The initial study was made with P/G7 and P/G8 conduits represented as-built, but without the underdrain well (fig. 6). Figure 10 shows the as-built conduit entrance at the canal headwall. Figure 11 shows a typical siphon elbow. Figure 3 shows the two conduits and siphons in place for testing.

Air at the Siphon Crown

With conduit P/G8 flowing full (as-built), air was permitted to enter the siphon by momentary removal of an air valve stopper in the plastic conduit, figure 12. For a P/G8 discharge of 800 ft^3/s, the air pocket remained in the vicinity of the siphon crown and it could be removed with the vacuum pump, figure 12A. With P/G8 discharging 1,600 ft^3/s, the air pocket became displaced by higher flow velocities downstream of the crown. At 1,600 ft^3/s and an air pocket shorter than 12 feet, the trailing edge of the pocket was a sufficient distance downstream of the crown to prevent the vacuum pump from removing it, figure 12B. For 1,600 ft^3/s, but with a physically induced air pocket length greater than 12 feet, the trailing edge of the pocket could be seen even upstream of the crown and, therefore, susceptible to partial removal by the vacuum pump until the size was reduced to 12 feet. Upon reduction in length, of course the pocket would move downstream of the crown beyond the influence of the vacuum pump.

Even though the air pocket size could be varied in the model for a given flow, the variation should be regarded as a physically (artificially) induced transient condition that probably would not prevail had the model been operated a length of time sufficient for the pocket to reach a steady-state condition. Thus, in the prototype, the position and size of the air pocket would be a function of discharge and time immediately following unit startup, but would stabilize after an undetermined length of time.

The vacuum pump can be used to purge all air from a siphon crown only at low pump or turbine flows. If air accumulation is found to be a problem during normal prototype turbine operation, means should be provided to tap the air pocket at several locations down the penstock toward the pump-turbine unit.

Canal Headwall Flow Conditions

Air-entraining vortices formed in the canal near the headwall with either or both conduits simulating turbine design flow of 2,300 ft^3/s. Corrective measures are required to prevent formation of such vortices.

Siphon Crown Pressure

Pressures at the siphon crown varied with turbine discharge and canal water surface elevation. The minimum attainable pressure (-24.5 inches of mercury) occurred with 2,300 ft^3/s turbine flow and headwall water surface elevation 1562.5. The siphon crown pressure (vacuum) varied directly with canal water surface elevation for a given discharge. Figure 13 shows the siphon crown head versus turbine discharge at a constant headwall canal water surface elevation 1566 (as-built curve).

Conduit Head Loss, As-built (Existing) Structure

Total head loss from the canal headwall to a station 77.5 feet down the penstock toward the pump-turbine unit was 3.42 feet for a discharge of 2,300 ft^3/s with vortices present. Canal headwall modifications to prevent vortices also could be expected to reduce conduit entrance losses and, thereby reduce the total head loss.

CONDUIT ENTRANCE NO. 2

A conduit entrance modification not requiring removal of the as-built headwall and conduit entrance roof was installed in conduit P/G7, figure 14. The large-radius streamlined entrance was designed to eliminate vortices and reduce entrance losses. In the model, the upstream overhead portion of the streamlined entrance was extended above P/G7 and P/G8 (adjacent conduits) to ensure proper approach and conduit entrance flows, figure 15A. The modified curved roof is tangent to the sloping roof of the rectangular-to-circular transition at a station upstream of the transition, as shown on figures 14 and 15B.

Operation with this modification was satisfactory for one turbine operating at discharges up to 2,500 ft^3/s and water surfaces at the canal headwall above 1563.6. For 2,300 ft^3/s, head loss from the canal headwall to a station 77.5 feet downstream from the siphon crown was 3.01 feet, or 0.41 foot less than with the as-built design, table 1. Air-entraining vortices did not form with this modification.

RECTANGULAR CONDUIT — ENTRANCE NO. 3

The magnitude of pressure at the siphon crown prompted investigations regarding changes that might alleviate the vacuum and increase wall pressures and, therefore, provide safer operation. One scheme was to modify the siphon conduit by replacing the circular section with a rectangular section from the headwall up to the crest or high point of the siphon conduit, and a short distance down the other side. The cross sectional area remained the same and the invert trace of the rectangular section was on the same invert trace as the original circular conduit. Since the invert

Table 1.— *Conduit head loss station 77.5 feet downstream from the siphon crown, canal water surface at headwall is 1562.0 (Q* = 2,300 ft³/s)

Conduit design	Pressure head drop ft	$\frac{V^2}{2g}$ ft	Head loss ft	Headloss / $\frac{V^2}{2g}$
As-built	9.84	6.422	3.42	0.532
No. 2	9.43	6.422	3.01	0.469
Rectangular	11.14	7.042	4.10	0.582
No. 4	9.33	6.422	2.91	0.453
Recommended	9.35	6.422	2.93	0.456

elevation at the crest remained the same, the crown elevation became lower with the rectangular conduit.

Part of conduit entrance No. 2 was used in No. 3 — up to the station where the No. 2 vertical dimension was reduced to the 9-ft value of the new (No. 3) rectangular conduit, figure 16. The section elevation of the transition and beyond to the constant-slope approach to the crown is shown also. The entrance No. 2 side walls were tapered inward from 12 feet 4-½ inches wide at the headwall to 12 feet wide at the location of the beginning of the as-built transition. The 9-foot-high by 12-foot-wide rectangular conduit continued on downstream of the siphon crown about 104 feet, and the rectangular conduit bottom followed the trace of the as-built conduit throughout as shown on figure 17. The P/G7 siphon and conduit curves in plan view 9°38′47″ (fig. 5).

When air was introduced in the siphon crown, a small air pocket formed and clung to the inside radius (elbow) and roof, figure 18A. A larger air pocket covered the top surface from sidewall to sidewall, figure 18B. Evacuating air through a single port from the rectangular siphon crown was difficult with the vacuum pump, since the lateral location of the air pocket varied with discharge and air pocket size.

With the rectangular siphon elbow flowing full, pressures varied with discharge at the crown as shown on figure 13. Although the rectangular crown was 3 feet lower than that of the circular conduit, for 2,300 ft³/s the pressure head at the crown was only 0.9 foot greater than in the circular siphon. The smallness in difference was caused in part by greater hydraulic losses in the rectangular conduit and a lesser head recovery because of centrifugal forces in the siphon elbow.

Installing rectangular conduits in the prototype would be quite costly, since replacement of about 225 feet of each presently installed circular conduit would be required. The advantage appears minor; i.e., an additional safety tolerance of less than 1 foot of head in the siphon crown at design flow. Therefore, the rectangular conduit concept was abandoned.

At this point in the studies, the structural and hydraulic situation was re-examined and the decision was made to limit modifications to those that could be made *downstream* from the headwall. Otherwise, it was thought that the expense and structural problems would be quite formidable. Since the configuration of conduit entrance No. 2 was good, new designs were planned to include modifications wholly downstream from the headwall.

CONDUIT ENTRANCE NO. 4

Conduit entrance No. 4 design reduced the cross-sectional area of the No. 3 rectangular conduit to nearly the same area as the downstream 12-foot-diameter conduit. In modelling P/G7 and P/G8, the large-radius roof of conduit entrance No. 2 (fig. 14) was extended downstream and flared so that the minimum vertical dimension upstream of the rectangular-to-circular transition was 9 feet 1-½ inches, figure 19. A roof of uniform slope was installed in the 36-foot-long transition. The conduit was 9 feet 1-½ inches high by 12 feet 4-½ inches wide at the upstream and 12 feet in diameter at the downstream end. In the headwall, on each side of both conduits, trashrack slots 12 inches wide by 6 inches deep were installed, figure 20A.

With this scheme turbine flow was satisfactory for one or both conduits operating except for the formation of air-entraining vortices in the trashrack slots, without racks in place. The head loss was 2.91 feet from the canal headwall to a location 77.5 feet downstream from the siphon crown at 2,300 ft^3/s, table 1.

The high point of the curved roof at the headwall was well above minimum canal water surface elevation, and the portion above water surface would not affect entrance hydraulics, figure 20B. Therefore, a smaller radius entrance roof would require lesser removal of the existing concrete than would be required for conduit entrance No. 4 and be less costly to install. Thus, conduit P/G7 was modified to reflect the new concept.

CONDUIT ENTRANCE NO. 5 — RECOMMENDED

The roof shape entrance downstream from the headwall was changed to double-radius curvature — a small radius beginning at the headwall and downstream a larger radius tangent to the 9-foot 1-½-inch-high conduit of entrance No. 4, figure 21. Conduit P/G7 was modified to the new configuration, and P/G8 remained as entrance No. 4. The 12-inch-wide by 6-inch-deep trashrack slots were included, but the underdrain well between P6 and P/G7 was not included, figure 22A.

Generally, flow with this scheme was satisfactory except for the formation of air-entraining vortices induced in the trashrack slots, figure 22B. When the slots were filled, as shown on figure 22A, air-entraining vortices did not form. The trashracks to be used during turbine flow, when lowered into the slots, would fill the slots effectively and prevent objectionable air entrainment. Any air passages that may remain between the slots and trashrack are not considered large enough to allow development of vortices. Head loss was 2.93 feet from the canal headwall to a location 77.5 feet downstream from the siphon at 2,300 ft^3/s, table 1.

Conduit entrance No. 5 appeared to be satisfactory for conduits P/G7 through P/G12.

CANAL HEADWALL MODIFICATIONS

With P/G7 modified earlier to conduit entrance No. 5, the P/G8 entrance was modified to represent conduit entrance No. 5, the underdrain well between P6 and P/G7, trashrack slots, siphon for P/G8 elbow, and about 300 feet of conduit downstream from P/G8 elbow. Conduits P/G9 through

P/G12 were installed with trashrack slots and conduit entrance No. 5 shapes 19.84 feet from the canal headwall to the downstream end of the curved entrance roof, figure 21. These four conduits then were attached to separate control pipes. A headbox was constructed to supply water to the system for the pump mode, figure 23. The basic headwall configuration is shown in plan view on figure 24. All headwall modification studies were simulated with 2,300 ft^3/s representing each turbine mode. The pump mode discharge was 1,600 ft^3/s per unit.

HEADWALL TEST 1

The leading edge of each divider pier was modified to a sharp nose extending upstream, figure 25. The upstream face of the underdrain well was chamfered on the "turbine side" only. Figure 26 shows five turbines operating (P/G11 closed) at a canal headwall water surface elevation 1566.0, representing Banks Lake of about elevation 1570.3 before drawdown at the headwall. A large air-entraining vortex formed as water flowed around the underdrain well from the "pump side" to the "turbine side." A small continuous vortex formed on the left side of any operating turbine intake when the turbine intake adjacent on the left was not operating. These two vortices can be seen on figure 26 upstream from P/G7 and P/G12. Random small transient vortices also formed upstream of the canal headwall for the full width of the six (turbine mode) conduit entrances.

HEADWALL TEST 2

For directing the flow at the canal headwall from the "pump side" to the "turbine side" of the underdrain well, a large-radius wingwall was installed, figure 27. Each dividing pier was supplied with a guide wall for full-flow depth to direct the oblique flow into the conduit entrances, figures 27 and 28A. Five turbines operating (P/G9 closed) at a headwall water surface elevation 1566.0 is shown on figure 28B. The large-radius wingwall attached to the underdrain well improved the flow into conduit P/G7; however, random air-entraining vortices continued to form elsewhere. A continuous vortex formed — as before — when a turbine entrance was closed to the left of an operating turbine, as shown by P/G10, figure 28B.

HEADWALL TEST 3

On each dividing pier, cantilevered guide walls were installed to suppress the tendency for rotational surface flow which could cause vortex formation, figures 29, 30A, and 37. The scheme was satisfactory in eliminating the continuous vortices at maximum Banks Lake elevation 1570.0 and Feeder Canal water surface elevation 1565.2 (fig. 30B); however, at those elevations random air-entraining transient vortices continued to form, and continuous air-entraining vortices formed at minimum canal water surface elevation 1562.

HEADWALL TESTS 4 AND 5

The cantilevered guide walls of test 3 were positioned 19°30′ toward the Feeder Canal centerline and tested [test 4 (fig. 31A)] without trashracks, and with trashracks, test 5 (fig. 32). Flow at the canal headwall appeared the same with or without trashracks. The 6- by 12-inch closed-side beams of the trashracks completely fill the trashrack slots, thereby eliminating air-entraining vortices that formed in open slots.

With this scheme flow was good for conduits P/G10, P/G11, and P/G12 at maximum canal water surface, but poor around the large-radius center wingwall and conduit entrances P/G7 and P/G8, figure 31B. For minimum canal water surface elevation 1562, continuous air-entraining transient vortices formed near the wingwall.

Model trashracks were in place for all subsequent headwall tests.

HEADWALL TEST 6

The large-radius center wingwall was redesigned with longer-radii curved surfaces so that it would not extend as far into unit P6 stream path (fig. 33), even with a greater pier length than shown in figures 27 and 29. With this design, and for five turbines operating, the flow pattern was unsatisfactory since continuous air-entraining vortices formed as water flowed around the longer-radius wingwall to the "turbine side."

HEADWALL TEST 7

Previous guide walls were removed, and new ones were attached to the second and fourth dividing piers in an attempt to direct the flow into three dual sets of turbines (conduits), figure 34. The design was unsatisfactory, since with any five turbines operating, air-entraining vortices formed around each guide wall.

HEADWALL TEST 8

Several schemes were tried with the assumption that turbine flow approaching the canal headwall could be guided into conduit entrances by deflector walls on the canal floor. The basic shape of the headwall and canal transition is shown on figure 35. Half-round guidewall noses (shown) were installed on the dividing piers between adjacent turbine conduit entrances. A reverse-curve deflector wall 12 feet high and 1-½ feet wide was installed as shown on figure 36. With this wall, flow was unsatisfactory. Water overtopped the deflector wall from right to left (looking toward the headwall) at the upstream portion of the wall and approached the conduit entrances from the left, forming air-entraining vortices at each operating turbine entrance.

HEADWALL TEST 9

A shorter single-radius curved deflector wall 7 feet high was installed on the flat portion of the canal transition, and a center dividing wall with a sloping top was extended 78.25 feet upstream from the underdrain well, figures 37 and 38A. The curved deflector wall had little discernible effect on the flow, and the sloping center dividing wall formed an obstruction to crossflow in the vicinity of the headwall, with resultant large air-entraining vortices, figure 38B.

HEADWALL TEST 10

The sloping center dividing wall of headwall test 9 was replaced with a straight cantilevered dividing wall 30 inches wide extending 15 feet upstream from the underdrain well, figures 39 and 40A. With this scheme, flow was good for units P/G9 through P/G12; however, intermittent air-entraining vortices formed and entered units P/G7 and P/G8, figure 40B.

HEADWALL TEST 11

The longer-radius center wingwall of headwell test 6 was modified by removing (cantilevered) a lower portion of the wingwall upstream of the underdrain well to a 1:1 slope from the floor to the 14-inch-diameter wingwall nose. The leading edge of the longer-radius cantilevered center wingwall was streamlined to a half-round, and the 14-inch-diameter wingwall nose was continued vertically to the canal floor as a supporting column, figures 41 and 42A. Generally, flow with this scheme was good, except that occasional air-entraining vortices formed upstream from unit P/G7 where the stream flowed around the wingwall nose "turbine-side," figure 42B.

HEADWALL TEST 12 — RECOMMENDED DESIGN

A center wingwall similar to that of headwall test 11, but with the upstream portion "turbine side" curving more sharply outward, was installed upstream from the underdrain well, figure 43. The back surface "pump side" of the model center wingwall was fabricated straight rather than with the 20-foot 9-¾-inch radius shown on figure 43. This was deemed expedient, since the back surface would have little effect on turbine flow. Pump flow from conduit P6 could be evaluated adequately realizing that the center wingwall was not modeled truly on that surface. The canal headwall design included half-round noses on the dividing piers between adjacent conduit entrances for units P/G7 through P/G12, and slot-filled trashracks in place, figure 44A. With this design, flow was excellent for any combination of one to five turbines operating. Figure 44B shows the tranquil conditions at the canal headwall while discharging 2,300 ft^3/s and with minimum permissible Feeder Canal water surface.

The fairly smooth canal headwall flow conditions with P/G7 and P/G8 operating, and with minimum and near maximum canal water surfaces, are shown in figures 44C and 44D. At the headwall, flow conditions became progressively more turbulent as additional turbines were put into operation, as shown on figures 44E through H. However, flow patterns with even the most adverse conditions, figure 44G, are acceptable and without air-entraining vortices.

When operating five turbines at a total flow of 11,500 ft³/s and with minimum permissible canal water surface elevation 1562 (Banks Lake El. 1569), the water depth at station 3 + 12.12 is only 1.65 feet above the critical depth. An increase of 3 percent in the total water demand for the turbines would cause critical flow at station 3 + 12.12, resulting in very rapid drawdown of the small pool between station 3 + 12.12 and the canal headwall. With a water surface elevation 1560.4 at the headwall, vapor pressure will exist at each siphon crown unless relieved by the siphon breakers or by air being drawn in from the conduit entrances. Air drawn in at the entrance would result in a reduction, or cessation of flow through the conduits, causing a bore wave in the canal which conceivably could overtop the headwall and the canal sides.

The conditions prevailing in the canal at the canal headwall for turbine flows of 8,700 ft³/s, and critical depth at station 3 + 12.12 are shown on figure 45. The water surface elevation at station 3 + 12.12 is 1558.6 and the canal flow should be restricted to not more than 8,300 ft³/s. The flow and depth situation shown on figure 45 would produce an unsatisfactory and very dangerous condition in the prototype installation.

Conduit Wall Pressures

Conduit wall pressures were recorded at the recommended design discharge of 2,300 ft³/s (one turbine) and with the canal headwall water surface at minimum operation elevation 1562.0. The head loss was 2.93 feet from the canal headwall to a station 77.5 feet downstream from the siphon crown. Wall pressure test results are shown on figure 46. The canal water surface and the discharge were set to produce the lowest permissible pressure in the system — a head of 24.5 inches of mercury *below* atmosphere at the siphon crown.

Banks Lake and Feeder Canal Headwall Relation

The combinations of Banks Lake and Feeder Canal headwall water surface elevations under which different numbers of turbines may be operated safely (2,300 ft³/s per turbine — design discharge) are shown on figure 47.

Figure 48 shows the turbine capacity (single turbine) for a constant canal headwall water surface elevation and different Banks Lake water surface elevations. It illustrates how the rated capacity can increase by as much as 15 percent. Only the 100-percent gate opening is shown on the envelope. Different openings would be required to achieve other points on both curves. The allowable negative pressure at the siphon crown is used to determine the minimum permissible Banks Lake water surface elevation. A similar family of curves may be plotted for other turbine discharges by determining the canal headwall water surface elevation for the allowable siphon crown pressure from figure 49, and the Banks Lake and Feeder Canal water surface combinations from figure 8.

Pump Flow

Pump flow appeared good up to 9,600 ft^3/s with each of P/G7 through P/G12 discharging 1,600 ft^3/s. The pump discharge from P/G12 was deflected by the canal wall causing a wave to rise about 1 foot above the average canal headwall water surface; however, the wave quickly dissipated and appeared to cause no adverse flow patterns.

The underdrain well and center wingwall (fig. 43) were moved to the dividing pier between P/G8 and P/G9. Unit P/G8 was operated to simulate P6 discharge. The wingwall deflected the discharge from P6 simulation and produced rough flow conditions along the canal headwall immediately after pump startup. However, the water surface quickly smoothed out as flow in the canal was established. Although the center wingwall supporting column is nearly in line with P6 conduit centerline (fig. 43) it should not cause objectionable flow conditions during normal pumping operation.

The normal prototype installation of the center wingwall and the streamlined conduit entrances for P/G7 and P/G8 is shown on figures 50, 51, and 52.

Lowered Canal Floor

For future installation of units P/G9 through P/G12, a test was made to observe the flow at the canal headwall with the canal floor lowered as shown on figures 53, 54, and 55. All six conduits operated with turbine flow. The proposed canal floor modifications extend more than 5,000 feet toward Banks Lake from the Feeder Canal headwall. However, the model included only about 800 feet of the Feeder Canal; therefore, the flow in the canal was not modelled accurately. A computation was made of the anticipated head losses in the canal with the floor lowered and water flowing from Banks Lake to the Feeder Canal headwall. Results of the computation are shown on figure 56.

The appearance of the flow at the canal headwall with six turbines operating (2,300 ft^3/s per unit) was very similar to that shown on figure 44G. Siphon elbow pressures were dependent on the discharge and the canal headwall water surface — the same as with the as-built floor — as shown on figure 46.

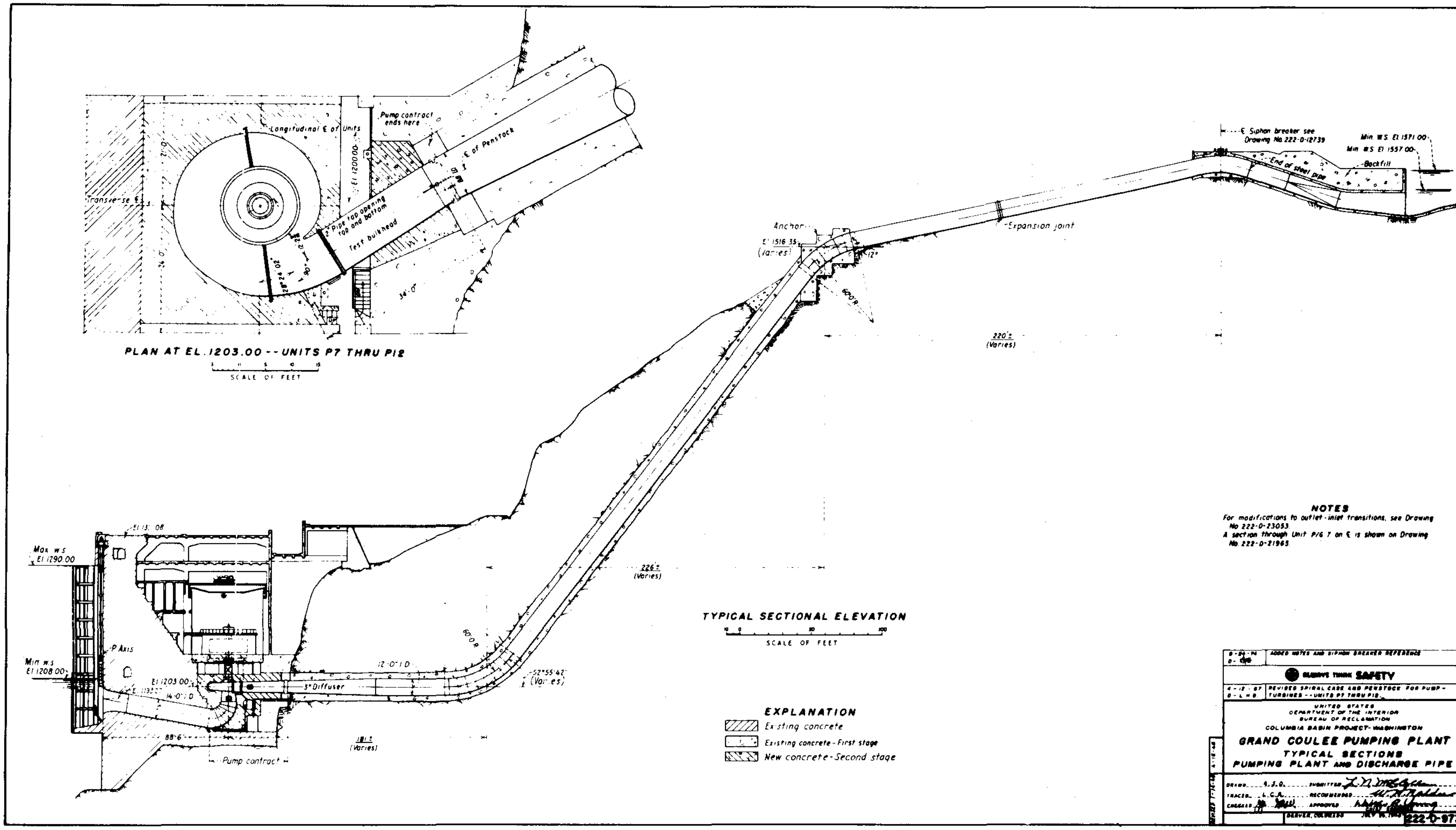


Figure 1. — Grand Coulee Pumping-Generating Plant -pumping plant and discharge pipe.

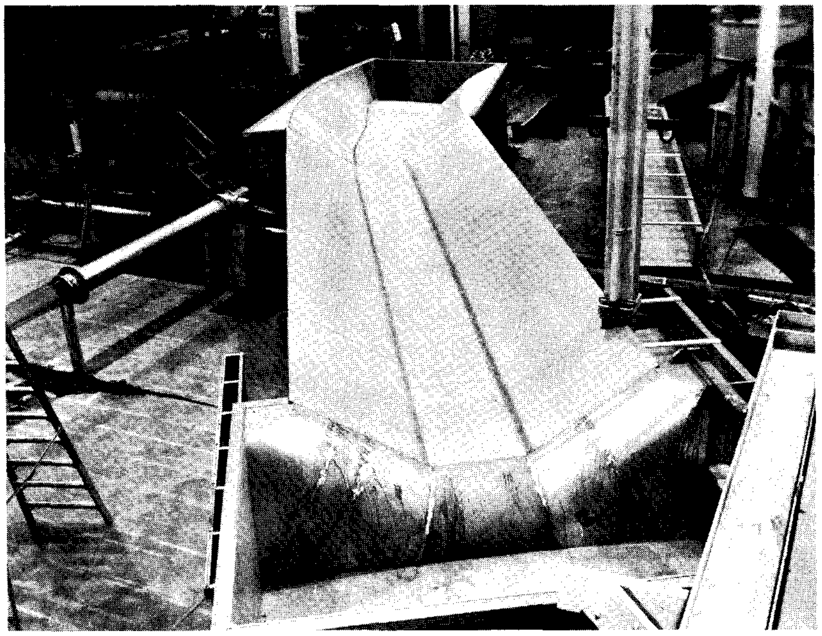


Figure 2. — Looking toward the canal headwall. The model canal includes the headwall, trapezoidal-to-rectangular transition, and about 550 feet (prototype) of straight canal - model scale 1:18.65. Photo H-1594-3NA

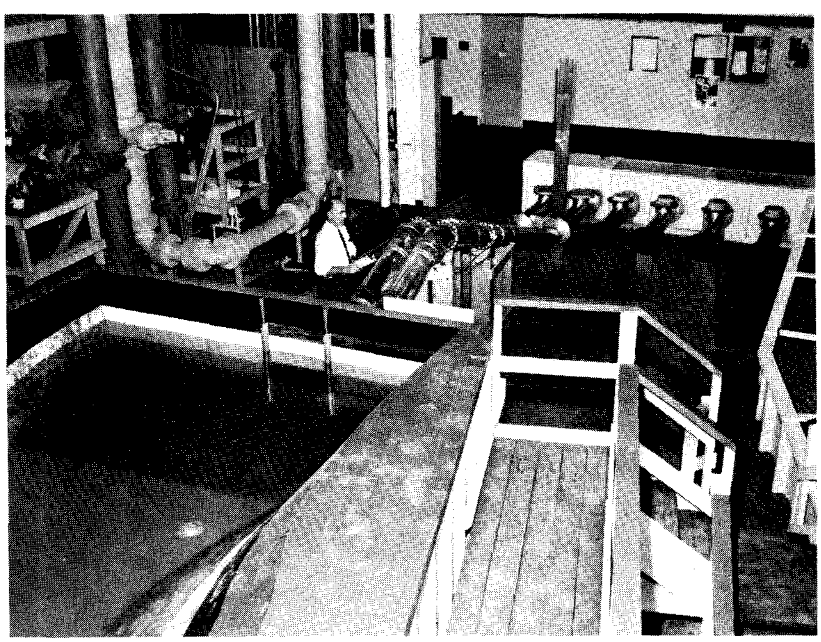


Figure 3. — Conduits P/G7 and P/G8 as-built. Photo H-1594-9NA

Figure 4. — View of Grand Coulee Pumping-Generating Plant. The pumping plant and intake structure is at the lower left, 12 conduits are near the center, and a portion of the Feeder Canal is at the upper right. Photo 1222-112-16462

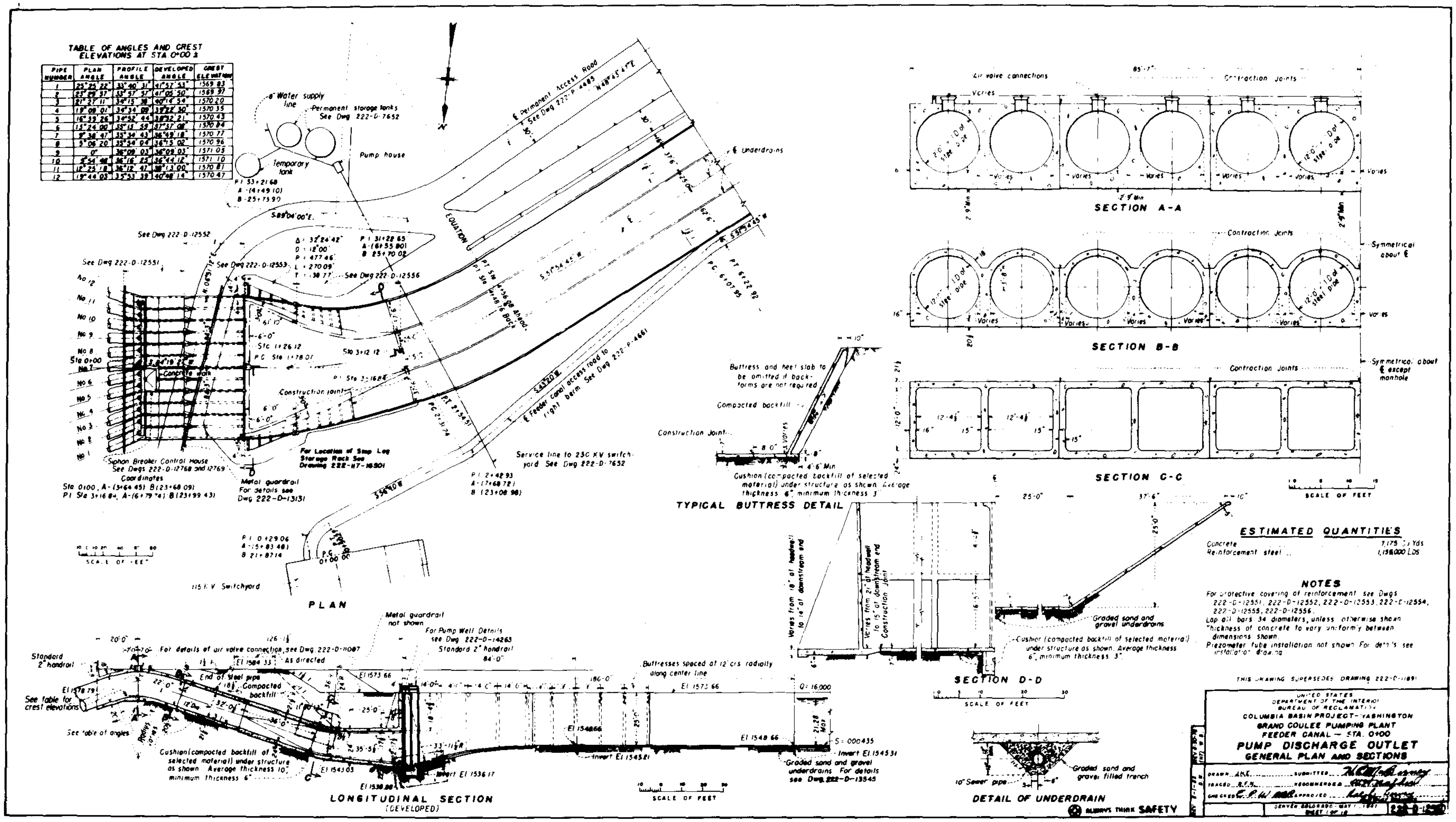


Figure 5. — Pump discharge outlet - plan and sections.

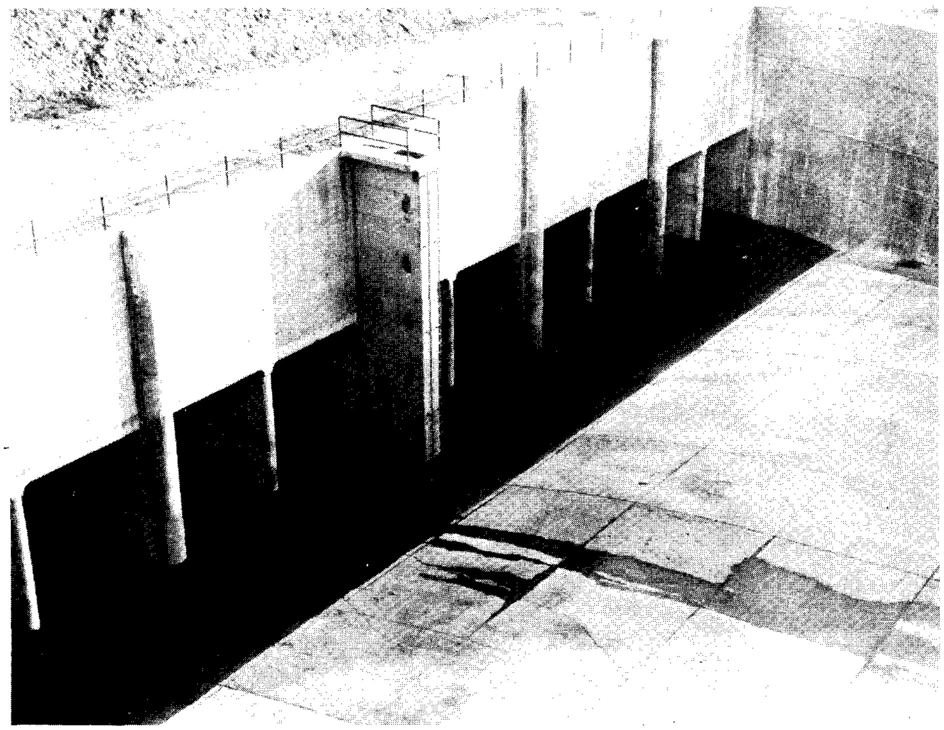


Figure 6. — Prototype (Feeder Canal) headwall showing the underdrain well between conduits P6 and P/G7. The six conduit entrances to be converted for dual operation modes are to the right of the underdrain well. Photo GB-11604

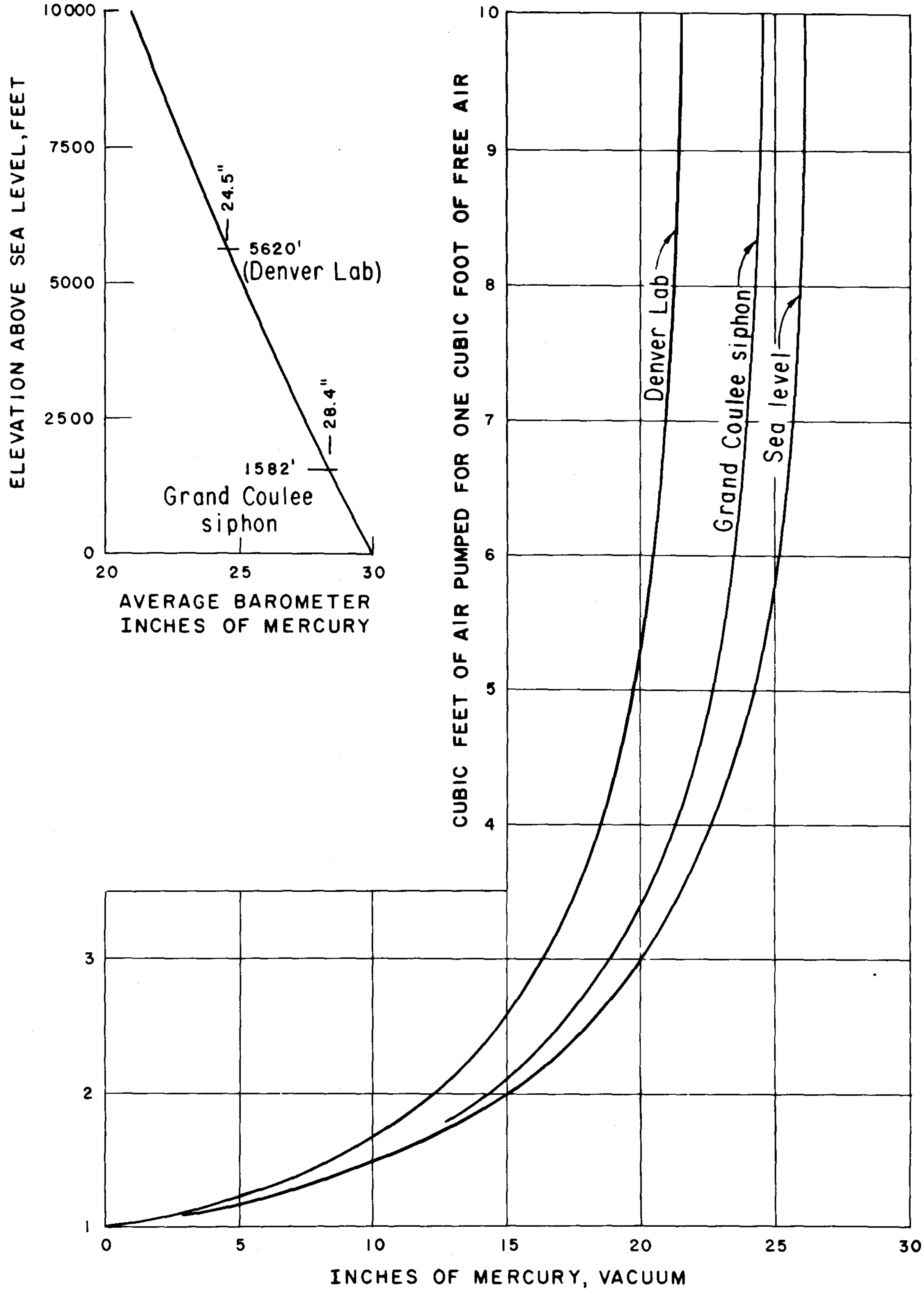


Figure 7. — Vaccum pump capacity for different elevations.

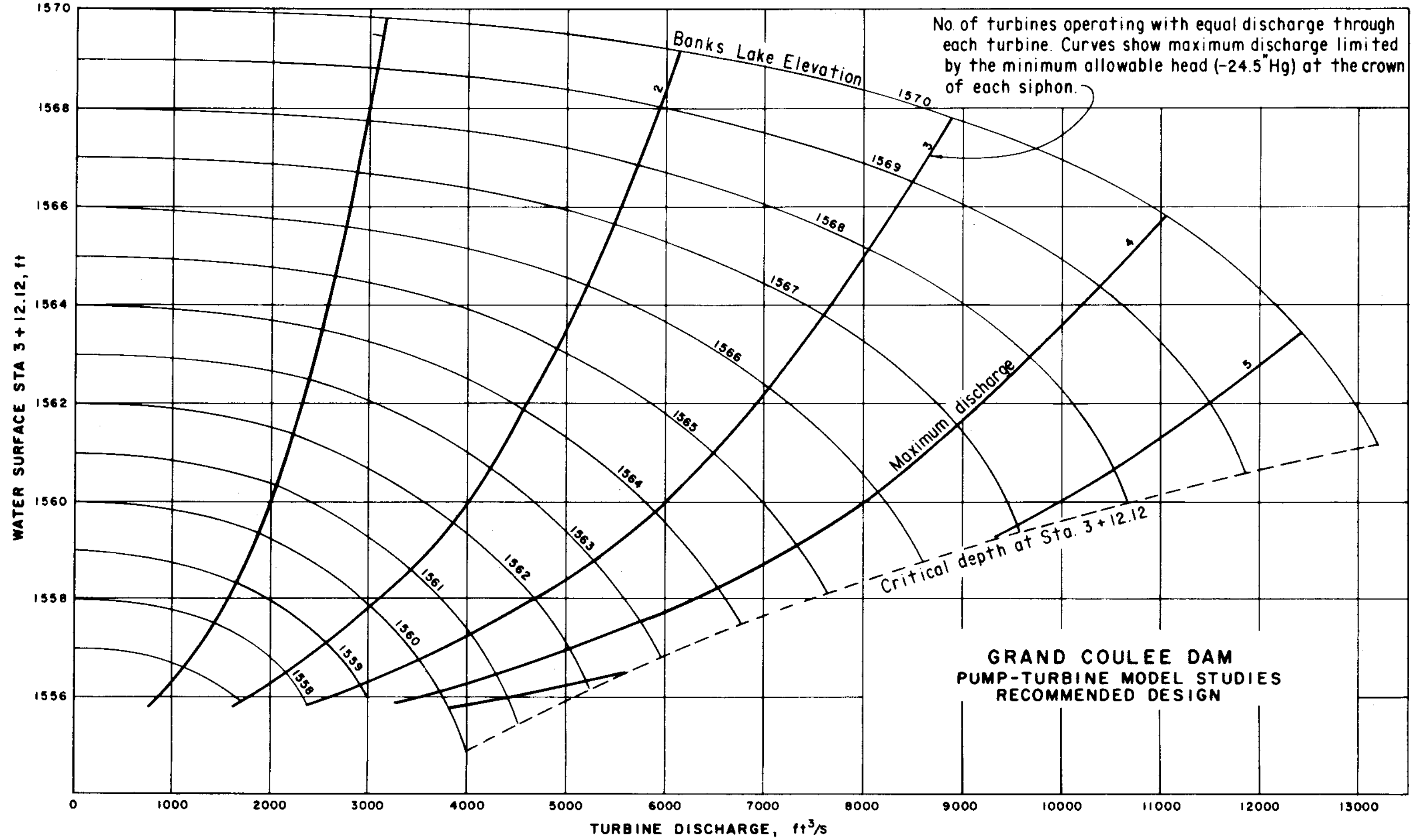


Figure 8. — Maximum turbine discharge versus Feeder Canal water surface elevation at station 3 + 12.12 - existing Feeder Canal floor.

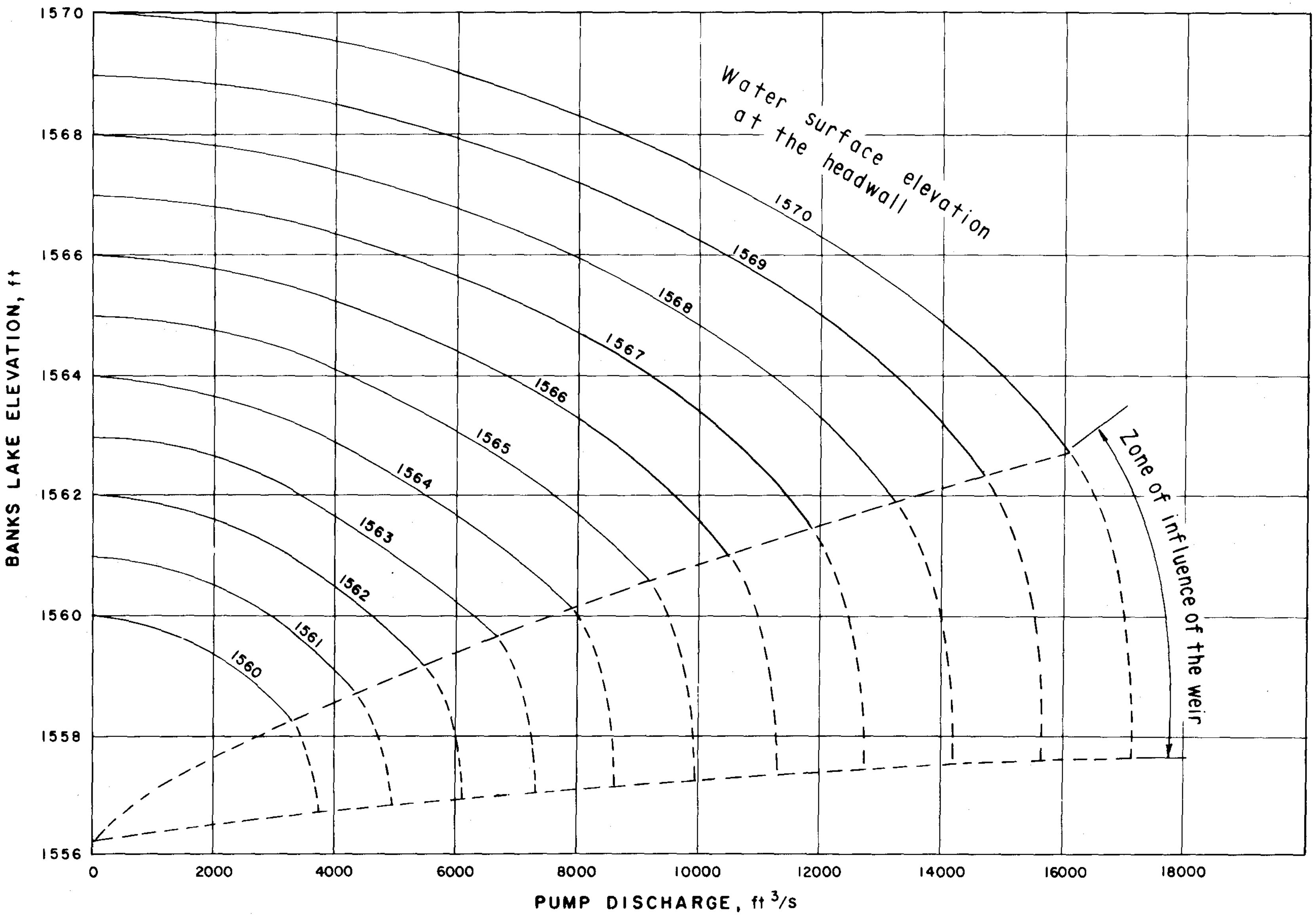


Figure 9. — Pump discharge versus Banks Lake elevation - head loss between the Feeder Canal headwall and Banks Lake.

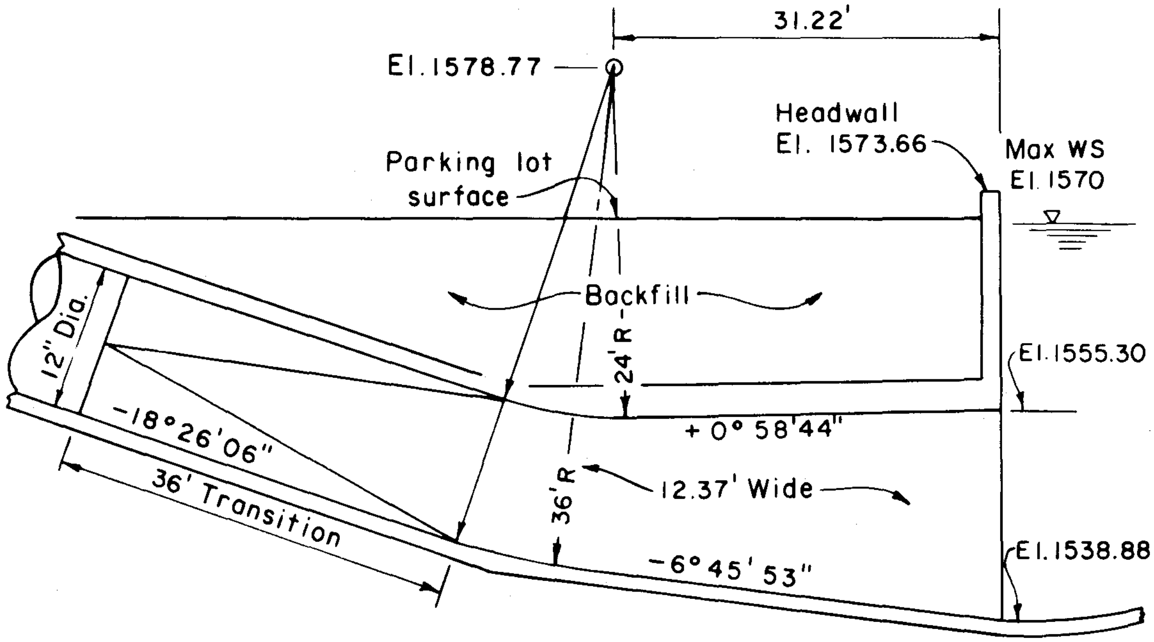


Figure 10. — As-built conduit entrances at the Feeder Canal headwall.

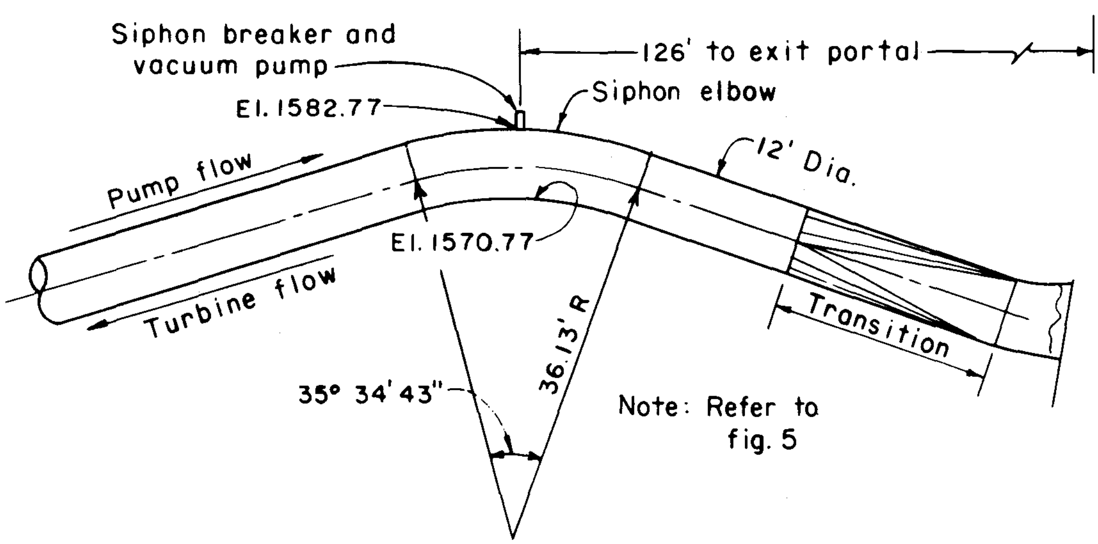
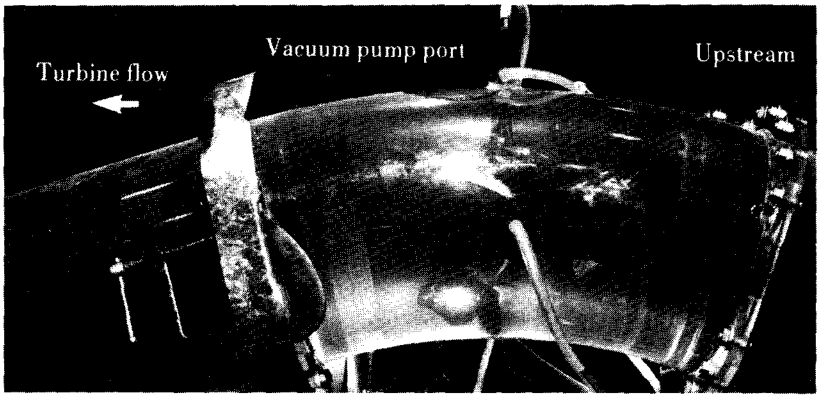
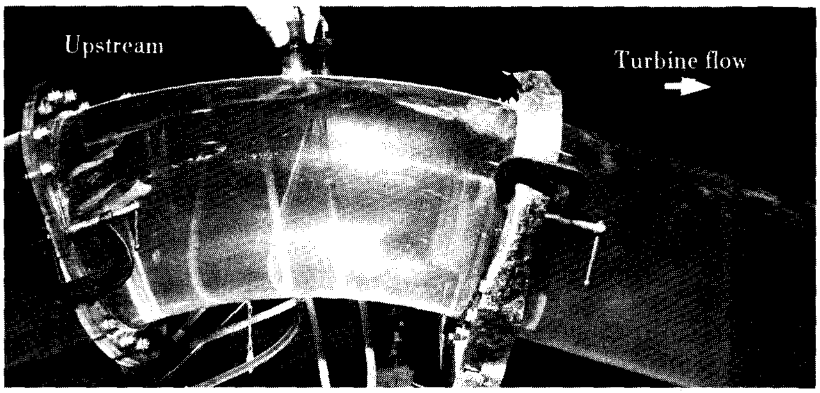


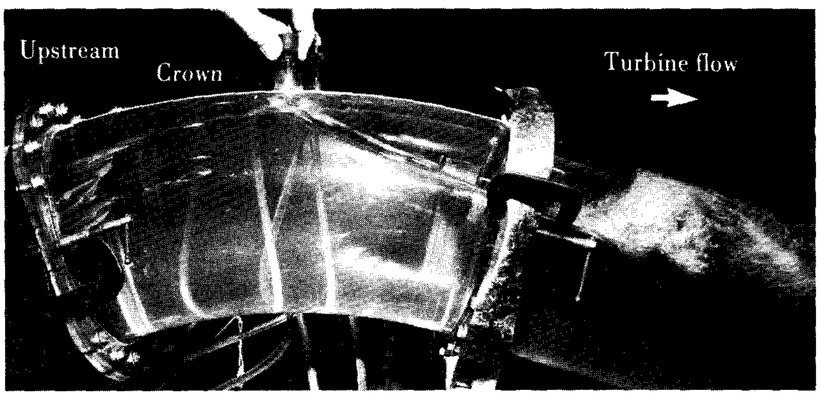
Figure 11. — Typical siphon elbow - slopes, angles, elevations, etc., vary slightly between outlets.



A. — Note air pocket directly under the vacuum pump port, 800 ft³/s. Photo H-1594-16



B. — The upstream edge of the 10-ft-long air pocket is downstream from the vacuum pump port, 1,600 ft³/s. Photo 1594-24



C. — The upstream edge of the 12-ft air pocket is under the vacuum pump port, 1,600 ft³/s. Photo 1594-25

Figure 12. — Siphon elbow with turbine flow.

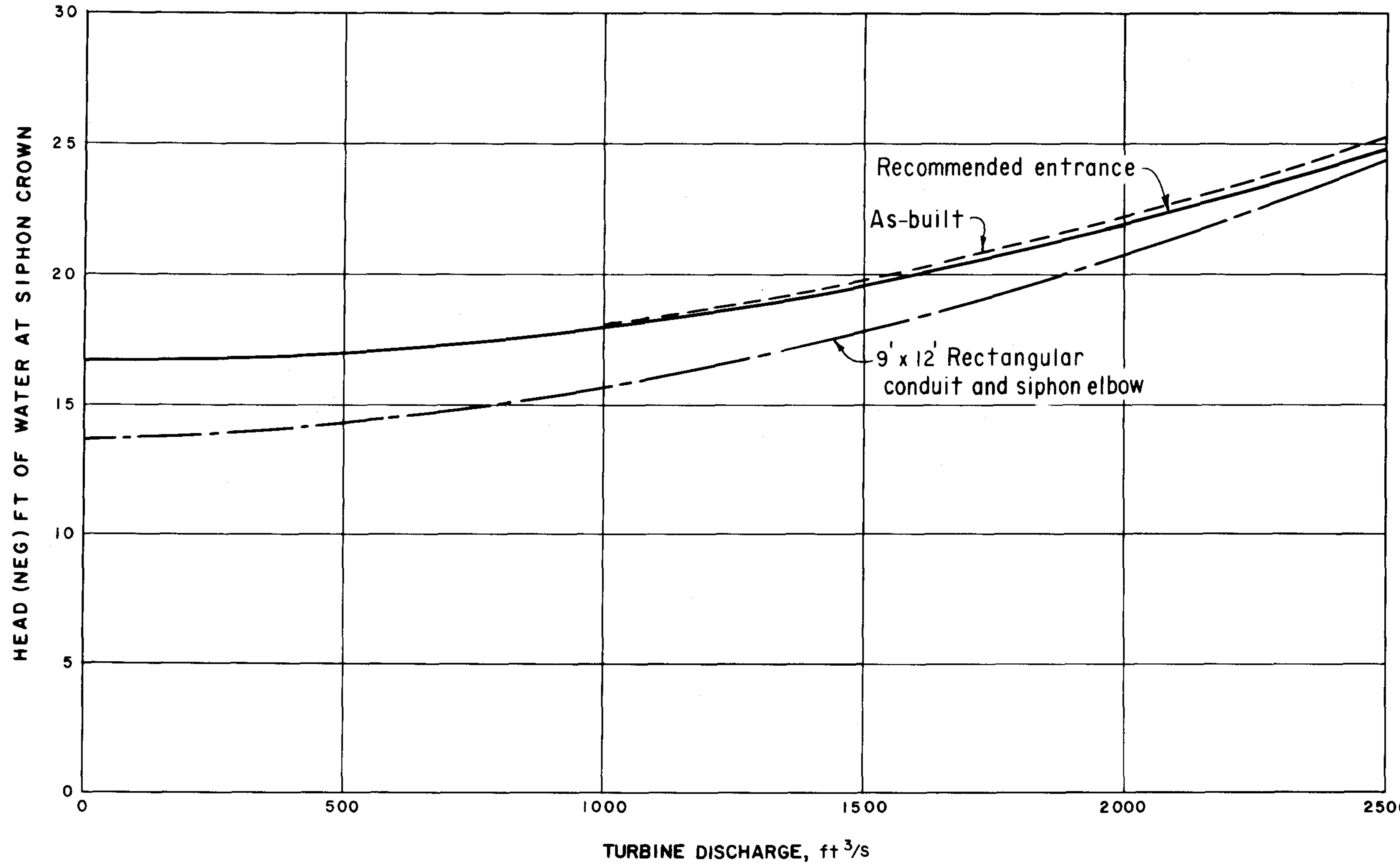


Figure 13. — Negative head at the siphon crown versus turbine discharge - canal water surface El. 1566.

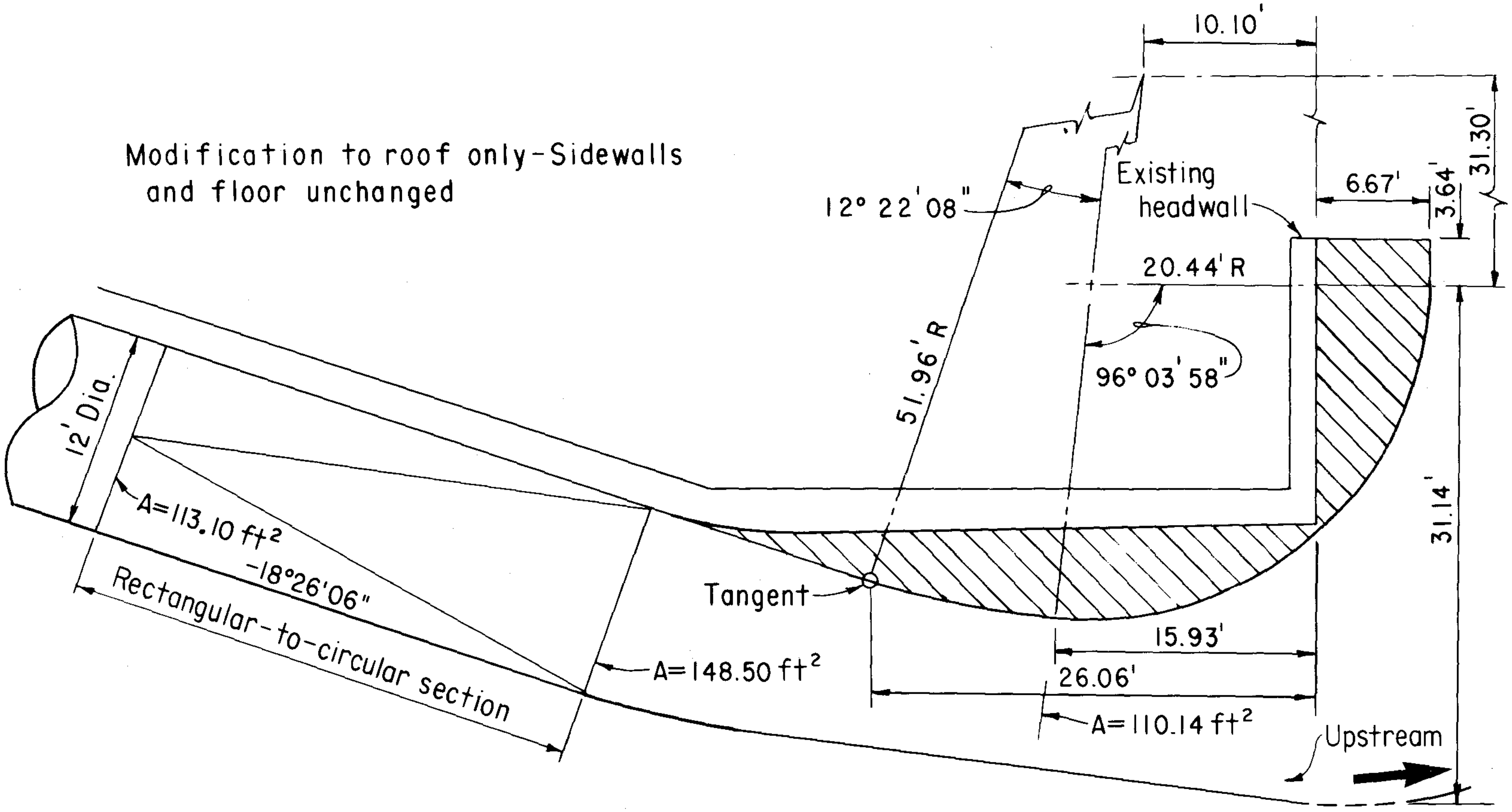
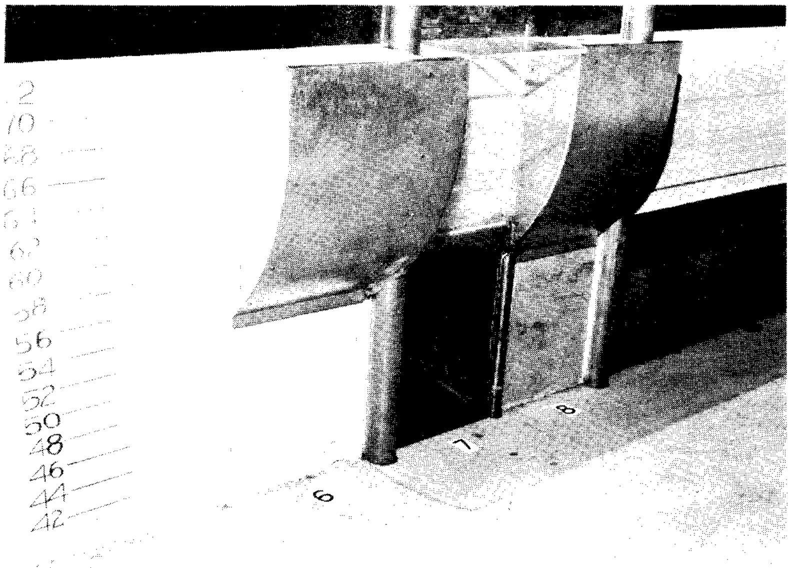
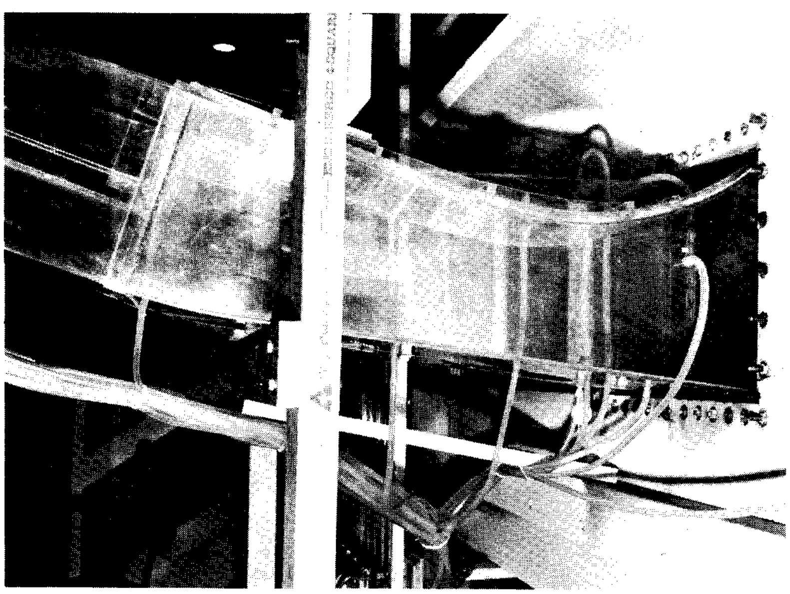


Figure 14. — Large-radius streamlined entrance extending upstream from the Feeder Canal headwall - conduit entrance No. 2.



A. — Canal headwall modification above conduits P6, P/G7 (plastic), and P/G8. Photo H-1594-37NA



B. — Modified conduit P/G7 downstream from the canal headwall.

Figure 15. — Streamlined entrance modifications extending from the canal headwall - conduit entrance No. 2. Photo 1594-38

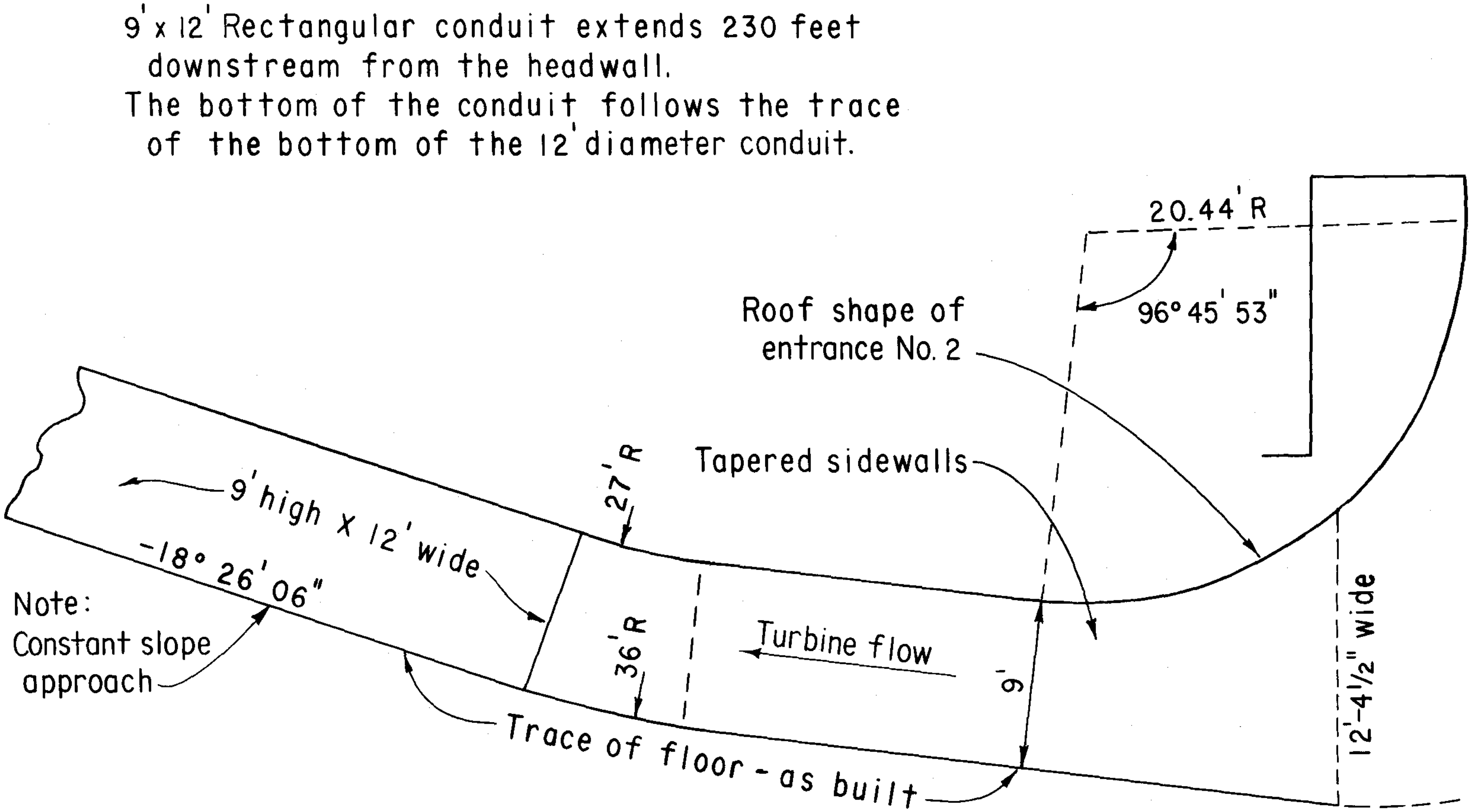


Figure 16. — Entrance for rectangular conduit.

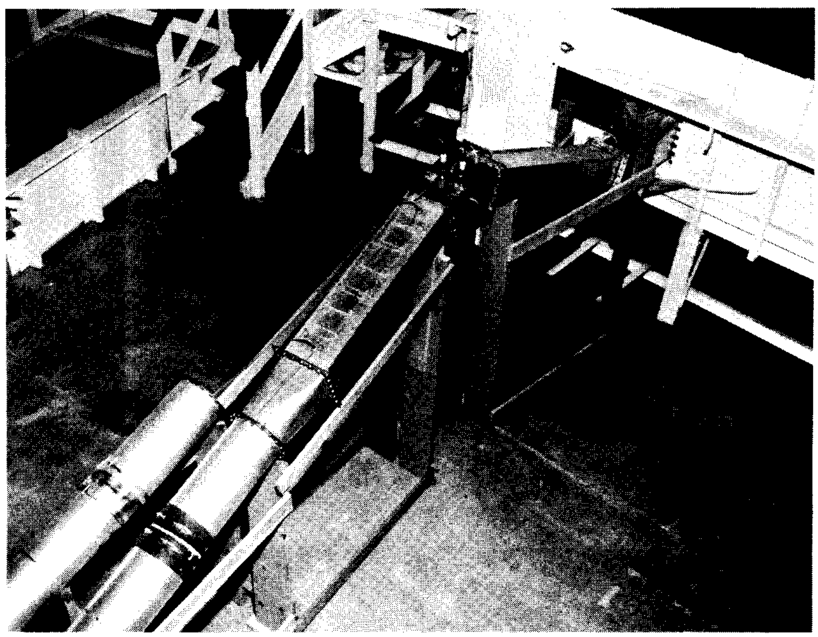
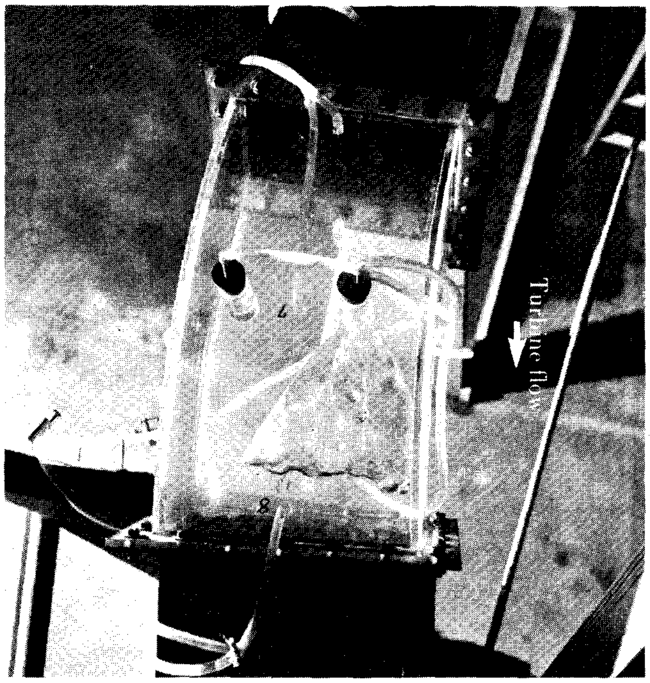
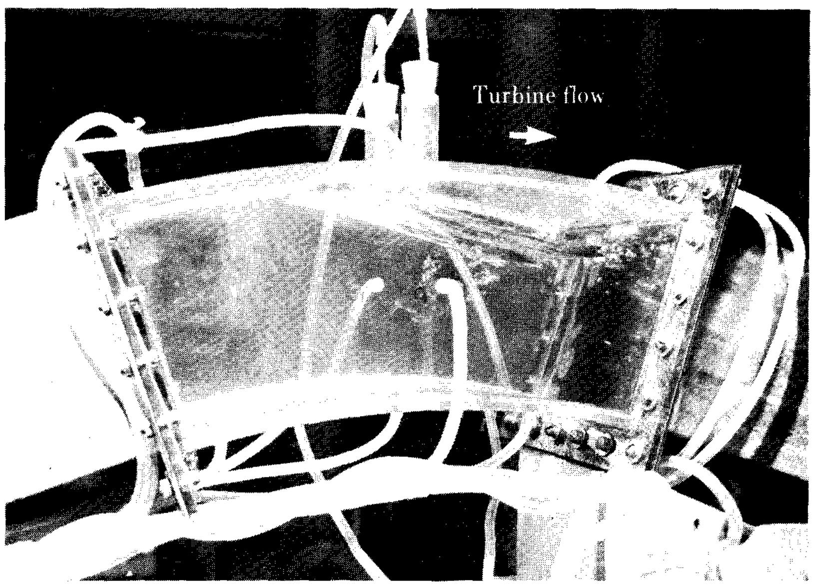


Figure 17. — Rectangular conduit (9 by 12 ft) and siphon elbow. Photo H-1594-41NA



A. — Small air pocket clinging to the inside of the elbow. Plan view. Photo H-1594-42NA



B. — Large air pocket full width of the elbow, but unsymmetrical in plan view. Elevation. Photo H-1594-43

Figure 18. — Rectangular siphon elbow showing air pocket.

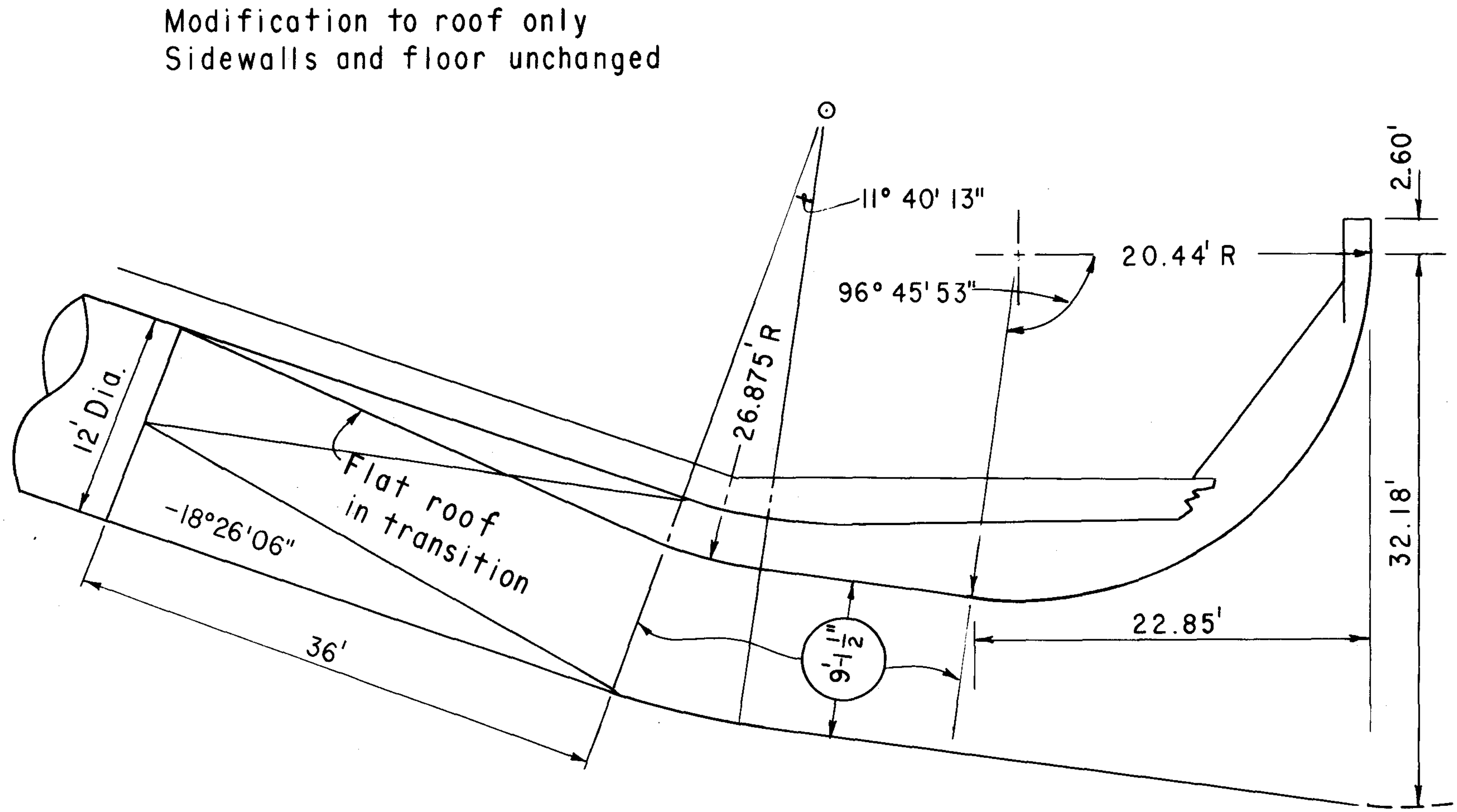
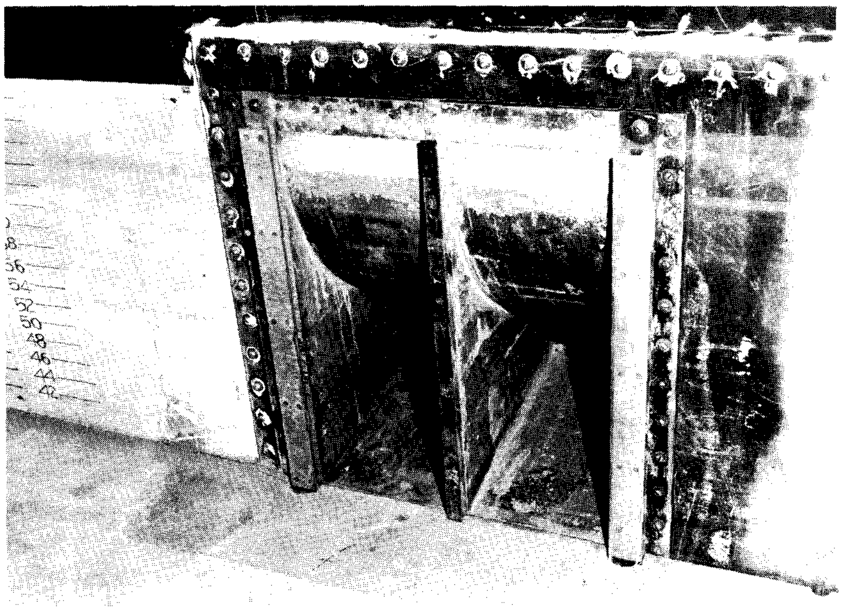
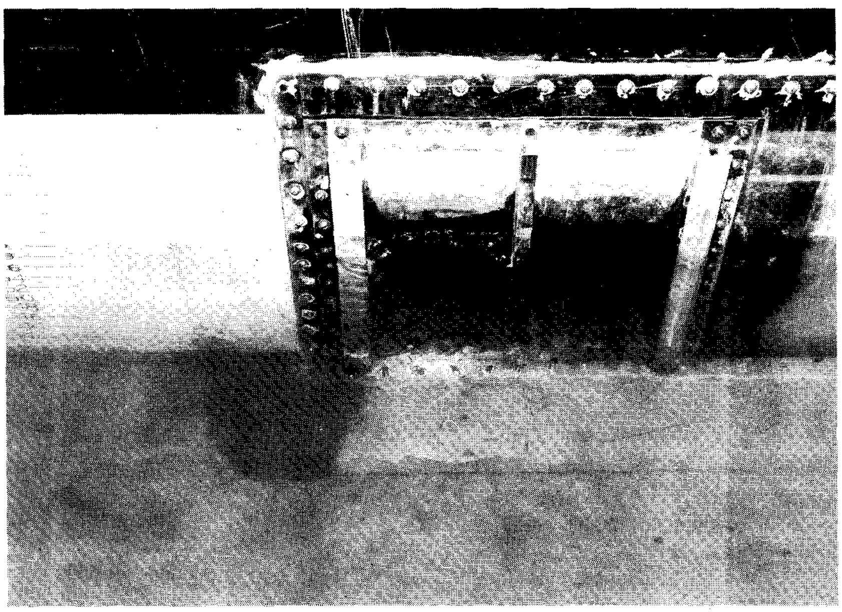


Figure 19. — Large-radius streamlined conduit entrance beginning flush with the Feeder Canal headwall.



A. — View upstream of conduits P/G7 and P/G8 with trashrack slots. Photo H-1594-63NA



B. — Conduit P/G7 only operating at 2,300 ft³/s, Banks Lake El. 1561.5, and Feeder Canal headwall W. S. El. 1561.0. Photo H-1594-64NA

Figure 20. — Conduit entrance No. 4 - Large-radius roof (refer to fig. 19).

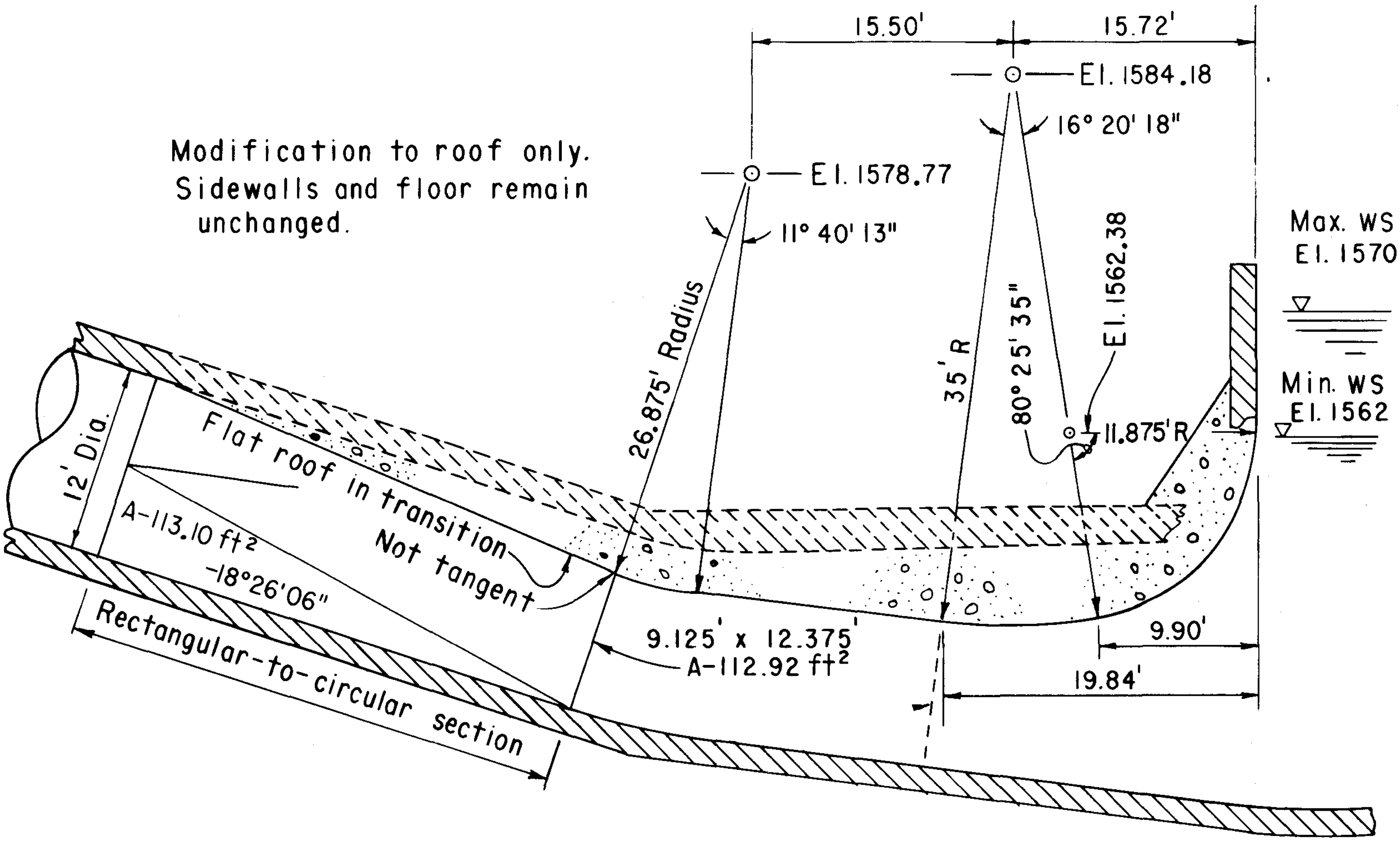
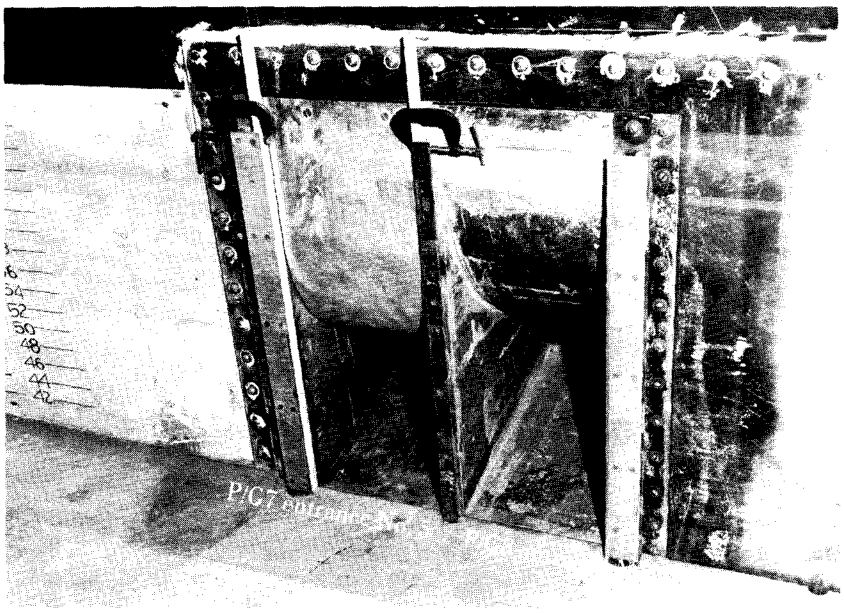


Figure 21. — Small-radius streamlined conduit entrance flush with Feeder Canal headwall - conduit entrance No. 5 recommended design.



A. — Unit P/G7 conduit entrance No. 5 on the left - recommended entrance design. Photo H-1594-61NA

B. — Conduit P/G7 discharging 2,300 ft^3/s - Note air-entraining vortex in the trashrack slot. Photo H-1594-46NA

Figure 22. — Recommended conduit modification - P/G7.

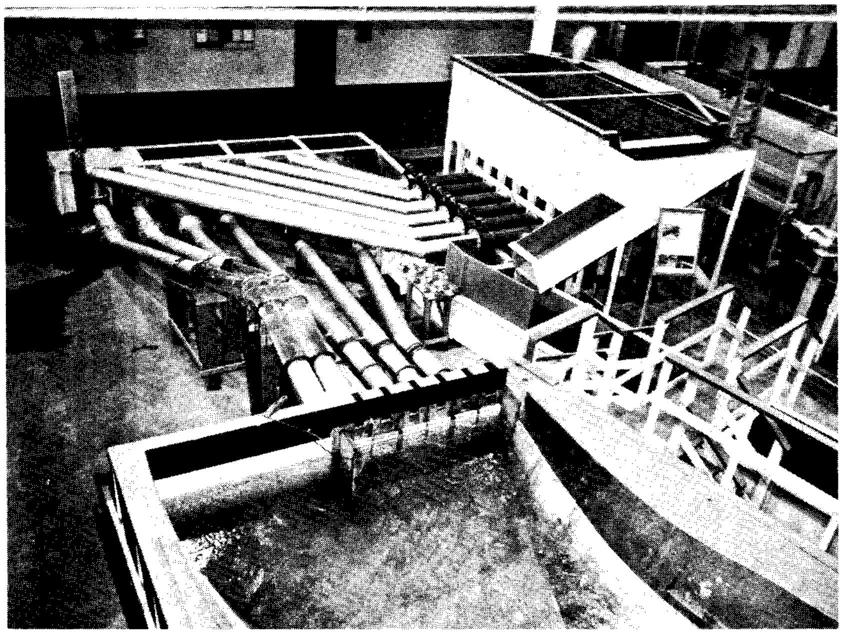


Figure 23. — View of completed model piping. Note headbox at upper right for supplying the pumping mode. Photo H-1594-153NA

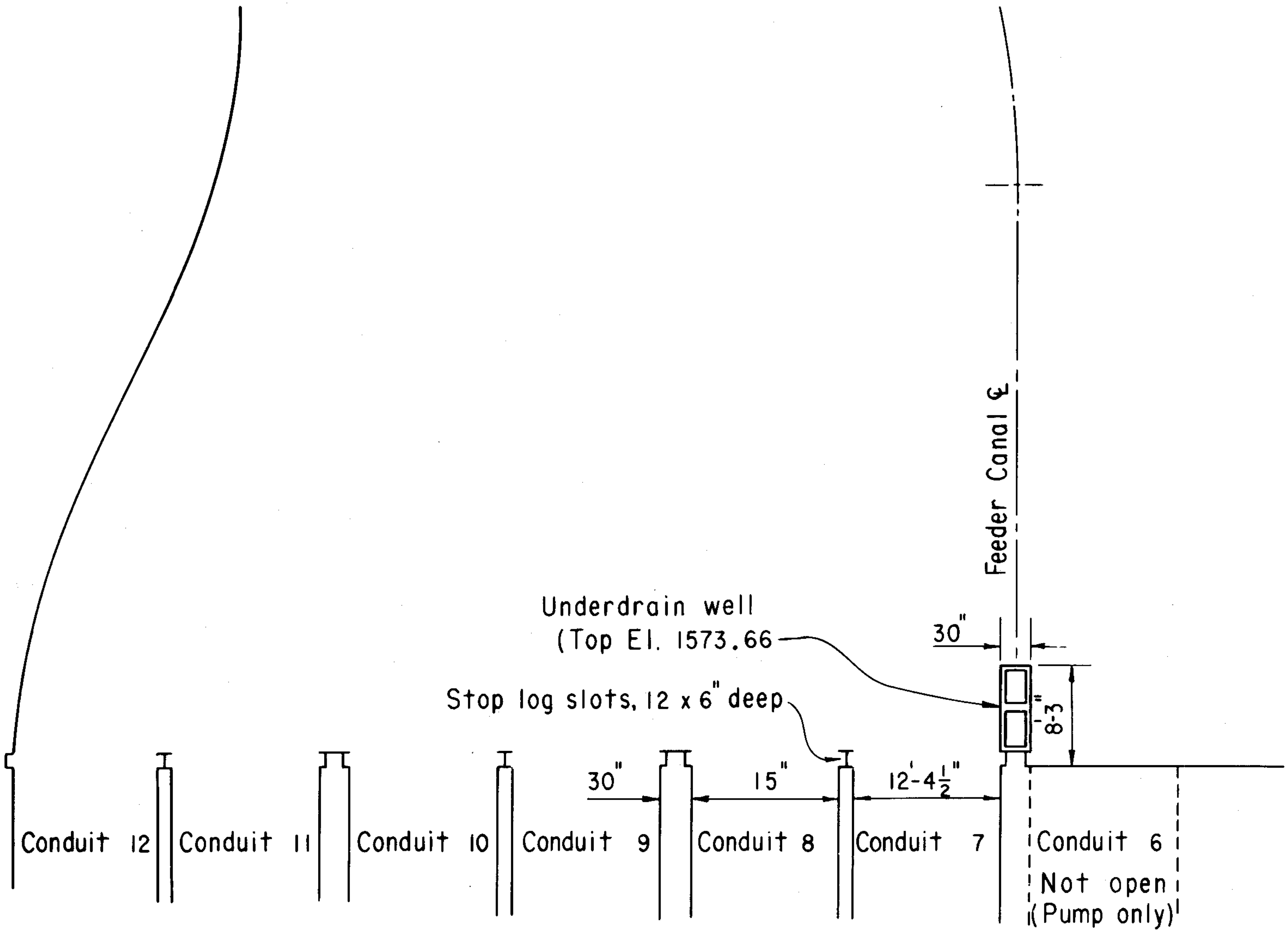


Figure 24. — Basic headwall configuration – pier nose investigations.

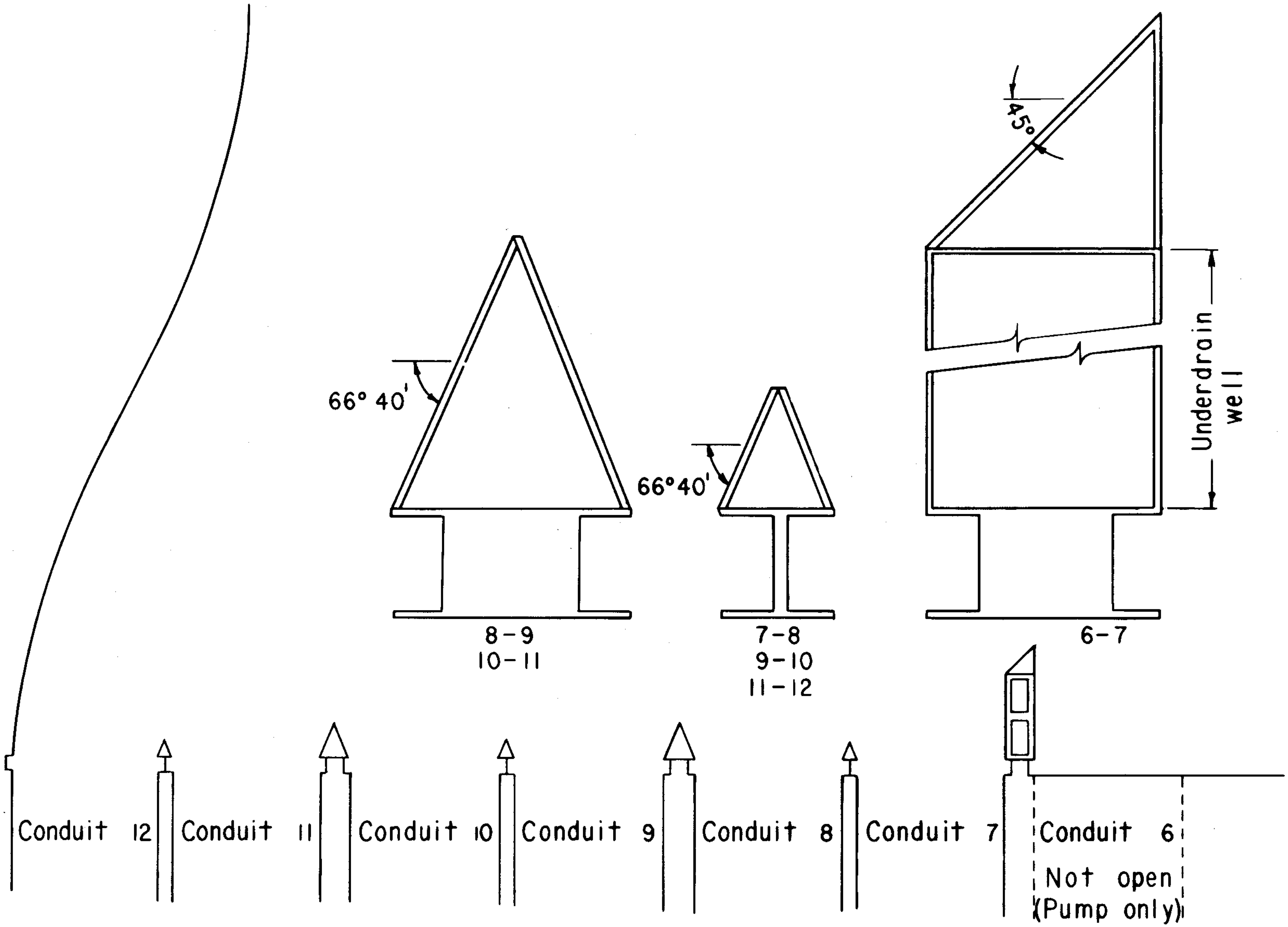


Figure 25. — Canal headwall test 1 - pier nose investigations.

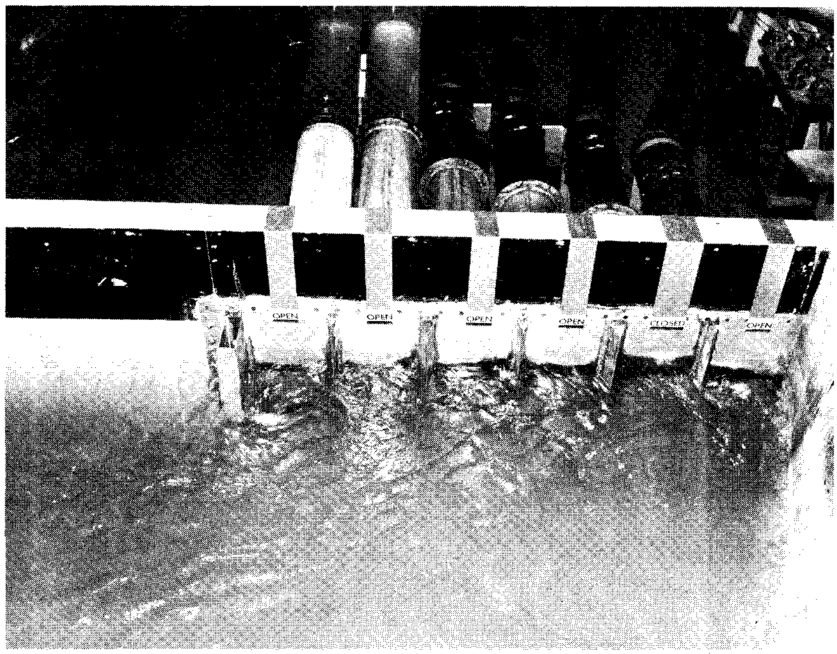


Figure 26. — Canal headwall test 1. Conduit entrance No. 5 for P/G7, 8, 9, 10, and 12 with each turbine at 2,300 ft³/s. Feeder Canal headwall W. S. El. 1566.0, and Banks Lake W.S. El. 1570.3. Note vortices at the entrances (refer to fig. 25).

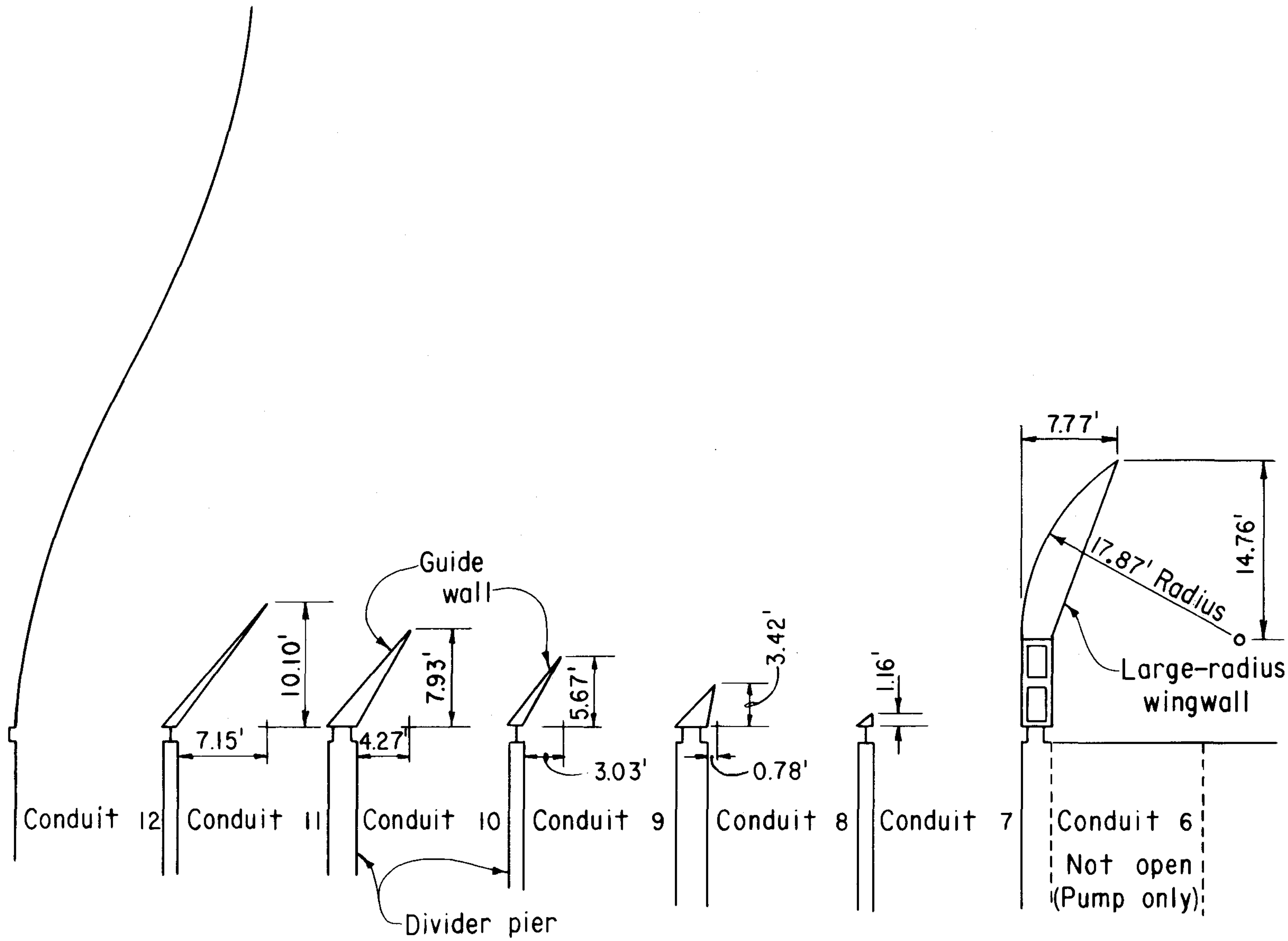
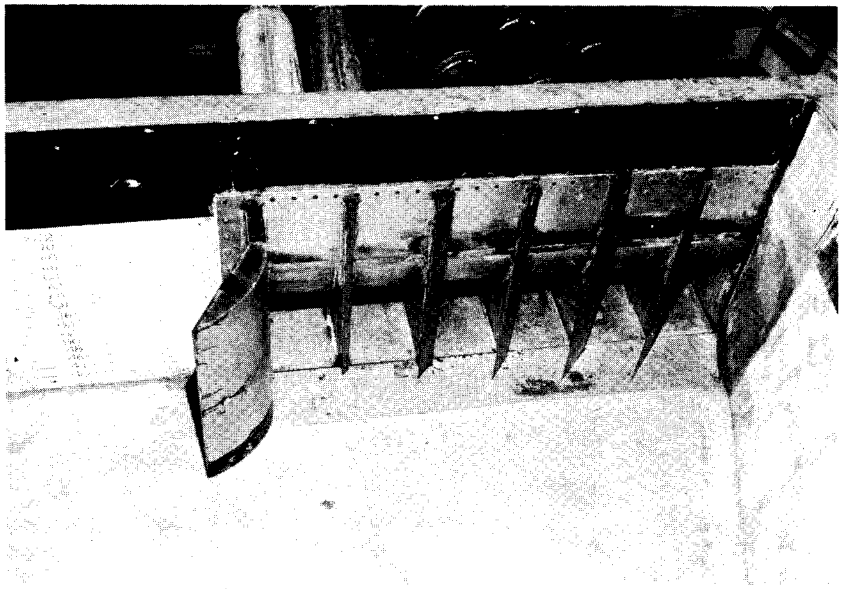
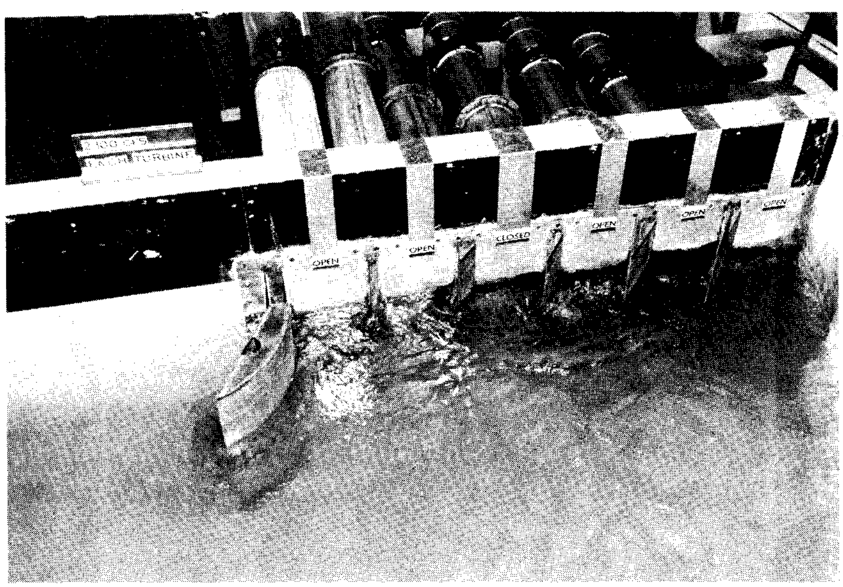


Figure 27. — Canal headwall test 2 - pier nose investigations.



A. — View looking downstream. Photo H-1594-78



B. — Conduit entrance No. 5 open for P/G7, 8, 10, 11, and 12 with each turbine at 2,300 ft^3/s. Feeder Canal headwall W. S. El. 1566.0 and Banks Lake El. 1570.3. Note large vortex at P/G10 entrance. Photo H-1594-74

Figure 28. — Headwall test 2 - obtuse and tapered guide walls with large radius-center wingwall (refer to fig. 27).

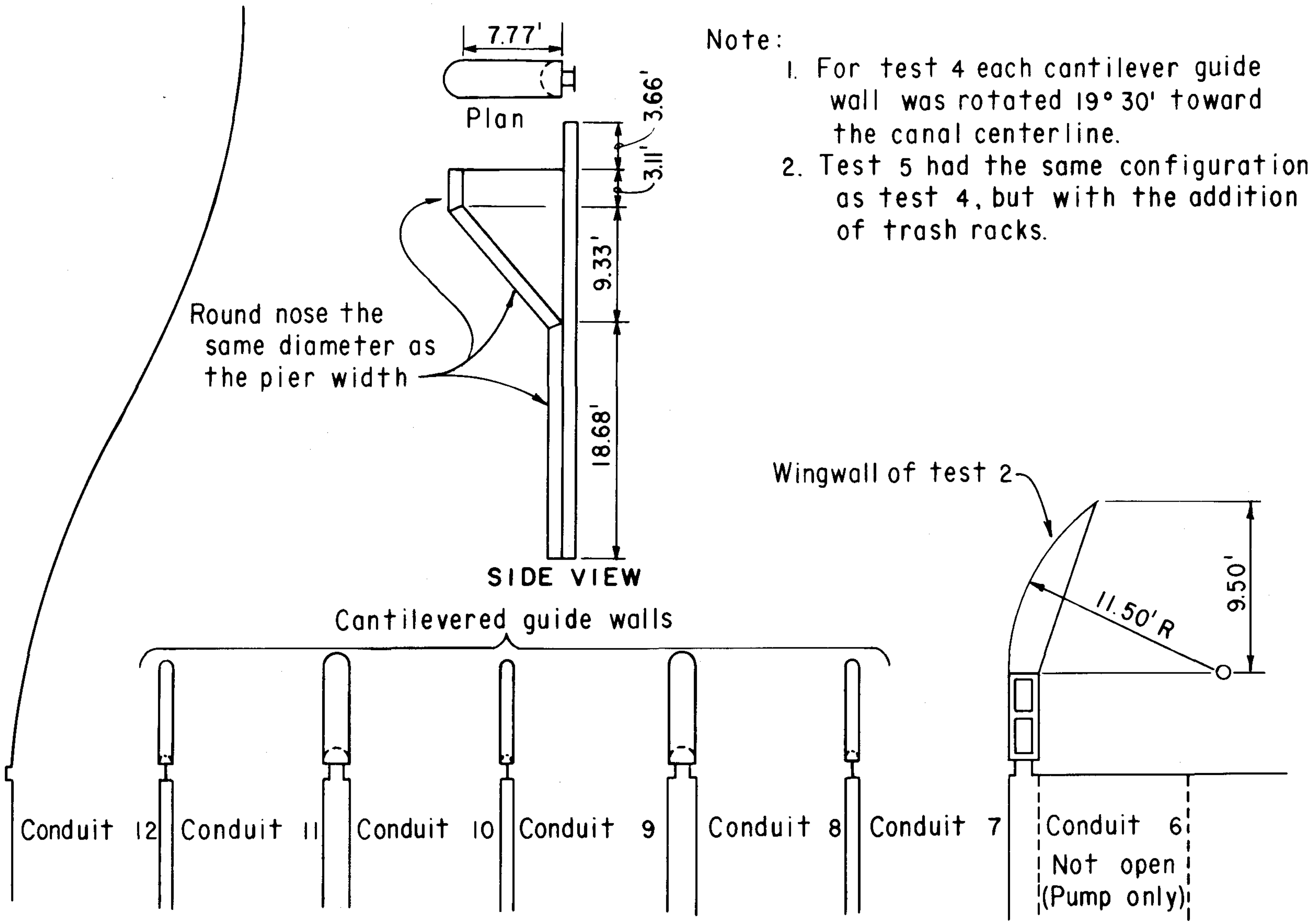
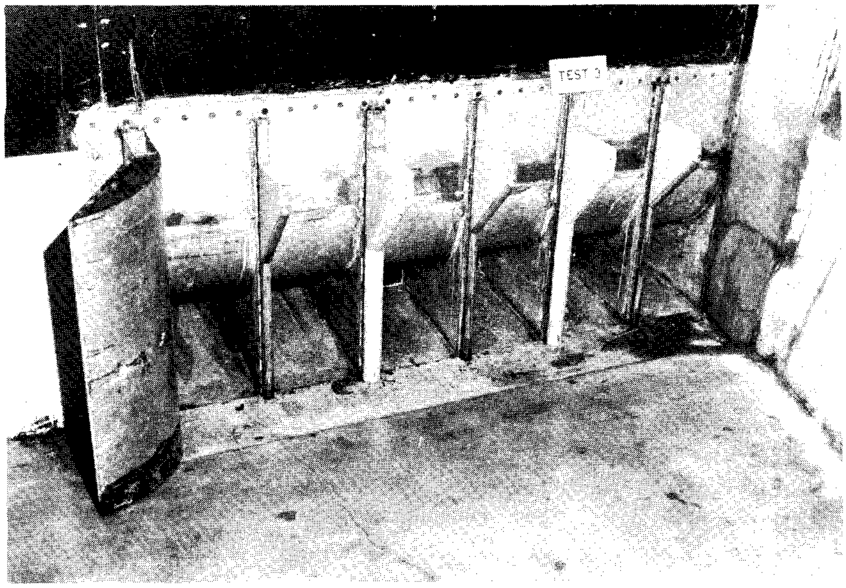
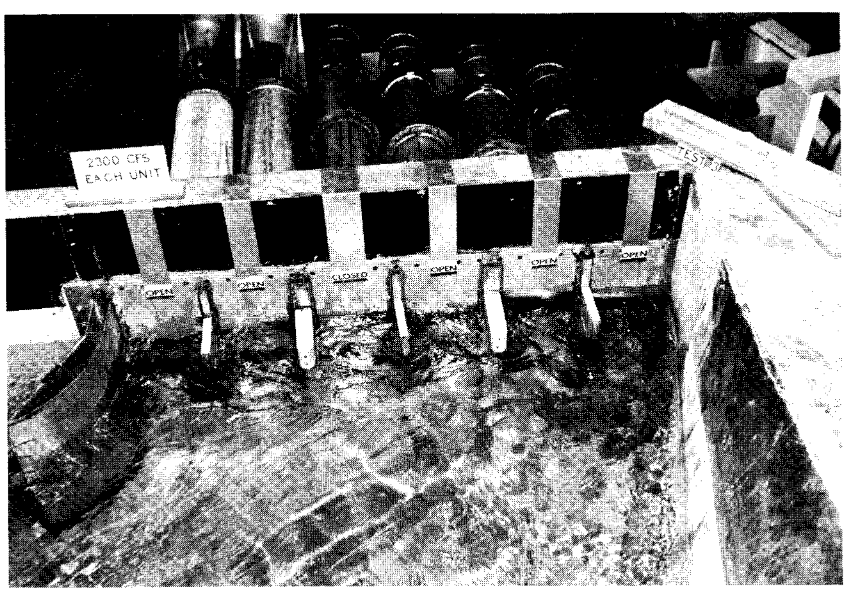


Figure 29. — Canal headwall test 3 - pier nose investigations.

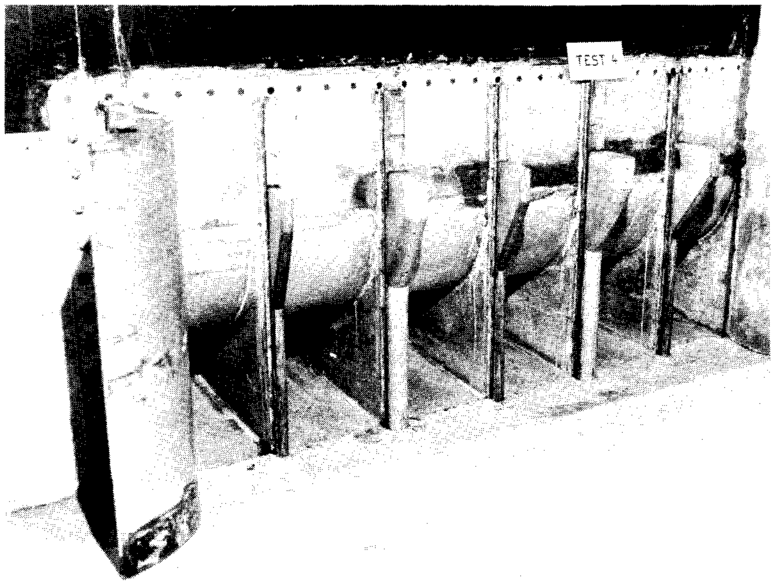


A. — Looking downstream. Photo H-1594-86NA

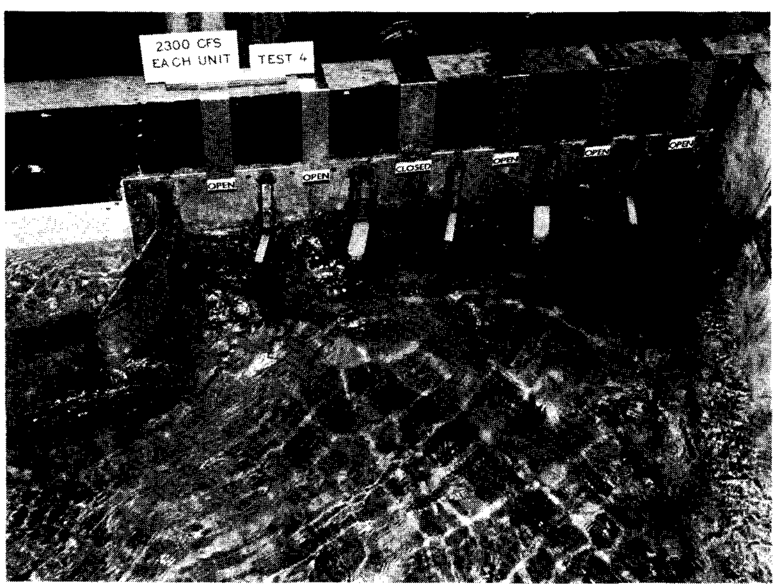


B. — Conduit entrance No. 5 open for P/G7, 8, 10, 11, and 12 with each turbine at 2,300 ft³/s. Feeder Canal headwall W. S. El. 1565.2 and Banks Lake El. 1570.0. Photo H-1594-81

Figure 30. — Canal headwall test 3 - cantilevered guide wall with larger- radius-center wingwall (refer to fig. 29).



A. — Looking downstream (without trashracks). Photo H-1594-94



B. — Conduit entrances P/G7, 8, 10, 11, and 12 open with each turbine at 2,300 ft^3/s. Canal headwall W. S. El. 1566.4 and Banks Lake El. 1570.5. Note poor flow conditions around the large-radius center wingwall at conduits P/G7 and P/G8. Photo H-1594-89

Figure 31. — Canal headwall test 4 - obtuse cantilevered guide walls with large-radius center wingwall (refer to fig. 29).

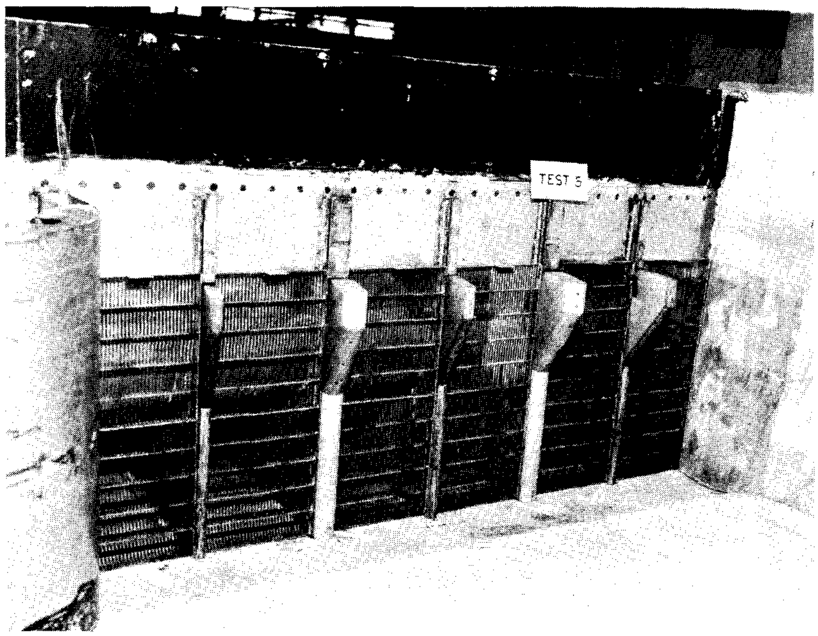


Figure 32. — Canal headwall test 5 - obtuse cantilevered guide walls with large-radius center wingwall and trashracks (refer to fig. 31). Photo H-1594-96NA

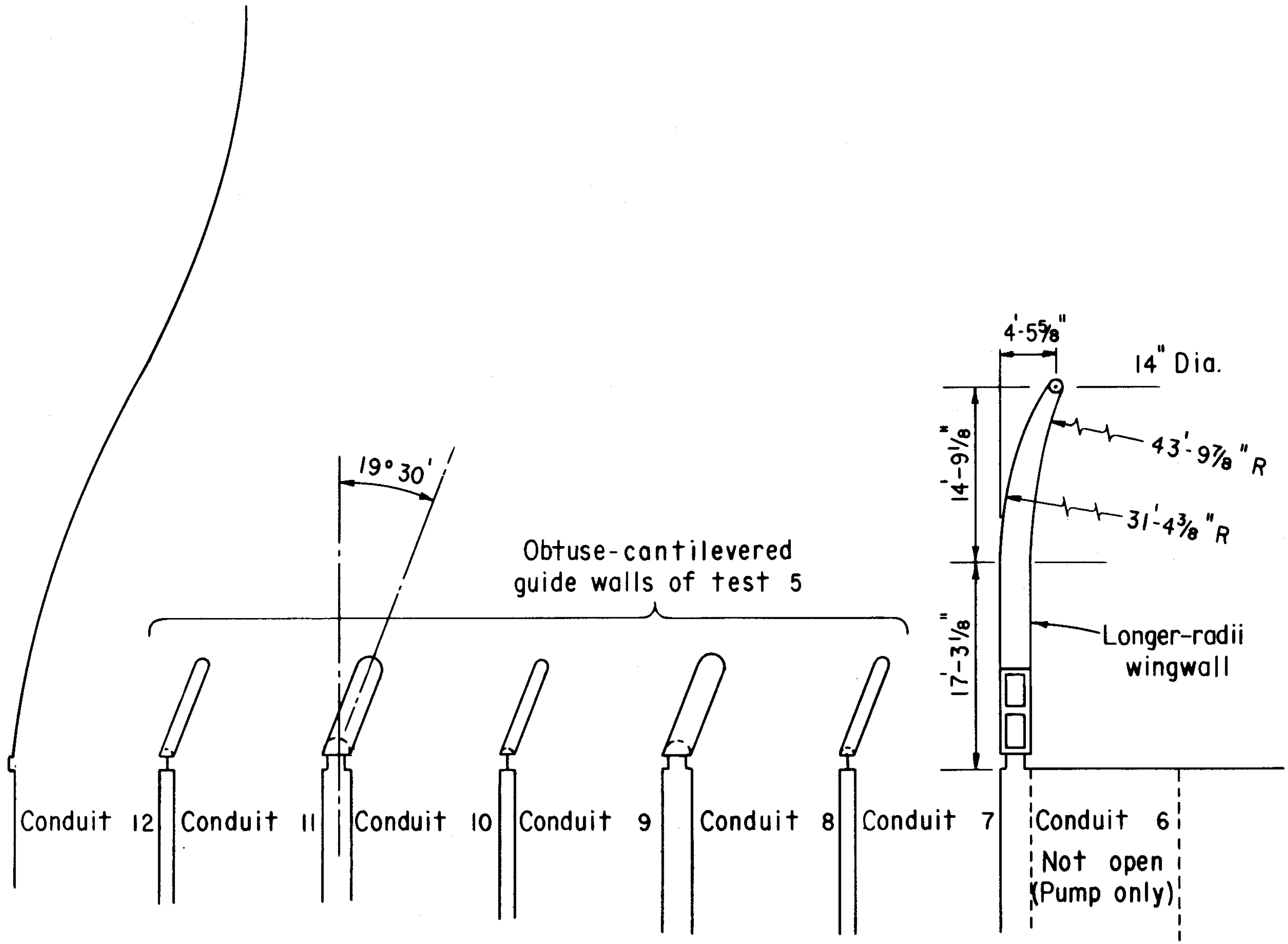


Figure 33. — Canal headwall test 6 - pier nose investigations.

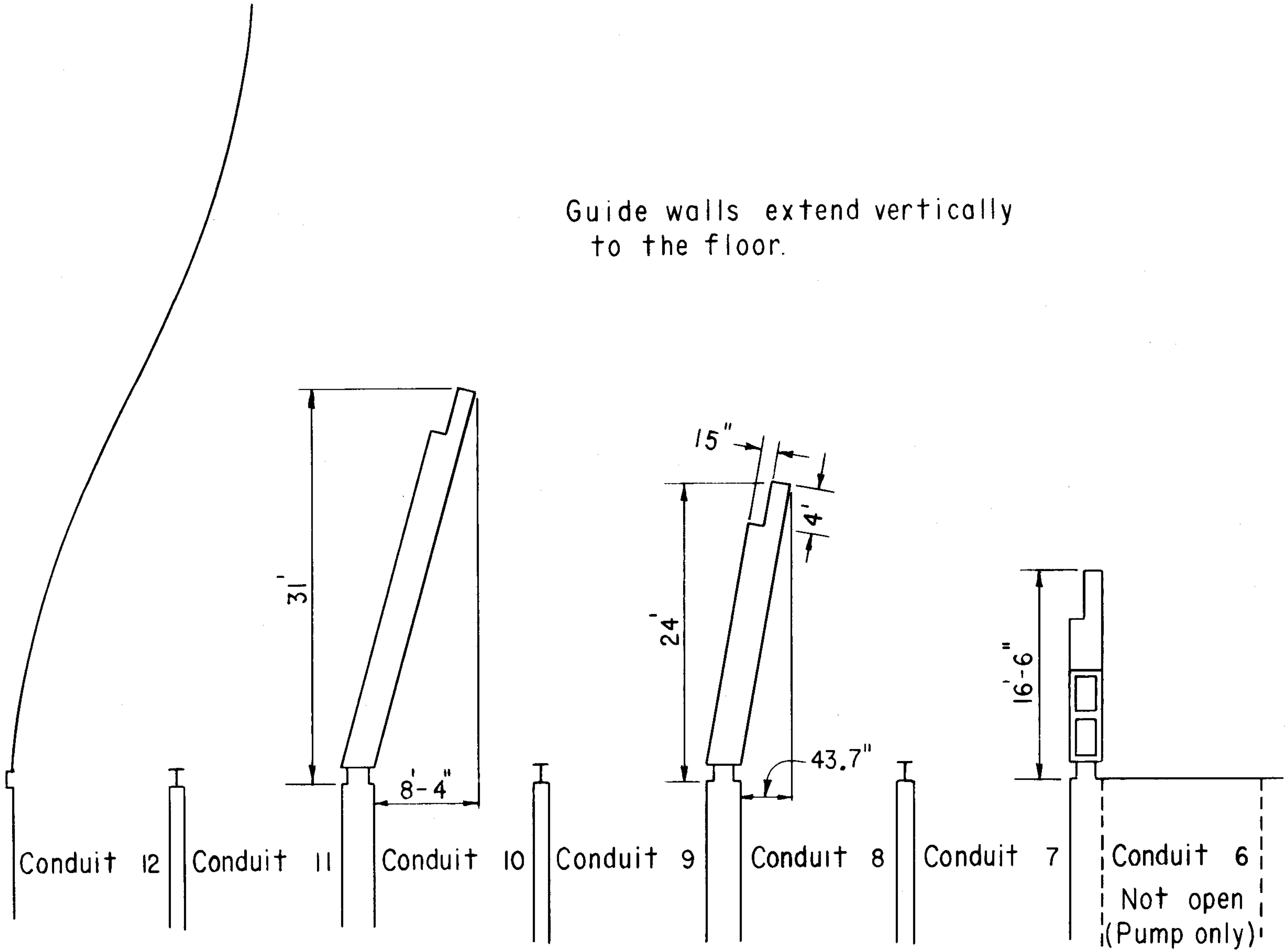


Figure 34. — Canal headwall test 7 - pier nose investigations.

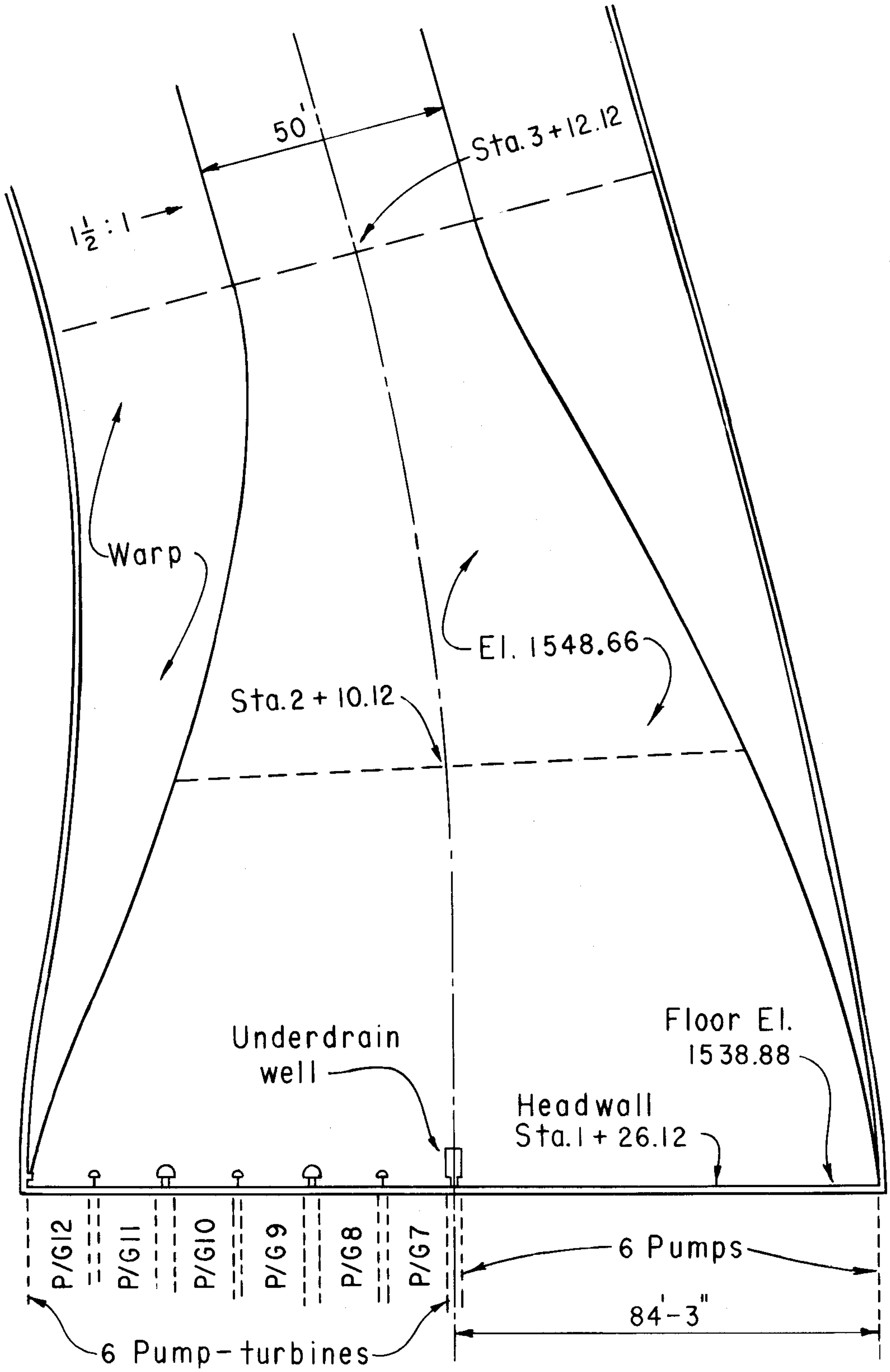


Figure 35. — Canal headwall tests 8, 9, and 10 – canal transition and headwall.

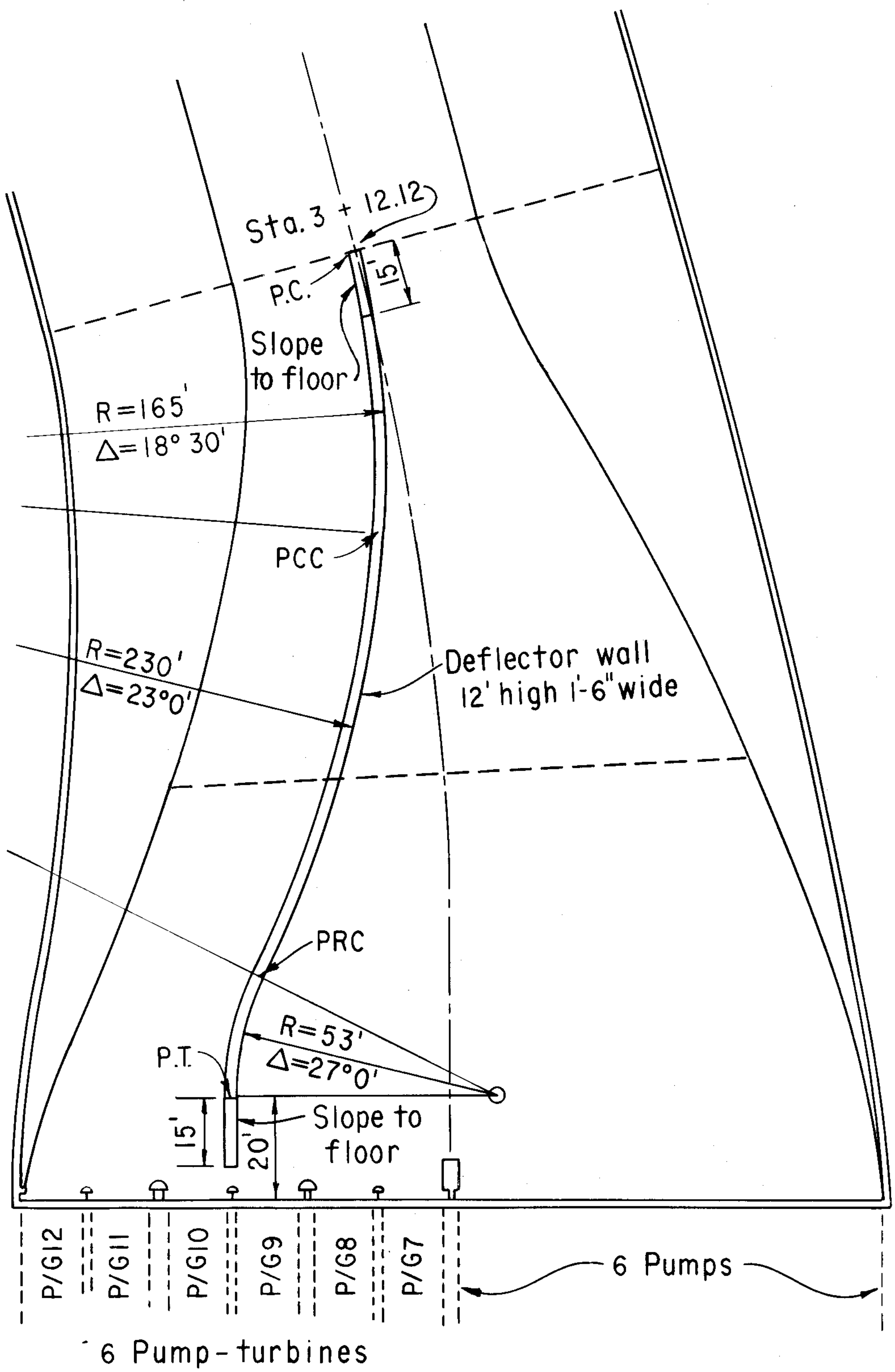


Figure 36. — Canal headwall test 8 - reverse-curve 12-ft-high deflector wall.

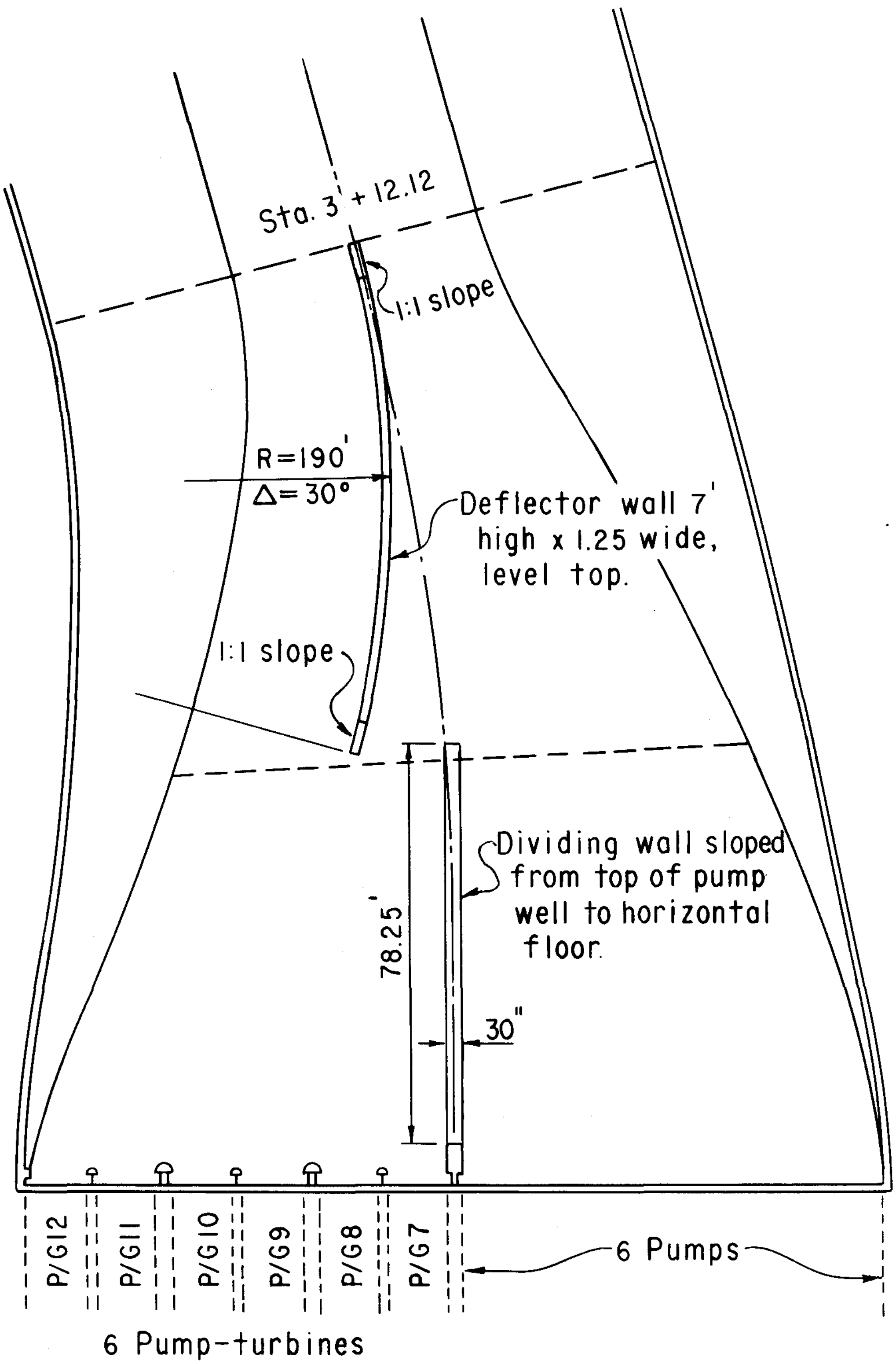
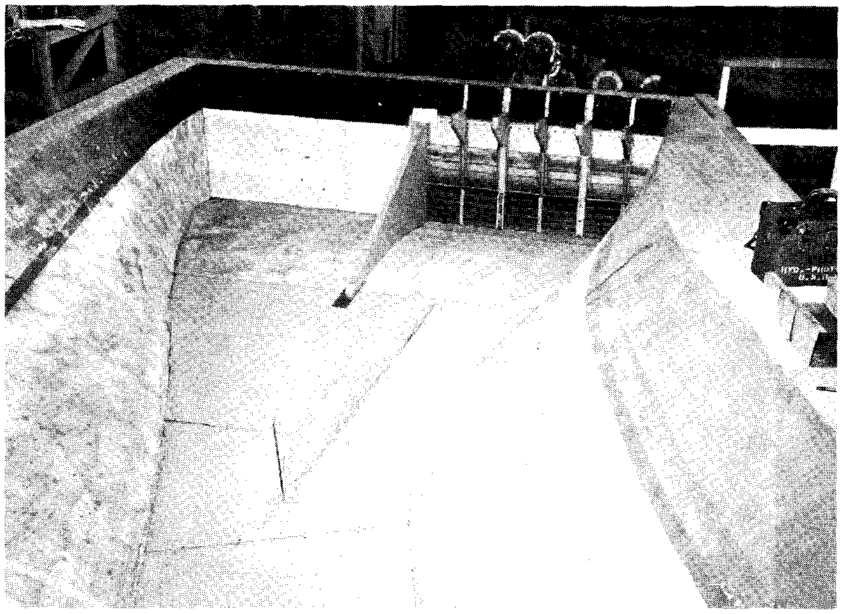
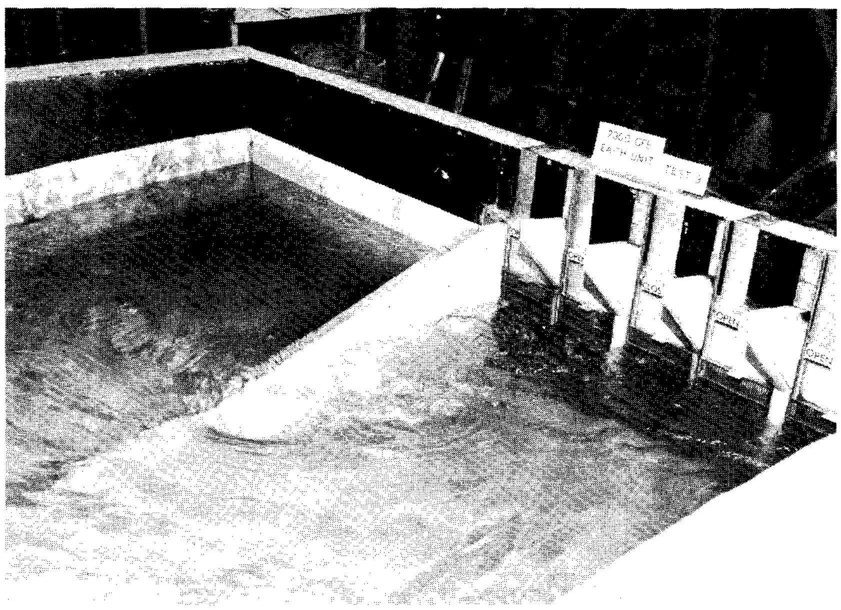


Figure 37. — Canal headwall test 9 - single-radius 7-ft-high deflector wall and center dividing wall.



A. — Looking downstream. Photo H-1594-106NA



B. — Canal headwall W. S. El. 1565.5, Banks Lake El. 1570.1, and total turbine flow of 11,500 ft^3/s. Note large drawdown at the sloping center dividing wall. Photo H-1594-109NA

Figure 38. — Canal headwall test 9 - curved deflector wall and center dividing wall (refer to fig. 37).

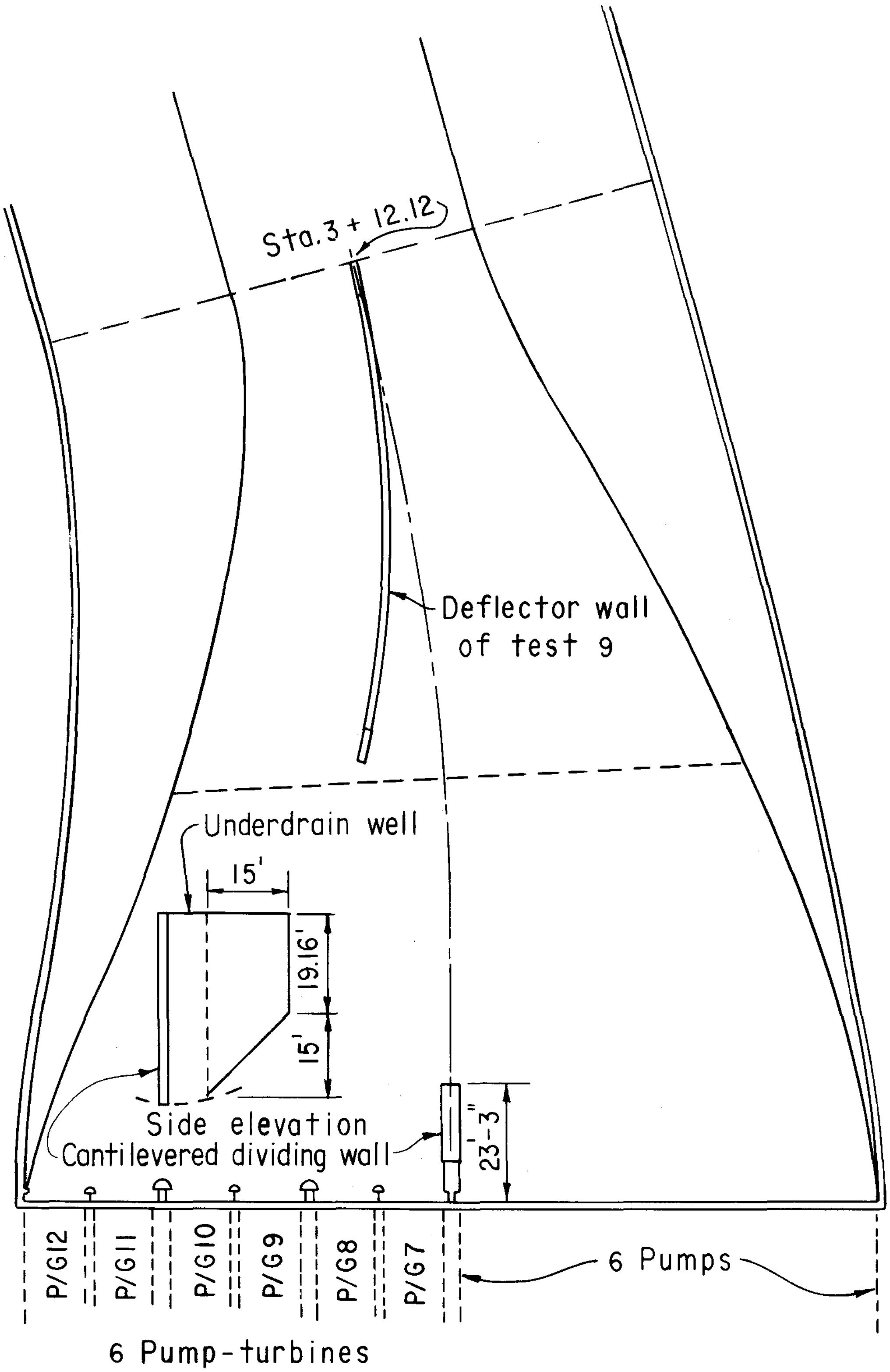
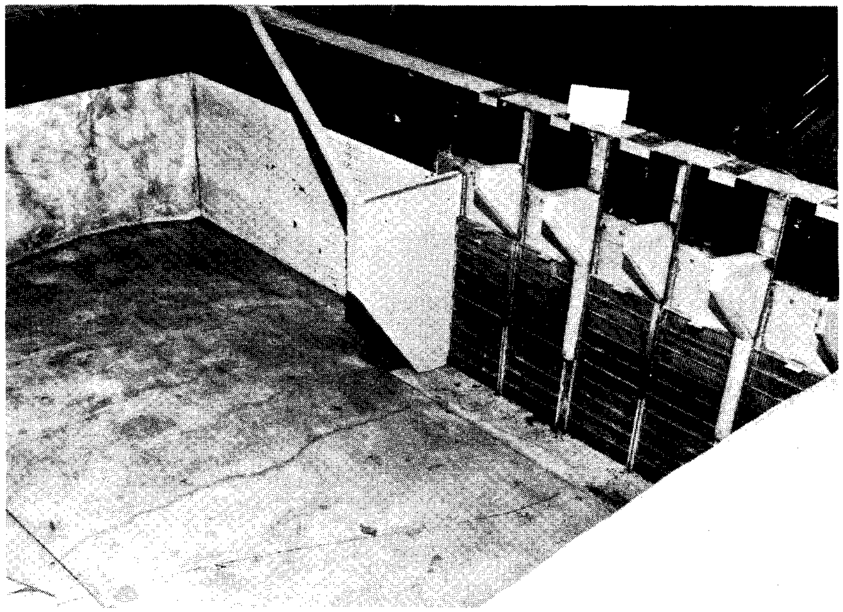
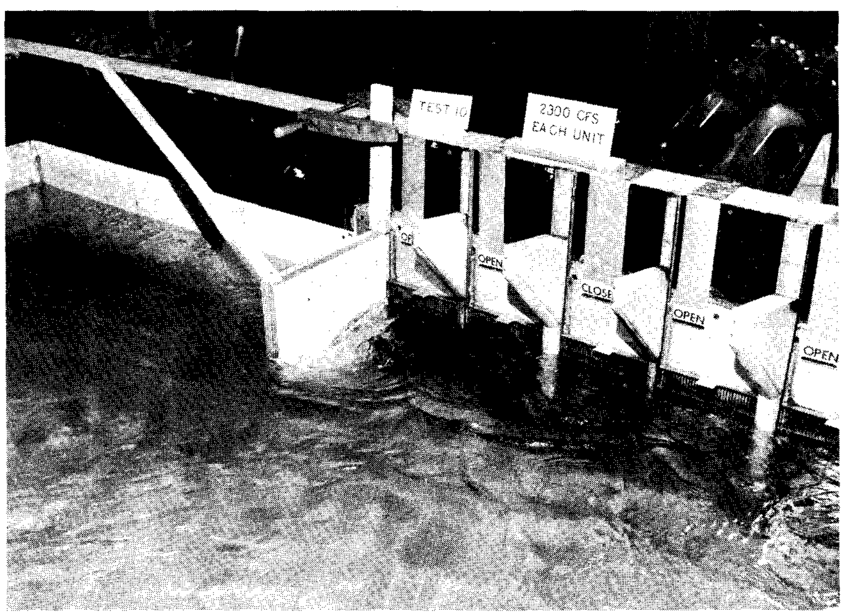


Figure 39. — Canal headwall test 10 - straight-cantilevered dividing wall attached to the underdrain well.



A. — Looking downstream. Photo H-1594-110



B. — Conduit entrances P/G7, 8, 10, 11, and 12 open with each turbine at 2,300 ft^3/s. Feeder Canal headwall W. S. El. 1565.8 and Banks Lake El. 1570.2. Air from vortex entered conduits P/G7 and P/G8. Photo H-1594-112NA

Figure 40. — Canal headwall test 10. - straight cantilevered dividing wall between conduit entrances P6 and P/G7 (refer to fig. 39).

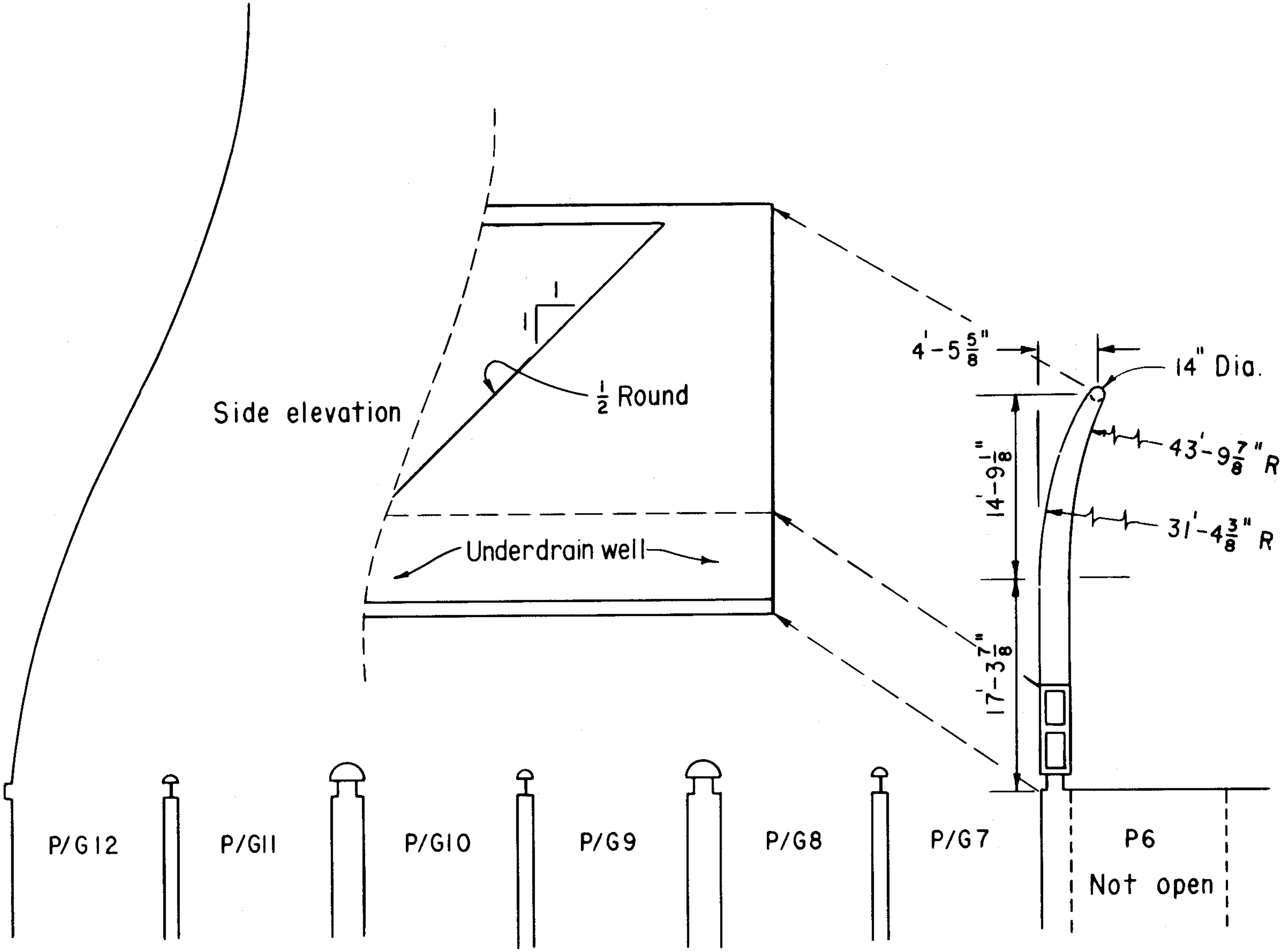
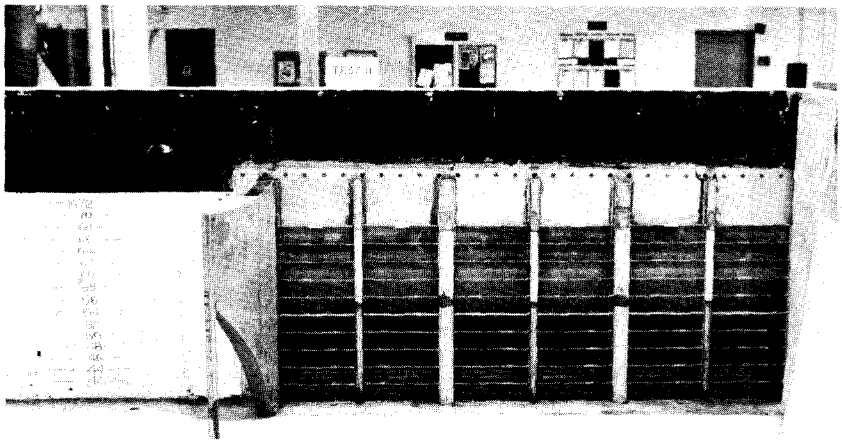
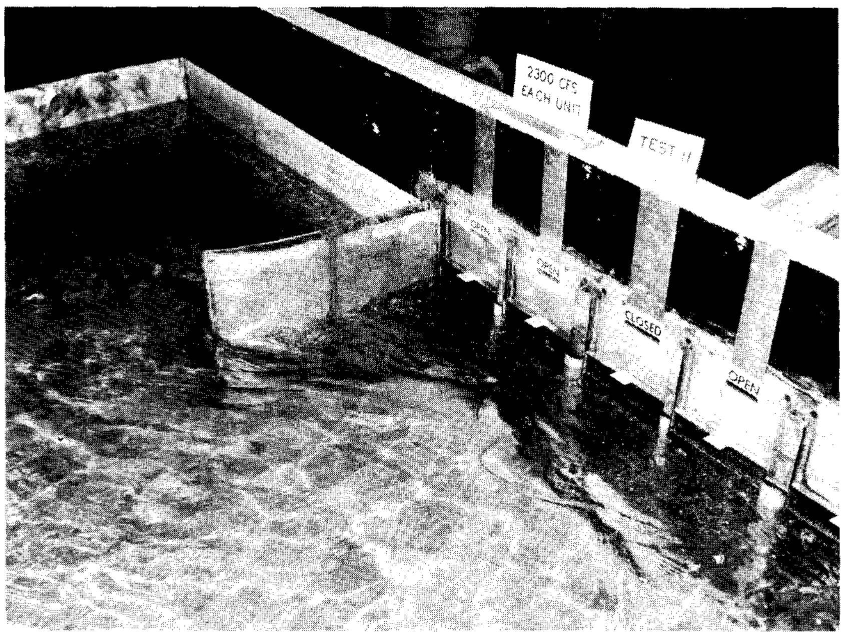


Figure 41. — Canal headwall test 11 - pier nose investigations.



A. — Looking downstream. Photo H-1594-114



B. — Conduit entrances P/G7, 8, 10, 11, and 12 open with each turbine at 2,300 ft^3/s. Feeder Canal headwall W. S. El. 1565.9 and Banks El. 1570.3. Note vortex at the center wingwall. Photo H-1594-130NA

Figure 42. — Canal headwall test 11 - longer-radius cantilevered center wingwall between conduit entrances P6 and P/G7 (refer to fig. 41).

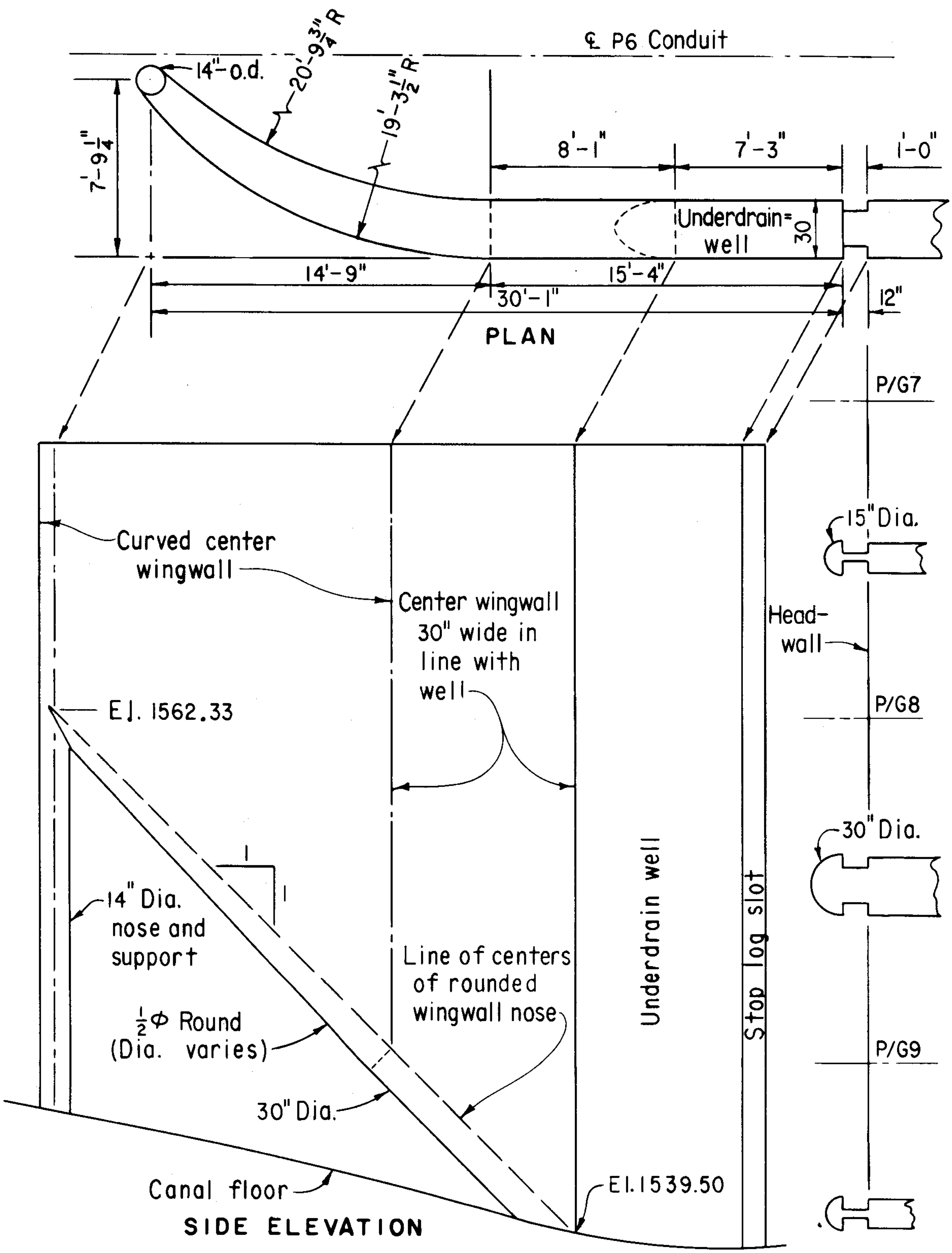
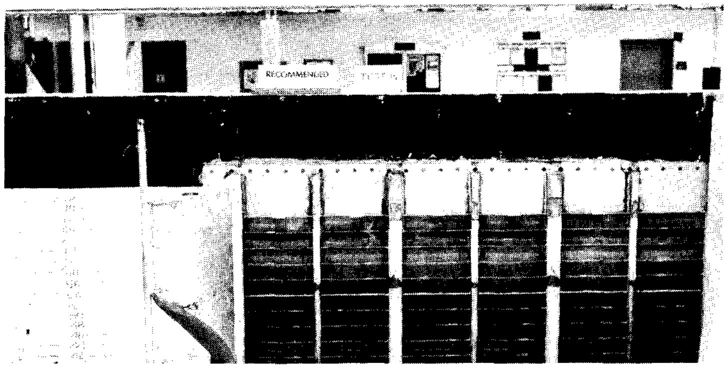
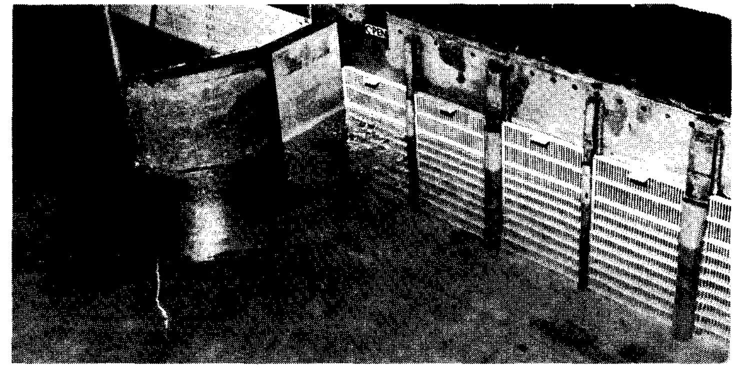


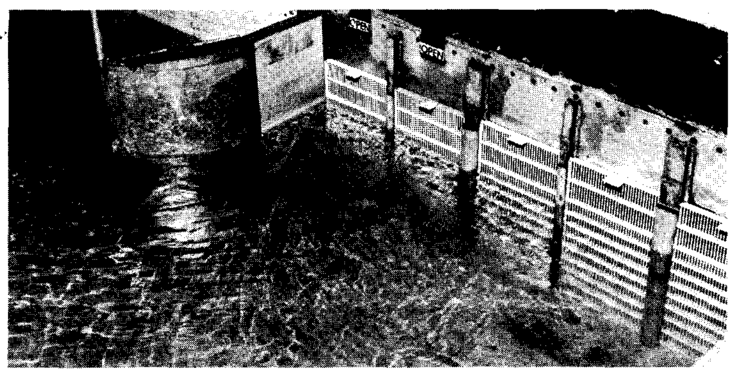
Figure 43. — Canal headwall test 12 - center wingwall between P6 and P/G7 - recommended design.



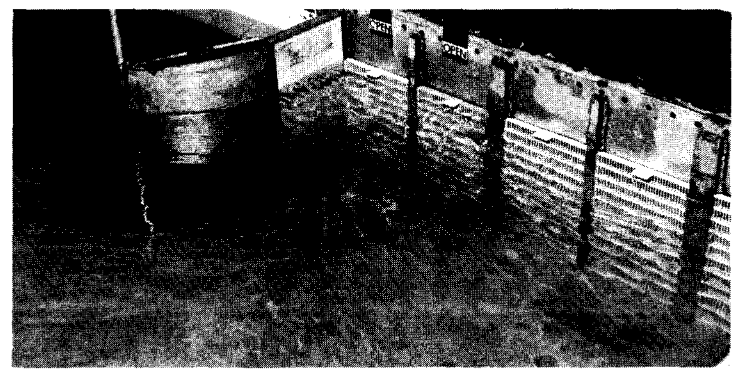
A. — Dry. Photo H-1594-116NA



B. — P/G7 open, headwall W. S. El. 1562.0 and Banks Lake El. 1562.5. Photo H-1594-135NA

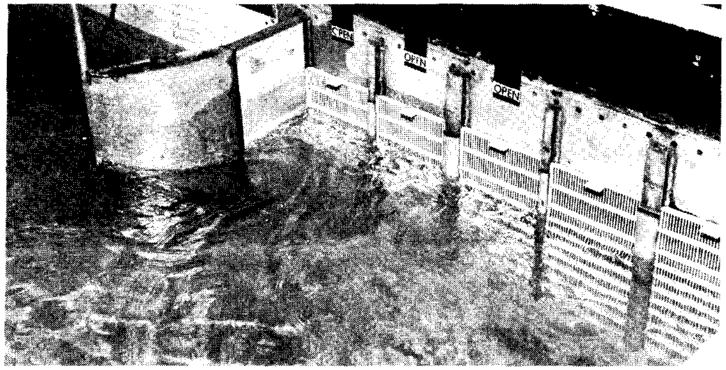


C. — P/G7 and P/G8 open, headwall W. S. El. 1562.0 and Banks Lake El. 1564.1. Photo H-1594-139NA

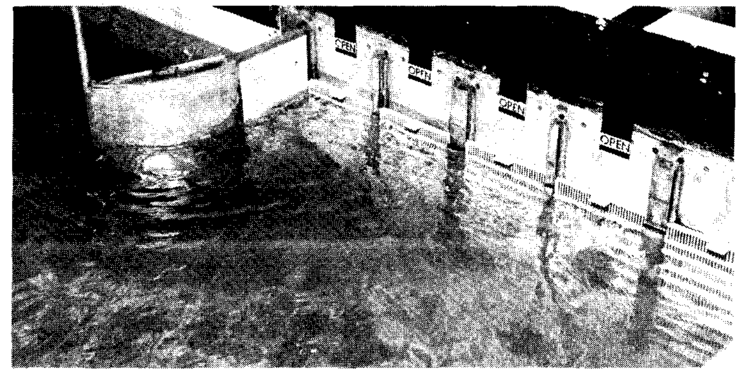


D. — P/G7 and P/G8 open, headwall W. S. El. 1569 and Banks El. 1569.5. Photo H-1594-137NA

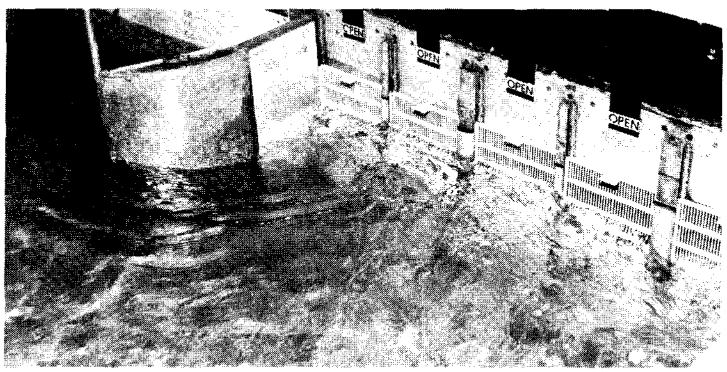
Figure 44. — Flow conditions at canal headwall - recommended design.



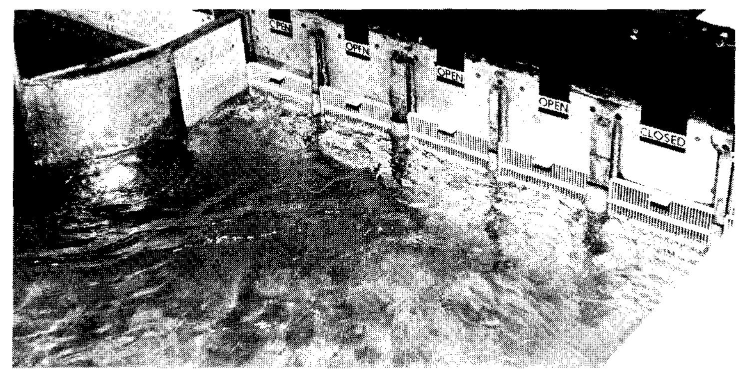
E. — P/G7 and P/G8 open, headwall W. S. El. 1562.0 and Banks Lake El. 1565.7. Photo H-1594-140NA



F. — P/G7 through 10 open, headwall W. S. El. 1567.6 and Banks Lake El. 1570.0. Photo H-1594-145NA



G. — P/G7 through 11 open, headwall W. S. El. 1562.5 and Banks Lake El. 1569.1. Photo H-1594-151NA



H. — P/G7 through 10, and 12 open, headwall W. S. El. 1565.2 and Banks Lake El. 1570.0. Photo H-1594-148NA

Figure 44. — Continued.

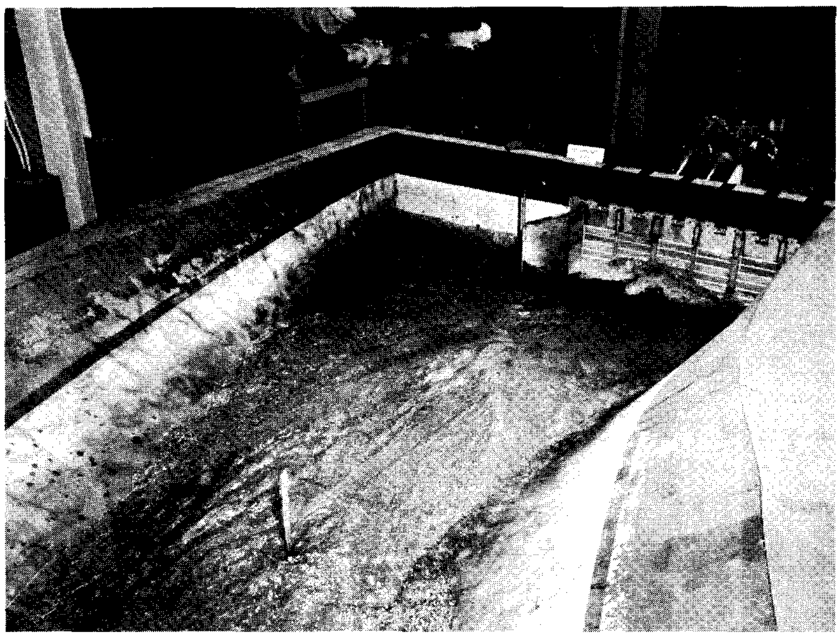


Figure 45. — Critical flow depth at station 3 + 12.12. Banks Lake El. 1566. Five turbines operating at a total flow of 8,700 ft^3/s. Critical depth (foreground) restricts the Feeder Canal flow to 8,300 ft^3/s resulting in a rapidly dropping canal headwall water surface. Photo H-1594-156NA

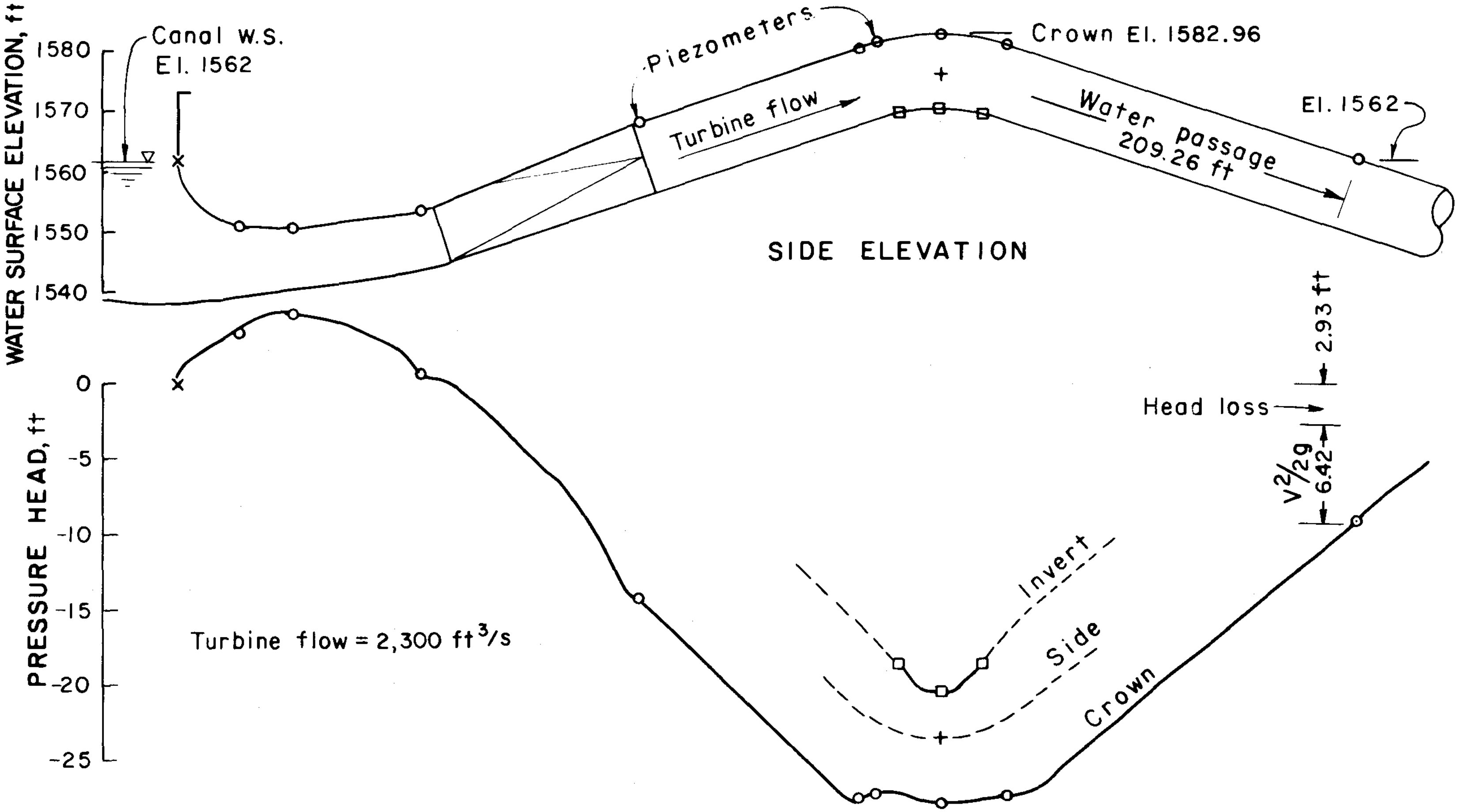


Figure 46. — Recommended conduit entrance design - P/G8 (refer to figs. 21 and 43).

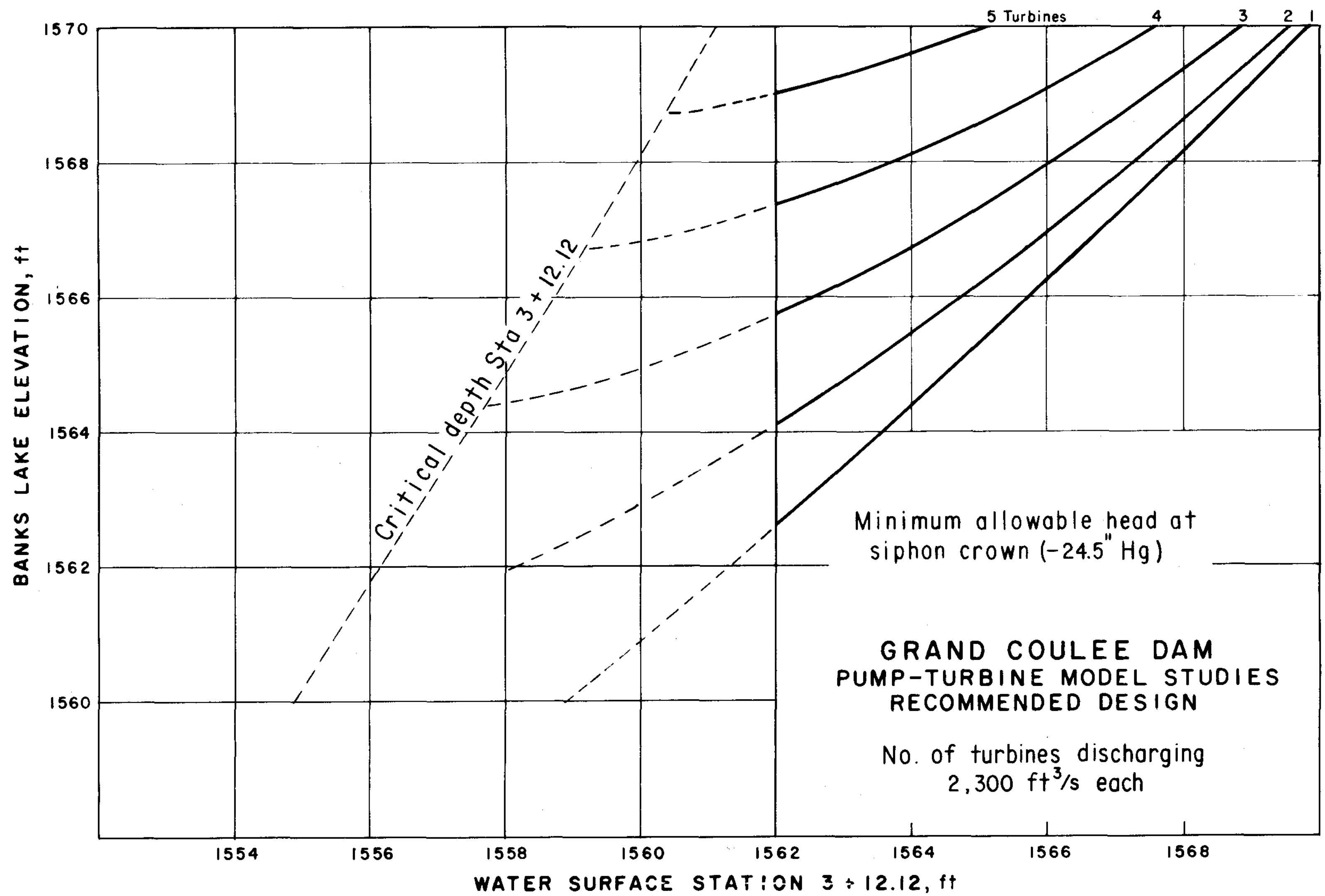


Figure 47. — Banks Lake versus Feeder Canal water surface elevations near the canal headwall for turbine operation.

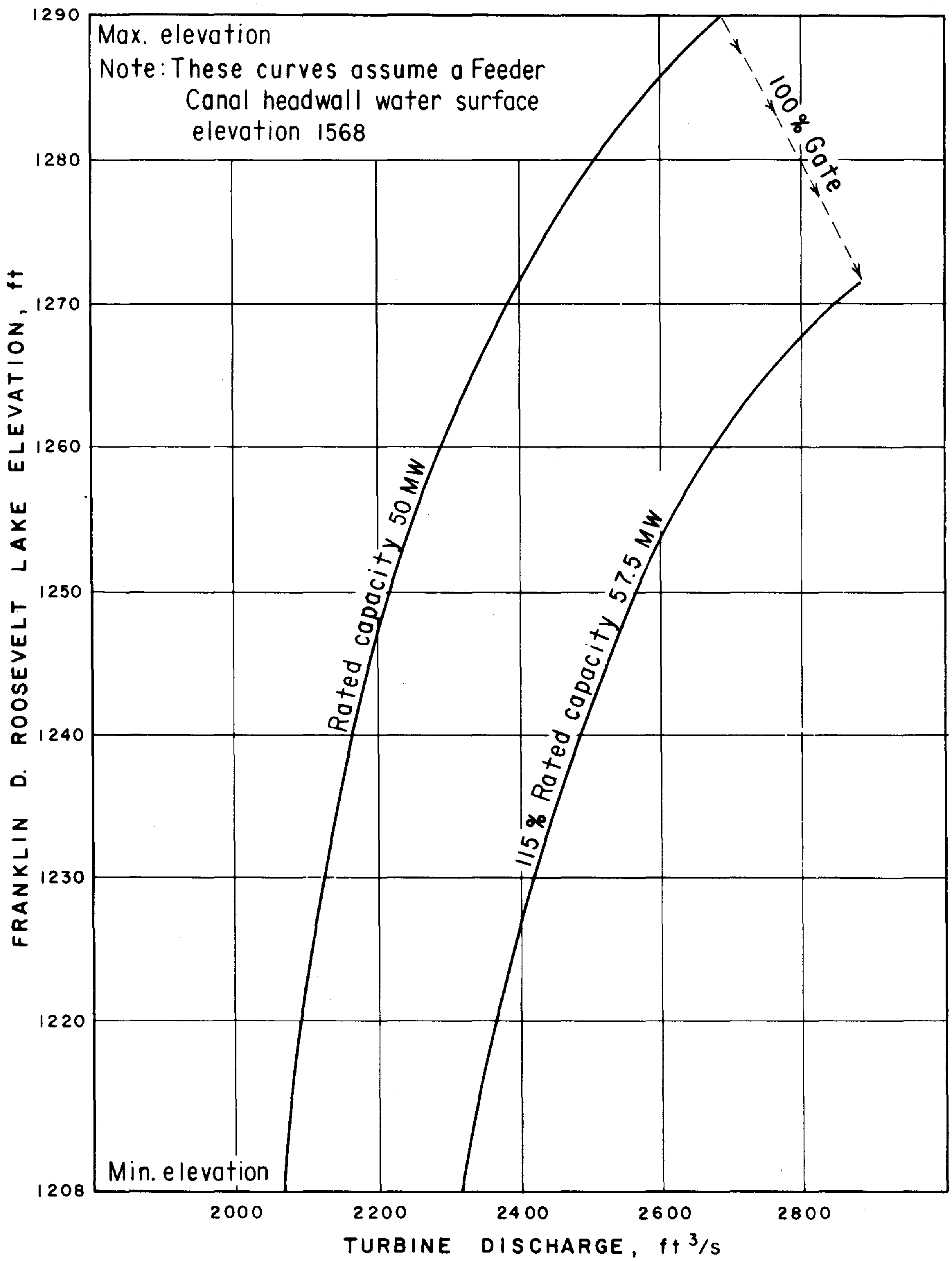


Figure 48. — Turbine discharge versus Franklin D. Roosevelt Lake water surface elevation. Note: Wicket gate openings would be different to obtain other points on both curves below the 100-percent shown.

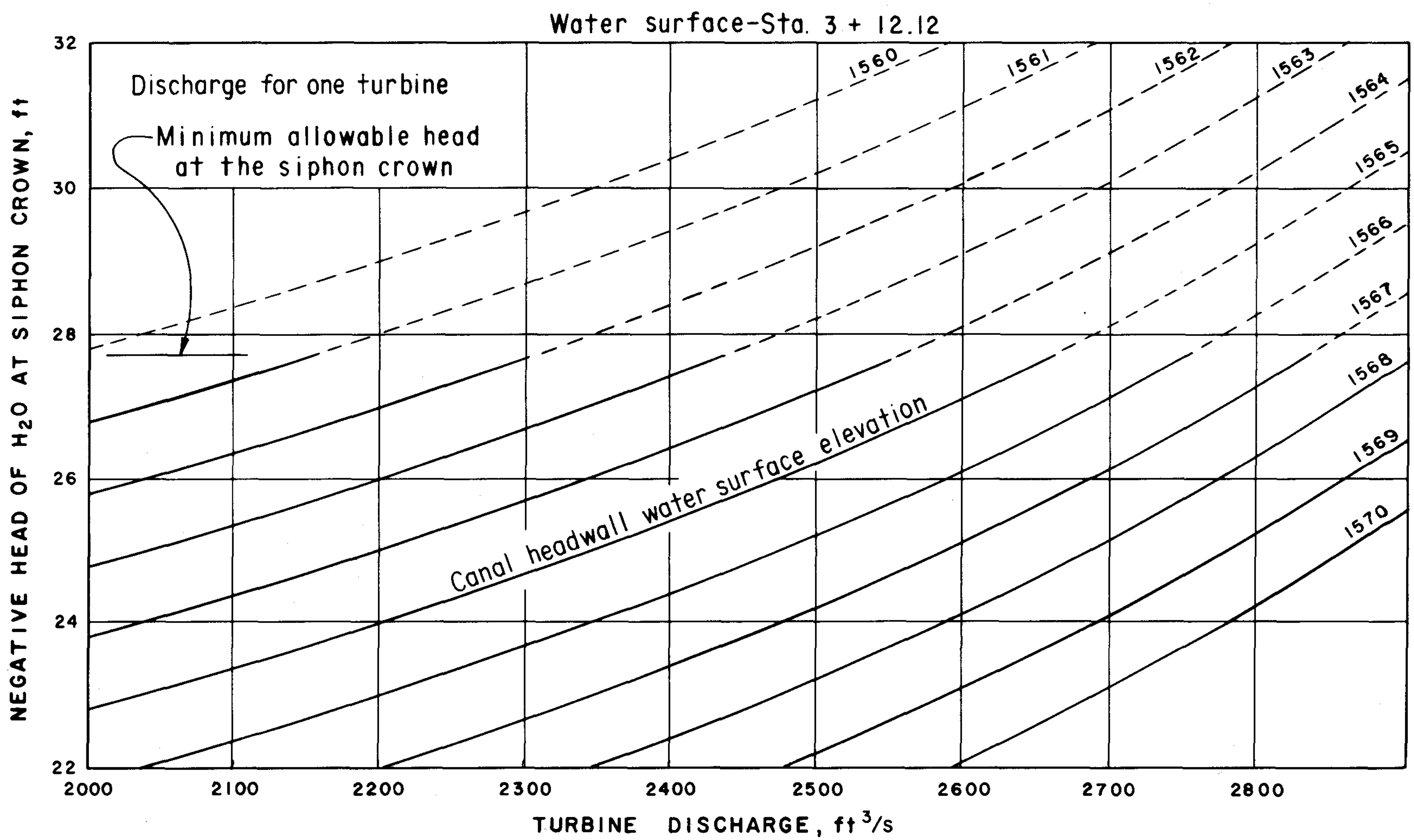


Figure 49. — Head variation at the siphon crown versus Feeder Canal headwall water surface elevation for one turbine operating.

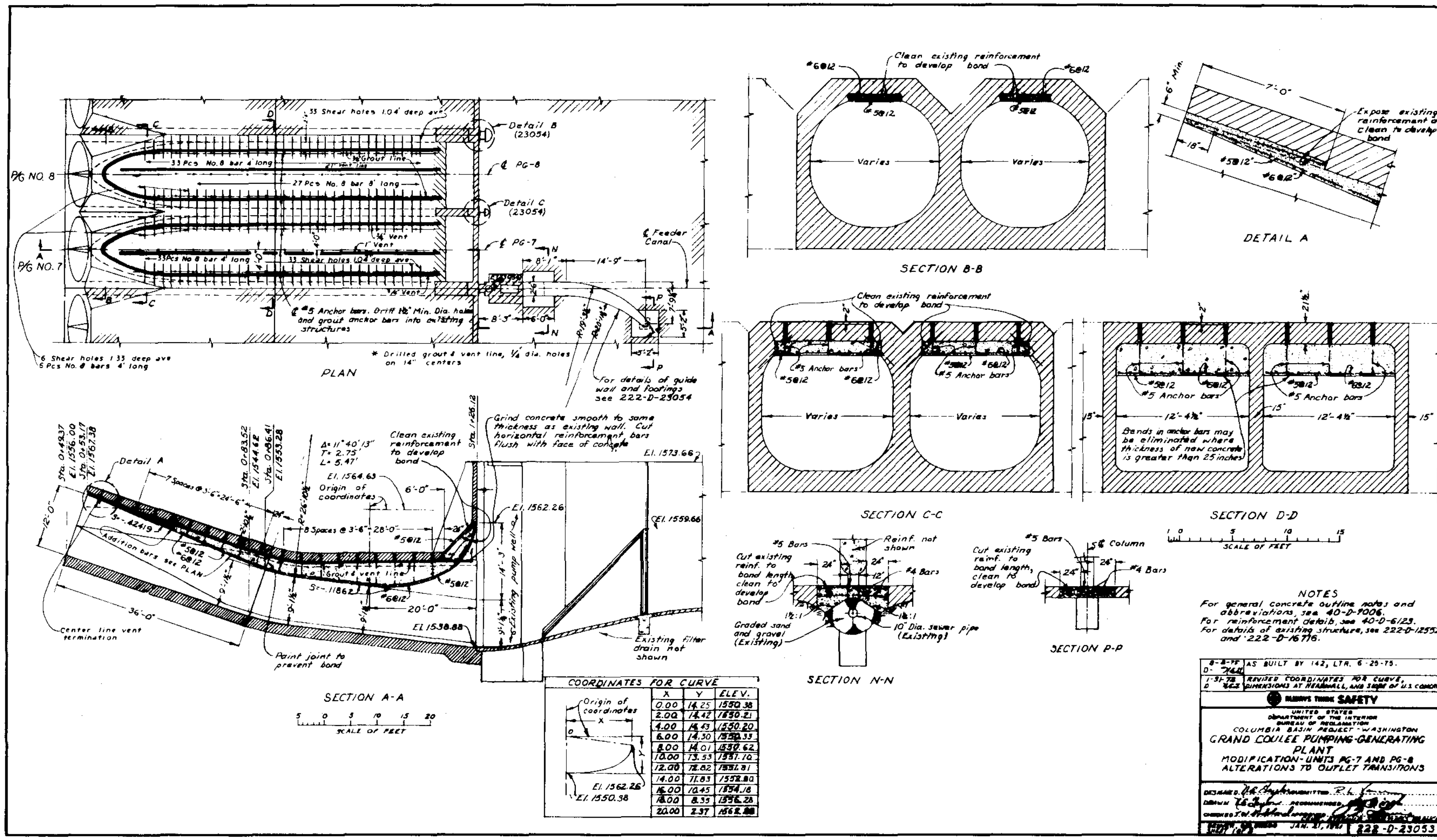


Figure 50. — Grand Coulee Pumping-Generating Plant – modification to units P/G7 and P/G8 outlets.

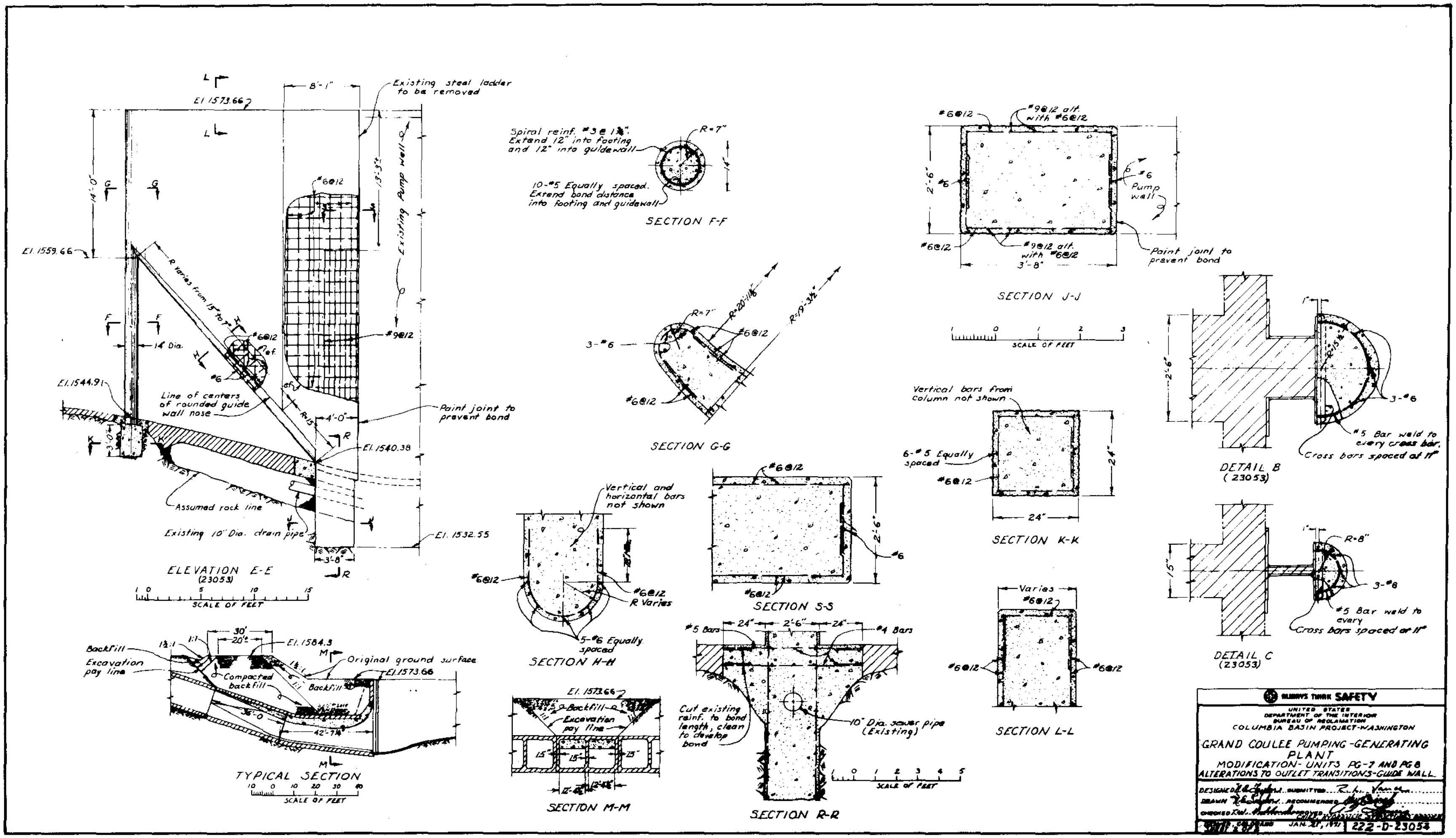


Figure 51. — Grand Coulee Pumping-Generating Plant - modifications to units P/G7 and P/G8 outlets and recommended center wingwall.

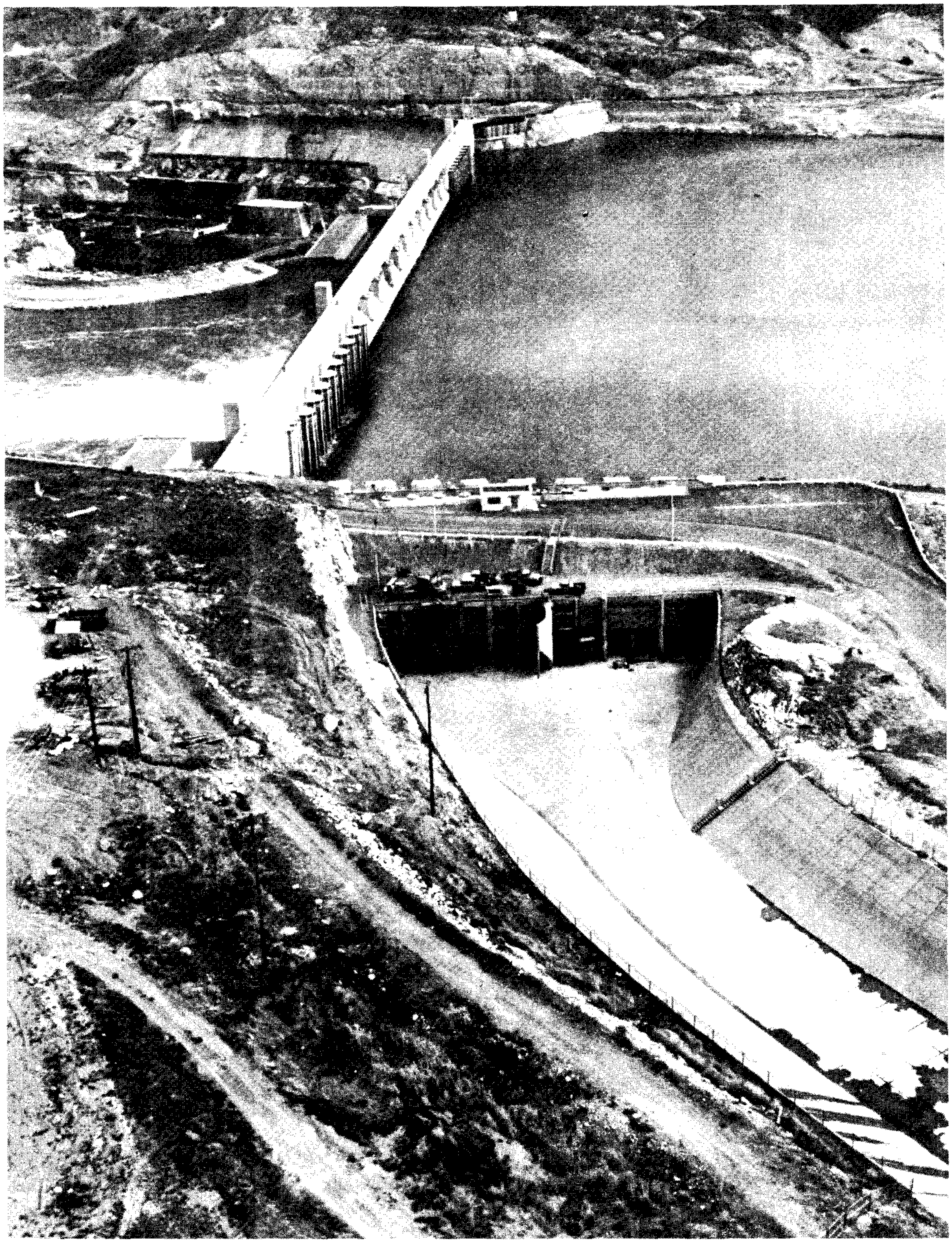


Figure 52. — View showing the modification of the outlet structure (right side) for units P/G7 and P/G8. Photo P-1222-142-23157-I

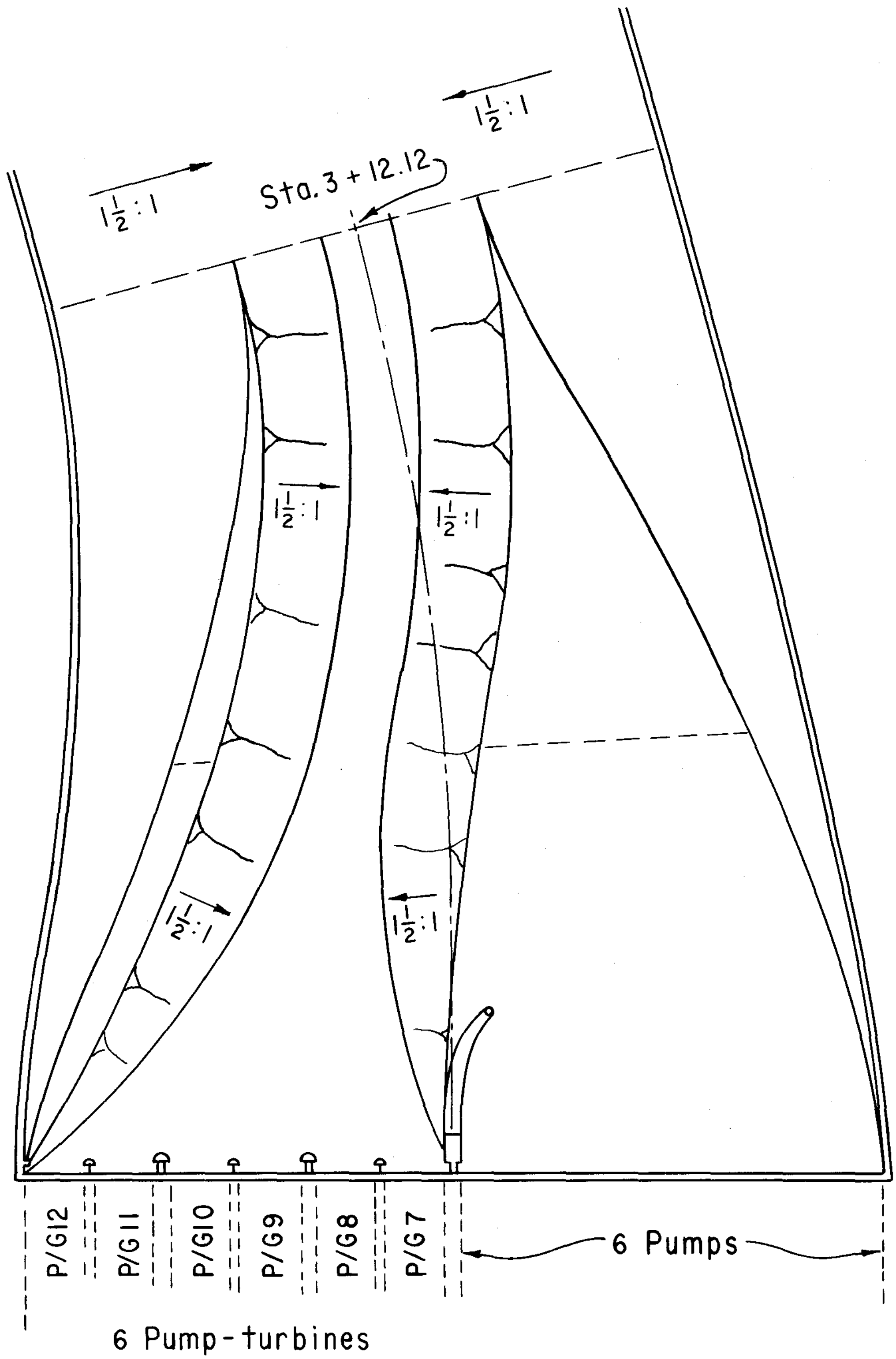
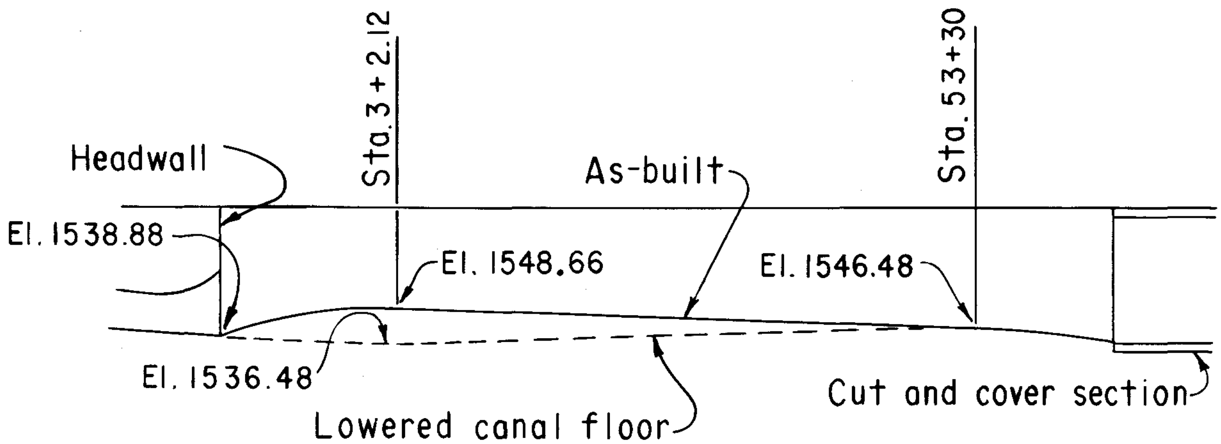
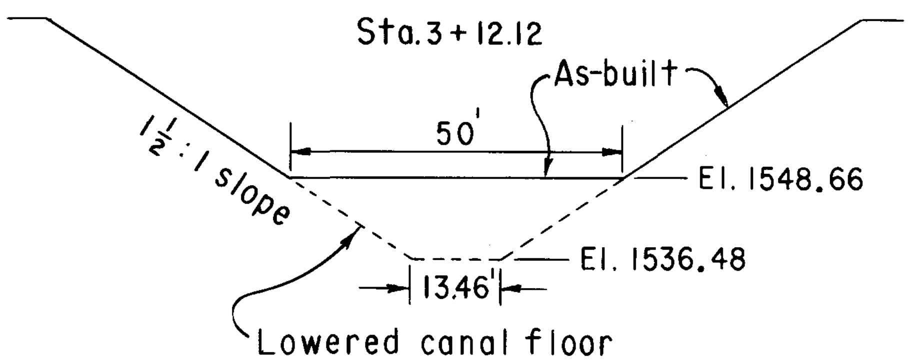


Figure 53. — Lowered Feeder Canal floor - plan.



ELEVATION



SECTION

Figure 54. — Lowered Feeder Canal floor - elevation and section.

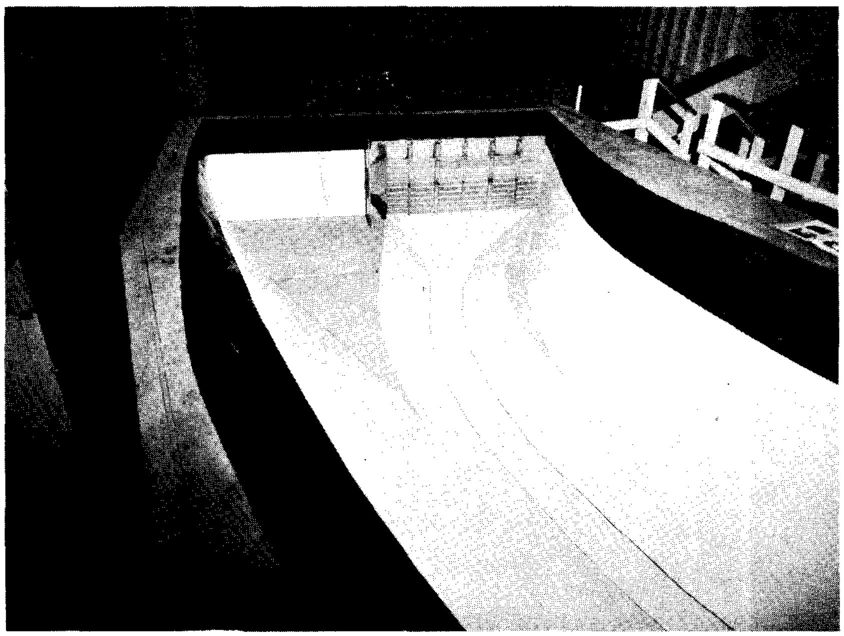


Figure 55. — Pump-turbine model conduit entrance studies - canal floor lowered to units P/G7 through 12. Photo H-1594-159NA

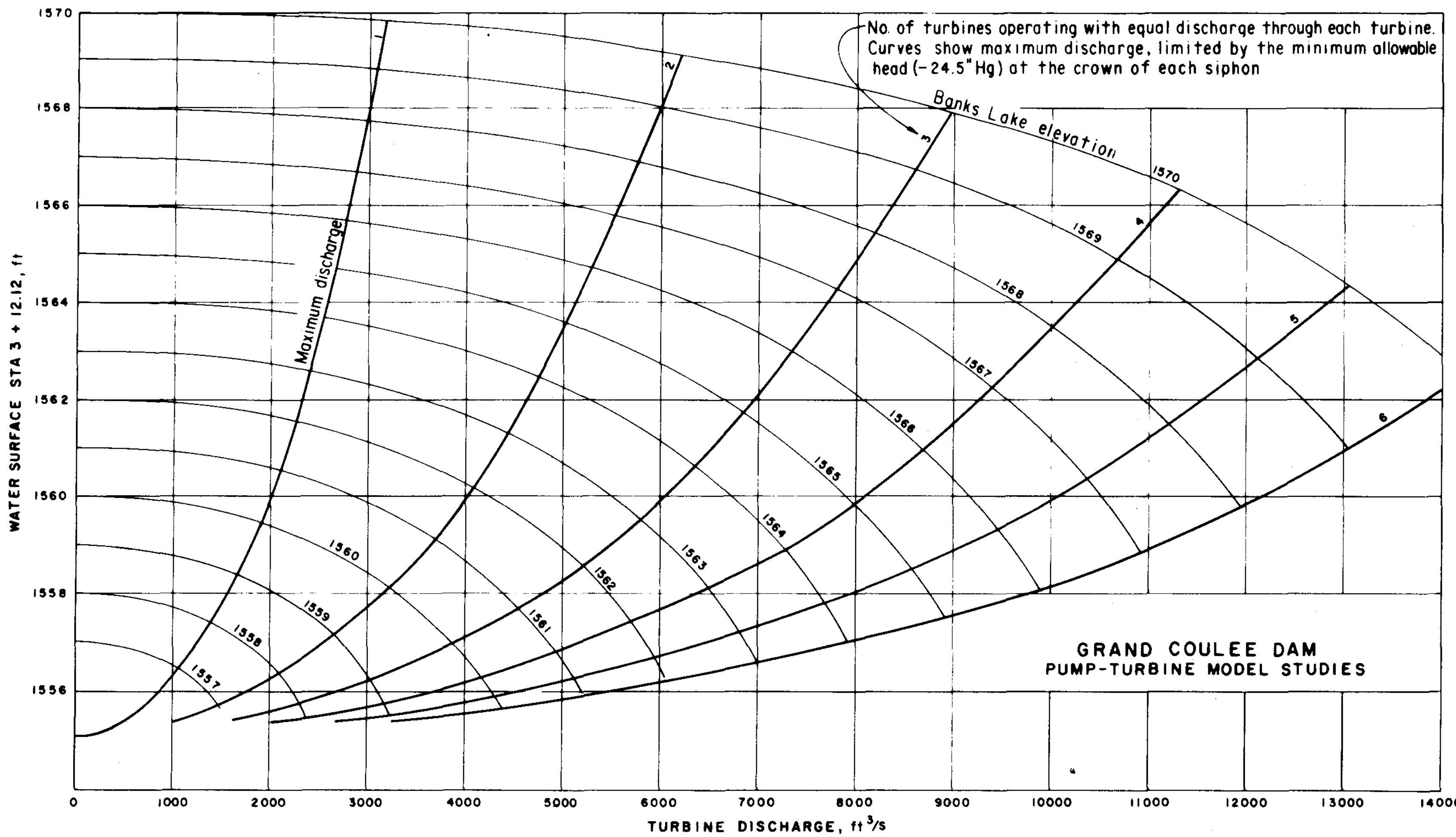


Figure 56. — Water surface elevation at station 3 + 12.12 and allowable maximum discharge. Feeder Canal floor lowered to El. 1536.48 at station 3 + 12.12.

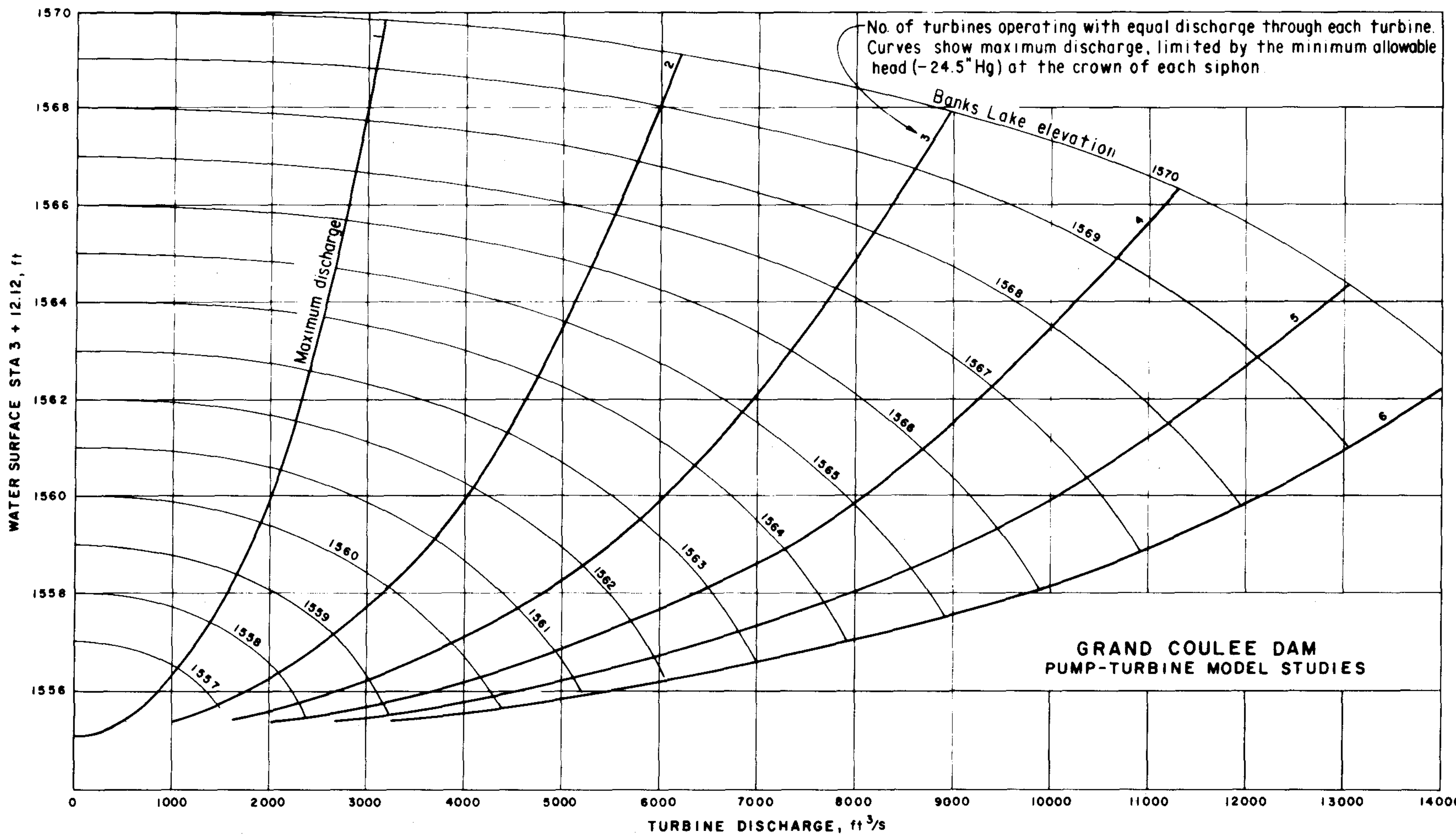


Figure 56. — Water surface elevation at station 3 + 12.12 and allowable maximum discharge. Feeder Canal floor lowered to El. 1536.48 at station 3 + 12.12.

A free pamphlet is available from the Service entitled, "Publications for Sale". It describes some of the technical publications currently available, their cost, and how to order them. The pamphlet can be obtained upon request to the Water and Power Resources Service, E&R Center, Bldg. 67, Denver, CO 80225, Attn:922.