TECHNICAL REPORT H-72-1

OUTLET WORKS FOR BRANCHED OAK AND COTTONWOOD SPRINGS DAMS OAK CREEK, NEBRASKA, AND COTTONWOOD SPRINGS CREEK, SOUTH DAKOTA

Hydraulic Model Investigation

by

J. L. Grace, Jr.

January 1972

Sponsored by U. S. Army Engineer District, Omaha

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

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ARMY-MRC VICKSBURG, MISS.

FOREWORD

The model investigation reported herein was authorized by the Office, Chief of Engineers, on 27 April 1965, at the request of the U. S. Army Engineer District, Omaha.

The studies were conducted in the Hydraulics Division of the U. S. Army Engineer Waterways Experiment Station during the period July 1965 to November 1968, under the direction of Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division, and Mr. T. E. Murphy, Chief of the Structures Branch, and under the general supervision of Mr. J. L. Grace, Jr., Chief of the Spillways and Conduits Section. The engineers in immediate charge of the model were Messrs. E. S. Melsheimer and B. P. Fletcher, assisted by Messrs. H. H. Allen and A. C. Spivey. This report was prepared by Mr. Grace.

During the course of the model investigation, Messrs. Linder, Patenode, Thompson, Sveum, Mellema, Horihan, Staley, Christian, Watson, Noble, Vovk, and Drake of the Omaha District; Mr. J. W. Nelson of the Kansas City District; Messrs. Weremy and Harrison of the Missouri River Division; Dr. Naudasher of the University of Iowa; and Mr. F. W. Blaisdell of the University of Minnesota, St. Anthony Falls Hydraulic Laboratory, visited the Waterways Experiment Station to observe tests, discuss results, and correlate these results with design studies.

Directors of the Waterways Experiment Station during the conduct of the investigation and the preparation and publication of this report were COL John R. Oswalt, Jr., CE, COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE. Technical Directors were Messrs. J. B. Tiffany and F. R. Brown.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
miles (U. S. statute)	1.609344	kilometers
square feet	0.092903	square meters
pounds	0.45359237	kilograms
feet per second	0.3048	meters per second
cubic feet per second	0.02831685	cubic meters per second
feet per second per second	0.3048	meters per second per second

SUMMARY

Model investigations of the outlet works for Branched Oak and Cottonwood Springs Dams were primarily concerned with hydraulic operating characteristics over a wide range of heads. Although the structures were similar in design and purpose, geometric differences, particularly the diameter of the conduits and the height of the riser shafts, required the use of separate model studies. Both studies were conducted with 1:10-scale models that reproduced portions of the approach area, the intake structure, and the outlet conduit. In addition, the Branched Oak model reproduced an SAF impact-type stilling basin and the downstream exit channel.

Pressures measured throughout the recommended design outlet works were positive with the exception of the square or sharp-edged weir crests of Branched Oak, where a minimum pressure of -7.5 ft was recorded in the vicinity of the weir crests for discharges at which the weirs controlled the flow. Rounded or streamlined weir crests such as those of the Cottonwood Springs outlet works are not subject to negative pressures in this area.

Although pressure conditions were satisfactory for both recommended intake structures, undesirable flow conditions (nappe flutter, sloshing, gulping, and vibration) were observed with various designs of both the 5D riser shaft inlet of Branched Oak and the 9.75D riser shaft inlet of Cottonwood Springs.

The following alterations to the original designs of one or both structures were investigated:

- a. Removal of cover plate and trashrack.
- b. Installation of air vents under the crests and through the cover plates.
- c. Rounding or streamlining the weir crests.
- d. Installation of a divider wall between the two weir crests.
- e. Variation in length of weir crests and height of cover plate above weir crests.

Of these alterations, those which provided a curved weir crest, divider wall, and proper cover-plate position were the most satisfactory. At the lower flows (weir controlled), the use of the curved crest

eliminated periodic nappe flutter by preventing separation of the discharge nappes from both weir crests. Nappe sloshing, which occurred as flow control changed from the weirs to the conduit, was eliminated by a divider wall placed between the crests. Gulping beneath the cover plate was eliminated by locating the cover plate at an elevation slightly above the minimum pool elevation required for conduit-controlled flow through the outlet works.

Performance of the original design SAF basin was satisfactory and the height of the basin training walls was sufficient to prevent overtopping. The exit channel immediately below the stilling basin was sloped downward and expanded laterally to provide an exit channel configuration that would permit dissipation of excess energy in turbulence rather than direct attack of the channel boundaries. A riprap plan of protection was developed for the recommended exit channel configuration.

OUTLET WORKS FOR BRANCHED OAK AND COTTONWOOD SPRINGS DAMS

OAK CREEK, NEBRASKA, AND COTTONWOOD SPRINGS CREEK, SOUTH DAKOTA

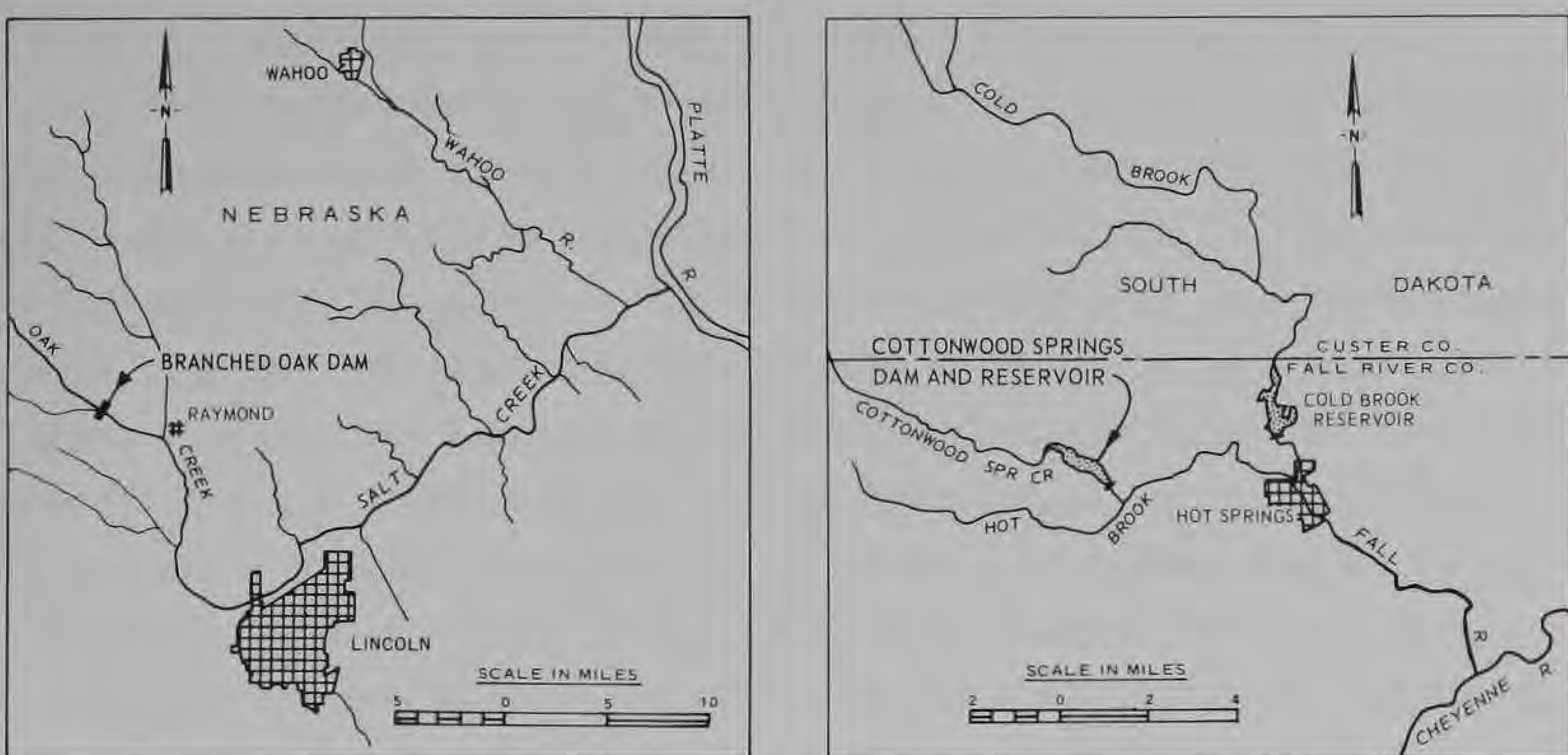
Hydraulic Model Investigation

PART I: INTRODUCTION

The Prototypes

1. The multipurpose Branched Oak Reservoir is located on Oak Creek about 3.5 miles* west and 1 mile north of Raymond, Nebr. (fig. 1, left). The Cottonwood Springs Reservoir, a similar project, is located on Cottonwood Springs Creek approximately 4.5 miles west of Hot Springs, S. Dak. (fig. 1, right). Both projects have primary functions of flood control, water supply, and recreation.

2. Both projects, as constructed, include a rolled-fill earth



Branched Oak   Cottonwood Springs

Fig. 1. Vicinity maps

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*, A table of factors for converting British units of measurement to metric units is presented on page vii.

dam, an uncontrolled outlet works consisting of a two-way drop inlet, a concrete conduit through the embankment, and a parabolic drop to an SAF stilling basin at the outlet. A general profile of each structure is shown in plates 1 and 2 and details of each structure are presented in plates 3 and 4. The Branched Oak outlet works with crest el 1284.0* is designed to discharge approximately 1240 cfs at maximum pool el 1314.0. The Cottonwood Springs outlet works with the crest at el 3875.0 is designed to discharge 500 cfs at the reservoir design pool el 3916.5. Dissimilarity in the projects results mainly from the riser shaft heights and conduit diameters of 5D and 6 ft for Branched Oak and 9.75D and 4 ft for Cottonwood Springs, respectively (D is diameter of the conduit). Low-level gate openings are provided in the upstream face of the riser shaft of each structure to permit lowering the reservoir to inspect the conduit, make shoreline repairs, or control fish population.

Need for and Purposes of Model Studies

3. Although design criteria for the two-way drop inlet or vertical shaft outlet works have been developed by comprehensive testing using both air and water in models at the St. Anthony Falls Hydraulic Laboratory (SAF) of the University of Minnesota and Swarthmore College, the models used were of relatively small scale for study of flow instabilities and of the tendency for surging during transition from weir control to pressure flow. A 1:10-scale model was used for specific study of performance to be anticipated in both the Branched Oak and Cottonwood Springs outlet works, and it was desired that the tests be conducted in a manner such that results would have general application to subsequent projects. The information desired required study of the overall performance of the structures, which involved investigation of pressures and cavitation tendencies throughout the intake and elbow transition, determination of losses in the structure, observation of flow conditions

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* All elevations (el) cited herein are in feet referred to mean sea level.

in the intake structures and conduits, and determination of the adequacy of the stilling basin and protective stone requirements in the exit channel.

PART II: THE MODELS

Description

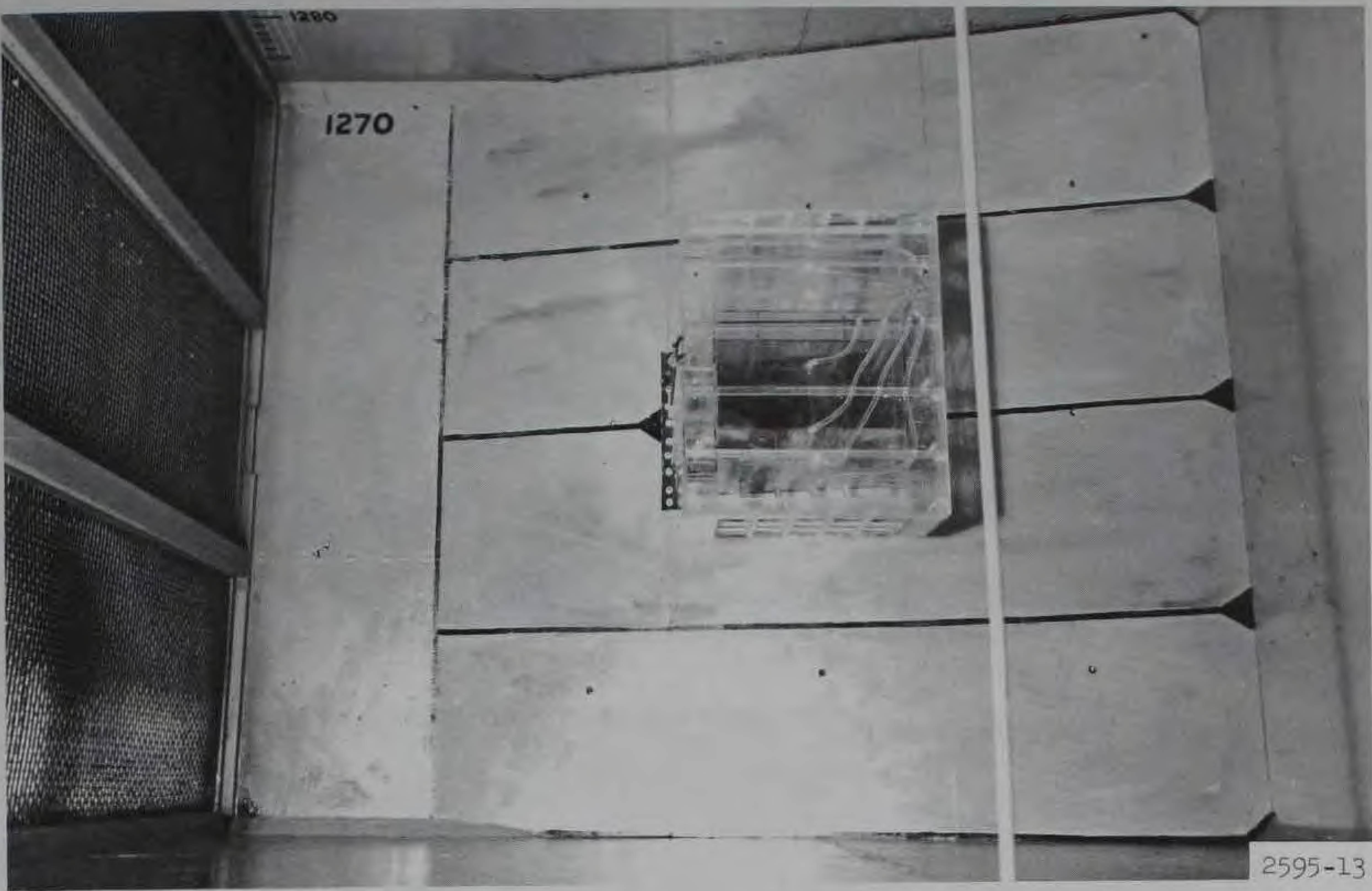
4. The Branched Oak and Cottonwood Springs models, constructed to an undistorted scale of 1:10, reproduced sufficient area of the reservoirs (fig. 2) to obtain natural conditions of approach flows to the intake structures. The intake structures and conduits were constructed of transparent plastic (fig. 3). The SAF basin was reproduced and tested only with the Branched Oak outlet. The stilling basin sidewalls and chute were fabricated of sheet metal, the basin and elements were made of wood, and the exit channel was molded in cement mortar (fig. 4).

5. Water used in operation of the models was supplied by pumps and discharges were measured by means of venturi meters. Steel rails set to grade along the sides of the flume provided a reference plane for measuring devices. Water-surface elevations were measured by means of point gages and velocities were measured with a pitot tube. Piezometers were installed throughout the intake structures and conduits for the measurement of pressures.

Design Considerations

6. In the design of the models, geometric similitude was preserved between model and prototype by means of an undistorted scale ratio. The accepted equations of hydraulic similitude, based on the Froudian relation, were used to express the mathematical relation between the dimensional and hydraulic quantities of the model and the prototype.

7. To make a valid study of flow conditions in the structures required that the prototype hydraulic grade lines be simulated in the model conduits. It is well known that it is impossible to satisfy the requirements of both the Reynolds and Froude criteria for complete similitude by using water in a model if water is the fluid in the prototype. Since hydraulic similitude between the models and prototype was



Branched Oak (with cover plate and trashrack)

Cottonwood Springs
(without cover plate
and trashrack)

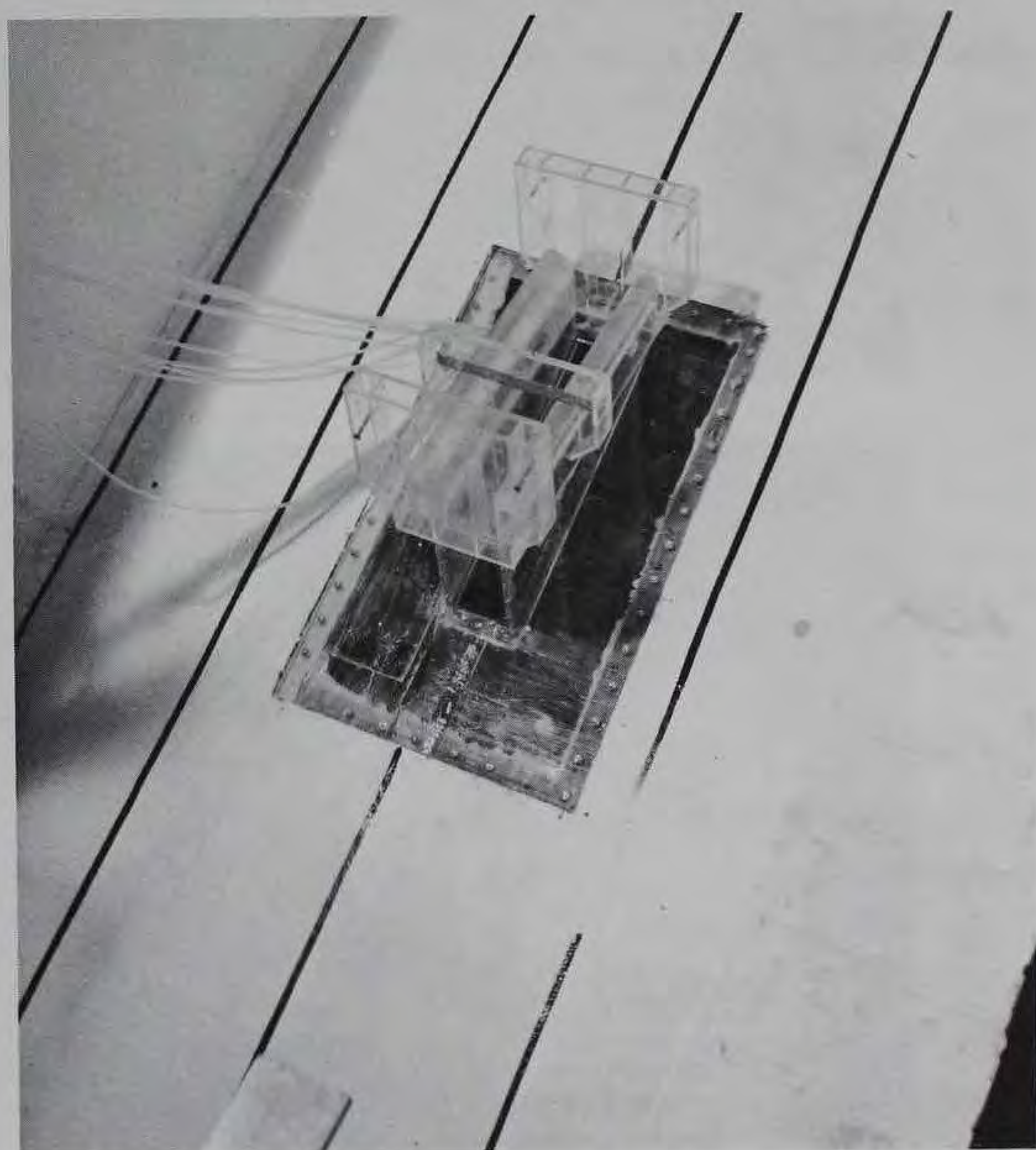
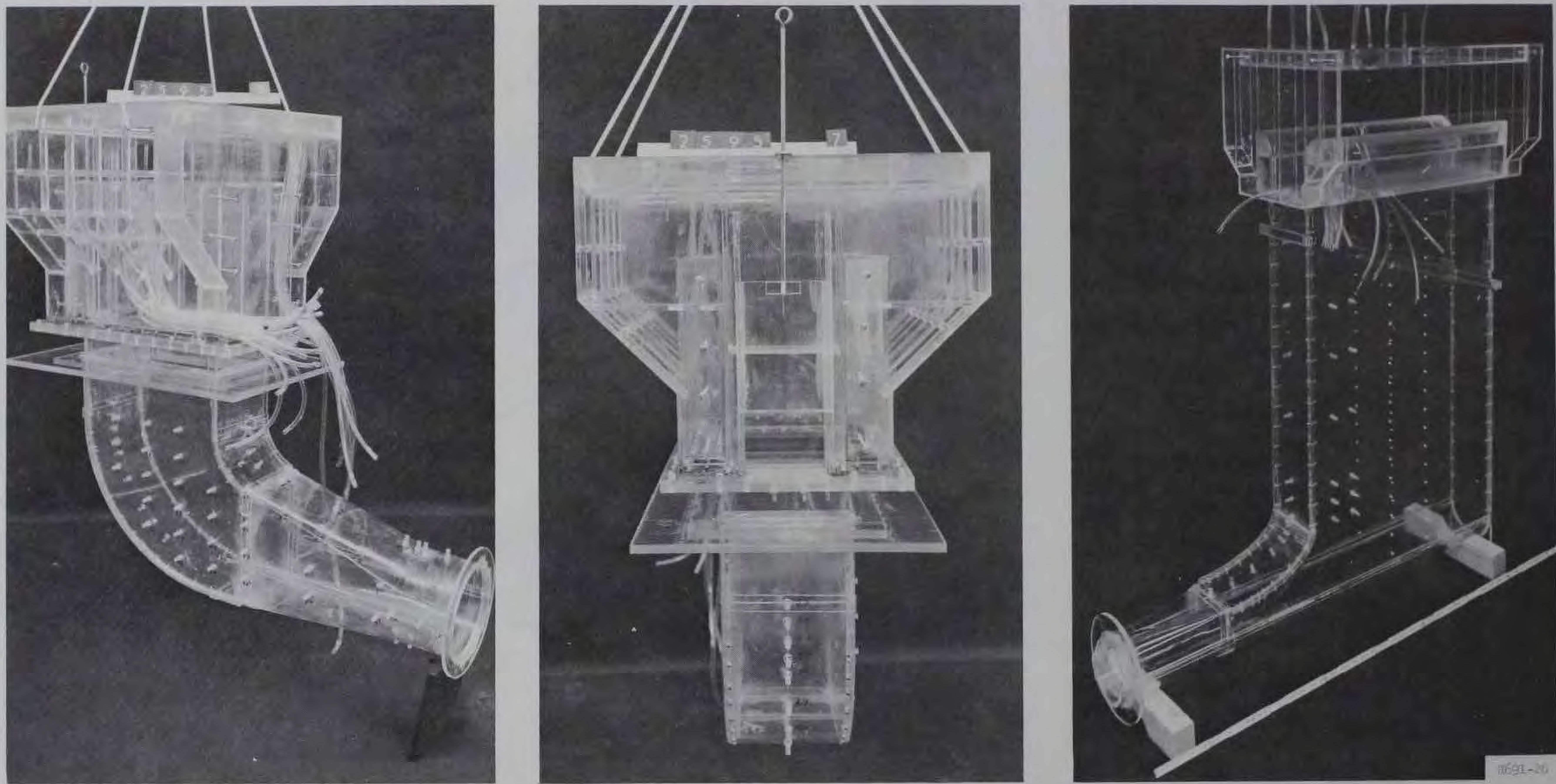


Fig. 2. Approach to intake structures



Branched Oak, right side — Branched Oak, upstream side — Cottonwood Springs

Fig. 3. The 1:10-scale models of Branched Oak and Cottonwood Springs intake structures

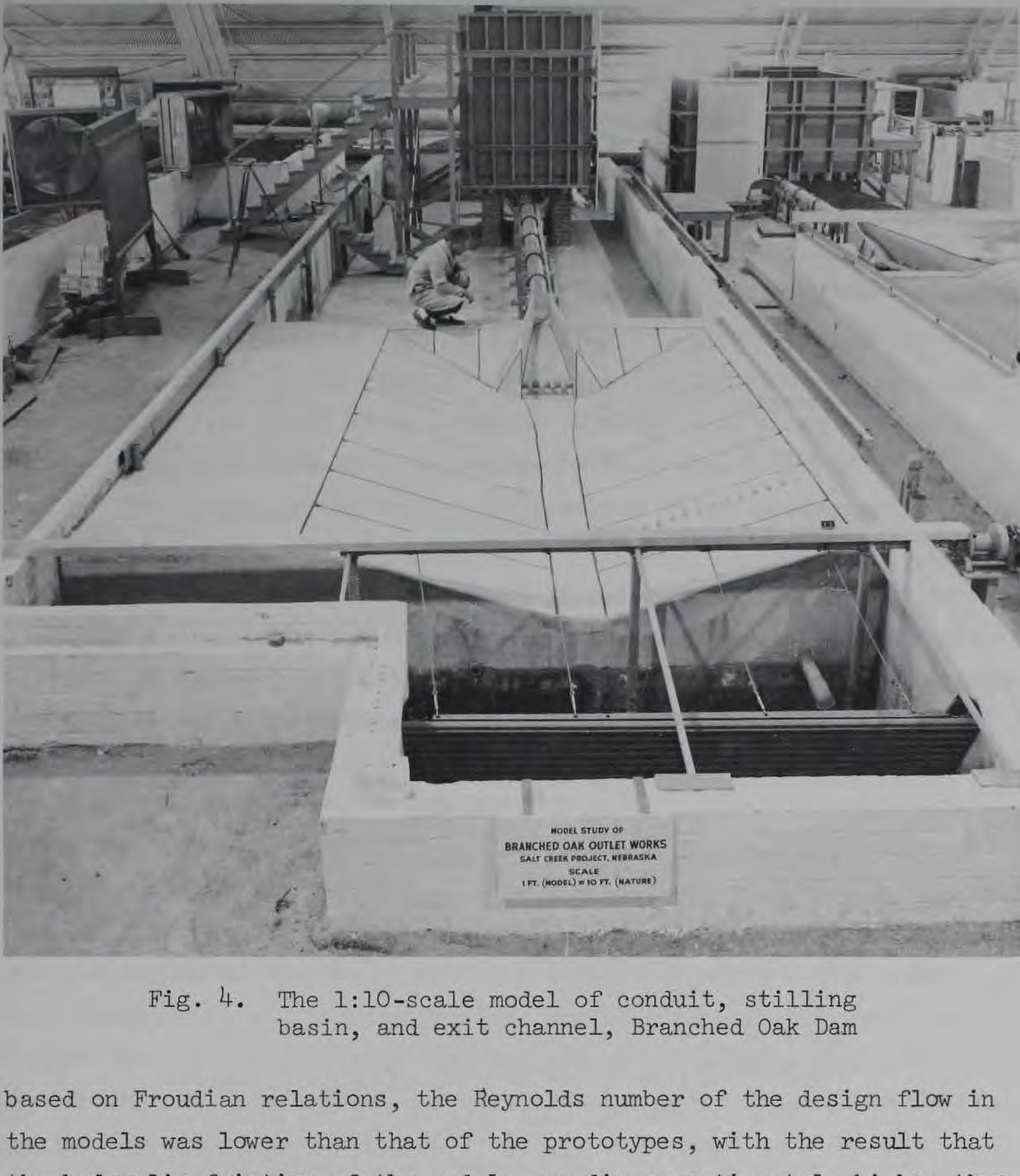


Fig. 4. The 1:10-scale model of conduit, stilling basin, and exit channel, Branched Oak Dam

based on Froudian relations, the Reynolds number of the design flow in the models was lower than that of the prototypes, with the result that the hydraulic friction of the models was disproportionately higher than that of the prototype. Therefore, the lengths of the model conduits were reduced to compensate for their excessive hydraulic resistance relative to those anticipated in the prototype conduits.

Scale Relations

8. General relations for transferences of the Branched Oak and Cottonwood Springs data to prototype equivalents are presented below:

Dimension	Ratio	Scale Relation
Length	L_r	1:10
Time	$T_r = L_r^{1/2}$	1:3.162
Velocity	$V_r = L_r^{1/2}$	1:3.162
Discharge	$Q_r = L_r^{5/2}$	1:316.230
Pressure	$P_r = L_r$	1:10
Roughness	$N_r = L_r^{1/6}$	1:1.468

9. Quantitative transfer of model data to prototype equivalents by the scale relations listed above is considered reliable except for negative model pressures which are only qualitatively reliable. Data on scour tendencies provided a basis of determination of the protective stone requirements and indicated the areas subject to severe attack.

PART III: TESTS AND RESULTS

Branched Oak Outlet Works

Description

10. Details of the two-way drop inlet or vertical shaft outlet works used as an uncontrolled intake structure for the Branched Oak outlet works are shown in plate 3. In terms of the 6-ft diameter of the conduit, D, the riser shaft is 5D high from the base or invert of the elbow (el 1254.0) to the crest of the weirs (el 1284.0). The vertical rectangular riser shaft is 2D long and 1D wide. The weirs on the sides of the riser shaft are 2D long, square or sharp-edged, and 2.25 ft thick. The bottom of the antivortex cover plate is located at el 1287.5, 3.5 ft above the crests of the weirs. A hydraulic transition is provided between the elbow at the base of the intake structure and the 6-ft-diam circular outlet conduit. Details of the outlet transition, SAF stilling basin, and original design exit channel downstream of the conduit outlet are presented in plate 1.

Approach flow conditions

11. Flow patterns in the approach to the intake structure are shown in photo 1. Surface and bottom currents were similar and symmetrical for all discharges. At the design discharge of 1240 cfs, intermittent surface vortices were observed, generally to the left or right and downstream of the structure. The cores of these vortices were 1 to 2 ft in diameter at the water surface and occasionally extended into the intake structure. Vorticity was most pronounced without the cover plate and trashrack, as expected; however, the effect on discharge characteristics appeared to be negligible. Vortex action was considerably greater with the cover plate attached and the trashrack removed than that observed with both devices. It is considered that severe vortex action will not be experienced with the original design intake; however, it is likely that some small intermittent vortices will occur.

Discharge characteristics

12. General discharge characteristics of the original design

outlet works (plate 5) indicate three flow controls will exist in the structure. Flow was regulated by the weirs for all heads and discharges up to 3.5 ft and 500 cfs, respectively. The outlet conduit controlled all releases equal to or greater than 1100 cfs when heads on the weirs and center of the conduit outlet portal were equal to or greater than 5.5 and 41 ft, respectively. The cover plate located 3.5 ft above the crests of the weirs controlled discharges between 500 and 1100 cfs when heads on the weirs ranged from 3.5 to 5.5 ft. Siphonic action was developed under these conditions as the vertical riser shaft tended to prime and flow full. No noticeable instability of flow was observed with the Branched Oak outlet works as the transition from one type of flow control to another was encountered; however, air entrainment was observed in the riser shaft during plate- or siphon-controlled flows. Conditions observed in the lower portion of the riser shafts with various types of flow control are presented in photo 2. Discharge characteristics of the outlet works are satisfied by the following relations:

$$Q = 2.48LH_W^{1.70} \qquad \text{(Weir-controlled flow)} \qquad (1)$$

$$Q = 0.75A\sqrt{2gH_o} \qquad \text{(Conduit-controlled flow)} \qquad (2)$$

where

Q = total discharge, cfs

L = total length of weir, ft

H_W = total head on weir, ft

A = area of outlet conduit, sq ft

g = gravitational constant, ft/sec^2

H_o = total head on center of conduit outlet portal, ft

Pressures

13. Pressures observed throughout the outlet works with piezometers located as shown in plates 6 and 7 are presented in tables 1-4. Pressures in the outlet conduit and elbow were positive during all flow conditions. A minimum pressure of -7.4 ft was observed in the vicinity of the weir crest during weir- and plate-controlled flow conditions;

however, cavitation is unlikely and adverse instability of flow was not apparent. Pressures were positive throughout the structure with all conduit-controlled discharges.

14. Pressures and hydraulic gradients observed with the cover plate and trashracks removed, which permitted only weir- or conduit-controlled flows with minimum disturbance and air entrainment, are presented in tables 5 and 6, respectively. Removal of the cover plate eliminated piezometers 1-7 and piezometers A, B, C, and D were added in the downstream, left, upstream, and right sides of the riser shaft, respectively. Piezometer A was installed at el 1278.0 and piezometers B-D were located at el 1276.0. Instantaneous pressures measured with electric pressure cells located in the crown and invert of the elbow and base of the intake structure are presented in plate 8. Pressures fluctuated from +5.0 to -0.5 ft of water at the crown (cell 1) and from +4.0 to +22.5 ft of water at the invert (cell 2) with weir-controlled flows falling down the vertical riser shaft. Pressure fluctuations were not discernible with conduit-controlled flows.

Entrance losses

15. Pressure gradients were determined for conduit-controlled flows assuming that the pressures indicated by piezometers 100-109 were within a region relatively free from the effects of boundary layer development and acceleration of flow at the entrance and outlet of the conduit. The slopes of these gradients were used to compute the resistance coefficient of the conduit and the total entrance loss attributable to the intake structure for various discharges. The conduit resistance coefficients determined were only slightly greater than those indicated by the smooth pipe curve of a Moody diagram for appropriate Reynolds numbers and indicated that the conditions of flow in the region between piezometers 100 and 109 were essentially as assumed. Values of the total entrance loss coefficient attributed to the intake structure (table 7) indicate that the total entrance head loss was equal to approximately 20 percent of the velocity head in the outlet conduit.

16. Additional tests were conducted in which piezometers in the riser shaft at el 1276.0 were read in conjunction with numbers 100-109

for the purpose of determining the separate losses in the intake structure. Using piezometers 100-109 as a reference, the hydraulic gradient was projected to sta 1+43.25 U.S., just inside the conduit entrance. The hydraulic gradient in the shaft was determined by piezometers located at el 1276.0. Using the above information and the pool elevation, the separate losses were determined and are presented for discharges ranging from 1150 to 1520 cfs in table 8. The head losses in the upper and lower portions of the intake structure are equal to approximately 13 and 7 percent, respectively, of the velocity head in the outlet conduit and about two-thirds and one-third, respectively, of the total entrance loss.

Stilling basin performance

17. The original stilling basin was designed in accordance with the well-known SAF stilling basin criteria developed by Blaisdell. Details of the impact-type basin (fig. 5), which utilizes chute blocks,

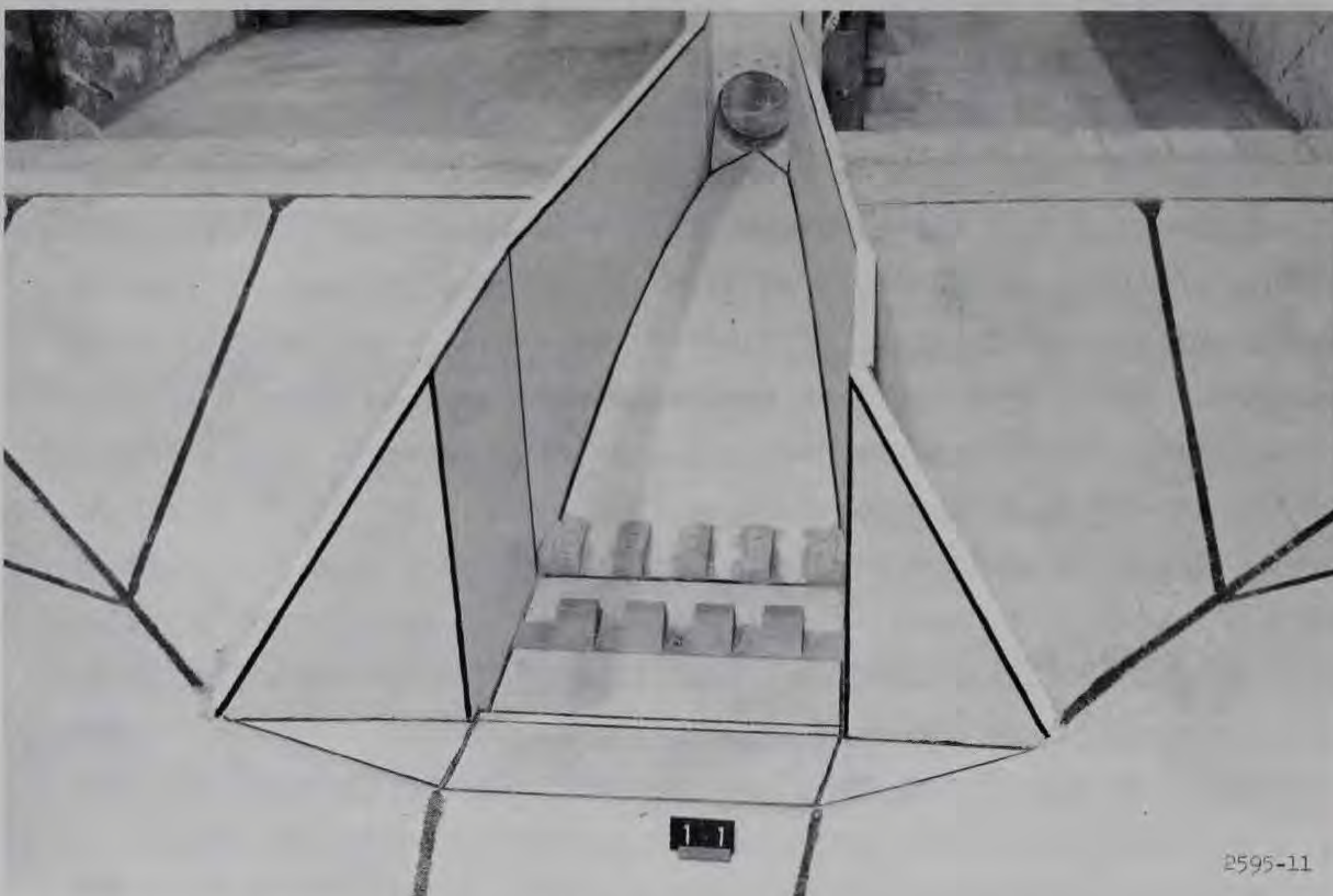
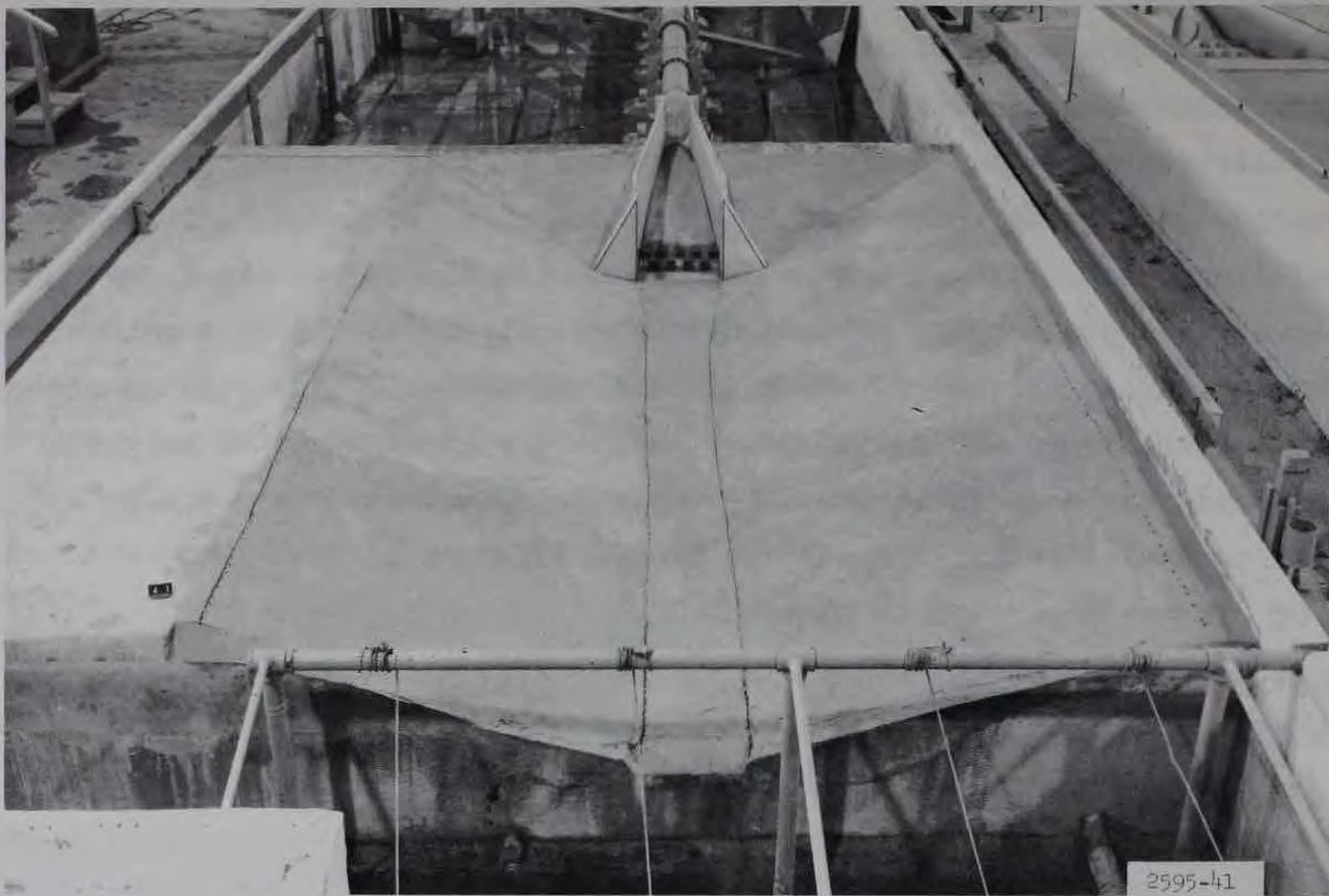


Fig. 5. Original design stilling basin, Branched Oak outlet works

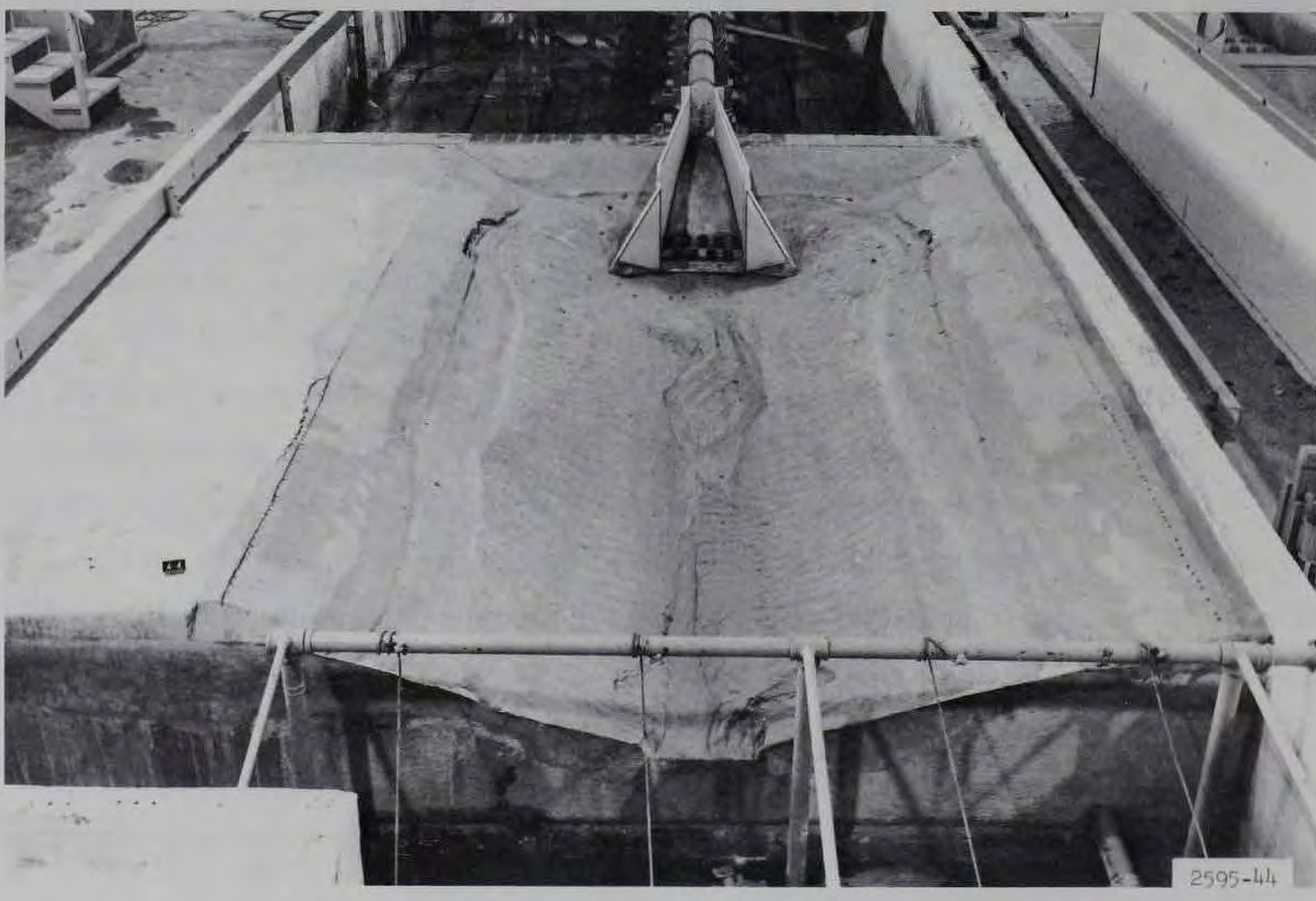
baffle piers, and an end sill to force and maintain a hydraulic jump on a relatively short horizontal apron, are presented in plate 1. Flow conditions observed with various discharges are shown in photo 3. Hydraulic jump action was lost and spray was induced when the tailwater was lowered 1.6 ft below normal with the design discharge. Although stilling basin action was very turbulent with the design discharge and normal tailwater depth, maximum bottom velocities in the exit channel immediately downstream of the basin did not exceed 20 fps. In general, basin performance was satisfactory, and it appeared that the height of the stilling basin walls could be reduced. Water-surface profiles and exit channel velocities resulting from discharges of 800, 1240, and 1500 cfs are presented in plates 9-11.

Exit channel configuration and protection

18. Since no practical energy dissipator or stilling basin dissipates all of the energy of the released flow, tests were conducted to evaluate the concept of providing for or preforming a "local scour hole" immediately downstream of the stilling basin in which the flow can expand and dissipate its excess energy in turbulence rather than in direct attack on the channel boundaries. The exit channel was molded in sand (fig. 6a) and subjected to flows of 1240 and 1500 cfs for periods of about 47 min (prototype), which is equivalent to a model test duration of 15 min. This operation time was used since experience indicates that sand under direct attack will be moved within this period, although deterioration of the channel will continue at a decreasing rate for many hours. The condition of the channel resulting from exposure to 1240 cfs is shown in fig. 6b. Sand scour patterns resulting from discharges of 1240 and 1500 cfs for a period of 47 min (prototype) are shown in plates 12 and 13. The recommended exit channel configuration (plate 14) was developed to approximate the scour hole geometry observed with the design discharge of 1240 cfs (plate 12). This plan provided for both vertical and horizontal expansion of flow and contained the excess turbulence (fig. 7) within the riprapped portion of the channel. The side slopes were extended on the 1-on-3 slope until intersection was obtained

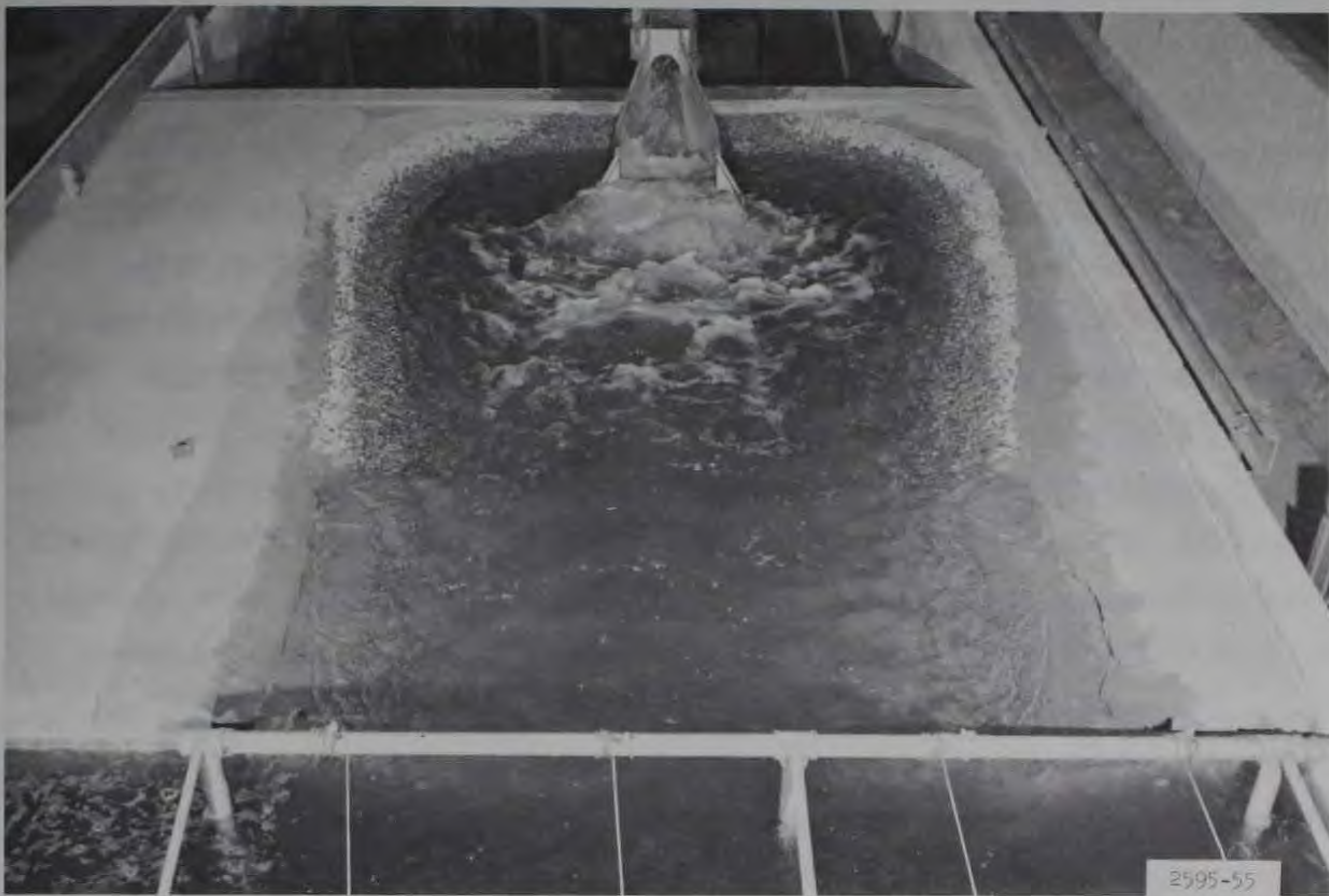


a. Before test



b. Configuration resulting from 1240-cfs discharge

Fig. 6. Original design stilling basin and exit channel molded in sand



Discharge 1500 cfs, TW el 1243.8 (normal)

Condition of scheme B riprap (undisturbed) after exposure to 1500-cfs flow and TW el 1243.8 for 1 hour (model) or 3 hours (prototype)

Fig. 7. Recommended exit channel configuration and scheme B riprap (W_{50} = 20 lb)

along the center line of the exit channel. The bottom protective stone immediately downstream of the end sill was sloped 1 on 4 to el 1227.7 and then was horizontal for a distance of 6 ft. The vertical expansion permitted development of a stable back roller that actually caused deposition of sand in the area downstream of the end sill (fig. 7). Riprap termed scheme B (stones with minimum, average, and maximum weights of 5, 20, and 50 lb, respectively) placed 15 in. thick remained stable with discharges as large as 1500 cfs and should be provided downstream to sta 3+90.

Effect of riser shaft height

19. Although the original design outlet works and the recommended exit channel configuration and scheme B riprap protection were considered satisfactory for the Branched Oak project, it was desired that tests and results be generalized as much as possible with available and limited resources. It was considered that the height of the riser shaft might be an important variable and tests were conducted to investigate performance of a similar structure with all dimensions the same as the original design except that the height of the riser shaft was 62 ft (10.33D) rather than 30 ft (3D).

20. Discharge characteristics of the outlet works with a 10.33D-high riser shaft were similar to those observed with the 3D-high riser shaft of the original design; however, the range of heads and discharges in which the cover plate controlled flow was increased. The weirs controlled discharges and heads on the weir crests up to 500 cfs and 3.5 ft, respectively, and in accordance with equation 1, paragraph 12. The outlet conduit controlled all releases equal to or greater than 1460 cfs where heads on the weirs and center of the conduit outlet portal were equal to or greater than 6.5 and 79.5 ft, respectively, and in accordance with the following equation:

$$Q = 0.72A\sqrt{2gH_o} \qquad (3)$$

Variables are defined in paragraph 12, and equations 2 and 3 differ only slightly. The higher riser shaft increased head loss and reduced capacity of the outlet works slightly as expected. The cover plate located 3.5 ft above the crests of the weirs controlled discharges between 500 and 1460 cfs when heads on the weirs ranged from 3.5 to 6.5 ft.

21. With heads less than 2.0 ft, the nappes adhered to the sides of the riser shaft and no noise or vibration was evident; however, as the head increased, the nappes separated from the sides of the shaft and intersected one another, forming an air seal in the shaft. The pressure in the shaft was reduced as a result until the nappes were drawn down sufficiently to break the seal and vent the shaft, and then this cycle was repeated rapidly. The rapid fluctuation of the nappes produced a popping noise and imparted considerable vibration to the model intake structure. As the water surface of the upper pool approached the bottom of the cover plate, the nappe fluctuation ceased; however a gulping noise and vibration were noted as slugs of air were drawn beneath the cover plate. This condition persisted while flow through the riser shaft demanded air. Air demand was nonexistent in the outlet works with discharges controlled sufficiently by the outlet conduit to raise the hydraulic gradient in the riser shaft to an elevation essentially the same as that of the weir crest. Thus, it was reasoned that plate-controlled flow conditions should not be permitted in outlet works of this type. This required provision of sufficient length of weirs, elevation of cover plate, and size of given length of conduit such that the weirs control flows up to that required to raise the hydraulic gradient in the shaft to the weir crests before the upper pool contacts the underside of the cover plate. Limited tests conducted with a valve on the downstream end of the conduit for regulation of the position of the hydraulic gradient indicated that the flow instabilities due to nappe flutter and nappe interference persisted with free and submerged weir flow conditions, respectively, in the 62-ft-high riser shaft outlet works provided with square or sharp-edged weirs. In general, it was concluded that the height of the riser shaft and particularly the vertical distance from the center of the conduit outlet portal to the crests of the weirs determine the minimum discharge at which the outlet conduit controls flow through outlet works of this type.

Effect of conduit length

22. Tests to investigate the separate effect of conduit length were conducted with the original design Branched Oak intake structure, which had a riser shaft height of 30 ft or 5D. The model conduit was shortened to simulate a prototype length of 153 ft rather than the original length of 380 ft. Discharge characteristics of the outlet works equipped with a shorter conduit were generally similar to those observed with the original length of conduit since the weirs controlled discharges up to 500 cfs, the cover plate controlled discharges ranging from 500 to 1120 cfs, and the conduit controlled flows in excess of 1120 cfs. Conduit-controlled discharge characteristics were satisfied by the following equation:

$$Q = 0.76A\sqrt{2gH_o} \qquad (4)$$

Variables are defined in paragraph 12, and equations 2 and 4 differ only slightly. The outlet works were slightly more efficient with a shorter conduit during conduit-controlled flow conditions since hydraulic losses were reduced somewhat, as expected.

23. The shortened conduit also increased air demand in the outlet works as did the higher riser shaft and nappe flutter was observed with heads of 2.5 to 3.4 ft and free flows over the square or sharp-edged weirs; gulping was experienced with plate-controlled flows. The excessive noise and flow instability generated with both the higher riser shaft and original conduit as well as the original riser shaft and a shorter conduit were not observed with the original design outlet works. The following modifications were attempted and found to be ineffective in preventing both nappe flutter with free flow over the square or sharp-edged weirs and gulping with plate-controlled flows:

a. Ventilating the structure with either nappe deflectors at each end of the weirs, an open manhole, or an elaborate aeration system.

b. Varying the elevation of the weir crests relative to one another.

c. Opening the low-level gate on the upstream face of the riser shaft.

d. Converting the intake to a siphon by installation of end walls that extended from the cover plate to the weir crests.

Regrettably, additional investigations with the Branched Oak model had to be terminated due to limited support funding and the fact that performance of the original design outlet works as proposed was considered satisfactory. Fortunately, the Omaha District Office had planned and designed a similar outlet works for the Cottonwood Springs project and at their request additional model studies of the two-way drop inlets or vertical shaft outlet works were initiated in June 1968.

Cottonwood Springs Outlet Works

Description

24. A profile of the original design Cottonwood Springs outlet works is shown in plate 2 and details of the intake structure are presented in plate 4. In terms of the 4-ft diameter of the outlet conduit, D, the riser shaft is 9.75D high from the base (el 3836.0) to the crest of the weirs (el 3875.0). The vertical rectangular riser shaft is 2D long and 1D wide. The weirs on the sides of the riser shaft are 2D long, 2 ft thick, and formed of compound radii of 0.25 and 1.75 ft. The bottom of the antivortex cover plate is located at el 3878.5, 3.5 ft above the crests of the weirs. A hydraulic transition is provided between the base of the riser shaft and the 4-ft-diam circular outlet conduit. Details of the transition are shown in plate 4, and those of the SAF stilling basin and exit channel are presented in plate 2.

25. The basic riser shaft of the model (fig. 3) was constructed of plastic with weir and cover-plate lengths equivalent to 5D; however, inserts were provided to permit simulation of various weir lengths and cover-plate heights. Model conduits were constructed of lengths of 38 and 68 ft, respectively, sufficient for simulation of the head losses anticipated with the design discharge (558 cfs) in both relatively smooth ($f_p = 0.0085$) and rough ($f_p = 0.015$) prototype conduits

573.5 ft long. Piezometers and pressure cells were located as shown in plate 15. It was desired that tests and results be generalized as much as possible.

<u>3D-long weirs and smooth conduit</u>

26. Initial tests were conducted with the cover plate located 3 ft above the crests of the compound curve shaped weirs and the shorter conduit simulating the relatively smooth prototype conduit. Discharge characteristics of the outlet works are presented in plate 16. The weirs controlled all discharges less than 430 cfs, that required for establishment of conduit control. Since 430 cfs was discharged with a head on the weirs of about 2.55 ft, the cover plate located 3 ft above the weirs did not control flow under any conditions. Discharge characteristics of this outlet works are described by the following relations:

$$Q = 3.93LH_W^{1.60} \qquad \text{(Weir-controlled flow)} \qquad (5)$$

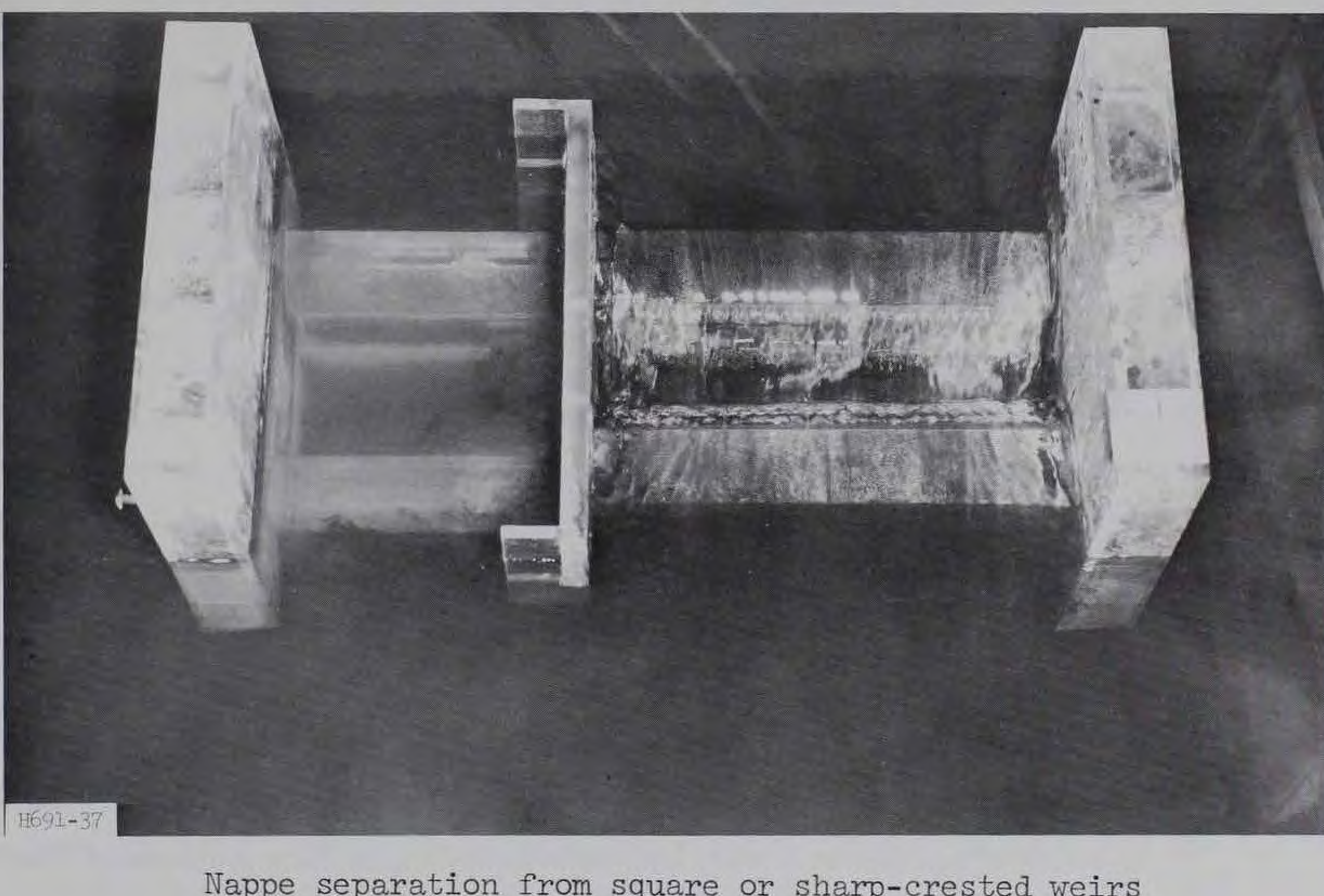
$$Q = 0.66A\sqrt{2gH_o} \qquad \text{(Conduit-controlled flow)} \qquad (6)$$

Variables are defined in paragraph 12.

27. The nappes did not separate from the compound curve shaped weirs (fig. 8); however, they could be forced to separate with heads on the crests in excess of 2 ft by artificial ventilation of the nappes with a yardstick or some other object simulating a log or debris. Flutter of the nappes could not be detected with the compound curve shaped weirs vented or unvented, and flow conditions were stable for all weir-controlled flows (heads on the crests and discharges up to 2.55 ft and 430 cfs, respectively).

28. With heads on the crests in the range of 2.6 to 3 ft, the nappes were submerged due to the effect of the conduit controlling flow; the resulting interference between the nappes produced a periodic sloshing of flow from side to side (fig. 9) and pressure fluctuations in the riser shaft of about 5 ft of water. Flow conditions resulting with heads in excess of 3 ft with the cover plate located 3 ft above the weirs or even removed were stable, and there was no air demand or

Adherence of nappes to compound curve shaped weirs



Nappe separation from square or sharp-crested weirs

Fig. 8. Free flow (150 cfs) over 3D-long weirs, Cottonwood Springs outlet works

Fig. 9. Sloshing or interference of nappes due to submergence from conduit-controlled discharge of 435 cfs

gulping experienced with this cover-plate location. Observations of general performance with cover-plate heights as small as 1 ft indicated that pressures in the riser shaft would be reduced to -7 ft of water and gulping or air demand would be increased as a result. Pressures remained positive throughout the outlet works with the cover plate located 3 ft above the weirs.

29. A 1-ft-thick divider wall was installed in the center of the riser shaft that extended from the cover plate to the elevation of the weir crests and proved to be ineffective in preventing the unstable sloshing action shown in fig. 9. The wall was extended to a position 2 ft below the weir crests or to the P.T. of the compound curve shaped weirs and the flow instability was eliminated (fig. 10). A total entrance loss equivalent to 0.093 of the velocity head in the conduit was observed with this design (table 9).

30. In general, these tests indicated that the flow instabilities

Fig. 10. Effectiveness of divider wall in preventing sloshing or nappe interference; discharge 435 cfs

resulting from nappe flutter and interference were eliminated by the compound curve shaped weir crests and the divider wall, respectively, and those due to excessive air demand (gulping) were prevented by locating the cover plate a distance above the weir crests slightly in excess of the head required on the weirs to release discharges that are controlled by the outlet conduit.

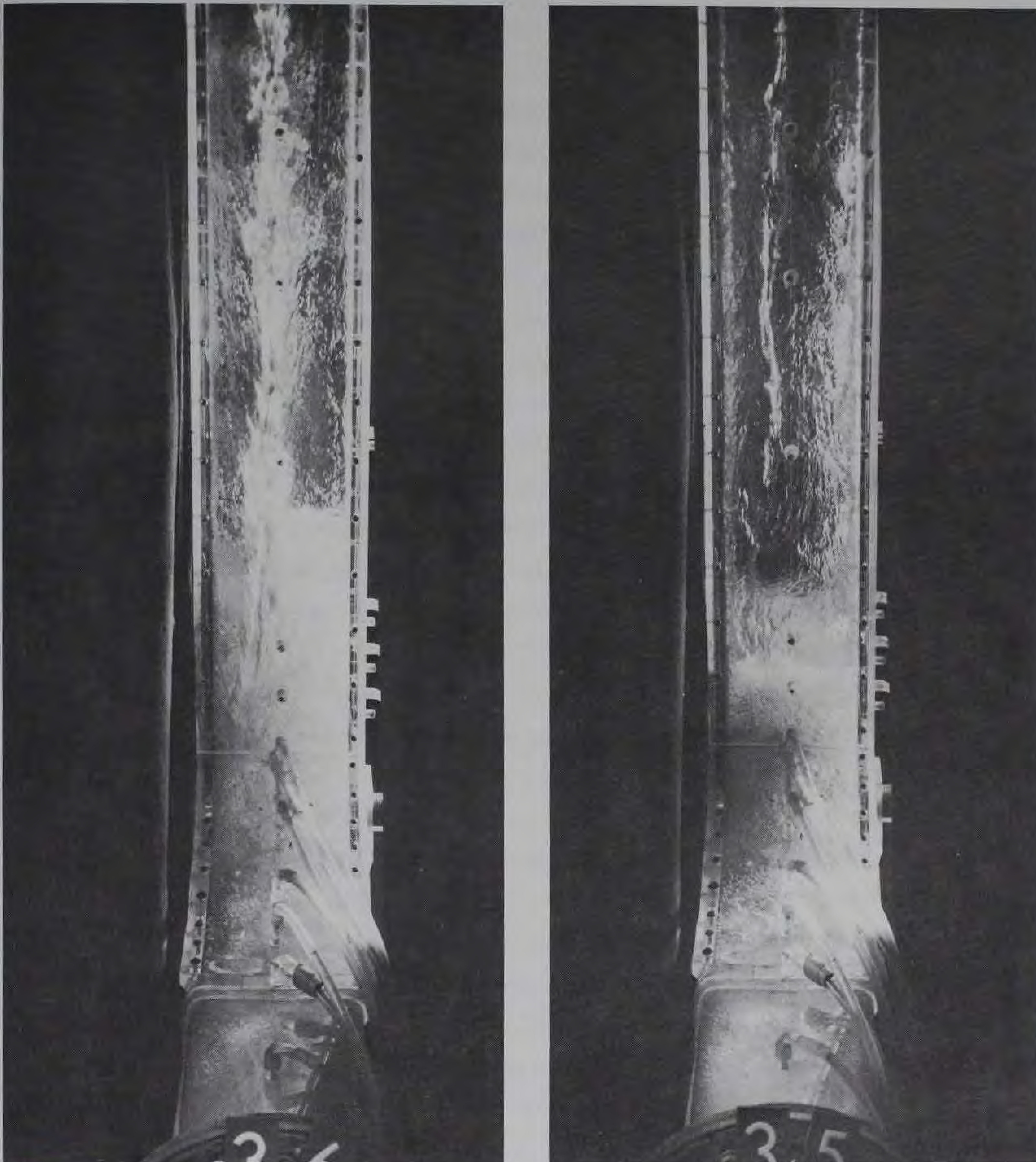
31. Model investigations with various shaped weir crests (square or sharp edged, semicircular or cylindrical, and the SAF design which utilizes a sharp-edged and flat upstream quadrant with a simple radius equivalent to one-half of the wall thickness downstream quadrant) indicated that the nappes would separate or spring clear of the weir crests. Only the square crests permitted nappe flutter when separation occurred and pressure fluctuations in the base of the riser shaft as great as 22.5 ft of water were present. All of the shapes permitted the sloshing

due to interference of the nappes when submerged and pressure fluctuations of about 5 ft of water occurred.

32. When the nappes separate from both weir crests and flow down the center of the riser shaft, the flow upon entering the water within the riser shaft tends to be deflected periodically from side to side and considerable vortex generation and shedding occur as the jet is deflected and resisted by the sidewalls (fig. 11). It is believed that the pulsating pressures and resultant loadings on the sidewalls are the forcing functions tending to vibrate such structures. The tendency for vibration is not evident when the nappes adhere or follow either one or both crests and sidewalls of the riser shaft. Separation of both nappes occurred immediately with the square crests. With the other shapes, only one nappe separated and the tendency for separation was greater with the SAF crest shape than with the semicircular crest shape. The compound curve crest shape is less likely to permit separation than any of the shapes investigated.

3D-long weirs and rough conduit

33. Performance of the 9.75D-high riser shaft with the 3D length of compound curve shaped weir crests was investigated with a longer model conduit that simulated a 4-ft-diam and 573.5-ft-long prototype conduit with a resistance coefficient of 0.015. Discharge characteristics of the outlet works are presented in plate 16. The longer or more resistant conduit controlled all discharges in excess of 360 cfs which required a head on the weirs of about 2.3 ft; therefore, it was concluded that the cover plate should be located at least 2.5 ft above the weirs for a design of this type. A divider wall that extended from the bottom of the cover plate down to the P.T. of the compound curve shaped weir crests and located in the center of the riser shaft prevented nappe interference or sloshing as the control of flow shifted from the weirs to the conduit. Positive pressures were observed throughout the outlet works under all conditions and a total entrance loss equivalent to 0.110 of the velocity head in the conduit was observed with this design. Separate and total losses attributable to the 9.75D-high intake structure



Nappes separated from weir crests; note flow down center of riser shaft, and deflection of jet and vorticity induced as flow plunges into water within riser shaft. Jet is periodically deflected from side to side

Adherence of nappes to weirs and sides of riser shaft; note flow in base of riser shaft is more stable than that resulting with nappes separated from weir crests

Fig. 11. Flow conditions in riser shaft with and without nappe separation from weir crests

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with the 3D-long compound curve shaped weirs and both lengths of conduit are presented in table 9.

2D-long weirs and smooth conduit

34. Performance of the 9.75D-high riser shaft with 2D-long compound curve shaped weirs was investigated initially with the model conduit simulating a 4-ft-diam, 573.5-ft-long prototype conduit with a resistance coefficient of 0.0085. Discharge characteristics of this design outlet works are presented in plate 17. The conduit controlled all discharges in excess of 435 cfs that required a head on the weirs and minimum cover-plate height of about 4 ft as well as an appropriate divider wall that extended 6 ft below the cover plate. Flow conditions were stable and pressures (table 10) throughout the outlet works were positive for all ranges of discharge. Separate and total entrance losses attributable to the intake structure equipped with both the compound curve and SAF-shaped weirs are presented in table 11. Performance of this design outlet works was satisfactory in all respects.

2D-long weirs and rough conduit

35. Discharge characteristics of the outlet works consisting of a 9.75D-high riser shaft with 2D-long compound curve shaped weirs and a 4-ft-diam, 573.5-ft-long prototype conduit with a resistance coefficient of 0.015 are presented in plate 17. The conduit controlled all discharges in excess of 360 cfs that required a head on the weirs and minimum cover-plate height of about 3.5 ft as well as an appropriate divider wall that extended 5.5 ft below the cover plate. Performance with either the SAF or compound curve shaped weirs was satisfactory and stable during all operating conditions. Pressures were positive throughout the outlet works under all conditions of operation. Separate and total entrance losses attributable to this design intake structure are presented in table 12.

Recommended design outlet works

36. Based upon the results of all tests conducted with outlet works similar to the original design proposed for the Cottonwood Springs project, it was concluded that an optimum design could be obtained by positioning the cover plate 4 ft rather than 3.5 ft above the 2D-long

compound curve shaped weirs and installing a 1-ft-thick, 6-ft-high, 2D-long divider wall in the center of the riser shaft beneath the cover plate.

37. It is recommended that two-way drop inlets or vertical shaft outlet works of the type investigated herein be designed and constructed to permit flow control by weirs and conduit only. For a given height of riser shaft and length and resistance of conduit, this requires that the conduit be sufficiently small, the weirs be sufficiently long, and the cover plate be located sufficiently above the weirs so that the energy gradient in the riser shaft will be positioned at or above the weir crests when the minimum outlet works discharge controlled by the conduit is released. Conduit-controlled discharge characteristics of these outlet works are satisfied by the following equation:

$$Q = CA\sqrt{2gH_o}$$

where

C = dimensionless discharge coefficient equal to $\sqrt{1/K}$

K = dimensionless loss coefficient equal to $H_o/\left(\frac{V^2}{2g}\right)$; ratio of total head to conduit velocity head

V = average velocity in conduit, fps

The minimum outlet works discharge controlled by the conduit may be calculated on the basis of the above equation, an estimate of the total loss coefficient (K), and an approximate H_o equivalent to the difference in elevation between the center of the outlet portal and the crests of the weirs. The conduit must be large enough to pass the design discharge with the maximum permissible pool elevation. The minimum desired storage or corresponding pool elevation will normally dictate the elevation of the weir crests.

38. It is recommended that the weir crests always be rounded or streamlined to prevent separation of flow from the weir crests and periodic flutter of the nappes as observed with the square or sharp-edged weirs in order to prevent the possibility of excessive noise and vibration. General discharge characteristics of the streamlined or rounded weirs such as those of the Cottonwood Springs intake structure are

described by the following equation:

$$Q = 3.93LH_W^{1.60} \qquad (5\ bis)$$

39. A divider wall should be placed in the center of the riser shaft that extends from the bottom of the cover plate to a position about 0.5D below the weir crests to prevent sloshing due to interference of the nappes as the weirs become submerged due to conduit control of flow through the outlet works. The bottom of the cover plate should be positioned at an elevation about 1 ft higher than the pool elevation required for establishing conduit-controlled flows through the outlet works. A converging transition should be provided between the riser shaft and outlet conduit to prevent orifice or inlet control at the conduit entrance and adverse pressure and flow conditions downstream. Intake structures designed on this basis should be relatively free of any adverse pressures or periodic flow instabilities such as nappe flutter, sloshing, and gulping that may produce objectionable and perhaps dangerous levels of noise and vibration.

40. The SAF stilling basin, an impact-type basin utilizing chute blocks, baffle piers, and an end sill on a relatively short horizontal apron, is an effective energy dissipator and particularly suited for drainage structures or outlet works with velocities and Froude numbers less than 60 fps and 4.5, respectively. The chute blocks and baffle piers positioned on the toe of the trajectory and in the upper third of the basin, respectively, are effective means of stabilizing hydraulic jumps of the oscillating type. Guidance relative to the width of this type of basin in terms of the diameter of the outlet conduit for various discharges is presented in WES Research Report H-71-1.*

41. The effectiveness of providing both vertical and lateral expansion of the exit area immediately downstream of an energy dissipator

* J. L. Grace, Jr., and G. A. Pickering, "Evaluation of Three Energy Dissipators for Storm-Drain Outlets; Hydraulic Laboratory Investigation," Research Report H-71-1, Apr 1971, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

was demonstrated during tests of the Branched Oak outlet works. Protective stone (50 lb maximum) remained stable in the recommended exit channel configuration where 400-lb stone was failed in an exit channel plan that provided no vertical or lateral expansion. The expansion permits dissipation of the excess energy of the flow from an energy dissipator of practical design in turbulence rather than in direct attack of the channel boundaries. Provision of such expansions makes it possible to stabilize the channel with rock of an economical size and provide factors of safety against riprap failure and costly maintenance.

Table 1

Pressures in Branched Oak Outlet Works Intake Structure and Elbow, Discharges 400 to 1240 cfs

Piezometer		Pressures in Prototype Feet of Water					
No.	El	Discharge 1240 cfs Pool El 1299.5	Discharge 1085 cfs Pool El 1288.6	Discharge 1000 cfs Pool El 1288.2	Discharge 800 cfs Pool El 1287.8	Discharge 600 cfs Pool El 1287.6	Discharge 400 cfs Pool El 1287.0
1	1287.5	10.9	0.0	0.0	*	*	*
2	1287.5	9.8	-0.2	-0.5	*	*	*
3	1287.5	9.2	-0.7	-1.0	*	*	*
4	1287.5	10.8	0.3	-0.5	*	*	*
5	1287.5	9.3	-0.7	-0.8	*	*	*
6	1287.5	10.1	0.0	-0.5	*	*	*
7	1287.5	9.8	0.0	0.0	*	*	*
8	1279.0	10.0	9.0	9.0	9.0	8.5	8.5
9	1281.0	8.0	7.0	7.0	7.0	6.5	6.0
10	1283.0	15.7	4.5	4.3	4.5	4.5	3.8
11	1283.8	10.2	0.2	0.2	1.2	2.2	2.2
12	1283.9	10.6	-7.4	-7.4	-4.4	-1.4	0.1
13	1284.0	3.0	-4.0	-4.0	-1.5	0.0	0.5
14	1284.0	5.0	-3.5	-2.0	0.0	1.5	0.7
15	1284.0	4.5	-3.5	-2.5	-2.0	-1.0	0.0
16	1283.9	0.1	-6.4	-4.9	-4.4	-3.4	-3.9
17	1283.8	1.2	-4.8	-4.8	-4.8	-3.5	-2.8
18	1283.0	3.0	-4.0	-4.0	-4.0	-3.0	-3.0
19	1281.0	7.0	-2.0	-3.0	-4.0	-2.5	-2.0
20	1299.0	11.0	2.0	1.0	-3.5	-2.5	-7.5
21	1277.0	14.0	5.0	2.0	-3.5	-3.0	-6.0
22	1275.0	16.3	7.5	5.0	-3.0	-3.0	-2.0
23	1271.0	20.5	11.8	9.5	0.5	-3.0	-0.5
24	1269.0	22.6	13.8	11.5	3.0	-3.0	-1.0
25	1266.0	28.0	18.5	16.0	8.0	*	*
26	1266.0	27.5	18.0	16.0	8.5	*	*
27	1266.0	26.5	17.0	15.0	7.5	*	*
28	1266.0	25.5	15.8	13.5	7.0	*	*
29	1266.0	19.5	12.0	10.0	4.5	*	*
30	1265.0	29.0	20.0	17.0	9.0	*	*
31	1265.0	15.0	8.0	7.0	4.0	*	*
32	1264.0	30.5	21.0	18.0	10.0	*	*
33	1264.0	30.0	20.5	18.0	10.5	*	*
34	1264.0	29.0	19.5	17.5	10.0	*	*
35	1264.0	26.5	17.5	15.5	8.0	*	*
36	1264.0	14.0	8.0	7.0	5.0	*	*
37	1263.0	31.5	22.0	19.0	12.0	*	*
38	1263.0	14.0	8.0	7.0	6.0	*	*
39	1262.0	33.0	23.0	20.0	13.5	*	*
40	1262.0	32.0	22.5	20.0	13.5	*	*
41	1262.0	31.0	22.0	19.5	13.0	*	*
42	1262.0	29.0	20.0	18.0	11.0	*	*
43	1262.0	24.0	16.5	14.5	8.0	*	*
44	1262.0	20.0	13.0	12.0	8.0	*	*
44-A	1262.0	19.0	12.0	10.0	8.0	*	*
45	1260.8	22.2	14.2	12.7	7.2	*	*
46	1259.6	9.4	5.4	5.4	3.4	*	*
47	1260.0	35.0	25.5	22.5	16.5	*	*
48	1260.0	34.0	24.5	21.5	15.5	5.5	0.5
49	1260.0	32.0	23.0	20.5	14.0	4.0	0.5
50	1260.0	28.5	20.0	18.0	12.0	4.0	0.5
51	1260.0	25.5	17.5	15.5	9.0	4.0	1.5
52	1261.0	24.0	16.0	15.0	8.0	4.5	5.5
53	1260.2	22.8	15.3	14.8	8.8	4.8	2.8
54	1259.2	19.3	13.3	12.8	9.8	5.3	1.3
55	1258.0	37.0	27.5	24.5	19.0	6.5	12.0
56	1258.0	36.0	27.0	24.0	18.0	11.5	10.5
57	1258.0	35.5	25.5	23.0	17.0	8.5	1.0
58	1258.0	32.0	23.0	21.0	15.0	6.0	1.0
59	1258.0	29.0	20.5	19.0	12.0	5.0	2.0
60	1258.0	24.0	17.5	16.0	10.0	5.5	1.0
61	1258.0	15.5	10.0	9.5	6.5	4.0	15.0
62	1256.0	39.0	29.5	26.0	21.0	10.0	6.5
63	1256.0	37.5	28.0	25.5	19.5	14.0	2.0
64	1256.0	35.0	26.0	24.0	17.5	9.0	3.0
65	1256.0	31.5	24.0	21.5	15.5	7.0	3.0
66	1256.0	27.0	19.5	8.5	12.5	7.0	5.0
67	1256.0	16.0	11.5	11.0	8.0	5.0	11.5
68	1254.0	38.5	29.0	27.0	20.5	14.0	4.5
69	1253.9	34.6	26.6	24.1	17.6	9.6	4.6
70	1253.7	29.3	22.3	20.8	14.8	8.3	4.8
71	1253.5	20.0	15.5	14.5	10.5	7.5	5.0
72	1259.5	1.0	0.5	1.5	1.5	1.5	*
73	1258.0	3.0	2.0	2.5	3.0	3.0	0.3
74	1256.5	11.5	8.0	8.0	5.0	3.5	3.5
75	1253.5	17.0	12.5	12.5	8.5	6.5	6.5

Note: Piezometer locations are shown in plate 6. Elevations are in feet referred to mean sea level.
* Air entrained in piezometer opening.

Table 2

Pressures in Branched Oak Outlet Works Circular Conduit, Discharges 400 to 1240 cfs

Piezometer		Pressures in Prototype Feet of Water					
No.	El	Discharge 1240 cfs Pool El 1299.5	Discharge 1085 cfs Pool El 1288.6	Discharge 1000 cfs Pool El 1288.2	Discharge 800 cfs Pool El 1287.8	Discharge 600 cfs Pool El 1287.6	Discharge 400 cfs Pool El 1287.0
76	1259.5	3.5	2.0	2.5	2.0	1.5	-0.2
77	1259.4	7.6	4.6	4.6	3.1	2.1	-1.1
78	1257.9	8.6	5.1	5.1	4.6	3.9	0.3
79	1256.4	10.6	7.6	7.6	5.1	3.1	2.1
80	1253.4	14.6	10.6	10.6	8.1	5.6	4.6
81	1257.5	7.5	4.5	5.5	2.5	1.5	0.4
82	1256.0	9.0	6.0	7.0	4.0	2.5	1.0
83	1253.0	12.0	9.0	8.5	6.5	5.0	4.5
84	1255.6	7.9	5.4	5.4	3.4	1.9	0.4
85	1252.6	11.4	8.4	8.4	5.9	4.7	3.4
86	1255.1	7.9	5.4	5.4	2.9	1.9	0.4
87	1252.1	11.4	8.4	8.9	6.0	4.9	3.4
88	1254.6	7.4	4.4	5.4	2.9	1.9	0.4
89	1251.6	10.9	7.4	8.4	5.4	4.7	3.8
90	1254.2	5.4	2.9	4.4	1.9	1.5	0.6
91	1251.2	9.4	7.4	7.4	5.9	4.9	3.6
92	1253.7	6.4	4.4	4.4	2.9	1.9	0.4
93	1250.7	9.4	7.4	7.4	5.4	4.9	3.4
94	1253.3	5.8	3.8	4.3	2.3	1.8	0.3
95	1250.3	8.8	6.8	7.3	5.3	4.8	3.3
96	1252.8	5.3	3.8	4.3	2.3	1.8	0.3
97	1249.8	8.3	6.8	7.3	5.3	4.8	3.3
98	1252.3	5.2	3.7	4.2	2.2	1.7	0.2
99	1249.3	8.2	6.7	7.2	5.2	1.7	3.2
100	1251.9	4.6	3.2	4.2	1.7	1.2	0.2
101	1248.9	8.0	6.2	7.2	5.2	4.2	3.2
102	1251.4	4.1	2.6	3.6	1.9	0.9	0.1
103	1248.4	7.1	6.1	6.6	4.9	4.1	2.9
104	1250.9	4.3	3.0	3.5	2.0	0.5	*
105	1247.9	6.5	5.5	6.0	5.0	4.0	2.8
106	1250.5	3.8	2.5	3.0	2.0	1.0	*
107	1247.5	6.5	5.2	6.0	5.0	3.9	3.0
108	1250.0	3.4	2.4	3.4	1.9	4.8	*
109	1247.0	6.4	5.4	6.4	4.9	4.1	3.4
110	1249.6	2.5	2.0	3.5	2.0	1.2	*
111	1246.6	7.0	6.0	6.5	5.5	4.8	3.8
112	1249.1	3.4	2.4	3.4	2.4	1.7	*
113	1246.1	5.4	4.9	5.9	5.2	4.3	3.4
114	1248.6	1.9	1.7	2.9	2.1	1.4	*
115	1245.6	4.4	4.4	5.4	4.9	3.9	2.4
116	1248.2	1.8	1.3	0.8	2.3	0.8	*
117	1245.2	1.8	1.8	2.8	2.8	3.5	2.5
118	1247.8	0.0	0.1	0.1	1.1	1.1	*
119	1244.8	5.1	6.1	5.1	5.1	4.1	5.1

Note: Piezometer locations are shown in plate 7. Elevations are in feet referred to mean sea level.
* Piezometer opening above water surface.

Table 3

Pressures in Branched Oak Outlet Works Intake Structure and Elbow, Discharges 1300 to 1535 cfs

Piezometer		Pressures in Prototype Feet of Water			
No.	El	Discharge 1535 cfs Pool El 1338.5	Discharge 1500 cfs Pool El 1330.8	Discharge 1400 cfs Pool El 1317.5	Discharge 1300 cfs Pool El 1305.5
1	1287.5	47.0	39.5	26.5	15.5
2	1287.5	48.5	39.8	26.5	16.0
3	1287.5	46.5	39.3	26.2	15.0
4	1287.5	49.0	40.5	26.5	16.3
5	1287.5	47.0	39.5	27.5	15.5
6	1287.5	47.5	40.5	26.5	16.0
7	1287.5	47.0	39.5	26.5	15.5
8	1279.0	59.5	29.8	35.5	26.5
9	1281.0	57.5	49.8	33.5	24.5
10	1283.0	53.5	46.0	32.5	21.0
11	1283.8	50.0	37.4	25.7	15.0
12	1283.9	30.6	23.1	13.1	4.9
13	1284.0	33.0	27.8	16.0	8.5
14	1284.0	38.0	30.5	19.5	13.0
15	1284.0	34.5	30.0	17.8	10.5
16	1283.9	26.6	11.6	13.1	4.6
17	1283.8	29.7	25.2	14.7	5.9
18	1283.0	32.0	26.0	15.7	6.0
19	1281.0	35.5	29.5	21.0	10.5
20	1279.0	41.8	35.0	22.5	16.0
21	1277.0	47.0	30.0	28.5	19.0
22	1275.0	49.0	43.5	30.7	21.5
23	1271.0	53.5	36.8	25.3	25.5
24	1269.0	55.0	49.0	37.3	27.5
25	1266.0	62.5	55.7	33.3	33.0
26	1266.0	61.5	54.8	42.5	32.5
27	1266.0	59.5	53.0	41.3	31.5
28	1266.0	56.5	50.1	38.7	29.5
29	1266.0	48.0	42.7	32.5	24.0
30	1265.0	64.0	57.0	44.3	34.5
31	1265.0	40.0	34.5	25.5	19.0
32	1264.0	65.5	58.0	35.7	35.5
33	1264.0	64.5	57.6	35.0	35.0
34	1264.0	62.5	56.0	45.0	33.5
35	1264.0	58.5	52.0	40.5	31.0
36	1264.0	37.5	32.8	24.5	17.5
37	1263.0	68.0	59.8	47.3	37.0
38	1263.0	36.0	31.0	22.7	16.5
39	1262.0	68.0	60.5	48.3	38.0
40	1262.0	67.5	60.5	47.5	37.5
41	1262.0	66.0	59.0	46.7	36.5
42	1262.0	61.5	45.5	43.7	34.0
43	1262.0	52.5	46.5	36.5	28.5
44	1262.0	45.5	41.0	30.8	24.0
44-A	1262.0	42.0	38.7	27.3	22.0
45	1260.8	47.7	42.5	33.5	26.2
46	1259.6	23.9	21.4	15.8	11.9
47	1260.0	70.0	63.5	50.3	40.0
48	1260.0	63.5	61.3	48.8	39.0
49	1260.0	65.0	58.5	46.5	36.5
50	1260.0	59.5	43.0	46.8	28.0
51	1260.0	53.0	46.0	37.3	29.5
52	1261.0	50.5	46.0	35.3	27.5
53	1260.2	48.3	43.3	34.1	26.3
54	1259.2	40.8	36.5	29.6	22.3
55	1258.0	72.0	65.8	51.4	42.5
56	1258.0	70.5	64.0	50.5	41.5
57	1258.0	68.5	61.7	49.6	39.5
58	1258.0	64.5	57.8	46.0	36.5
59	1258.0	58.5	51.7	41.7	33.5
60	1258.0	49.5	44.8	40.3	26.8
61	1258.0	32.8	30.0	22.5	17.5
62	1258.0	73.5	67.0	54.5	44.5
63	1258.0	71.5	65.0	52.8	42.5
64	1258.0	68.0	61.0	49.5	39.5
65	1258.0	62.5	56.0	45.0	36.5
66	1256.0	52.0	47.0	38.5	30.5
67	1256.0	33.0	30.0	38.5	18.5
68	1254.0	70.5	64.5	52.0	43.0
69	1253.9	64.6	59.1	48.1	38.9
70	1253.7	54.3	49.3	40.6	32.8
71	1253.5	38.5	34.8	27.9	22.9
72	1259.5	9.5	7.8	5.5	3.0
73	1258.0	11.5	10.0	7.0	3.5
74	1256.5	26.0	23.0	18.1	14.1
75	1253.5	32.5	29.5	23.8	19.5

Note: Piezometer locations are shown in plate 6. Elevations are in feet referred to mean sea level.

Table 4

Pressures in Branched Oak Outlet Works Circular Conduit

Discharges 1300 to 1535 cfs

Piezometer No.	Piezometer El	Pressures in Prototype Feet of Water: Discharge 1535 cfs Pool El 1338.5	Discharge 1500 cfs Pool El 1330.8	Discharge 1400 cfs Pool El 1317.5	Discharge 1300 cfs Pool El 1305.5
76	1259.5	12.0	11.0	8.0	4.3
77	1259.4	20.1	16.4	12.6	8.6
78	1257.9	21.1	18.6	13.8	10.1
79	1256.4	24.1	21.6	16.9	12.6
80	1253.4	28.1	25.6	20.7	16.1
81	1257.5	21.0	16.5	12.3	9.0
82	1256.0	20.5	18.5	14.3	10.8
83	1253.0	23.0	21.0	17.3	14.0
84	1255.6	18.4	16.4	12.7	9.4
85	1252.6	21.4	19.4	12.7	12.7
86	1255.1	17.4	15.9	12.5	9.4
87	1252.1	20.9	16.4	15.5	12.7
88	1254.6	15.9	14.4	11.0	8.4
89	1251.6	18.4	17.0	13.8	10.9
90	1254.2	12.4	11.9	8.4	6.4
91	1251.2	16.9	11.9	13.1	10.9
92	1253.7	14.4	12.4	9.7	7.8
93	1250.7	18.4	13.4	12.6	10.4
94	1253.3	12.3	11.4	8.5	6.3
95	1250.3	15.3	10.9	11.5	9.3
96	1252.8	11.8	10.3	8.1	6.3
97	1249.8	15.3	13.8	11.5	9.5
98	1252.3	11.7	10.5	8.2	6.3
99	1249.3	14.7	12.2	10.9	9.2
100	1251.9	9.6	8.3	6.4	1.1
101	1248.9	13.6	12.8	10.2	8.6
102	1251.4	9.0	7.8	6.0	4.9
103	1248.4	12.2	11.5	9.1	8.1
104	1250.9	9.0	8.0	6.0	4.8
105	1247.9	11.4	10.0	8.5	7.5
106	1250.5	7.3	7.0	5.0	4.0
107	1247.5	10.0	9.0	7.9	7.0
108	1250.0	6.4	5.4	4.4	3.5
109	1247.0	9.6	8.4	7.5	6.6
110	1249.6	4.9	4.0	3.5	3.0
111	1246.6	7.9	7.0	6.3	6.0
112	1249.1	6.1	5.2	4.4	3.7
113	1246.1	7.4	6.9	6.8	5.7
114	1248.6	2.7	2.3	2.1	1.8
115	1245.6	5.9	5.3	5.1	4.8
116	1248.2	2.0	1.8	1.6	1.4
117	1245.2	3.9	3.3	3.3	1.8
118	1247.8	1.5	1.3	1.1	1.1
119	1244.8	7.6	6.1	6.1	5.9

Note: Piezometer locations are shown in plate 7. Elevations are in feet referred to mean sea level.

Table 5

Pressures In Branched Oak Outlet Works Intake Structure and Elbow with Trashracks and Cover Plate Removed

Piezometer No.	Piezometer El	Pressures in Prototype Feet of Water: Discharge 1500 cfs Pool El 1325.0	Discharge 1240 cfs Pool El 1298.0	Discharge 1150 cfs Pool El 1291.45	Discharge 1070 cfs Pool El 1289.5	Discharge 800 cfs Pool El 1288.5	Discharge 600 cfs Pool El 1287.8	Discharge 300 cfs Pool El 1286.55
A	1278.0	36.0	13.7	9.5	3.0	-4.5	-1.5	0.5
B	1276.0	39.0	16.0	12.0	6.0	-3.0	-1.0	0.0
C	1276.0	39.0	16.5	12.0	6.0	-3.0	-1.0	0.0
D	1276.0	39.0	16.5	12.0	6.0	-3.0	-1.0	0.0
8	1279.0	46.0	19.0	12.5	10.4	9.5	8.5	7.7
9	1281.0	44.0	17.0	10.5	8.4	7.5	6.5	5.7
10	1283.0	42.0	15.0	8.3	6.0	5.0	4.5	3.6
11	1283.8	39.7	13.7	6.2	2.7	2.2	2.7	2.2
12	1283.9	38.1	11.5	3.1	-2.4	-2.9	-0.4	0.6
13	1284.0	37.0	11.0	4.0	0.0	0.5	0.5	0.8
14	1284.0	38.0	12.8	5.5	1.0	0.0	1.5	1.7
15	1284.0	30.0	7.0	0.5	-2.0	-1.5	-0.5	0.5
16	1283.9	23.1	0.4	-4.9	-5.9	-3.4	-4.9	-3.9
17	1283.8	25.2	3.5	-2.8	-5.8	-3.8	-3.8	-2.5
18	1283.0	26.0	4.5	-2.0	-5.0	-3.5	-3.5	-2.3
19	1281.0	28.0	8.5	2.0	-3.0	-3.5	-2.5	-1.5
20	1279.0	34.5	13.0	6.0	0.0	-3.0	-2.0	-2.0
21	1277.0	38.0	15.0	9.5	5.0	-3.0	-1.5	-1.0
22	1275.0	40.0	17.0	11.5	7.0	-3.0	-2.0	-1.5
23	1271.0	43.5	21.0	15.0	11.0	1.0	-1.0	0.0
24	1269.0	45.5	23.0	17.0	13.0	5.0	-2.0	0.0
25	1266.0	52.0	28.3	21.0	18.0	8.0	*	*
26	1266.0	51.5	28.0	21.0	7.0	8.5	*	*
27	1266.0	50.0	26.8	20.0	6.5	7.5	*	*
28	1266.0	47.0	24.5	18.5	5.5	7.0	*	*
29	1266.0	39.0	20.0	14.0	12.0	5.0	*	*
30	1265.0	53.0	29.0	22.5	19.0	9.0	*	*
31	1265.0	31.0	14.5	9.0	8.5	4.0	*	*
32	1264.0	55.0	30.5	23.5	20.0	8.0	*	*
33	1264.0	54.0	30.0	23.5	20.0	11.0	*	*
34	1264.0	52.5	29.0	22.5	19.0	10.5	*	*
35	1264.0	49.0	27.0	20.0	17.5	9.5	*	*
36	1264.0	29.0	13.5	8.0	8.0	6.5	*	*
37	1263.0	55.5	31.5	25.0	21.0	12.5	*	*
38	1263.0	28.0	12.5	7.5	7.5	7.0	*	*
39	1262.0	57.0	33.0	26.0	22.0	14.0	*	*
40	1262.0	56.5	32.5	26.5	22.0	13.5	*	*
41	1262.0	55.5	31.5	24.5	21.5	13.0	*	*
42	1262.0	52.5	29.0	22.5	19.5	12.0	*	*
43	1262.0	44.0	23.5	18.5	16.0	9.0	*	*
44	1262.0	37.5	20.0	13.5	13.0	8.0	*	*
44-A	1262.0	35.5	18.0	12.0	12.0	8.0	*	*
45	1260.8	41.7	22.7	11.2	14.7	9.0	*	*
46	1259.6	21.4	9.4	4.9	6.4	2.4	*	*
47	1260.0	59.5	35.0	28.5	24.5	15.5	*	*
48	1260.0	58.0	34.0	27.5	24.0	15.5	2.5	*
49	1260.0	55.5	32.5	25.5	22.0	14.5	2.5	*
50	1260.0	50.0	29.0	22.5	20.7	12.0	2.5	*
51	1260.0	44.0	25.5	20.0	16.0	9.5	3.0	*
52	1261.0	43.5	24.0	18.0	15.0	8.0	4.0	*
53	1260.2	40.8	22.8	17.3	15.8	8.8	4.1	*
54	1259.2	39.8	19.3	13.8	13.8	8.8	3.3	*
55	1258.0	61.5	37.0	30.0	26.5	19.0	13.0	6.0
56	1258.0	60.5	36.5	30.5	25.5	19.0	7.0	2.5
57	1258.0	58.5	35.5	28.5	25.0	18.5	5.0	2.0
58	1258.0	54.5	33.0	27.5	23.0	15.0	4.0	1.0
59	1258.0	49.5	29.0	24.5	28.5	12.5	4.0	*
60	1258.0	42.0	25.0	20.0	25.5	10.0	3.0	*
61	1258.0	28.0	15.0	11.0	10.5	7.0	14.0	*
62	1256.0	63.5	39.0	33.0	28.0	22.0	15.0	*
63	1256.0	62.0	38.0	32.0	27.0	19.5	10.5	5.5
64	1256.0	58.5	36.0	29.0	25.5	17.0	5.0	2.5
65	1256.0	53.5	42.5	26.0	23.5	15.0	5.0	1.0
66	1256.0	44.0	27.5	22.0	19.5	12.0	5.0	1.0
67	1256.0	29.0	16.5	12.5	12.0	8.0	5.0	1.0
68	1254.0	62.0	39.0	32.5	28.0	21.0	12.0	7.5
69	1253.9	56.6	35.1	29.6	25.6	18.1	7.1	2.1
70	1253.7	47.3	29.8	24.3	22.3	14.8	7.3	2.3
71	1253.5	36.5	20.5	16.0	15.5	10.5	6.5	2.8
72	1259.5	8.5	1.5	0.5	1.0	1.5	0.0	*
73	1258.0	10.0	3.0	2.0	2.8	3.0	1.5	2.5
74	1256.5	22.0	12.0	10.5	9.0	6.0	2.8	0.5
75	1253.5	28.5	17.5	15.0	13.0	9.0	5.8	2.5

Note: Piezometer locations are shown in plate 6. Elevations are in feet referred to mean sea level.
* Air entrained in piezometer opening.

Table 6

Hydraulic Gradient Elevations in Branched Oak Outlet Works Circular Conduit with Trashracks and Cover Plate Removed

Piezometer		Hydraulic Gradient Elevations in Prototype Feet Referred to Mean Sea Level						
No.	El	Discharge 1500 cfs Pool El 1325.0	Discharge 1240 cfs Pool El 1298.0	Discharge 1150 cfs Pool El 1291.45	Discharge 1070 cfs Pool El 1289.5	Discharge 800 cfs Pool El 1288.5	Discharge 600 cfs Pool El 1287.8	Discharge 300 cfs Pool El 1286.55
76	1259.5	1271.0	1263.5	1261.5	1262.0	1261.5	1260.5	1260.3
77	1259.4	1276.0	1267.0	1265.0	1264.0	1262.0	1261.5	1260.8
78	1257.9	1275.5	1266.5	1265.0	1264.0	1263.0	1259.5	1260.0
79	1256.4	1277.0	1267.5	1265.8	1265.0	1261.5	1259.0	1257.0
80	1253.4	1278.0	1268.5	1266.5	1265.3	1261.5	1258.5	1256.0
81	1257.5	1273.5	1265.0	1264.0	1262.5	1260.0	1258.5	1258.5
82	1256.0	1273.5	1265.5	1264.0	1262.5	1260.0	1258.3	*
83	1253.0	1273.5	1265.5	1264.0	1262.5	1260.0	1258.0	1256.0
84	1255.6	1271.0	1264.0	1262.5	1261.5	1259.0	1257.5	*
85	1252.6	1271.5	1264.0	1262.5	1261.5	1259.0	1257.0	1255.5
86	1255.1	1270.0	1263.5	1262.0	1261.0	1258.0	1256.5	*
87	1252.1	1270.5	1263.8	1262.0	1261.0	1258.5	1256.5	1255.3
88	1254.6	1268.5	1262.0	1260.5	1260.0	1257.5	1256.0	*
89	1251.6	1268.0	1261.5	1260.5	1259.5	1257.5	1256.0	1254.5
90	1254.2	1265.0	1259.5	1258.5	1258.5	1256.5	1255.5	*
91	1251.2	1266.5	1260.5	1259.5	1259.0	1257.0	1255.5	1254.3
92	1253.7	1265.5	1260.0	1259.0	1259.0	1256.0	1255.2	*
93	1250.7	1265.5	1260.0	1259.0	1258.5	1256.0	1255.2	1253.8
94	1253.3	1263.5	1259.0	1258.0	1258.0	1255.5	1254.4	*
95	1250.3	1263.5	1259.0	1258.0	1258.0	1255.5	1254.4	1253.2
96	1252.8	1263.0	1258.3	1257.5	1257.5	1255.0	1254.0	*
97	1249.8	1263.0	1258.3	1257.5	1257.5	1255.0	1254.0	1252.5
98	1252.3	1262.5	1257.8	1257.0	1257.0	1254.5	1253.5	*
99	1249.3	1262.0	1257.6	1257.0	1257.0	1254.5	1253.3	1252.3
100	1251.9	1260.0	1256.5	1255.5	1256.0	1254.0	1252.8	*
101	1248.9	1260.5	1256.5	1256.0	1256.0	1254.0	1252.8	1251.6
102	1251.4	1259.0	1255.5	1255.0	1255.0	1253.5	1252.3	*
103	1248.4	1258.5	1255.3	1254.7	1255.0	1253.0	1252.3	1251.2
104	1250.9	1258.5	1255.3	1254.7	1254.8	1253.0	1251.9	*
105	1247.9	1258.0	1254.7	1254.3	1254.5	1252.5	1251.7	1250.5
106	1250.5	1257.0	1254.3	1253.8	1254.0	1252.5	1251.4	*
107	1247.5	1257.0	1254.2	1253.5	1254.0	1252.5	1251.2	1250.0
108	1250.0	1255.5	1253.3	1252.5	1253.0	1252.5	1250.8	*
109	1247.0	1255.5	1253.3	1252.5	1253.0	1252.0	1250.7	1249.5
110	1249.6	1254.0	1252.5	1252.0	1252.8	1251.5	1250.3	*
111	1246.6	1254.0	1252.5	1252.0	1252.8	1251.5	1250.3	1249.3
112	1249.1	1254.5	1252.5	1252.0	1252.5	1251.5	1250.3	*
113	1246.1	1252.8	1251.5	1251.3	1252.0	1251.0	1250.0	1249.0
114	1248.6	1252.8	1250.0	1250.0	1251.0	1250.5	1249.5	*
115	1245.6	1251.0	1250.3	1250.0	1251.0	1250.5	1249.5	1248.5
116	1245.2	1249.0	1249.5	1248.0	1250.0	1249.5	1248.5	*
117	1245.2	1249.0	1249.5	1248.0	1250.0	1249.5	1248.5	1248.0
118	1247.8	1249.0	1248.0	1248.0	1249.0	1249.0	1248.5	*
119	1244.8	1250.0	1249.5	1249.5	1251.0	1250.0	1248.5	1248.5

Note: Piezometer locations are shown in plate 7.
* Piezometer opening above water surface.

Table 7

Total Head Loss in Branched Oak Original

Design Intake Structure

Discharge cfs	Pool El	Energy Gradient El*	Head Loss Feet of Water, H_e	Loss Coefficient**
1225	1299.5	1294.5	5.0	0.172
1290	1305.5	1299.8	5.7	0.177
1420	1317.5	1309.5	8.0	0.204
1550	1330.8	1321.5	9.3	0.200
1625	1338.5	1328.8	9.7	0.189
			Average	0.188

Note: Elevations are in feet referred to mean sea level.

* Determined from hydraulic gradients based on piezometers 100-109 extended to sta 1+63.25 U.S.

** Loss coefficient = $H_e / \frac{V^2}{2g}$ where H_e is head loss in feet and $\frac{V^2}{2g}$ is velocity head in feet within the tunnel.

Table 8

Separate and Total Losses in Branched Oak Original Design Intake Structure

Discharge cfs	Pool El	Energy Gradient El* at Sta 1+63.25 U.S.	Energy Gradient El** at Sta 1+43.25 U.S.	H_c	H_t	H_e	K'_c	K_c	K_t	K_e
1150	1293.5	1290.0	1288.3	3.5	1.7	5.2	0.882	0.137	0.067	0.204
1205	1298.2	1294.3	1292.6	3.7	1.9	5.6	0.850	0.132	0.068	0.200
1360	1311.3	1306.5	1304.1	4.8	2.4	7.2	0.865	0.133	0.067	0.200
1520	1326.7	1320.4	1317.3	6.3	3.1	9.4	0.910	0.140	0.069	0.209
					Average		0.877	0.135	0.068	0.203

Note: Elevations are in feet referred to mean sea level.

$H_e = K_e V^2/2g$ = total entrance loss in feet where V is the velocity in the conduit.

$H_c = K'_c V_r^2/2g$ or $K_c V^2/2g$ = loss in feet from the water surface to el 1276.0 in riser shaft where V_r is the velocity in the riser shaft.

$H_t = K_t V^2/2g$ = loss in feet from el 1276.0 in riser shaft to just inside the conduit entrance.

$H_e = H_c + H_t$

* Determined from hydraulic gradients based on piezometers located in shaft at sta 1+63.25 and el 1276.0.

** Determined from hydraulic gradients based on piezometers 100-109 extended to sta 1+43.23 U.S.

Table 9

Separate and Total Losses in Cottonwood Springs Intake Structure

Compound Curve Crests and Lengths = 3D

Discharge cfs	Pool El	Energy Gradient El at Conduit Entrance	Energy Gradient El* at CL of Shaft	H_c	H_t	H_e	K_c	K_t	K_e
	Divider Wall = 5.0 ft, f_p (Tunnel) = 0.0085 , Cover Plate = 3.0 ft								
580	3905.20	3902.10**	3904.88	0.32	2.78	3.10	0.0096	0.083	0.093
	Divider Wall = 4.5 ft, f_p (Tunnel) = 0.0150 , Cover Plate = 2.5 ft								
430	3894.50	3892.50†	3894.25	0.25	1.75	2.00	0.0137	0.096	0.110

Note: Elevations are in feet referred to mean sea level.

$H_e = K_e V^2/2g$ = total entrance loss in feet where V is the velocity in the conduit.

$H_c = K_c V^2/2g$ = loss in feet from the upper pool to energy gradient in riser shaft.

$H_t = K_t V^2/2g$ = loss in feet from energy gradient in riser shaft to just inside the conduit entrance.

$H_e = H_c + H_t$

* Determined from hydraulic gradients based on piezometers in shaft (19-20) at el 3858.0

** Determined from hydraulic gradients based on piezometers 55-64 extended to conduit entrance.

† Determined from hydraulic gradients based on piezometers 55-72 extended to conduit entrance.

Table 10

Pressures in Cottonwood Springs Outlet Works Intake Structure, Elbow, and Smooth Tunnel (f_p = 0.0085); Compound Curve Crests with Lengths = 2D (D = 4.0 ft), 6.0-ft Divider Wall, and 4.0-ft Cover Plate

Piezometer No.	Piezometer El	Pressures in Prototype Feet of Water	Piezometer No.	Piezometer El	Pressures in Prototype Feet of Water
1	3879.00	32.9	41	3836.00	41.6
2	3879.00	31.7	42	3835.90	36.2
3	3879.00	32.2	43	3835.79	30.8
4	3879.00	31.4	44	3835.69	31.8
5	3879.00	31.5	45	3835.58	31.8
6	3874.50	30.0	46	3835.48	30.8
7	3875.00	19.8	47	3835.37	29.8
8	3874.93	24.3	48	3835.27	28.1
9	3874.69	23.5	49	3835.16	28.5
10	3874.15	22.1	50	3835.06	26.7
11	3873.65	20.2	51	3834.95	24.6
12	3873.25	22.2	52	3834.85	25.3
13	3871.50	28.7	53	3834.74	24.3
14	3869.00	31.1	54	3834.64	22.6
15	3865.00	35.1	55	3834.53	21.2
16	3867.00	33.2	56	3834.43	20.6
17	3862.00	38.1	57	3834.32	19.5
18	3862.00	38.0	58	3834.22	19.5
19	3858.00	41.9	59	3834.11	18.3
20	3858.00	41.9	60	3834.01	17.5
21	3853.00	46.9	61	3833.90	16.8
22	3853.00	47.0	62	3833.79	16.0
23	3847.50	52.7	63	3833.69	14.5
24	3847.50	52.6	64	3833.58	14.0
25	3846.00	53.9	65	3833.48	14.0
26	3846.00	52.8	66	3833.37	12.9
27	3844.50	53.3	67	3833.27	11.8
28	3844.50	49.4	68	3833.16	10.8
29	3844.00	43.4	69	3833.06	10.1
30	3844.00	41.0	70	3832.95	9.5
31	3843.26	40.8	71	3832.85	8.2
32	3842.62	43.4	72	3832.74	7.6
33	3842.07	42.8	73	3832.64	6.9
34	3841.36	41.2	74	3832.53	6.2
35	3840.13	39.5	75	3832.43	5.4
36	3840.00	38.3	76	3832.32	4.0
37	3838.00	42.9	77	3832.22	3.0
38	3836.00	45.0			
39	3840.00				
40	3838.00	39.7			

Note: Elevations are in feet referred to mean sea level. Discharge 570 cfs, pool el 3905.54.

Table 11

Separate and Total Losses in Cottonwood Springs Intake Structure

Crest Length = 2D , f_p (Tunnel) = 0.0085

Discharge cfs	Pool El	Energy Gradient El* at Conduit Entrance	Energy Gradient El** at CL of Shaft	H_c	H_t	H_e	K_c	K_t	K_e
			Compound Curve Crest Shape, No Cover Plate						
498	3891.66	3886.11	3891.06	0.60	4.95	5.55	0.025	0.203	0.228
			Compound Curve Crest Shape, Cover Plate = 4.0 ft, Divider Wall = 6.0 ft						
570	3905.54	3898.77	3904.83	0.71	6.06	6.77	0.022	0.189	0.211
			SAF Crest Shape, No Cover Plate						
527	2896.70	3891.24	3896.21	0.49	4.97	5.46	0.018	0.182	0.200
			SAF Crest Shape, Cover Plate = 4.0 ft, Divider Wall = 5.0 ft						
575	3906.00	3899.84	3905.07	0.93	5.23	6.16	0.029	0.161	0.190

Note: Elevations are in feet referred to mean sea level.

$H_e = K_e V^2/2g$ = total entrance loss in feet where V is the velocity in the conduit.

$H_c = K_c V^2/2g$ = loss in feet from the upper pool to energy gradient in riser shaft.

$H_t = K_t V^2/2g$ = loss in feet from the energy gradient in riser shaft to the conduit entrance.

$H_e = H_c + H_t$

* Determined from hydraulic gradients based on piezometers 55-64 extended to conduit entrance.
** Determined from hydraulic gradients based on piezometers in shaft (19-20) at el 3858.0.

Table 12

Separate and Total Losses in Cottonwood Springs Intake Structure

Crest Length = 2D , f_p (Tunnel) = 0.015

Discharge cfs	Pool El	Energy Gradient El* at Piezometer No. 42	Energy Gradient El** at CL of Shaft	H_c	H_t	H_e	K_c	K_t	K_e
			Compound Curve Crest Shape, No Cover Plate						
440	3899.56	3894.80	3898.95	0.61	4.15	4.76	0.032	0.218	0.250
			Compound Curve Crest Shape, Cover Plate = 3.5 ft, Divider Wall = 5.5 ft						
430	3896.25	3891.97	3895.80	0.45	3.83	4.28	0.025	0.211	0.236
			SAF Crest Shape, No Cover Plate						
418	3892.15	3887.95	3891.75	0.40	3.80	4.20	0.023	0.221	0.244
			SAF Crest Shape, Cover Plate = 3.5 ft, Divider Wall = 4.5 ft						
415	3892.00	3887.90	3891.65	0.35	3.75	4.10	0.021	0.222	0.243

Note: Elevations are in feet referred to mean sea level.

$H_e = K_e V^2/2g$ = total entrance loss in feet where V is the velocity in the conduit.

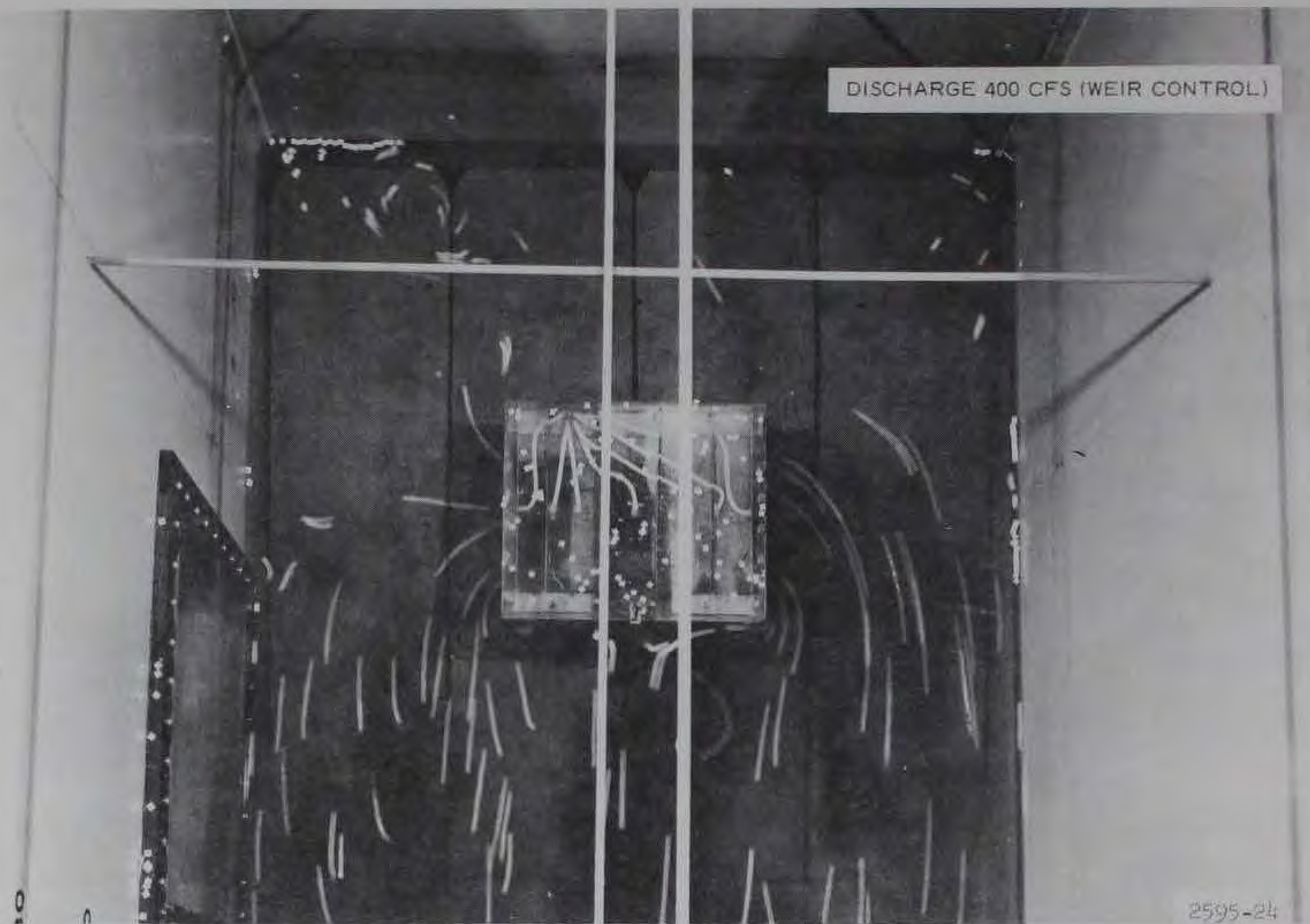
$H_c = K_c V^2/2g$ = loss in feet from the upper pool to energy gradient in riser shaft.

$H_t = K_t V^2/2g$ = loss in feet from energy gradient in riser shaft to just inside the conduit entrance.

$H_e = H_c + H_t$

* Determined from hydraulic gradients based on piezometers 55-72 extended to conduit entrance.
** Determined from hydraulic gradients based on piezometers in shaft (19-20) at el 3858.0.

PHOTOGRAPHS



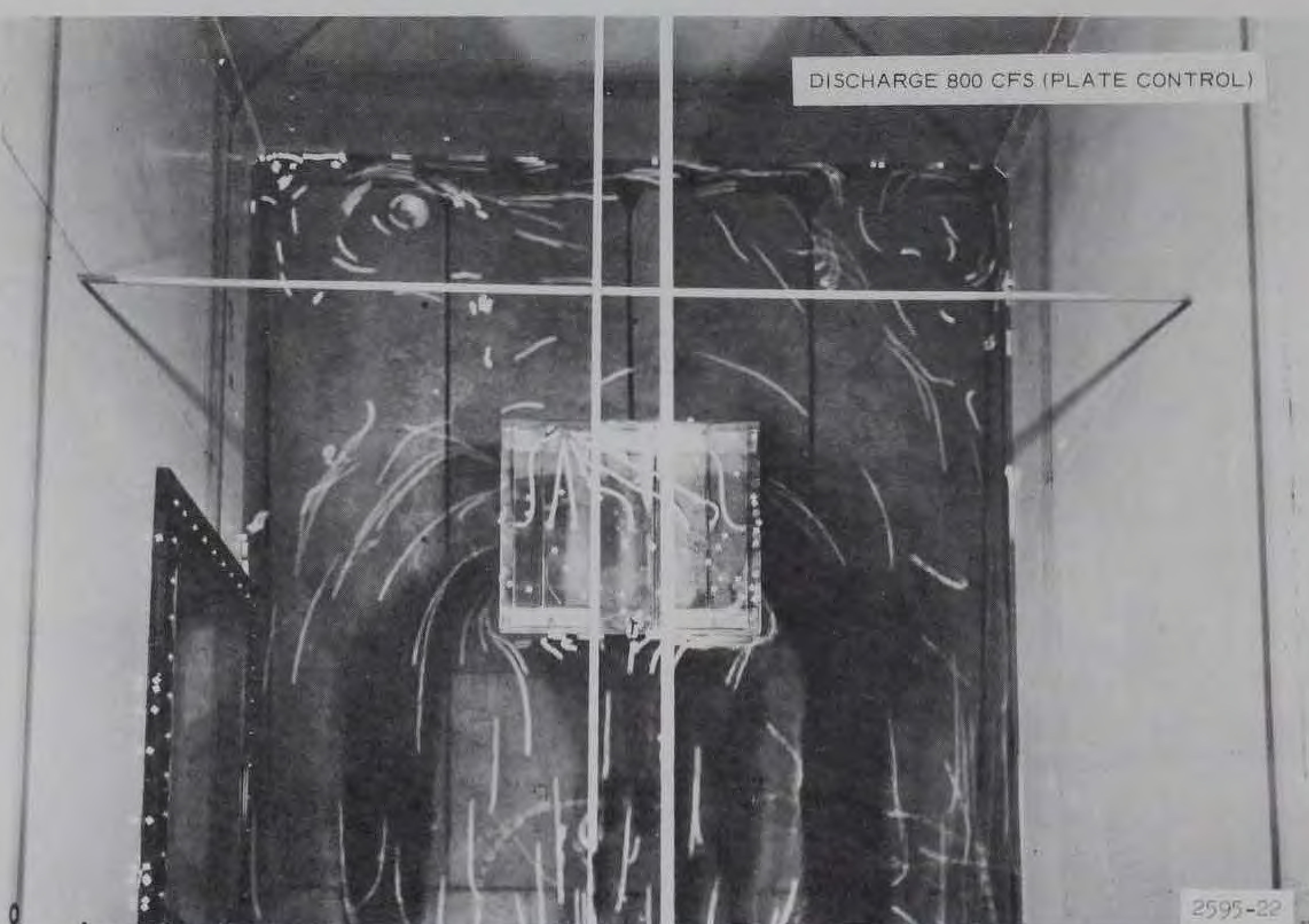
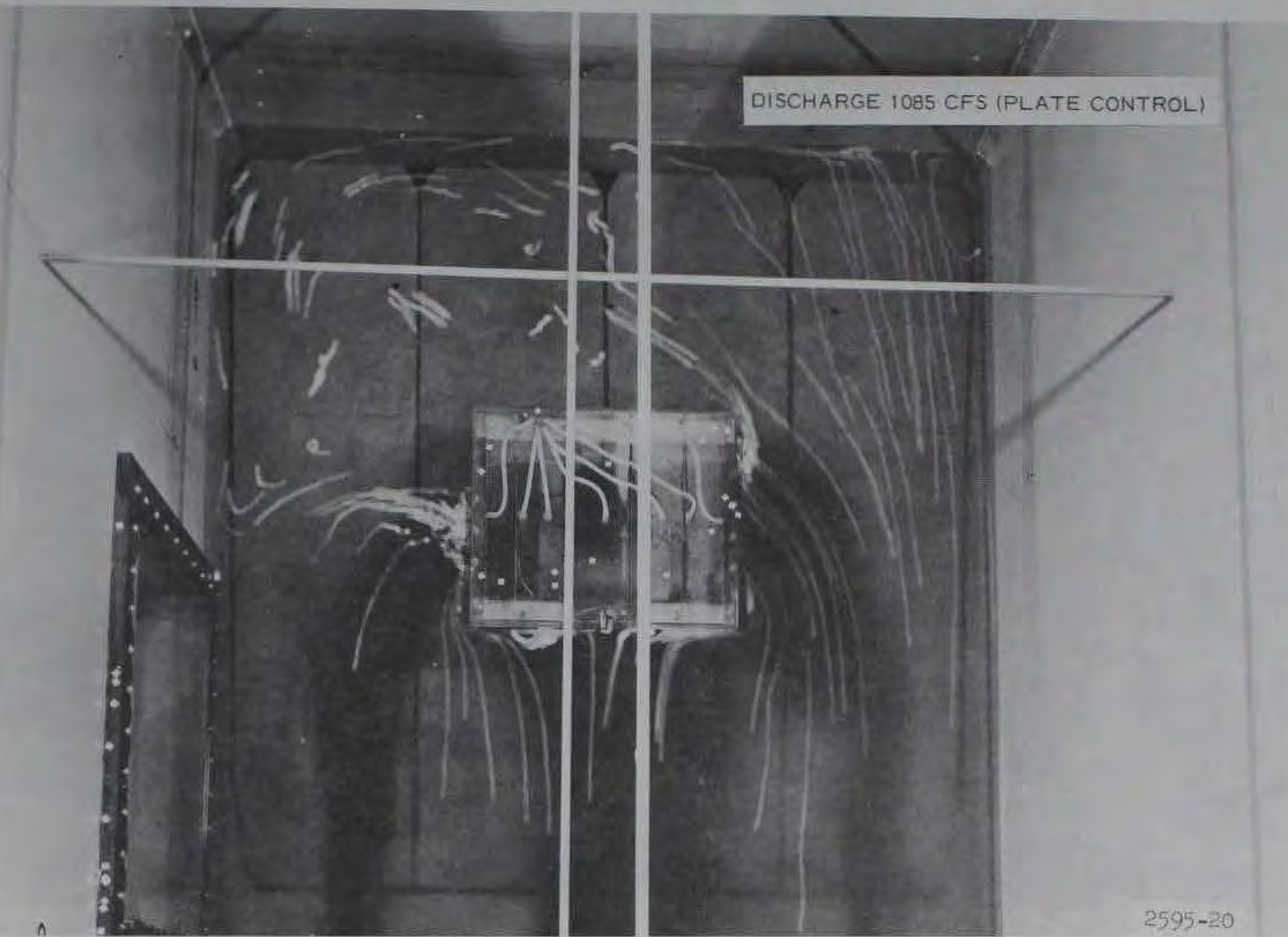


Photo 1. Approach flow patterns; Branched Oak outlet works (sheet 1 of 2)



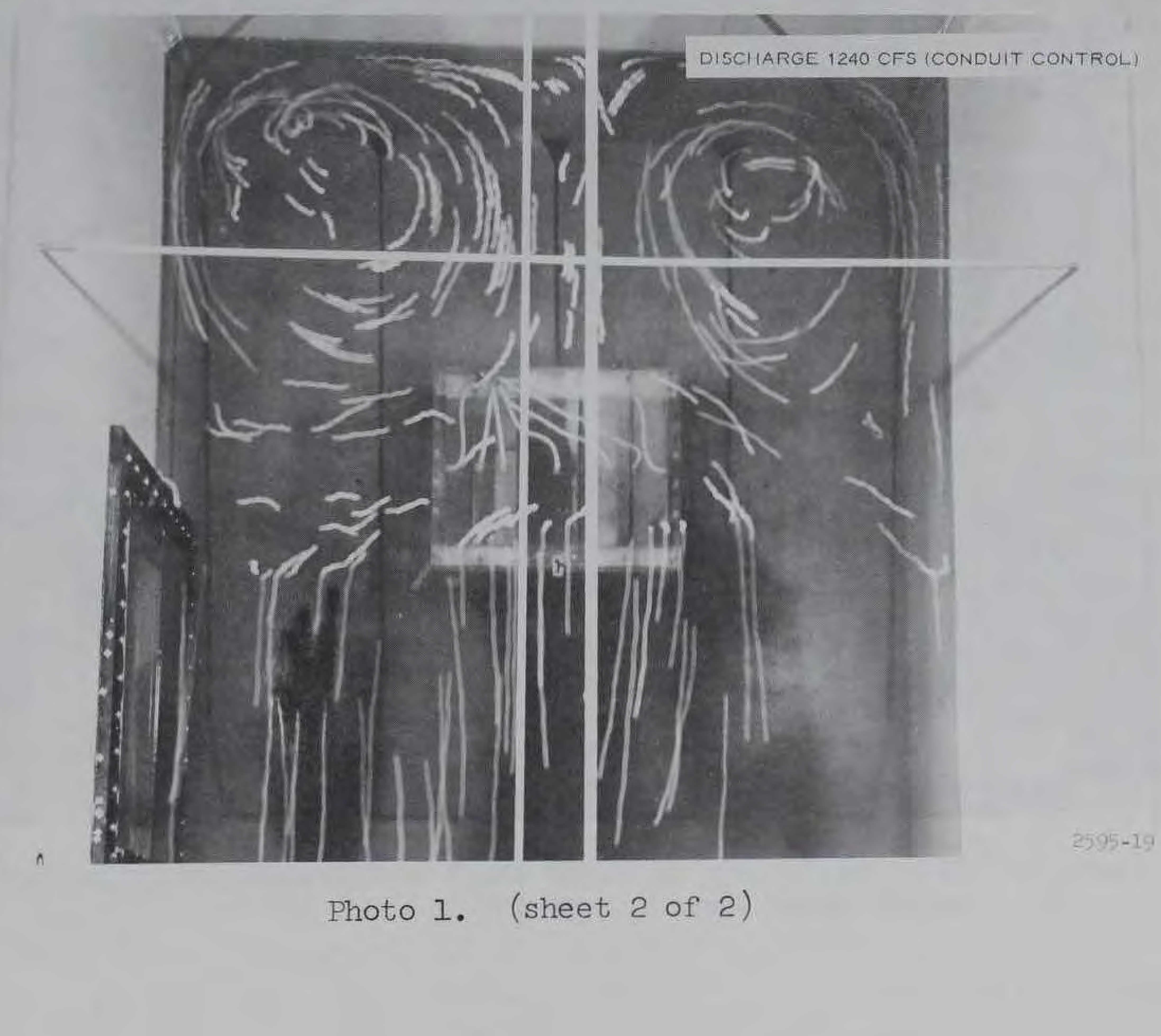
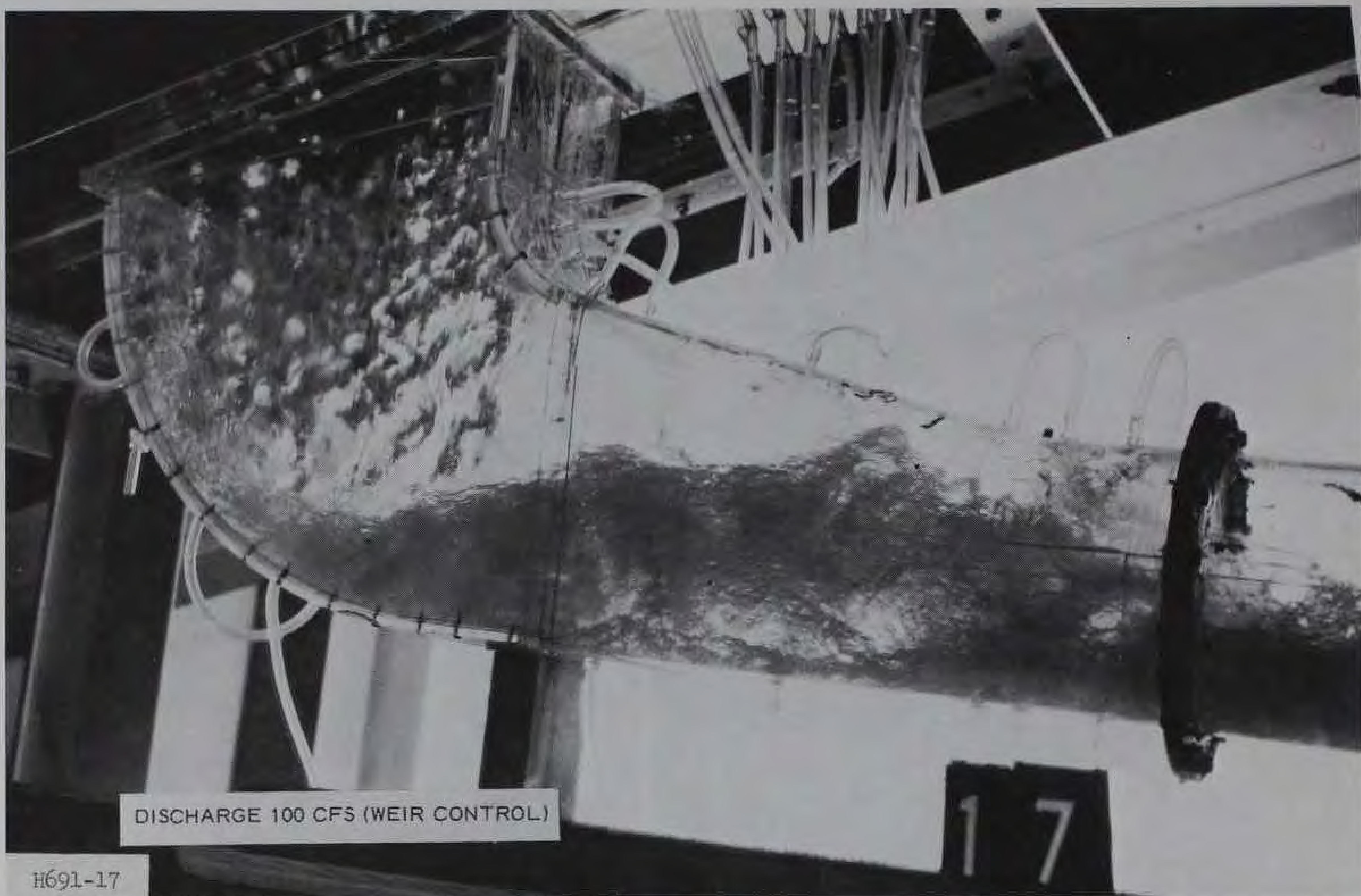


Photo 1. (sheet 2 of 2)



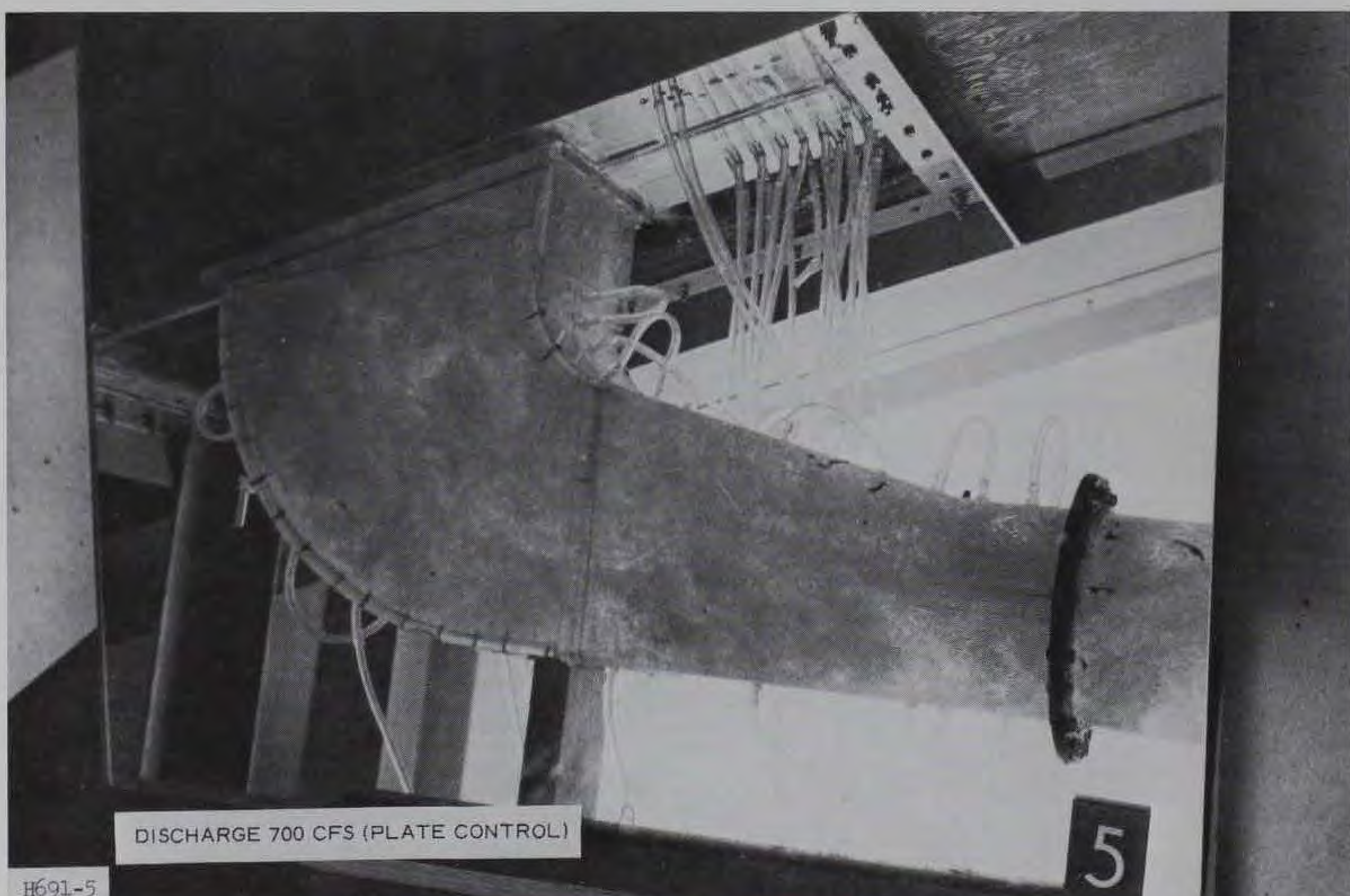


Photo 2. Flow conditions in riser shaft and transition; Branched Oak outlet works (sheet 1 of 2)

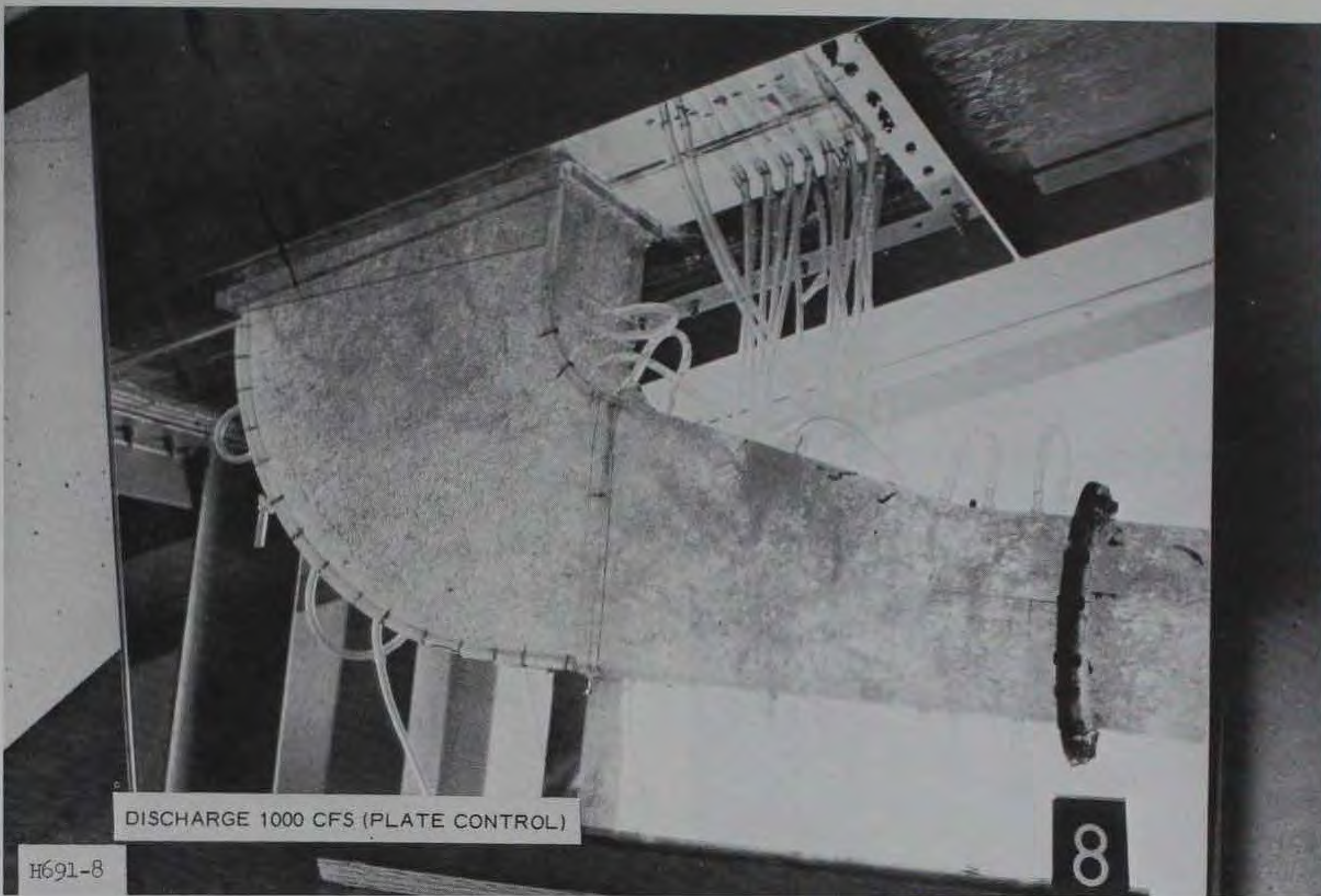


Photo 2. (sheet 2 of 2)

Photo 3. Performance of original design stilling basin; Branched Oak outlet works (sheet 1 of 3)

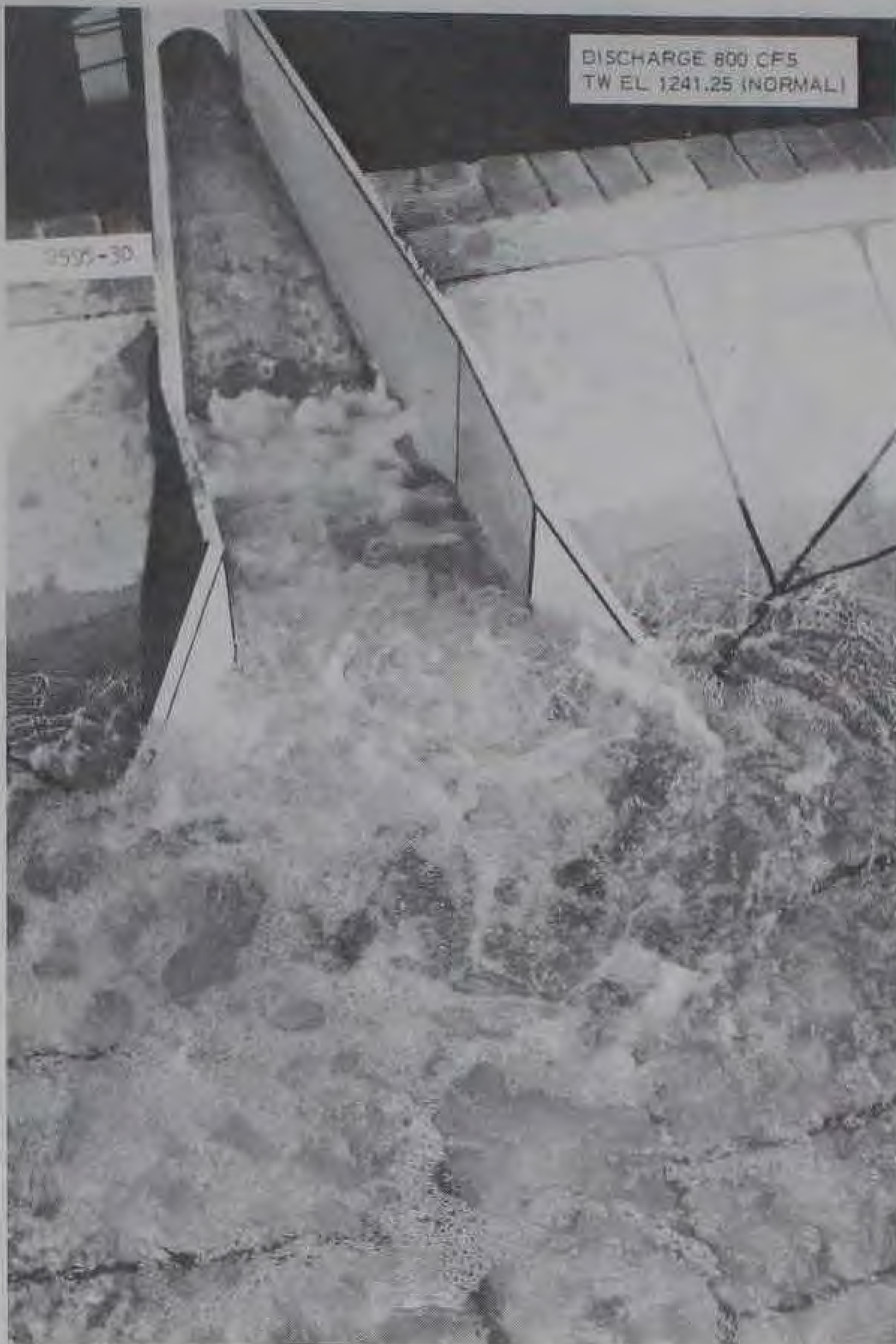
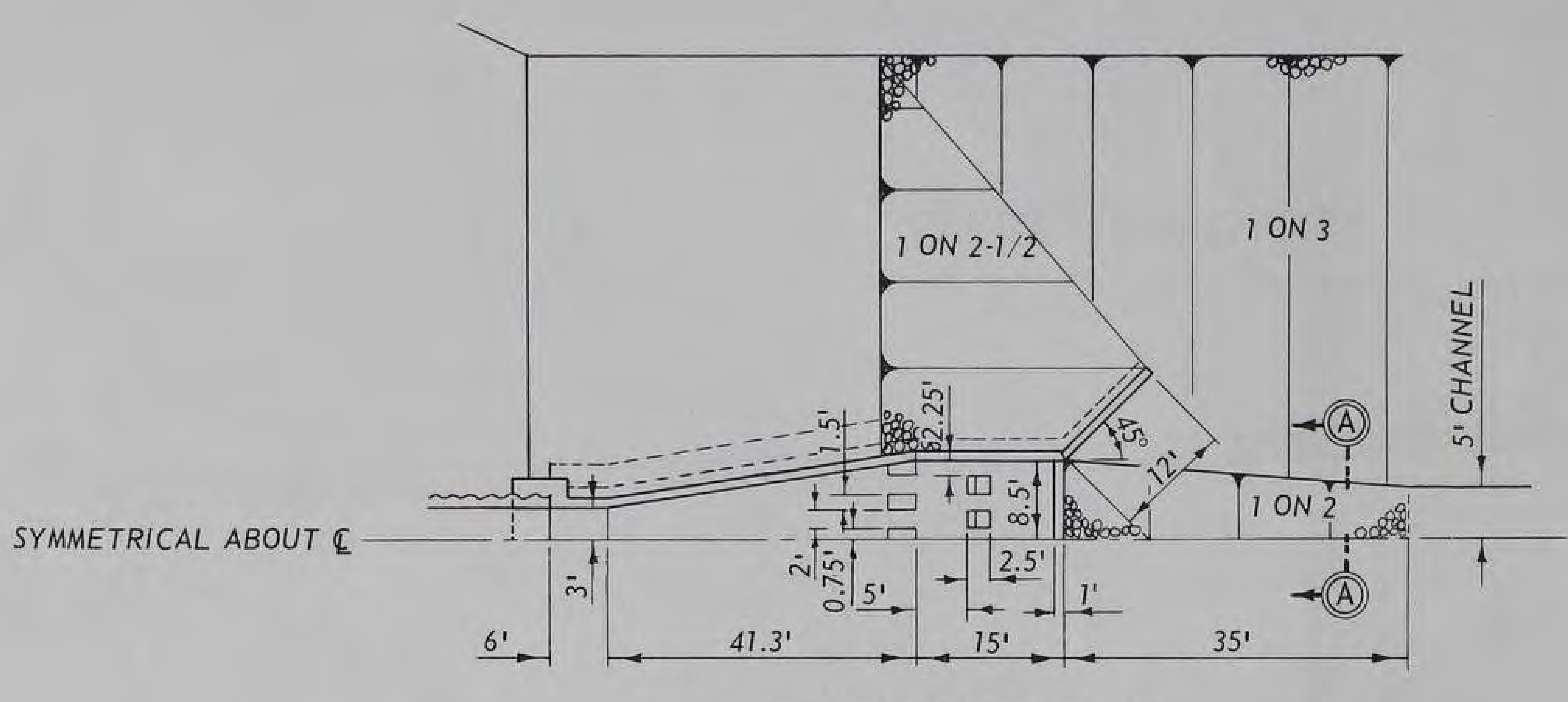
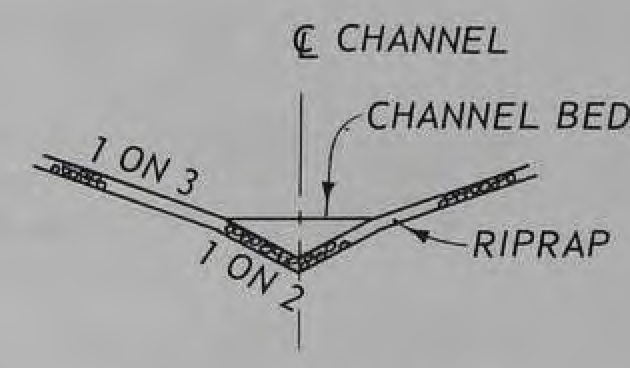


Photo 3. (sheet 2 of 3)

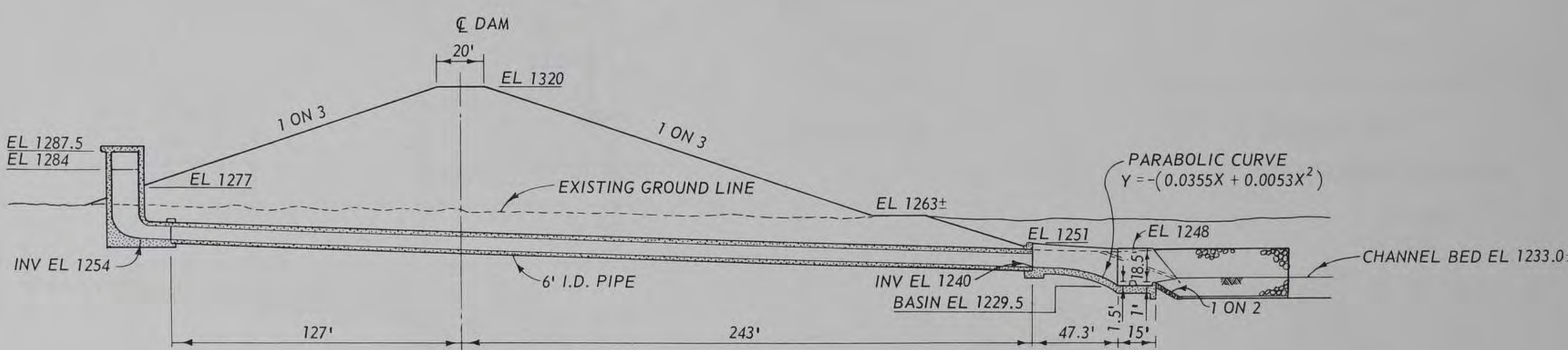
Photo 3. (sheet 3 of 3)



PLAN OF STILLING BASIN



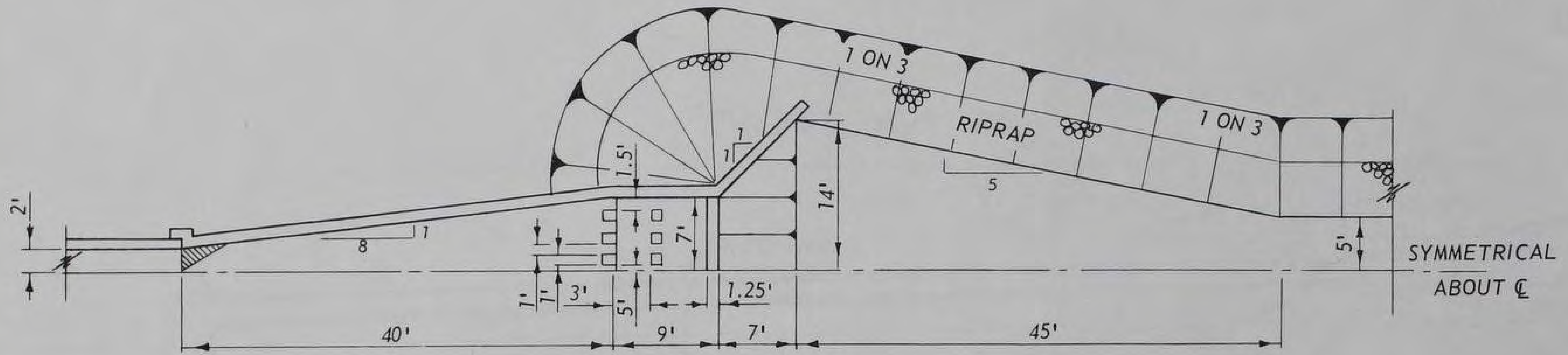
SECTION A-A



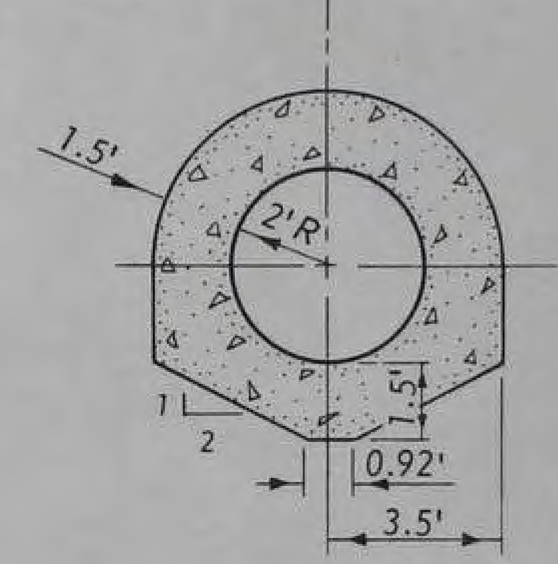
PROFILE OF OUTLET WORKS

DETAILS OF
BRANCHED OAK OUTLET WORKS
NOT TO SCALE

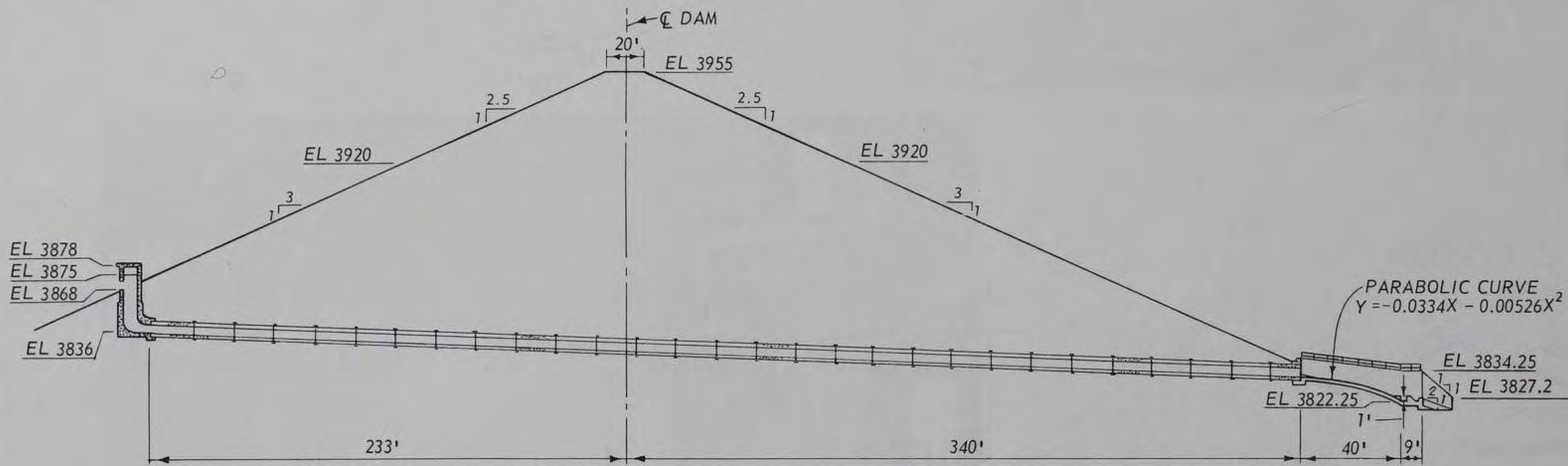
PLATE 2



PLAN OF STILLING BASIN

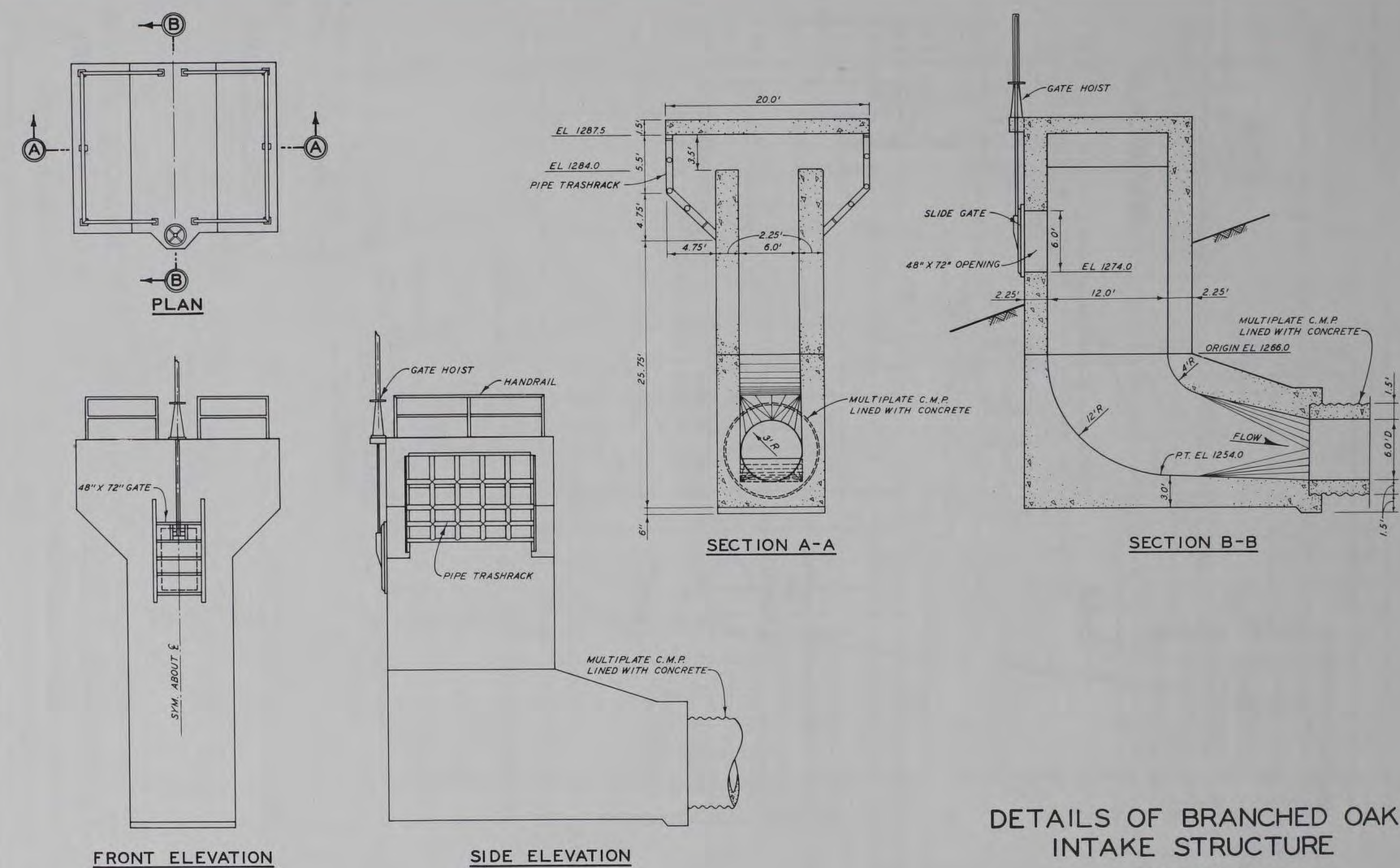


MAXIMUM CONDUIT SECTION



PROFILE OF OUTLET WORKS

DETAILS OF
COTTONWOOD SPRINGS OUTLET WORKS
NOT TO SCALE



DETAILS OF BRANCHED OAK INTAKE STRUCTURE

SCALE IN FEET

5 0 5 10 15

PLATE 3

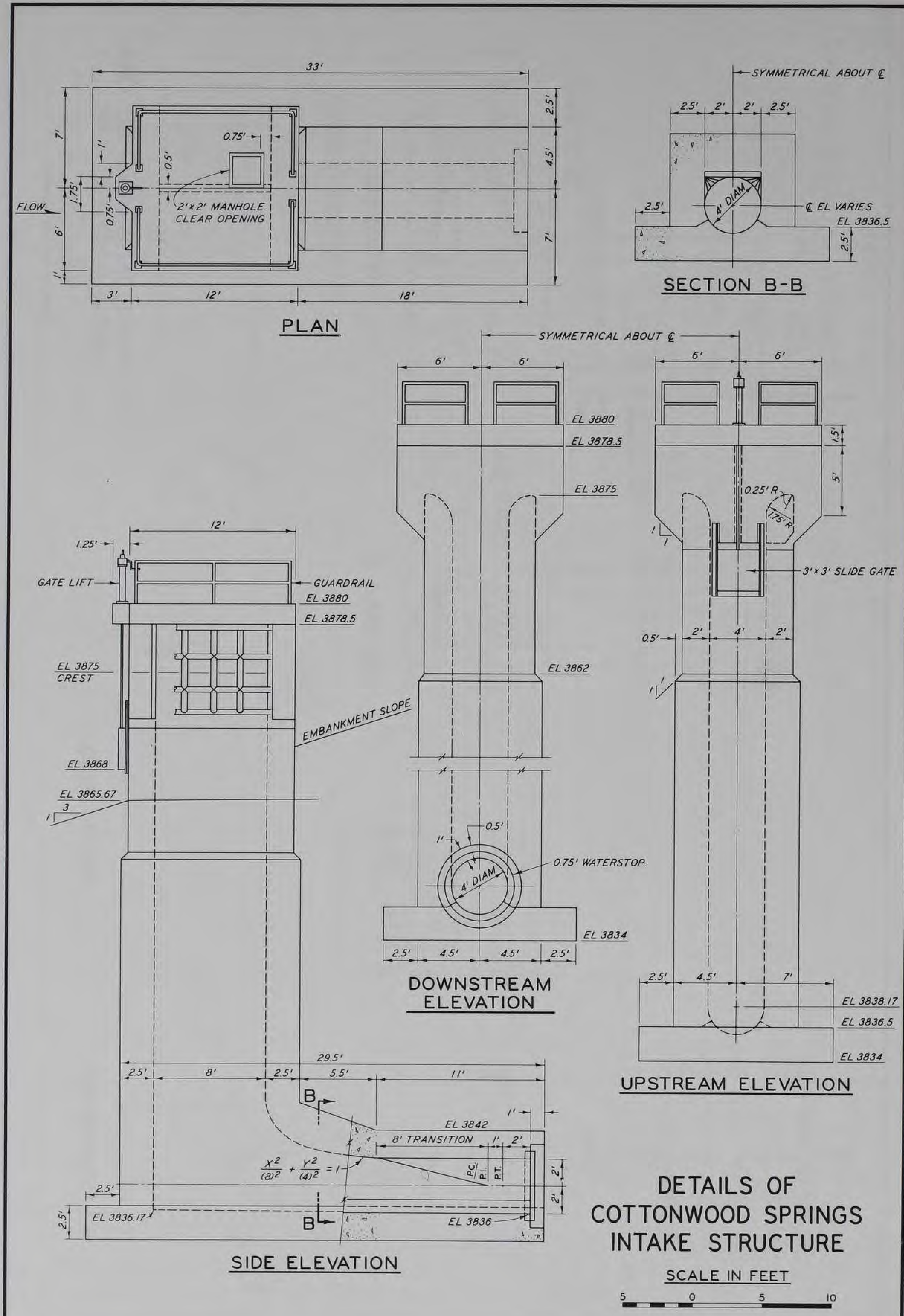
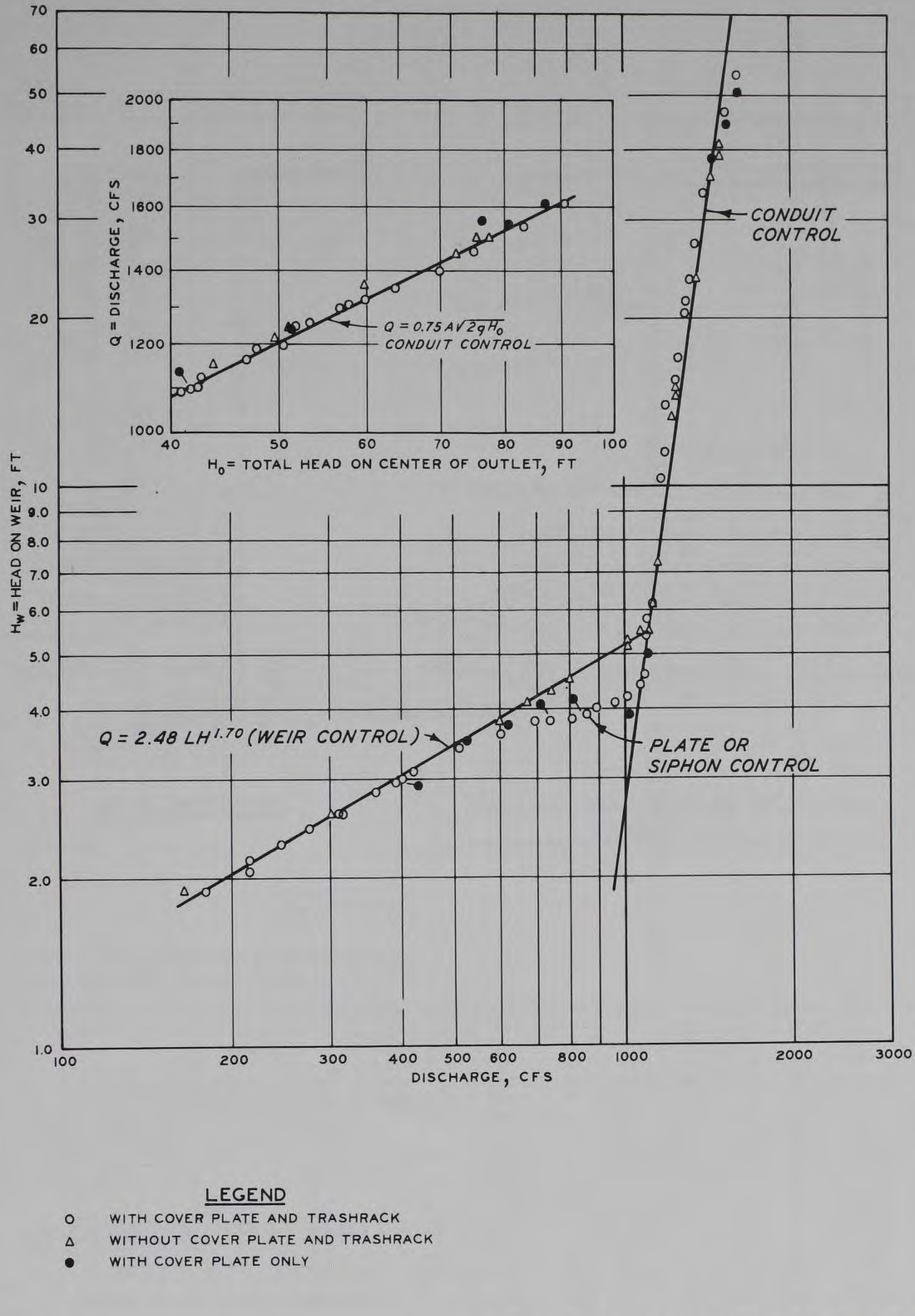

PLAN
33'
FLOW
2'x2' MANHOLE CLEAR OPENING
0.75'
0.5'
1.75'
3'
12'
18'
SECTION B-B
SYMMETRICAL ABOUT ℄
2.5'
2'
4' DIAM
℄ EL VARIES
EL 3836.5
DOWNSTREAM ELEVATION
EL 3880
EL 3878.5
EL 3875
EL 3862
0.75' WATERSTOP
EL 3834
UPSTREAM ELEVATION
0.25' R
1.75' R
3'x3' SLIDE GATE
EL 3838.17
SIDE ELEVATION
GATE LIFT
GUARDRAIL
EL 3875 CREST
EMBANKMENT SLOPE
EL 3868
EL 3865.67
29.5'
5.5'
11'
EL 3842
8' TRANSITION
P.C.
P.I.
P.T.
EL 3836.17
EL 3836
$\frac{X^2}{(8)^2} + \frac{Y^2}{(4)^2} = 1$
DETAILS OF
COTTONWOOD SPRINGS
INTAKE STRUCTURE
SCALE IN FEET
5 0 5 10

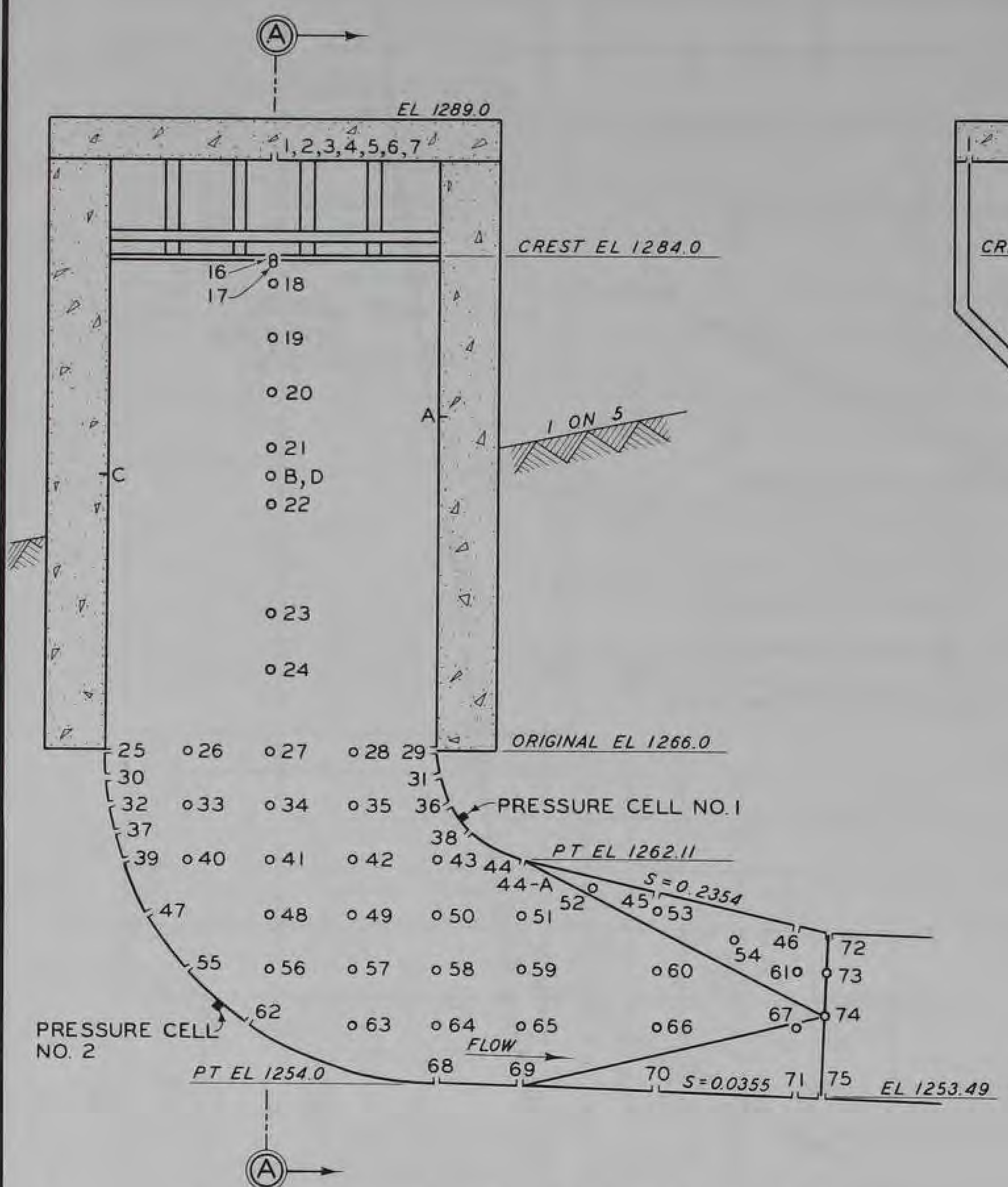
PLATE 4



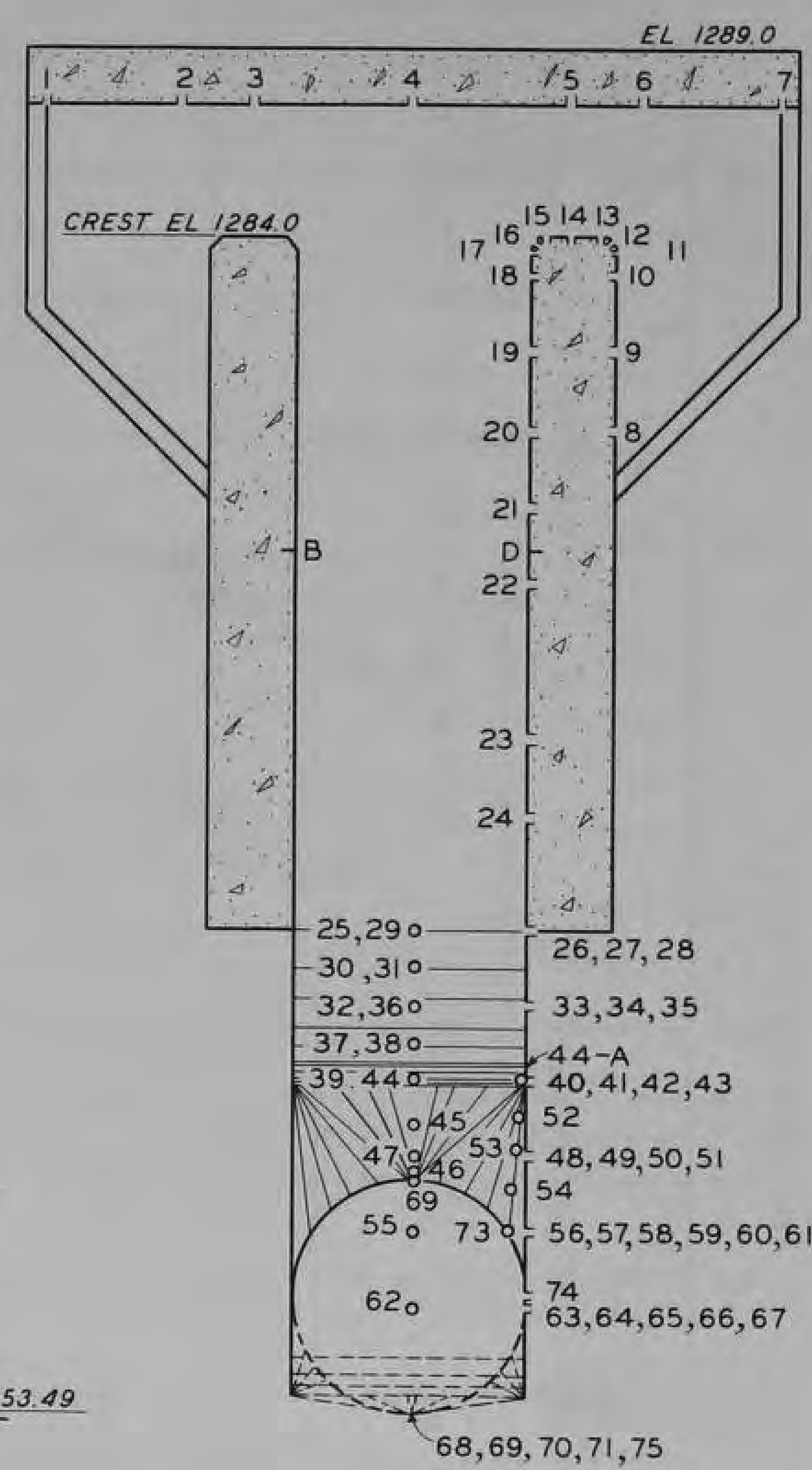
DISCHARGE CHARACTERISTICS

BRANCHED OAK OUTLET WORKS

2D-LONG SHARP-CRESTED WEIRS



SECTION ALONG CENTER LINE OF CONDUIT



SECTION A-A

NOTE: ELEVATION OF PRESSURE CELL NO. 1 - 1263.5
ELEVATION OF PRESSURE CELL NO. 2 - 1257.0

PIEZ NO.	PIEZ EL	PIEZ NO.	PIEZ EL	PIEZ NO.	PIEZ EL	PIEZ NO.	PIEZ EL	PIEZ NO.	PIEZ EL
1	1287.5	20	1279.0	39	1262.0	57	1258.0	A	1278.0
2	1287.5	21	1277.0	40	1262.0	58	1258.0	B	1276.0
3	1287.5	22	1275.0	41	1262.0	59	1258.0	C	1276.0
4	1287.5	23	1271.0	42	1262.0	60	1258.0	D	1276.0
5	1287.5	24	1269.0	43	1262.0	61	1258.0		
6	1287.5	25	1266.0	44	1262.0	62	1256.0		
7	1287.5	26	1266.0	44-A	1262.0	63	1256.0		
8	1279.0	27	1266.0	45	1260.8	64	1256.0		
9	1281.0	28	1266.0	46	1259.6	65	1256.0		
10	1283.0	29	1266.0	47	1260.0	66	1256.0		
11	1283.8	30	1265.0	48	1260.0	67	1256.0		
12	1283.9	31	1265.0	49	1260.0	68	1254.0		
13	1284.0	32	1264.0	50	1260.0	69	1253.9		
14	1284.0	33	1264.0	51	1260.0	70	1253.7		
15	1284.0	34	1264.0	52	1261.0	71	1253.5		
16	1283.9	35	1264.0	53	1260.2	72	1259.5		
17	1283.8	36	1264.0	54	1259.2	73	1258.0		
18	1283.0	37	1263.0	55	1258.0	74	1256.5		
19	1281.0	38	1263.0	56	1258.0	75	1253.5		

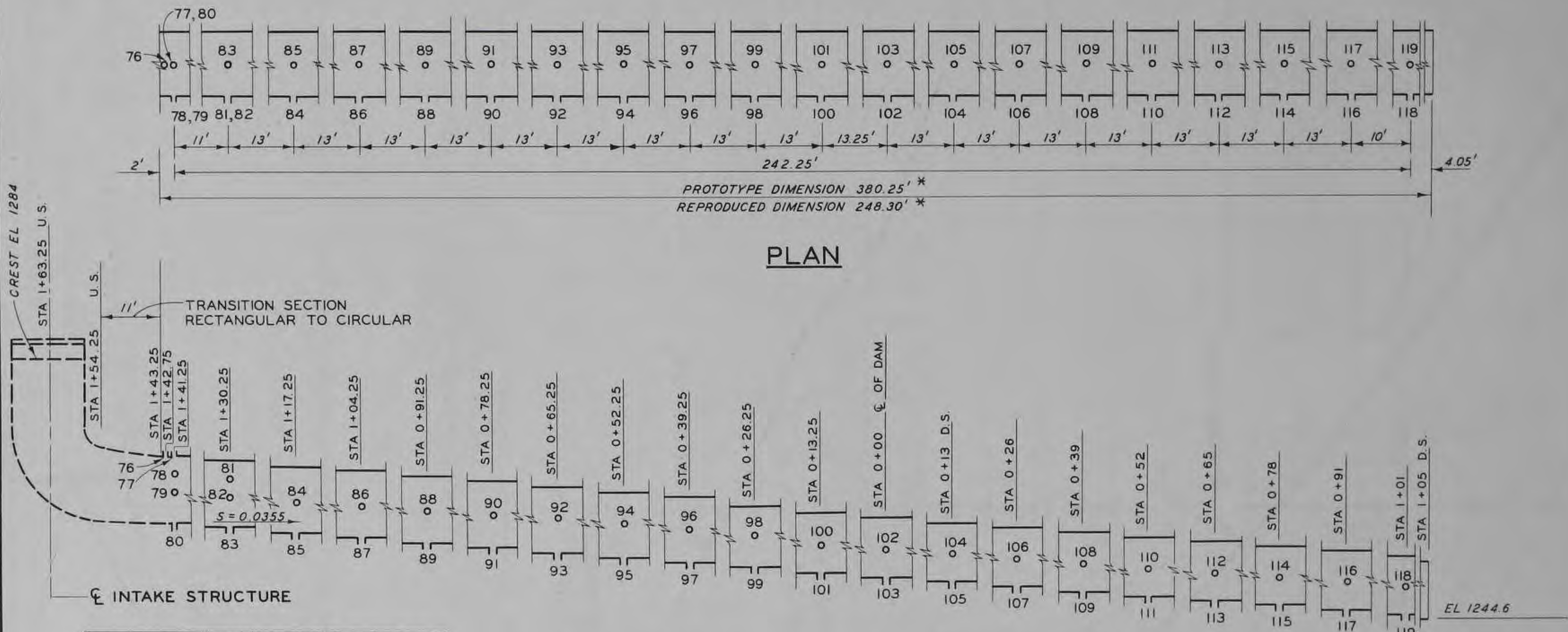
PIEZOMETER LOCATIONS

INTAKE STRUCTURE

BRANCHED OAK OUTLET WORKS

TYPE I (ORIGINAL) DESIGN

SCALE IN FEET



VERTICAL SECTION THROUGH ℄ OF CONDUIT

PIEZ NO.	PIEZ EL	PIEZ NO.	PIEZ EL	PIEZ NO.	PIEZ EL
76	1259.5	91	1251.2	106	1250.0
77	1259.4	92	1253.7	107	1247.5
78	1257.9	93	1250.7	108	1250.0
79	1256.4	94	1253.3	109	1247.0
80	1253.4	95	1250.3	110	1249.6
81	1257.5	96	1252.8	111	1246.6
82	1256.0	97	1249.8	112	1249.1
83	1253.0	98	1252.3	113	1246.1
84	1255.6	99	1249.3	114	1248.6
85	1252.6	100	1251.9	115	1245.6
86	1255.1	101	1248.9	116	1248.2
87	1252.1	102	1251.4	117	1245.2
88	1254.6	103	1248.4	118	1247.8
89	1251.6	104	1250.9	119	1244.8
90	1254.2	105	1247.9		

* AS FRICTION LOSSES IN THE PLASTIC MODEL WERE GREATER THAN PROTOTYPE LOSSES, IT WAS NECESSARY TO SHORTEN THE MODEL CONDUIT AS SHOWN TO SIMULATE ACCURATELY THE HYDRAULIC GRADE LINE AT THE INTAKE STRUCTURE

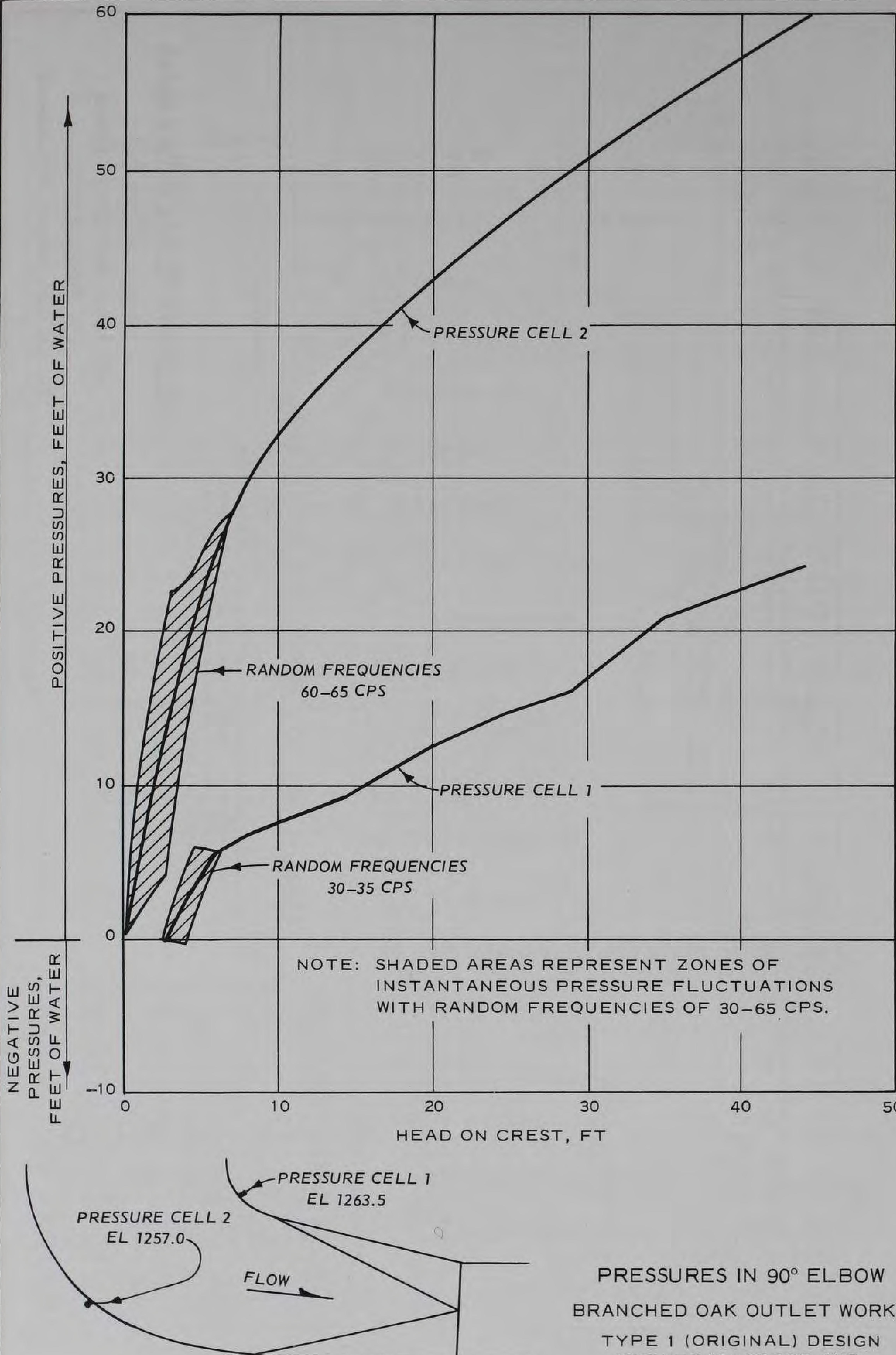
PIEZOMETER LOCATIONS

CIRCULAR CONDUIT

BRANCHED OAK OUTLET WORKS

SCALE IN FEET

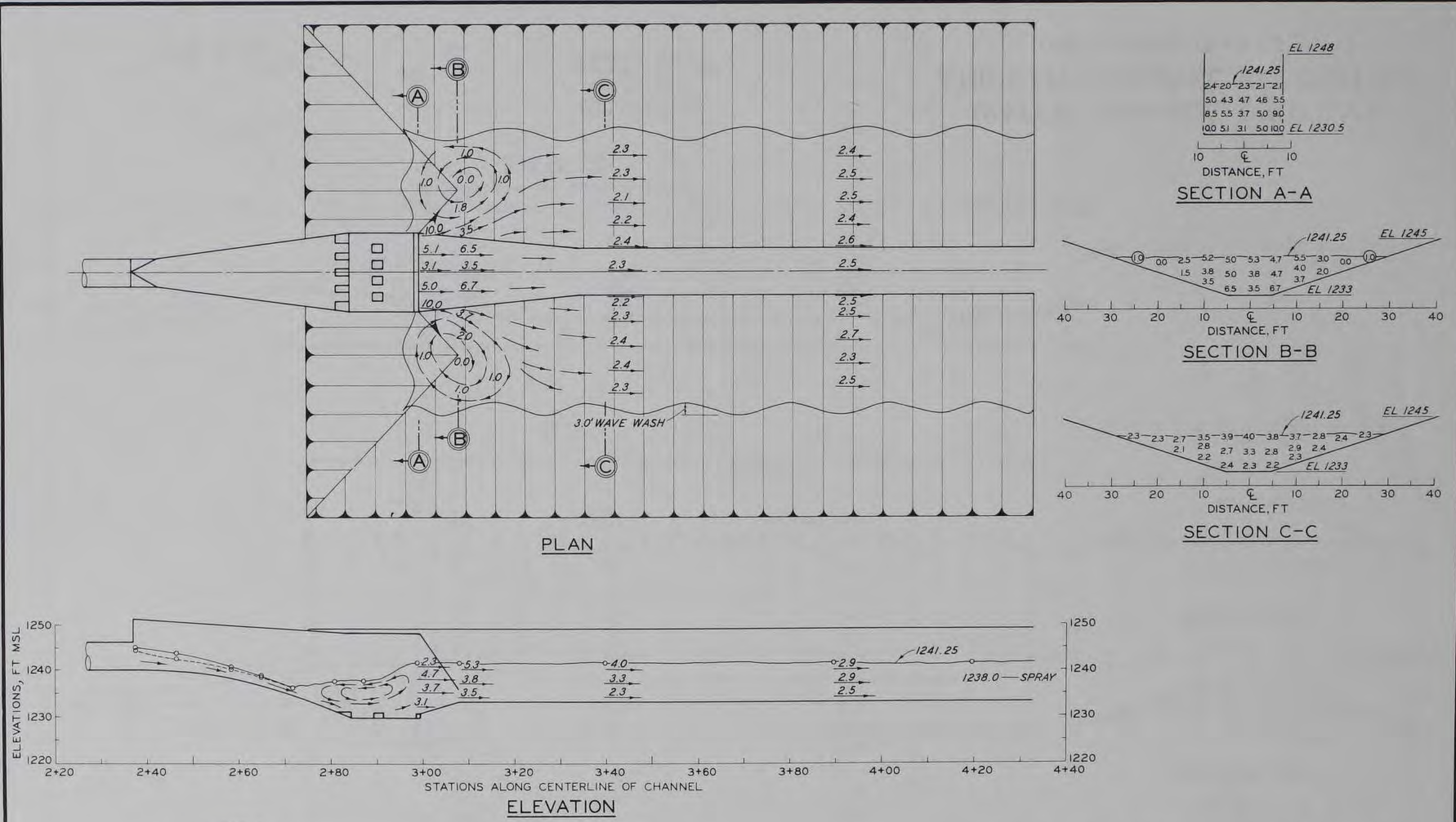
25 0 25 50



PRESSURES IN 90° ELBOW

BRANCHED OAK OUTLET WORKS

TYPE 1 (ORIGINAL) DESIGN WITH TRASHRACKS AND COVER PLATE REMOVED



LEGEND

○ UPSTREAM VELOCITY
—— ℄ PROFILE
- - - WALL PROFILE

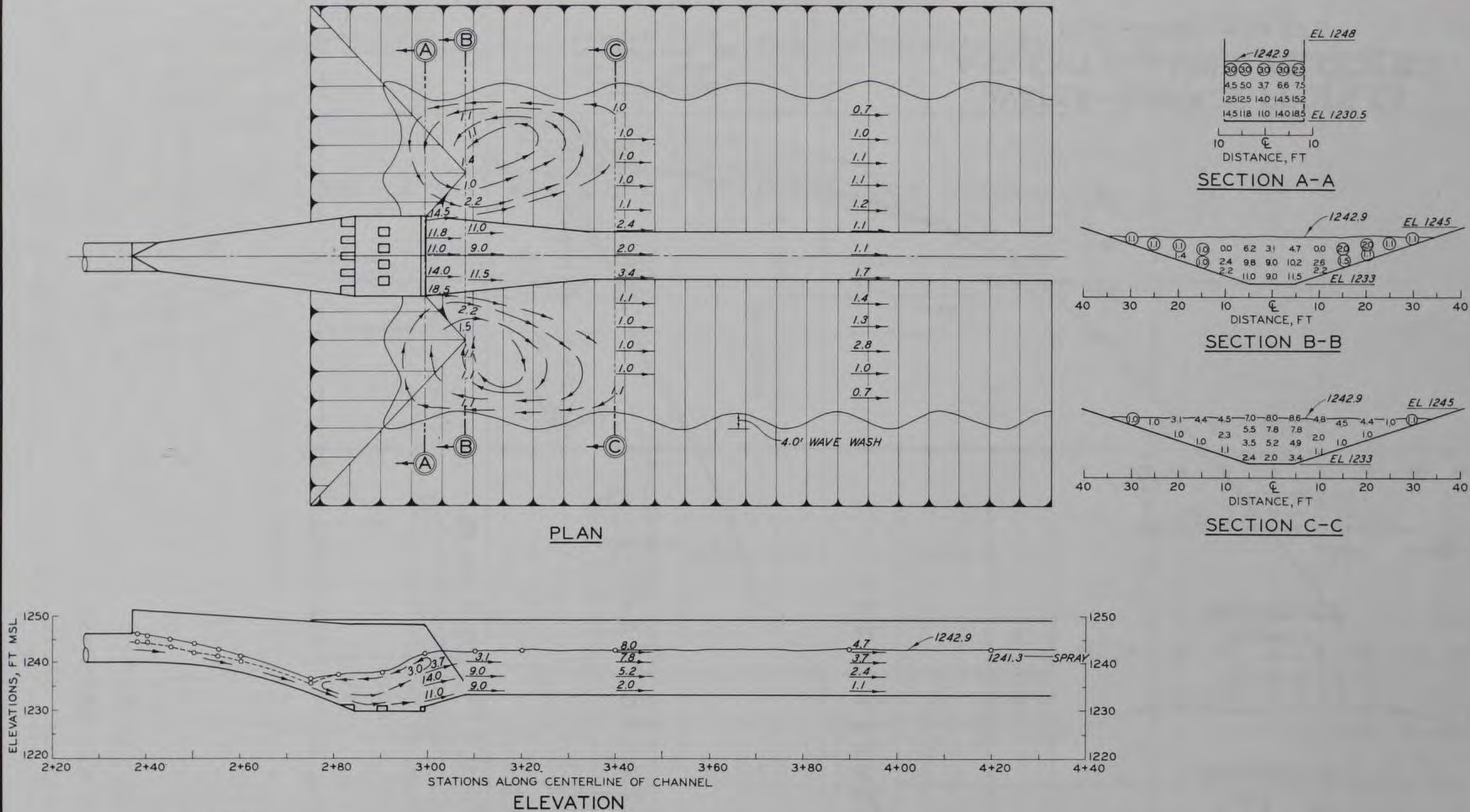
NOTE: VELOCITIES ARE GIVEN IN PROTOTYPE FEET PER SECOND 1 FT OFF BOTTOM

TEST CONDITIONS

POOL EL 1288.55
DISCHARGE 800 CFS
TAILWATER EL 1241.25

WATER-SURFACE PROFILES AND EXIT CHANNEL VELOCITIES

DISCHARGE 800 CFS



LEGEND

○ UPSTREAM VELOCITY
—— ℄ PROFILE
– – – WALL PROFILE

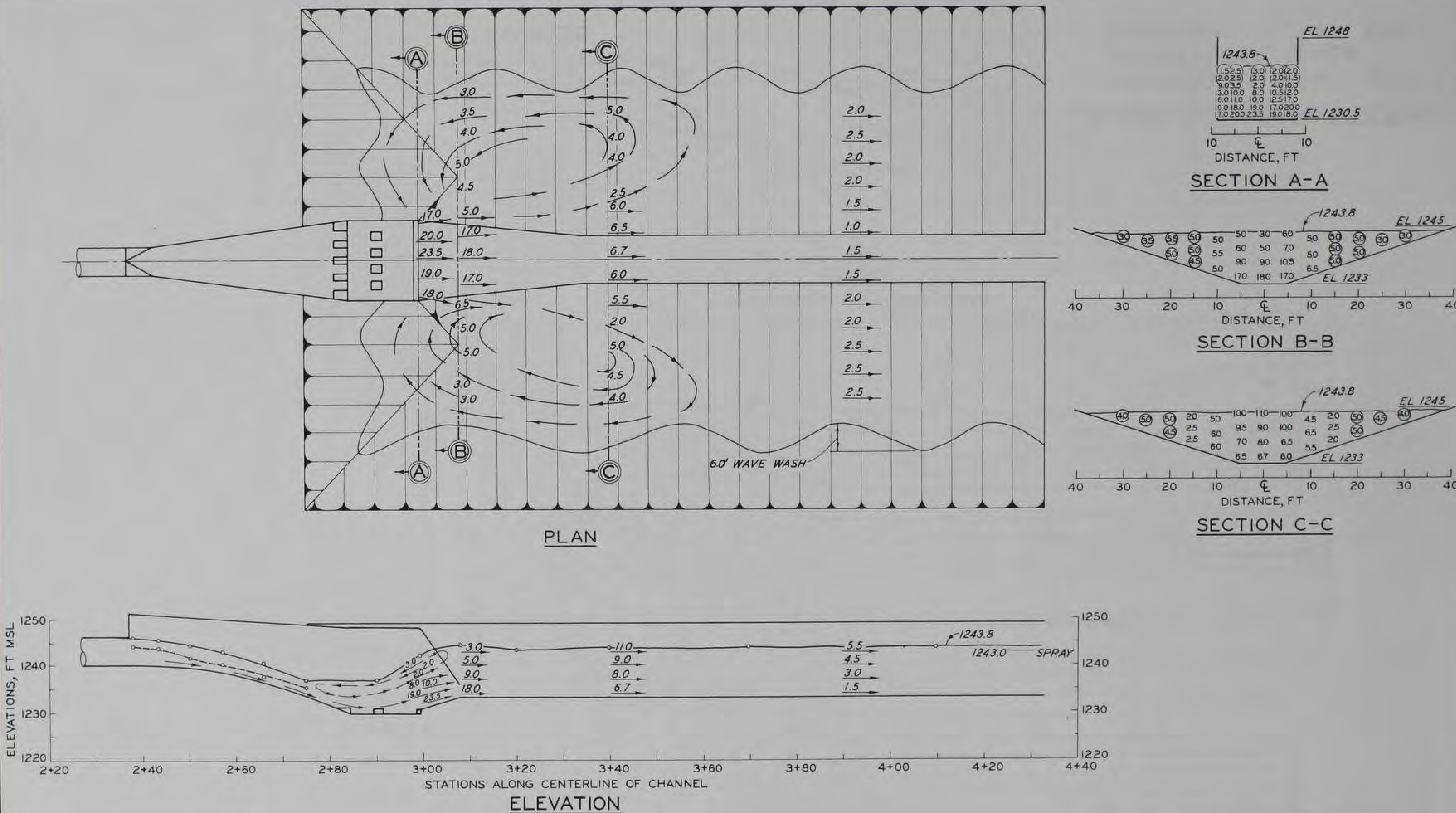
NOTE: VELOCITIES ARE GIVEN IN PROTOTYPE FEET PER SECOND 1 FT OFF BOTTOM

TEST CONDITIONS

POOL EL 1296.5
DISCHARGE 1240 CFS
TAILWATER EL 1242.9

WATER-SURFACE PROFILES AND EXIT CHANNEL VELOCITIES

DISCHARGE 1240 CFS



LEGEND

○ UPSTREAM VELOCITY
—— ℄ PROFILE
- - - WALL PROFILE

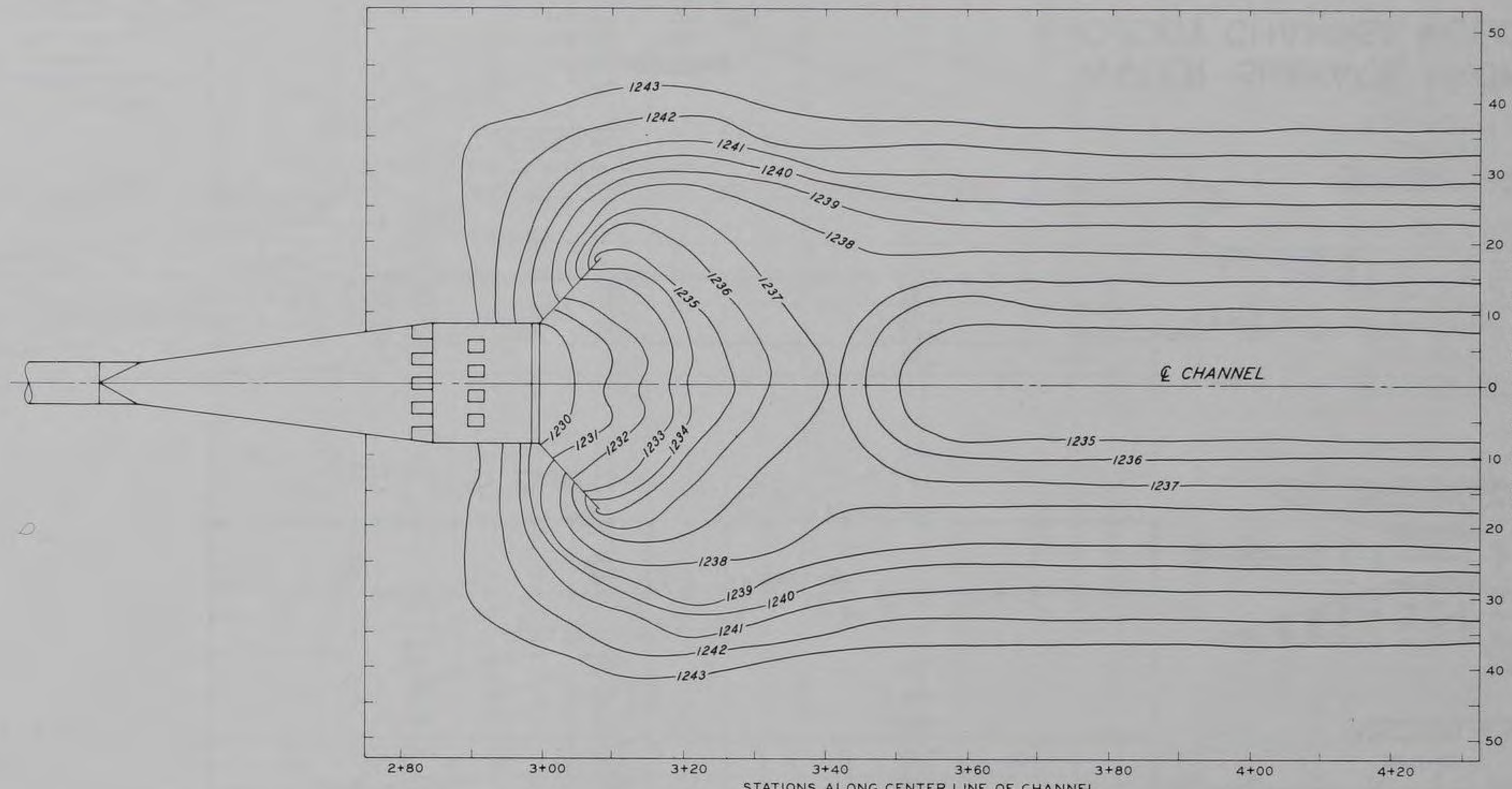
NOTE: VELOCITIES ARE GIVEN IN PROTOTYPE FEET PER SECOND 1 FT OFF BOTTOM

TEST CONDITIONS

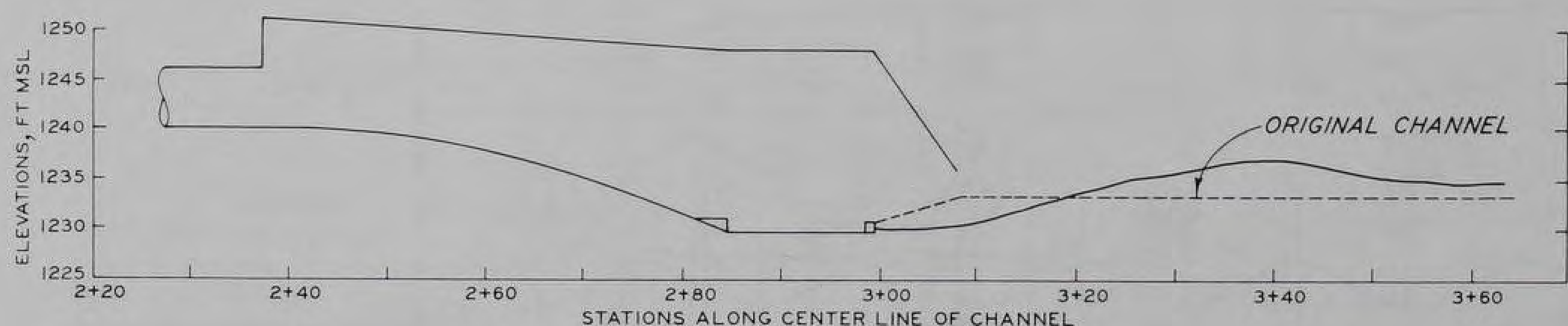
POOL EL 1330
DISCHARGE 1500 CFS
TAILWATER EL 1243.8

WATER-SURFACE PROFILES AND EXIT CHANNEL VELOCITIES

DISCHARGE 1500 CFS



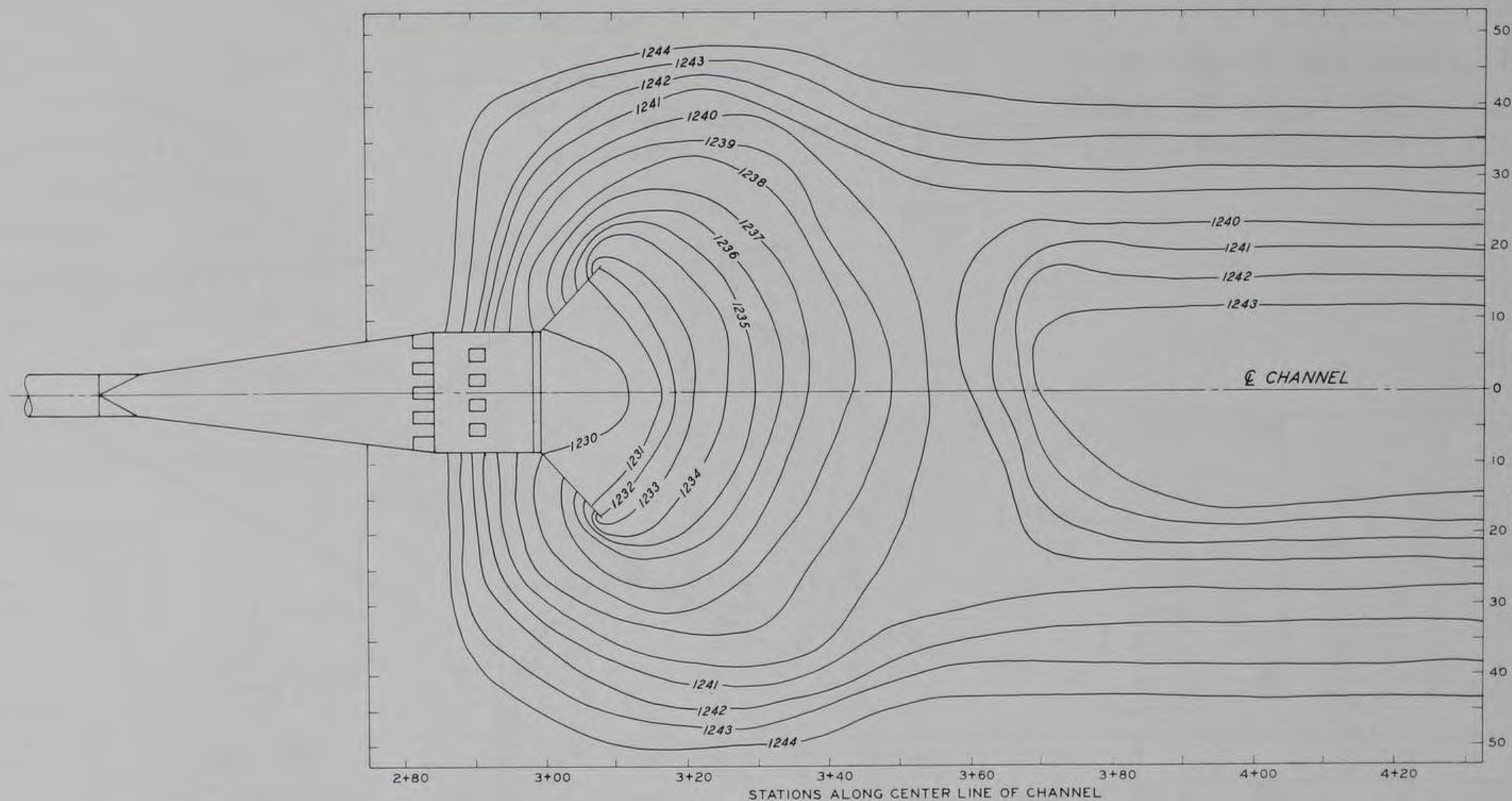
PLAN



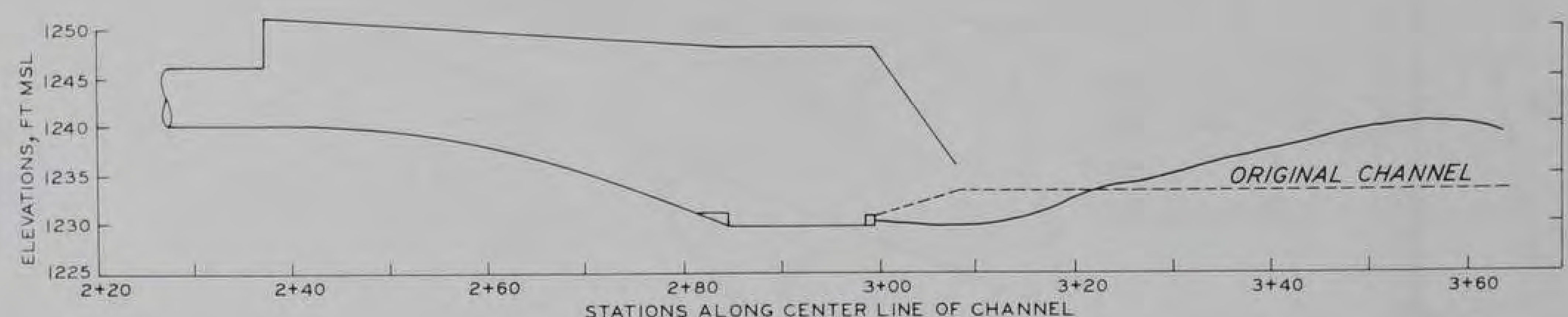
ELEVATION

SAND SCOUR PATTERN

DISCHARGE 1240 CFS
TAILWATER EL 1242.9
DURATION 47 MIN



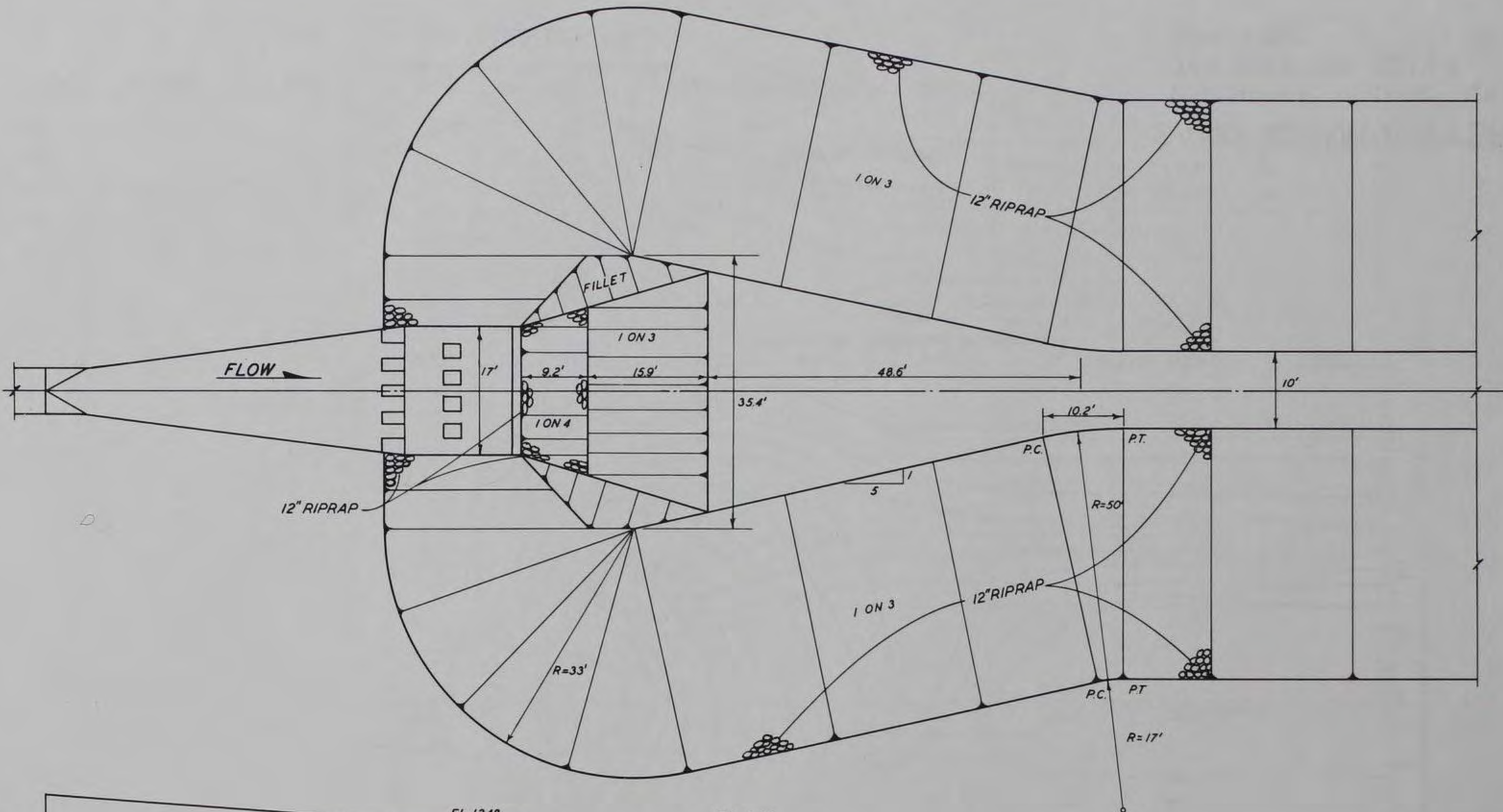
PLAN



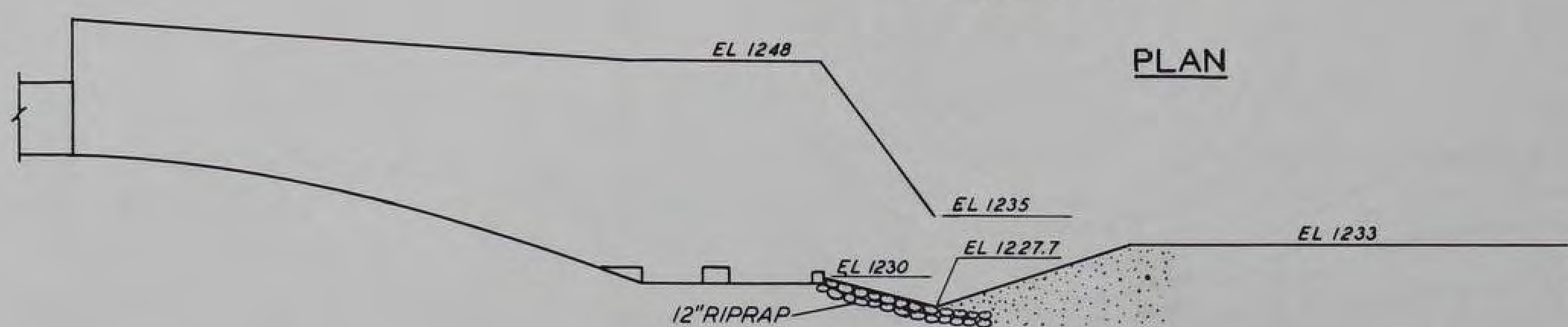
ELEVATION

SAND SCOUR PATTERN

DISCHARGE 1500 CFS
TAILWATER EL 1243.8
DURATION 47 MIN



PLAN



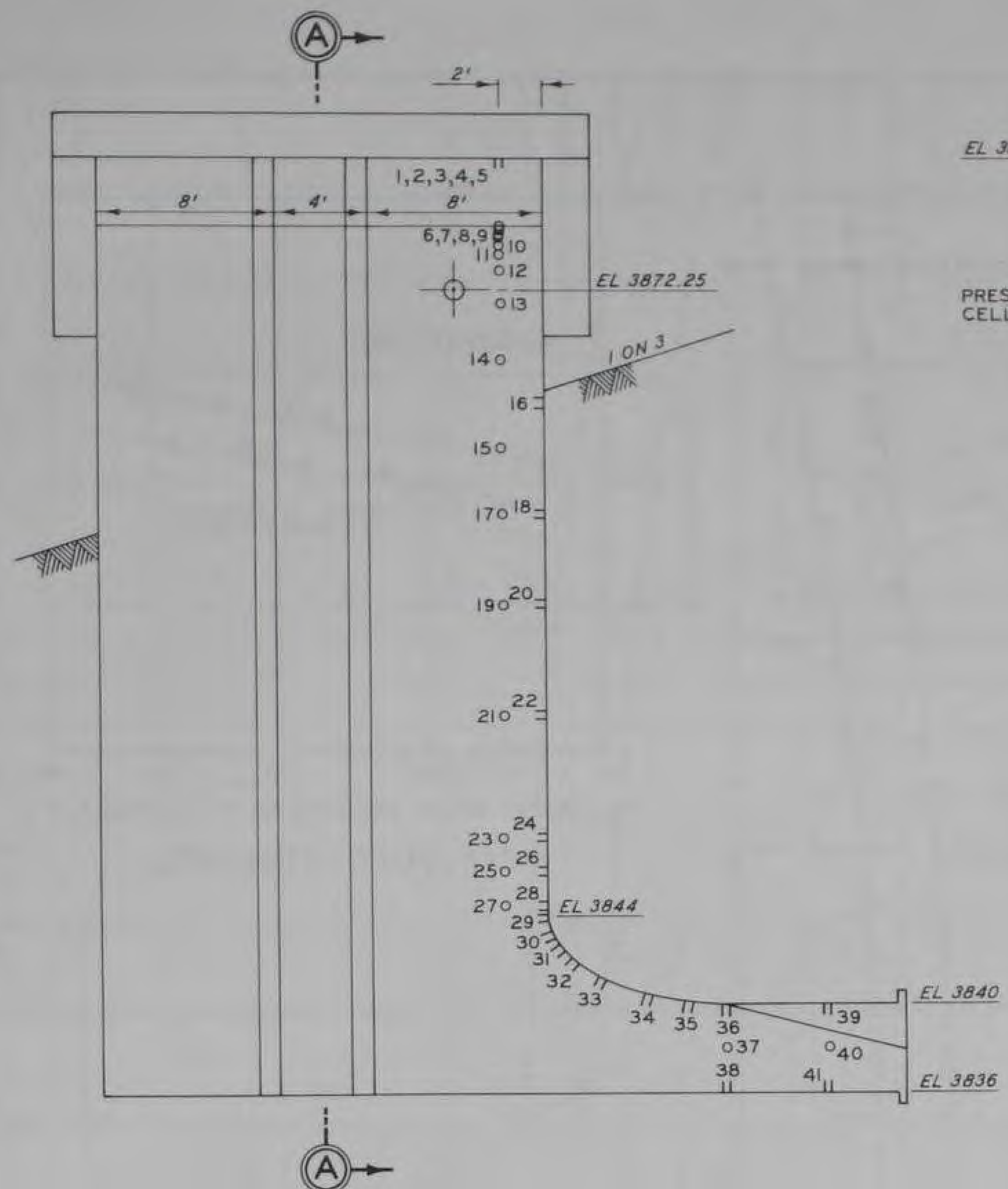
CENTER-LINE SECTION

RECOMMENDED EXIT CHANNEL CONFIGURATION AND RIPRAP PLAN

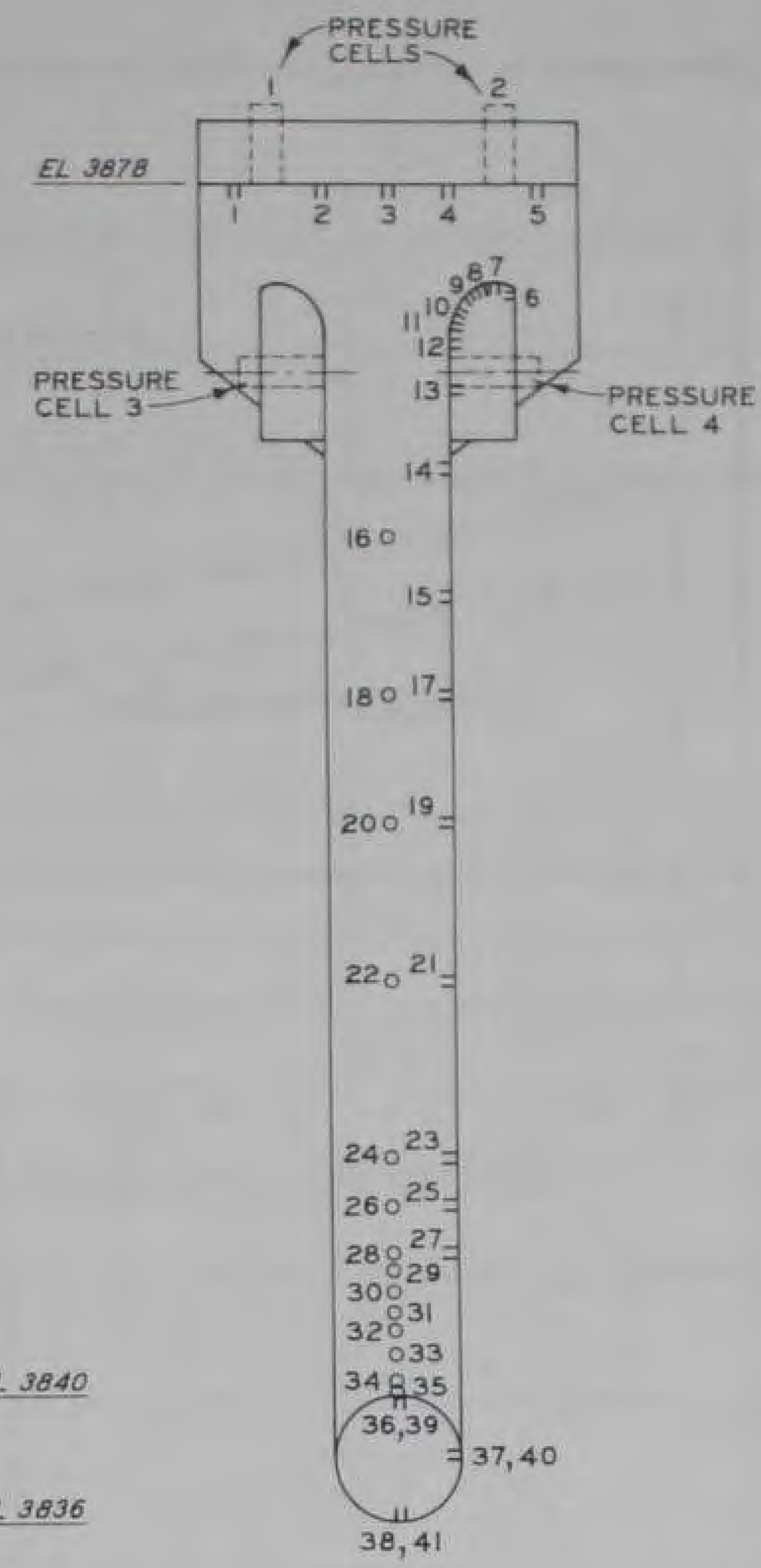
BRANCHED OAK OUTLET WORKS

SCALE IN FEET

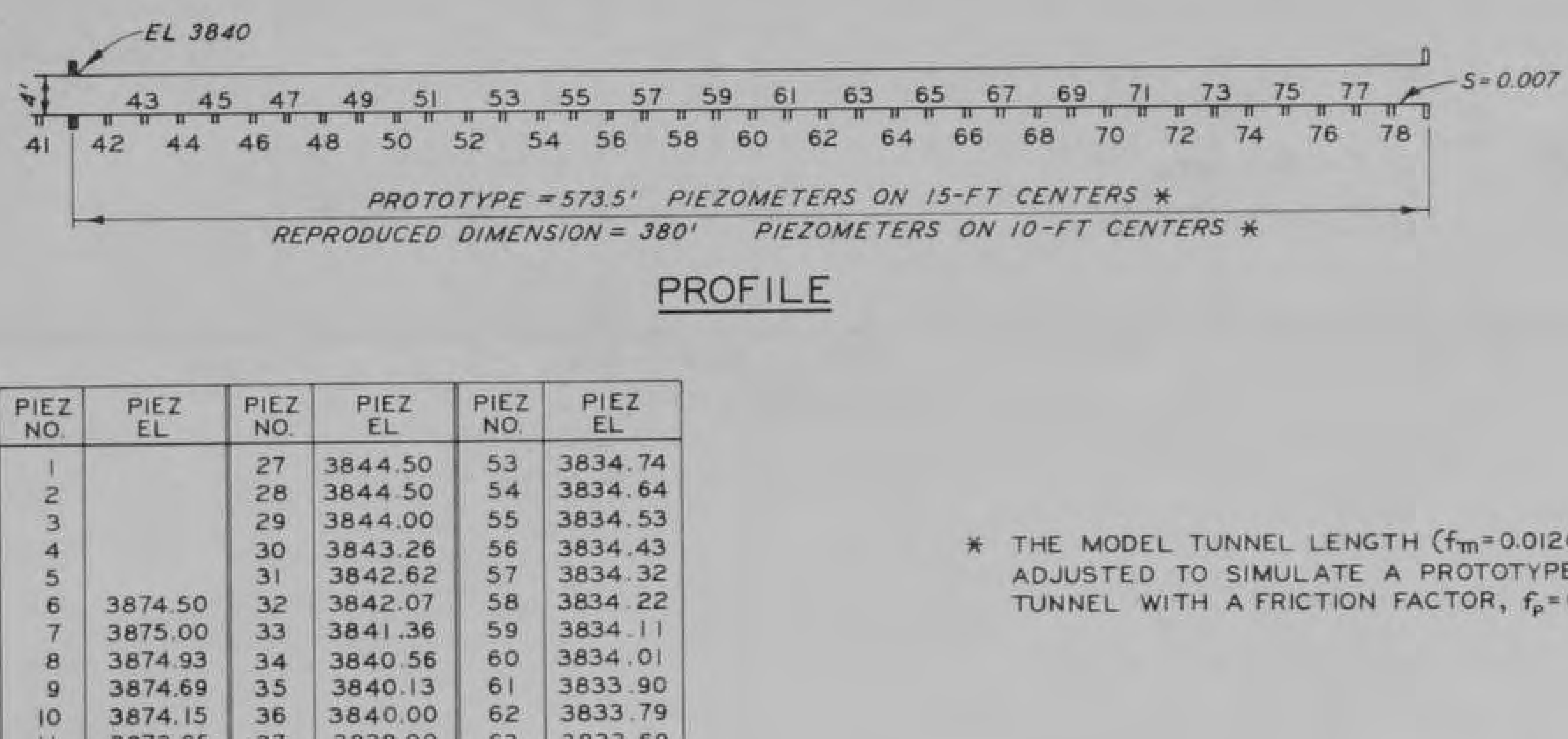
10 0 10 20



SECTION ALONG CENTER LINE



SECTION A-A



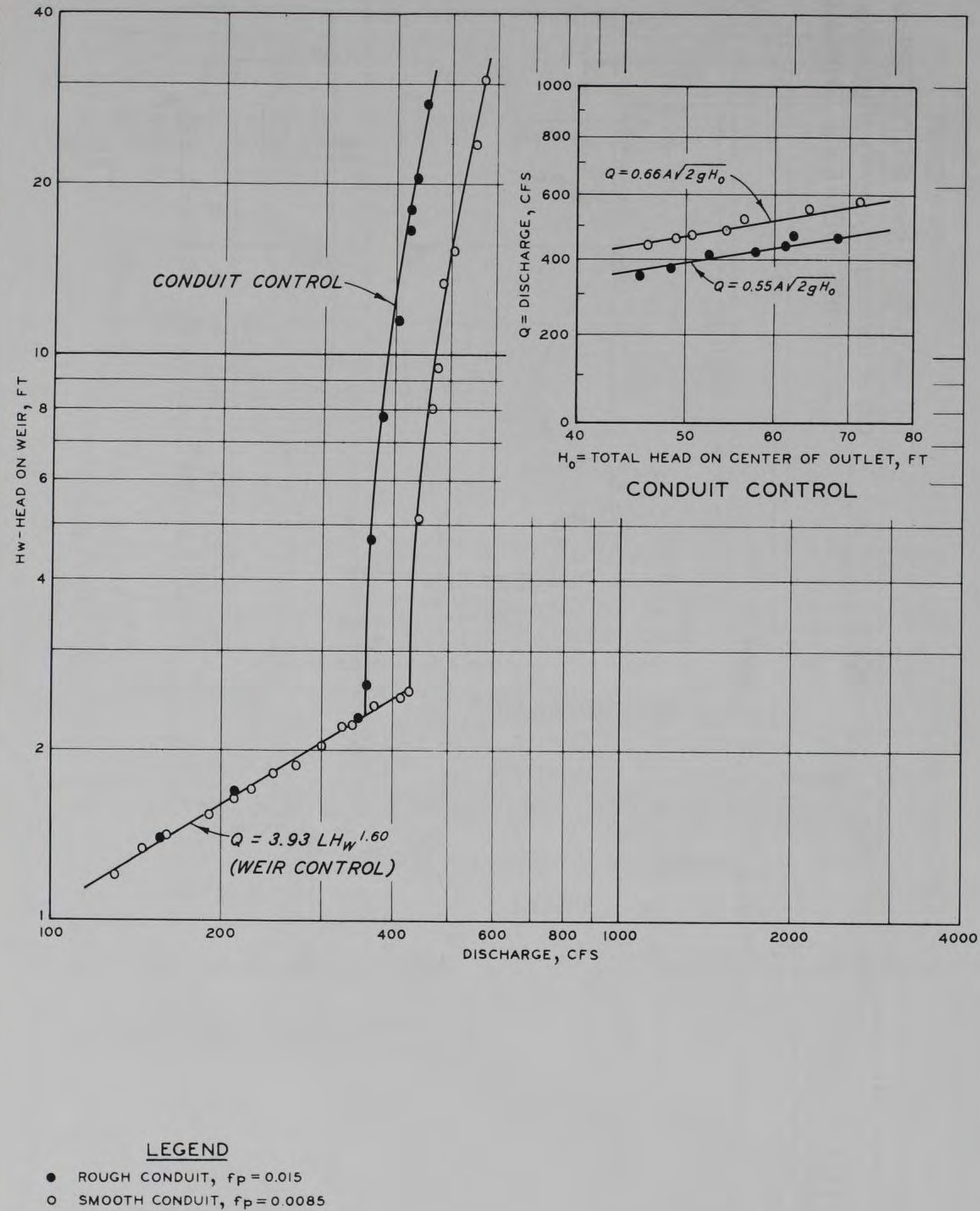
PROFILE

PIEZ NO.	PIEZ EL	PIEZ NO.	PIEZ EL	PIEZ NO.	PIEZ EL
1		27	3844.50	53	3834.74
2		28	3844.50	54	3834.64
3		29	3844.00	55	3834.53
4		30	3843.26	56	3834.43
5		31	3842.62	57	3834.32
6	3874.50	32	3842.07	58	3834.22
7	3875.00	33	3841.36	59	3834.11
8	3874.93	34	3840.56	60	3834.01
9	3874.69	35	3840.13	61	3833.90
10	3874.15	36	3840.00	62	3833.79
11	3873.65	37	3838.00	63	3833.69
12	3873.25	38	3836.00	64	3833.58
13	3871.50	39	3840.00	65	3833.48
14	3869.00	40	3838.00	66	3833.37
15	3865.00	41	3836.00	67	3833.27
16	3867.00	42	3835.90	68	3833.16
17	3862.00	43	3835.79	69	3833.06
18	3862.00	44	3835.69	70	3832.95
19	3858.00	45	3835.58	71	3832.85
20	3858.00	46	3835.48	72	3832.74
21	3853.00	47	3835.37	73	3832.64
22	3853.00	48	3835.27	74	3832.53
23	3847.50	49	3835.16	75	3832.43
24	3847.50	50	3835.08	76	3832.32
25	3846.00	51	3834.95	77	3832.22
26	3846.00	52	3834.85	78	3832.11

* THE MODEL TUNNEL LENGTH (f_m = 0.0126) WAS ADJUSTED TO SIMULATE A PROTOTYPE CONCRETE TUNNEL WITH A FRICTION FACTOR, f_p = 0.0085.

PIEZOMETER LOCATIONS

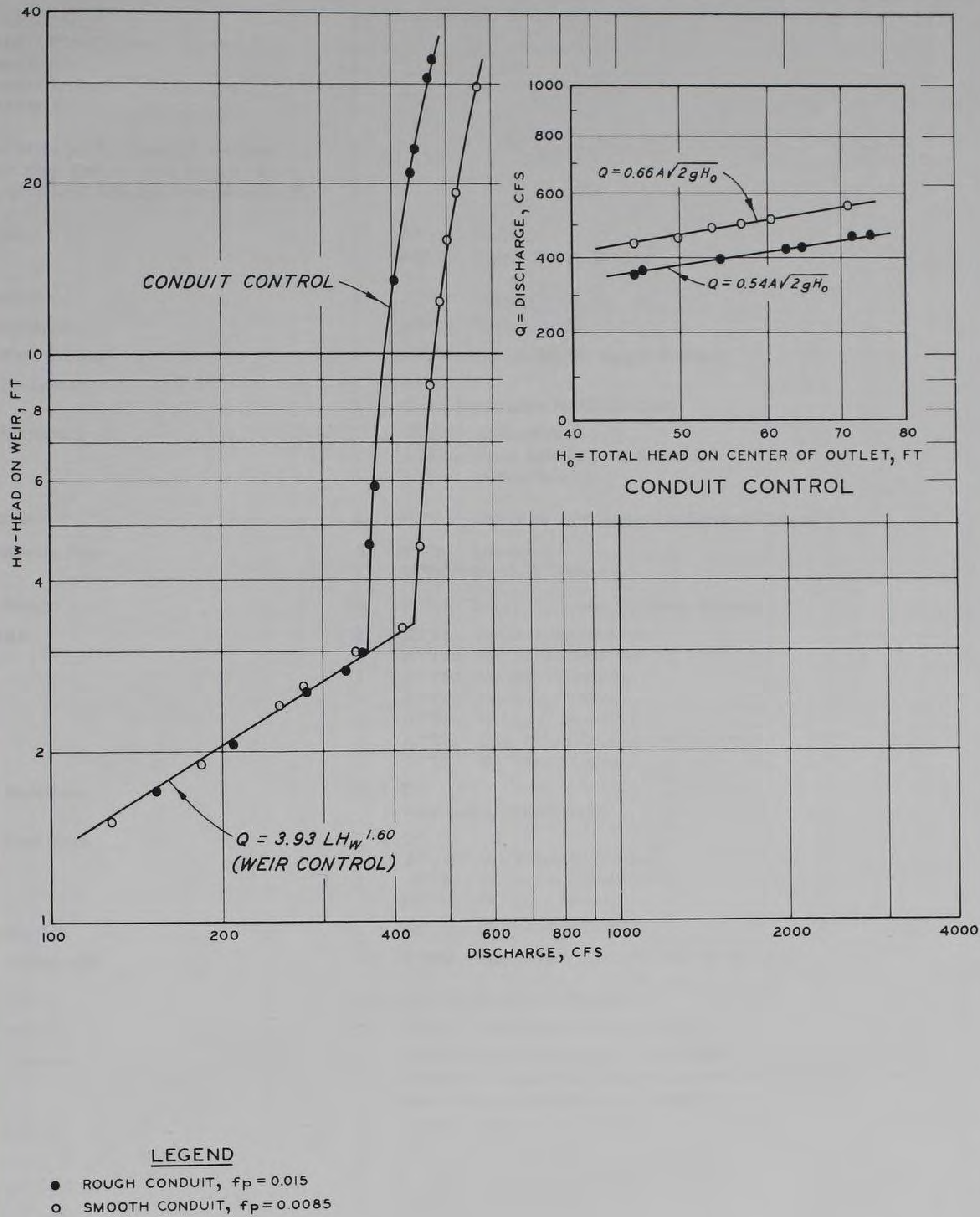
COTTONWOOD SPRINGS OUTLET WORKS



DISCHARGE CHARACTERISTICS

COTTONWOOD SPRINGS OUTLET WORKS

3D-LONG COMPOUND CURVE WEIRS



DISCHARGE CHARACTERISTICS
COTTONWOOD SPRINGS OUTLET WORKS
2D-LONG COMPOUND CURVE WEIRS

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13. ABSTRACT
Model investigations of the outlet works for Branched Oak and Cottonwood Springs Dams were primarily concerned with hydraulic operating characteristics over a wide range of heads. Although the structures were similar in design and purpose, geometric differences required the use of separate model studies, which were conducted with 1:10-scale models that reproduced portions of the approach area, the intake structure, and the outlet conduit. The Branched Oak model also reproduced an SAF impact-type stilling basin and downstream exit channel. Both models indicated undesirable flow characteristics such as nappe flutter, sloshing, and gulping which tended to vibrate the structures. Tests indicated that the flutter could be eliminated by rounding the weir crests; the nappe sloshing could be eliminated by providing a divider wall between and parallel to the weir crests; and the gulping beneath the cover plate eliminated by placing the cover plate at an elevation above that of the upper pool when the conduit begins to control flow. Performance of the original design SAF basin was satisfactory and the height of the basin training walls was sufficient to prevent overtopping. The exit channel was sloped downward and expanded laterally to permit dissipation of excess energy in turbulence rather than direct attack of channel boundaries. A riprap plan of protection was developed for the recommended exit channel configuration.

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