DIVERSION, POWER AND IRRIGATION TUNNELS HYDRAULIC MODEL STUDIES

TARBELA DAM PROJECT
INDUS RIVER
WEST PAKISTAN

CIVIL ENGINEERING DEPARTMENT

ENGINEERING RESEARCH CENTER
COLORADO STATE UNIVERSITY
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FINAL REPORT

OF

HYDRAULIC MODEL STUDIES

FOR

DIVERSION, POWER, AND IRRIGATION TUNNELS

TARBELA DAM PROJECT
INDUS RIVER
WEST PAKISTAN

Prepared for
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by

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PREFACE

The Engineering Research Center at Colorado State University is located between two lakes, Horsetooth Reservoir of the Colorado Big Thompson Project, and College Lake. The laboratories of the Center were strategically placed to utilize the high head, 250 feet, available from the reservoir and the storage capacity of the lakes. The Center is the focal point for research and graduate education.

There are four principal parts to the Center: the offices for staff and graduate students, the hydraulics laboratory, the fluid dynamics laboratory, and the outdoor hydraulics - hydrology laboratory. The research activities of the center are fluid mechanics, hydraulics hydrology, ground-water, soil mechanics, hydro-biology, geomorphology and environmental engineering.

The hydraulics laboratory includes 50,000 square feet of floor space in which basic and applied research activities are undertaken. The floor of the laboratory is constructed over a large sump system, having one acre foot capacity, which permits recirculation of water through the various research facilities. Generally, pumps are used for recirculation but the high head and large flow capacity from the reservoir can also be utilized.

The Center includes well equipped machine and woodwork shops. All research facilities of the Center are constructed on site and in the case of this model study, necessary metal work, carpentry, and nearly all the plastic work was done by personnel in the shops. The shop personnel are particularly well experienced in the art and skill of model construction.

This model study was undertaken by Colorado State University with close coordination with Tippetts-Abbett-McCarthy-Stratton (TAMS) of New York, for whom this work was done. The urgent need of hydraulic information for purposes of planning and design was recognized from the beginning and all information obtained from the model studies relevant to those purposes were transmitted to TAMS in advance of this report. Decisions affecting model construction tests or testing program, or time schedules were made with mutual consent through assessment of appropriate information and consideration and accord with project planning.

Grateful acknowledgement is hereby expressed by the writers to personnel at TAMS for their cooperation, to personnel of the shops for their ingenious contributions in solving model construction problems, particularly in the plastic works, and to others contributing to the model study and the preparation of this report.

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SUMMARY

Hydraulic model studies were performed for the tunnels of the Tarbela Dam to be used for diversion, power and irrigation. Specific studies were made on entire models of Tunnels 1 and 3 and portions of Tunnel 4.

Tunnels 1 and 2 will operate satisfactorily for diversion as designed excepting that a slight modification to the outlet deflector is suggested.[1] The modification involves increasing the height of the wall by 15 feet and increasing the angle of deflection a slight amount to keep the jet away from the stilling basin of Tunnel 3. If the three intake gates are closed individually, large unbalanced forces will develop across the piers in the intake; these forces will be avoided if the gates are closed in unison. Air vents are suggested at all intake gate chambers to prevent low pressures from developing in the tunnel during gate closure. The temporary flow ceiling in the tunnels below the vertical power intake shafts need not be constructed from the viewpoint of hydraulic conditions. Tunnel 1 will operate satisfactorily as a power tunnel. When the service gates in the central gate chamber are used to shut off the flow under emergency conditions, large unbalanced forces will develop across the pier in the gate chamber if the gates are closed individually but will be avoided if they are closed in unison.

Tunnels 3 and 4 are satisfactorily designed and will operate effectively provided the radial gates are closed or opened nearly in unison. If one gate is full open while the other is half open, a local cavitation area will develop at a point near the crotch of the bifurcation. Provided the radial gates have nearly the same opening and are opened or closed nearly simultaneously, low pressure will not develop.

The walls immediately downstream from the radial gates should be constructed as shown in Scheme A (Figure 4) to prevent water fins from developing at the wall and causing spray into the gate chamber and over the walls of the chute. The divider wall of the chute may be omitted, for it had no effect on the hydraulic jump in the stilling basin. The chute curvature was satisfactory. The stilling basin performed satisfactorily for all reservoir levels below 1425 and was indeed satisfactory also at maximum reservoir level of 1550 from the standpoint that scour at the end of the basin was not enough to endanger the structure. The model construction, and details of the tests performed are described in this report.

[1] Decision to include construction of the first stage of the powerhouse concurrently with the dam was made after completion of these tests and resulted in elimination of the outlet deflector.

I. INTRODUCTION

General Description of Project[2]

Tarbela Dam, proposed for construction on the upper Indus in West Pakistan, is a major feature in the system of works implementing the Indus Waters Treaty and the Indus Basin Development Fund Agreement of 1960. The dam site is some 29 miles upstream from the Attock bridge, which is about midway between Rawalpindi and Peshawar in the northern part of West Pakistan. In its initial stage, the project will provide 6.6 MAF of live storage on a river where the average annual unregulated flow is 61 MAF. It will be the first step in a long-range plan to develop extensive off-channel storage. It will also make possible an ultimate installed hydroelectric generating capacity of 2,100,000 KW.

The dam, shown in Figure 1, consists of an embankment across the 9,000-foot width of the main river valley, a group of 4 tunnels in the rock of the right abutment to provide for irrigation releases and future power, two saddle spillways cut through the rock of the left bank and discharging into a side valley, and two auxiliary embankment dams to close the upstream end of the side valley.

The Tarbela reservoir will have an ultimate gross storage capacity of 11.1 MAF (elevation 1550) and a capacity at the assumed minimum drawdown of 1.8 MAF (elevation 1300), leaving a net usable capacity of 9.3 MAF. In the case of 2-stage construction, the initial stage would provide a net usable capacity of 6.6 MAF (elevation 1500) upon completion. The assumed minimum level of drawdown, elevation 1300, will provide a depth of 200 feet of water at the dam. The full reservoir depth will be 400 feet for stage I and 450 feet for the completed project.

The main embankment dam will be constructed using material excavated from the spillway channel and from the tunnels and diversion channel; additional material required will be obtained from nearby borrow areas. The two saddle spillways on the left bank will have conventional overflow crests with radial gates and will discharge into channels leading to the large excavated channel along the natural side valley, the Dal Darra, which returns to the main Indus downstream of the dam. The total spillway capacity will be about 1,400,000 cfs at full reservoir level for both stages of construction.

The four tunnels will follow a curved alignment through the rock abutment at the right end of the dam. They will serve for river diversion during the final stage of construction, and ultimately for power and irrigation releases. Tunnels 1 and 2, closest to the river channel, will be reserved for future power; each tunnel will serve a group of 4 turbines and generators, each of 175,000 KW capacity. As initially constructed, the tunnels will be concrete lined throughout; later, when the power units are installed, they will be lined with steel downstream of the gates, located in mid-tunnel shafts. Tunnels 3 and 4 will be used for diversion during construction and later for irrigation releases. Each will be equipped with shut-off gates in a mid-tunnel shaft and with a Y-branch leading to a pair of radial control gates at the outlet. These tunnels will be concrete lined upstream and steel lined downstream of the shut-off gates. Tunnel 3 will eventually be converted to serve the third stage of power development.

Description of the Tunnels

The geometric alignment of the four tunnels in plan and their relative location one to another is shown in Fig. 2. The relative location of the tunnels with respect to the dam can be seen in Fig. 1. Profiles of the tunnels to indicate slope and some details are also given on Fig. 2, while further dimensional details of the intake structures, gate sections, transitions, and outlet works are given in Figures 3 and 4.

The tunnels are numbered 1 through 4 top to bottom, on Fig. 2 (left to right as viewed by an observer looking downstream) and the method of reference to the various tunnels hereafter in this report will be by numbers, for example as tunnel 3. All the tunnels are essentially parallel in horizontal alignment, although they vary in diameter and in slope.

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[2] The project is described as conceived prior to completion of the work covered by this report, i.e., as the first stage of a two-stage project. Subsequently, the concept was changed to include immediate construction of the dam for full reservoir level (El. 1550) and of the portion of the power plant served by Tunnel No. 1, resulting in changes in some of the features described herein.

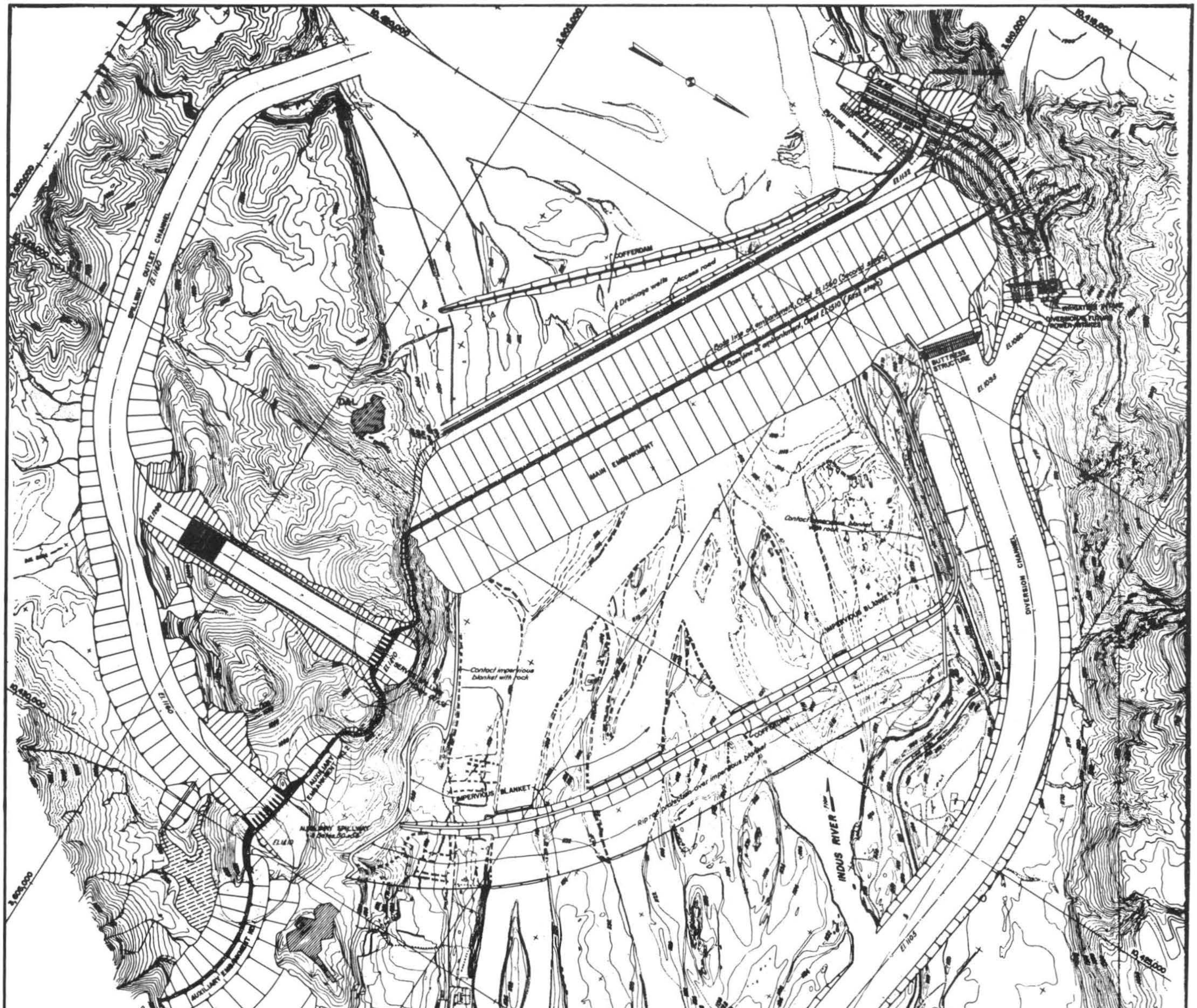


FIGURE 1 GENERAL PLAN OF DAM

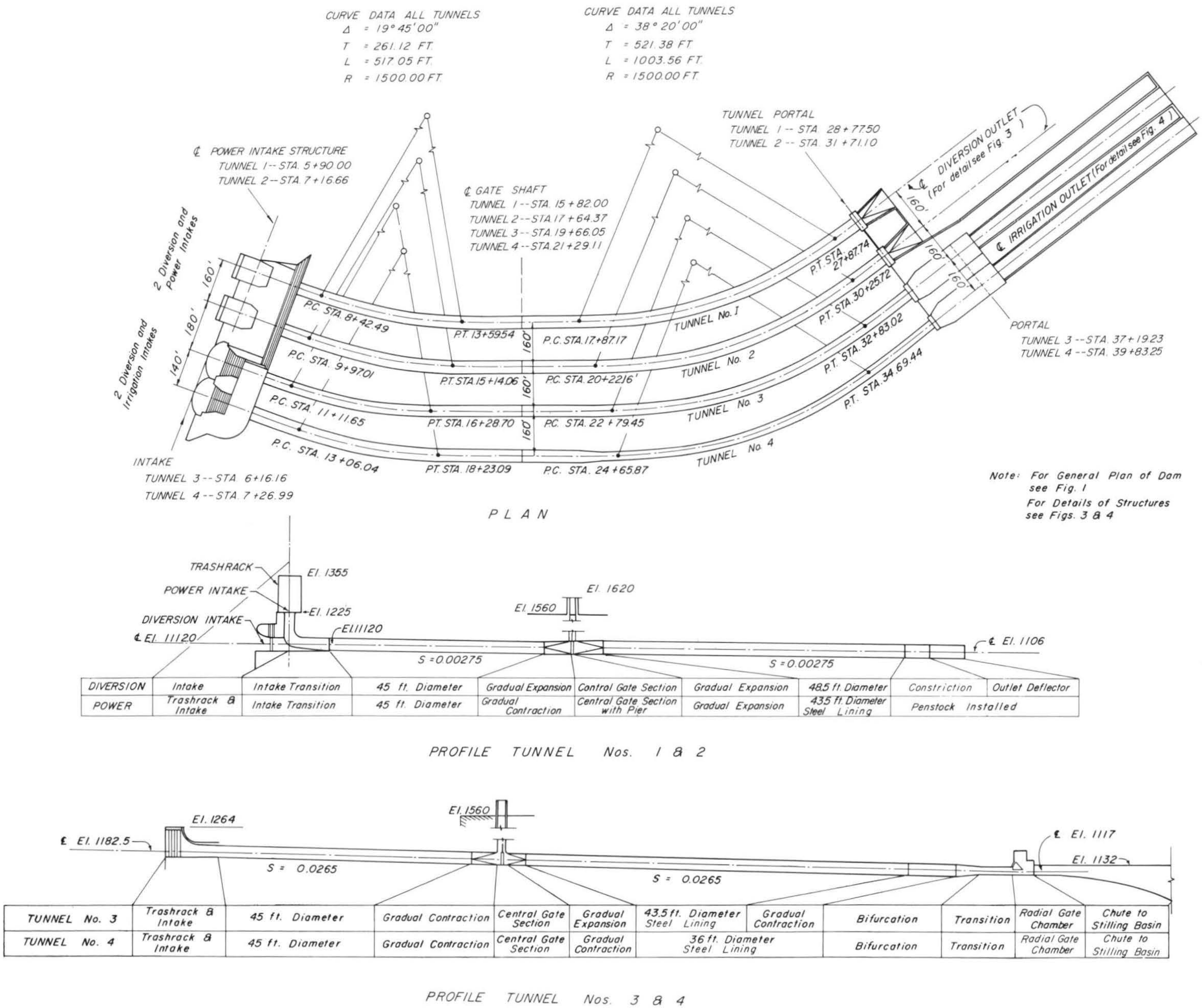


FIGURE 2 GENERAL ALIGNMENT OF TUNNELS

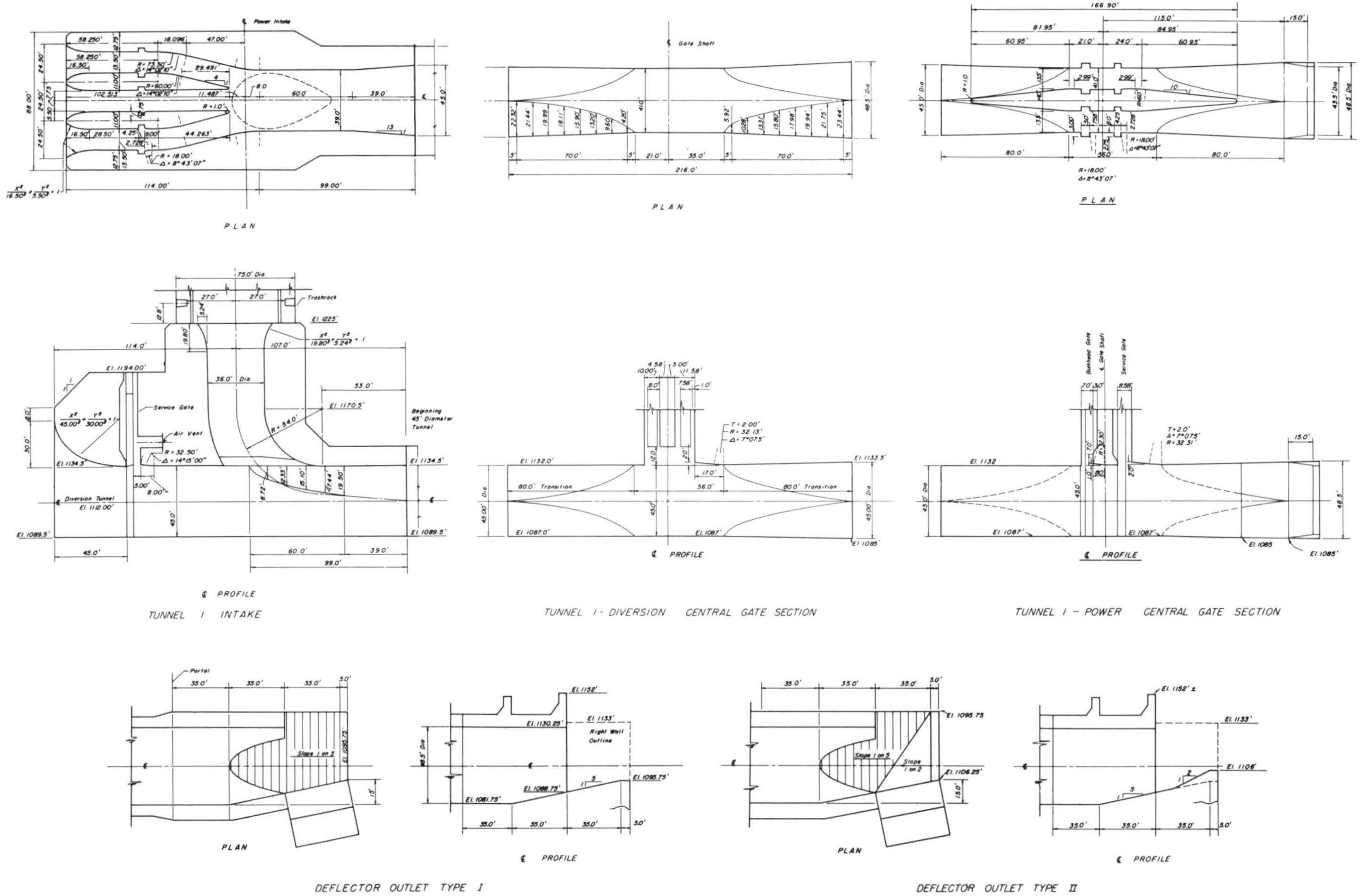


FIGURE 3 TUNNEL I DETAILS OF STRUCTURES

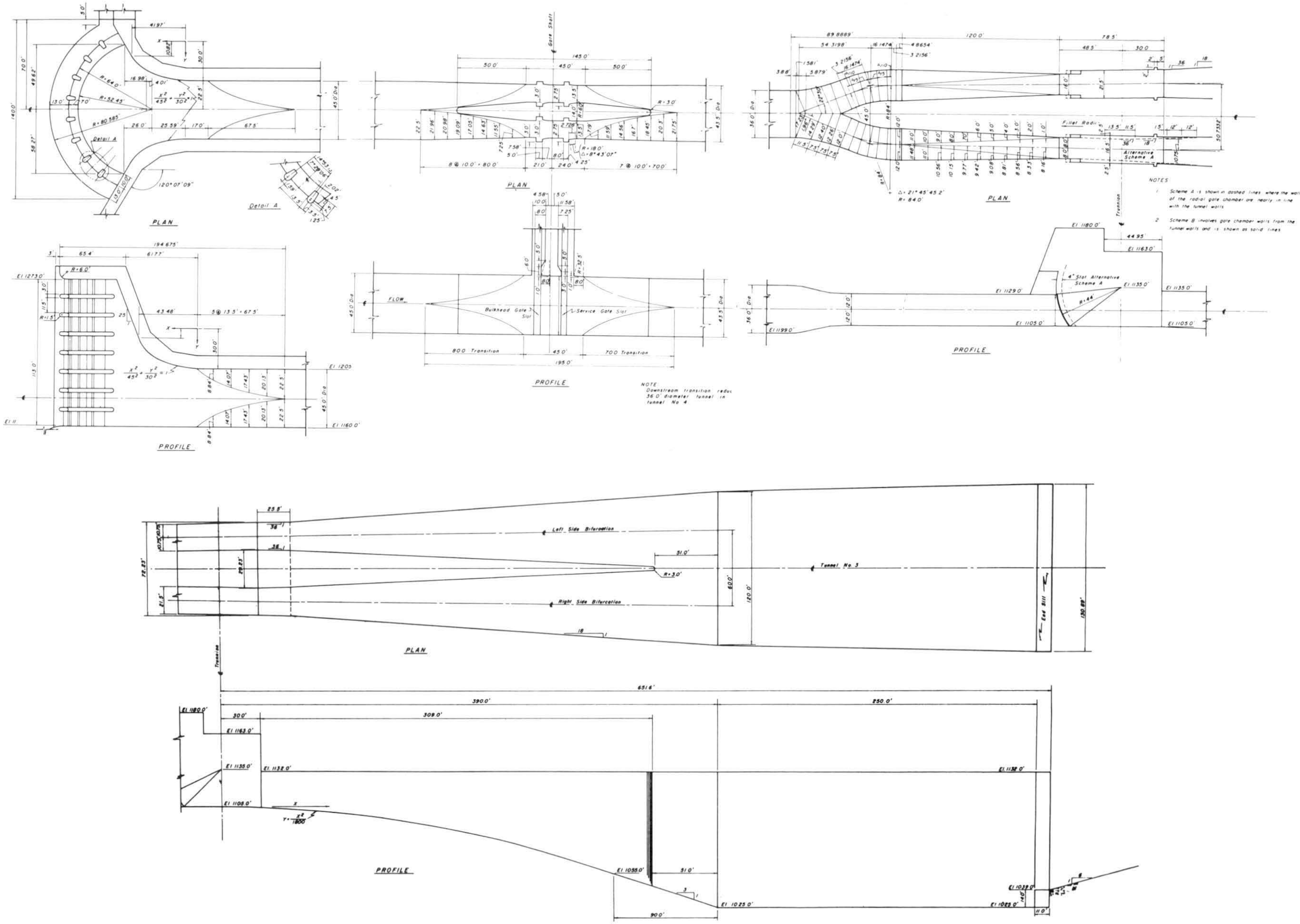


FIGURE 4 TUNNEL 3 - DETAILS OF STRUCTURES

The diversion intake structure to Tunnel 1 (see Fig. 3; identical for Tunnel 2) is 73.5 feet wide and 75 feet high at the entrance. The floor of the intake is level at elevation 1089.5 feet.[3] There are three vertical fixed-wheel gates with net openings 13'6" wide by 45' high in the intake structure which will be used to close the diversion tunnel.

The gate shafts are sealed at elevation 1194 and air vents will be connected to the gate chambers.

The 36-foot diameter vertical shaft which will form the permanent intake for power will be sealed by a hemispheric bulkhead at the entrance, elevation 1225. The plans provide for construction of a temporary roof between the vertical shaft and the horizontal tunnel at the intersection, with holes in the roof to enable equalization of pressure above and below. Possible need for this roof was subject to model investigation.

The size of all tunnels extending from the entrance structures to the central gate chamber is 45 feet in diameter with appropriate transitions for changes in shape from circular to rectangular or vice versa. Downstream from the gates Tunnels 1 and 2 are 48.5 feet in diameter which will be reduced to 43.5 feet by installation of steel liners when the power plant is constructed. Tunnel 3 is 43.5 feet in diameter and Tunnel 4 is 36 feet in diameter.

Outlet constrictions are contemplated for Tunnels 1 and 2 to prevent negative pressures along the crowns of the tunnels near the portals and deflectors are considered essential to deflect the flow, especially at Tunnel 2, to protect the base of the stilling basin wall of Tunnel 3 from scour. Outlet structures, types I and II shown in Fig. 3 were suggested for study in the model. Other possible arrangements were to be included in studies with the general river model in Pakistan.

The central gate chambers house two vertical lift service and two emergency bulkhead gates in all the tunnels. The gates, gate slots, and center wall in Tunnels 1 and 2 will be constructed after the diversion is completed and conversion is made to power tunnels. All service gates and bulkheads have net openings 13'6" wide by 45' high. The service gates are designed to close against the flow, while the bulkheads will close only under balanced pressure conditions.

Radial control gates will be required at the outlets of Tunnels 3 and 4 to regulate the discharge and in order to keep their sizes within reasonable proportions the flow in each of these tunnels will be divided by a wye branch at the outlet. Even so, the radial gates will be 16 feet wide and 24 feet in vertical height. Two schemes were considered for alignment of walls in the radial gate structure in relation to the walls of the tunnels. Both schemes are shown in Fig. 4. In Scheme A a nearly in-line arrangement is shown with gate slots for the radial gates, while in Scheme B the walls were offset by 2.5 ft.

Downstream from the radial gates, stilling basins of very large sizes will be required to dissipate the energy. The chute length in the approach to the stilling basin is 390 feet with a divider wall to permit gradual merging of the flow from both legs of the wye branch. The stilling basin itself is 250 feet long with walls 107 feet high. There is a square end-sill 14 feet high at the end of the stilling basin. Variation in length of the chute divider wall was investigated in the tests. The results were coordinated with those from Nandipur, where a model of the two stilling basins and exit channel was operated concurrently with the tests described herein.

Proposed Tunnel Operation

River diversion through the tunnels will occur after the wet season of the year in which the final portion of the main embankment is to be completed. The gates of the buttress structure shown in Fig. 1 will be lowered, closing the last remaining waterway in the river valley and forcing the flow into Tunnels 1 and 2. Prior to this time, Tunnels 1 and 2 will have been completed, incorporating the river-diversion features described earlier; Tunnels 3 and 4 will have been completed in their final form; and a plug of rock temporarily closing the tunnel entrance channel will have been removed.

During the diversion period, each of the Tunnels 1 and 2 will remain open until its diversion capacity is no longer needed. At that time it will be closed, and it will remain closed thereafter. As the season advances, both the anticipated flood flows to be carried by the tunnels and the capacity of the tunnels will vary. Immediately after diversion, the anticipated peak dry season flows will be relatively small, but the available head on the tunnels and reservoir storage will also be small. As the embankment closure section rises, the four tunnels will be capable of passing increasingly greater reservoir inflows because of the increase in available head and storage. By the beginning of the wet season, the capacity of the four tunnels will have increased enough to pass safely the much greater wet season flows anticipated. By the middle of the wet season, the four tunnels will provide sufficient excess diversion capacity to permit the final closure of first one, and then the other of Tunnels 1 and 2.

Early closure of these tunnels and judicious operation of the gates in Tunnels 3 and 4 will make possible significant storage of water during the period preceding full completion of the embankment. A procedure has been devised to determine the earliest dates on which the closure may be effected without endangering the uncompleted dam. This procedure is to be applied in the field and will take cur-

[3] All elevations or levels expressed in numbers in this report will be understood to have the dimensions of feet whether or not it is explicitly stated.

rent conditions of reservoir level and embankment height into account in scheduling the closures. The highest reservoir level that may occur before the diversion tunnels are closed is elevation 1500, approximately.

After final closure, Tunnels 1 and 2 will be prepared for their ultimate use. The diversion intakes will be sealed off; the central gate structures completed, and the vertical intakes opened. Tunnels 3 and 4 will continue to be operated to furnish water for irrigation.

Scope of the Model Study

The purpose of the model studies was to investigate the hydraulic conditions within the tunnels for the entire range of possible discharges and velocities. The objectives for the different tunnels are listed separately below:

A. Tunnel No. 1 (Tunnel No. 2 similar)

1. Diversion (with flow ceiling below the vertical shaft)

(a) Determine through visual observation, photographs, and pressure data the flow characteristics throughout the tunnel for the range of expected discharges.

(b) Measure low pressures if any, on the boundaries.

(c) Determine the most suitable closure sequence of the diversion intake gates.

(d) Measure the air demand in the model at the intake gate shafts.

(e) Determine the magnitude of the unbalanced pressures on the piers within the intake structure.

(f) Calculate the form loss coefficients at the entrance and at changes in cross-section of the tunnel.

(g) Study the effect of outlet constriction at the tunnel portal and the deflector.

2. Diversion (with flow ceiling removed)

Evaluate the flow conditions at the junction of the vertical shaft with the horizontal tunnel during diversion and gate closure.

3. Power

(a) Investigate possible low pressure areas on the walls of the vertical shaft and transition to the horizontal tunnel.

(b) Study hydraulic conditions at all tunnel sections and in particular at the central gate structure during normal operation of the powerhouse, during failure of a penstock, and during emergency service gate closure.

(c) Determine the magnitude of pressure differences across the pier in the central chamber during unequal service gate closure.

(d) Determine form loss coefficients.

B. Tunnel No. 3

Irrigation

(a) Observe flow conditions and measure pressures through the tunnel for the full range of expected discharges.

(b) Measure low pressures within the intake structure, transitions, and sections involving changes in geometry.

(c) Determine magnitude of differential hydraulic pressures at the pier in the central gate structure.

(d) Determine form loss coefficients.

(e) Measure pressures in the bifurcation with equal, and various combinations of unequal flow.

(f) Determine which of the two alternatives proposed for the walls beyond the radial gate will be most satisfactory.

(g) Investigate performance of the chute and stilling basin.

C. Tunnel No. 4

Irrigation

Determine possible differences in flow and pressure conditions at the bifurcation due to change in diameter of the tunnel from 43.5 ft in Tunnel 3 to 36 ft in Tunnel 4.

Chronology of Model Tests

The model was designed to utilize the same head box and tail box arrangements for testing all tunnels. The intakes for the diversion and power phases on Tunnel 1 were modeled separately, and later when observations for both phases were satisfactorily completed, the two intakes were joined to investigate the effects of eliminating the temporary roof at the junction of the vertical shaft with the horizontal tunnel.

Tunnel 1 for diversion was tested initially. The complete tunnel as designed was assembled prior to obtaining any test results. When the tests were completed the tunnel was changed to represent the power phase without inclusion of the power plant or manifold to the turbines. The discharge was controlled by a restriction at the tunnel outlet.

The complete arrangement of Tunnel 3 was tested next including the radial control gates and the stilling basin, followed by tests to determine the effects of the tunnel diameter change for Tunnel 4. At the completion of these studies the combined diversion-power intake for Tunnel 1 was installed and tested.

Evaluation of all model data obtained from tests along with tests and re-runs, additional testing and verification of data were accomplished with minimum down-time resulting from model changes.

Selection of Scale and Model Criteria

Similitude in the sense used here is the indication of full scale phenomena based on smaller models. Since the objectives of the models were to develop kinematically and dynamically similar flows to the prototype, it is clear that geometrical similarity must be maintained. Dimensional analysis will show both Froude and Reynolds numbers to be dominantly important for the objectives of this study. For instance, in the open channel flow aspects of the model the effects of the Froude number are more important than those of the Reynolds number, but for closed conduit flow the reverse is true. It is not possible to achieve conformance of both Froude and Reynolds numbers simultaneously, for a fluid does not exist which provides the required ratio of density to viscosity. Therefore, it was necessary to select the Froude criterion in determining the geometric scale with the knowledge that some scale effects, that is, departure from strict dynamic similitude, would exist within the confines of the tunnel under full flow.

Analysis of several model scales from considerations of the nature of the data required, conditions of flow, laboratory space and economy of cost indicated that a model-to-prototype ratio of about 1:70 was most feasible. The actual scale selected for all models in this study was 1:69.6. This scale was determined by the available sizes of commercially manufactured cast acrylic resin tubes which were used to represent the different diameter tunnels.

With reference to the scale effect mentioned earlier, the greater wall roughness in the plastic pipe as compared to the theoretically scaled roughness of the concrete and steel lined walls of the prototype created head losses that were greater in the model as compared to the prototype. To adjust for this greater head loss, it is possible to reduce the length of the model tunnel, or to increase the slope of the tunnel as compared to the prototype, or to use a combination of the two methods. It is to be noted however in passing, that whichever method is utilized, the adjustment serves only a small range of discharges because a single adjustment cannot account for changing wall friction factors with Reynolds number in the full range of discharges. Since it did not appear practical in this study to reduce the length of the model tunnel without affecting the distribution of velocities within the tunnel, the model slope was increased. Two slopes were utilized in the tests of the diversion phase of Tunnel 1 to reproduce flows for a discharge range of from 110,000 to 140,000 cfs (slope .0114) and from 10,000 to 40,000 cfs (slope .003). No slope adjustment or tunnel length adjustments were made for Tunnels 3 and 4. Some characteristic ratios between model and prototype are given in Table 1 at the selected model scale.

TABLE 1

MODEL-PROTOTYPE SCALE RATIOS

Parameter	Scale Ratio		Absolute Magnitudes	
	Function of the Length	Numerical Ratio	Prototype	Model
Length	L_r	1:69.6	1 ft	0.172 in.
Area	L_r^{2}	1:4844	1000 ft^2	0.206 ft^2
Velocity	$L_r^{1/2}$	1:8.343	1 ft/sec	0.120 ft/sec
Discharge	$L_r^{5/2}$	1:40413	100,000 cfs	2.474 cfs
Time	$L_r^{1/2}$	1:8.343	1 min	7.19 sec

II. TUNNEL NO. 1 - DIVERSION

Model Construction

The general limits of the model for Tunnel 1 are shown in Fig. 5, where the overlapping limit lines result because Tunnels 1, 3, and 4 were modeled individually and the same model head box and tail box arrangements were used. Only significant segments of the reservoir and downstream river bed were included in each model. Dimensions of the model facilities and actual laboratory arrangement are given in Fig. 6 and a photograph of the completed construction of the model for Tunnel 1 is added in Fig. 7 to assist the reader's perspective and appreciation of physical model size.

The head box was constructed of plywood and waterproofed with fiberglass lining. The inside dimensions were 10 ft wide by 10 ft long and 8 ft deep. Plexiglass windows were installed in portions of two adjacent walls (see Fig. 8) to facilitate visual observation of the intake models for diversion and power which projected into the headbox.

The tail box was constructed to the size indicated in Fig. 6. The areal extent of the box representing corresponding areal coverage of the river was considered sufficient to provide effective control of the river tail water level. It was not deemed necessary to include a greater area of the river because simultaneously with this model, studies were being conducted on a general river model in Nandipur, Pakistan, where more realistic relative effects of tunnel discharge and river flow could be investigated.

Water was supplied by a 14 inch turbine pump to the head box. The reservoir water level was regulated by an 8-inch bypass at the pump and an 8-inch control valve at the head box. These features are indicated in Fig. 6. A rock baffle was utilized to develop uniform approach conditions to the tunnel intake. Topography of the approach channel to the intake within the reservoir was not reproduced in the model. The velocity of approach flow in the head box was designed to be small to be assured that no artificial effects would be created in the model to influence the results. Discharge measurements through the tunnel were made with a calibrated 120^0 weir in a weir box placed downstream of the tail box. The tailwater, or downstream river level was controlled by a hinged gate at the entrance to the weir box.

The diversion intake, gates, transitions, and tunnels were constructed with clear plexiglass to facilitate visual flow observations. The curved wall sections of the intake structure were heat molded to shape over templates which were modeled carefully to the prototype dimensions given in Fig. 3. The piers, gates and all straight sections were machined from solid pieces of plexiglass stock. A view of the completed intake model and transition as attached to the head box is shown in Fig. 9. The horizontally curved circular tunnel sections were molded from straight cast acrylic plastic tubes. The tubes were filled with hot oil and by controlling both pressure and temperature, the tubes were molded to desired curvature within a preformed exterior plaster of paris mold.

The outlet deflector for Tunnel 1 was constructed of wood and coated with a thin layer of fiberglass resin for protection from water. In general, all wood surfaces exposed to water were treated with fiberglass resin.

The locations of the many piezometers used to measure pressures at the boundaries along the tunnel are shown in the following figures:

- Figure 10 - piezometer locations in the diversion intake wall.
- Figure 11 - intake pier piezometer locations.
- Figure 12 - locations along the centerline of the intake.
- Figure 13 - piezometer locations in the intake transition.
- Figure 14 - piezometer locations along the tunnel.
- Figure 15 - piezometer locations in the central gate section and the adjoining transitions.

After testing was completed on the power intake (described hereinafter), the vertical shaft of the power intake was joined with the diversion intake structure as shown in Fig. 16 to make a new model to determine the effects on the flow in the tunnel with the ceiling removed. The vertical shaft was sealed at the top by a flat plate rather than with a hemispheric bulkhead, but the difference would not have any effect on the tests. A petcock was attached to the plate to permit release of air trapped in the vertical shaft. Piezometers were installed at specific locations given in Fig. 17 to measure pressures in the crown of the tunnel downstream of the junction.

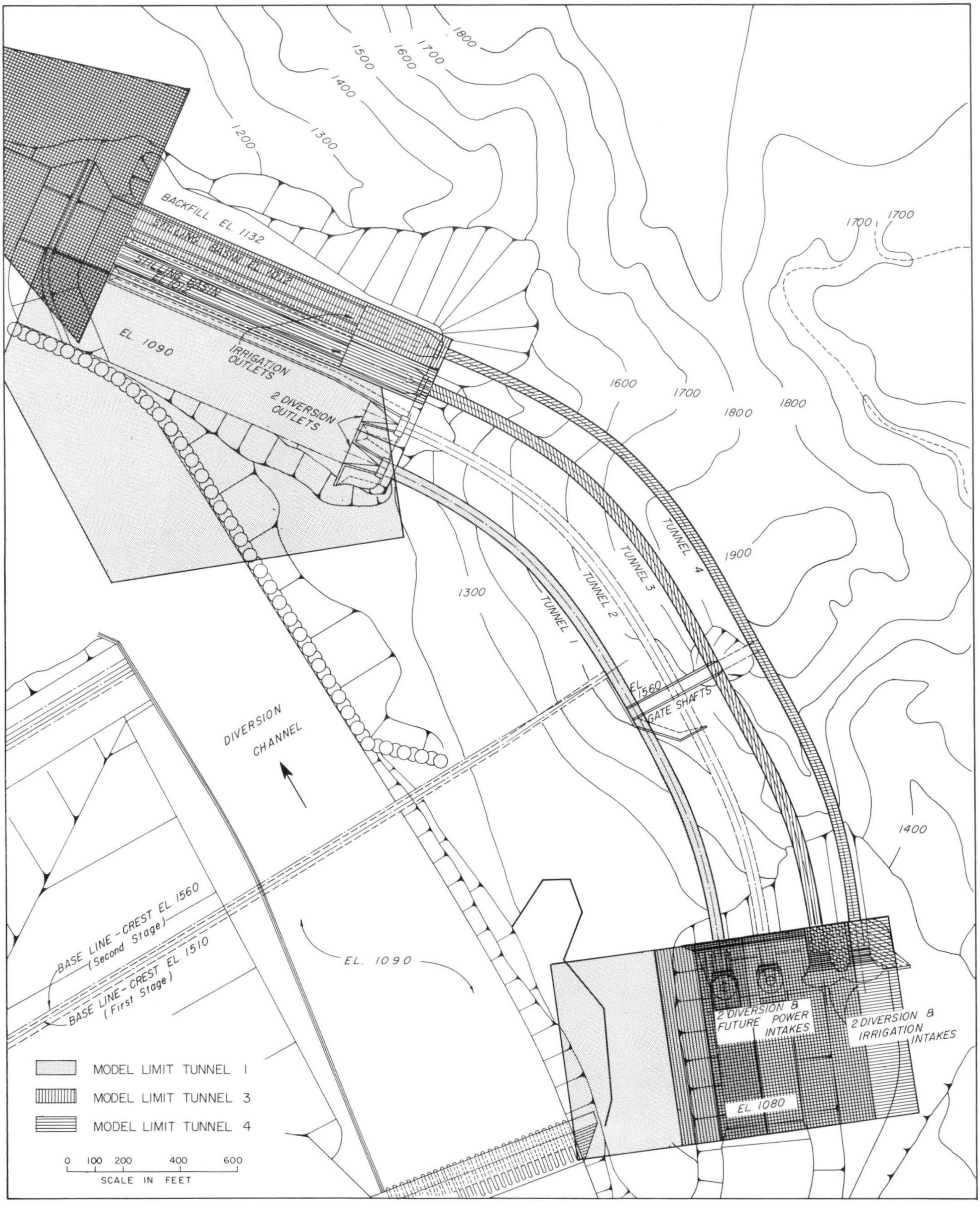


FIGURE 5 GENERAL PLAN LIMITS OF MODEL CONSTRUCTION

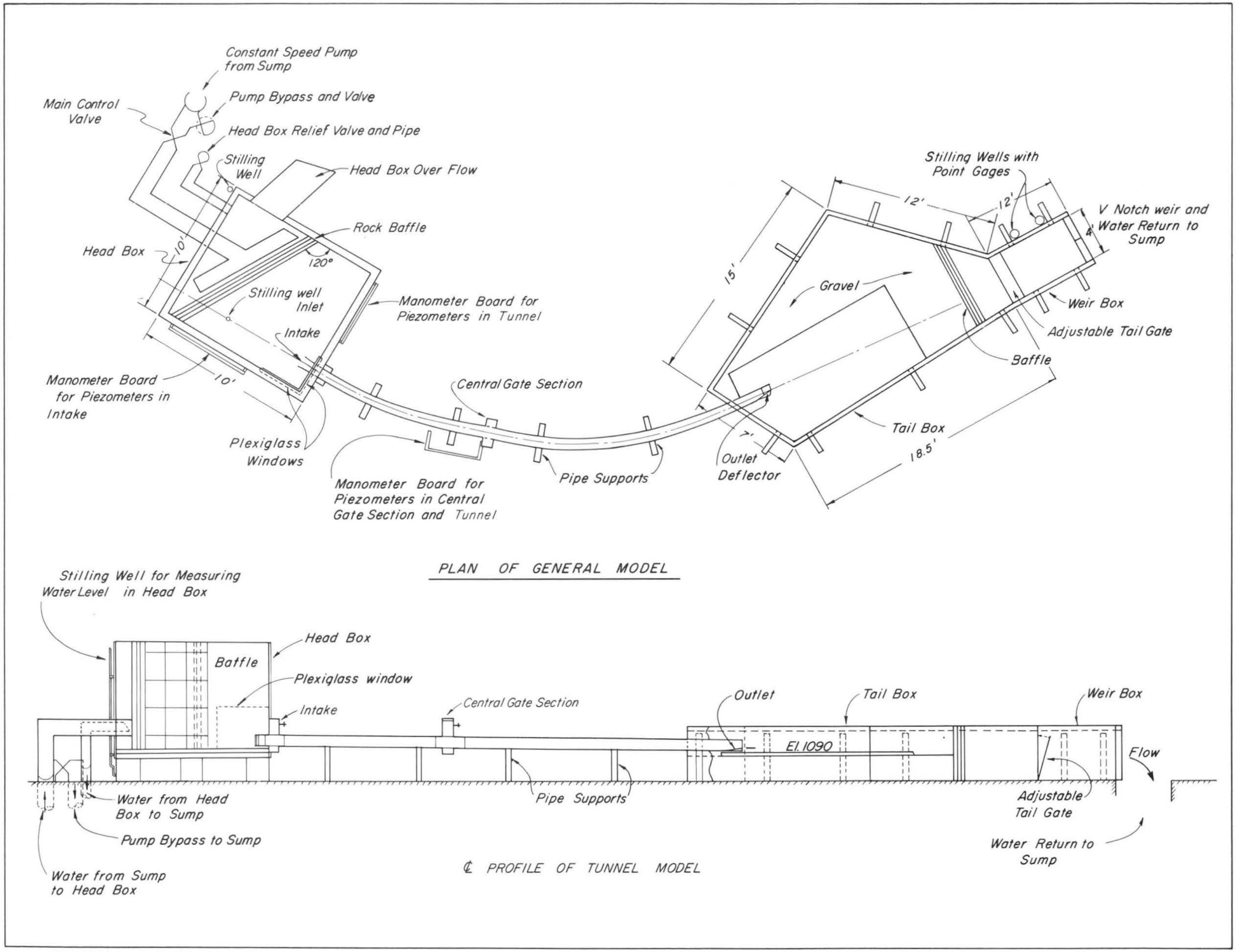


FIGURE 6 SCHEMATIC DRAWING OF GENERAL MODEL

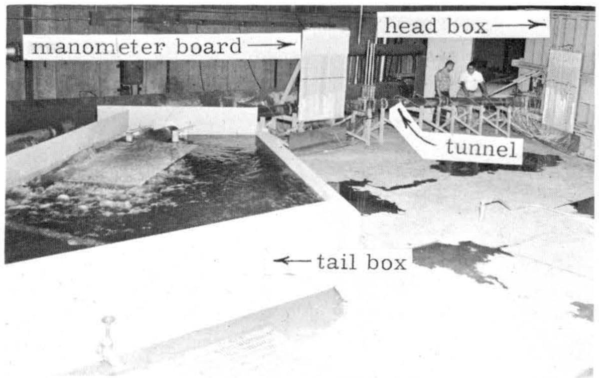


Fig. 7. Photograph of completed model.

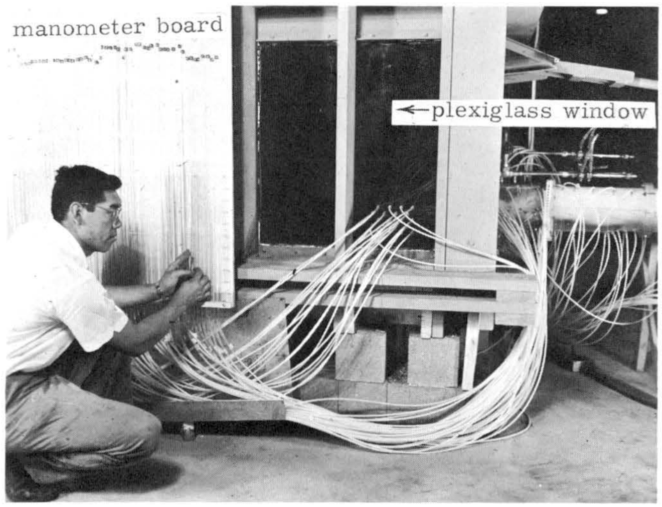


Fig. 8. View of the plexiglass window in the side of the head box.

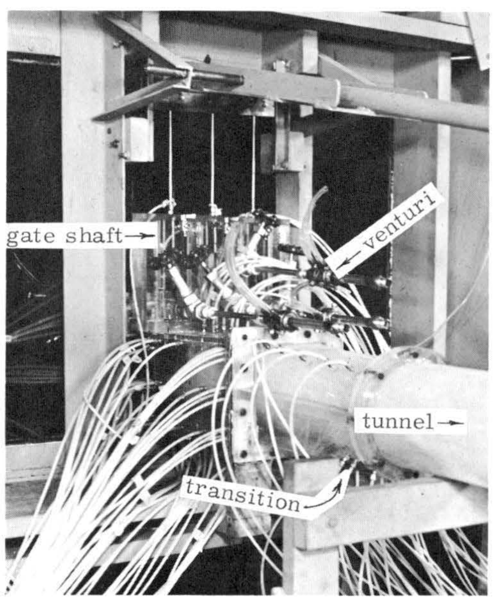
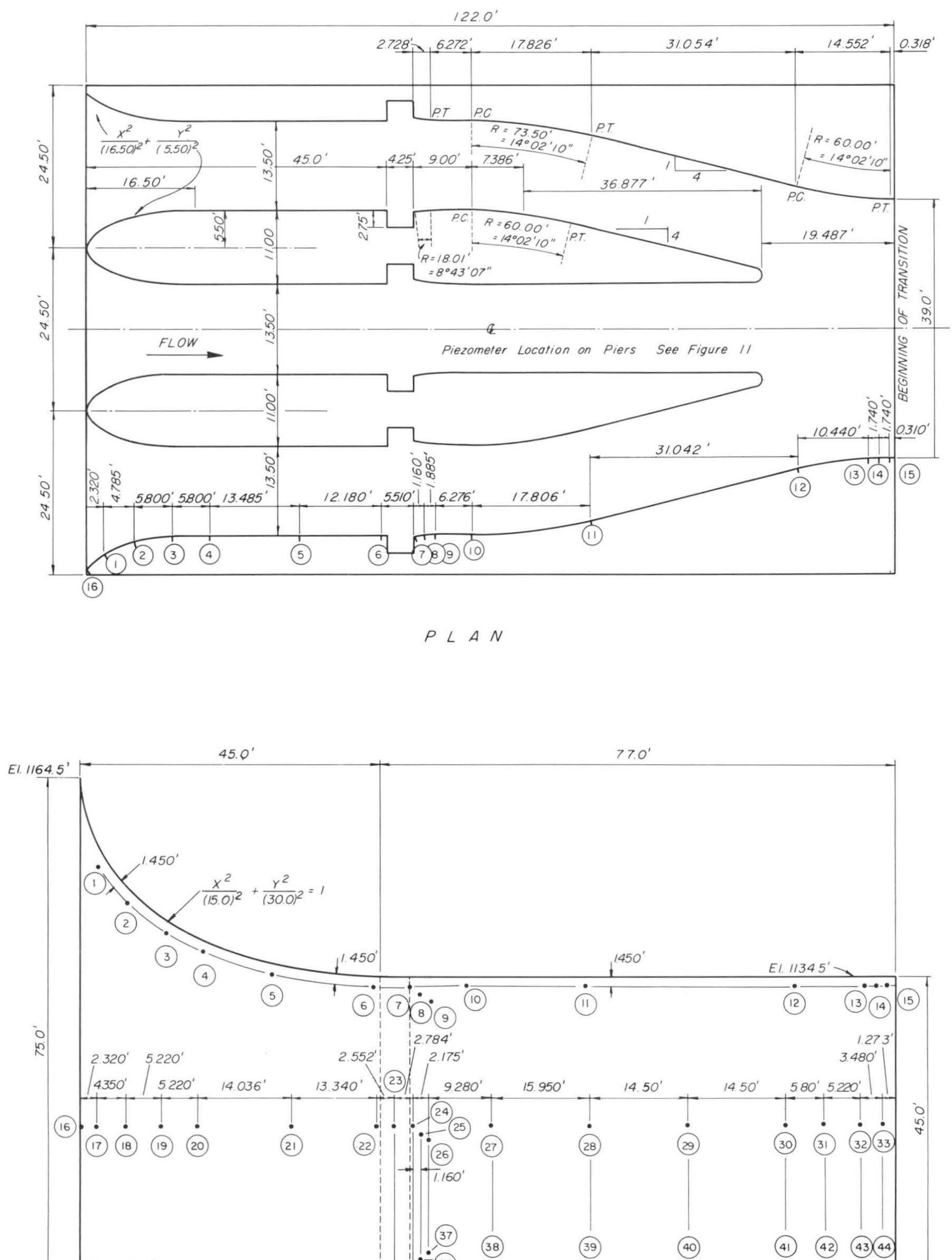


Fig. 9. Intake, gates, air vents, and transition tunnel 1 - diversion.



Piezometer Number	Elevation In Feet
1	1152.1
2	1146.5
3	1141.7
4	1138.5
5	1134.3
6	1133.0
7	1133.0
8	1132.0
9	1130.9
10	1133.0
11	1133.0
12	1133.0
13	1133.0
14	1133.0
15	1133.0
16 - 24	1112.1
25	1110.8
26	1109.8
27 - 33	1112.1
34, 35	1090.9
36	1092.2
37	1093.4
38 - 44	1090.9

FIGURE 10 TUNNEL 1 – DIVERSION INTAKE WALL PIEZOMETER LOCATION

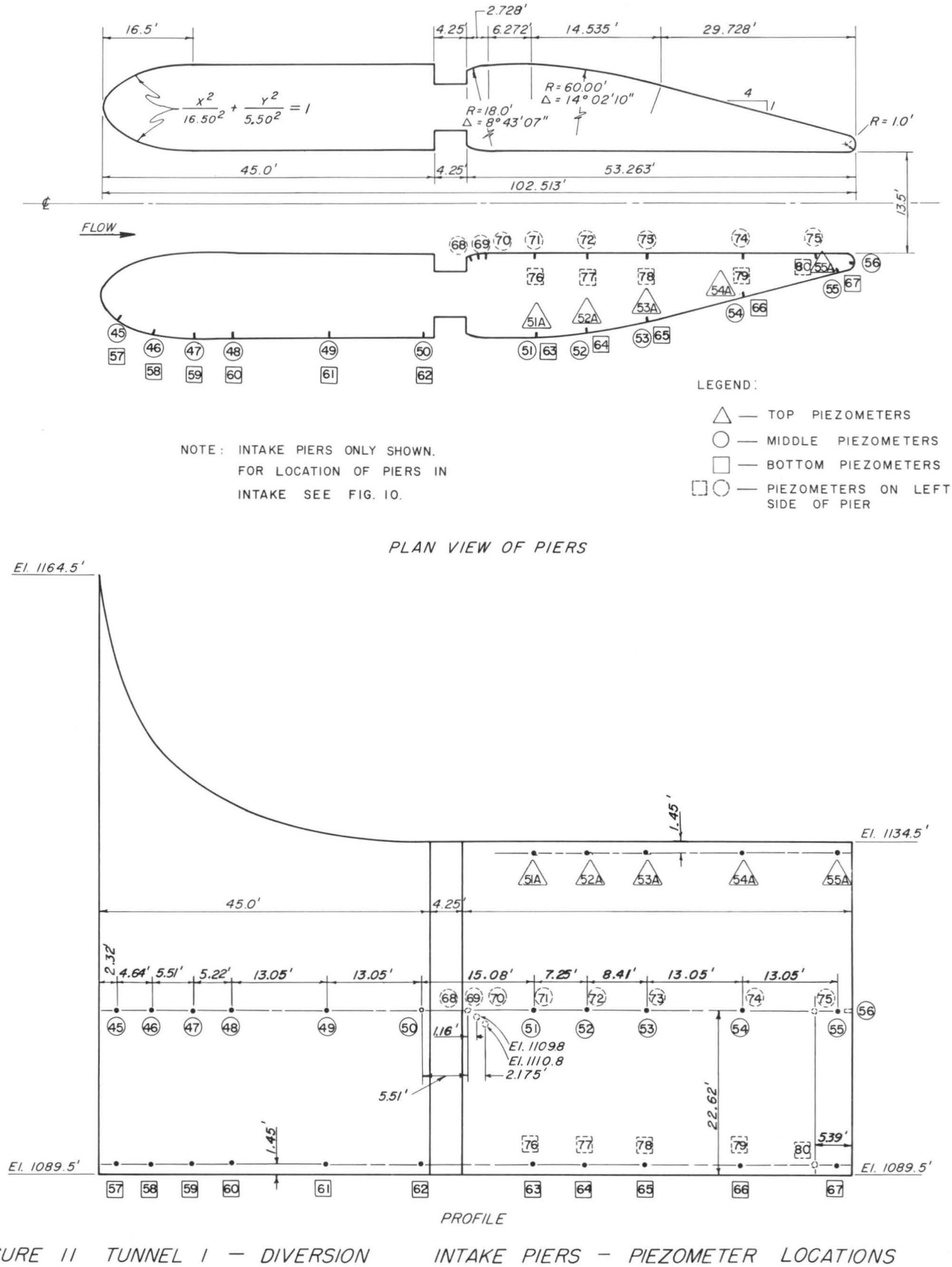


FIGURE 11 TUNNEL 1 — DIVERSION INTAKE PIERS — PIEZOMETER LOCATIONS

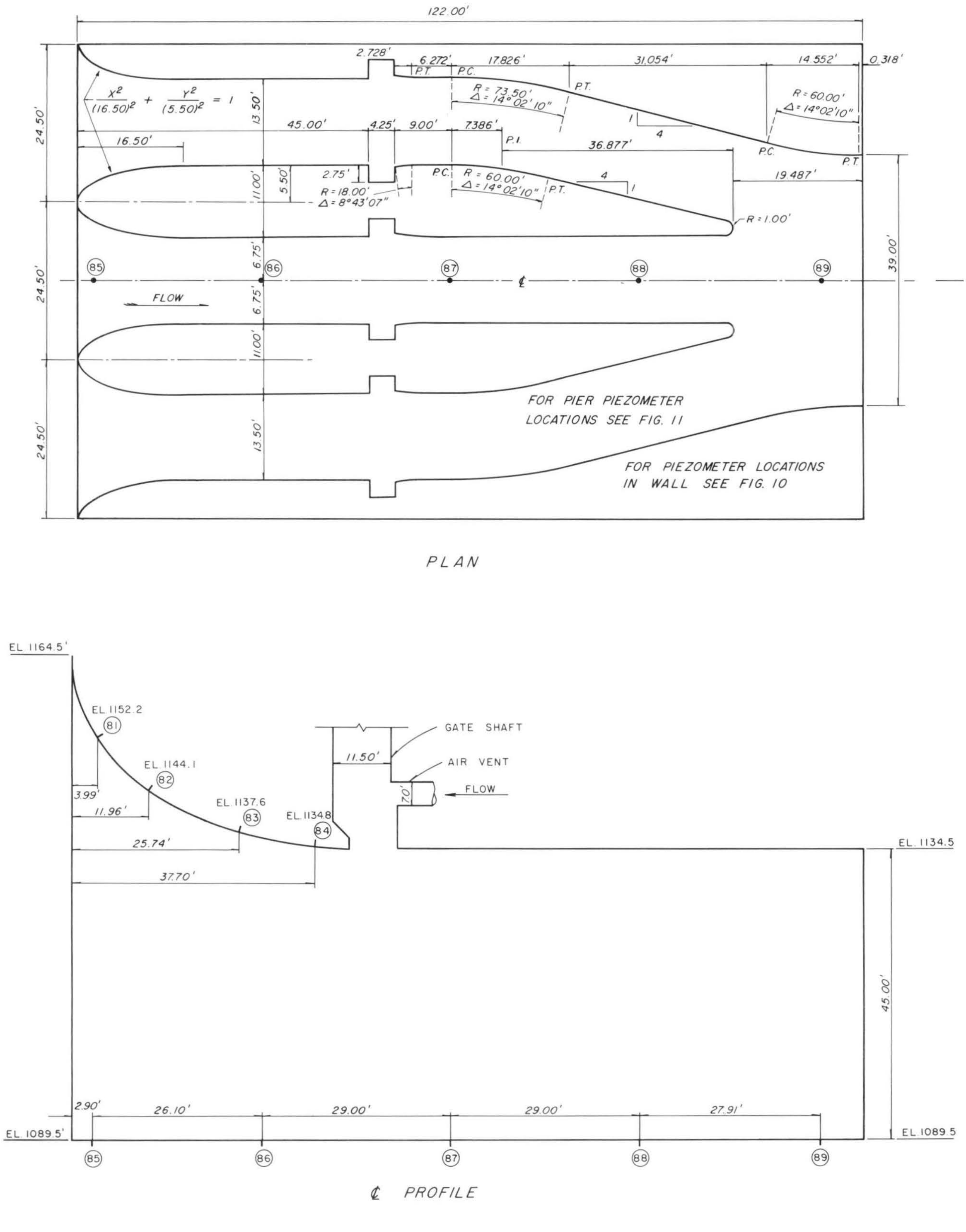


FIGURE 12. TUNNEL 1-DIVERSION INTAKE PIEZOMETER LOCATIONS ALONG CENTER LINE

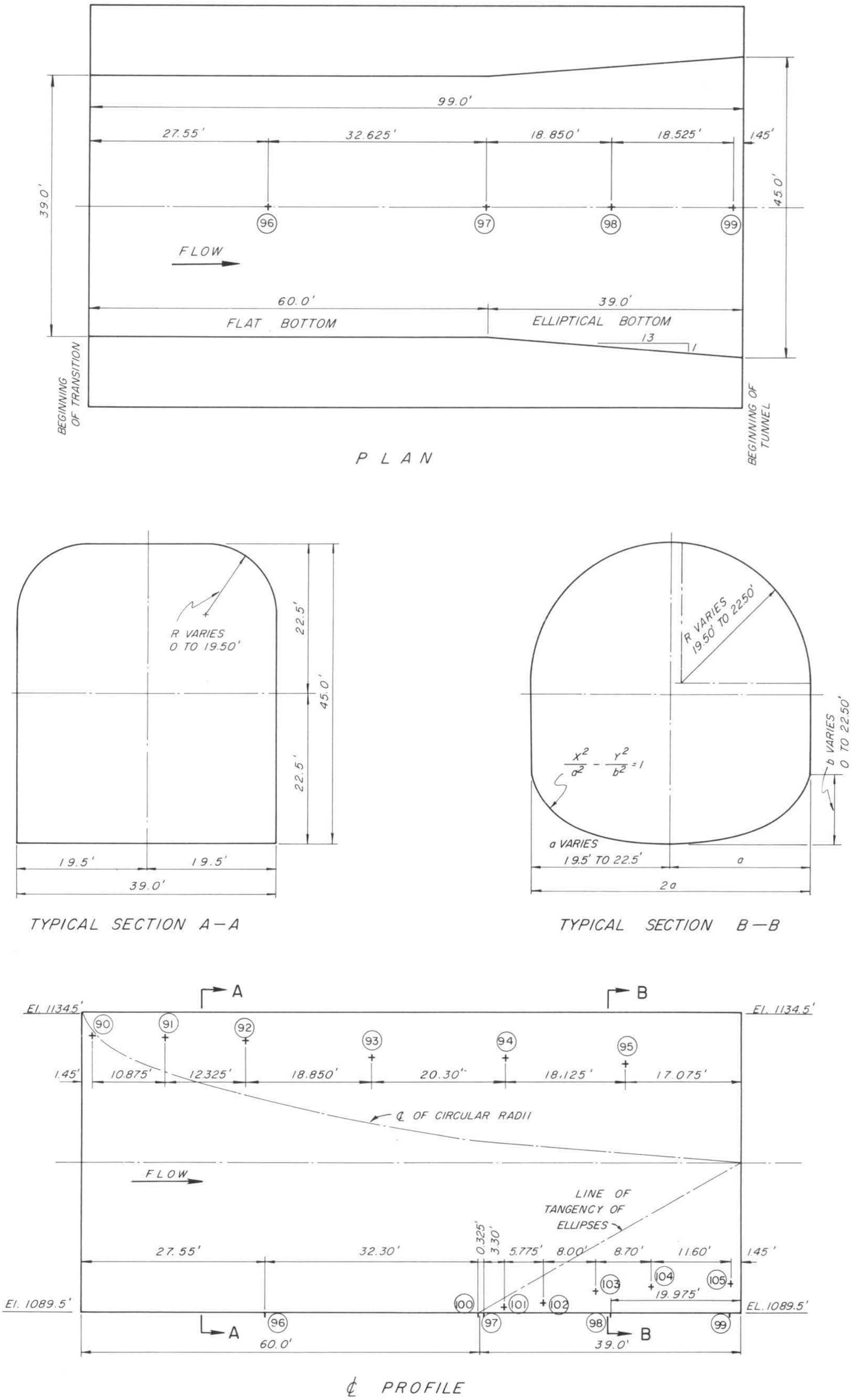


TABLE OF PIEZOMETER ELEVATIONS

Piezo. No.	Elev. Ft.
90	1131.1
91	1130.9
92	1130.4
93	1127.6
94	1127.6
95	1127.0
96	1089.5
97	1089.5
98	1089.5
99	1089.5
100	1089.5
101	1090.5
102	1091.2
103	1092.7
104	1093.5
105	1094.1

FIGURE 13 TUNNEL 1 — DIVERSION INTAKE TRANSITION PIEZOMETER LOCATIONS

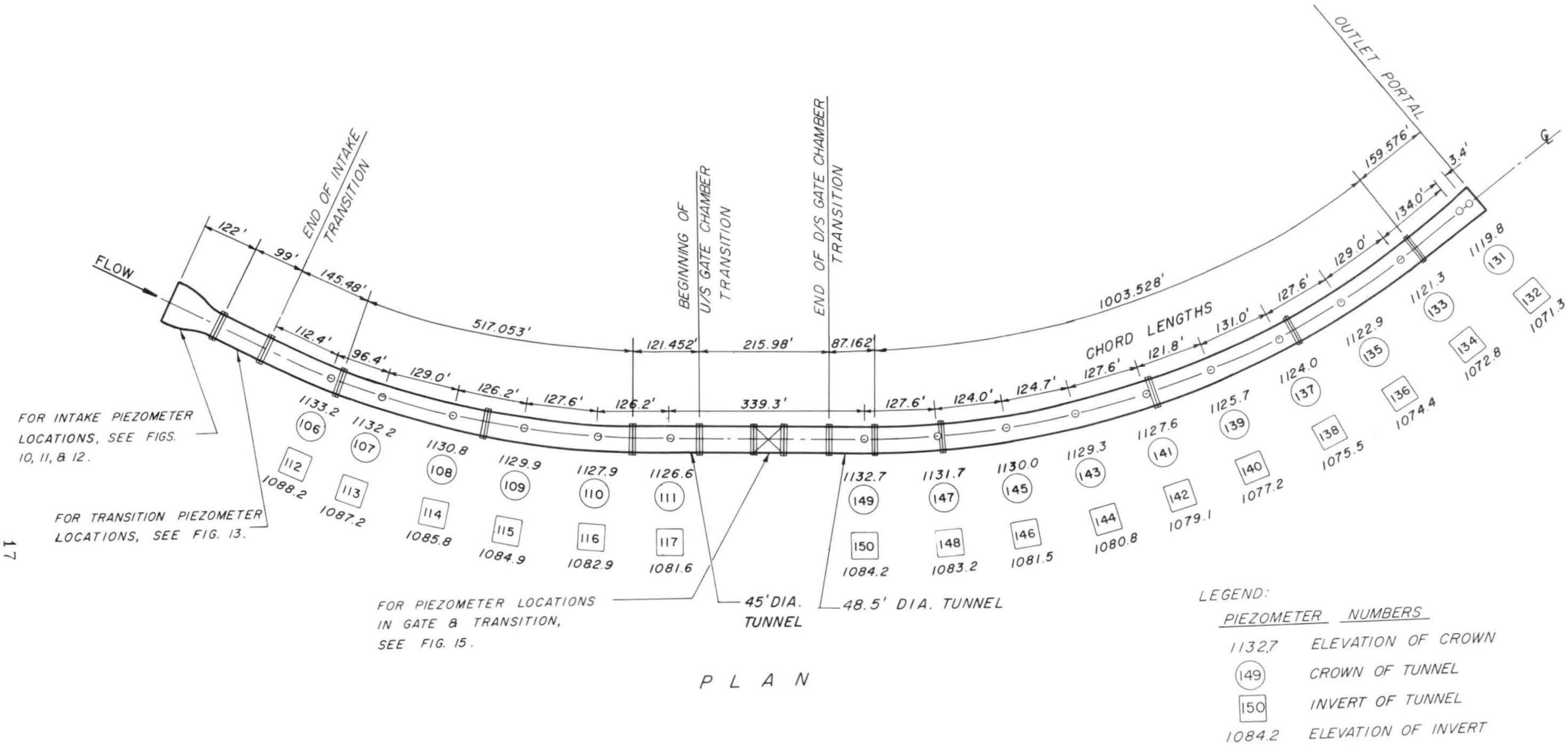
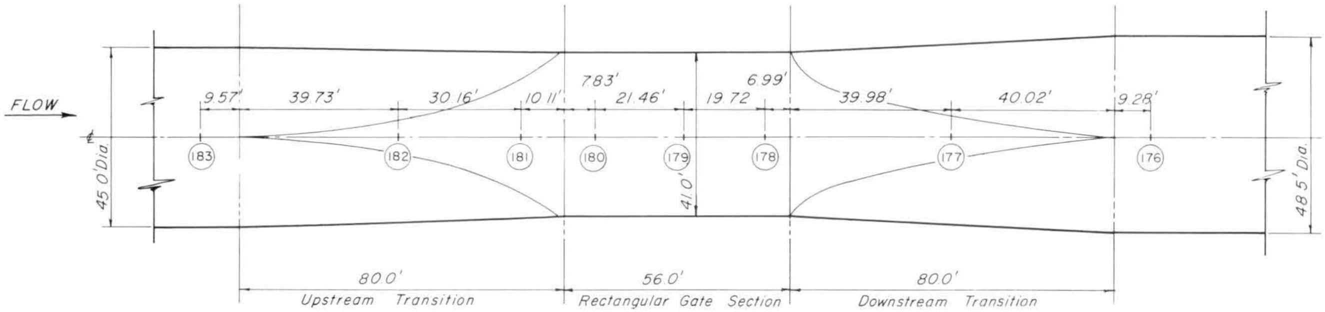


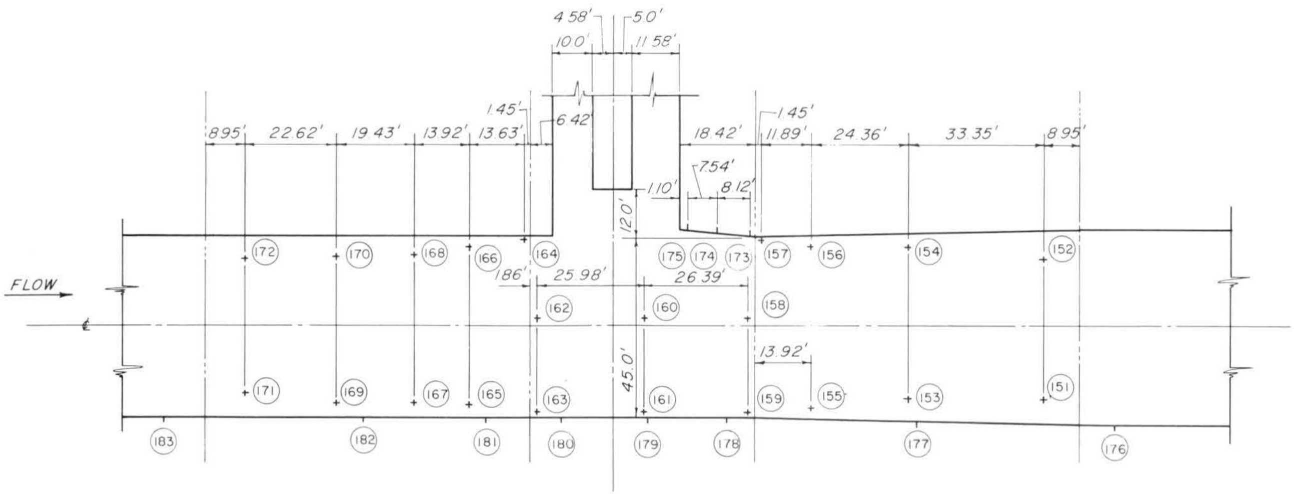
FIGURE 14 TUNNEL 1 – DIVERSION PIEZOMETER LOCATIONS



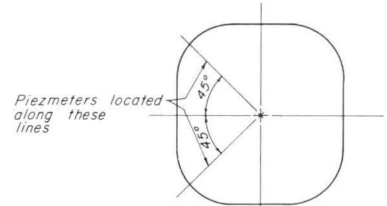
PLAN

TABLE OF PIEZOMETER ELEVATION

Piezometer Number	Elevation	Piezometer Number	Elevation
151	1090.1	168	1127.9
152	1124.9	169	1091.1
153	1091.4	170	1127.5
154	1128.2	171	1093.3
155	1088.7	172	1127.0
156	1129.6	173	1131.0
157	1131.0	174	1132.4
158	1111.5	175	1133.6
159	1088.5	176	1084.8
160	1111.5	177	1084.9
161	1088.5	178	1087.0
162	1111.5	179	1087.0
163	1088.5	180	1087.0
164	1131.0	181	1087.5
165	1090.1	182	1087.8
166	1129.7	183	1088.5
167	1091.4		



¢ PROFILE



TYPICAL SECTION LOOKING DOWNSTREAM THROUGH TRANSITIONS

FIGURE 15 TUNNEL 1 - DIVERSION CENTRAL GATE CHAMBER AND TRANSITIONS PIEZOMETER LOCATIONS

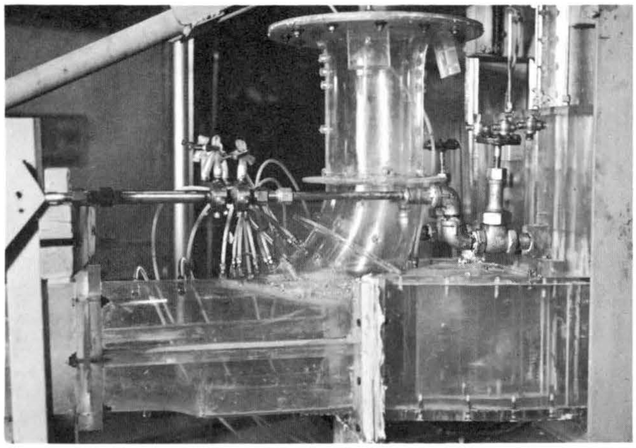


Fig. 16. Arrangement of the combined diversion and vertical power shaft model with ceiling removed for Tunnel 1.

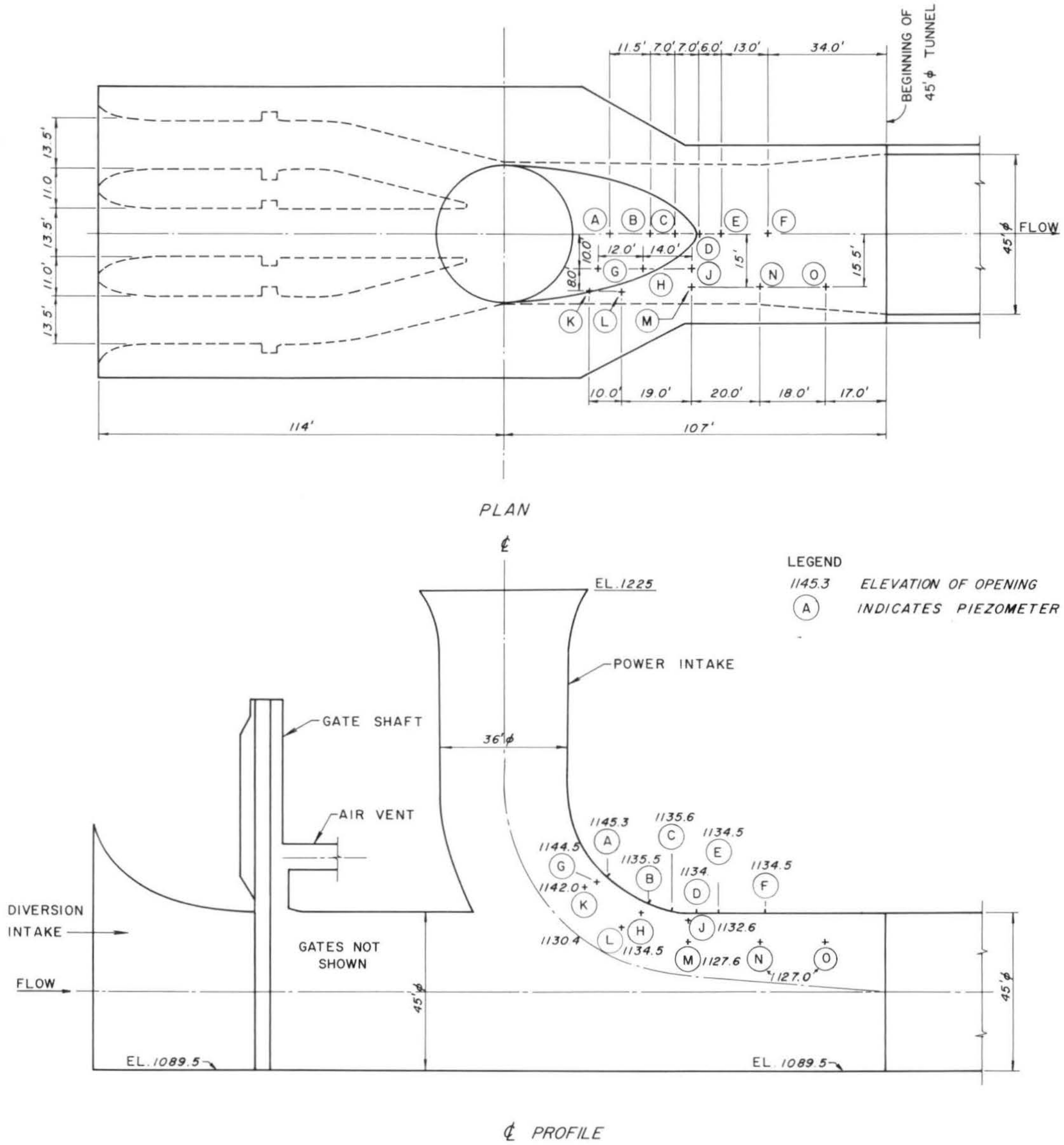


FIGURE 17 TUNNEL 1 - DIVERSION INTAKE WITHOUT CEILING PIEZOMETER LOCATIONS

Model Tests and Results

Description of Flow Conditions - With Ceiling - Measured model discharge curves for the diversion stage of Tunnel 1 are shown in Fig. 18. The curves are identified for the two different tunnel slopes used in the model as explained previously. The curves apply only to the model and should not be used directly to predict prototype discharges. They are included here so that the reader may better relate discharge to reservoir elevation or vice versa when only one quantity is mentioned in the following discussion.

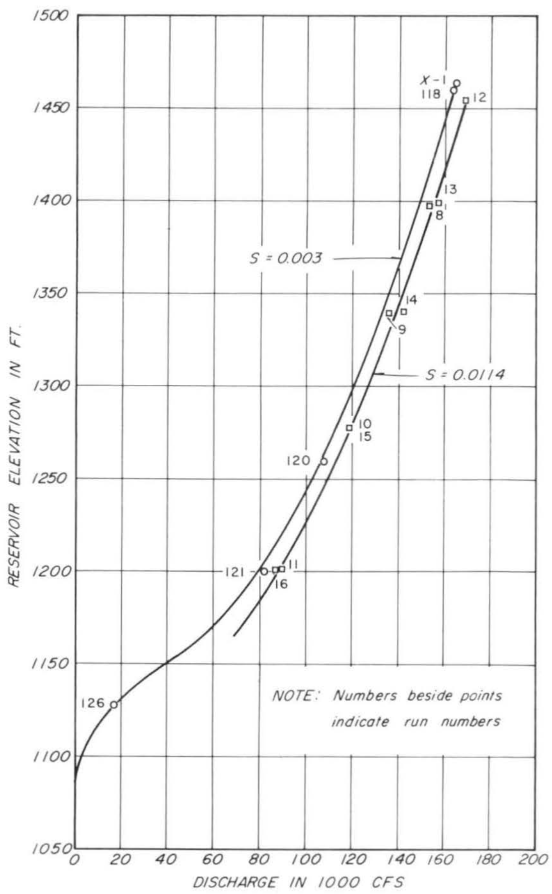


FIGURE 18 TUNNEL 1 DIVERSION MODEL DISCHARGE CAPACITY CURVES

In the tests with the model tunnel slope at 0.003, which more closely represents the prototype tunnel slope of the two slopes tested, open channel flow was maintained throughout the length of the tunnel so long as the reservoir surface level was below elevation 1135. Pictorially, a sequence of photographs in Fig. 19 shows flow in the tunnel from the intake, Fig.19(a), to the outlet, Fig. 19(d). The reservoir surface was at elevation 1127 and the discharge was 17,100 cfs. Surface waves were generated in the transition downstream of the intake, as seen in Fig. 19(a) caused by the rapid change in geometry of the invert from rectangular to circular. The waves, although relatively large in amplitude, did not create concern either at that section or farther downstream in the tunnel. The shape of this transition was necessarily peculiar in form because it was designed for adaptation to both the diversion intake in the first stage and to the power intake in the second stage of construction. Thus for the transition, hydraulic flow conditions alone could not govern the shape. Since no serious difficulties could be conceived to arise because of the presence of waves, and since structural and construction problems would arise with changes in transition geometry, modification was not attempted. It can be seen in Fig. 19(b) that the surface waves were damped before reaching the central gate chamber and the flow surface was relatively smooth through the transition upstream of the gate chamber. Waves of smaller amplitude were again generated at the downstream transition from the gate chamber but no problem was created.

At reservoir levels greater than 1150, the tunnel flowed full. Vortices were created in the reservoir at nearly all levels which submerged the intake, but despite small amounts of air entrained no problems arose from these vortices. Peculiarities in flow occurred in the model for reservoir levels between 1135 and 1150. When the reservoir level rose above elevation 1135 and filled the tunnel entrance, the outlet of the tunnel also filled because of the constriction there while in the remainder of the tunnel there was free surface flow. Gradually as the reservoir level increased, flow at sections of the tunnel alternately filled the tunnel and broke free from the crown and the undulation caused air to be admitted at the intake which was trapped along the crown of the tunnel and conveyed downstream with the flow to the gate chamber and released. This undulation also occurred between the gate chamber and the outlet. The frequency of undulation although not measured was small, and was viewed to be more of a phenomenon than cause for concern.

Description of Flow Conditions - Without Ceiling - The flow condition with and without the flow ceiling was the same when the tunnel did not flow full. At reservoir levels greater than 1150, when the tunnel was filled, air was trapped in the vertical shaft as shown in Fig. 20. There was little turbulent motion within the vertical shaft as evidenced by the smooth water surface in the photograph. When the air was released through the petcock at the top representing a vent to be installed in the prototype, the vertical shaft was filled as the reservoir level rose, and there was essentially smooth flow in the tunnel as the static water in the vertical shaft formed a fluid ceiling at the junction.

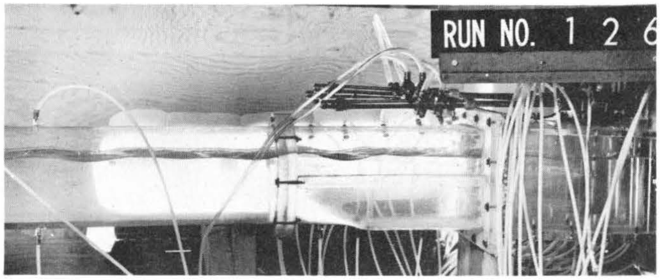


Fig. 19(a) Flow through intake and transition.

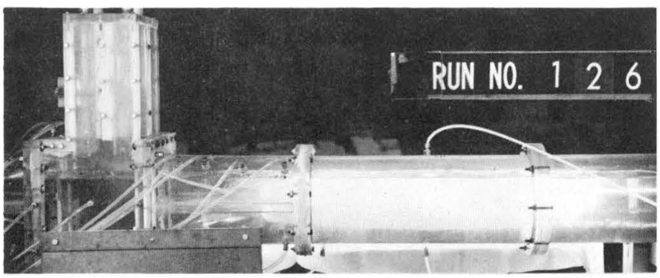


Fig. 19(b) Flow upstream of central gate chamber.

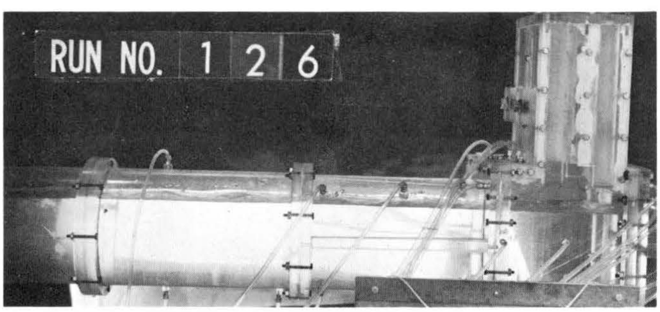


Fig. 19(c) Flow downstream of central gate chamber.

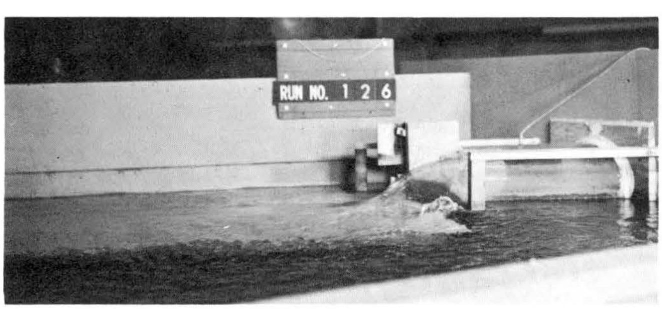


Fig. 19(d) Flow at tunnel portal.

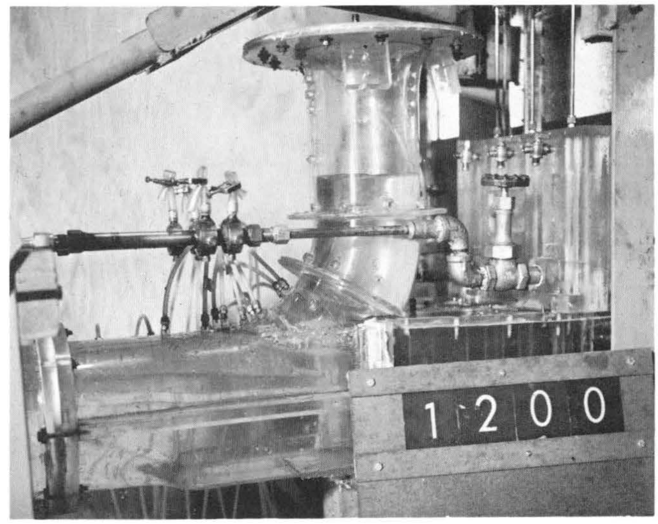
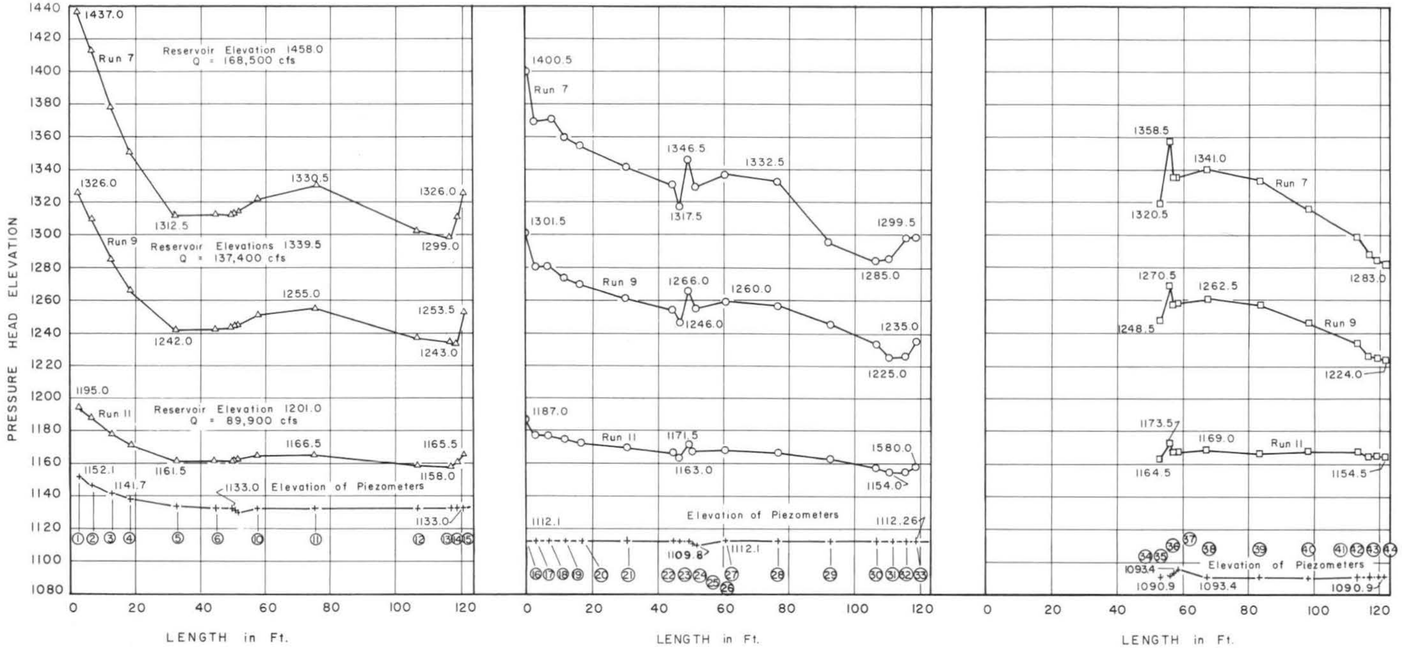


Fig. 20. Flow with ceiling removed.

<u>Pressures, With Ceiling</u> - Pressures measured at various points along the tunnel wall were positive for the entire range of discharges. Significant model data for the tunnel are included in Appendix A, tables A-1 through A-3, at the end of this report. To better visualize the magnitude of the piezometric heads in the tunnel, piezometer gradients are plotted in Fig. 21 at the intake wall for three reservoir levels of 1201, 1339.5 and 1458 (see Fig. 10 for piezometer locations). In Fig. 22 piezometer gradients are drawn at the central gate chamber wall for the same reservoir levels. Pressures were positive at every measured point.

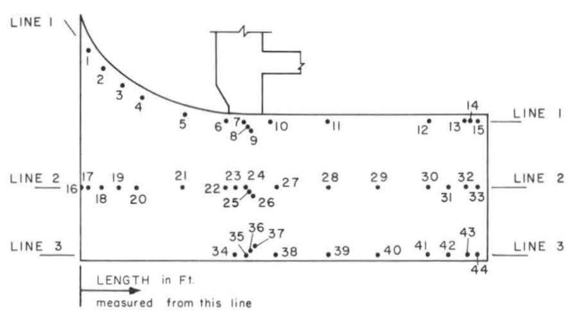
<u>Pressure, Without Ceiling</u> - The piezometric heads measured at the junction of the vertical shaft and horizontal tunnel were positive. The magnitudes of pressure heads are tabulated in Table A-4 of the appendix. Pressures were positive at all points measured, and in the remainder of the tunnel there was no change from conditions with the ceiling.



PRESSURE HEADS ALONG LINE 1-1 PRESSURE HEADS ALONG LINE 2-2 PRESSURE HEADS ALONG LINE 3-3

TABLE OF PIEZOMETER ELEVATIONS

LINE 1-1 PIEZO NO.	LINE 1-1 ELEV. FT.	LINE 2-2 PIEZO NO.	LINE 2-2 ELEV. FT.	LINE 3-3 PIEZO NO.	LINE 3-3 ELEV. FT.
1	1152.1	16	1112.1	34	1090.9
2	1146.5	17	1112.1	35	1090.9
3	1141.7	18	1112.1	36	1092.2
4	1138.5	19	1112.1	37	1093.4
5	1134.3	20	1112.1	38	1090.9
6	1133.0	21	1112.1	39	1090.9
7	1133.0	22	1112.1	40	1090.9
8	1132.0	23	1112.1	41	1090.9
9	1130.9	24	1112.1	42	1090.9
10	1133.0	25	1110.8	43	1090.9
11	1133.0	26	1109.8	44	1090.9
12	1133.0	27	1112.1		
13	1133.0	28	1112.1		
14	1133.0	29	1112.1		
15	1133.0	30	1112.1		
		31	1112.1		
		32	1112.1		
		33	1112.1		



NOTES:

1. For piezometer locations, see elevation view of wall.
2. The piezometric heads are indicated in prototype elevation. To determine pressure heads, subtract the elevation of the piezometer given in the table.

FIGURE 21 TUNNEL 1 — DIVERSION PIEZOMETRIC HEADS AT INTAKE WALL

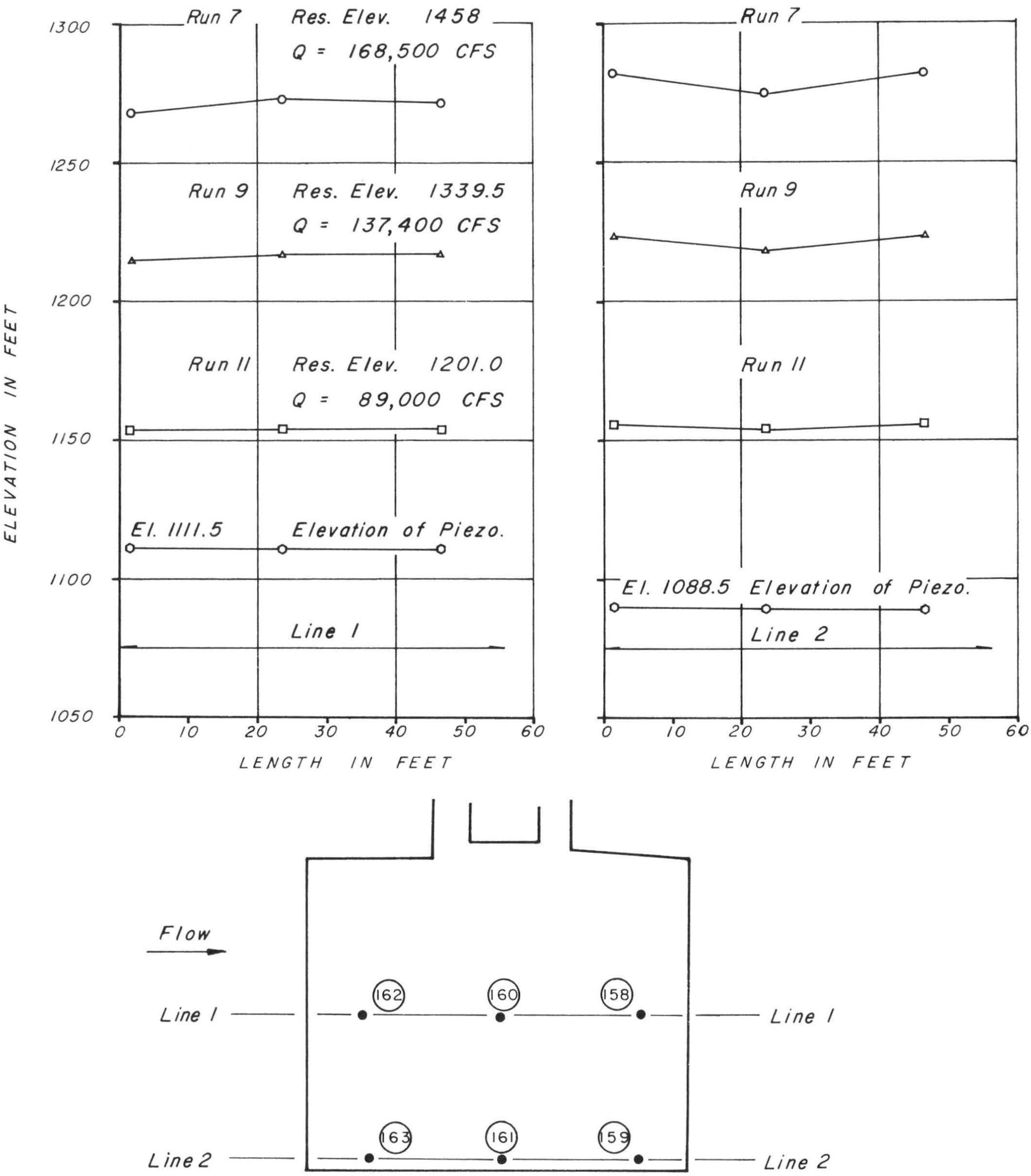


FIGURE 22 TUNNEL 1 — DIVERSION PRESSURE ON GATE CHAMBER WALL

Form Loss Coefficients, Intake Gates Open

The energy gradients through the tunnel measured at various reservoir levels are given in Fig. 23 for the model tunnel slope at 0.003. Energy gradients for tunnel slope at 0.0114 are given in Fig. 24. From the curves in these figures the form loss coefficients were calculated and are tabulated in Table 2. The form loss coefficient is as defined in the equation:

$$H_L = K_i \frac{V_d^2}{2g}$$

where

H_L = head loss between the upstream and downstream sections of the appropriate structure in ft

V_d = velocity at the downstream section in ft/sec

K_i = form loss coefficient

i = 1, 2, 3, 4, 5

1 = the diversion intake

2 = the transition downstream of intake

3 = transition upstream of central gate chamber

4 = gate section and downstream transition

5 = gravitational acceleration = 32.2 ft/sec^2

It is to be noted that the head loss due to friction is included in the value of H_L used to calculate the coefficients.

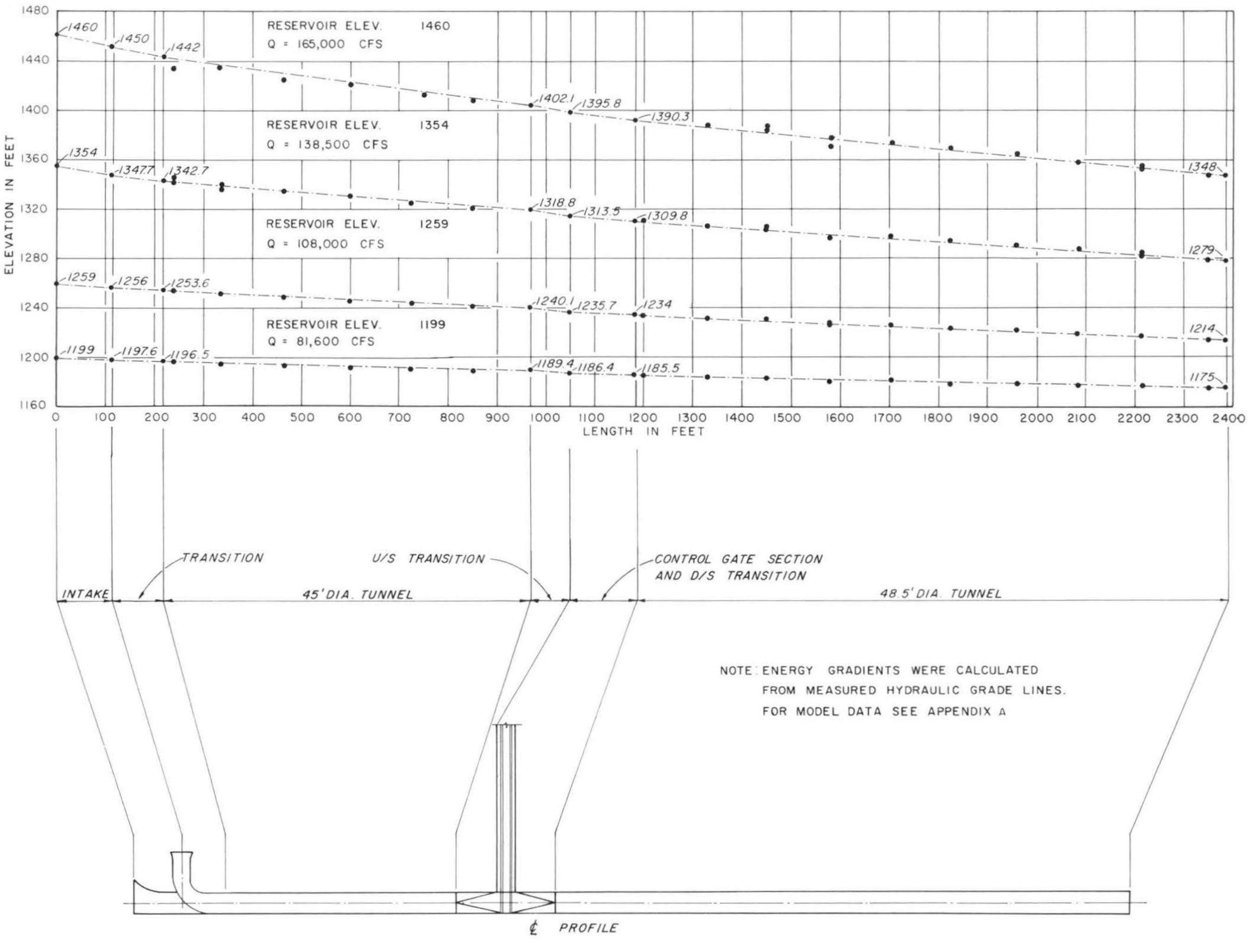


FIGURE 23 TUNNEL I — DIVERSION ENERGY GRADIENTS FOR TUNNEL SLOPE = 0.003

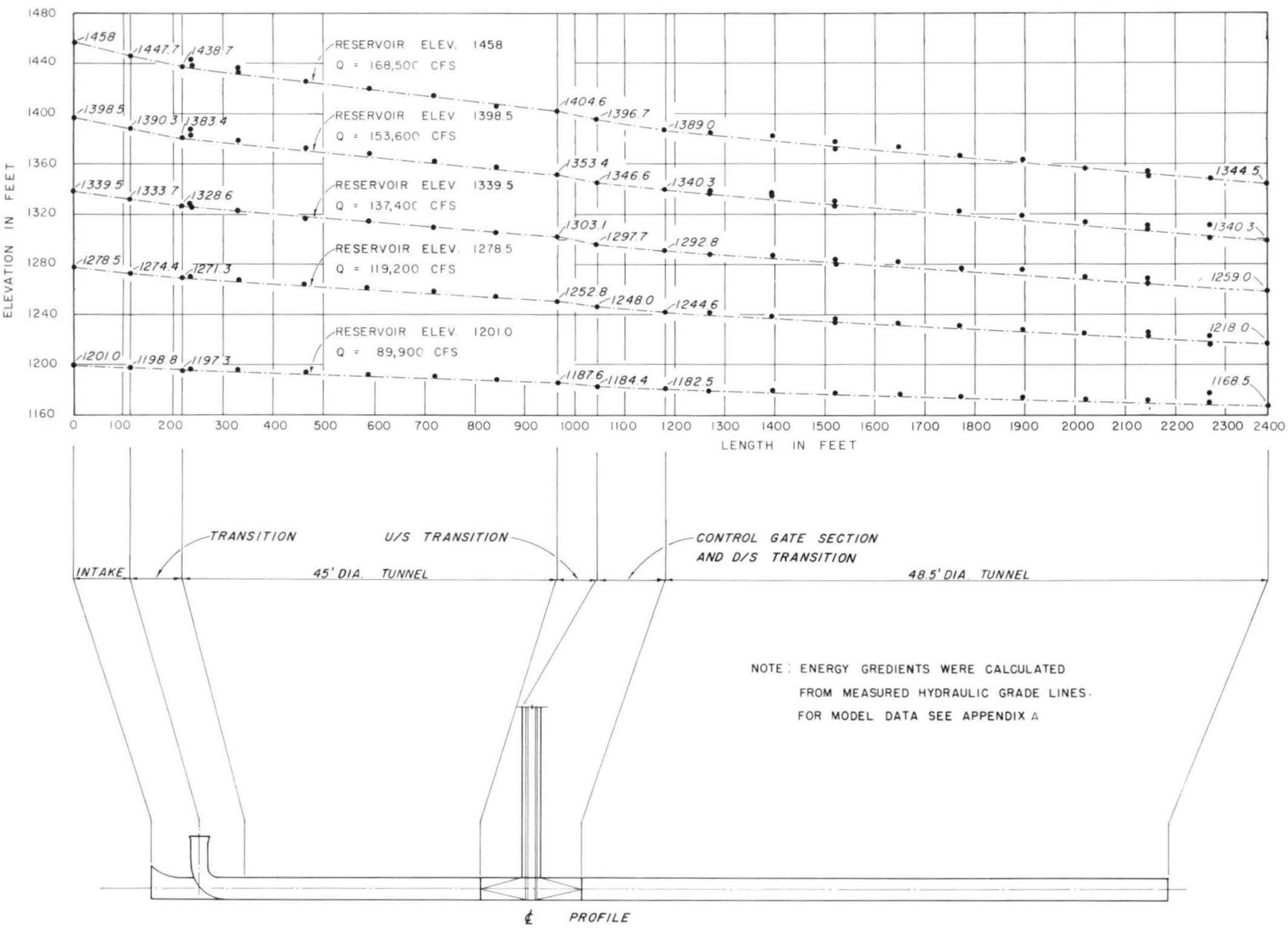


FIGURE 24 TUNNEL 1 — DIVERSION ENERGY GRADIENTS FOR TUNNEL SLOPE = 0.0114

Closure of Intake Gates - There are various sequences possible in closing the three intake gates. All three gates could be closed in unison or singly in any arbitrary order.

The model studies included measurement of air flow required at the gate shaft caused by closure of the gates, measurement of pressures on the walls of the tunnel at selected points and observation of flow conditions during closure. The physical arrangement of venturi meters used to measure air flow rate, and model control devices for air intake, can be seen in the photograph of Fig. 9. The air intakes of the model were connected to a compressed air source with a pressure regulator and valves to control the air flow. Compressed air was used because the pressure differential created in the model was relatively small, and sufficient air could not be drawn through the air vents from ambient room pressures to represent prototype quantities and velocities. Use of compressed air was more expedient than increasing the size of the vents in the model. The venturi meters, 1/2 by 3/8 inch were calibrated prior to use.

Gate Closure in Unison - Under the proposed operating conditions of the prototype tunnels described earlier, the level of the reservoir during closure will be regulated according to field conditions. Closure tests were made therefore at several reservoir levels in the range from 1200 to 1460. As a criterion for vent design, it was decided that the minimum pressure within the tunnel during gate closure should be minus 15 feet of equivalent prototype water head.

TABLE 2

MODEL LOSS COEFFICIENTS FOR TUNNEL NO. 1 - DIVERSION.

		Model Tunnel Slope = 0.0114					Model Tunnel Slope = 0.003			
Reservoir elevation		1458	1398.5	1339.5	1278.5	1201.0	1460	1354	1259	1199
Discharge		168500	153600	137400	119200	89900	164000	138500	108000	81600
Intake	H_L	10.3	8.2	5.8	4.1	2.2	9.5	6.3	3.0	1.4
	V	92.45	84.28	75.39	65.40	49.33	89.99	75.99	59.26	44.77
	$\frac{V^2}{2g}$	132.86	110.30	88.26	66.42	37.79	125.75	89.67	54.53	31.12
	K_1	0.078	0.074	0.066	0.062	0.058	0.076	0.070	0.055	0.045
Transition downstream from intake	H_L	9	6.9	5.1	3.1	1.5	8.2	5.0	2.4	1.1
	V	105.97	96.60	86.48	74.97	56.54	103.14	87.11	67.92	51.32
	$\frac{V^2}{2g}$	174.37	144.90	116.13	87.27	49.64	165.18	117.83	71.63	40.90
	K_2	0.052	0.048	0.044	0.036	0.030	0.050	0.042	0.034	0.027
Transition upstream from central gate section	H_L	7.9	6.8	5.4	4.8	3.2	7.0	5.3	4.4	3.0
	V	91.33	83.25	74.53	64.61	48.73	88.89	75.07	58.54	44.23
	$\frac{V^2}{2g}$	129.52	107.62	86.25	64.82	36.87	122.69	87.51	53.21	30.38
	K_3	0.061	0.063	0.063	0.074	0.087	0.057	0.061	0.083	0.099
Central gate and transition downstream	H_L	7.7	6.3	4.9	3.4	1.9	5.9	3.7	1.7	0.9
	V	91.18	83.12	74.35	64.50	48.65	88.74	74.95	58.44	44.16
	$\frac{V^2}{2g}$	129.10	107.28	85.84	64.60	36.75	122.28	87.23	53.03	30.28
	K_4	0.060	0.059	0.057	0.053	0.052	0.048	0.042	0.032	0.030

Air was not required at any reservoir level until the gates were approximately 75 percent open.[4] At about 70 percent open a hydraulic jump formed downstream of the gates. Depending upon the rate of air flow admitted into the tunnel the hydraulic jump would be stationary or moving. Figures 25(a) through (c) show stationary hydraulic jumps with increasing reservoir levels from 1200 to 1350. By increasing the air flow rate into the tunnel, the pressure within the intake above the water surface increased and a moving hydraulic jump was formed. This condition is depicted in Fig. 25(d) and (e) where the jump in Fig. 25(c) moved to the transition upstream of the gate as in Fig. 25(e).

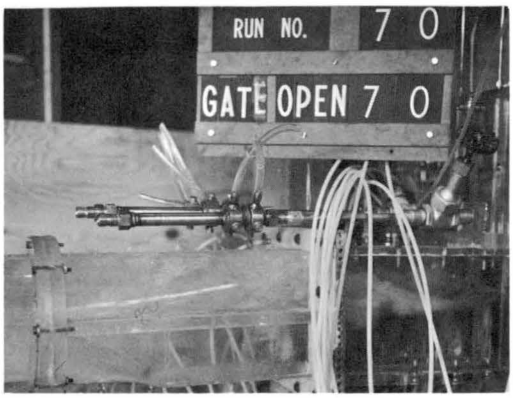


Fig. 25(a) Hydraulic jump downstream from the intake gates at reservoir level 1200.

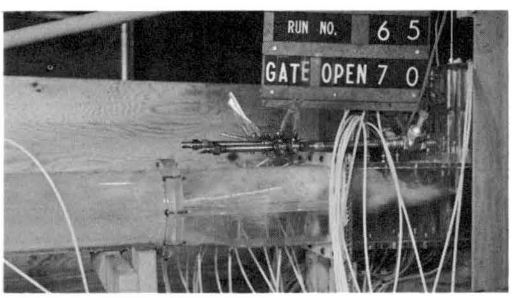


Fig. 25(b) Hydraulic jump in the tunnel at reservoir level 1260.

Fig. 25(c) Hydraulic jump in the tunnel at reservoir level 1350.

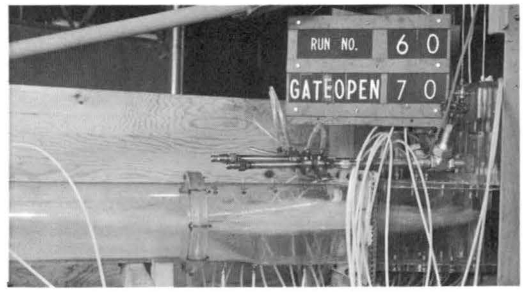


Fig. 25(d) No jump in the tunnel at reservoir 1356 with adequate air flow at gate shaft.

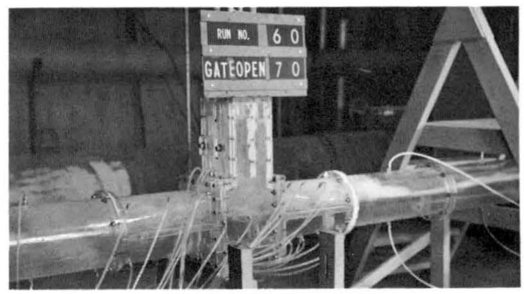


Fig. 25(e) Jump located upstream of central gate shaft.

At constant reservoir level and continuous closure of the gates, with proper vent sizes to the gate shafts, a hydraulic jump will move continuously downstream, and depending upon the time rate of closure, the jump will be swept out of the tunnel before the gates are half closed. Air that was drawn through the vents was released through the central gate chamber. When the hydraulic jump moved into the central gate chamber, the need for air at the intake gate shafts ceased,[5] because air required by the jump was supplied by the central gate shaft.

The model data for air flow rates are given in Fig. 26 for gate closure at reservoir level 1460. Air discharge is shown as a function of gate opening and pressure inside the intake structure above the water surface in equivalent prototype feet of head. Because pressure heads in the model were converted to prototype dimensions, fictitious heads such as -60, -80 feet, etc., can result. These fictitious values are included in the figure to lend support to the trend lines drawn through the data, and the dashed line for -15 foot head which meets the design criterion, was interpolated. It is suggested that an air flow rate of 13,000 cfs be used for design of vents.

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[4] To avoid confusion gate positions in this report will always be referenced to the open position. For example, a gate will be referred to as being 75% open rather than 25% closed.

[5] This condition existed in the model, but in the prototype air flow through the vents is expected differently as discussed on page 28.

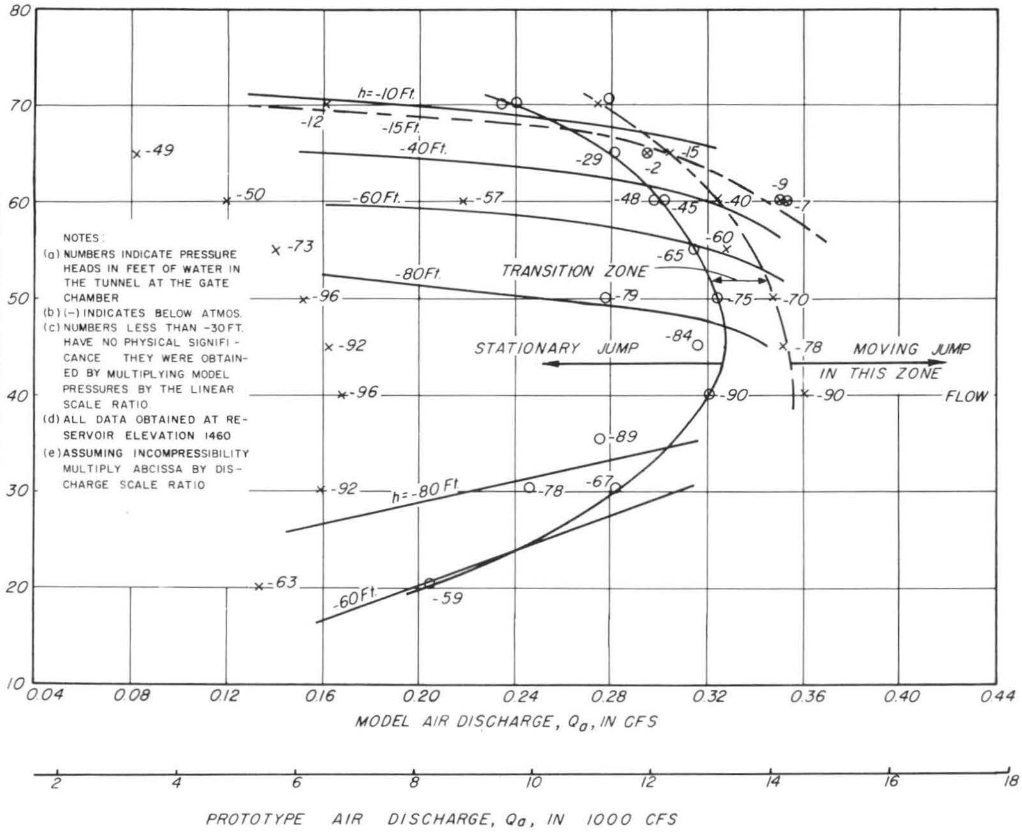


FIGURE 26 TUNNEL I - DIVERSION - AIR DEMAND AT INTAKE FOR GATE CLOSURE IN UNISON

A suggested design curve for sizing air vents at regulated outlet works by the Corps of Engineers[6] is redrawn in Fig. 27, together with laboratory results of studies by Kalinske and Robertson,[7] and data from the present study. The suggested design curve of the Corps of Engineers is the upper envelope of air demand data taken on prototype structures and includes full tunnel flow and partially full flows. Contrary to the present model results, air demand for the prototype apparently continues even after the hydraulic jump sweeps out. In general, the prototype studies indicated maximum air requirements at two points in the closure of slide and tractor gates. One maximum point was observed at a gate position between 60 and 80 percent open, where the tunnel probably flowed full and the second maximum of lesser magnitude at a gate position of about 5 percent. Undoubtedly at this opening free surface flow prevailed through the length of the tunnel, and the air demand would seem to be related to the shear at the air-water inface developed by the high velocity flow which would "pull" the air along with the flow. The air-demand would also be interrelated with the break-up of the free surface and the entrainment of air in the flow.

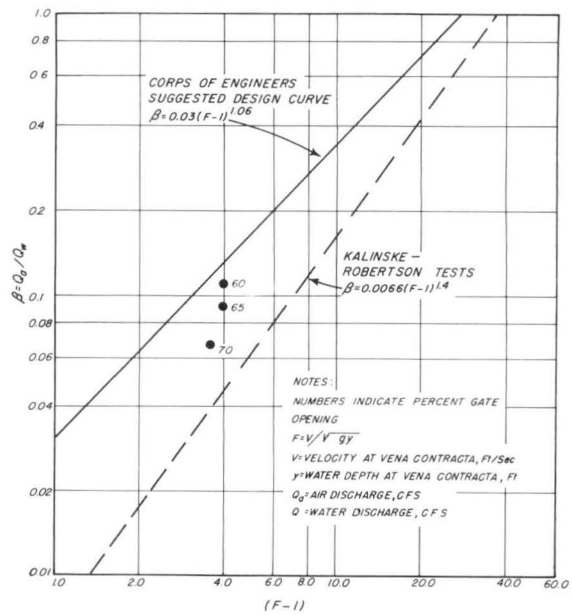


FIGURE 27 TUNNEL I - DIVERSION AIR DEMAND DOWNSTREAM FROM INTAKE GATES

[6] Corps of Engineers, Hydraulic Design Criteria, Chart 050-1, revised 1964.

[7] Kalinski, A. A., I. W. Robertson, "Entrainment of air in flowing water - closed conduit flow," Trans. ASCE, Vol. 108, 1943, pp. 1435-1447.

Low pressures were measured at the wall downstream of the gates as shown in Figs. 28 and 29, during gate closure. Extreme values occurred at reservoir elevation 1460 and gates 70 percent open. Tabular values of pressure heads are given in Table A-2 of Appendix A. The high velocity flow from the right gate and the diverging intake and pier walls with respect to the flow caused low pressures to be formed in these areas. No other low pressure area was evident in the model during gate closure. Unbalanced pressures did not exist across the piers within the intake structure because of balanced flow through each passageway.

Flow at the junction with the vertical shaft, without the ceiling is shown in Fig. 30 during gate closure. The photograph in the figure shows the condition at 60 percent gate opening. As the gates closed and air was drawn into the tunnel, the hydraulic jump extended downstream to the junction and the water in the vertical shaft flowed out as air which was supplied from the vents rose into the shaft. The flow of water from the vertical shaft was gradual and appeared to create no problem in the flow. The pressure in the shaft was about the same as the pressure in the tunnel downstream of the gates. The hemispherical bulkhead should be designed to withstand the total pressure of the head above in the reservoir plus the reduced pressure within the tunnel.

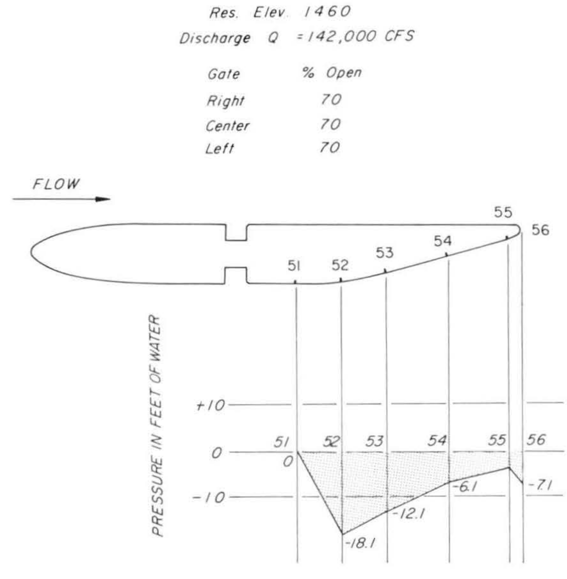


FIGURE 29 TUNNEL 1 - DIVERSION LOW PRESSURES ON PIER AT 70% UNIFORM GATE OPENNING

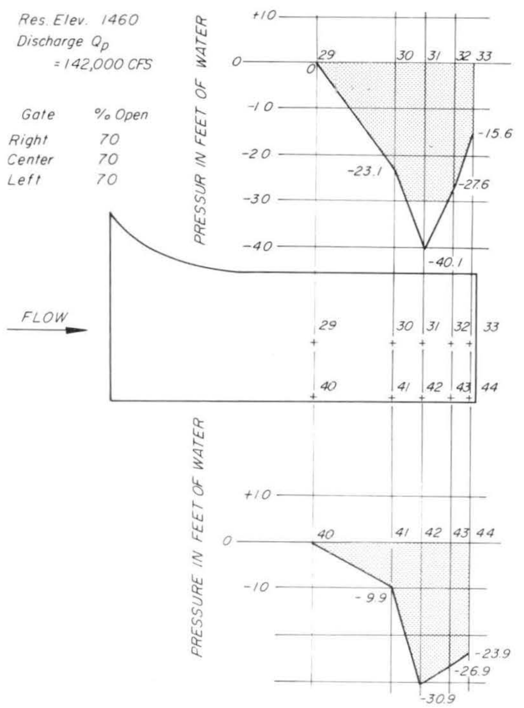


FIGURE 28 TUNNEL 1 - DIVERSION LOW PRESSURES ON INTAKE WALL AT 70% UNIFORM GATE OPENNING

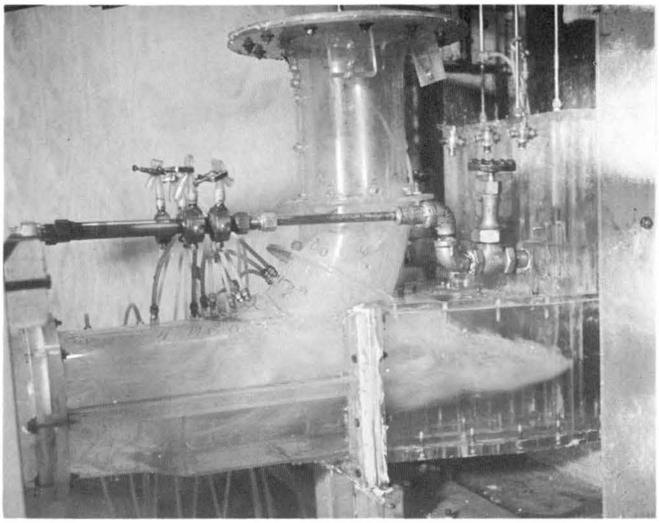


Fig. 30. Intake gates 60 percent open.

Unsymmetric Gate Closure - Test results of various gate closure sequence was to first close the center gate, then either the right or the left gate and finally the remaining gate. The center gate could be closed completely without creating need for air through the vents at any gate chamber. Since it did not matter which gate was closed next, let it be assumed for purpose of this discussion that the left gate was closed second, and the right gate last.

As soon as the left gate was slightly closed, approximately to 95 percent open position, some air was drawn in through the vent at the left chamber. At approximately the 90 percent open position, air was drawn in through all vents but was measurable only through the left vent. A moving hydraulic jump was created with further closing of the gate. When the gate reached 65 percent open, and the pressure within the waterway was minus 15 feet of water head, the jump was swept out and there was no further demand for air at the intake gate vents.

Data for air requirement in the model during gate closure was as shown in Fig. 31. The negative pressures within the intake are given in terms of prototype feet of water head and values such as -35, -44, etc., are fictitious in terms of the prototype, although the respective model values of -0.5 ft and -0.64 ft are realistic and were measured in the model. It is interesting to note that air flow rate required to cause the hydraulic jump to move downstream was almost constant and nearly independent of the gate position. The model air flow rate required was 0.30 cfs, slightly less than the air flow required for simultaneous gate closure.

Air vents were not required at all three gate shafts for the non-uniform closure although when the vents were opened, air was drawn through all vents. Vents at the left and right gate shafts would be required but the vent at the center could be omitted if the gates were to be operated in this order.

The non-uniform closure of the gates caused large magnitudes of unbalanced pressures across the pier in the intake. The maximum differential was obtained when the center and left gates were closed and the right gate full open at a section immediately upstream of the gates. With reservoir elevation at 1462 the head difference was 312 feet between the piezometric head at piezometer 50, and static head at the same level on the opposite side of the pier (see Fig. 11 for location). At the level of piezometer 62 (near the base of the pier) the differential head was 292 feet. The pressure conditions and head differentials across the piers described above were unaffected by removal of the ceiling.

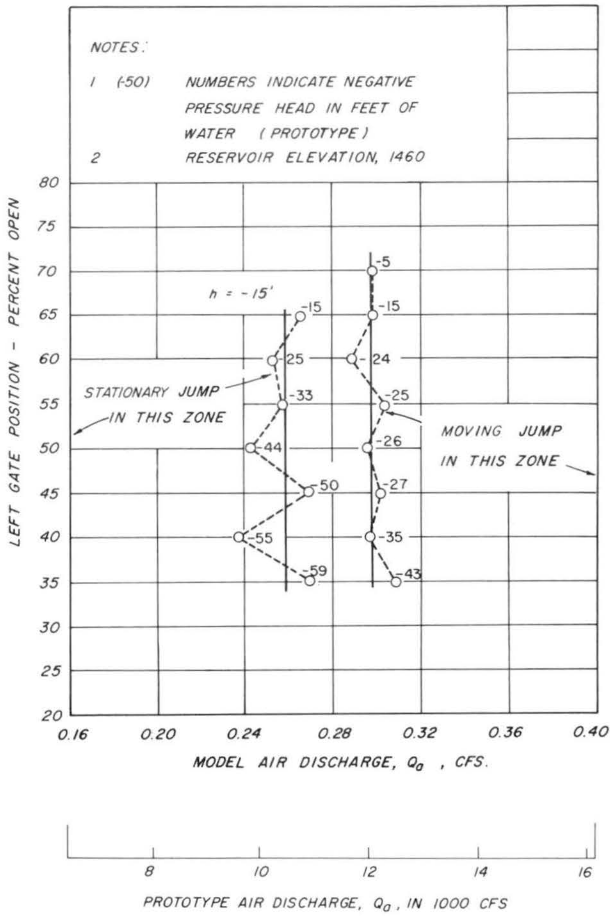


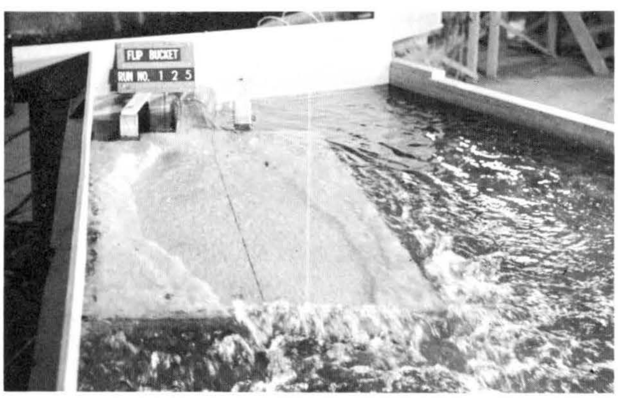
FIGURE 31 TUNNEL I - DIVERSION AIR DEMAND FOR SEPARATE GATE CLOSURE

Outlet Deflector

Arrangement and dimensions of Type I and Type II outlet deflectors were shown in Fig. 4. The deflectors would function during only one year while tunnels are used for diversion. The effects of the Type I structure on the flow at the outlet are shown in the series of photographs on the succeeding pages for flows which varied from 81,600 cfs to 163,000 cfs for reservoir elevations from 1200 to 1456 respectively. In all of these studies an inerodible floor was constructed at elevation 1090 to represent the limits of the rock excavation. Some tests were run with pea gravel riverbed at the outlet, which resulted in scour holes that extended to the floor of the model, a depth of approximately 2.5 ft. The pea gravel size was 1/4-in median diameter with the largest individual pieces no greater than 3/8-in diameter. The photographs of Figs. 32 through 35 show that the impinging jet of water caused standing waves to be formed with considerable turbulence and "white" water. The standing wave to the right could cause problems with scour of the base of the stilling basin wall.

Various modifications were made which involved changing the wall angle, in an effort to deflect the jet of water away from the stilling basin. However, because any increase in angle effectively created more constriction of the outlet, the discharge was reduced. From tests of several modifications, the arrangement drawn in Fig. 36 was found to be most suitable. The height of the wall was increased by 15 feet and a break in wall angle was made in mid-length to increase the deflection of the jet. Some photographs of the resulting flow at comparative discharges with those in Figs. 32 through 35 are shown in Figs. 39 through 40 respectively. Although the tail water levels were higher in the latter series, thereby effectively creating a deeper impact pool for the deflected jet of water, the relative improvements of the modification are nevertheless noticeable. The position of the jet and impact points were more favorable to the stilling basin wall than the original arrangement.

Additional testing of the deflector, especially with respect to Type II, had been scheduled but changes in concept and planning eliminated need for deflectors, thus Type II was not tested.



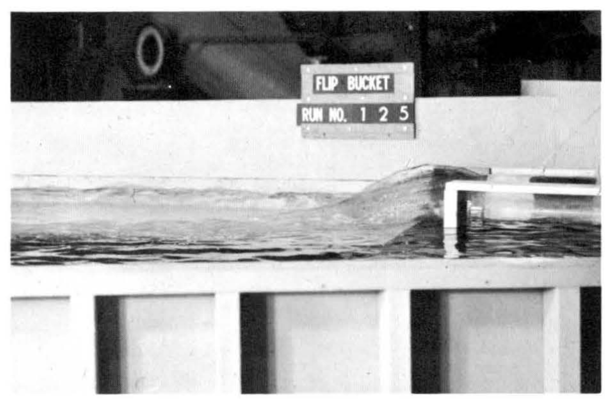


Fig. 32. Type I Deflector-Original design, Reservoir level 1200, Q = 81,600 cfs, Tail water level 1101.

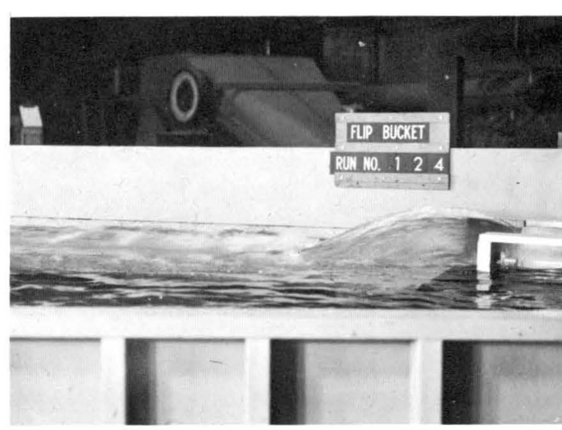


Fig. 33. Type I Deflector-Original design, Reservoir level 1262, Q = 108,300 cfs, Tail water level 1105.

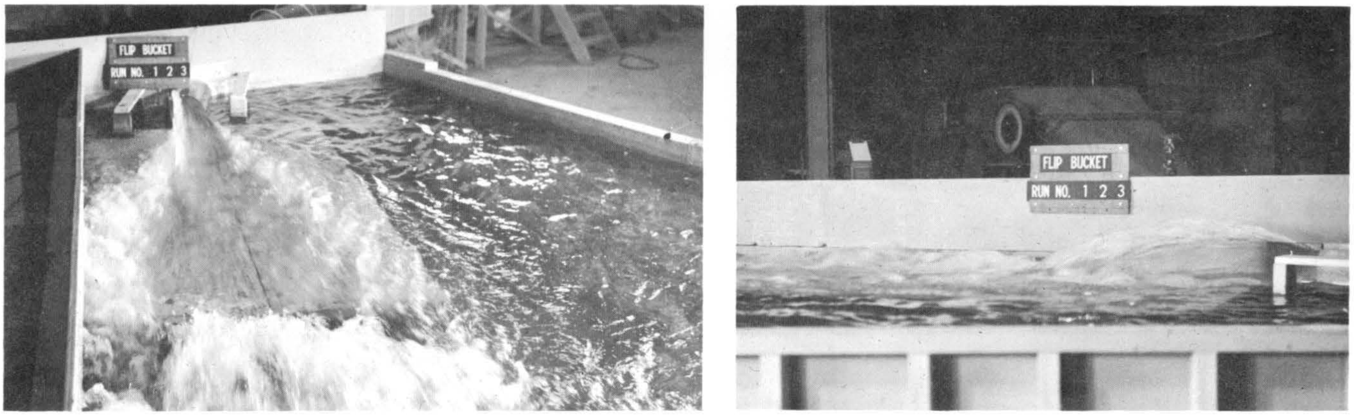


Fig. 34. Type I Deflector-Original design, Reservoir level 1365, Q = 140,600 cfs, Tail water level 1107.

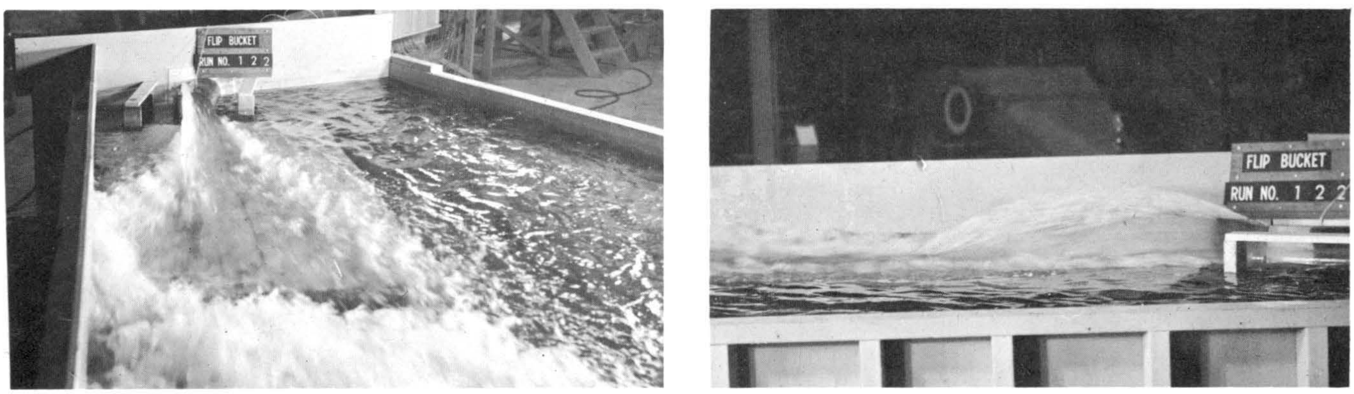


Fig. 35. Type I Deflector-Original design, Reservoir level 1456, Q = 163,000 cfs, Tail water level 1108.

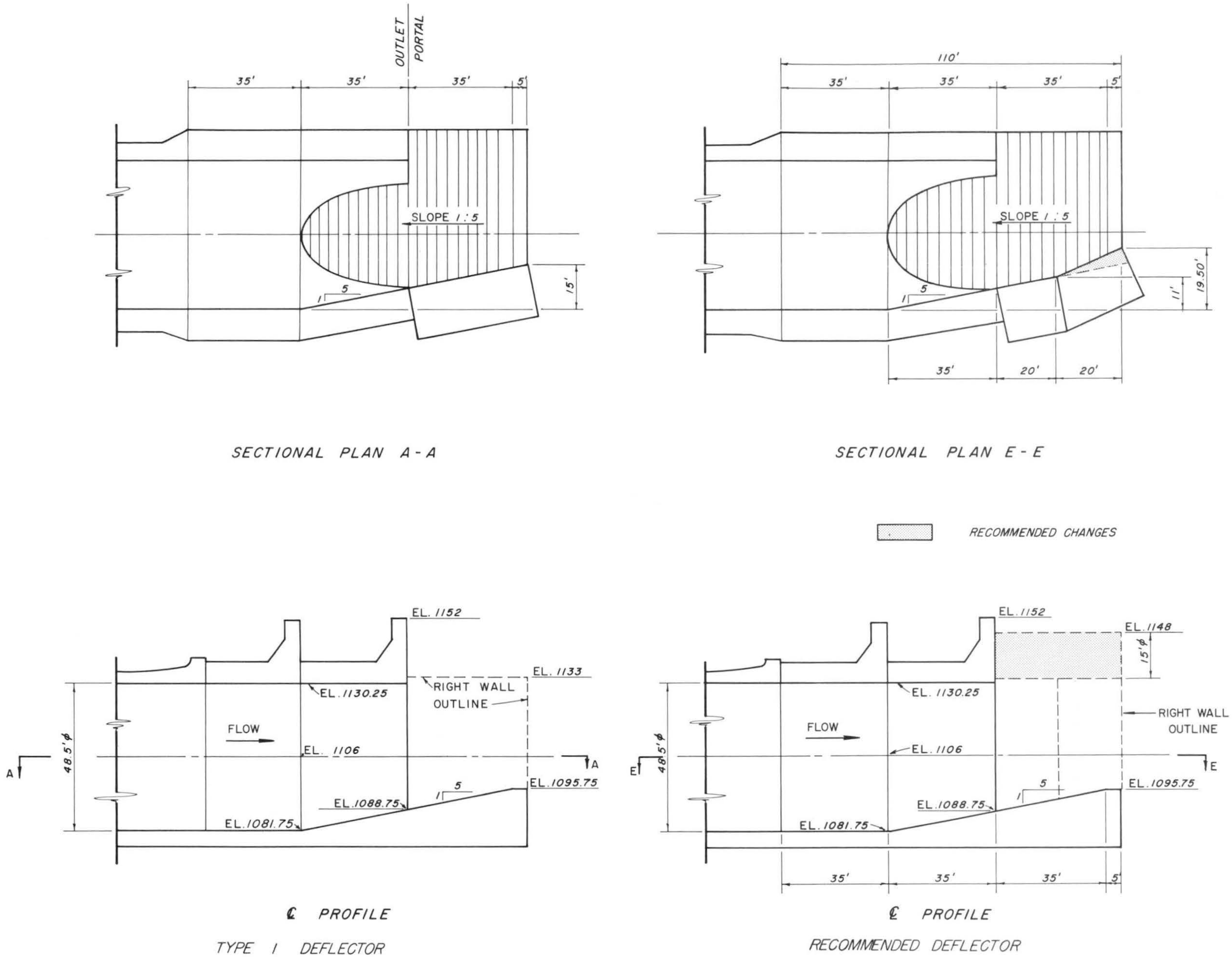


FIGURE 36 TUNNEL I-DIVERSION OUTLET DEFLECTOR

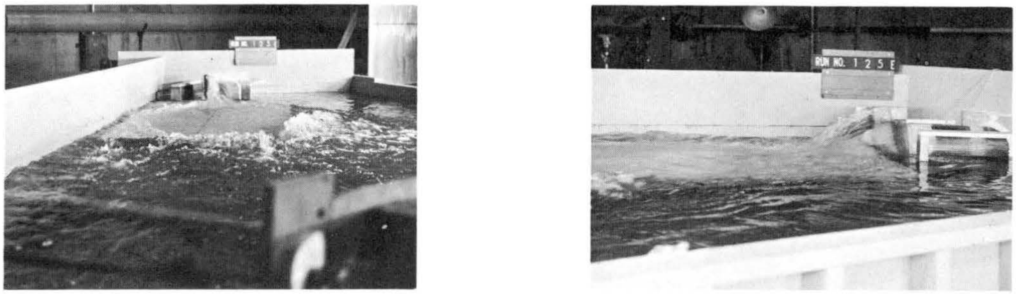


Fig. 37. Recommended Deflector, Modified Type I, Reservoir level 1200, Q = 81,600 cfs, Tail water level 1100.

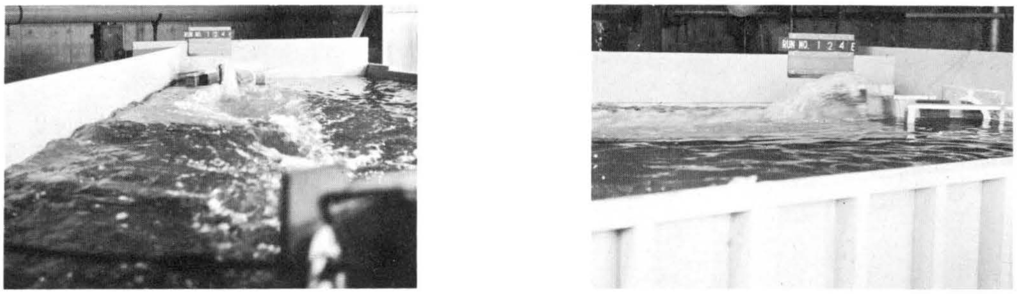


Fig. 38. Recommended Deflector, Modified Type I, Reservoir level 1258, Q = 107,000 cfs, Tail water level 1109.

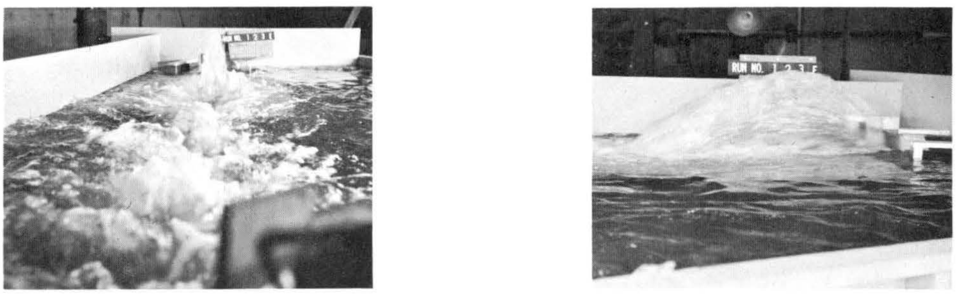


Fig. 39. Recommended Deflector, Modified Type I, Reservoir level 1361, Q = 139,500 cfs, Tail water level 1115.

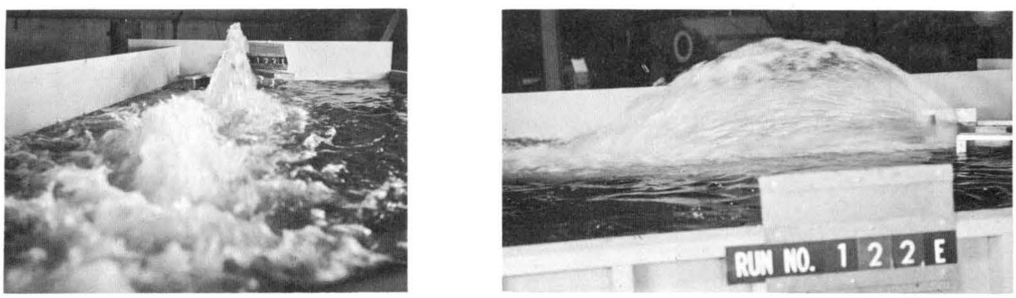


Fig. 40. Recommended Deflector, Modified Type I, Reservoir level 1462, Q = 164,000 cfs, Tail water level 1116.

Model Construction

The intake shaft to the power tunnel was formed in six plastic sections and glued together. Construction tolerances were held to $\pm$ 0.010 inch. Fig. 41 shows the completed model without the trash rack structure which was installed within the head box as shown in Fig. 42. The arrangement of the plexiglass windows in the head box mentioned earlier can be clearly seen in this photograph. Note also that the entire transition to the circular tunnel was placed within the head box. Very stiff polyethylene tubing was used to connect the manometer to the piezometers within the head box to be assured that external pressures on the tubing were not transmitted to readings on the manometers.

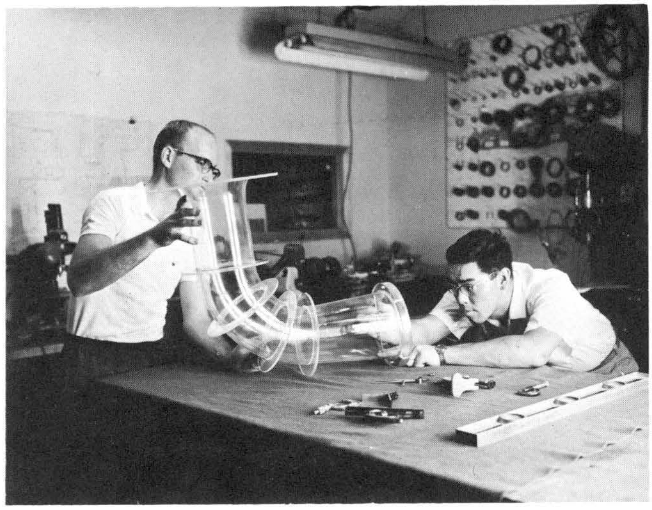


Fig. 41. Intake vertical shaft and transition for Tunnel 1 - Power.

Service gates and a pier were added to the central gate structure and the 48.5 ft diameter tunnel was replaced with a 43.5 ft diameter tunnel was replaced with a 43.5 ft diameter tunnel downstream of the gate section. A photograph of the gate section is shown in Fig. 43. The penstock and distribution manifold were not modeled. There was instead an adjustable control constructed at the outlet to the tunnel, as shown in Fig. 44, to regulate the flow through the system to represent reservoir elevations and discharges calculated for the prototype. The prototype discharges and reservoir elevations reproduced in the model were as follows:

Reservoir Elevation	Discharge in cfs
1550	24,200
1514	27,500
1400	22,200
1300	17,800

The last three of the above points represent full-gate discharges through four turbines at the reservoir levels indicated. The first point represents the discharge at maximum head with the turbine gate openings cut back to match the maximum rated generator output. There was no adjustment to the slope of the tunnel as was done to Tunnel 1 for diversion. The same slope was used in the model as designed for the prototype.

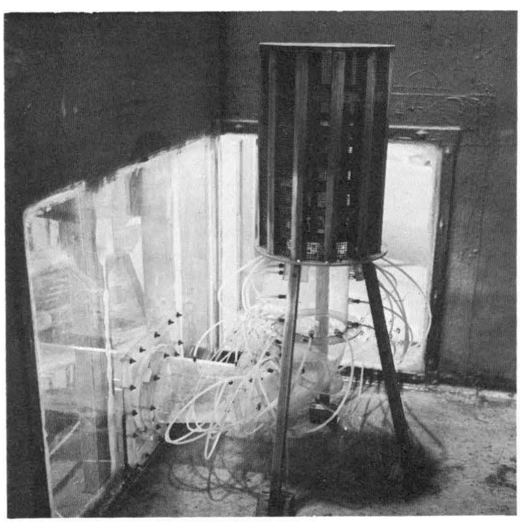


Fig. 42. Installation of the vertical shaft, transition and trash rack structure inside the head box.

Piezometers were located in the vertical shaft as dimensioned in the drawing of Fig. 45. The piezometers could not be located exactly on the vertical and horizontal planes through the center of the tunnel because of construction seams. Thus they were slightly offset as shown in the various sectional views. Piezometers located in the tunnel are shown in Fig. 46 and those in the central gate chamber walls and pier are shown in Fig. 49. The piezometers in the transition upstream of the central gate chambers are shown in Fig. 15.

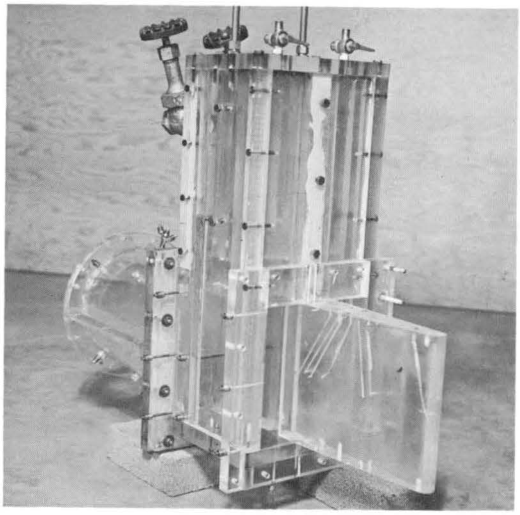


Fig. 43. Central gate section for Tunnel 1 - Power.

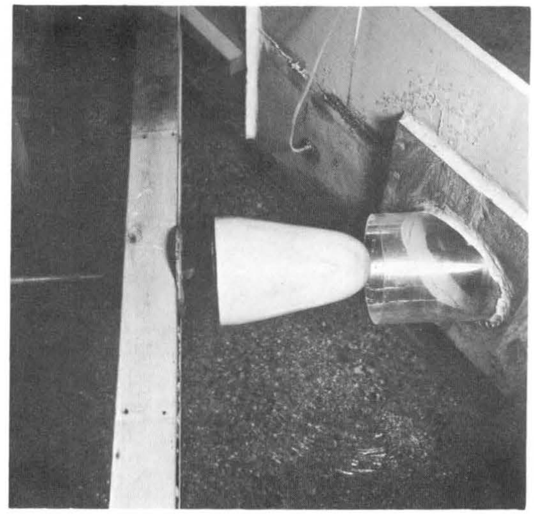
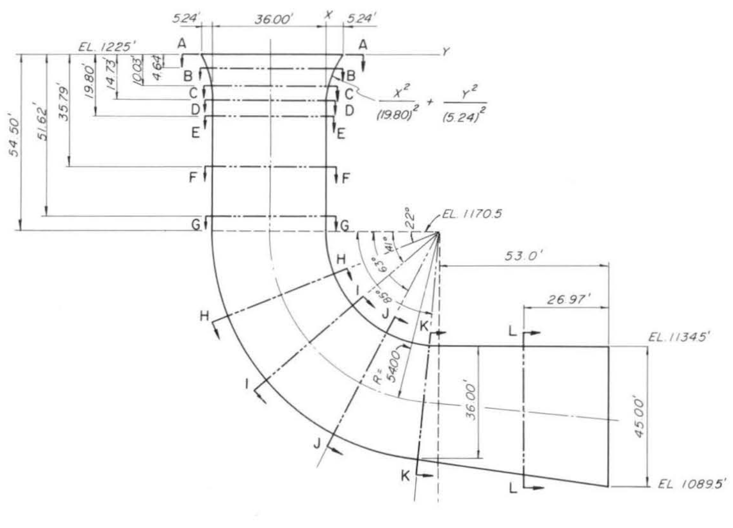


Fig. 44. Adjustable control at the tunnel outlet.



℄ PROFILE VERTICAL SHAFT, BEND & TRANSITION

TABLE OF PIEZOMETER ELEVATIONS

Piezo. No.	Elev. Ft.	Piezo. No.	Elev. Ft.	Piezo. No.	Elev. Ft.
Section A – A		Section G - G		Section J – J	
1a	1225.00	7a	1173.38	35a	1120.37
21a	1225.00	15a	1173.38	25a	1133.13
Section B – B		22a	1173.38	12a	1137.27
2a	1220.36	31a	1173.38	28a	1133.13
20a	1220.36	32a	1173.38	Section K–K	
Section C – C		Section H – H		36a	1116.37
3a	1214.97	14a	1155.86	26a	1129.69
19a	1214.97	23a	1154.01	11a	1134.60
Section D – D		30a	1154.01	27a	1129.69
4a	1210.27	33a	1149.08	9a	1098.91
18a	1210.27	Section I – I		Section L–L	
Section E – E		34a	1132.72	10a	1134.60
5a	1205.16	24a	1142.06		
17a	1205.16	13a	1145.31		
Section F – F		29a	1142.06		
6a	1189.21	8a	1119.90		
16a	1189.21				

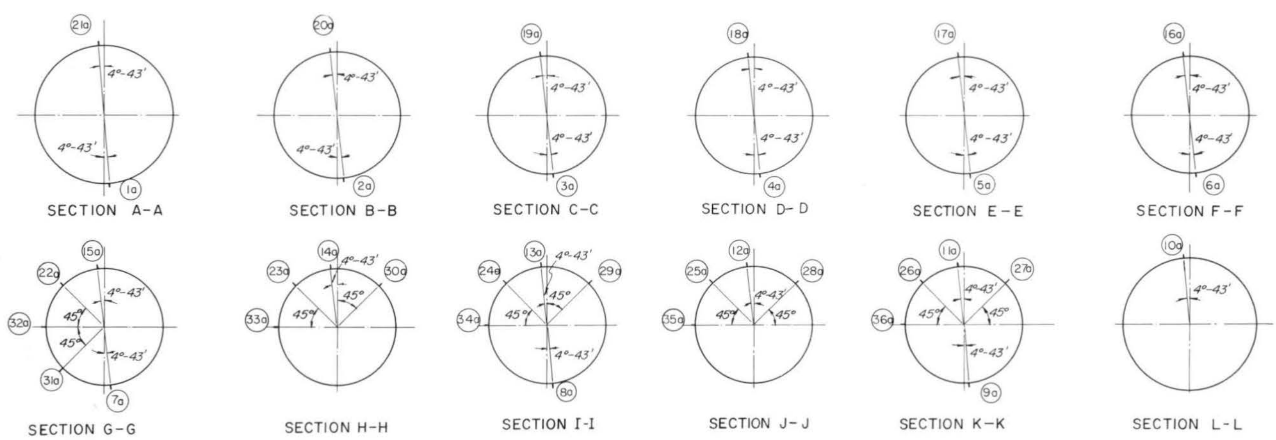


FIGURE 45 TUNNEL 1 - POWER INTAKE SHAFT PIEZOMETER LOCATIONS

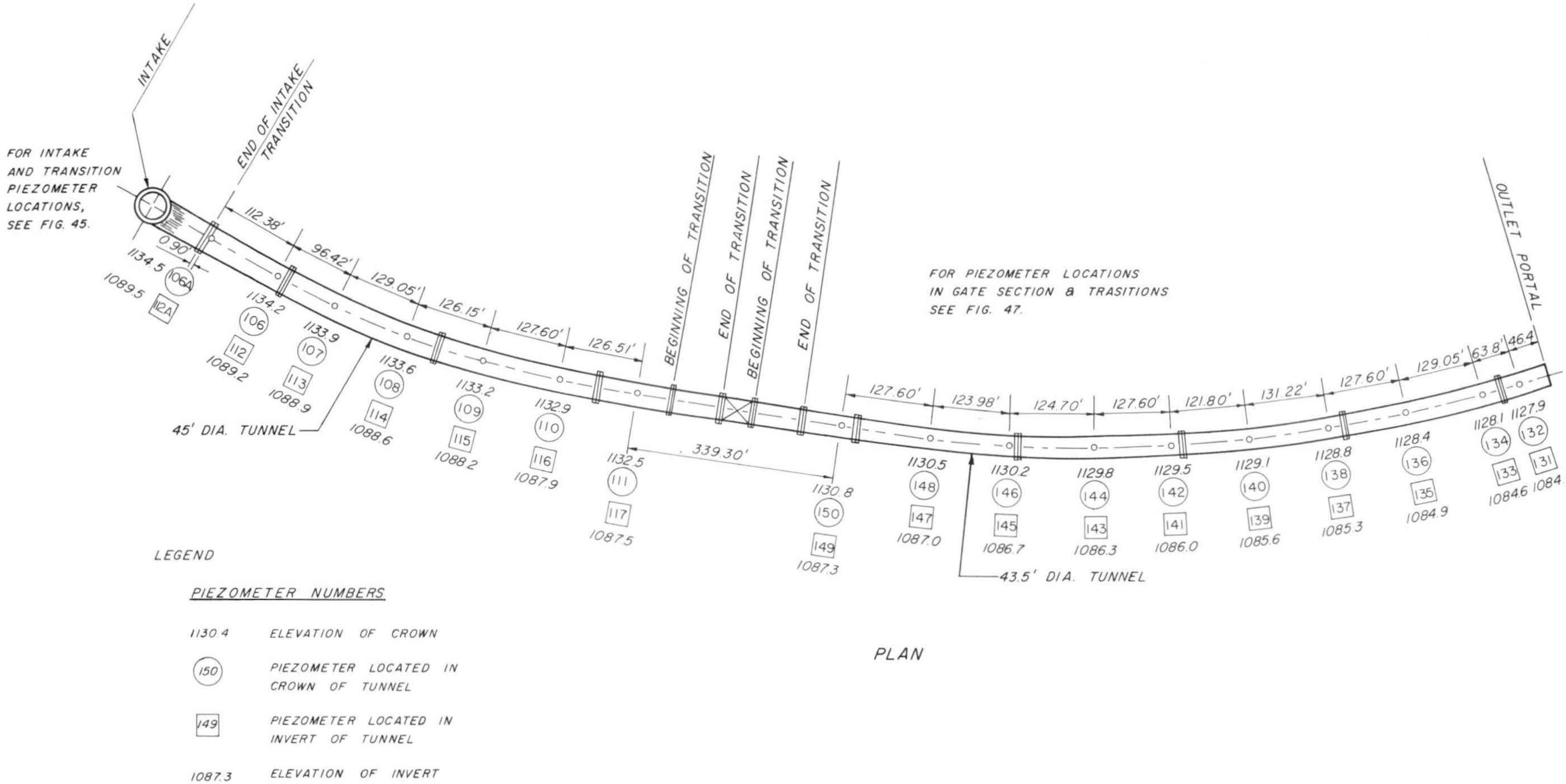


FIGURE 46 TUNNEL 1 – POWER PIEZOMETER LOCATIONS

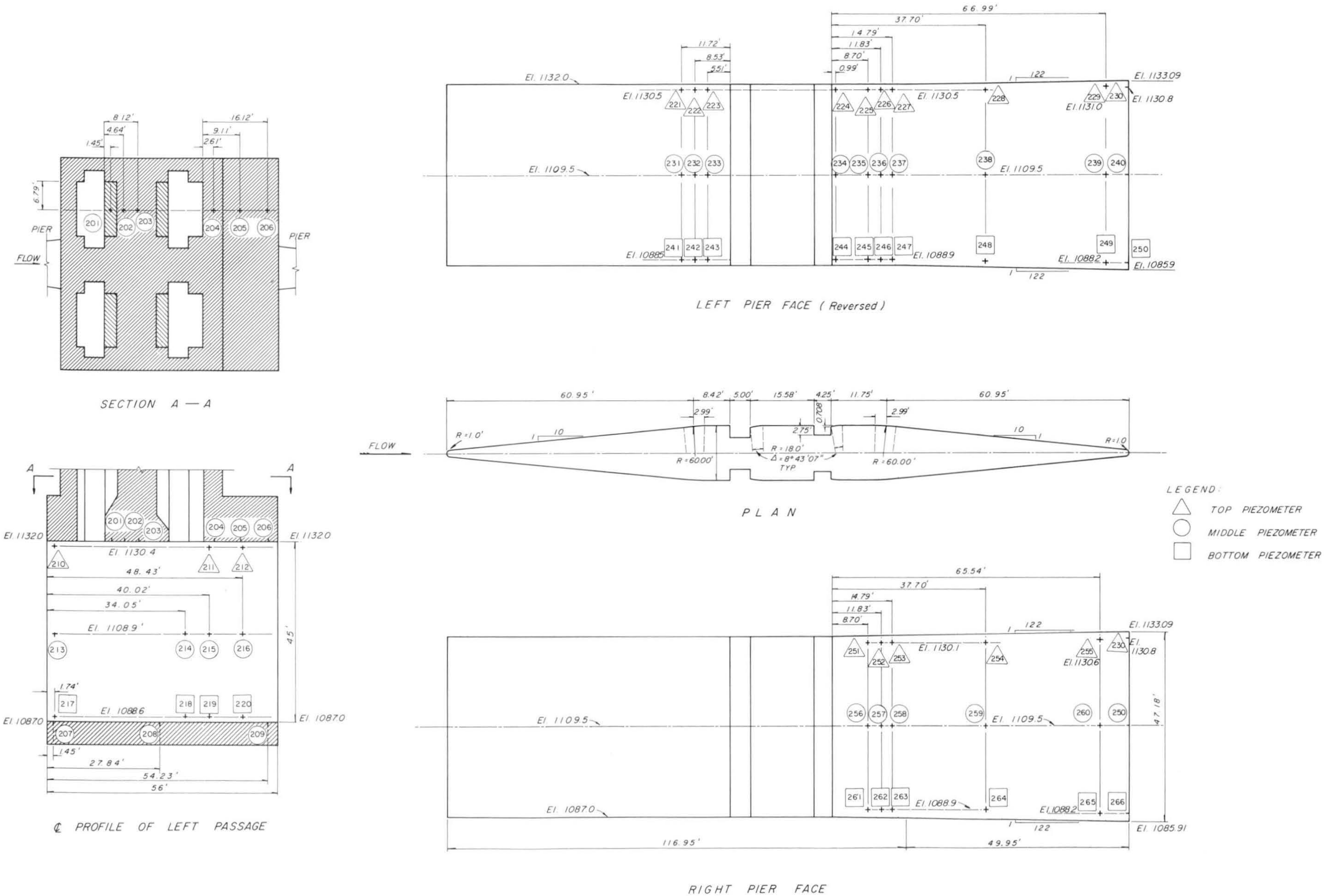


FIGURE 47 TUNNEL 1 — POWER CENTRAL GATE SECTION PIEZOMETER LOCATION

Model Tests and Results

Reservoir elevation 1300 was the minimum operating level expected in the prototype. The pressures along the vertical shaft from minimum to maximum reservoir levels were positive. No changes were required in the dimensions of the shaft or the transition to the circular tunnel. The table in Fig. 48 presents the pressure heads measured in the vertical shaft and transition at the four reservoir elevations listed above. Hydraulic conditions through the entire tunnel were satisfactory. Low pressure zones were not evident in the central gate chamber (see Table B-1 of Appendix B).

Normal closure of the service gates will not be a problem because the valves at the turbines will be closed prior to gate closure. However, if the service gates should require closure for emergency reasons, some consideration should be given to hydraulic conditions that could develop within the tunnel. A discharge of 43,500 cfs with the reservoir at elevation 1550 was taken as representing an extreme emergency condition due to partial failure of the penstock between the tunnel portal and the powerhouse. When the service gates were closed symmetrically, pressures at the walls of the chamber and gate pier were always positive for every gate opening. The flow downstream of the gate with 12,500 cfs discharge at reservoir elevation 1551 and 5 percent opening is shown in Fig. 49. There was adequate ventilation of the hydraulic jump through the gate shaft and although velocities were large in the flow beneath the gates negative pressures were not produced at the boundaries. The pressures were balanced across the pier within the gate shaft.

With unsymmetric closure of the two service gates, extreme conditions in flow and pressures occurred when one gate was full open and the other closed. At reservoir elevation 1552 and discharge of 42,000 cfs through one passageway, a maximum head differential of 63 feet of water developed across the pier at a section immediately upstream of the service gate. Pressures were positive everywhere in the chamber and tunnel downstream of the gates.

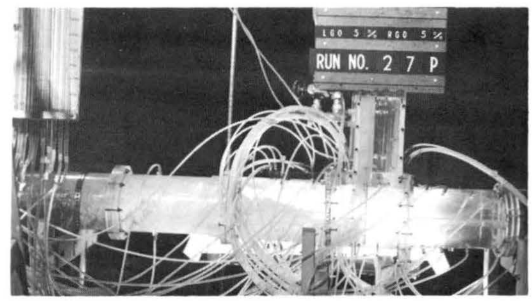
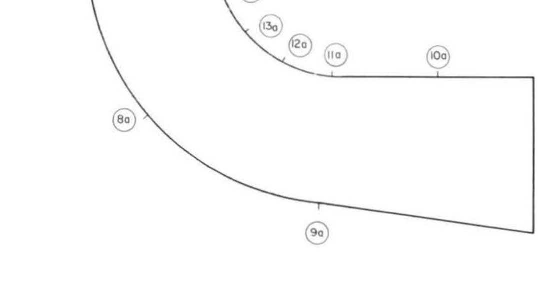


Fig. 49. Flow at the central gate during emergency closure. Gate opening 5 percent, Reservoir elevation 1551, Q = 12,500 cfs.



℄ PROFILE

TABLE OF PRESSURE HEADS IN FEET OF WATER

Run Number	1 P	Z P	3 P	4 P
Reservoir Elevation	1550.5	1514.0	1398.5	1299.0
Discharge Q =	24,200	27,500	22,200	17,800
Piezometer Number	Pressure Head	Pressure Head	Pressure Head	Pressure Head
1a	320.0	281.0	168.5	71.0
2a	324.6	286.6	173.6	75.6
3a	330.0	291.0	178,0	805
4a	334.2	294.7	182.7	85.2
5a	339.3	300.3	187.8	89.8
6a	354.8	315.8	203.3	106.8
7a	372.6	333.6	220.6	122.6
8a	427.6	389.6	275.6	177.1
9a	446.1	406.6	293.6	196.6
10a	408.4	370.4	256.9	160.4
11a	407.4	367.4	255.9	159.4
12a	402.7	363.7	252.2	156.2
13a	392.7	351.7	242.2	147.2
14a	382.1	341.6	231.6	136.6
15a	369.6	329.6	217.6	121.6
16a	354.8	315.3	203.8	106.3
17a	339.3	300.3	187.8	90.8
18a	334.2	295.2	182.7	85.7
19a	330.0	291.0	178.5	81.0
20a	325.1	286.6	173.6	76.1
21a	319.0	280.0	168.0	70.5

FIGURE 48 TUNNEL I. – POWER PRESSURE HEADS IN VERTICAL INTAKE AND TRANSITION

IV. TUNNEL NO. 3

Model Construction

The head box arrangement for Tunnel 3 was the same as for Tunnel 1. The tail box was altered to fit the change in alignment, length of tunnel and the stilling basin. The completed tunnel model is shown in the photograph of Fig. 50. The intake structure, the bifurcation and radial gate chamber models are shown in Figs. 51 and 52 respectively.

The chute and stilling basin were constructed with vertical walls. When the design was changed to battered walls and warped transition walls for structural reasons, the change was not included in this model because model construction was completed and because further studies of the stilling basin were to be conducted in Pakistan.

The locations of piezometers used to measure pressures in Tunnel 3 are detailed in the figures listed below:

Fig. 53 - piezometers in the intake structure

Fig. 54 - piezometers in the transition downstream of the intake

Fig. 55 - piezometers in the central gate

Fig. 56 - piezometers in the transition downstream

Fig. 57 - tunnel piezometers

Fig. 58 - piezometers in the bifurcation and downstream transition

Fig. 59 - piezometers in chute and stilling basin.

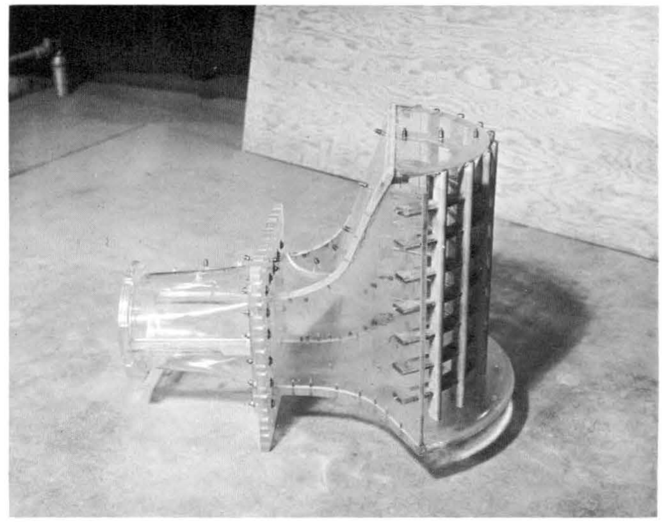


Fig. 51. Intake to Tunnel No. 3 and the transition to the circular tunnel.

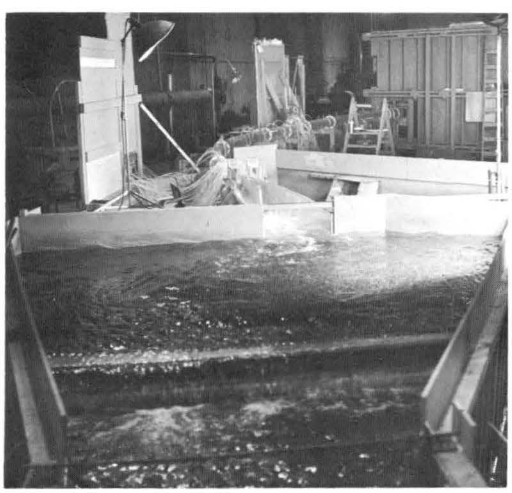


Fig. 50. Completed model of Tunnel 3.

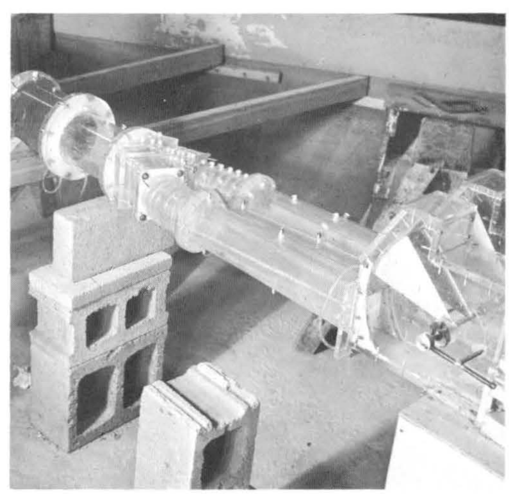


Fig. 52. Bifurcation and radial gate structure.

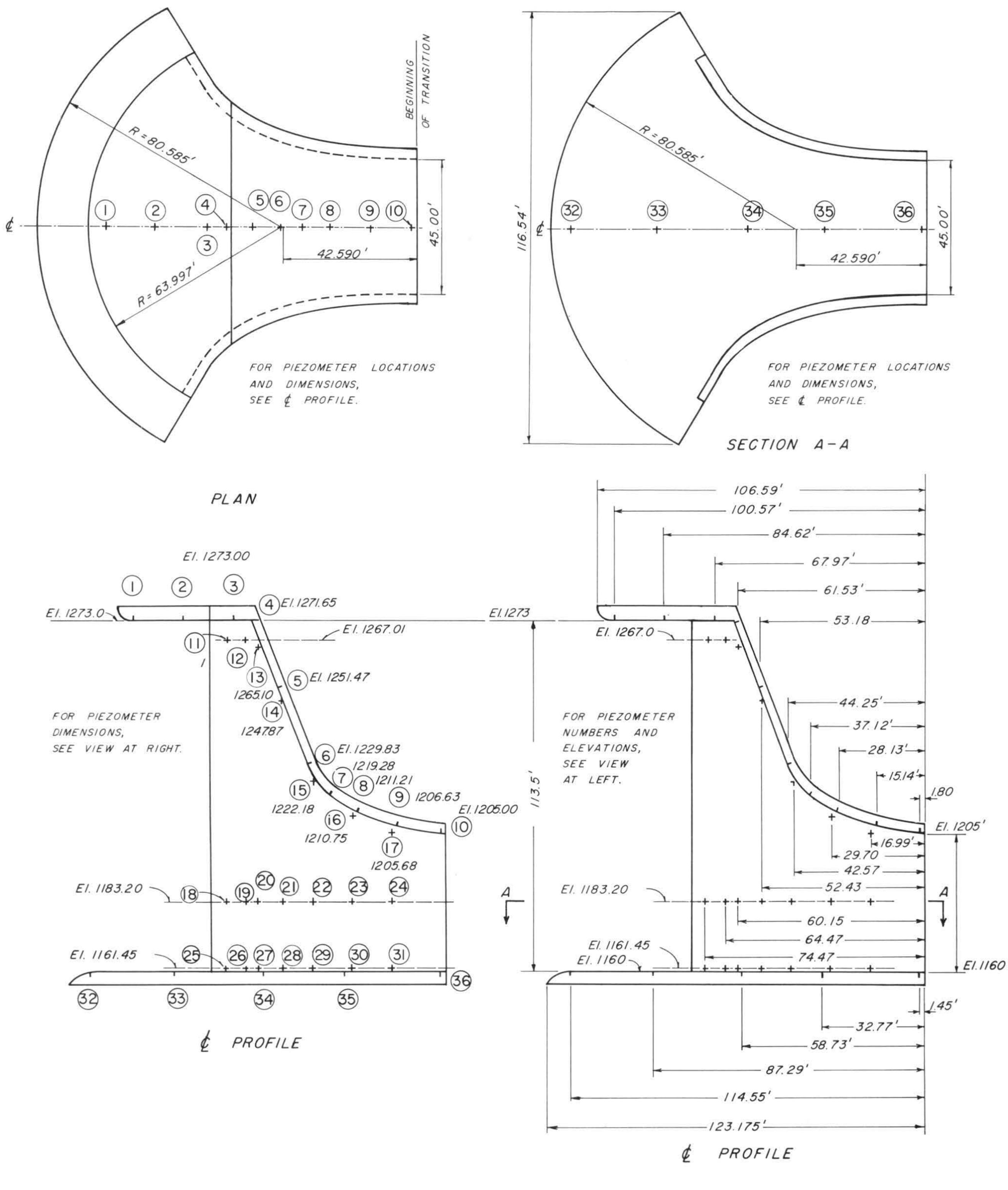


FIGURE 53 TUNNEL 3 – INTAKE PIEZOMETER LOCATIONS

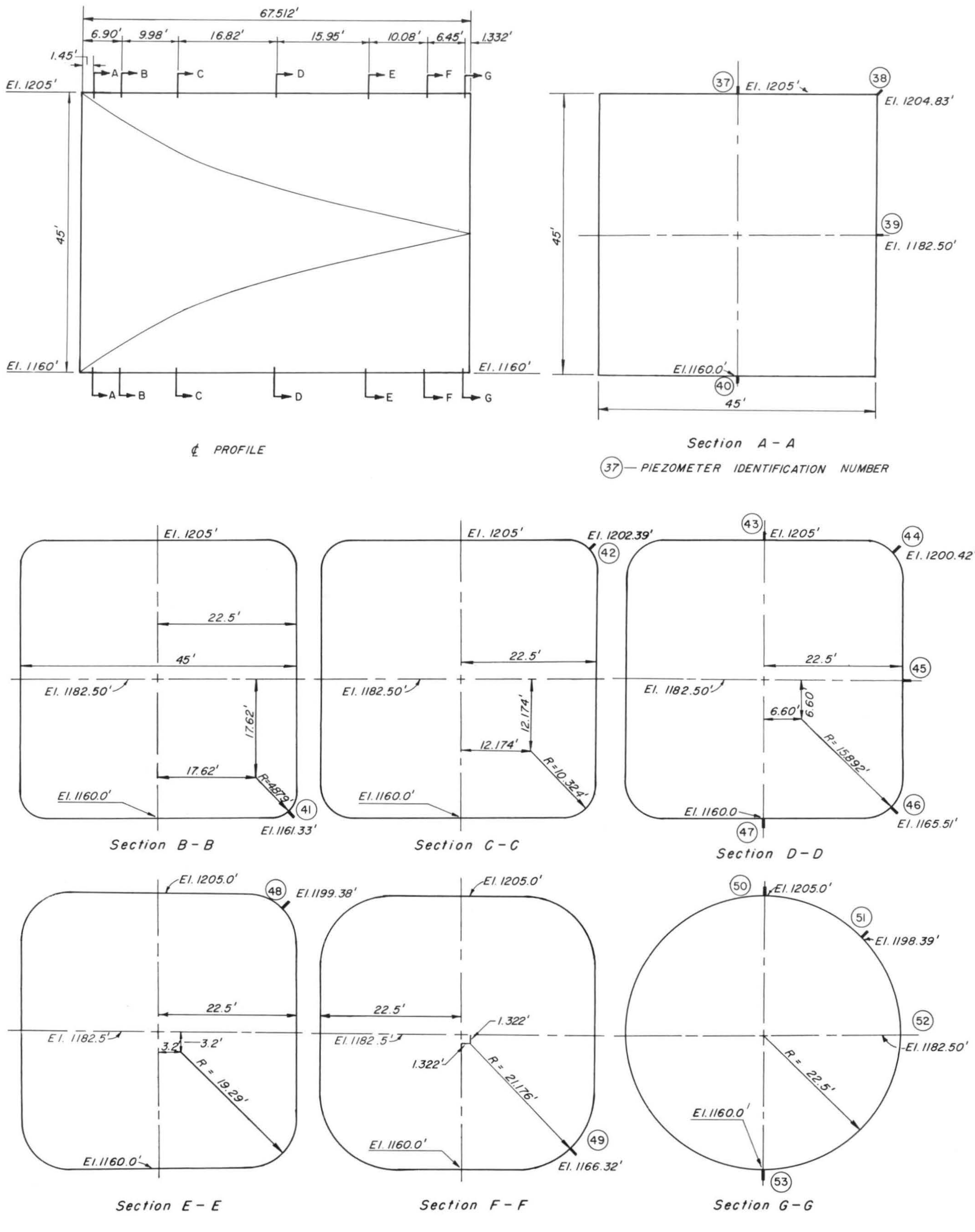
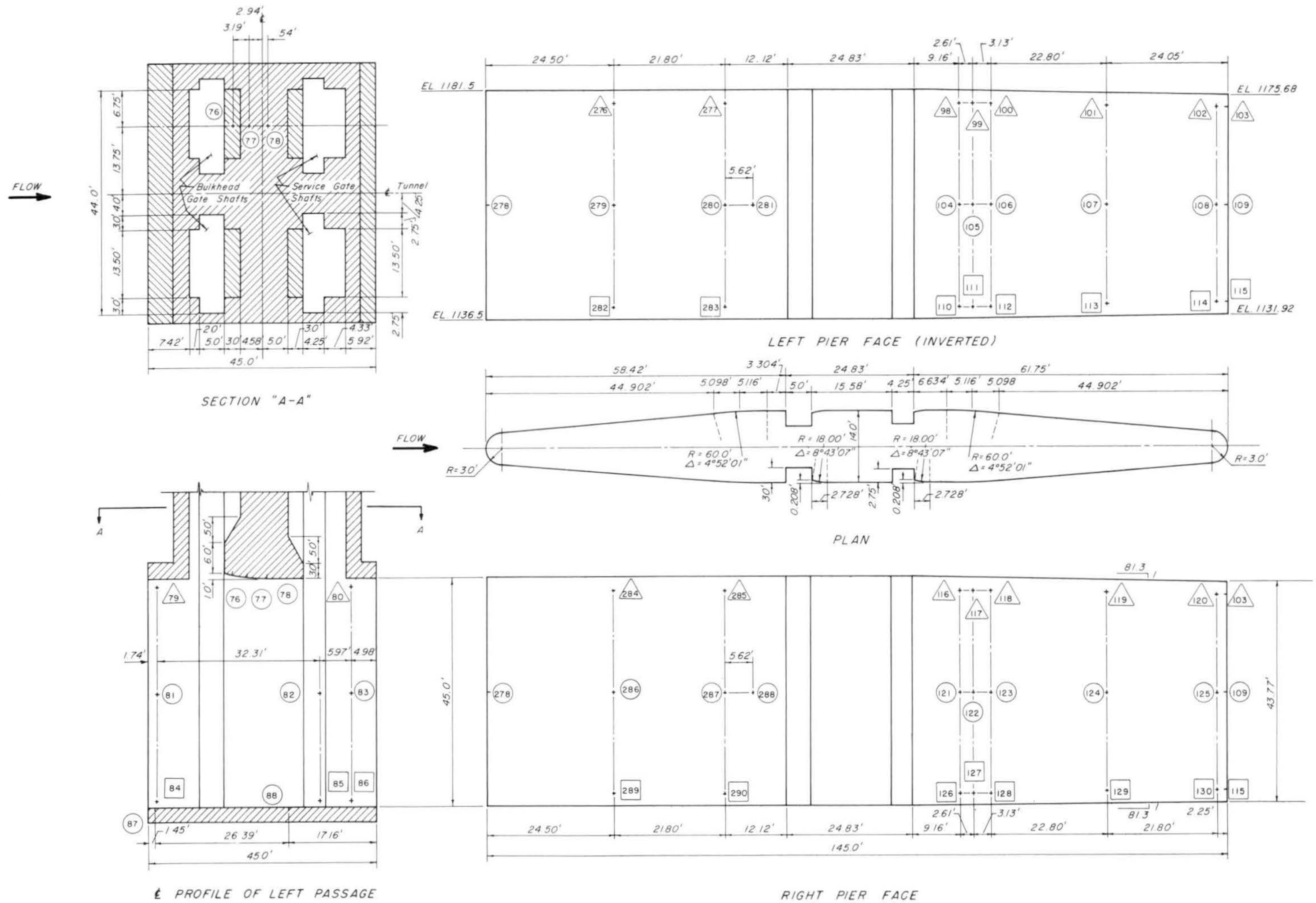


FIGURE 54 TUNNEL 3 TRANSITION DOWNSTREAM FROM INTAKE PIEZOMETER LOCATIONS



Piezometer Number	Elevation
76	1180.5
77	1179.9
78	1179.7
79	1178.6
80	1177.5
81 - 83	1157.1
84	1136.1
85 - 86	1135.1
87	1135.2
88	1134.7
98 - 100	1176.9
101	1175.0
102	1174.9
103	1174.1
104 - 106	1155.9
107 - 108	1154.6
109	1153.8
110 - 112	1136.6
113	1135.6
114 - 115	1134.6
116 - 118	1176.9

Piezometer Number	Elevation
119	1175.0
120	1174.9
121 - 123	1155.9
124 - 125	1154.6
126 - 128	1136.6
129	1135.6
130	1134.6
276	1179.0
277	1178.0
278	1159.0
279	1158.0
280 - 281	1157.0
282	1137.0
283	1136.0
284	1179.0
285	1178.0
286	1158.0
287 - 288	1157.0
289	1137.0
290	1136.0

LEGEND:
△ Top Piezometers
○ Middle Piezometers
□ Bottom Piezometers

FIGURE 55 TUNNEL 3 CENTRAL GATE SECTION PIEZOMETER LOCATIONS

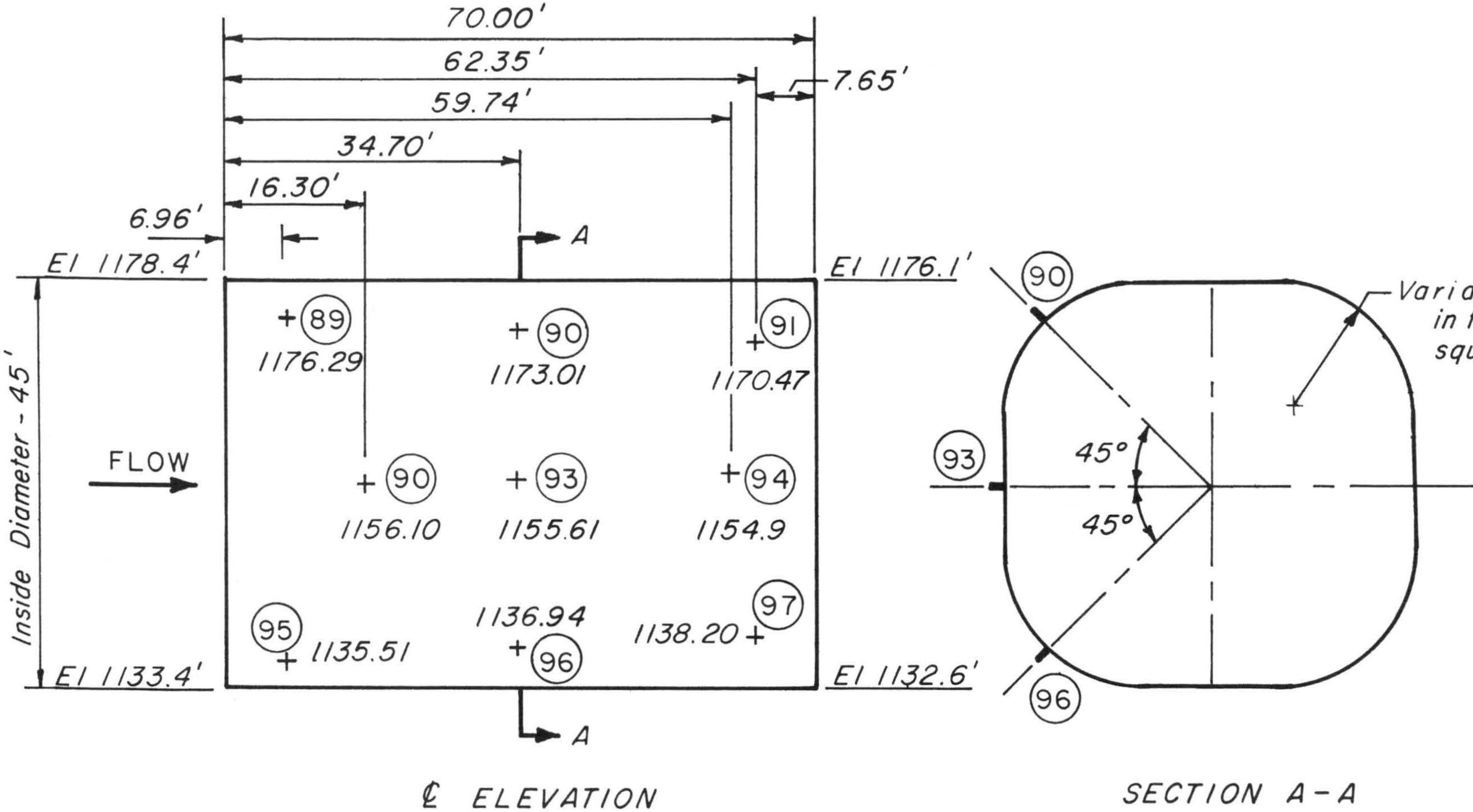


FIGURE 56 TUNNEL 3 TRANSITION DOWNSTREAM FROM CENTRAL GATE SECTION PIEZOMETER LOCATIONS

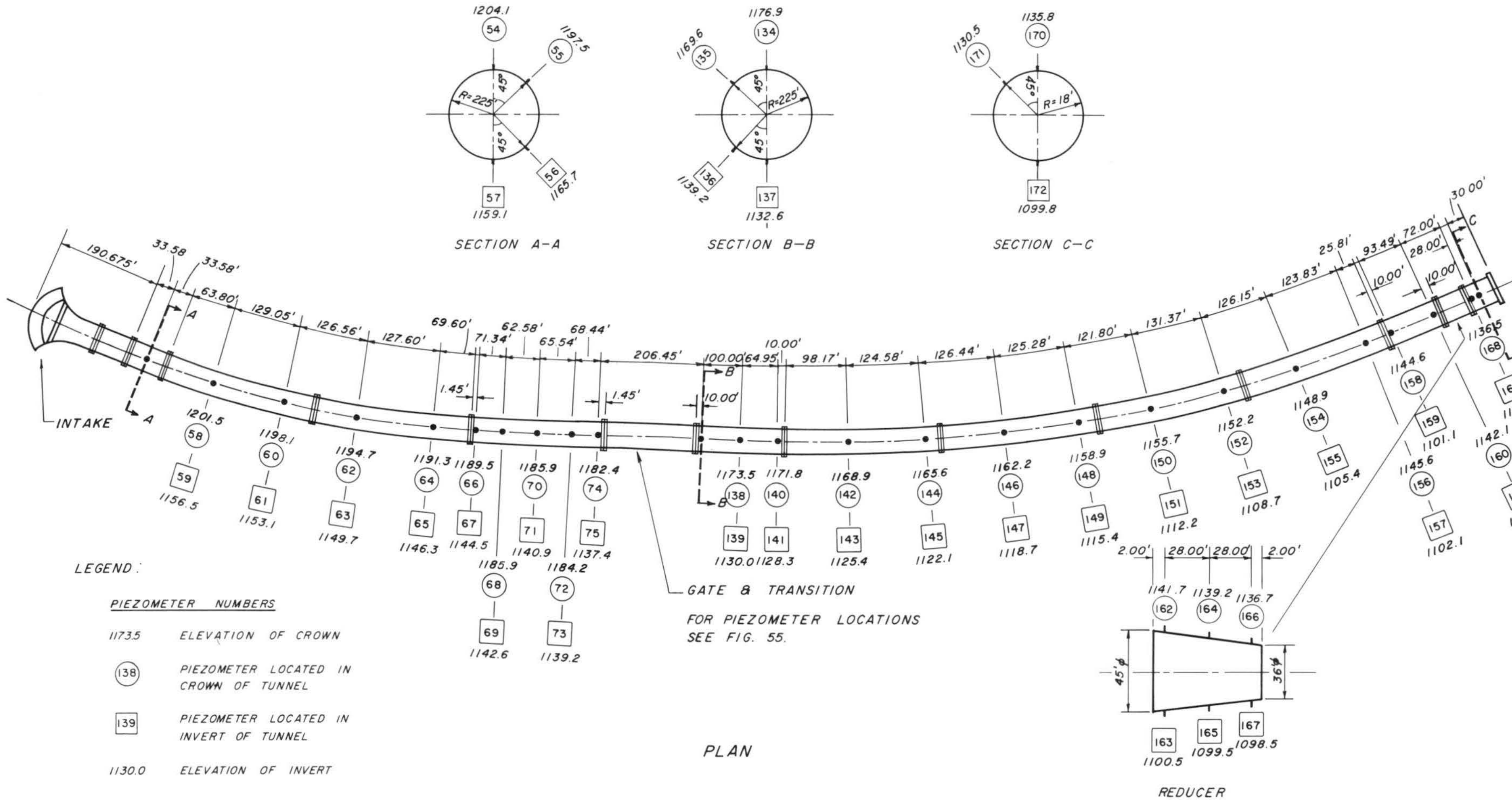


FIGURE 57 TUNNEL 3 PIEZOMETER LOCATIONS

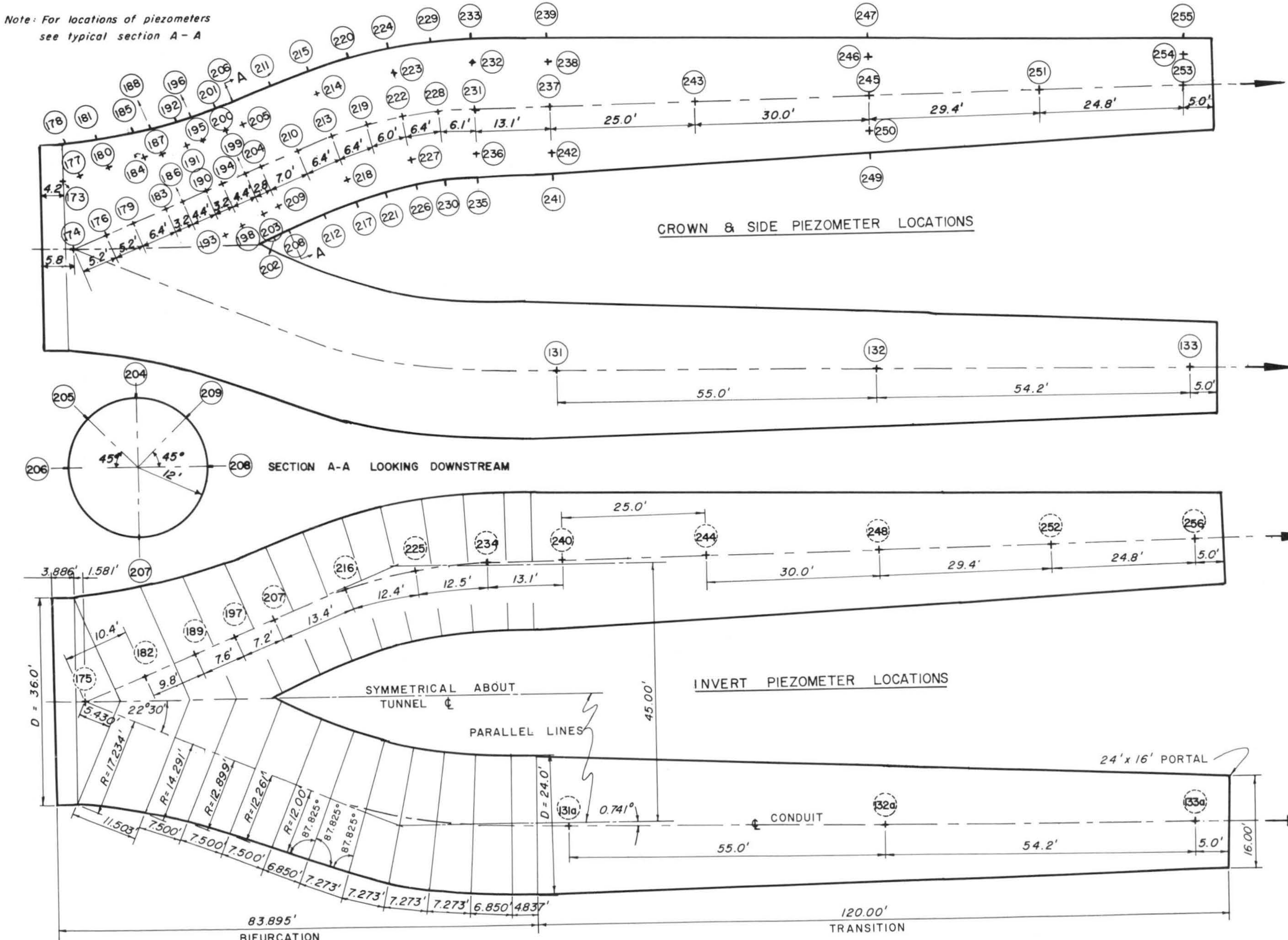


FIGURE 58 TUNNEL 3 — BIFURCATION AND TRANSITIONS PIEZOMETER LOCATIONS

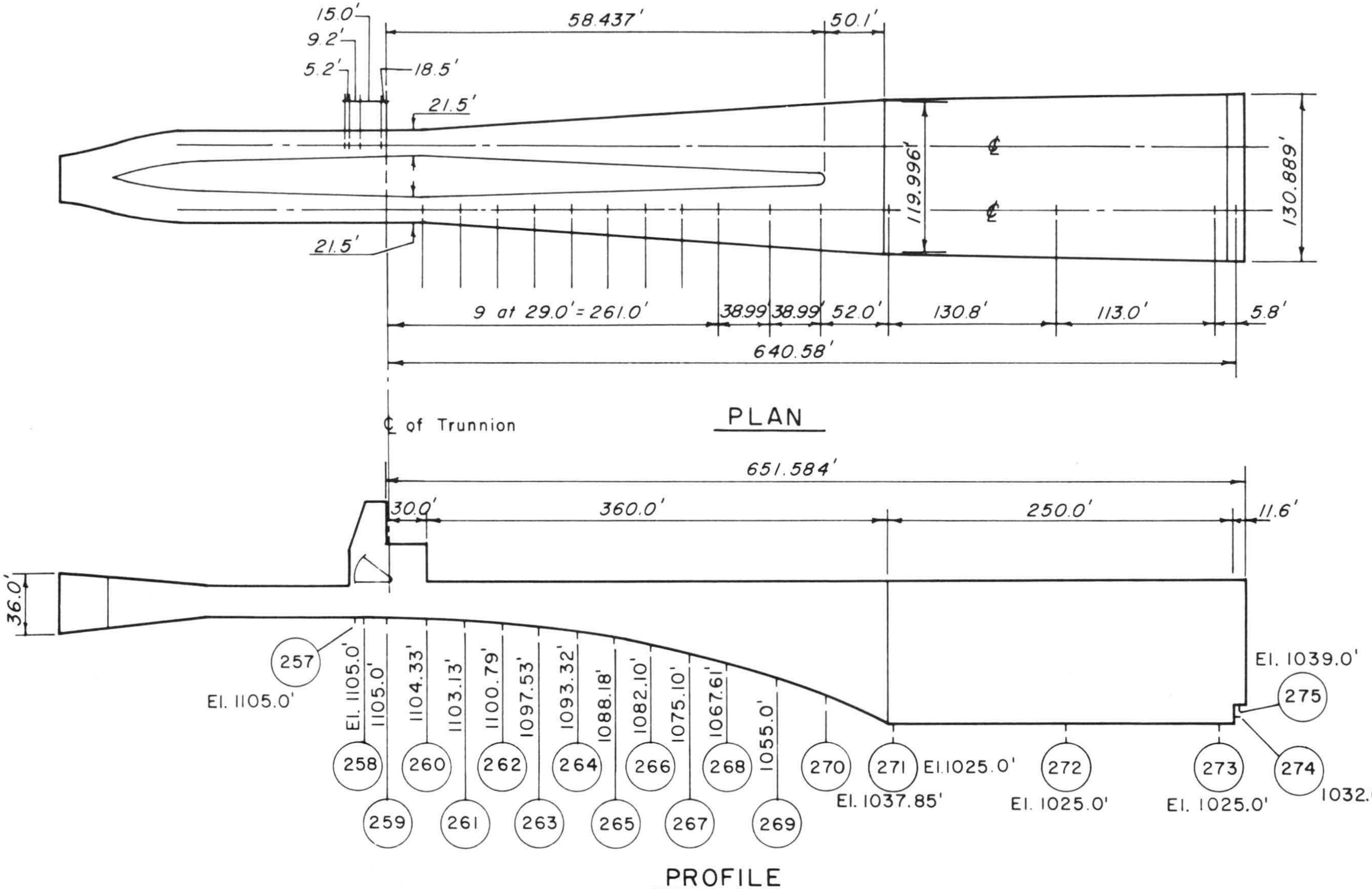


FIGURE 59 TUNNEL NO. 3 STILLING BASIN AND RADIAL GATE CHAMBER PIEZOMETER LOCATION

Model Tests and Results

Description of Flow - Model discharge curves for Tunnel 3 are given in Fig. 60. The curves are intended for reference only and should not be used directly as prototype rating curves.

After closure of Tunnels 1 and 2, preparatory to power penstock conversion, Tunnels 3 and 4 will operate as diversion tunnels which could require that the radial gates remain full open. In the range of reservoir levels from 1160 to approximately 1185, flow in the tunnel was essentially open channel flow. The tunnel slope was super-critical, and the flow was controlled at the intake. At the central gate chamber, there was a rise in water surface level because of the change in geometry and the flow obstruction offered by the pier. Beyond the pier, the flow accelerated in the tunnel. The contraction of the tunnel from 43.5 to 36 ft in diameter caused a rise in water surface through the transition and the bifurcation.

When the reservoir level rose above 1185, the rise in water surface at the gate chamber and the transition to the bifurcation closed the tunnel and caused hydraulic jumps to form at those sections. The hydraulic jumps remained essentially stationary in location as the discharge increased with continued rise of water surface in the reservoir. At reservoir elevation 1205, the tunnel at the intake was sealed and an air pocket formed between the intake and the gate section. Almost simultaneously an air pocket was also formed between the gate section and the bifurcation. The pressure in these air pockets was positive. The hydraulic jumps entrained the trapped air and eventually the tunnel flowed full. At reservoir elevation 1225 completely full tunnel flow occurred, and no further flow irregularity was observed in any part of the tunnel.

During the embankment closure and reservoir filling period, the control gates can remain closed while the reservoir is between elevations 1185 and 1225, with Tunnels 1 and 2 providing all necessary discharge capacity. After completion of the dam, the reservoir will never be drawn below elevation 1300.

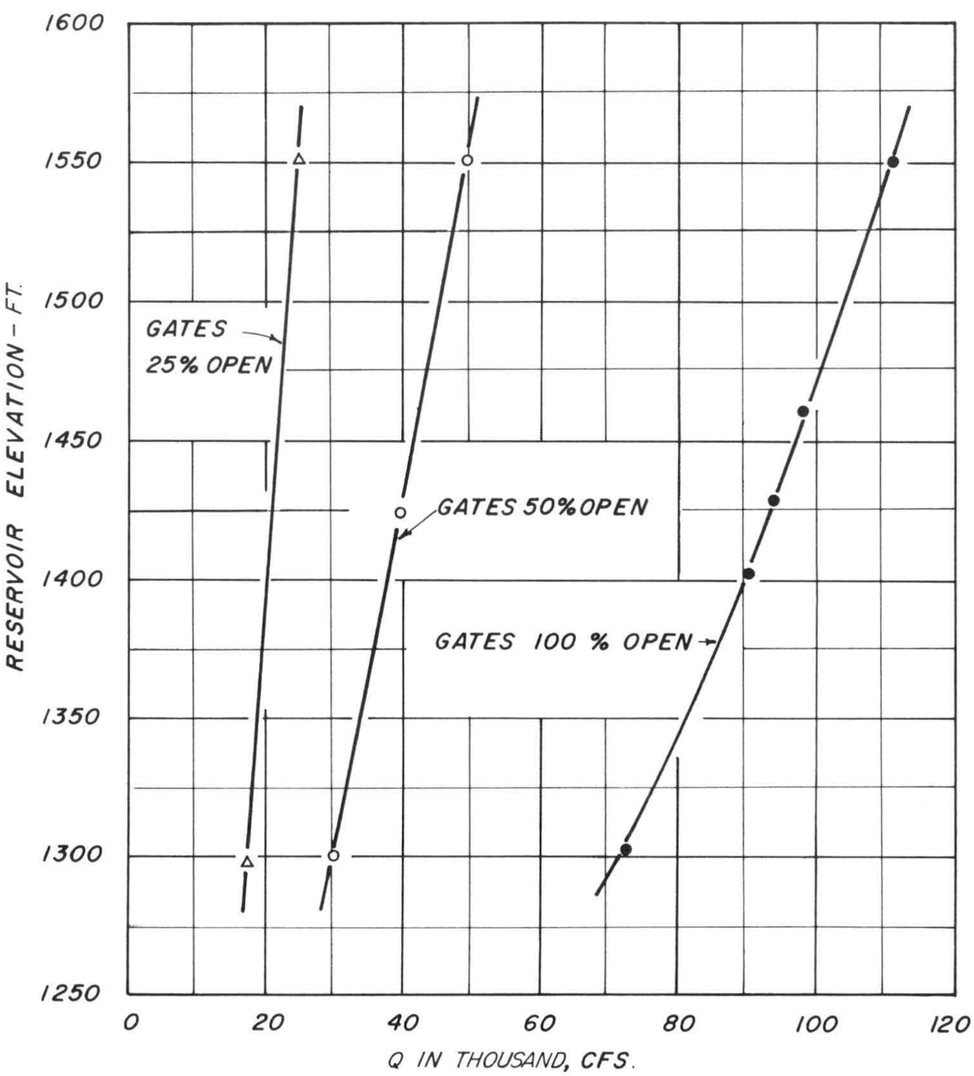


FIGURE 60 TUNNEL 3 – DISCHARGE RATING CURVE

Form Loss Coefficients - Radial Gates Open - The energy gradients through the tunnel measured at four reservoir levels of 1305, 1400, 1460, and 1550 are drawn on Fig. 61 and the data are recorded in Tables C-1, C-2 and C-3 of Appendix C. From these curves, form loss coefficients were calculated as tabulated in Table 3. The form loss coefficients K_i was defined on page 24 in terms of the velocity head at the downstream section of the structure concerned, where i = 5, 6, 7, 8, 9 and 10 where

5 = intake and transition,

6 = transition upstream of the central gate chamber,

7 = central gate chamber and transition downstream,

8 = transition from 43.5 to 36 ft diameter

9 = bifurcation,

10 = transition to the radial gate structure.

Head losses due to friction in each section are included in the form losses.

Service Gates - Symmetric Closure - Pressures measured at all piezometers in the central gate chamber were positive with the gates in the open position. Closure of the service gates would probably be made only after the radial gates were closed, so that normally there would be no problem effecting closure. The discussion herein considers an extreme condition, where the service gates required to be closed when the radial gates were both full open and reservoir elevation was maximum.

As the gates were closed simultaneously, a hydraulic jump was formed in the tunnel downstream of the gates at about 70 percent open position. By the time the gates closed to 40 percent, the jump was swept out of the tunnel and free flow occurred.

Negative pressures were recorded near the downstream end of the pier from 50 percent open to near closure, because the high velocity flow tended to separate from the boundary but did not actually separate. Prototype vapor pressures were recorded at piezometers near the base of the pier. Pressure data are given in the tables of Appendix C.

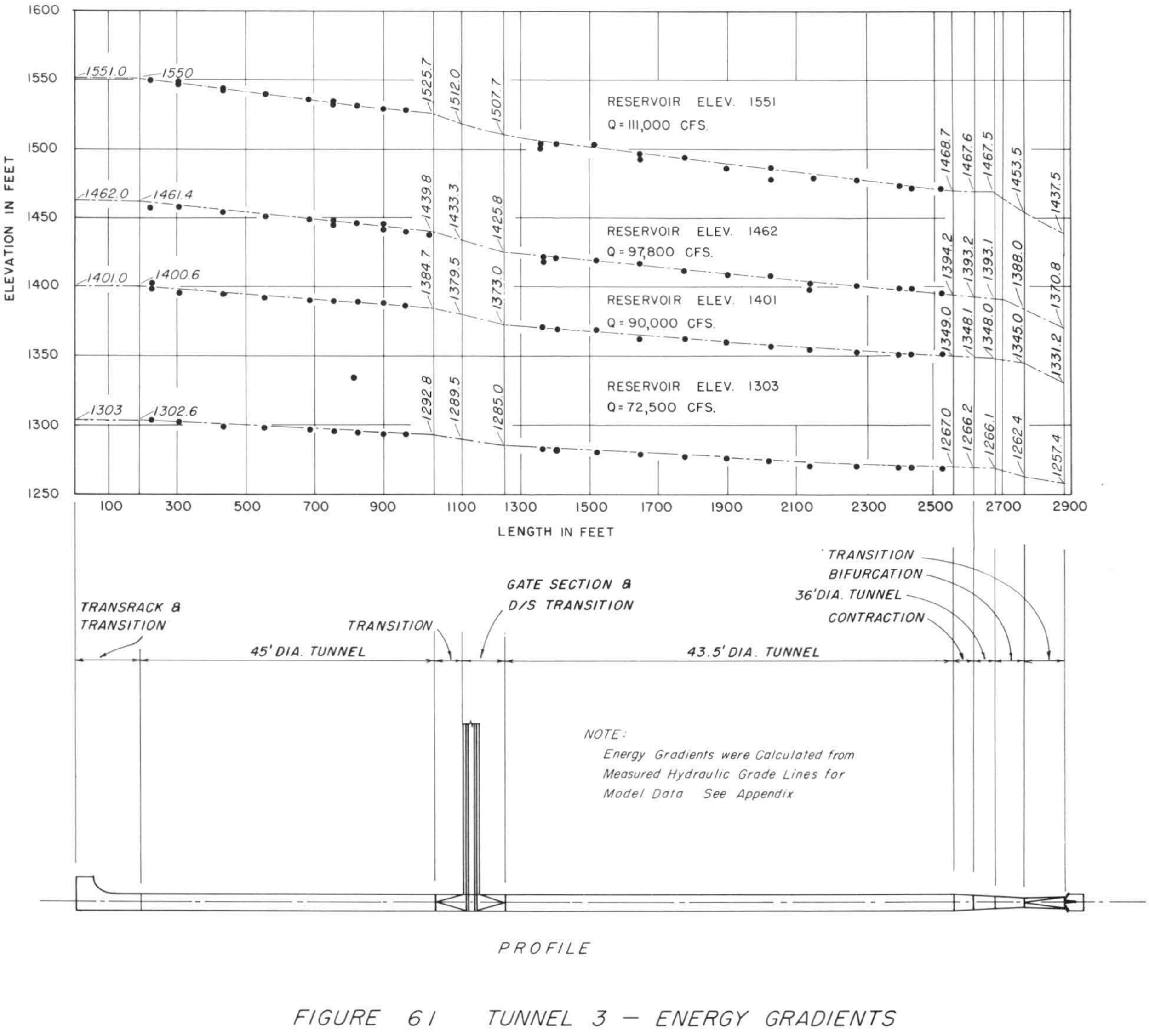


FIGURE 61 TUNNEL 3 — ENERGY GRADIENTS

TABLE 3

MODEL LOSS COEFFICIENTS FOR TUNNEL NO. 3 .

Reservoir elevation		1551	1462	1401	1303
Discharge		111000	97800	90000	72500
Intake and transition	H_L	1.0	0.6	0.4	0.2
	V	69.81	61.51	56.60	45.60
	$\frac{V^2}{2g}$	75.67	58.75	49.74	32.29
	K_5	0.013	0.010	0.008	0.006
Transition upstream from central gate	H_L	8.7	6.5	5.2	3.3
	V	91.36	80.49	74.07	59.67
	$\frac{V^2}{2g}$	129.61	100.60	85.19	55.29
	K_6	0.067	0.065	0.061	0.060
Gate and downstream transition	H_L	9.3	7.5	6.5	4.5
	V	74.70	65.81	60.57	48.79
	$\frac{V^2}{2g}$	86.65	67.25	56.97	36.96
	K_7	0.107	0.112	0.114	0.124
Transition 43.5 to 36'	H_L	1.1	1.0	0.9	0.8
	V	109.04	96.07	88.41	71.22
	$\frac{V^2}{2g}$	184.62	143.31	121.37	78.76
	K_8	0.006	0.007	0.007	0.010
Bifurcation	H_L	14.0	10.1	7.5	3.7
	V	122.52	107.95	99.34	80.02
	$\frac{V^2}{2g}$	233.09	180.95	153.24	99.43
	K_9	0.060	0.056	0.049	0.037
Transition downstream from bifurcation	H_L	16.0	12.2	9.3	5.0
	V	144.53	127.34	117.19	94.40
	$\frac{V^2}{2g}$	324.36	251.79	213.25	138.38
	K_{10}	0.049	0.048	0.044	0.036

Service Gates - Unsymmetric Closure - It was assumed in this part of the study that one service gate would be completely closed before the other was closed. A hydraulic jump formed in the tunnel when one gate was closed to about 70 percent open with the other gate open. The jump remained in the tunnel until one gate was completely closed and the remaining gate was about 75 percent closed. A view of the flow downstream of the gates is shown in the photograph of Fig. 62.

The largest differential pressure head was developed across the pier at a section immediately upstream of the gates when one gate was closed and the other full open. The magnitude of the differential pressure head was approximately 360 feet of water with the reservoir at 1550. Pressure heads of minus 9 feet also developed at the wall of the pier just upstream of the bulkhead gate slot, and also downstream of the service gate. Although undesirable, these pressures were considered to be safe in terms of the prototype.

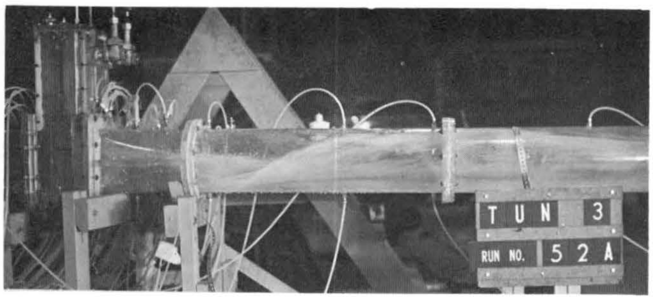


Fig. 62. Flow in Tunnel 3 downstream of the gate chamber, Right gate closed, Left open 75 percent.

Radial Gates - Symmetric Closure - Flow through the bifurcation was satisfactory for all symmetric positions of the radial gates throughout the full range of reservoir levels from 1160 to 1550. Positive pressures were measured at piezometers within the bifurcation and transition downstream of the bifurcation except as expected, some negative pressures were measured at the roof of the transition near the portal where the hydraulic gradient terminated in the flow and not at the crown of the tunnel. This condition of course was with the gates full open, and as soon as the radial gates are slightly closed, the hydraulic gradient rose above the tunnel. Magnitudes of the pressure heads measured within the bifurcation at reservoir level 1550 and radial gates in the full open position are tabulated in Table C-4 of the appendix.

Radial Gates - Unsymmetric Closure - During unsymmetric closure of the radial gates with one gate completely closed and the other fully open, and reservoir at maximum elevation, localized negative pressures were measured within the bifurcation. The reduced pressure zone was at the horizontal centerline just downstream from the crotch of the bifurcation and was on the side where the water flowed. A pressure head of minus 8.5 feet was measured at piezometer 202 (see Fig. 58 for location) when the right gate was closed 50 percent[8] with the left gate open. When the right gate was completely closed, piezometer 202 indicated prototype vapor pressure. Pressure heads measured in the bifurcation are tabulated in Table C-4.

Radial Gate Chamber - The walls in the gate chamber were offset 2.75 feet at the radial gates shown as Scheme B in Fig. 4. This arrangement was not satisfactory because fins were created at the walls by the diverging flow from the radial gate, which caused considerable spray within the gate chamber. The water fins extended above the tops of the chute walls for almost the entire chute length. The photograph in Fig. 63 shows the origin of the fin in the radial gate chamber for reservoir level 1300.

The alternate arrangement, Scheme A, of the chamber walls (see Fig. 4) was tested in the left gate chamber. This arrangement was satisfactory and the fins were eliminated as shown in Fig. 64.

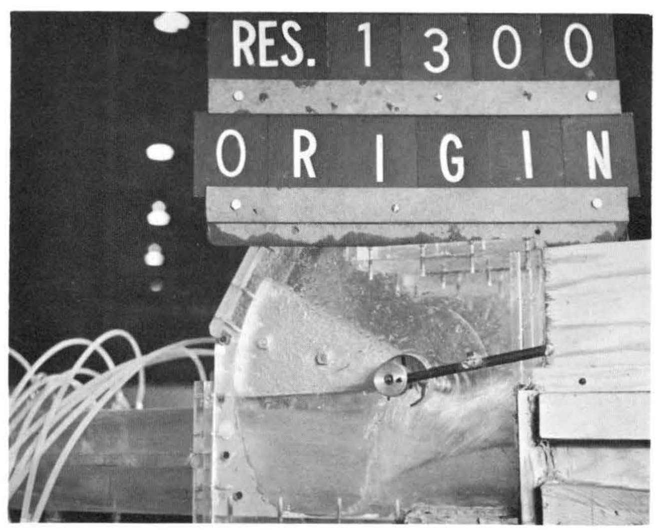


Fig. 63. View of the fins created in the radial gate chamber.

[8] Percent of radial gate opening is defined as percent of angular movement to full open position.

Fig. 64. The fin was eliminated in Scheme A.

Stilling Basin

Chute - Pressures measured on the floor of the chute are shown in Fig. 65 with maximum reservoir level 1550 and both left and right radial gates 25 percent open. Pressures measured at this position are shown rather than for larger gate openings because the velocities beneath the gates were larger, consequently, pressures were minimum. Negative pressure heads of -3.2 and -0.1 feet were measured at piezometer 265 and 266 respectively (see Fig. 58 for location). Other pressures were positive and are tabulated in Table C-5 of Appendix C. Negative pressure of -3.2 feet was the lowest recorded on the chute. At lower reservoir levels, pressures on the chute increased because the velocities reduced.

The length of the divider wall on the chute was reduced to observe relative effects on the flow in the chute and stilling basin. The first wall tested was 309 feet long with vertical walls, hereafter this will be referred to as the original divider wall. The shortest was 207 feet long with walls on a 1:12 batter. Tests were also made with the divider wall removed.

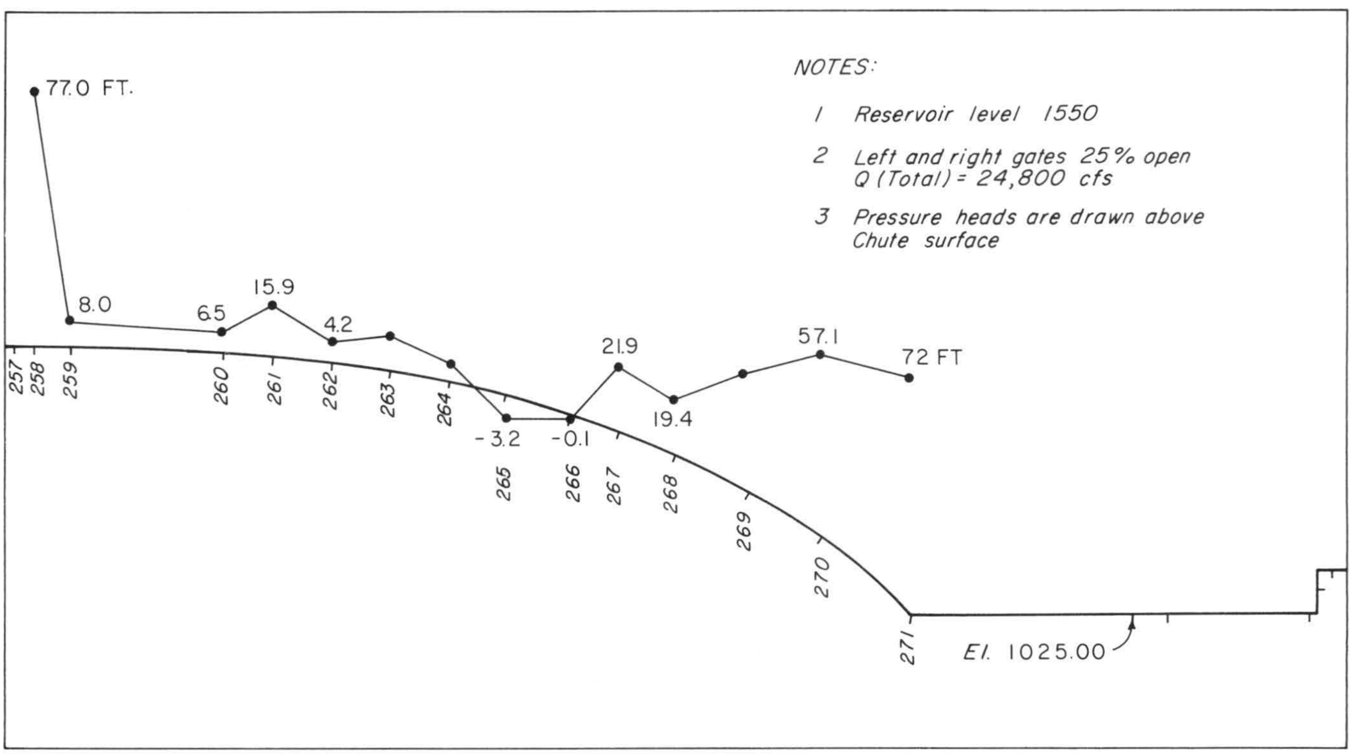


FIGURE 65 PRESSURE HEADS ON THE CHUTE FLOOR

Figure 66 shows the flow in the stilling basin with the original divider wall installed and both radial gates fully open at reservoir level 1550. The base of the hydraulic jump was located within the divided chute. With the wall reduced to 207 feet the base of the jump was in the same position but beyond the end of the wall as seen in Fig. 67. Even when the divider wall was removed completely, the flow in the chute appeared satisfactory. A fin was created however, where the high velocity flow joined together as seen in Fig. 68. Flow over the chute and in the stilling basin with flow only on one side of the 207 ft long divider wall is shown in Fig. 69.

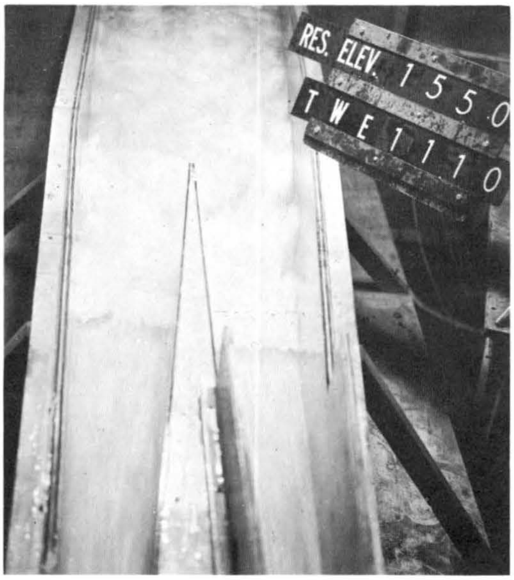


Fig. 66. Flow in the chute with the original wall. Q = 111,000 cfs.

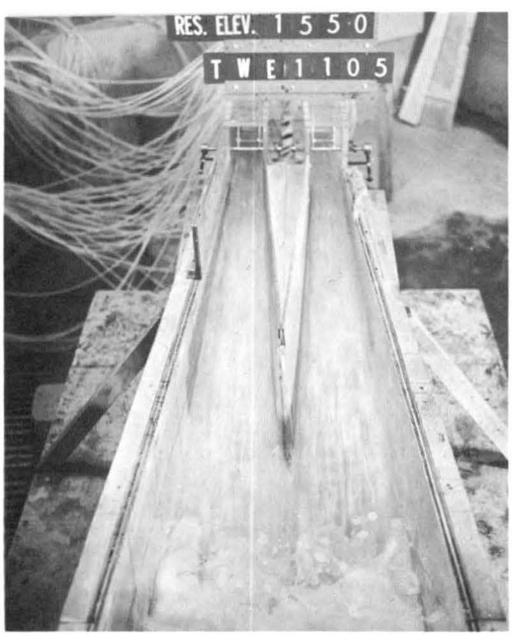


Fig. 67. Divider wall length reduced to 207 feet.

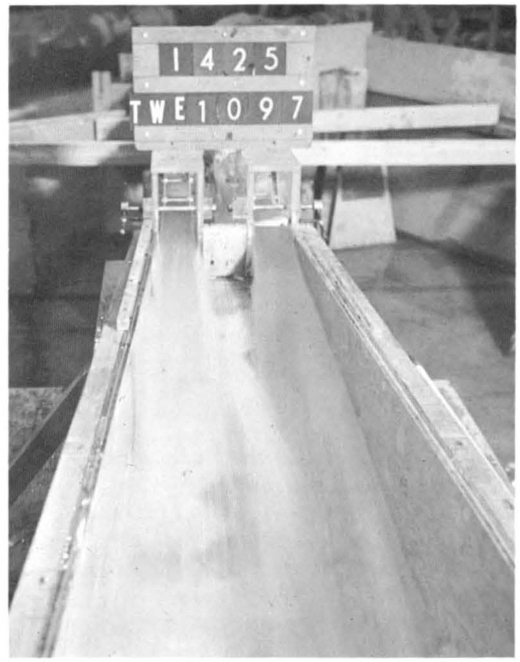


Fig. 68. Divider wall removed. Note formation of fin at the center.

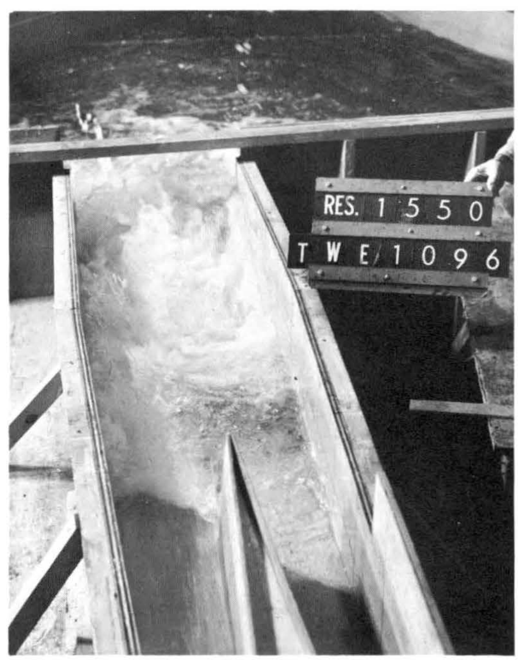


Fig. 69. Flow through one side only. Divider wall length 207 ft.

The Basin

The original length of the stilling basin was 250 feet measured from the end of the chute to the end sill which was 14 ft high. Several modifications to the basin were tested as listed below:

1. Increased the height of the sill 10 feet from 14 to 24 ft.
2. Increased length of basin 50 feet from 250 to 300 ft with 14 ft sill.
3. Increase length of basin 50 feet and increased sill height to 24 ft.
4. Increased length of basin 100 feet with 14 ft sill.
5. Increased length of basin 100 feet and increased sill height to 24 ft.

At each modification and the "original" basin, tests were conducted at three discharges with varying tailwater levels. The calculated tailwater rating curves in the river near the tunnel outlets are given in Fig. 70. In the model tests, higher tailwater levels were used than those indicated in the curves and the results could be interpreted as lowered basin floor. Lower tailwater levels than the curves were used to test the stability of the jump in the stilling basin and also to subject the river downstream of the basin to severe scour conditions. Together with these studies, changes were made with the chute divider wall, and the basins were subjected to unequal flows from the left and right sides of the bifurcation. As previously discussed, the radial gates are recommended to be operated symmetrically. Under this condition, as explained before, the chute divider wall did not affect the hydraulic jump.

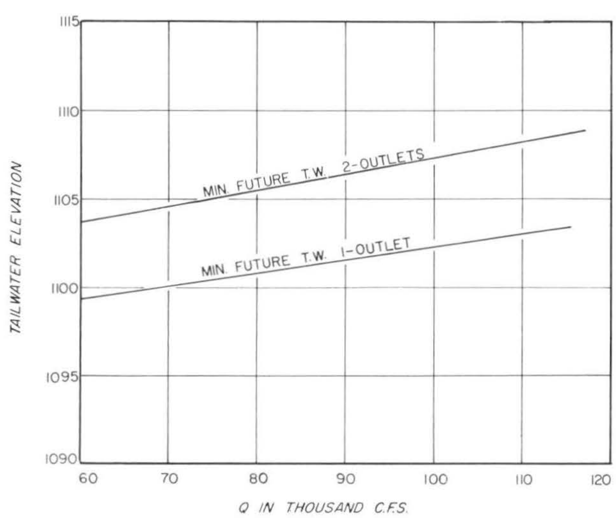


FIGURE 70. TAILWATER RATING CURVES.

At any reservoir level the stilling basin must effectively dissipate the energy for the maximum discharge, i.e. radial gates full open. Hence, this discussion will be confined to that condition. Tests for partial gate openings were also made, but when the full open flow was satisfactorily discharged through the basin, there was no problem with partial gate openings.

At the minimum reservoir operating level of 1300, the discharge was approximately 71,000 cfs. The energy in the flow was effectively dissipated in the original basin as well as in all modified basins. Tests were made at tailwater levels from 1095 to 1109. Figures 71(a) and (b) show photographically the jumps in the stilling basin at tailwater 1109, and 1095 respectively. In Fig. 71(c) the contoured streambed downstream of the basin shows that scour was negligible. Similar photographs for the modified basins are not shown here but the basin performed satisfactorily at this reservoir level and discharge.

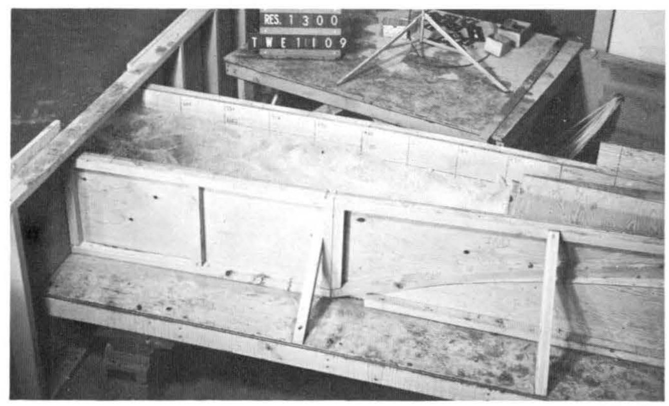


Fig. 71(a). Hydraulic jump in the stilling basin at Tail water 1109. Reservoir El. 1300. Q = 71,000 cfs.

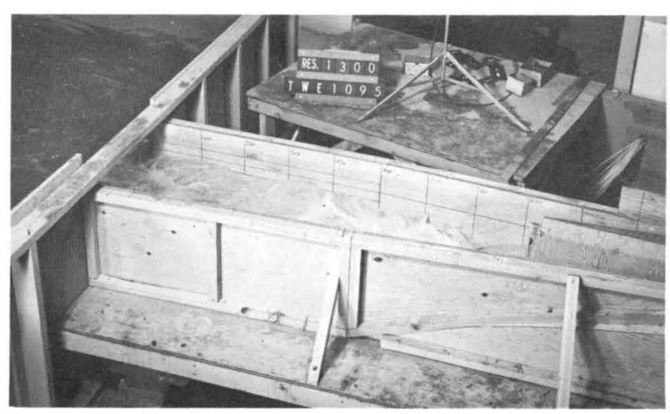


Fig. 71(b). Hydraulic jump in the stilling basin at Tail water 1095. Reservoir El. 1300.

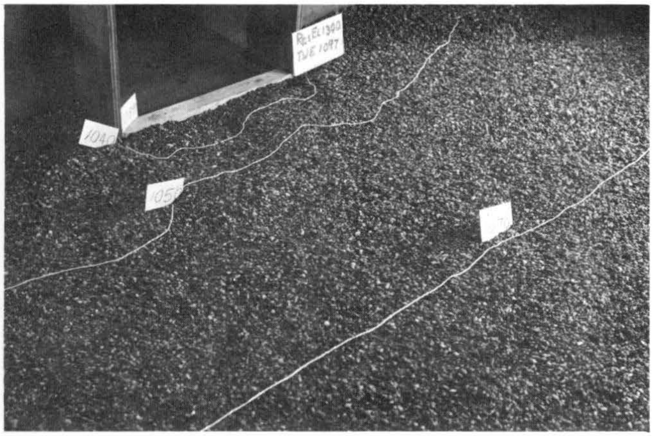


Fig. 71(c). Scour downstream of basin.

At reservoir level 1425, the discharge was 93,000 cfs. The original basin was adequate to dissipate the energy of the flow. Figures 72(a)(b) and (c) respectively show the stilling basin flow conditions at tailwater levels of 1114 and 1097 and scour resulting downstream with tailwater at 1097. The tailwater level increase from 1097 to 1114 moves the hydraulic jump upstream in the basin by approximately 90 to 100 feet. The scour downstream with the lower tailwater was not serious although depths up to 10 feet were indicated. The modified basins performed equally satisfactorily.

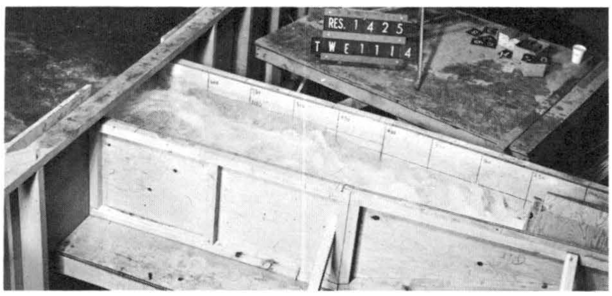


Fig. 72(a). Hydraulic jump in the stilling basin at Tail water 1114. Reservoir El. 1425. Q = 93,000 cfs.

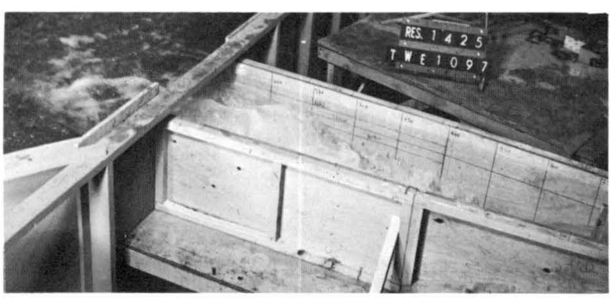


Fig. 72(b). Hydraulic jump in the stilling basin at Tail water 1097.

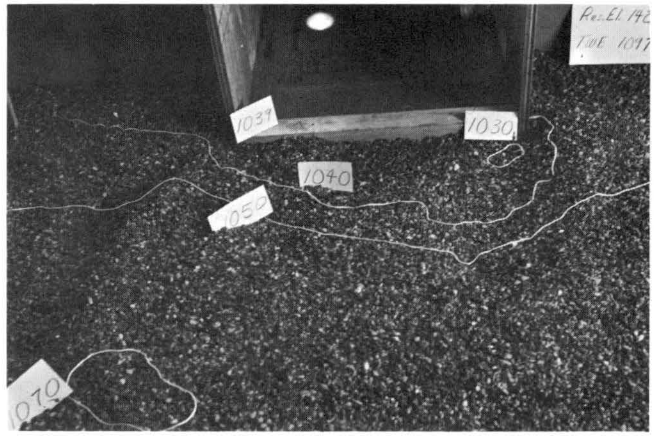


Fig. 72(c). Scour downstream from basin.

At reservoir level 1550, the discharge was 111,000 cfs. For a tailwater level of 1111, the basin was considered barely adequate hydraulically to contain the jump. Reduction of the tailwater to 1104 moves the jump downstream and part of the jump was beyond the limits of the basin. At tailwater 1098, the jump moved further downstream. These conditions are shown in Figs. 73(a) (b) and (c) respectively. Although the jump could not be contained within the basin at tailwater 1098, the resulting scour downstream was not severe. The scour depth was approximately 20 feet at the end sill.

Increase in the length of the basin and height of the end sill were only slightly more successful in containing the jump within the basin. In Fig. 74 the profiles of the hydraulic jumps are drawn for the various modifications. With tailwater level at 1111, the jumps were confined within the basin, but at lower tailwater levels of 1104 and 1098, as the length of the basin was increased, the jump moved downstream, and portions of the hydraulic jumps extended beyond the basin. Scour of the river bed downstream was essentially the same as that shown in Fig. 73(d) for all modified basins at that tailwater. Increase in tailwater level to 1111 did not decrease the scour depth materially. The reduction of maximum scour depth was only 2 to 3 feet. These results indicate that the original basin would be satisfactory despite the fact that the hydraulic jump could not be entirely contained within the confines of the basin. Additional stilling basin studies were being made in the general model in Nandipur at the time this report was written, where concurrent flows from the other tunnels could also be tested. The results of those tests should be studied.

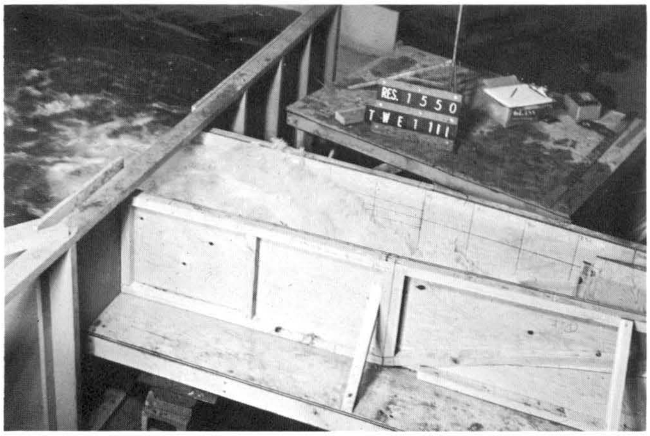


Fig. 73(a). Hydraulic jump in the stilling basin at Tail water 1111. Reservoir El. 1550. Q = 111,000 cfs.

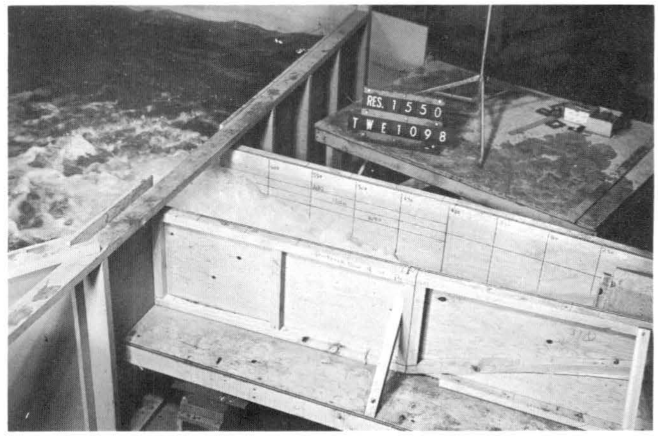


Fig. 73(c). Hydraulic jump in the stilling basin at Tail water 1098. Reservoir El. 1550.

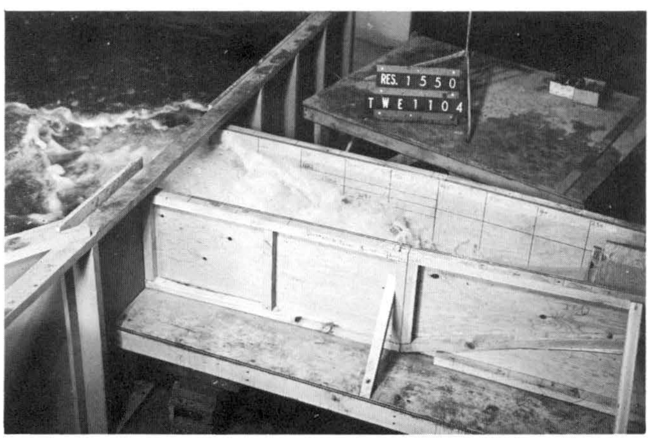


Fig. 73(b). Hydraulic jump in the stilling basin at Tail water 1104. Reservoir El. 1550.

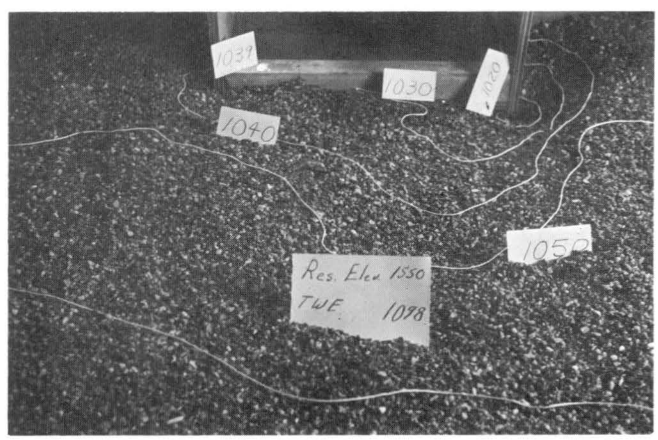


Fig. 73(d). Scour downstream from the stilling basin at Tail water 1098.

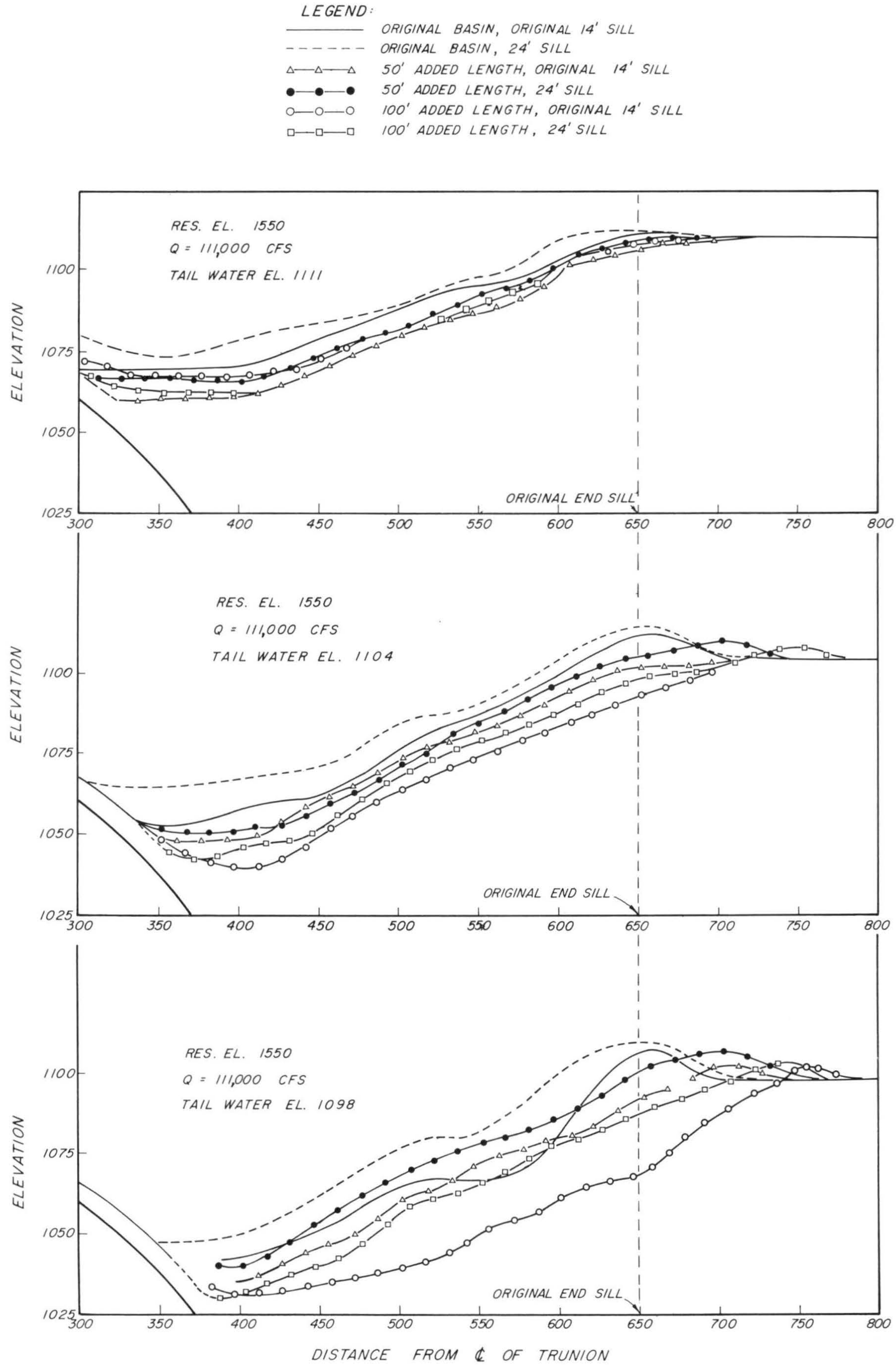


FIGURE 74 HYDRAULIC JUMP PROFILES

V. TUNNEL NO. 4

Essentially the same flow and pressure conditions were evident in the bifurcation for Tunnel 4 as were noted for Tunnel 3. During symmetrical closure of the radial gates, flow conditions were satisfactory and positive pressures existed at the bifurcation and the transition downstream. During unsymmetrical closure of the radial gates, localized negative pressures were measured at the same point at the crotch of the bifurcation as previously noted for Tunnel 3. Data are tabulated in Appendix D. The magnitude of these negative pressures was the same as those measured in Tunnel 3. Flow conditions in the chute and stilling basin were the same as in Tunnel 3.

VI. CONCLUSIONS AND RECOMMENDATIONS

Tunnel 1 - Diversion

Tunnel 1 for diversion with and without the flow ceiling, performed equally satisfactorily. It is recommended therefore that the ceiling be eliminated. Pressures at the boundaries throughout the length of the tunnel were observed to be positive for the range of reservoir levels from 1090 to 1460.

Closure of the three intake gates should be effected in unison to avoid large unbalanced forces on the piers upstream of the gates. Air vents will be required during gate closure, and should be supplied to all three gate shafts. The maximum air flow rate determined from the model was 13,000 cfs which was sufficient to meet the criterion that the pressure within the tunnel should not be less than -15 ft of water head. During closure of the gates low boundary pressures were developed where the wall diverged from the flow.

All transitions in the tunnel were designed adequately from the hydraulic viewpoint. Tunnel curvature was satisfactory with regard to flow conditions and boundary pressures. Flow through the central gate section was satisfactory for the entire range of discharges which could occur. No modification was required.

The deflector at the outlet (for Tunnel 2 as well as Tunnel 1) should be modified slightly to prevent the outflow jet from impacting too closely to the base of the stilling basin wall for Tunnel 3. It is suggested that the right wall be increased in height by approximately 15 feet, beginning from the portal, and the wall should be projected further into the outflow, beginning at a point midway between the portal and the end of the wall. Refer to Figure 36 for dimensions.

Tunnel 1 - Power

Tunnel 1 for power plant operation should be entirely satisfactory as designed. The service gates in the central gate chamber could be used to stop the flow in case of emergency, but the gates should be closed simultaneously to avoid large unbalanced forces on the pier at a section upstream of the gates.

Tunnel 3

The flow in Tunnel 3 above the minimum operating reservoir level of 1300 was satisfactory. The intake structure was adequately designed and no low pressures occurred at the boundaries. Pockets of air were formed in the tunnel when the reservoir was between 1205 and 1225, but it is anticipated that the reservoir level will not be lower than 1300 during normal operation.

Normal flow conditions through the central gate chamber was satisfactory. If the service gates were closed with the radial gates completely open as it might be necessary in case of emergency, low pressures were developed on the wall of the pier near the base downstream from the gates. The gates should be closed simultaneously to avoid large unbalanced forces on the wall upstream of the gates.

If the radial gates are not opened symmetrically, negative pressures could develop in an area immediately downstream of the crotch along the horizontal plane through the centerline. Although the measured low pressure area was small, vapor pressures will be reached when one gate is fully open and the other nearly closed. If the radial gates are at nearly equal openings low pressures will not develop in the bifurcation.

The walk of the radial gate chamber should begin as closely as possible in line with the walls of the tunnel. With an offset, the high velocity diverging flow impinged against the wall, created a high fin of water to develop considerable spray into the radial gate chamber and over the chute walls. No change is suggested for the vertical curvature of the chute. Although it was not tested in the model, warped and battered walls of the chute from vertical to 1:12 should not materially affect pressures on the chute floor. The divider wall may be reduced in length or eliminated completely, provided the radial gates are operated uniformly. With no divider wall, a fin formed on the chute (see Fig. 68) but it will not create any problems.

The stilling basin performed satisfactorily for the entire range of discharges and tailwater variations even though the jump was not entirely contained at maximum discharge and tailwater levels below 1104. This statement is based upon the fact that scour downstream was not too severe. Increasing the length of the basin by 100 feet or increasing the height of the end sill did not lead to total confinement of the jump. At reservoir levels below 1425 the hydraulic jump was completely contained in the stilling basin for the entire range of tailwater levels from 1097 to 1114.

Tunnel 4 will perform satisfactorily. The comments on Tunnel 3 apply equally to Tunnel 4.

APPENDICES

A. Tunnel 1 - Diversion

Table A-1 - Pressure heads at intake and downstream transition walls.
Table A-2 - Pressure heads on the pier during closure of the intake gates in unison.
Table A-3 - Pressure heads on the pier during closure individually.
Table A-4 - Pressure heads at the central gate and adjoining transitions.
Table A-5 - Pressure heads along circular tunnel wall.

B. Tunnel 1 - Power

Table B-1 - Pressure heads along central gate walls and piers and adjoining transitions.
Table B-2 - Pressure heads along circular tunnel wall.

C. Tunnel 3

Table C-1 - Pressure heads along intake and downstream transition walls.
Table C-2 - Pressure heads on circular tunnel walls.
Table C-3 - Pressure heads along central gate and pier and adjoining transition walls.
Table C-4 - Pressure heads in bifurcation, downstream transition, and radial gate chamber.
Table C-5 - Pressure heads along stilling basin chute and floor.

D. Tunnel 4

Pressure heads in bifurcation, downstream transition, and radial gate chamber.

TABLE A-1

PRESSURE HEADS AT INTAKE AND DOWNSTREAM TRANSITION WALLS

Intake Gates Open

Pressures in Feet of Water

Run No.	7	8	9	10	11
Reservoir elevation	1458.0	1398.5	1339.5	1278.5	1201.0
Discharge	168,500	153,600	137,400	119,200	89,900
Tunnel Slope	0.0114	0.0114	0.0114	0.0114	0.0114
Piezometer Number*	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head
1	274.9	230.4	173.9	116.9	42.9
2	267.5	215.0	163.5	109.5	42.9
3	236.8	189.3	143.8	96.3	27.3
4	212.1	169.0	128.5	86.0	33.5
5	177.7	142.2	107.7	72.2	27.2
6	179.5	144.5	109.5	74.0	28.5
7	180.5	146.0	111.0	74.5	28.0
8	181.5	147.0	111.0	75.5	29.0
9	184.1	149.1	114.1	78.1	31.1
10	189.5	154.0	118.0	80.0	32.0
11	197.5	160.0	122.0	83.0	33.5
12	170.5	136.5	104.5	70.0	26.0
13	166.0	134.0	102.0	78.0	25.0
14	178.5	144.5	110.0	74.0	28.0
15	193.0	157.0	120.5	81.5	32.5
16	288.4	240.9	189.4	139.9	75.4
17	258.4	208.9	168.9	123.9	65.9
18	258.9	208.9	169.4	123.9	65.4
19	247.9	204.4	161.9	117.9	62.4
20	242.4	199.9	157.9	114.9	60.4
21	229.9	189.9	149.9	109.4	57.4
22	218.9	181.4	142.9	104.4	54.4
23	205.4	169.9	133.9	97.4	50.9
24	234.4	194.9	153.9	112.9	59.4
25	210.2	183.2	144.7	106.2	56.2
26	220.7	184.2	145.2	107.2	57.2
27	225.4	187.9	147.9	107.9	56.4
28	220.4	183.4	144.9	105.4	54.9
29	183.9	172.4	132.9	96.4	50.4
30	172.9	162.9	120.4	87.4	44.9
31	173.9	143.4	112.9	81.9	41.9
32	187.9	143.9	113.9	81.9	42.4
33	187.4	154.9	122.9	88.9	45.9
34	229.6	193.6	157.6	120.1	73.6
35	267.6	226.1	179.6	128.1	82.6
36	243.3	204.8	166.3	126.3	75.8
37	241.6	203.5	165.1	124.6	74.4
38	250.1	210.6	171.6	130.1	78.1
39	243.6	204.6	167.1	126.6	76.1
40	226.6	190.1	155.6	118.1	76.6
41	209.1	175.6	143.6	110.1	67.1
42	198.1	166.6	136.1	104.1	64.1
43	196.1	165.1	135.1	103.1	64.1
44	192.1	162.1	133.1	102.1	63.6
45	315.9	260.9	206.9	151.9	79.9
46	277.9	229.4	182.9	133.4	69.9
47	255.9	206.9	164.4	119.9	62.9
48	239.4	201.9	159.9	110.3	61.4
49	227.4	187.9	148.9	108.9	56.9
50	216.4	178.9	141.4	102.9	53.4
51	195.9	162.4	128.4	93.4	48.9
52	184.9	152.9	120.9	87.9	45.9
53	192.9	159.9	126.9	91.9	47.9
54	202.9	167.9	132.9	96.4	50.4
55	201.9	166.9	132.4	95.9	49.9

Run No.	7	8	9	10	11	118	119	120	121
Reservoir elevation	1458.0	1398.5	1339.5	1278.5	1201.0	1460.0	1354.0	1259.0	1199.0
Discharge	168,500	153,600	137,400	119,200	89,900	165,000	138,500	108,000	81,600
Tunnel Slope	0.0114	0.0114	0.0114	0.0114	0.0114	0.003	0.003	0.003	0.003
Piezometer Number*	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head
51A	165.0	132.5	101.0	67.5	24.5	**	**	**	**
52A	164.5	132.5	101.0	67.5	24.5	**	**	**	**
53A	173.5	140.0	106.5	72.0	26.5	**	**	**	**
54A	183.5	148.0	113.0	76.5	28.5	**	**	**	**
55A	181.0	146.0	111.5	75.5	28.0	**	**	**	**
56	214.9	176.9	140.4	101.4	52.4	**	**	**	**
57	298.0	251.5	205.0	155.0	91.5	**	**	**	**
58	272.0	230.0	187.5	142.5	84.5	**	**	**	**
59	256.5	217.0	177.0	135.0	80.5	**	**	**	**
60	258.0	217.0	177.0	134.5	80.0	**	**	**	**
61	252.5	212.5	173.0	132.0	70.0	**	**	**	**
62	242.5	204.0	166.0	126.5	76.0	**	**	**	**
63	225.5	190.5	155.5	118.5	72.0	**	**	**	**
64	214.0	182.5	149.0	114.0	69.0	**	**	**	**
65	218.0	184.0	150.5	115.0	69.5	**	**	**	**
66	225.5	190.0	155.0	118.0	71.5	**	**	**	**
67	225.0	190.0	155.0	118.0	71.5	**	**	**	**
68	241.9	199.0	159.9	116.9	61.9	**	**	**	**
69	223.2	184.2	147.2	107.2	56.7	**	**	**	**
70	225.7	186.7	149.2	108.7	57.7	**	**	**	**
71	217.9	179.4	142.9	103.9	53.4	**	**	**	**
72	216.9	178.4	141.9	102.9	47.9	**	**	**	**
73	214.9	176.9	140.9	102.3	52.4	**	**	**	**
74	212.9	174.9	138.9	101.4	51.9	**	**	**	**
75	210.4	173.4	137.9	100.1	50.9	**	**	**	**
76	244.5	205.5	167.5	128.0	76.0	**	**	**	**
77	241.5	203.0	165.5	126.5	74.5	**	**	**	**
78	239.5	201.0	164.0	125.0	75.0	**	**	**	**
79	235.5	198.0	161.5	123.0	73.5	**	**	**	**
80	233.0	196.0	160.0	122.0	71.5	**	**	**	**
81	282.3	225.3	171.8	115.3	42.8	282.8	169.8	97.8	42.8
82	240.9	192.9	148.9	99.4	37.9	243.9	163.9	86.9	39.9
83	179.4	143.4	108.9	82.4	25.4	184.4	124.4	66.4	30.9
84	168.2	132.7	100.2	66.2	22.7	173.2	117.2	62.2	29.2
85	255.0	212.0	174.5	133.5	79.5	255.5	188.5	124.5	83.5
86	262.0	219.5	179.5	136.5	81.0	264.5	195.5	126.5	85.5
87	248.0	208.5	180.5	130.0	77.5	251.5	186.5	121.5	82.5
88	238.5	200.5	164.0	125.5	75.0	241.5	179.5	117.5	80.5
89	232.0	195.5	160.0	122.0	73.5	236.5	175.5	115.5	78.5
90	208.4	169.4	129.9	89.9	37.9				
91	170.6	137.1	104.6	70.6	26.6	**	**	**	**
92	164.6	132.1	100.6	68.1	25.1	**	**	**	**
93	152.4	122.4	93.4	63.4	23.9	**	**	**	**
94	133.9	107.4	81.4	54.9	19.4	**	**	**	**
95	146.5	118.0	90.0	61.0	23.0	**	**	**	**
96	207.5	175.0	143.0	109.5	66.5	213.5	154.4	105.5	73.5
97	199.5	168.5	138.0	105.5	64.5	205.5	153.5	102.5	71.5
98	185.0	157.0	128.5	99.0	61.0	191.5	143.5	97.5	68.5
99	180.5	153.0	125.5	96.5	60.0	187.5	140.5	95.5	67.5
100	232.5	197.0	160.5	121.5	73.5	**	**	**	**
101	216.5	182.5	149.0	113.5	68.5	**	**	**	**
102	175.8	156.8	128.8	98.8	60.3	**	**	**	**
103	177.3	149.3	122.3	93.8	56.8	**	**	**	**
104	180.5	151.5	124.0	94.5	56.5	**	**	**	**
105	156.9	132.4	107.9	82.6	49.9	**	**	**	**

* See Figures 10, 12, 13 for Piezometer locations.
** No data recorded.

TABLE A-2

PRESSURE HEADS ON THE PIER DURING CLOSURE OF THE INTAKE GATES IN UNISON .

Pressure Heads in Feet of Water

Run No.	51	58	59	70	71
Reservoir elevation	1460. 0	1362. 0	1356. 0	1200. 0	1200. 0
Discharge	142, 000	119, 500	109, 000	70, 000	67, 000
Air Vents#	3	2	2	3	3
% Gates Open	70	70	60	70	65
Piezometer Number*	Pressure Head**	Pressure Head**	Pressure Head**	Pressure Head**	Pressure Head**
51A					
52A		7. 0			
53A		- 5. 0			
54A		-16. 0			
55A		- 8. 0			
51		2. 9		6. 9	1. 4
52	-18. 1	-13. 1		1. 4	-0. 6
53	-12. 1	- 8. 1		6. 4	-0. 1
54	- 6. 1	- 2. 1		7. 9	-3. 1
55	- 3. 6	1. 9		10. 4	-3. 6
56	- 7. 1			10. 9	-0. 1
57					
58					
59					
60					
61					
62					
63					
64			- 1. 5		
65			-14. 0		

Run No.	51	58	59
Reservoir elevation	1460. 0	1362. 0	1356. 0
Discharge	142, 000	119, 500	109, 000
Air Vents#	3	2	2
% Gates Open	70	70	60
Piezometer Number*	Pressure Head**	Pressure Head**	Pressure Head**
66			-12. 5
67			-22. 0
68			-32. 1
69			- 5. 8
70			6. 2
71			
72			
73			
74			
75			
76			
77			
78			
79			- 9. 0
80			-13. 0

* See Figure 11 for Piezometer locations.
** During unison closure of the gates, large unbalanced loads on the piers did not exist and all pressure heads not recorded were noted only as positive.
\# Air vents denoted as 2 indicates air supplied to the central gate chamber by 2 air vents.
\# Air vents denoted as 3 indicates air supplied through a separate vent to each of the 3 gate chambers.

TABLE A-3

PRESSURE HEADS ON THE PIER DURING CLOSURE OF THE INTAKE GATES INDIVIDUALLY

Pressure Heads in Feet of Water

Run No.	7	74	78	103	115	87	105	117
Reservoir elevation	1458.0	1463.0	1458.0	1362.0	1199.0	1462.0	1360.0	1202.0
Discharge - cfs	168,500	156,500	126,000	113,500	63,000	104,100	90,500	52,000
Gates - % Open								
Left	100	100	50	50	50	0	0	0
Center	100	0	0	0	0	0	0	0
Right	100	100	100	100	100	100	100	100
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
45	315.9	243.9	185.9	114.9	44.9	136.9	87.9	37.9
46	277.9	202.9	144.9	78.9	33.9	87.9	50.9	26.9
47	255.9	164.9	101.9	40.9	23.9	32.9	13.9	14.9
48	234.9	152.9	87.9	31.9	20.9	17.9	2.9	11.9
49	227.4	120.9	53.9	1.9	11.9	- 25.1	- 30.1#	1.9
50	216.4	105.9	25.9	- 21.1	4.9	- 62.1#	- 58.1#	- 7.1
51	195.9	68.9	- 28.1	- 61.1#	- 7.1	**	-104.1#	-21.1
52	184.9	47.9	- 61.1#	- 84.1#	-14.1	**	**	-34.1#
53	192.9	62.9	- 49.1#	- 69.1#	-13.1	**	-108.1#	-24.1
54	202.9	82.4	- 39.1#	- 47.1#	- 3.1	-109.1#	- 85.1#	-17.1
55	201.9	69.9	**	- 56.1#	-12.1	**	- 96.1#	-22.1
56	214.9	92.9	- 44.1#	- 23.1	- 5.1	- 74.9#	- 62.1#	-15.1
57	298.0	210.0	139.0	77.0	50.0	72.0	44.0	40.0
58	272.0	185.0	118.0	59.0	44.0	51.0	30.0	37.0
59	256.5	154.0	79.0	28.0	36.0	- 3.0	- 6.0	26.0
60	258.0	164.0	95.0	39.0	38.0	19.0	9.0	29.0
61	252.5	152.0	79.5	27.0	34.0	1.0	- 5.0	24.0
62	242.5	138.0	58.0	12.0	30.0	- 21.0	- 19.0	9.0
63	225.5	104.0	5.0	- 26.0	18.0	- 79.0#	- 63.0#	6.0
64	214.0	88.0	- 23.0	- 45.0#	13.0	**	- 83.0#	0.0
65	218.0	92.5	- 26.0	- 41.0#	13.0	**	- 80.0#	0.0
66	225.5	105.5	- 27.0	- 30.0	16.0	- 90.0#	- 69.0#	2.0
67	225.0	100.5	**	- 41.0#	13.0	**	- 78.0#	- 3.0
68	241.9	93.9	- 52.1#	- 23.1	- 4.1	- 88.1#	**	**
69	223.2	95.2	- 55.8#	- 23.8	- 4.8	- 88.8#	**	**
70	225.7	96.2	- 57.8#	- 22.8	- 1.8	- 90.8#	**	**
71	217.9	92.9	8.9	23.9	38.4	- 87.1#	**	**
72	216.9	92.9	1.9	19.9	33.9	- 32.1	**	**
73	214.9	92.9	- 3.1	12.9	24.9	- 44.1#	**	**
74	212.9	92.9	- 1.6	14.9	30.9	- 41.1#	**	**
75	210.4	92.9	1.9	15.9	29.9	- 45.1#	**	**
76	244.5	114.0	- 43.0#	- 20.0	17.0	- 84.0#	**	6.0
77	241.5	114.0	- 43.0#	- 20.0	16.0	- 86.0#	**	6.0
78	239.5	114.0	- 43.0#	- 20.0	16.0	- 86.0#	**	6.0
79	235.5	114.0	- 43.0#	- 20.0	16.0	- 83.0#	**	6.0
80	233.0	114.0	- 43.0#	- 19.0	16.0	- 86.0#	**	6.0
51A	165.0	28.0	- 43.0#	-102.0#	-25.0	**	**	-32.0
52A	164.5	27.0	- 68.0#	-103.0#	-34.0#	**	**	-48.0#
53A	173.5	34.2	- 70.0#	- 83.0#	-28.0#	**	- 26.0	-27.0
54A	183.5	57.0	- 43.0#	- 56.0#	- 2.0	**	- 3.0	-33.0#
55A	181.0	55.0	- 39.0#	- 45.0#	-11.0	**	- 84.0#	-21.0

* See Figure 11 for Piezometer locations.
** No data recorded.
\# Negative pressure heads read below vapor pressure of about -32.0 feet of water.
This has no physical meaning in the prototype except to indicate possible cavitation.

TABLE A-4

PRESSURE HEADS AT THE CENTRAL GATE AND ADJOINING TRANSITIONS

Intake Gates Open
Pressure Heads in Feet of Water

Run No.	7	8	9	10	11	118	119	120	121
Reservoir elevation	1458.0	1398.5	1339.5	1278.5	1201.0	1460.0	1354.0	1259.0	1199.0
Discharge-cfs	168,500	153,600	137,400	119,200	89,900	165,000	138,500	108,000	81,600
Tunnel Slope	0.0114	0.0114	0.0114	0.0114	0.0114	0.003	0.003	0.003	0.003
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
151	174.3	146.8	119.8	91.8	56.8	**	**	**	**
152	140.5	112.5	85.5	57.0	22.0	**	**	**	**
153	173.5	146.5	108.5	90.5	55.5	**	**	**	**
154	135.7	118.2	80.7	53.2	18.2	**	**	**	**
155	171.2	143.7	117.7	90.7	56.7	**	**	**	**
156	132.8	105.3	78.3	51.3	16.3	**	**	**	**
157	135.4	106.4	78.9	50.9	14.9	**	**	**	**
158	153.9	125.4	98.4	70.9	25.4	**	**	**	**
159	186.9	157.4	127.9	98.4	60.4	**	**	**	**
160	155.4	126.9	98.9	71.4	35.4	**	**	**	**
161	179.4	150.9	122.9	94.9	58.9	**	**	**	**
162	149.4	122.9	97.4	69.4	34.4	**	**	**	**
163	187.4	157.4	128.4	98.4	60.4	**	**	**	**
164	146.4	115.9	85.9	55.9	17.4	**	**	**	**
165	170.8	142.3	116.8	89.8	55.3	**	**	**	**
166	128.7	101.7	75.7	49.2	14.7	**	**	**	**
167	161.5	135.5	110.5	85.0	52.0	**	**	**	**
168	124.0	98.0	72.5	47.5	15.0	**	**	**	**
169	147.8	124.8	101.3	78.3	48.3	**	**	**	**
170	109.4	86.4	63.9	41.4	11.4	**	**	**	**
171	135.1	113.6	93.6	71.1	43.6	**	**	**	**
172	101.9	79.9	58.9	37.4	9.9	**	**	**	**
173	114.9	90.9	67.9	43.9	13.4	126.0	82.0	45.0	21.0
174	142.5	112.5	83.5	54.0	16.5	150.6	99.6	53.6	25.1
175	150.8	120.8	89.8	57.1	17.8	160.4	104.4	55.4	26.4
176	176.1	149.1	122.6	95.6	60.6	186.2	138.2	96.2	70.2
177	170.5	144.5	119.0	93.0	59.5	181.1	136.4	95.9	69.6
178	176.4	148.9	122.9	94.9	59.4	184.0	137.0	94.0	69.0
179	169.9	143.9	118.4	92.4	58.4	178.0	133.0	92.0	67.0
180	178.9	150.4	123.4	95.4	59.9	187.0	138.0	95.0	69.0
181	181.4	152.9	124.9	96.4	59.9	189.5	140.5	96.5	69.0
182	158.6	134.1	109.6	85.1	54.1	168.2	125.2	87.2	64.2
183	137.9	116.9	96.4	75.4	48.4	146.2	110.0	78.5	59.0

* See Figure 15 for Piezometer locations.
** Data not recorded.

TABLE A-5

PRESSURE HEADS ALONG CIRCULAR TUNNEL WALL

Intake Gates Open
Pressure Heads in Feet of Water

Run No.	12	13	14	15	16	118	119	120	121
Reservoir elevation	1454.0	1398.5	1338.0	1280.6	1201.0	1460.0	1354.0	1259.0	1199.0
Discharge-cfs	168,500	155,600	137,400	119,200	87,900	165,000	138,500	108,000	81,600
Tunnel Slope	0.0114	0.0114	0.0114	0.0114	0.0114	0.003	0.003	0.003	0.003
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
106	133.3	108.3	79.8	53.3	16.3	140.1	94.1	49.1	22.1
107	127.2	103.2	76.2	50.2	14.7	133.2	89.2	46.2	21.2
108	119.7	96.7	71.2	47.2	13.7	123.9	82.9	43.9	19.9
109	113.6	91.6	68.1	44.1	12.6	119.4	79.4	41.4	18.9
110	109.6	88.6	65.6	43.1	13.1	113.0	75.0	39.0	17.5
111	103.4	84.9	62.9	41.9	11.9	107.9	71.9	36.9	16.9
112	172.3	148.8	121.8	96.8	59.8	179.1	135.1	93.1	66.6
113	169.8	156.3	119.8	95.3	59.8	177.2	133.2	92.2	65.2
114	163.7	142.2	116.2	92.2	58.7	169.9	128.9	88.9	64.4
115	159.6	137.6	114.6	90.6	58.1	165.4	125.4	86.4	63.4
116	153.6	132.6	111.1	88.1	61.6	158.0	120.0	84.0	62.0
117	149.4	129.4	108.9	86.4	57.4	153.4	116.9	82.9	61.4
131	98.1	96.6	73.6	48.6	18.6	177.4	126.4	89.4	67.4
132	131.6	116.1	88.6	82.6	60.1	92.9	60.9	30.4	12.9
133	96.1	78.1	58.6	39.6	12.6	147.2	113.2	81.2	63.2
134	149.6	130.6	110.1	90.1	62.1	101.2	66.7	33.7	14.7
135	99.5	81.0	61.0	41.0	13.0	152.1	116.6	83.6	64.1
136	153.0	134.0	113.0	92.5	64.0	104.6	68.6	35.1	15.6
137	108.4	87.9	65.9	43.9	14.4	159.0	121.0	86.5	65.5
138	156.9	136.4	114.4	92.4	62.9	110.5	72.5	37.5	17.0
139	108.2	87.7	65.2	43.7	13.2	161.8	123.8	87.8	65.8
140	158.2	137.2	114.7	92.1	61.7	113.8	75.3	39.3	17.8
141	113.3	92.8	68.3	45.3	13.3	167.8	126.8	89.3	66.8
142	183.8	142.3	117.8	94.3	61.8	120.3	78.8	41.3	18.3
143	111.1	89.6	66.1	43.1	11.6	164.6	124.6	88.6	66.6
144	165.1	143.1	118.1	94.6	61.1	123.1	80.6	42.1	18.6
145	121.9	98.9	72.9	48.4	13.9	179.4	134.4	93.4	68.9
146	169.9	146.9	121.4	96.4	61.9	128.9	83.9	43.9	19.4
147	121.2	97.7	71.7	47.2	12.7	179.2	134.2	93.7	69.2
148	190.7	147.7	120.2	96.7	61.7	130.7	86.2	45.7	20.7
149	**	102.7	75.2	50.2	13.2	184.6	138.1	95.6	69.6
150	**	150.2	123.7	98.7	61.7	136.1	89.1	47.1	21.1

* See Figure 14 for Piezometer locations

** Data not recorded (pressures were positive)

TABLE A-6

PRESSURE HEADS AT JUNCTION OF DIVERSION INTAKE TRANSITION WITHOUT CEILING AND POWER INTAKE

Intake Gates Open
Pressure Heads in Feet of Water

Reservoir elevation	1460	1200		1460	1200
Discharge - cfs	167,000	89,000		167,000	89,000
Piezometer Number*	Pressure Head	Pressure Head	Piezometer Number	Pressure Head	Pressure Head
A	170.0	16	H	160.0	15
B	170.0	21	J	125.0	13
C	132.0	11	K	155.0	19
D	112.0	10	L	160.0	25
E	126.0	11	M	141.0	24
F	130.0	14	N	130.0	20
G	165.0	17	O	139.0	24

* See Figure 17 for Piezometer locations.

TABLE B-1

PRESSURE HEADS ALONG CENTRAL GATE WALLS AND PIERS AND ADJOINING TRANSITIONS

Pressure Heads in Feet of Water

Run No.	5P	14P	15P	16P	17P	18P	19P	20P	21P	24P	25P	27P
Res. elev.	1550.0	1550.0	1550.0	1550.0	1550.0	1550.0	1550.0	1550.0	1550.0	1550.0	1550.0	1550.0
Discharge cfs	43,200	42,000	42,000	42,000	42,000	42,000	38,000	31,200	19,800	40,400	31,500	12,500
Gates-% open												
Right	100	50	25	0	100	100	0	0	25	50	25	5
Left	100	100	100	100	50	0	75	50	0	50	25	5
Piezometer Number*	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head	Pres. Head
151	439.9	427.9	422.9	409.9	427.9	408.9	331.9	208.9	71.9	353.9	206.9	41.9
152	405.1	392.6	387.1	375.1	392.1	374.1	285.1	162.1	27.1	313.1	165.1	10.1
153	436.6	420.6	421.1	401.6	423.6	406.6	317.6	191.6	65.6	347.6	210.6	35.6
154	399.8	383.8	377.3	364.8	386.3	370.8	276.8	151.8	23.8	312.8	170.8	7.8
155	436.8	416.3	408.3	393.3	425.8	410.8	307.3	183.3	38.3	348.3	198.3	25.3
156	396.4	376.4	368.9	353.4	385.4	369.9	265.4	153.4	22.3	311.4	173.4	-63.6
157	395.0	374.5	366.0	351.0	384.0	369.0	265.0	153.0	24.0	311.0	172.0	2.0
158	**	**	**	**	**	**	**	**	**	**	**	**
159	**	**	**	**	**	**	**	**	**	**	**	**
160	**	**	**	**	**	**	**	**	**	**	**	**
161	**	**	**	**	**	**	**	**	**	**	**	**
162	**	**	**	**	**	**	**	**	**	**	**	**
163	**	**	**	**	**	**	**	**	**	**	**	**
164	395.5	377.0	370.0	355.0	405.0	406.0	372.0	389.0	408.0	402.0	329.0	419.0
165	434.9	414.9	405.9	389.9	444.9	446.9	402.9	416.9	442.9	438.9	426.9	459.9
166	395.3	374.8	366.3	349.3	405.8	407.3	366.3	385.3	406.3	401.3	389.3	420.3
167	435.6	417.6	409.6	393.6	444.1	445.6	406.6	420.6	443.6	439.6	427.6	458.6
168	399.1	381.1	373.1	357.1	406.6	408.6	372.1	386.1	408.1	403.1	391.1	422.1
169	428.9	420.9	411.9	394.9	444.4	443.9	407.9	421.9	443.9	440.9	427.9	458.9
170	400.5	384.5	375.5	359.5	408.0	408.5	373.5	386.5	407.5	404.5	391.5	422.5
171	436.7	432.7	431.2	428.7	440.7	442.2	418.7	440.7	450.7	440.7	427.7	456.7
172	403.0	398.5	397.0	393.0	407.0	409.0	402.0	406.0	416.0	407.0	391.0	423.0
173	**	**	**	**	**	**	**	**	**	**	**	**
174	**	**	**	**	**	**	**	**	**	**	**	**
175	**	**	**	**	**	**	**	**	**	**	**	**
176	**	**	**	**	**	**	**	**	**	**	**	**
177	**	**	**	**	**	**	**	**	**	**	**	**
178	**	**	**	**	**	**	**	**	**	**	**	**
179	**	**	**	**	**	**	**	**	**	**	**	**
180	**	**	**	**	**	**	**	**	**	**	**	**
181	**	**	**	**	**	**	**	**	**	**	**	**
182	**	**	**	**	**	**	**	**	**	**	**	**
183	442.5	442.5	443.5	443.5	443.5	443.5	449.5	453.5	457.5	445.5	432.5	461.5
201	394.0	375.0	367.5	352.0	406.0	403.5	379.0	389.0	407.0	402.0	389.0	418.0
202	391.0	368.0	358.0	341.0	406.0	404.0	380.0	388.0	395.0	402.0	405.0	406.0
203	391.0	368.0	358.0	341.0	406.0	402.5	381.0	382.0	402.0	402.0	403.0	413.0
204	393.0	373.0	365.0	350.0	393.0	367.0	262.0	147.0	66.0	309.0	174.0	45.0
205	393.0	373.0	365.0	349.0	393.0	367.0	262.0	147.0	31.0	309.0	170.0	15.0
206	389.0	366.0	355.0	336.0	393.0	367.0	262.0	146.0	23.0	309.0	170.0	33.0
207	436.0	417.0	408.0	393.0	448.0	448.5	402.0	415.0	442.0	439.0	447.0	462.0
208	436.0	413.5	404.0	386.0	440.0	449.0	363.0	429.0	303.0	406.0	360.0	368.0
209	437.0	417.5	409.0	393.0	431.0	412.0	330.0	418.0	94.0	368.0	229.0	46.0
210	392.6	369.6	358.6	341.6	405.6	404.6	364.6	385.6	406.6	401.6	408.6	418.6
211	393.6	373.1	363.6	348.6	384.6	369.1	263.6	151.6	26.6	300.6	171.6	8.6
212	392.6	369.6	358.6	342.6	384.6	368.6	263.6	151.6	23.6	300.6	171.6	9.6
213	415.1	393.1	383.1	367.1	426.1	427.1	380.1	395.1	423.1	418.1	426.1	440.1
214	414.1	390.1	380.1	363.1	406.1	390.1	313.1	171.1	46.1	322.1	191.1	14.1
215	414.1	391.1	381.1	365.1	406.1	389.6	303.1	176.1	45.1	324.1	191.1	13.1
216	415.1	393.1	384.1	367.1	406.1	390.1	287.1	174.1	45.1	324.1	191.1	14.1
217	437.8	421.3	414.8	401.8	446.8	411.3	409.8	421.8	443.8	439.8	446.8	460.8
218	434.4	412.4	403.4	386.4	434.4	410.4	341.4	288.4	189.4	393.4	289.4	26.4
219	434.4	412.4	403.4	386.4	433.4	410.4	338.4	261.4	126.4	381.4	251.4	43.4
220	436.9	418.4	410.4	395.4	432.4	410.4	342.4	257.4	137.4	380.4	259.4	60.4
221	392.5	374.5	360.5	348.5	404.5	404.5	362.5	384.5	403.5	400.5	407.5	416.5
222	391.5	375.5	368.0	354.5	399.5	395.5	372.0	389.5	406.5	400.5	407.5	416.5
223	390.5	368.0	358.5	341.5	404.5	404.5	364.5	389.5	406.5	401.5	408.5	416.5
224	392.5	369.5	363.5	343.5	384.5	368.5	265.5	153.5	27.5	310.5	172.5	39.5
225	393.5	372.5	361.5	348.5	384.5	368.5	265.5	153.5	26.5	311.5	172.5	53.5
226	392.5	371.5	359.5	346.5	384.5	368.5	265.5	152.5	24.5	311.5	172.5	50.5
227	392.5	369.5	368.5	343.5	384.5	368.5	265.5	152.5	24.5	311.5	172.5	48.5
228	395.5	376.5	376.5	354.5	384.5	368.5	265.5	152.5	24.5	310.5	171.5	22.0
229	397.0	382.0	377.0	364.0	384.0	368.0	267.0	146.0	39.0	308.0	166.0	35.0
230	398.2	383.2	358.7	366.2	384.2	368.2	266.2	145.2	21.2	313.2	172.2	33.2

* See Figure 47 for Piezometer locations.

** Data not recorded.

TABLE B-1 (Continued)

Run No. / Piezometer Number*	5P Pres. Head	14P Pres. Head	15P Pres. Head	16P Pres. Head	17P Pres. Head	18P Pres. Head	19P Pres. Head	20P Pres. Head	21P Pres. Head	24P Pres. Head	25P Pres. Head	27P Pres. Head
231	412.5	389.5	378.5	362.5	435.5	426.5	377.5	395.5	424.5	417.5	426.5	438.5
232	410.5	388.0	379.0	359.0	425.5	426.5	374.5	393.5	422.5	417.5	425.5	437.5
233	413.5	389.5	383.5	361.5	425.5	426.5	375.5	393.5	422.5	417.5	425.5	438.5
234	413.5	392.5	378.5	367.5	405.5	388.5	318.5	175.5	45.5	333.5	193.5	25.5
235	412.5	388.5	377.0	361.5	405.5	389.0	293.5	176.5	45.5	333.5	193.5	44.5
236	410.5	387.5	377.5	359.5	405.5	389.5	287.5	176.5	45.5	331.5	194.5	17.5
237	410.5	388.5	389.5	360.5	405.5	388.5	285.5	175.5	45.5	332.5	193.5	71.5
238	416.5	397.5	396.5	375.5	405.5	388.5	285.5	170.5	43.5	330.5	192.5	5.5
239	418.5	402.5	397.0	385.5	405.5	388.5	286.5	168.5	37.5	330.5	185.5	18.5
240	419.5	402.5	382.5	387.5	405.5	388.5	295.5	174.5	41.5	325.5	181.5	21.5
241	434.5	413.0	401.0	387.5	431.5	446.5	397.5	413.5	440.5	436.5	445.5	458.5
242	433.5	411.0	401.5	383.5	431.5	446.5	393.5	409.5	438.5	435.5	443.5	458.5
243	434.0	411.5	403.5	384.5	431.5	446.5	393.5	409.5	438.5	435.5	443.5	456.5
244	434.0	413.5	399.5	386.5	436.5	410.5	348.5	305.5	196.5	403.5	310.5	34.5
245	432.1	409.1	399.1	381.6	431.1	410.1	328.1	241.1	91.1	371.1	225.1	39.1
246	433.1	409.1	400.1	381.1	428.1	410.1	322.1	224.1	67.1	365.1	211.1	32.1
247	433.1	410.1	410.6	383.1	417.1	410.1	319.1	214.1	60.1	361.1	207.1	31.1
248	437.0	418.5	418.5	397.0	426.5	410.5	317.5	203.5	71.5	358.5	217.5	36.5
249	**	**	**	**	**	**	**	**	**	**	**	**
250	440.3	425.8	419.8	409.8	426.8	410.8	325.8	203.8	72.8	354.8	205.8	36.8
251	391.9	383.9	377.9	367.9	371.9	346.9	283.9	164.9	30.9	311.9	169.9	53.9
252	391.9	383.9	377.9	367.9	370.9	344.9	283.9	164.9	30.9	311.9	169.9	52.9
253	391.9	383.9	377.4	367.9	369.9	342.9	283.9	164.9	30.9	311.9	169.9	55.9
254	400.9	383.4	376.9	367.9	377.9	355.9	281.9	164.9	30.9	310.9	168.9	46.9
255	397.4	382.9	376.4	367.4	382.4	354.4	281.4	164.4	30.4	309.4	164.4	14.4
256	410.5	403.5	398.5	386.5	388.5	360.5	304.5	185.5	51.5	322.5	190.5	15.5
257	410.5	404.5	398.5	388.5	387.5	358.5	305.5	185.5	51.5	332.5	190.5	68.5
258	410.5	404.0	397.5	388.5	389.5	360.5	304.5	185.5	51.5	332.5	190.5	68.5
259	410.5	403.5	396.5	388.5	398.5	376.0	304.5	185.5	51.5	331.5	188.5	21.5
260	416.5	403.0	398.5	388.5	403.5	388.5	302.5	185.5	51.5	329.5	183.5	17.5
261	431.1	428.1	418.1	409.1	409.1	381.1	327.1	206.1	72.1	368.6	221.1	21.1
262	431.1	426.6	420.1	409.1	409.1	381.1	327.1	205.1	72.1	363.6	211.1	18.1
263	431.1	425.6	418.1	409.1	410.1	383.1	327.1	206.1	72.1	360.1	209.1	18.1
264	436.5	425.5	417.5	409.5	419.5	387.5	327.5	206.5	72.5	355.5	216.5	28.5
265	439.8	425.8	418.8	409.8	425.8	407.8	327.8	205.8	72.8	353.8	211.8	39.8

TABLE B-2

PRESSURE HEADS ALONG CIRCULAR TUNNEL WALLS

Central Gates Open
Pressure Heads in Feet of Water

Run No	1 P	2 P	3 P	4 P	5 P	6 P
Reservoir Elevation	1550.0	1514.0	1400.0	1300.0	1550.0	1550.0
Discharge-cfs	24,200	27,500	22,200	17,800	43,200	33,100
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
106A	407.5	369.5	257.0	161.5	394.5	395.5
106	408.8	371.8	257.8	161.8	396.8	397.8
107	408.6	371.6	258.1	162.1	397.1	397.1
108	408.9	371.4	258.4	162.4	397.4	397.4
109	408.8	371.8	258.8	162.8	391.8	397.8
110	406.6	369.6	257.6	162.1	392.1	396.1
111	410.5	372.5	259.0	163.0	393.5	398.5
112A	451.5	415.0	302.0	206.0	437.5	439.5
112	452.8	416.8	302.8	207.3	441.8	442.8
113	453.1	417.1	303.6	207.6	442.1	443.1
114	453.9	416.9	303.4	207.4	441.4	443.4
115	453.8	416.8	303.8	207.8	441.8	443.8
116	454.6	417.1	304.1	208.1	442.1	444.1
117	454.5	417.5	304.5	208.5	441.5	444.5
131	455.1	416.1	304.1	209.6	434.6	438.6
132	369.1	**	261.6	167.1	393.1	398.1
133	457.4	417.4	305.4	210.4	437.4	442.4
134	413.9	373.9	261.4	166.9	393.9	398.9
135	457.1	417.1	304.6	210.1	437.6	442.1
136	413.6	373.6	261.1	166.6	394.1	398.6
137	456.7	417.7	304.7	209.7	437.9	441.7
138	413.2	373.2	261.2	166.2	393.2	398.2
139	456.4	417.4	304.4	209.4	437.4	441.4
140	412.9	374.4	260.9	165.9	393.9	397.9
141	456.5	417.5	304.0	209.0	438.0	441.0
142	413.5	374.0	260.5	165.5	394.5	397.5
143	456.7	416.7	304.2	208.7	438.2	440.7
144	413.2	373.7	260.7	165.7	394.7	397.7
145	**	**	**	**	438.3	440.8
146	412.8	373.3	260.8	165.3	394.8	397.3
147	**	417.0	304.0	208.5	438.0	441.0
148	412.5	373.5	260.5	165.5	394.5	397.5
149	455.7	416.7	303.7	208.7	438.7	440.7
150	412.2	374.7	260.2	165.7	395.2	397.2

* See Figure 46 for Piezometer Locations.
**Data not recorded.

TABLE C-1

PRESSURE HEADS ALONG INTAKE AND DOWNSTREAM TRANSITION WALLS

Central and Radial Gates Open
Pressure Heads in Feet of Water

Run No.	1	2	3	4	22
Reservoir Elevation	1551.0	1462.0	1401.0	1303.0	1428.5
Discharge-cfs	111,000	97,800	90,000	72,500	94,000
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
1	278.0	189.0	128.0	30.0	153.0
2	278.0	189.0	128.0	30.0	152.5
3	278.0	189.0	128.0	30.0	152.5
4	179.4	190.3	129.3	31.4	154.3
5	299.5	210.5	56.5	53.5	174.5
6	317.2	245.7	158.2	70.2	192.7
7	311.7	225.7	155.7	74.7	192.7
8	298.8	217.8	153.8	74.8	186.8
9	289.4	211.4	157.4	72.4	181.4
10	289.0	211.0	196.0	74.0	181.0
11	284.0	195.0	134.0	36.0	160.0
12	284.0	195.0	133.5	36.0	160.0
13	285.9	196.9	139.9	37.9	161.9
14	303.1	214.1	152.6	55.1	179.1
15	319.8	231.8	172.8	76.8	197.8
16	309.2	219.2	164.2	75.2	188.2
17	286.3	209.3	157.3	73.3	174.8
18	364.8	232.8	216.8	119.8	241.8
19	363.8	275.8	215.8	117.8	241.3
20	361.8	273.8	214.8	116.8	239.8
21	357.8	269.8	210.8	114.8	235.8
22	344.8	259.8	202.8	109.8	227.8
23	332.8	249.8	194.8	104.8	218.8
24	323.8	243.8	189.8	101.8	212.8
25	388.5	298.0	238.5	140.5	264.5
26	386.5	297.0	237.5	139.5	263.5
27	384.5	296.0	235.5	138.5	261.5
28	376.5	289.5	230.5	135.5	256.5
29	365.5	281.5	224.5	131.5	249.5
30	352.5	271.0	216.0	127.5	240.0
31	348.5	268.5	213.5	124.5	237.5
32	391.0	301.0	240.0	142.0	267.0
33	389.0	300.0	239.0	141.5	266.5
34	383.0	295.0	235.0	139.0	262.0
35	364.0	281.0	224.0	132.0	249.5
36	360.0	283.5	219.0	127.0	240.0
37	**	227.4	179.4	**	**
38	302.3	221.7	167.7	80.2	192.2
39	**	**	**	**	**
40	349.0	267.9	213.0	**	**
41	350.7	270.2	214.7	125.7	239.7
42	299.7	220.6	166.6	79.7	189.6
43	288.2	211.7	159.2	74.2	182.2
44	289.6	213.6	161.6	77.6	184.1
45	311.5	234.5	181.5	96.5	204.5
46	326.5	249.5	197.5	113.0	219.5
47	325.2	257.2	204.7	119.2	228.2
48	282.6	211.6	159.6	76.6	183.6
49	309.7	236.7	186.7	105.7	214.7
50	274.0	196.0	153.5	70.0	179.0
51	275.6	201.6	153.6	71.6	174.6
52	295.5	221.5	171.5	90.0	193.0
53	318.1	244.2	194.1	112.6	212.6

* See Figures 53 and 54 for Piezometer locations.
**Data not recorded.

TABLE C-2

PRESSURE HEADS ON CIRCULAR TUNNEL WALLS

Central and Radial Gates Open.
Pressure Heads in Feet of Water.

Run No.	1	2	3	4	22	Run No.	1	2	3	4	22
Reservoir elevation	1551.0	1462.0	1401.0	1303.0	1428.5	Reservoir elevation	1551.0	1462.0	1401.0	1303.0	1428.5
Discharge - cfs	111,000	97,800	90,000	72,500	94,000	Discharge - cfs	111,000	97,800	90,000	72,500	94,000
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
54	269.4	195.9	146.9	66.4	168.9						
55	275.5	202.5	153.5	123.0	175.0						
56	308.3	234.3	184.3	104.8	207.3	146	245.8	183.8	144.8	76.8	161.8
57	314.9	240.9	190.4	111.4	212.4	147	288.3	226.3	187.3	120.3	202.8
58	270.5	197.5	144.5	68.5	169.5	148	241.1	183.1	144.1	79.1	153.1
59	314.5	232.5	190.5	113.5	211.5	149	284.6	226.6	187.6	121.6	196.6
60	268.9	196.9	146.4	69.4	169.9	150	241.3	183.3	144.3	70.3	161.8
61	313.9	241.9	191.4	114.4	214.9	151	278.8	225.8	187.8	122.8	203.8
62	269.3	197.3	147.3	71.3	171.3	152	237.8	179.8	145.3	79.8	157.8
63	314.3	242.3	192.3	116.3	216.3	153	284.3	227.3	189.3	125.3	206.3
64	269.2	198.7	147.7	72.7	172.7	154	241.1	183.1	147.1	84.1	163.6
65	313.7	243.7	194.7	117.7	226.7	155	284.6	227.6	190.6	127.6	207.6
66	364.5	196.5	150.5	73.5	171.0	156	240.4	184.4	147.4	86.4	163.9
67	313.0	244.5	195.5	119.5	217.5	157	273.9	227.9	190.9	129.9	207.9
68	268.4	200.4	150.4	75.4	173.4	158	240.4	185.4	148.4	87.4	165.4
69	312.4	245.4	195.4	120.4	216.9	159	273.9	228.9	191.9	130.9	208.9
70	268.1	201.1	152.1	76.1	173.1	160	241.8	186.3	149.8	88.8	165.8
71	350.1	279.1	233.1	157.1	254.1	161	286.3	229.8	193.3	132.3	210.3
72	267.8	198.8	152.8	76.8	173.3	162	233.3	188.3	151.3	89.3	168.3
73	312.8	244.3	197.9	121.8	217.8	163	288.5	232.5	195.5	132.5	212.5
74	266.6	198.6	152.6	77.6	172.6	164	210.8	162.8	130.8	76.8	144.8
75	312.6	244.1	198.6	123.1	219.1	165	250.5	202.5	170.5	119.5	185.0
134	245.9	183.9	140.9	71.9	159.9	166	152.3	117.3	93.3	54.3	103.3
135	250.4	188.4	146.4	78.4	165.4	167	180.5	146.5	124.5	87.5	134.0
						168	150.5	115.5	92.5	54.5	102.5
136	280.4	218.4	176.4	108.4	194.9	169	183.5	149.5	126.5	88.5	136.5
137	288.4	227.4	184.4	115.4	204.4	170	149.2	115.2	92.2	54.2	102.2
138	243.5	182.5	141.5	93.5	159.5						
139	284.0	223.0	182.0	136.0	201.0	171	154.5	119.5	97.5	59.5	107.5
140	243.2	182.2	140.2	93.2	159.7	172	187.2	152.2	129.2	91.2	140.2
141	288.7	226.7	183.7	136.7	203.7						
142	248.1	181.1	142.6	94.1	160.1						
143	291.6	226.1	186.6	137.6	202.1						
144	240.4	181.4	143.4	94.4	156.9						
145	287.9	225.9	186.9	138.9	202.9						

* See Figure 57 for Piezometer locations.

TABLE C-3

PRESSURE HEADS ALONG THE CENTRAL GATE AND PIER AND ADJOINING TRANSITION WALLS

Radial Gates Open.
Pressure Heads in Feet of Water.

Run No.	1	22	4	52	57	63	53	58	60
Reservoir elevation	1551.0	1428.5	1303.0	1551.0	1429.0	1299.0	1550.0	1423.0	1300.0
Discharge	111,000	94,000	72,500	91,000	76,000	53,000	106,100	80,900	64,200
% Central Gate Open									
Left Gate	100	100	100	100	100	100	75	75	75
Right Gate	100	100	100	0	0	0	75	75	75
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
76	280.3	155.8	68.3	61.3	38.3	6.3	308.3	196.3	91.3
77	219.3	140.3	59.3	**	- 8.7	0.3	305.3	198.3	93.3
78	219.3	139.8	59.3	- 12.7	- 7.7	**	314.3	203.3	96.3
79	242.4	157.4	107.3	75.4	47.4	23.4	276.4	177.4	81.4
80	230.5	149.5	71.5	24.5	15.5	8.5	53.5	27.5	- 4.5
81	245.9	164.9	83.9	25.9	22.9	23.9	272.9	178.9	91.9
82	237.9	158.9	79.9	- 2.1	5.9	13.9	146.9	97.9	44.9
83	236.9	158.4	79.9	- 5.1	0.1	10.9	119.9	78.9	33.9
84	286.9	177.4	110.9	126.9	97.9	69.9	301.9	208.9	117.9
85	264.9	183.9	105.4	46.9	43.9	44.9	189.9	134.9	74.9
86	269.9	188.9	106.9	52.9	45.9	46.8	190.9	134.9	74.9
87	270.8	186.8	104.8	56.8	48.8	38.3	287.8	200.8	112.8
88	264.3	185.3	105.3	30.3	32.3	3.7	220.3	157.3	86.3
89	225.7	146.2	64.7	**	**	**	53.7	32.7	- 7.3
90	228.0	148.0	68.0	**	**	**	57.0	36.0	- 5.0
91	245.5	160.5	74.5	10.5	- 1.5	**	71.5	42.5	5.5
92	241.9	162.9	81.9	4.9	5.9	13.9	93.9	62.9	23.9
93	249.4	168.4	85.4	20.4	11.4	10.4	74.4	52.4	17.4
94	262.1	177.1	91.1	37.1	17.1	8.1	83.1	59.1	25.1
95	272.5	189.5	106.5	51.5	43.5	42.5	178.5	117.5	64.5
96	268.1	186.1	105.1	37.1	27.1	25.1	109.1	79.1	42.1
97	276.8	182.8	106.8	41.8	20.8	9.8	115.8	82.8	43.8
98	212.1	136.1	58.1	**	**	**	55.1	27.1	- 3.9
99	210.1	134.1	57.1	**	**	**	54.1	27.1	**
100	211.1	135.1	57.1	**	**	**	53.1	28.1	**
101	225.0	146.0	64.0	**	**	**	56.0	29.0	**
102	222.1	143.1	63.1	17.1	**	**	51.1	26.1	**
103	233.9	152.9	67.9	25.9	**	**	81.9	48.9	**
104	229.1	154.1	77.1	**	**	1.1	90.1	58.1	21.1
105	225.1	152.1	76.1	**	**	- 2.9	76.1	50.1	18.1
106	230.1	154.6	77.1	**	**	1.1	79.1	53.1	19.1
107	245.4	165.4	85.4	15.4	6.4	7.4	72.4	53.4	19.4
108	241.4	162.9	83.4	**	**	**	47.4	32.4	**
109	256.2	173.2	88.2	46.2	17.2	**	70.2	45.2	**
110	255.4	175.9	100.6	- 4.6	6.4	24.4	55.4	108.4	38.4
111	244.4	174.4	96.4	- 7.6	3.4	21.4	144.4	99.4	53.4
112	257.4	177.4	99.4	4.4	12.4	25.4	144.4	100.4	55.4
113	265.4	185.4	104.4	29.4	23.4	26.4	114.4	82.4	44.4
114	263.4	184.4	103.4	25.4	6.4	- 11.6	71.4	57.4	32.4
115	274.4	191.9	107.4	70.4	38.4	x	115.4	83.4	45.4
116	204.1	130.6	54.1	26.1	2.1	x	52.1	24.1	**
117	198.1	126.1	52.1	26.1	1.1	x	52.1	**	**
118	205.1	130.1	54.1	26.1	1.1	x	51.1	**	**
119	221.0	142.5	62.5	27.0	0.0	x	53.0	**	**
120	222.1	143.1	62.1	26.1	- 0.9	x	54.1	27.1	**
121	219.1	140.1	69.6	47.1	17.1	x	58.1	37.1	**
122	212.1	146.1	73.1	47.1	17.1	x	92.1	63.1	32.1
123	220.1	147.1	73.6	47.1	17.1	x	69.1	47.1	13.1
124	241.4	162.4	82.4	58.4	18.4	x	70.4	48.4	17.4
125	236.4	158.9	80.4	47.4	16.4	x	39.4	24.4	**

* See Figures 55 and 56 for Piezometer locations.
** Data not recorded (Piezometer malfunction).
x At Atmospheric Pressure.

TABLE C-3 (Continued)

Run No.	1	22	4	52	57	63	53	58	60
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
126	237.4	164.4	91.4	65.4	37.4	x	149.4	103.4	59.4
127	234.4	160.4	91.4	65.4	38.4	x	121.4	86.4	48.4
128	249.4	172.9	86.4	65.4	38.4	x	138.4	96.4	55.4
129	261.4	182.4	102.4	64.4	39.4	x	112.4	77.4	47.4
130	266.4	181.4	102.4	66.4	40.4	x	60.4	48.4	27.4
276	230.0	**	70.0	64.0	40.0	20.0	267.0	170.0	78.0
277	227.0	**	65.0	21.0	11.0	6.0	263.0	167.0	77.0
278	372.0	**	136.0	242.0	133.0	73.0	374.0	248.0	135.0
279	262.0	**	91.0	86.0	63.0	42.0	288.0	191.0	99.0
280	241.0	**	83.0	16.0	15.0	18.0	269.0	179.0	92.0
281	233.0	**	78.0	- 9.0	- 2.0	10.0	262.0	173.0	89.0
282	284.0	**	111.0	107.0	85.0	62.0	309.0	212.0	120.0
283	267.0	**	103.0	56.0	49.0	44.0	289.0	203.0	113.0
284	234.0	**	66.0	335.0	225.0	107.0	270.0	172.0	81.0
285	218.0	**	55.0	335.0	227.0	101.0	264.0	167.0	92.0
286	254.0	**	88.0	282.0	212.0	121.0	288.0	191.0	101.0
287	229.0	**	78.0	357.0	248.0	131.0	271.0	178.0	94.0
288	221.0	**	75.0	358.0	248.0	131.0	263.0	173.0	91.0
289	276.0	**	109.0	376.0	266.0	150.0	308.0	210.0	122.0
290	260.0	**	103.0	381.0	269.0	153.0	291.0	199.0	115.0

TABLE C-4

PRESSURE HEADS IN THE BIFURCATION, DOWNSTREAM TRANSITION, AND RADIAL GATE CHAMBER.

Central Gates Open
Pressure Heads in Feet of Water.

Run No.	1	39	44	41	42
Reservoir elevation	1551.0	1549.0	1550.0	1551.0	1550.5
% Radial Gate Open Left Gate	100	100	50	100	0
Right Gate	100	50	100	0	100
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
173	**	264.3	282.3	328.3	352.3
174	185.0	291.0	291.0	346.0	346.0
175	221.0	331.0	332.0	384.0	383.0
176	191.0	291.0	297.0	343.0	347.5
177	182.6	259.6	284.6	321.6	353.0
178	159.0	251.0	287.0	319.0	367.0
179	111.5	274.5	294.5	326.5	352.5
180	177.0	253.0	291.0	310.0	355.0
181	155.0	254.0	299.0	313.0	367.5
182	155.5	304.0	325.5	337.5	382.5
183	178.0	235.0	295.0	281.0	355.5
184	147.1	224.1	295.1	272.1	356.1
185	133.0	230.0	306.0	278.0	368.5
186	114.5	219.5	299.5	255.5	359.0
187	141.5	208.0	298.5	249.5	359.0
188	127.0	215.0	308.0	256.0	369.0
189	166.5	246.5	326.5	285.5	386.0
190	111.2	272.2	301.2	200.2	361.2
191	94.0	169.0	301.0	197.0	360.0
192	102.0	180.0	312.0	204.0	369.5
193	179.0	189.0	321.0	155.0	362.0
194	116.8	168.8	306.8	177.8	359.8
195	103.3	168.3	308.3	186.3	360.3
196	111.0	174.0	316.0	196.0	370.0
197	140.2	187.2	334.2	201.2	384.2
198	169.3	163.3	337.3	163.3	362.3
199	103.0	134.0	319.0	133.0	368.5
200	97.5	134.5	308.5	148.5	361.5
201	112.0	136.0	317.0	268.0	371.0
202	186.0	- 8.5	379.0	- 63.0#	371.0
203	136.5	109.5	335.5	93.5	359.5
204	103.0	118.0	311.0	114.0	358.0
205	109.5	136.5	309.5	144.5	364.5
206	118.0	151.0	317.0	163.0	370.0
207	129.0	149.0	336.0	148.0	386.0
208	135.0	43.0	354.0	- 31.0	382.0
209	117.0	102.5	329.5	74.5	366.5
210	87.0	101.0	308.0	94.0	361.0
211	120.0	140.0	318.0	142.0	373.0
212	78.0	96.0	324.0	60.0	373.0
213	99.0	114.0	309.0	110.0	361.0
214	123.5	141.5	312.5	144.5	365.5
215	137.0	161.0	322.0	166.0	373.0
216	142.0	138.0	333.0	135.0	385.0
217	62.0	81.0	314.0	90.0	374.0
218	67.5	78.5	307.5	62.5	365.5
219	98.0	113.0	310.0	110.0	362.0
220	144.0	164.0	324.0	175.0	373.0
221	110.0	125.0	323.0	107.0	373.0
222	**	**	**	**	**
223	131.5	151.5	317.0	156.5	364.5
224	147.0	169.0	326.0	182.0	373.0
225	**	134.0	422.0	136.0	385.0
226	35.0	53.0	306.0	67.0	374.0
227	53.5	64.5	304.5	64.5	364.5
228	92.0	106.0	312.0	108.0	361.0
229	141.0	160.0	328.0	170.0	373.0
230	45.0	69.0	310.0	69.0	373.0
231	98.0	111.0	315.0	114.0	361.0
232	114.5	127.5	319.5	130.5	365.5
233	128.0	143.0	328.0	151.0	374.0
234	113.0	125.0	339.0	129.0	385.0
235	68.0	85.0	316.0	89.0	373.0
236	75.5	90.5	317.5	91.5	364.5
237	89.0	105.0	314.0	106.0	361.0
238	95.5	110.5	317.5	112.5	365.5
239	109.0	124.0	325.0	127.0	373.0
240	115.0	132.0	338.0	135.0	385.0
241	106.0	122.0	326.0	120.0	373.0
242	89.5	106.5	316.5	104.5	365.5
243	69.0	92.0	313.0	88.0	361.0
244	93.0	117.0	338.0	115.0	386.0
245	45.0	65.0	314.0	60.0	362.0
246	50.0	70.0	316.0	65.0	363.0
247	58.0	76.0	326.0	73.0	374.0
248	71.0	91.0	338.0	88.0	386.0
249	63.0	80.0	326.0	80.0	374.0
250	48.0	67.0	316.0	62.0	364.0
251	12.0	28.0	311.0	21.0	362.0
252	41.0	55.0	333.0	51.0	386.0
253	- 15.0	- 19.0	326.0	- 15.0	362.0
254	- 9.5	- 11.5	326.5	- 10.5	362.5
255	- 3.0	- 5.0	312.0	- 2.0	374.0
256	12.0	11.0	301.0	14.0	386.0
257	10.0	9.0	214.0	13.0	386.0
258	5.0	8.0	100.0	12.0	386.0
259	7.0	7.0	7.0	14.0	**

* See Figures 58 and 59 for Piezometer locations.
** Data not recorded (Piezometer malfunction).
\# Negative pressure heads read below vapor pressure of about -32 feet of water. This has no physical meaning in the prototype except to indicate possible cavitation.

TABLE C-5

PRESSURE HEADS ALONG STILLING BASIN CHUTE AND FLOOR.

Central Gates Open.
Pressure Heads in Feet of Water.

Run No.	1	22	4	37	28	21	38	18
Reservoir elevation	1551.0	1428.5	1303.0	1551.0	1424.0	1301.5	1551.0	1298.0
Discharge	111,000	94,000	72,500	49,000	39,900	30,000	24,800	17,500
% Radial - Gates Open in Unison .	100	100	100	50	50	50	25	25
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
260	12.5	18.0	14.0	11.5	9.5	6.5	6.5	5.5
261	13.9	16.9	15.4	13.9	9.9	6.9	15.9	5.9
262	2.3	6.7	9.7	3.2	4.2	3.2	4.2	2.2
263	11.5	9.5	12.5	8.5	7.5	4.5	10.5	4.5
264	8.7	9.7	9.2	4.7	4.7	4.2	5.7	2.7
265	1.8	2.3	6.3	- 2.2	0.8	1.3	- 3.2	- 0.2
266	2.9	3.4	6.9	1.9	0.9	1.9	- 0.1	0.9
267	10.9	10.9	8.9	12.9	11.9	8.9	21.9	6.9
268	- 0.6	0.4	5.4	- 1.6	11.4	12.4	19.4	3.4
269	12.0	20.0	18.0	21.0	29.0	27.0	35.0	17.0
270	45.1	48.1	44.6	51.1	50.1	57.6	57.1	42.1
271	119.0	91.5	75.0	72.0	73.0	67.0	72.0	57.0
272	55.0	65.0	70.0	65.0	71.0	69.0	74.0	59.0
273	85.0	82.0	75.0	71.0	74.0	69.0	75.0	59.0
274	90.0	81.0	69.0	65.0	67.0	62.5	68.0	52.0
275	64.0	64.0	59.0	55.0	59.0	55.0	61.0	45.0

* See Figure 59 for Piezometer locations.

TABLE D.

PRESSURE HEADS IN THE BIFURCATION, DOWNSTREAM TRANSITION, AND RADIAL GATE CHAMBER

Central Gates Open.
Pressure Heads in Feet of Water.

Run No.	1 Bif.	2 Bif.	3 Bif.	4 Bif.	5 Bif.
Reservoir elevation	1550.0	1550.0	1552.0	1551.0	1552.0
Dishcarge-cfs	103,000	51,000	80,000	80,000	65,900
% Radial Gates Open					
Left Gate	100	50	100	50	100
Right Gate	100	50	50	100	25
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
173	126.3	350.3	243.3	252.2	292.3
174	161.0	354.0	269.0	263.0	313.0
175	208.0	392.0	311.0	306.0	363.0
176	169.0	356.0	271.0	271.0	311.0
177	128.6	350.6	239.6	256.6	286.6
178	116.0	357.0	235.0	259.0	284.0
179	152.5	353.5	254.5	266.5	293.5
180	126.0	351.0	232.0	262.0	276.0
181	127.0	359.0	235.0	269.0	280.0
182	187.5	385.5	286.5	299.5	325.3
183	155.0	348.0	216.0	265.0	232.0
184	110.1	347.1	204.1	265.1	244.1
185	116.0	357.0	211.0	276.0	250.0
186	120.5	347.5	200.5	269.5	230.5
187	104.5	346.5	189.5	268.5	224.5
188	111.0	356.0	198.0	278.0	233.0
189	150.5	374.0	231.5	296.5	260.5
190	97.2	341.2	158.2	271.2	179.2
191	86.0	342.0	154.0	271.0	179.0
192	94.0	351.0	163.0	282.0	188.0
193	157.0	357.0	174.0	291.0	167.0
194	102.8	342.8	150.8	276.8	164.8
195	83.3	343.3	150.3	276.3	170.3
196	101.0	352.0	160.0	284.0	180.0
197	125.2	367.0	174.2	301.2	186.2
198	147.3	355.3	149.3	304.3	144.3
199	91.0	340.0	123.0	278.0	127.0
200	87.5	340.5	128.5	277.5	139.5
201	100.0	355.0	144.0	288.0	157.0
202	160.0	364.5	- 29.0	348.0	- 52.0#
203	117.5	350.5	110.5	304.5	95.5
204	88.0	341.0	113.0	282.0	115.0
205	93.5	345.5	129.5	281.5	138.5
206	104.0	355.0	144.0	289.0	156.0
207	114.0	366.0	142.0	305.0	145.0
208	119.0	357.0	45.0	323.0	- 15.0
209	101.5	346.5	97.5	297.5	79.5
210	77.0	339.0	96.0	278.0	95.0
211	105.0	355.0	133.0	290.0	139.0
212	70.0	346.0	93.0	295.0	77.0
213	85.0	341.0	103.0	280.0	110.0
214	106.5	348.5	134.5	284.5	141.5
215	120.0	358.0	152.0	292.0	161.0

Run No.	1 Bif.	2 Bif.	3 Bif.	4 Bif.	5 Bif.
Reservoir elevation	1550.0	1550.0	1552.0	1551.0	1552.0
Discharge-cfs	103,000	51,000	80,000	80,000	65,900
% Radial Gates Open					
Left Gate	100	50	100	50	100
Right Gate	100	50	50	100	25
Piezometer Number*	Pressure Head	Pressure Head	Pressure Head	Pressure Head	Pressure Head
216	109.0	365.0	131.0	304.0	234.0
217	54.0	343.0	74.0	284.0	88.0
218	59.5	338.5	72.5	277.5	73.5
219	85.0	341.0	106.0	280.0	111.0
220	125.0	359.0	158.0	294.0	171.5
221	96.0	357.0	118.0	293.0	124.0
222	**	**	**	**	**
223	113.5	349.5	143.5	287.3	153.5
224	128.0	359.0	162.0	296.0	173.0
225	106.0	364.0	128.0	305.0	134.0
226	30.0	337.0	47.0	276.0	61.0
227	44.5	334.5	58.5	274.5	63.5
228	78.0	339.0	99.0	285.0	104.0
229	122.0	358.0	153.0	298.0	163.0
230	40.0	339.0	57.0	280.0	66.0
231	83.0	341.0	105.0	285.0	111.0
232	97.5	346.5	121.5	289.5	129.5
233	111.0	356.0	137.0	298.0	146.0
234	100.0	363.0	120.0	306.0	125.0
235	61.0	345.0	79.0	286.0	86.0
236	67.5	339.5	84.5	282.5	89.5
237	79.0	340.0	98.0	285.0	103.0
238	84.5	344.5	103.5	288.5	108.5
239	96.0	333.5	117.0	298.0	123.0
240	107.0	365.0	126.0	310.0	131.0
241	96.0	353.0	114.0	298.0	119.0
242	82.5	342.5	100.5	287.5	104.5
243	69.0	337.0	85.0	284.0	89.0
244	93.0	361.0	110.0	308.0	114.0
245	47.0	332.0	59.0	280.0	62.0
246	52.0	335.0	64.0	283.0	67.0
247	58.0	344.0	70.0	292.0	73.0
248	74.0	357.0	86.0	304.0	89.0
249	63.0	345.0	75.0	293.0	74.0
250	49.0	334.0	61.0	281.0	64.0
251	17.0	326.0	22.0	276.0	23.0
252	45.0	348.0	50.0	298.0	51.0
253	- 12.0	346.0	- 24.0	289.0	- 14.0
254	- 7.5	345.5	- 8.5	290.5	- 8.5
255	2.0	324.0	1.0	277.0	3.0
256	16.0	310.0	15.0	266.0	16.0
257	17.0	221.0	16.0	189.0	14.0
258	16.0	112.0	16.0	94.0	15.0
259	17.0	2.0	16.0	4.0	16.0

* See Figures 58 and 59 for Piezometer locations.
** Data not recorded (Piezometer malfunction).
\# Negative pressure heads read below vapor pressure of -32 feet of water. This has no physical meaning in the prototype except to indicate possible cavitation.