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October 1993

US Army Corps
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Waterways Experiment
Station

Mud Mountain Outlet Structure

Hydraulic Model Investigation

by Charles H. Tate, Jr.
Hydraulics Laboratory

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Prepared for U.S. Army Engineer District, Seattle

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Waterways Experiment Station
3909 Halls Ferry Road
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Final report

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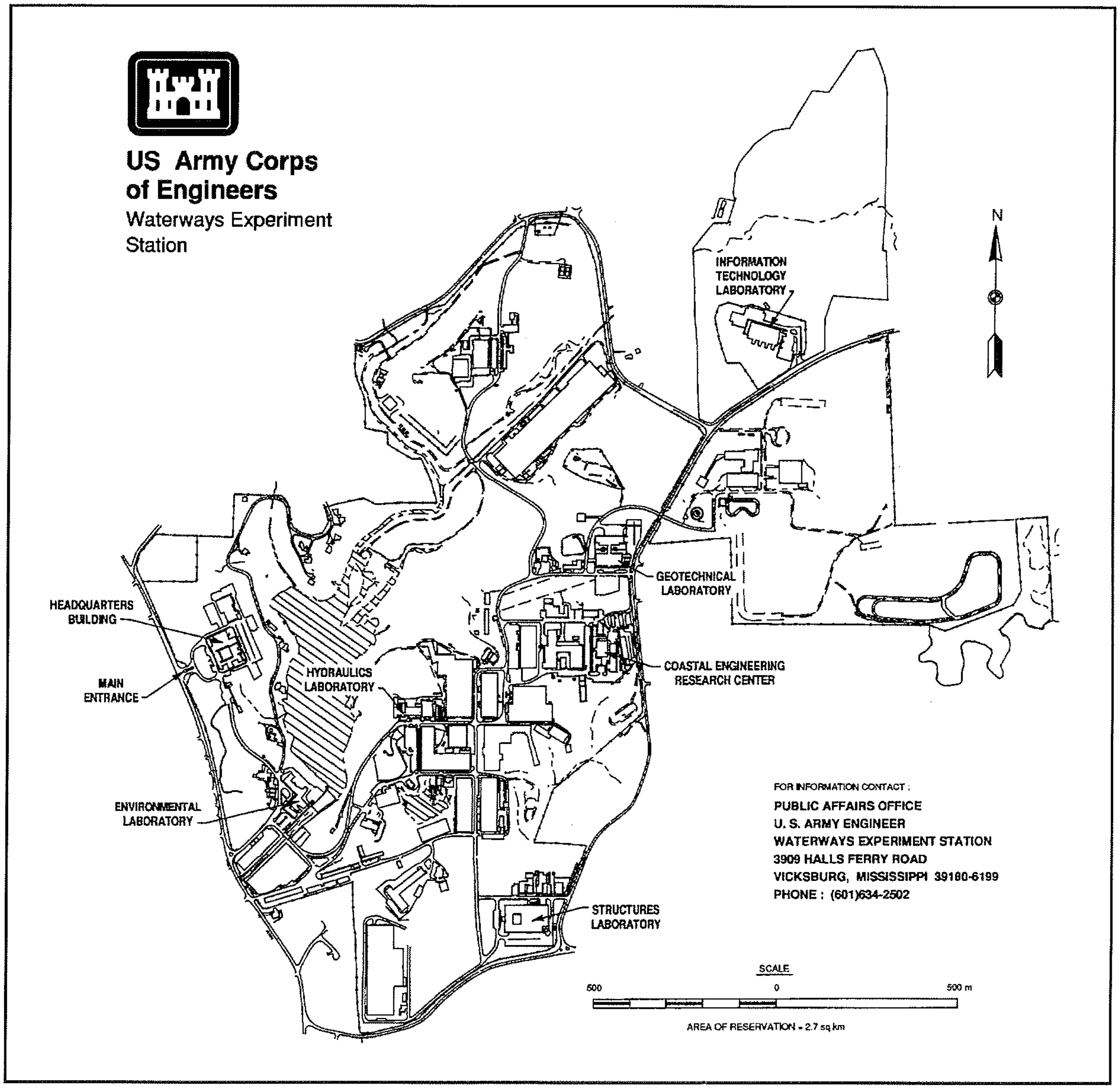

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Contents

Preface

The model investigation reported herein was authorized by the Headquarters, U.S. Army Corps of Engineers, on 9 April 1985 at the request of the U.S. Army Engineer District, Seattle. The investigation was stopped by the Seattle District on 15 June 1987 and restarted on 15 December 1987, due to problems associated with siting the intake structure.

The studies were conducted during the period April 1985 to July 1991 in the Hydraulics Laboratory (HL) of the U.S. Army Engineer Waterways Experiment Station (WES), under the direction of Messrs. F. A. Herrmann, Jr., Director, HL, and R. A. Sager, Assistant Director, HL; and under the general supervision of Messrs. G. A. Pickering, Chief, Hydraulic Structures Division (HSD), HL, and J. F. George, Chief, Locks and Conduits Branch (LCB), HSD. Tests were conducted by Messrs. C. H. Tate, Jr., J. Cessna, T. Murphy, and V. Stewart, LCB, and the report was prepared by Mr. Tate.

The model was constructed by Messrs. Edward A. Case, Joseph M. Lyons, and Mitchell A. Simmons of the Model Shop, Engineering and Construction Services Division, WES, under the supervision of Mr. Sidney J. Leist, Chief of the Model Shop.

COL Phillip Hall, Commander, Seattle District; Messrs. R. P. Sellevold, Dick Regan, Jim Lencioni, Ed Zappel, and Paul Noyes of the Seattle District; Mr. Bruce McCartney of the U.S. Army Engineer Division, North Pacific; and Mr. Sam Powell of the Headquarters, U.S. Army Corps of Engineers, visited WES during the course of the model study to observe model operation and correlate results with concurrent design works.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
feet of water (39.2 °F)	2.98898	kilopascals
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers

1 Introduction

The Prototype

Mud Mountain Dam is located on the White River approximately 8 miles[1] southeast of Enumclaw in west-central Washington (Figure 1). The headwaters of the White River are on the northeast slopes of Mount Rainier, which has had historic volcanic activity. Mud Mountain Dam is an earth- and rock-fill structure built primarily during 1939-1942 and officially finished in 1953. It serves as a major flood control element for the Puyallup River Basin above Tacoma, WA. The dam is a single-purpose project for flood control, and no conservation pool is maintained above the dam. Flow is stored as required to prevent levee overtopping in the lower Puyallup Valley.[2] The project has a maximum authorized flood control release of 17,600 cfs. Due to conditions in the channel downstream from the dam and upstream from the project's flood control location, bank-full capacity of the channel immediately downstream of the dam is approximately 8,000 to 10,000 cfs.

The existing project has two separate flood control outlet tunnels with separate intake structures (Figure 2). An 1,800-ft-long, 9-ft-horseshoe gated tunnel passes the flow from the bottom of the approach channel (Figure 2 and Plate 1) and is subjected to high sediment flows as a result of previous Mount Rainier volcanic activity. This tunnel flows full at discharges Q of 2,000 to 2,500 cfs with a maximum capacity of approximately 4,600 cfs. A 2,000-ft-long, 23-ft-diam tunnel with a slope of 0.0102 releases flood flows from higher in the flood control pool (Figure 2 and Plate 2) and is not usually subjected to high sediment flows. The downstream 45 percent of the 23-ft-diam tunnel houses three 8.5-ft-diam penstocks carrying flow to the outlet where flow is controlled with fixed-cone valves. The project also has a 315-ft-wide uncontrolled spillway (Figure 2) to pass flows greater than can be handled with the tunnels.

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1 A table of factors for converting non-SI units of measurement to SI units is presented on page v.

2 U.S. Army Engineer District, Seattle. (1986). "Dam Safety Assurance Program, Mud Mountain Dam, Washington," General Design Memorandum No. 26, Seattle, WA.

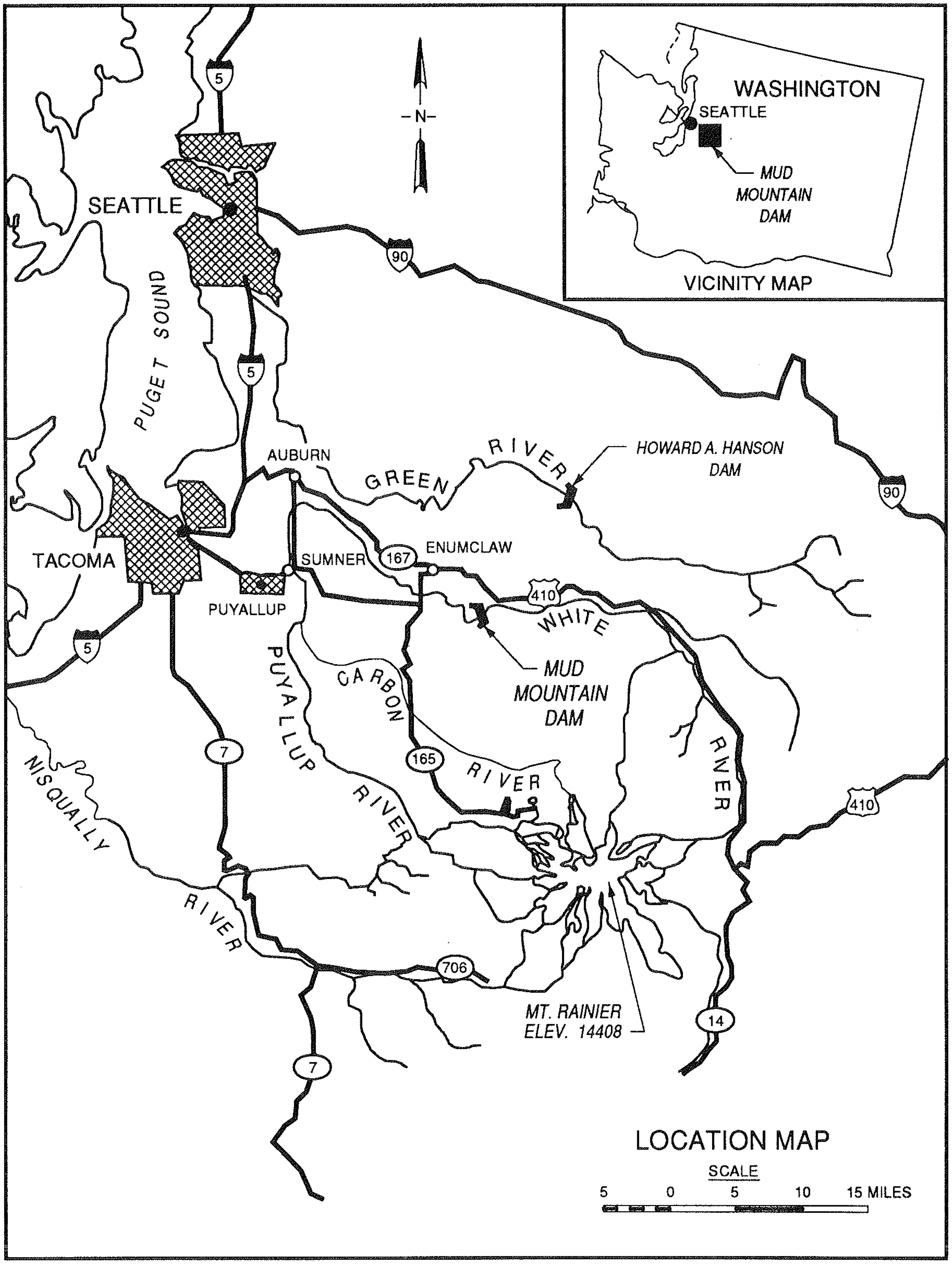

Figure 1. Project location

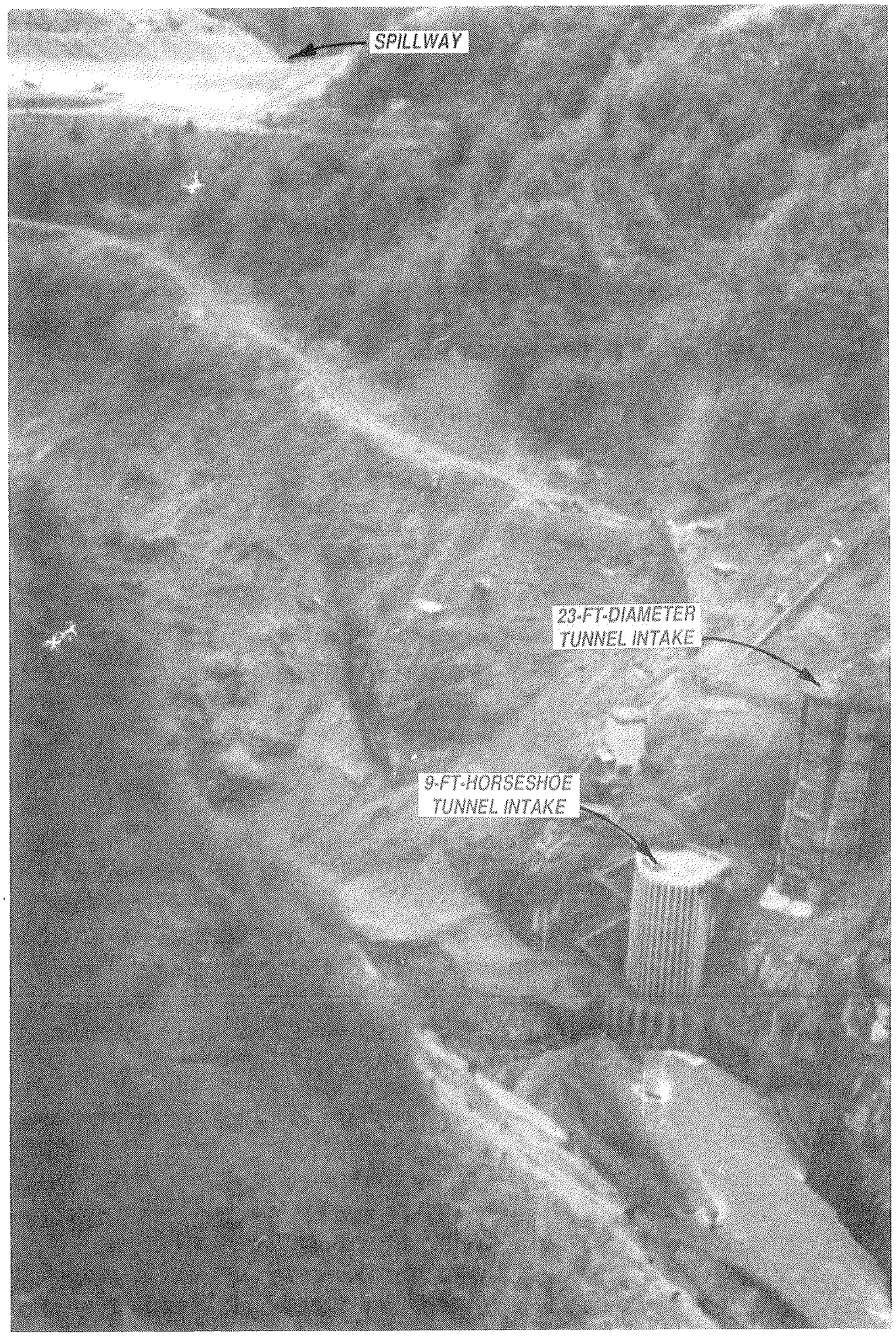

Figure 2. Intake towers and vicinity. White River flows from bottom right.

Engineering studies by the U.S. Army Engineer District, Seattle, concluded that the use of the project without modifications could result in dam failure by overtopping during a Spillway Design Flood or from loss of reservoir control caused by blockage of the outlet tunnels by the large quantity of debris and sediment present in the system. The reconnaissance report recommended several modifications including a new intake tower and modifying the controls to the 23-ft-diam tunnel. A plan was developed by the Seattle District[1] that included constructing a new 50-ft-diam intake tower that contained the entrance and control gate for the 9-ft-horseshoe tunnel and two intakes and control gates at different elevations for the 23-ft-diam tunnel. The tower was designed to function as a large trashrack to handle the sediment and debris conditions at Mud Mountain Dam. Structural design of the trashrack elements was based on a maximum pressure differential of 50 ft across the trashrack. The existing tunnels were connected to the new tower with curved connecting tunnel sections (Plate 3). This design removed the fixed-cone valves and penstocks from the 23-ft-diam tunnel and added a horizontally curved flip bucket exit structure to direct the flow into the center of the exit channel. The design flow of 17,600 cfs at the design pool elevation of 1215[2] was split with 4,600 cfs passing through the 9-ft-horseshoe tunnel and 13,000 cfs passing through the 23-ft-diam tunnel. Capacity of the modified 23-ft-diam tunnel was designed to be greater than the 13,000-cfs design discharge.

Purpose and Scope of Study

This study was conducted to determine the hydraulic adequacy of the design proposed by the Seattle District. The model study was designed to determine the approach conditions to the intake tower and the flow conditions through the intake tower, the tunnel entrances, the transitions to the 23-ft-diam tunnel, the modified 23-ft-diam tunnel, the exit structure, and the exit channel. Where necessary, new designs were developed and alternative designs tested. Extreme blockage conditions of the intake tower were tested to verify assumed trashrack pressure losses and discharge characteristics.

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1 U.S. Army Engineer District, Seattle, op. cit.

2 All elevations (el) and stages cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

2 Physical Model

Description

A 1:30-scale model was used to test the original design proposed by the Seattle District and several alternative designs and modifications. The intake tower and near field topography were constructed in a 21.5-ft diam, 12-ft-high (model) steel tank. Approximately 350 ft of approach geometry was simulated (Photo 1). The 50-ft-diam intake tower, the entire 23-ft-diam tunnel, and all connecting structures were constructed using clear acrylic plastic. The original design connecting structures consisted of two 16-ft-high tunnels downstream from the tainter gates that joined at the downstream end of the splitter wall, the transition from rectangular to 23-ft-high flat-bottom horseshoe-shaped tunnel, the 500-ft-radius curve, and the transition from horseshoe to existing circular tunnel (Plates 3 and 4). To correctly model the flow fields in the proposed intake tower, the intake and gate for the 9-ft-horseshoe tunnel were reproduced in the model (Plate 5). The original design flip bucket exit structure was included in the exit area, which reproduced approximately 300 ft of the exit channel up to el 900. The exit area was constructed of hard foam with a thin concrete mortar coating and designed to accommodate preformed channel scour up to 40 ft deep (Photo 2).

Flow to this model was supplied through a circulating system. Discharges were measured with paddle-wheel flowmeters and controlled with gate valves. Point gages, external scales, and free-surface piezometers were used to measure water-surface elevations throughout the model. Velocities were measured in the model with propeller meters. Flow conditions were observed for the different designs tested with flow conditions being recorded photographically.

Scale Relations

The accepted equations of hydraulic similitude, based on the Froudian criteria, were used to express mathematical relations between the dimensions and hydraulic quantities of the model and prototype. General relations for the transference of model data to prototype equivalents are in the following tabulation. Model measurements of discharge, water-surface elevations, and velocities can be transferred quantitatively to prototype equivalents by means of the scale relations.

Characteristic	Dimension[1]	Scale Relations Model:Prototype
Length	L_r	1:30
Area	$A_r = L_r^2$	1:900
Velocity	$V_r = L_r^{1/2}$	1:5.477
Discharge	$Q_r = L_r^{5/2}$	1:4,930
Roughness coefficient	$N_r = L_r^{1/6}$	1:1.763

[1] Dimensions are in terms of length.

Tunnel Adjustment

The coefficient of roughness of the surface of the acrylic plastic used for the model tunnel had previously been determined to be approximately 0.009 (Manning's n). Basing similitude on the Froudian relation, the *n* value would be equivalent to a prototype *n* of 0.016. The *n* value used in the design and analysis of the prototype tunnel varied from 0.013 to 0.018; therefore, the model tunnel slope downstream from the connecting curve was adjusted to correct for this difference in the *n* values of the model and prototype. The tunnel downstream of the gates to the downstream end of the connecting tunnel was not adjusted because the jet downstream of the gates is not distortable and would not correctly follow a distorted invert.

3 Tests and Results

Original Design

Discharge rating relations

Initial testing of the original design was directed toward developing discharge rating relations for several release configurations. Pool elevation versus discharge relations were determined for the 23-ft-diam tunnel with high pool elevations and the 9-ft-horseshoe tunnel gate closed to determine the maximum capacity of the intakes to the 23-ft-diam tunnel. The relations that were developed and plotted in Plate 6 should not be extended below pool el 990. At lower pool elevations, the velocity through the trashrack increased causing additional energy losses and slightly lower discharges for a given pool elevation than indicated by the curves plotted in Plate 6. Pool el 1215 is the maximum design elevation for operation of the flood control intakes and is the maximum value shown in Plate 6. The maximum capacity of the 23-ft-diam tunnel intakes was approximately 19,500 cfs.

Discharge rating curves for partial gate openings were developed for gate 1 and are shown in Plate 7. A discharge rating curve for both gates 1 and 2 fully open (11.5 ft) is also shown in this plate.

The discharge capacity and trashrack pressure differential of the proposed intake tower were determined for two trashrack blockage and sediment inflow conditions. The first was with the tower completely blocked up to el 1080 and 75 percent blocked (by area) between el 1080 and 1100. This condition, as simulated in the model and illustrated in Photo 3, represents the estimated sediment buildup and debris blockage from a Standard Project Flood (SPF) condition as determined by the Seattle District. The model results are shown in Plate 8 with the computed discharge curve supplied by the Seattle District. Due to the way the model was constructed with a sheet metal lip at the top of the tower, the pool elevations shown for flows between 7,000 and 15,000 cfs are artificially high as indicated with a bar drawn between el 1100 and the data points. Pool elevations below 1110 could result in free-falling flow in the tower with gates 1 and 2 both open. For nonfree-falling conditions, the measured pressure differential between the pool and the inside of the tower is shown on the right side of Plate 8 and is less than the design value of 50 ft.

For this condition, the model results indicated the structure would pass more than the computed flow. The second blockage condition was with the tower completely blocked up to el 1015 and 90 percent blocked between el 1015 and 1100 representing the estimated sediment buildup and debris blockage from the Project Design Flood (PDF) condition. The PDF is estimated to have a recurrence interval significantly longer than once in 500 years. Test results, shown in Plate 9, indicate the intake tower will pass more than the authorized flood control discharge of 17,600 cfs at pool el 1215. Pool elevations below 1110 could result in free-falling flow in the tower with gates 1 and 2 both open. For nonfree-falling conditions, the measured pressure differential between the pool and the inside of the tower is shown on the right side of Plate 9 and is less than the design value of 50 ft. For both blockage conditions, a strong vortex formed over the intake tower for pool elevations between 1100 and 1120, but decreased in intensity before disappearing at an approximate pool elevation of 1150. An example of the vortex is shown in Photo 4 at a pool elevation of around 1110. The vortex stabilized over a specific opening in the top of the tower, which indicated that flow conditions were specific to the type of blockage that occurred. Prototype flow conditions between pool el 1100 and 1150 may vary from those observed in the model due to the nature of the blockage.

Pressures

Pressures in the intakes were monitored upstream from gates 1, 2, and 3. Observed average pressures indicate that significant negative pressures could occur along and near the floor of the intake to gate 1 with the gate fully open and the pool elevation above 1065. The lowest pressures were observed in the center of the bottom of the intake. Plots of the observed pressures for fully open gates are shown in Plates 10-25 and the data are in Tables 1-5. The minimum pressures could be raised to 10 ft below the piezometer elevations (the normally applied limit to avoid cavitation) by closing the gate to a 99 percent open position. Plots of observed intake floor pressures with a gate opening of 10.5 ft are shown in Plates 26-28 and the data are in Table 6. Centerline invert pressures were also recorded for tunnels 1 and 2 between sta 3+60 (approximately the gate seat) and 4+55, shown in Plates 29 and 30. There were no adverse pressure conditions observed at these locations.

Flow conditions

Intake tower. Gate openings greater than 50 percent on gates 1 and 2 caused increasingly severe vortex action with increasing gate opening inside the intake tower at pool elevations below 1000. For these conditions, a large vortex formed to the outside of the intake to the open gate. Vortex formation was also observed with only gate 3 operating and pool elevations below 960. For these conditions, a vortex formed off the center splitter wall and crossed in front of the intake to the 9-ft tunnel while another vortex formed at the splitter wall.

General hydraulic conditions were observed at pool el 1120 with the intake tower blocked up to el 960. Gate 3 was set to release the approximate tunnel flow capacity of 3,900 cfs and gates 1 and 2 were varied. Gate 1 was initially set fully open and gate 2 was closed. The gates were then moved in 25 percent increments until gate 1 was closed and gate 2 was fully open. These tests were also conducted with gate 3 closed. No adverse hydraulic conditions were observed in the intake tower for these tests.

Tunnel. Open-channel flow conditions were maintained in the 23-ft-diam tunnel for all conditions tested. The tunnel slope in the model downstream from the connecting curve was adjusted to reproduce the energy gradient for a Manning's n value of 0.018 with the original design. For single gate operation, flow through gate 2 rode the right side of the curve downstream of the gates and flowed fairly smoothly throughout the structure (Photos 5 and 6). Flow through gate 1 was not as smooth with single gate operation. At full pool and full gate operation, the surface of the jet downstream of the gate intermittently impacted the gate trunnion recess and tended to adhere to the top of the 16-ft-high tunnel immediately downstream of the gates. Very minor throttling of the control gate significantly stabilized the jet downstream of the gate. Once downstream of the splitter wall, the flow crossed the tunnel and impacted the right side of the curve (Photo 7). This impact and sudden direction change caused the flow to roll over the tunnel and then to slosh back up the side of the tunnel at approximately the transition to the existing circular tunnel (Photo 8). This difference in flow conditions resulted in various degrees of energy dissipation in the curve and affected flow conditions at the tunnel exit. Flow at the design pool with both gates fully open is shown in Photos 9 and 10. Discharge for this condition is approximately 19,500 cfs, which is significantly greater than the design discharge of 13,000 cfs and the maximum project authorized flood control discharge of 17,600 cfs. As with single gate operation, flow intermittently impacted the gate trunnion recess and tended to adhere to the top of the 16-ft-high tunnel downstream of gate 1. Flow rode the right side of the curve downstream of the gates and rolled over the tunnel near the downstream end of the connecting curve. Within approximately 100 ft downstream of the curve, a major portion of the flow sloshed back over the top of the tunnel as a broken spray nearly filled the tunnel. Closing the air vents downstream of the gates did not affect flow conditions, indicating that the tunnel was not priming or flowing full with both gates fully open.

Exit structure. The proposed design for the exit structure did not adequately turn the flow downstream, which resulted in the exit flow impacting at the base of the bluff opposite the exit structure (Photo 11). Due to the flip bucket design of the exit structure, a hydraulic jump formed in the tunnel near the exit structure at low flows and nearly blocked the tunnel before being swept out with increasing flow. Due to the extreme turbulence in the exit channel and the relatively short length of the model exit channel, it was not possible to accurately simulate the computed prototype tailwater elevations. Most testing was conducted without model tailwater to determine the impact location of the exit flow in the exit channel.

Alternate Designs

Type 2 design connecting curve

Observation of flow conditions in the original 500-ft-radius connecting curve led to a decision to try a shorter radius connecting curve. A primary benefit of using a shorter radius curve was that additional existing tunnel could be used and less new tunnel would need to be constructed with a significant cost reduction. Discussions between the U.S. Army Engineer Waterways Experiment Station and the Seattle District resulted in testing a 250-ft-radius connecting curve with a 23-ft-diam circular cross section (type 2 design connecting curve). The type 2 design connecting curve was used to replace the original 500-ft-radius curve, which had a flat bottom horseshoe cross section, saving over 60 ft of the existing 23-ft-diam tunnel (Plate 31). The reduced radius permitted the transition from rectangular to circular cross section to be located in the straight reach of tunnel immediately upstream of the connecting curve. The portion of tunnel from upstream of the curve to the gates was constructed with the roof of each section of the tunnel at the same elevation. This resulted in the roof of tunnel 1 being 23 ft high and the roof of tunnel 2 sloping from 23 ft high at the upstream end of the transition to approximately 30 ft high at the gate trunnion. This portion of the tunnel was constructed to allow the tunnel roof to be lowered to test other tunnel height designs. The gate trunnions were unchanged in the model from the original design. The circular cross section through the curve was more energy efficient than the original design, resulting in improved flow conditions and reduced flow depths in the downstream tunnel. Flow conditions in the tunnel from downstream of the gates to downstream of the connecting curve for pool el 1215 and gates 1 and 2 fully open (maximum discharge condition) are shown in Photos 12 and 13. With both gates fully open, the flow spiraled twice around the inside of the tunnel before remaining basically on the invert. Flow conditions with the design pool elevation with only gate 1 fully open are shown in Photos 14 and 15 and with only gate 2 fully open in Photos 16 and 17. With only gate 1 fully open, the flow passed over the top of the tunnel once, while for only gate 2 fully open, the flow rode the right side of the connecting curve and did not go over the top of the tunnel. Photos 18 and 19 show flow conditions in the tunnel for the design pool el 1215, with a 13,000-cfs discharge (the design condition) with equal gate openings.

Water-surface elevations along the left wall downstream of gate 1 and upstream of the connecting curve were highly variable for full gate openings at high pools. At times the flow occasionally struck the trunnion. Maximum flow depths along the left wall of tunnel 1 are shown in Plate 32, and along the right wall of tunnel 2 in Plate 33, for several flow conditions. These maximum flow depths are representative of maximum flow runup on the outside walls and not the general flow depth or the general flow runup. The runup flow was generally less than 2 ft thick along the outside walls. For partial gate openings, the flow depth immediately downstream of the gates was generally less than the height of the gate opening. At full gate opening, the flow depth was generally less than 12 ft but exhibited surges where the water surface flashed to greater depths.

The depth of flow in the 23-ft-diam tunnel downstream of the connecting curve is shown in Plate 34 for several flow scenarios. For discharges greater than approximately 14,000 cfs, flow exiting the connecting curve spiraled around the outside of the tunnel prior to settling on the bottom of the tunnel about 100 ft downstream of the connecting curve. This condition is evident in the highly variable flow depths shown for the upstream section of the tunnel in Plate 34. The spiraling flow did not seal the tunnel or set up a potential tunnel priming situation.

Exit structure modifications

Several modifications to the exit structure were tested to develop a design that would place the majority of the flow impact near the center of the exit channel and away from the right bank of the exit channel. A simple circular curved extension (type 2 design exit structure) to the tunnel was not acceptable due to the distance the exit structure was required to extend into the exit channel. Several elliptical curve combinations were tested to develop the combination required to place the flow impact in the desired location in the exit channel (type 3-7 design exit structures). The type 7 design exit structure shown in Plate 35 met the impact location goal. The slope of the existing tunnel was continued through the exit structure with this design. Varying radius 30-ft-long fillets were used in the bottom quadrants of the exit structure to transition the 23-ft-diam tunnel to a rectangular section. Flow conditions through the exit structure and into the exit channel (without tailwater) are shown in Photos 20 and 21 for a discharge of 19,500 cfs at pool el 1215 with both gates fully open. Water-surface elevations along the left and right walls of the type 7 design exit structure are shown in Plates 36 and 37 for several flow conditions. Piezometers were installed in the floor and left wall of the type 7 design exit structure as shown in Plate 38. Pressures for various flow conditions are shown in Tables 7-16. Impact areas for the exiting flow are shown for several flow conditions in Plates 39-45. The grid shown in these plates is 25 ft by 25 ft and is deflected 45 deg to the right of the tunnel center line at the extended sta 21+50. The model was tested through the anticipated discharge-tailwater relationship without the tailwater impacting the flow through the exit structure. The tunnel was forced to prime by manually obstructing the exit, then removing the obstruction, resulting in the tunnel rapidly returning to open-channel flow.

Intake tower modifications

Strong vortices formed inside the original design intake tower for large gate openings and pool elevations below approximately 1020. Although the vortex conditions were not unacceptable, an effort was made to minimize the vortex action. Due to the large amount of floating debris that could pass through the trashrack, most of the typical vortex suppression methods could present operational or maintenance problems in this structure. Several arrangements of horizontal beams located at el 960 were studied with the intention of reducing the vortex strength (type 1-4 design baffles). Best results were obtained with the type 4 design baffle, which was 3 ft wide by 5 ft deep, with the top of the beam located at el 960. The plan location of the beams is shown in Plate 46. Maximum average velocities in the vortices that remained with this design were observed at pool el 1008, and those velocities just above the beams are shown in Plate 47. Descriptions of the vortex activity without beams and with the type 4 design baffle are in Tables 17 and 18, respectively.

Based on a value engineering suggestion, the Seattle District developed a new intake tower design (type 2 design intake tower). The type 2 design intake tower differed from the original design primarily in that the rear deck was lowered from el 1040 to 970 and the air shaft was moved away from the trashrack, as shown in Photo 22 and Plate 48. The structural members of the tower remained the same as the original design.

Vortex conditions were improved with the type 2 design intake tower. Vortices were present inside the intake tower for pool elevations up to 1022, but were not as strong or as large as those observed in the original design. A description of the vortex activity is provided in Table 19.

In an effort to simplify construction, the downstream deck was raised from el 970 to 976, tying the deck to the lower edge of a trashrack compression ring with the top at el 980 (type 3 design intake tower). Vortex activity was similar to that of the type 2 design intake tower. The type 4 design vortex suppression baffle, developed for the original design intake tower, was tested with the type 3 design intake tower and had minimal impact on the vortex activity. A spider web shaped baffle, with seven longitudinal ribs and two equally spaced connecting members, was installed on the downstream half of the intake tower (type 5 design baffle). Tests indicated that this design decreased vortex action, but not significantly. The connecting members were removed (type 6 design baffle) resulting in little impact on the vortex action. Numerous other devices were tested with little success. Based on test results of previous designs, the Seattle District furnished a design that satisfied the structural and seismic requirements. This design (type 7 design baffle) included four inverted T-shaped horizontal beams and numerous vertical ribs attached to the upper trashrack members, as shown in Photo 23. The type 7 design baffle significantly reduced the vortex activity. Test results are provided in Table 20.

The pool elevation versus discharge relation for the 23-ft-diam tunnel with gates 1 and 2 fully open was developed for the type 3 design intake tower without the type 7 baffle and was found to be:

$$\textit{discharge, cfs} = 1{,}255\ (\textit{pool el} - 921.82)^{0.5}$$

The 23-ft-diam tunnel discharge at pool el 1215 was approximately 21,500 cfs. The addition of the type 7 design baffle to the type 3 design intake tower noticeably reduced the discharge capacity of the structure due to the additional energy loss caused by the baffle. A rating relation was not determined for this condition because the 23-ft-diam tunnel was still capable of passing the project's maximum authorized flood control release of 17,600 cfs.

Tunnel flow conditions

Water-surface elevations along the outside walls downstream of gates 1 and 2 were monitored for the type 3 design intake tower with and without the type 7 design baffle. The maximum water-surface depth above the invert is shown in Plates 49 and 50 for flows through tunnels 1 and 2 without the type 7 design baffle. These are the maximum depths along the outside walls and are not representative of the average depths in each tunnel. Generally, flow stayed less than 18 ft above the floor along the outside walls with occasional surges to the depths shown in Plates 49 and 50. Flow did not strike the 23-ft-high roof or the gate trunnions. The jets downstream of the gates were more variable with the type 7 design baffle in place, as shown in Plates 51 and 52. The maximum flow depth almost reached the model roof in tunnel 1 for this design combination.

Decreased Tunnel Roughness

Although the Seattle District had estimated the design condition Manning's n of the prototype tunnel to be 0.018 due to potential surface roughness that could occur as a result of the sediment-laden flow at Mud Mountain Dam, tests were conducted to determine the effects on flow conditions in the tunnel and exit channel should the prototype roughness result in a smoother tunnel. The tunnel slope downstream from the connecting curve was adjusted to reproduce the energy gradient for a Manning's n value of 0.013. This was the smallest value considered reasonable in the prototype.

Tunnel

The depth of flow in the 23-ft-diam tunnel downstream of the connecting curve is shown in Plate 53 for several flow conditions with the model simulating a prototype Manning's n value of 0.013. Flow exiting the connecting curve spiraled around the outside of the tunnel prior to settling on the bottom of the tunnel. This condition is evident in the highly variable flow depths shown for the upstream section of the tunnel in Plate 53.

Exit area

Flow conditions through the type 7 design exit structure and into the exit channel (without tailwater) are shown in Photos 24-27 for the design and several other flow conditions with a prototype Manning's n value of 0.013. Water-surface elevations are shown along the left and right walls of the type 7 design exit structure in Plates 54 and 55. Generally, the water-surface elevations are similar to those determined for the rougher n value except at the downstream end of the left wall where the smoother n results in slightly higher water-surface elevations. Exit structure pressures for various flow conditions are shown in Tables 21-26. Generally, the pressures are similar to or slightly higher than the pressures observed for the rougher n value. The significant difference was observed for piezometers 1 and 8 (located on the invert) where the smooth n value resulted in significantly greater pressures for the higher flows.

Final Model Design

The trashrack structure above el 960 was modified based on seismic design criteria that the type 3 design intake tower could not accommodate (type 4 design intake tower). The center pier was eliminated, additional compression rings were added, and the shape of the vertical members was modified. At the request of the Seattle District, only the vortex action within the type 4 design intake tower and the flow profiles downstream from the gates to the downstream end of the splitter wall were evaluated in the model. Above pool el 1080, the minor vortex action was usually located toward the left side of the intake tower and usually passed through gate 1. Some vortex activity was always present when the pool elevation was within the intake tower, but the vortex always remained within the tower. This action was not severe as with the original design and did not appear to cause any problems with the operation of the outlet works. Water-surface profiles downstream from the gates to the end of the splitter wall with full pool and fully open gate conditions were slightly more unstable compared to the type 3 design intake tower. Some of the unstable water-surface conditions downstream of gate 1 may be caused by this vortex action. Reducing the gate openings to 75 percent did not have a significant impact on the vortex action until pool elevations exceeded 1020. A significant reduction did occur for the full range of pool elevations when the gates were set at 50 percent open.

The final model design consisted of the type 4 design intake tower connected to the type 2 design connecting curve by 23-ft-high tunnels with the rectangular-to-circular transition located at the upstream end of the connecting curve. The type 7 design exit structure was used at the downstream end of the existing 23-ft-diam tunnel.

4 Conclusions and Recommendations

The proposed modifications to the Mud Mountain Dam 23-ft-diam flood control tunnel and the proposed intake tower should function satisfactorily for the design condition (pool el 1215 and 13,000-cfs discharge) with the type 4 design intake tower, the type 2 design connecting curve, and the type 7 design exit structure included in the final model design. In combination with the 9-ft-horseshoe tunnel, such operation of the 23-ft-diam tunnel will provide for the project's total authorized flood control release of 17,600 cfs.

Average pressures along a portion of the invert in the bell mouth entrance leading to gate 1 with the pool above el 1065 and full gate openings (11.5 ft) were sufficiently low to cause cavitation conditions in the prototype. Average pressures in this reach can be increased to 10 ft below the piezometer (the general limit for cavitation) by closing the gate approximately 1 percent. Invert pressures can be significantly improved by limiting the gate opening to 10.5 ft when pool elevations exceed 1065.

Simulations of theoretically computed sediment and debris blockages of the intake tower trashrack for the PDF and the SPF conditions indicate that, with pool elevations above 1125, the intake tower design can meet operational outflow requirements without exceeding the structural design criteria of a maximum 50-ft pressure differential between the outside and inside of the trashrack. Free-falling flow conditions are possible inside the trashrack for large gate openings and the pool lower than el 1110 and could result in greater than design pressure differentials across the trashrack. Monitoring of prototype pressure differentials and gate operations is recommended to avoid exceeding the design pressure differentials.

The 23-ft-diam tunnel will pass more than 20,000 cfs with gates 1 and 2 fully open (11.5 ft) at the 1215 pool elevation. However, such operations produce some undesirable, but not unacceptable, flow conditions in the tunnel downstream of the gates. At the 1215 pool elevation, the 23-ft-diam tunnel will pass the 13,000-cfs design flow with the gates open approximately 75 percent (approximately 8.6 ft) without the undesirable flow conditions. Approximately the maximum authorized release of 17,600 cfs can be released (16,900 cfs) through the 23-ft-diam tunnel with the gates open 10.5 ft

(91 percent) without undesirable flow conditions. This will allow some additional operational flexibility. Gate openings in excess of 10.5 ft should be used only in extreme conditions.

Vortex activity existed to some extent with all intake tower designs tested. Although vortex suppression devices tested in some of the intake tower designs showed some degree of effectiveness in reducing vortex strength, the inclusion of such devices within the Mud Mountain Dam inlet tower may cause maintenance and operational problems that could be more severe than potential vortex-induced problems. Such devices were not tested in the type 4 design intake tower because the vortex action was relatively weak and elimination of the central intake tower pier significantly complicated the design of such devices.

The model tests were conducted with clean water, which presents very little resistance to vortex formation. Confetti and surface foam tended to break up the vortex action indicating that the vortex was relatively weak. High flows at Mud Mountain Dam usually have high suspended sediment loads and a large quantity of floating woody debris, which are expected to inhibit vortex formation. The Seattle District's evaluation suggests that a relatively low frequency and short duration of prototype operation should exist at the conditions shown to present the most severe vortex action in the model. Accordingly, vortex action is not expected to be a major problem in the prototype of the type 4 design intake tower.

The water surface immediately downstream of gates 1 and 2 for the 23-ft-diam tunnel was somewhat unstable for full gate openings and pool elevations above 1050. The model was tested with walls 23 ft tall or taller downstream of the gates to the transition to the 23-ft-diam tunnel. For less than full gate openings, the flow surface was more stable with very rare surges to the maximum height shown in Plates 49 and 50. Generally, the maximum flow surface for these conditions was less than 18 ft above the floor along the outside walls. Accordingly, a roof height of 18 ft or more should provide acceptable flow conditions for less than full gate openings. For fully open gates, the 18-ft high roof should provide less than desirable but functional flow conditions without causing the tunnel to prime.

The type 2 design connecting curve and transition joining the new and existing portions of the 23-ft-diam tunnel is hydraulically superior to the original design horseshoe connecting curve. The type 2 connecting curve design allows the high-velocity flow of discharges in excess of 13,000 cfs to spiral around the perimeter of the tunnel with minimal flow disturbance. This design also eliminates approximately 60 ft of new tunnel construction with a significant reduction in construction costs. Open-channel flow is maintained throughout the 23-ft-diam tunnel for the range of Manning's n values tested (0.013-0.018). Maximum flow depths in the 23-ft-diam tunnel are approximately 12-13 ft with discharges approximately 20,000 cfs.

The type 7 exit structure directs the outflow toward the left center of the outlet channel sufficiently to meet the design objectives without backing flow into the outlet tunnel for the anticipated discharge-tailwater relationships. This design minimizes the excavation required to modify the existing outlet structure and does not require demolition of any of the existing tunnel resulting in cost savings over the original design presented in the design memorandums.

Table 1
Tunnel 1 Bottom Pressures Given By Hydraulic Grade Line, Original Design, Gate 1 Fully Open

Station	Piezometer El	Hydraulic Grade Line Elevations								
		Left Bottom Corner			Center Bottom			Right Bottom Corner		
		Pool El 1215	Pool El 1165	Pool El 1090	Pool El 1215	Pool El 1165	Pool El 1090	Pool El 1215	Pool El 1165	Pool El 1090
3+35.2	923.2	1193.2	1147.5	1078.6	1153.5	1114.5	1057.0	1183.0	1139.0	1072.8
3+35.4	923.4	1154.5	1116.5	1056.5	1098.0	1070.0	1025.0	1147.5	1110.5	1052.8
3+35.8	923.8	1115.0	1085.0	1035.0	1077.3	1051.5	1013.5	1109.0	1080.2	1031.0
3+36.9	924.3	1044.0	1025.5	995.5	1063.5	1040.2	1005.8	1045.3	1026.3	995.7
3+38.5	924.8	961.5	956.6	949.4	996.3	985.4	969.0	922.0	924.0	928.2
3+39.9	924.9	918.3	921.2	925.5	954.5	951.0	945.7	939.5	937.2	936.0
3+41.1	925.0	913.5	916.3	919.0	890.0	898.6	910.3	911.3	914.5	921.0
3+42.1	925.0	906.0	911.2	918.5	909.0	913.6	920.0	909.5	913.5	918.2
3+46.4	924.6	903.7	909.0	916.8	930.5	931.5	931.5	903.6	909.5	909.5
3+48.9	924.2	937.0	936.4	935.0	—	—	—	—	—	—
3+49.3	924.1	939.0	937.5	936.6	—	—	—	—	—	—
3+49.9	924.0	939.0	937.8	937.2	—	—	—	—	—	—
3+53.1	923.4	940.0	939.3	937.5	—	—	—	—	—	—

Note: Blanks indicate that no data were obtained.

Table 2
Tunnel 1 Top Pressures Given By Hydraulic Grade Line, Original Design, Gate 1 Fully Open

Station	Piezometer El	Hydraulic Grade Line Elevations								
		Left Top Corner			Center Top			Right Top Corner		
		Pool El 1215	Pool El 1165	Pool El 1090	Pool El 1215	Pool El 1165	Pool El 1090	Pool El 1215	Pool El 1165	Pool El 1090
3+35.2	941.9	1195.5	1152.5	1081.6	—	—	—	1189.0	1143.5	1075.0
3+35.4	941.6	1168.6	1130.0	1067.1	1152.5	1115.5	1055.5	1163.5	1125.5	1061.0
3+35.8	941.2	—	—	—	—	—	—	1144.4	1108.2	1050.0
3+36.9	940.3	1129.5	1097.0	1043.7	1129.5	1096.8	1042.5	1122.5	1090.5	1038.0
3+38.5	939.3	1081.5	1055.0	1014.8	1082.2	1057.5	1016.0	1053.5	1031.2	999.0
3+39.9	938.7	1046.5	1026.1	995.6	1058.5	1036.6	1003.2	1028.5	1011.0	985.5
3+41.1	938.3	1027.0	1009.2	984.7	1040.0	1020.5	991.7	1008.0	994.5	974.5
3+42.1	938.0	1016.0	1002.0	980.6	1027.8	1011.0	985.5	1015.5	1000.2	978.0
3+46.4	936.5	948.0	948.0	940.0	938.2	937.5	936.5	939.5	939.0	937.0
3+49.9	935.9	959.0	957.8	946.0	—	—	—	935.0	935.0	936.5
3+53.1	935.2	955.6	951.7	945.5	—	—	—	944.0	942.0	939.5

Note: Blanks indicate that no data were obtained.

Table 3
Tunnel 1 Center Pressures Given By Hydraulic Grade Line, Original Design, Gate 1 Fully Open

		Hydraulic Grade Line Elevations					
		Left Center			Right Center		
Station	Piezometer El	Pool El 1215	Pool El 1165	Pool El 1090	Pool El 1217.7	Pool El 1164.4	Pool El 1088.2
3+35.2	930.9	1168.0	1127.0	1069.2	1116.5	1079.5	1031.0
3+35.4	930.9	1140.0	1112.0	1050.0	1099.0	1067.0	1022.8
3+35.8	930.9	1116.0	1087.5	1034.0	—	—	—
3+36.9	930.9	1096.0	1069.0	1022.5	1075.0	1048.0	1010.5
3+38.5	930.9	1050.0	1032.0	1001.0	1049.0	1025.8	997.5
3+39.9	930.9	1016.0	998.0	978.5	—	—	—
3+41.1	930.9	998.0	986.0	970.0	1012.0	998.0	976.5
3+42.2	930.9	985.0	985.0	961.8	995.0	984.0	967.8
3+46.4	930.2	951.0	949.5	947.0	971.5	964.0	953.8
3+48.9	929.7	932.0	931.0	931.0	—	—	—
3+49.3	929.7	942.5	940.5	938.7	—	—	—
3+49.6	929.7	938.3	937.5	937.0	—	—	—
3+49.9	929.7	923.0	922.0	929.0	932.8	932.2	933.3
3+53.1	929.2	942.0	940.5	938.2	—	—	—

Note: Blanks indicate that no data were obtained.

Table 4
Tunnel 2 Pressures Given By Hydraulic Grade Line, Original Design, Gate 2 Fully Open

		Hydraulic Grade Line Elevations										Hydraulic Grade Line Elevations at Right Center		
		Left Top Corner			Center Top			Right Top Corner						
Station	Top Piezometer El	Pool El 1216.5	Pool El 1115.4	Pool El 992.6	Pool El 1216.5	Pool El 1115.4	Pool El 992.6	Pool El 1216.5	Pool El 1115.4	Pool El 992.6	Right Center Piezometer El	Pool El 1216.5	Pool El 1115.4	Pool El 992.6
3+35.1	925.3	1144.8	1069.0	969.5	1107.5	1045.5	961.8	1167.5	1084.0	980.7	915.8	1090.0	1030.0	960.8
3+35.2	924.7	1106.5	1044.0	966.0	1070.0	1020.5	955.0	1040.8	1067.0	974.0	915.8	1122.5	1050.0	961.5
3+35.4	924.3	—	—	—	1088.5	1031.0	957.4	1109.0	1046.0	967.2	915.8	1091.0	1032.0	961.5
3+35.8	924.0	1045.5	1002.0	950.0	1077.5	1018.0	953.3	1067.0	1017.0	956.0	915.8	1059.0	1011.0	954.0
3+36.9	923.3	944.2	936.5	928.0	1021.5	987.0	943.8	988.0	964.0	937.0	915.8	1008.0	978.0	942.0
3+38.5	922.6	927.5	925.5	922.0	986.5	954.5	939.0	935.5	930.0	926.0	915.8	—	—	—
3+39.9	922.2	—	—	—	943.5	933.5	928.0	932.9	928.5	925.2	915.8	984.0	963.0	936.0
3+42.1	921.8	944.0	935.5	926.0	937.5	935.5	925.8	942.2	935.0	925.7	915.8	972.8	954.0	933.0
3+46.6	921.5	—	—	—	—	—	—	961.6	947.5	932.0	915.8	964.0	949.0	931.5
3+56.5	921.5	—	—	—	—	—	—	967.7	951.0	930.0	915.8	958.0	946.0	930.0

Note: Blanks indicate that no data were obtained.

Table 5
Tunnel 3 Pressures Given By Hydraulic Grade Line, Original Design, Gate 3 Fully Open

Station	Top Piezometer El	Hydraulic Grade Line Elevations									Left Center Piezometer El	Hydraulic Grade Line Elevations at Left Center		
		Left Top Corner			Center Top			Right Top Corner						
		Pool El 1215	Pool El 1120	Pool El[1] 1215	Pool El 1215	Pool El 1120	Pool El[1] 1215	Pool El 1215	Pool El 1120	Pool El[1] 1215		Pool El 1215	Pool El 1120	Pool El[1] 1215
2+79.0	902.9	1204.2	1112.0	1205.5	1181.0	1096.0	1187.0	1203.5	1111.4	1207.2	—	—	—	—
2+79.2	902.7	1191.0	1102.5	1193.4	1173.5	1091.6	1180.0	1196.5	1106.5	1202.0	896.0	1183.5	1098.0	1181.0
2+79.6	902.3	1185.5	1098.6	1187.2	1172.0	1089.8	1175.1	1189.5	1102.0	1197.5	896.0	1183.2	1098.0	1181.6
2+80.6	901.7	1169.7	1088.0	1171.5	1171.7	1089.6	1174.4	—	—	—	896.0	1175.2	1093.2	1173.6
2+82.3	901.0	1154.8	1077.7	1156.0	1166.0	1086.0	1168.5	1162.0	1083.0	1164.5	896.0	1169.3	1089.0	1168.3
2+83.7	900.7	1146.5	1072.8	1148.6	1160.6	1082.4	1161.5	1152.2	1076.4	1152.2	896.0	1163.5	1085.2	1163.0
2+85.9	900.4	1151.3	1075.7	1151.7	—	—	—	1153.0	1076.6	1151.8	895.9	1161.3	1083.7	1161.2
2+90.3	900.3	1158.5	1081.0	1158.8	1159.5	1081.0	1159.3	1161.5	1082.7	1160.2	895.8	1162.4	1084.5	1162.2
3+00.3	900.1	—	—	—	1162.0	1083.0	1162.2	—	—	—	—	—	—	—

Note: Blanks indicate that no data were obtained.
[1] Gate 1 fully open also.

Table 6
Tunnel 1 Bottom Pressures Given By Hydraulic Grade Line, Original Design, Gate 1 Open 10.5 Ft

		Hydraulic Grade Line Elevation								
		Left Bottom Corner			Center Bottom			Right Bottom Corner		
Station	Piezom-eter El	Pool El 1215	Pool El 1165	Pool El 1090	Pool El 1215	Pool El 1165	Pool El 1090	Pool El 1215	Pool El 1165	Pool El 1090
3+35.2	923.2	1202.0	1154.5	1083.6	1176.5	1133.6	1069.2	1194.6	1149.0	1078.7
3+35.4	923.4	1177.2	1134.5	1069.0	1141.0	1104.5	1049.0	1172.0	1130.0	1066.6
3+35.8	923.8	1151.6	1113.5	1055.1	1127.0	1093.0	1041.0	1148.0	1111.5	1053.0
3+36.9	924.3	1106.0	1076.2	1030.3	1118.0	1085.6	1035.5	1108.5	1077.5	1030.7
3+38.5	924.8	1053.0	1032.7	1000.5	1075.5	1050.3	1012.3	1029.0	1012.2	986.5
3+39.9	924.9	1027.0	1010.7	985.2	1040.0	1021.0	992.5	1036.8	1018.5	988.5
3+41.1	925.0	1013.0	1000.0	976.6	1008.8	994.0	975.0	1021.2	1008.0	985.0
3+42.1	925.0	1021.8	1003.7	980.7	1016.0	1001.5	979.3	1020.5	1005.0	981.6
3+46.4	924.6	1014.6	1000.5	978.3	1022.8	1007.0	982.5	1013.8	999.5	978.0
3+48.9	924.2	1038.2	1018.5	990.5	—	—	—	—	—	—
3+49.3	924.1	1039.0	1020.0	991.5	—	—	—	—	—	—
3+49.9	924.0	991.0	981.5	960.5	—	—	—	—	—	—
3+53.1	923.4	1016.8	1002.5	980.0	—	—	—	—	—	—

Note: Blanks indicate that no data were obtained.

Table 7
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Fully Open, n = 0.018, Discharge 19,500 cfs, Pool El 1215

Piezometer No.	El above Floor ft	Pressure ft
1	0	10.5
2	0	24.0
3	5	23.5
4	10	20.6
5	15	14.1
6	20	9.4
7	25	6.8
8	0	27.0
9	0	38.1
10	5	33.7
11	10	30.5
12	5	35.2
13	10	29.6
14	5	36.1
15	10	26.9
16	5	33.7
17	0	7.2

Table 8
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Open 10.5 ft, n = 0.018, Discharge 16,900 cfs, Pool El 1215

Piezometer No.	El above Floor ft	Pressure ft
1	0	9.0
2	0	21.6
3	5	18.7
4	10	17.3
5	15	10.6
6	20	10.9
7	25	4.7
8	0	22.5
9	0	33.0
10	5	29.5
11	10	24.8
12	5	30.1
13	10	23.9
14	5	30.7
15	10	20.6
16	5	28.9
17	0	6.0

Table 9
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Equal Gate Openings, n = 0.018, Discharge 17,600 cfs, Pool El 1215

Piezometer No.	El above Floor ft	Pressure ft
1	0	9.3
2	0	21.9
3	5	19.6
4	10	17.6
5	15	11.1
6	20	7.6
7	25	5.3
8	0	22.8
9	0	33.0
10	5	29.2
11	10	24.8
12	5	30.4
13	10	24.5
14	5	31.0
15	10	20.9
16	5	28.3
17	0	6.6

Table 10
Piezometric Pressure, Feet Above Piezometer, Type 7 Exit Structure, Equal Gate Openings, n = 0.018, 23-Ft Tunnel Design Condition, Discharge 13,000 cfs, Pool El 1215

Piezometer No.	El above Floor ft	Pressure ft
1	0	7.5
2	0	18.3
3	5	16.9
4	10	14.3
5	15	6.9
6	20	4.6
7	25	3.2
8	0	18.6
9	0	27.9
10	5	24.4
11	10	19.1
12	5	25.0
13	10	15.5
14	5	23.5
15	10	10.4
16	5	19.6
17	0	5.7

Table 11
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Fully Open, n = 0.018, Discharge 16,365 cfs, Pool El 1125

Piezometer No.	El above Floor ft	Pressure ft
1	0	9.9
2	0	21.0
3	5	18.4
4	10	15.8
5	15	10.2
6	20	6.7
7	25	5.3
8	0	22.5
9	0	32.7
10	5	28.0
11	10	24.2
12	5	28.6
13	10	23.6
14	5	29.8
15	10	21.5
16	5	27.1
17	0	6.9

Table 12
Piezometric Pressure, Feet Above Piezometer, Type 7 Exit Structure, Both Gates Open 10.5 ft, n = 0.018, Discharge 14,000 cfs, Pool El 1125

Piezometer No.	El above Floor ft	Pressure ft
1	0	7.8
2	0	17.4
3	5	16.0
4	10	12.8
5	15	7.5
6	20	5.2
7	25	4.1
8	0	22.5
9	0	27.6
10	5	23.8
11	10	19.1
12	5	24.4
13	10	21.0
14	5	25.6
15	10	15.8
16	5	23.2
17	0	6.9

Table 13
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Fully Open, n = 0.018, Discharge 14,265 cfs, Pool El 1075

Piezometer No.	El above Floor ft	Pressure ft
1	0	8.4
2	0	18.6
3	5	16.3
4	10	13.7
5	15	8.7
6	20	5.8
7	25	4.7
8	0	20.4
9	0	28.8
10	5	24.1
11	10	20.9
12	5	25.9
13	10	20.3
14	5	25.9
15	10	17.6
16	5	22.9
17	0	7.2

Table 14
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Fully Open, n = 0.018, Discharge 8,900 cfs, Pool El 980

Piezometer No.	El above Floor ft	Pressure ft
1	0	7.5
2	0	13.5
3	5	10.3
4	10	7.1
5	15	3.9
6	20	0.0
7	25	0.0
8	0	14.4
9	0	18.0
10	5	13.6
11	10	9.2
12	5	13.6
13	10	8.3
14	5	13.6
15	10	6.5
16	5	12.1
17	0	6.0

Table 15
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Fully Open, n = 0.018, Discharge 6,300 cfs, Pool El 950

Piezometer No.	El above Floor ft	Pressure ft
1	0	6.0
2	0	10.2
3	5	7.0
4	10	4.7
5	15	1.8
6	20	0.0
7	25	0.0
8	0	10.8
9	0	13.8
10	5	9.7
11	10	5.6
12	5	9.4
13	10	4.1
14	5	8.5
15	10	2.0
16	5	6.7
17	0	5.4

Table 16
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Fully Open, n = 0.018, Discharge 2,170 cfs, Pool El 925

Piezometer No.	El above Floor ft	Pressure ft
1	0	3.6
2	0	4.8
3	5	0.0
4	10	0.0
5	15	0.0
6	20	0.0
7	25	0.0
8	0	4.8
9	0	5.4
10	5	0.0
11	10	0.0
12	5	0.0
13	10	0.0
14	5	0.0
15	10	0.0
16	5	0.0
17	0	3.0

Table 17
Vortex Formation, No Baffles in Intake, Both 23-ft Tunnel Gates Fully Open, Original Design Outlet Tower

Pool El	Result
1022	Rotational circulation patterns began to set up. Small surface dimples and infrequent vortices of short duration form. Small pieces of trash noted being pulled toward gates in spiraling manner.
1020-1018	Clockwise circulation pattern sets up over gate 2. Core vortices form and dissipate over both gates, with strongest over gate 2. No noticeable entrainment of air from surface to gate.
1017-1010	Vortices strengthen with some air being pulled below surface. Circulation pattern is clockwise over gate 2, counterclockwise over gate 1.
1008-996	Air-entraining vortices form over each gate, with strongest and most continuous over gate 2. Some air pulled from surface to gate.
995-985	Very strong air-entraining vortices nearly continual over each gate. Strongest vortices form in this range of pools.
984-970	Vortices of varying size and duration continue to form and dissipate.
969-950	Numerous small cores form and dissipate. Some air entrained by occasional larger vortices, which form and dissipate fairly rapidly.

Table 18
Tower Vortex Formation with Type 4 Baffle in Place, Both 23-ft Tunnel Gates Fully Open, Original Design Outlet

Pool El	Result
1022-1019	Small cores rapidly form and dissipate with small amounts of air pulled below the surface.
1018-994	Air-entraining vortices form and dissipate over both gates, with strongest over gate 2. When tail of vortex crosses baffle, it is momentarily broken up.
993-987	Continuous vortices form over each gate, but with less entrainment of air.
986-984	Formation of small vortices with some air pulled below the surface.
983-960	Formation of some surface dimples and small cores.

Note: With the type 4 baffle in place, the size of vortex core formation is reduced, and the duration of air entrainment is shortened. The range of pool elevations at which larger vortices occur is somewhat reduced.

Table 19
Vortex Formation, No Baffles in Intake, 23-ft Tunnel, Gates 1 and 2 Fully Open, Type 2 Outlet Tower

Pool Elevation	Result
1022	Rotational circulation pattern begins to set up. Small vortices form and dissipate.
1020	Vortex size and duration increase slightly. Vortex moves across downstream side of outlet tower. Some periods when no vortex is visible.
1018	A counterclockwise vortex forms over gate 2. Swirls and surface dimples in left side of tower (looking downstream).
1017-1010	Two vortices form over gate 2 occasionally entraining air. Length of duration varies for both.
1008-996	Vortices on the downstream side of tower entrain air. Vortices are not continuous, but reform quickly after dissipating.
995-985	An air-entraining vortex forms in the downstream side of the tower and is nearly continuous, with most air entrained through gate 2. Occasional formation of two vortices at the same time. When vortices collide, they dissipate, but quickly reform.
984-980	Air-entraining vortices form over each gate. Duration is not long, but vortices quickly reform after breaking up.
979-970	Surface velocity increases in the outlet tower. Vortices are smaller, but continue to form and dissipate.
970-960	Surface dimples and small vortices of short duration form. At pool el 960, swirls and dimples form around piers on both sides of upstream trash racks.

Note: Vortex formation in the type 2 outlet tower is somewhat reduced in that vortices are not as large or continuous as in the type 1 outlet tower.

Table 20
Vortex Beams and Vanes, Type 7 Baffle, Type 3 Outlet Tower, 23-ft Tunnel, 9-ft Tunnel Gate Closed

Pool El	Result
Gates 1 and 2 Fully Open	
1020	No vortices. Occasional surface swirls. Water surface relatively calm.
1016	Same
1012	Occasional small vortices attempt to form on surface, dissipate rapidly.
1005	Same
1000-996	Numerous small-core vortices form over center line of tower. Some air bubbles and trash noted pulled below surface. Vortices are not strong and duration is short.
	Same type of vortices attempts to form over gate 1 also.
985-975	Surface swirls, no core vortices. Swirls form off the center support of structure.
Gates 1, 2, and 3 Fully Open	
985	Vortex forms over gate 3, some air entrained. Duration is generally short.
990	Vortices form between gates 1 and 2, but dissipate fairly rapidly.
1000	Small vortices form and quickly break up.

Table 21
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Fully Open, n = 0.013, Discharge 21,500 cfs, Pool El 1215

Piezometer No.	El above Floor ft	Pressure ft
1	0	25.5
2	0	30.0
3	5	26.5
4	10	20.0
5	15	15.0
6	20	11.5
7	25	2.0
8	0	39.9
9	0	40.5
10	5	35.5
11	10	32.0
12	5	37.0
13	10	33.5
14	5	34.0
15	10	30.5
16	5	4.6
17	0	9.6

Table 22
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Open 10.5 ft, n = 0.013, Discharge 16,900 cfs, Pool El 1215

Piezometer No.	El above Floor ft	Pressure ft
1	0	21.0
2	0	24.0
3	5	22.6
4	10	16.1
5	15	12.0
6	20	10.0
7	25	0
8	0	34.5
9	0	34.5
10	5	31.0
11	10	50.0
12	5	29.5
13	10	27.5
14	5	28.0
15	10	26.0
16	5	1.9
17	0	6.9

Table 23
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Equal Gate Openings, n = 0.013, Discharge 17,600 cfs, Pool El 1215

Piezometer No.	El above Floor ft	Pressure ft
1	0	21.6
2	0	25.5
3	5	22.6
4	10	16.4
5	15	12.6
6	20	11.2
7	25	0
8	0	34.5
9	0	34.5
10	5	30.4
11	10	26.0
12	5	30.4
13	10	27.5
14	5	28.0
15	10	26.0
16	5	2.5
17	0	7.5

Table 24
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Open, n = 0.013, 23-ft Tunnel Design Condition, Discharge 13,000 cfs, Pool El 1215

Piezometer No.	El above Floor ft	Pressure ft
1	0	18.0
2	0	21.6
3	5	19.0
4	10	12.5
5	15	9.6
6	20	7.6
7	25	0
8	0	28.5
9	0	28.8
10	5	24.4
11	10	19.1
12	5	21.1
13	10	18.5
14	5	16.6
15	10	16.6
16	5	1.6
17	0	6.6

Table 25
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Fully Open, n = 0.013, Discharge 15,500 cfs, Pool El 1075

Piezometer No.	El above Floor ft	Pressure ft
1	0	18.3
2	0	22.5
3	5	19.6
4	10	13.4
5	15	10.5
6	20	1.9
7	25	0
8	0	30.0
9	0	30.6
10	5	26.5
11	10	22.1
12	5	26.5
13	10	21.5
14	5	22.0
15	10	17.9
16	5	4.0
17	0	9.0

Table 26
Piezometric Pressure, Feet above Piezometer, Type 7 Exit Structure, Both Gates Fully Open, n = 0.013, Discharge 8,900 cfs, Pool El 980

Piezometer No.	El above Floor ft	Pressure ft
1	0	12.6
2	0	14.4
3	5	11.5
4	10	8.9
5	15	7.5
6	20	0
7	25	0
8	0	18.0
9	0	18.6
10	5	14.5
11	10	9.2
12	5	14.5
13	10	9.8
14	5	13.0
15	10	9.5
16	5	1.0
17	0	6.0

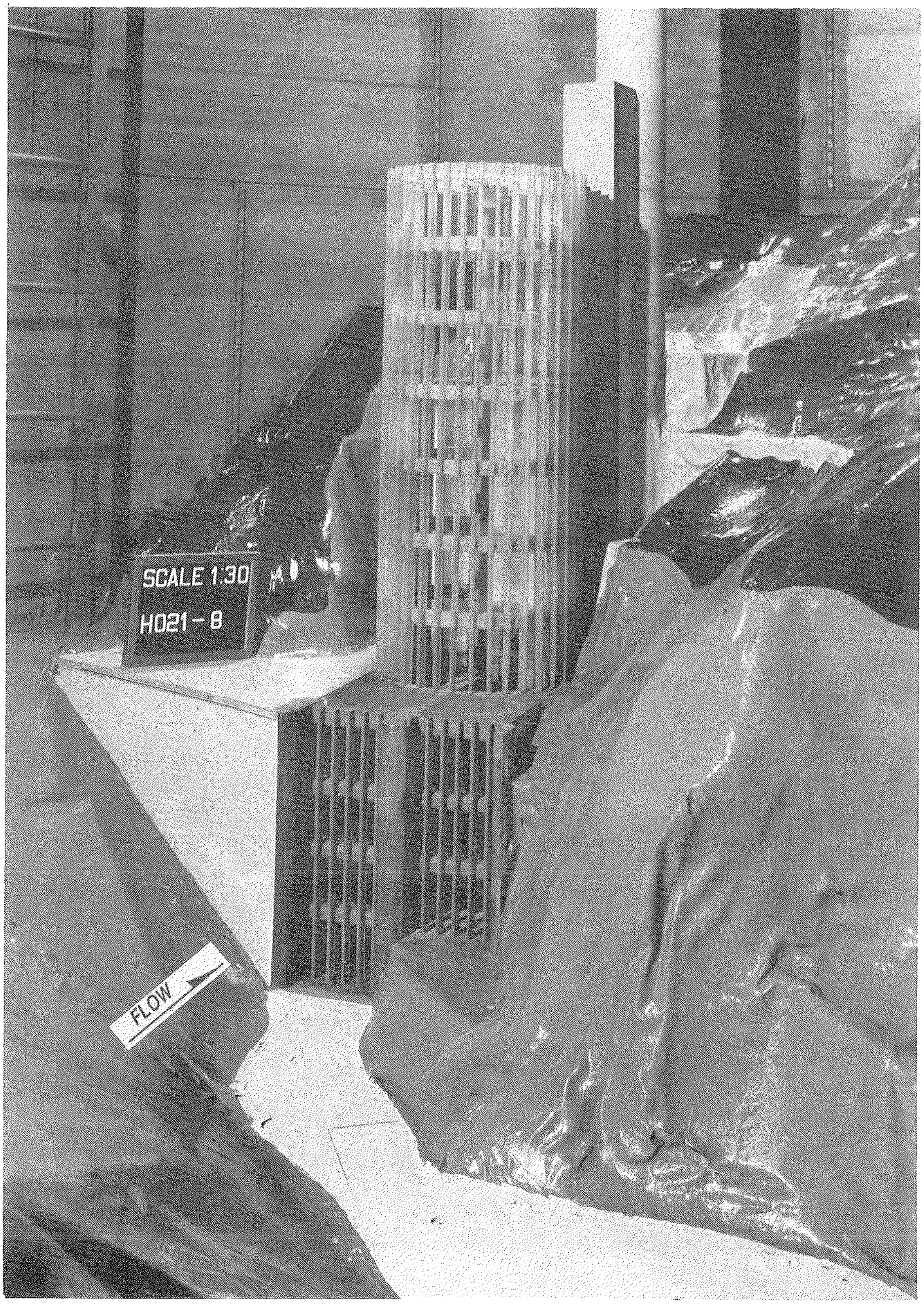


Photo 1. Original design outlet tower and near field topography

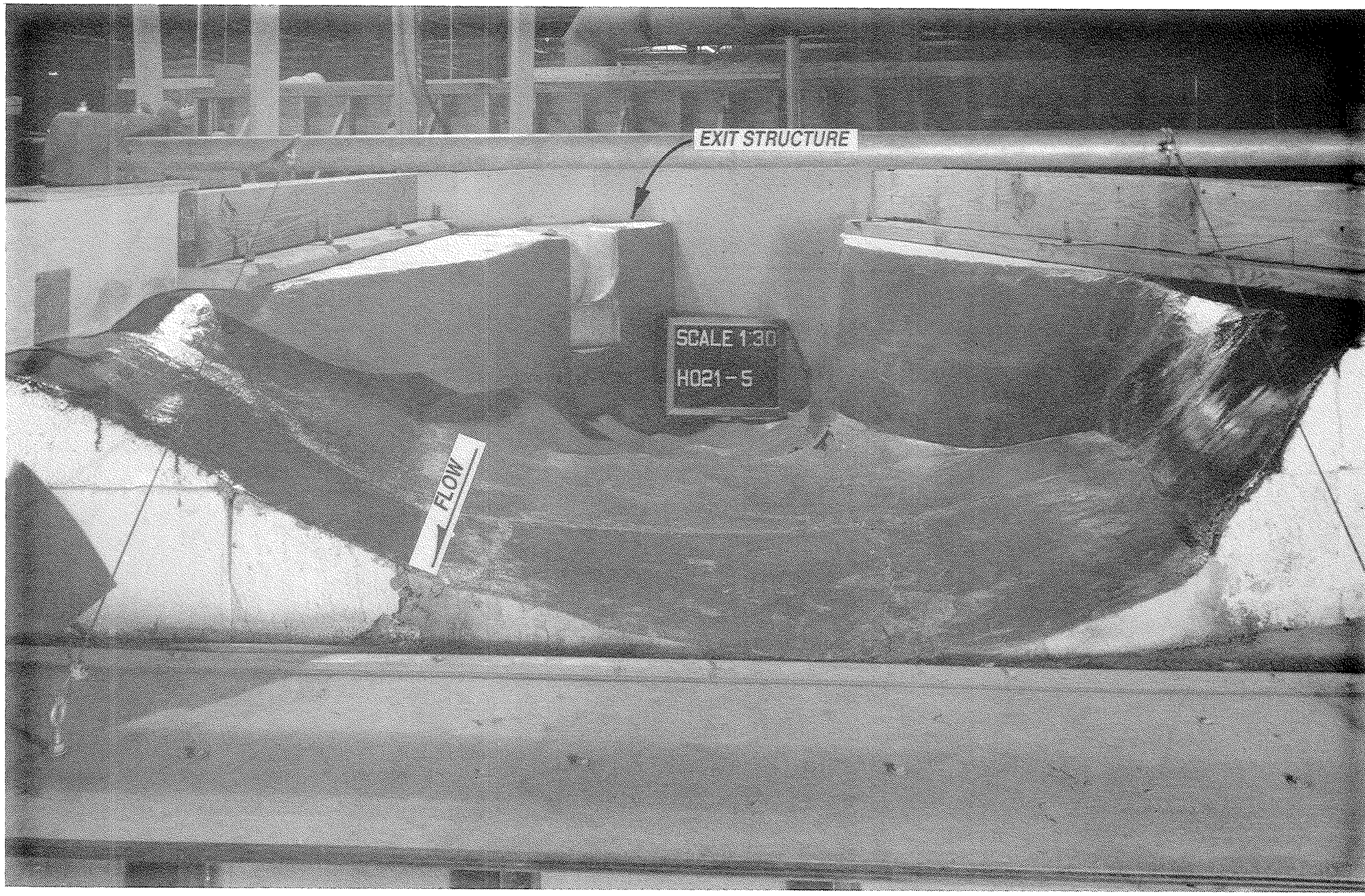


Photo 2. Original design exit structure and exit channel, looking upstream

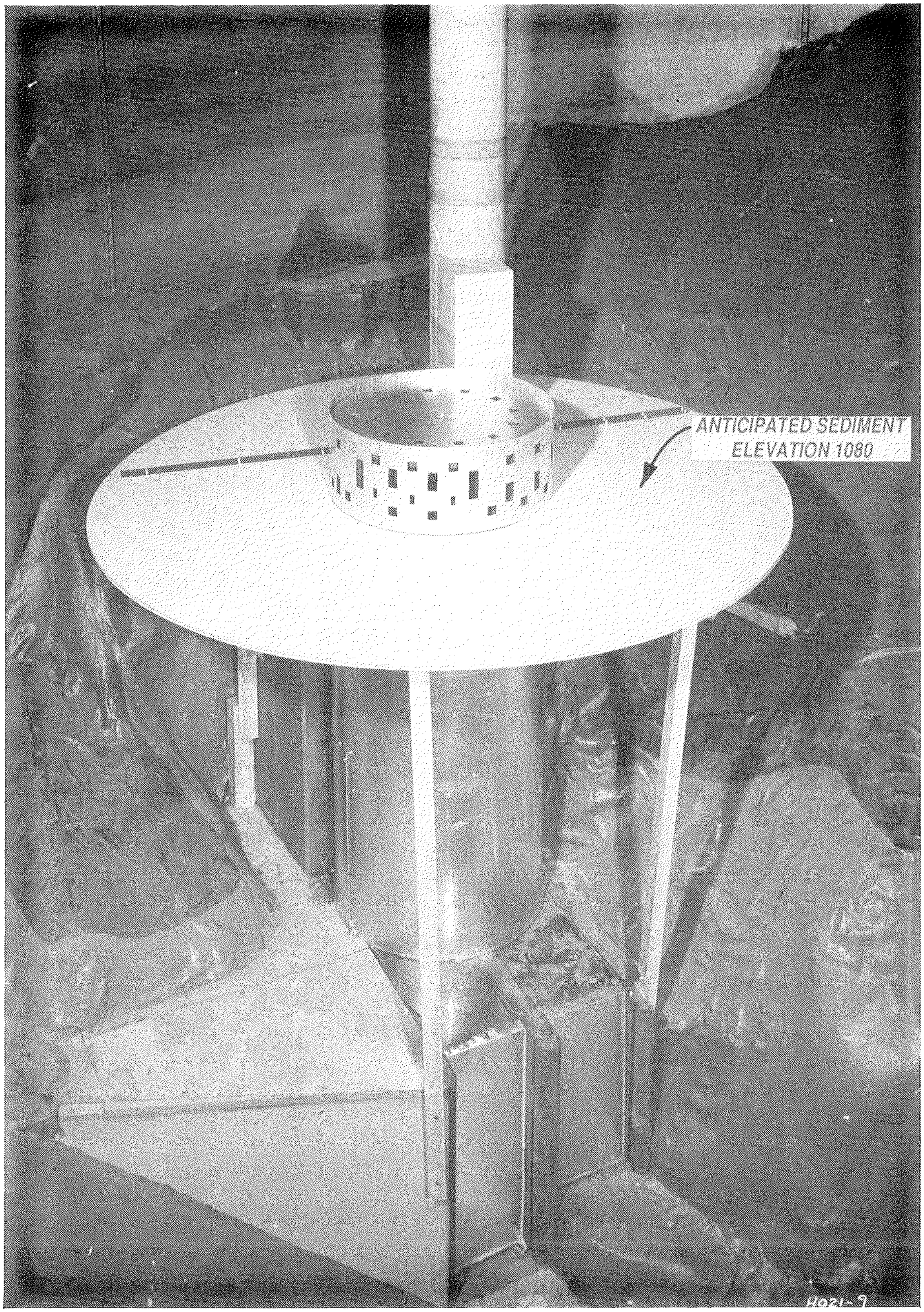


Photo 3. SPF condition simulation, original design

Photo 4. Flow at pool el 1110 and SPF trashrack blockage conditions, original design, discharge 9,700 cfs

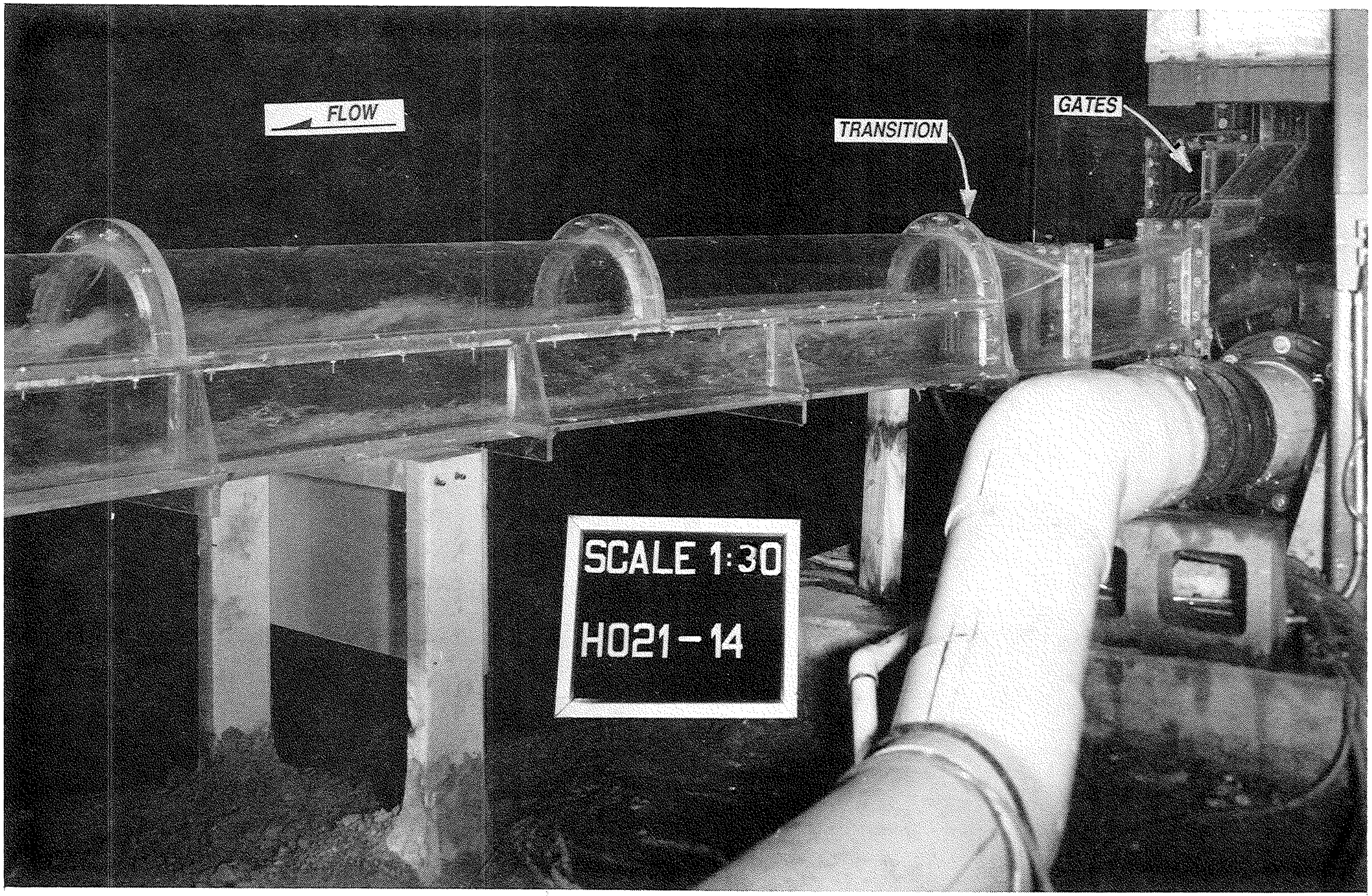


Photo 5. Flow through fully open gate 2 at pool el 1215, original design, discharge 10,200 cfs, sta 3+65 to sta 5+00

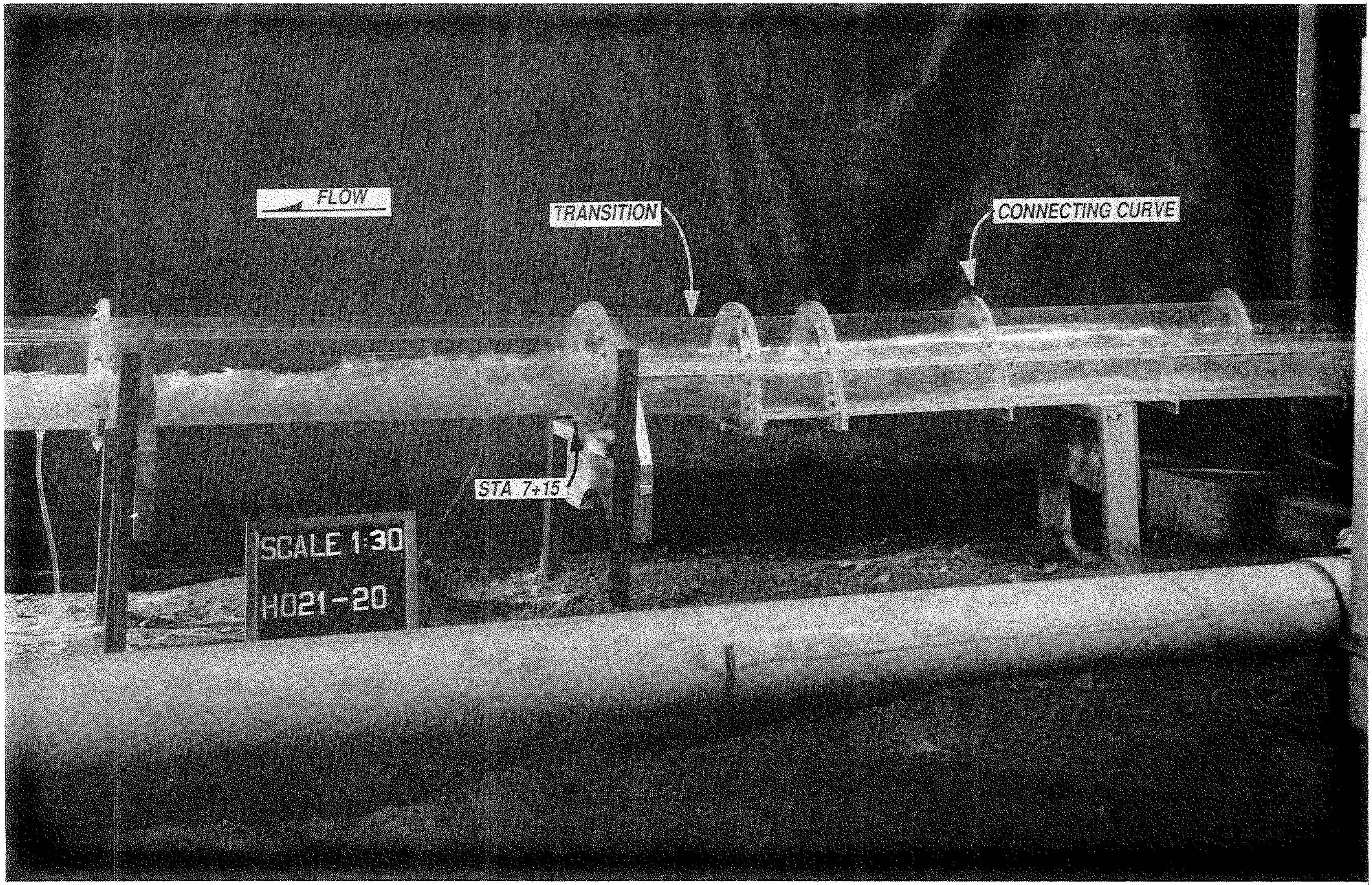


Photo 6. Flow through fully open gate 2 at pool el 1215, original design, discharge 10,200 cfs, sta 5+00 to sta 8+50

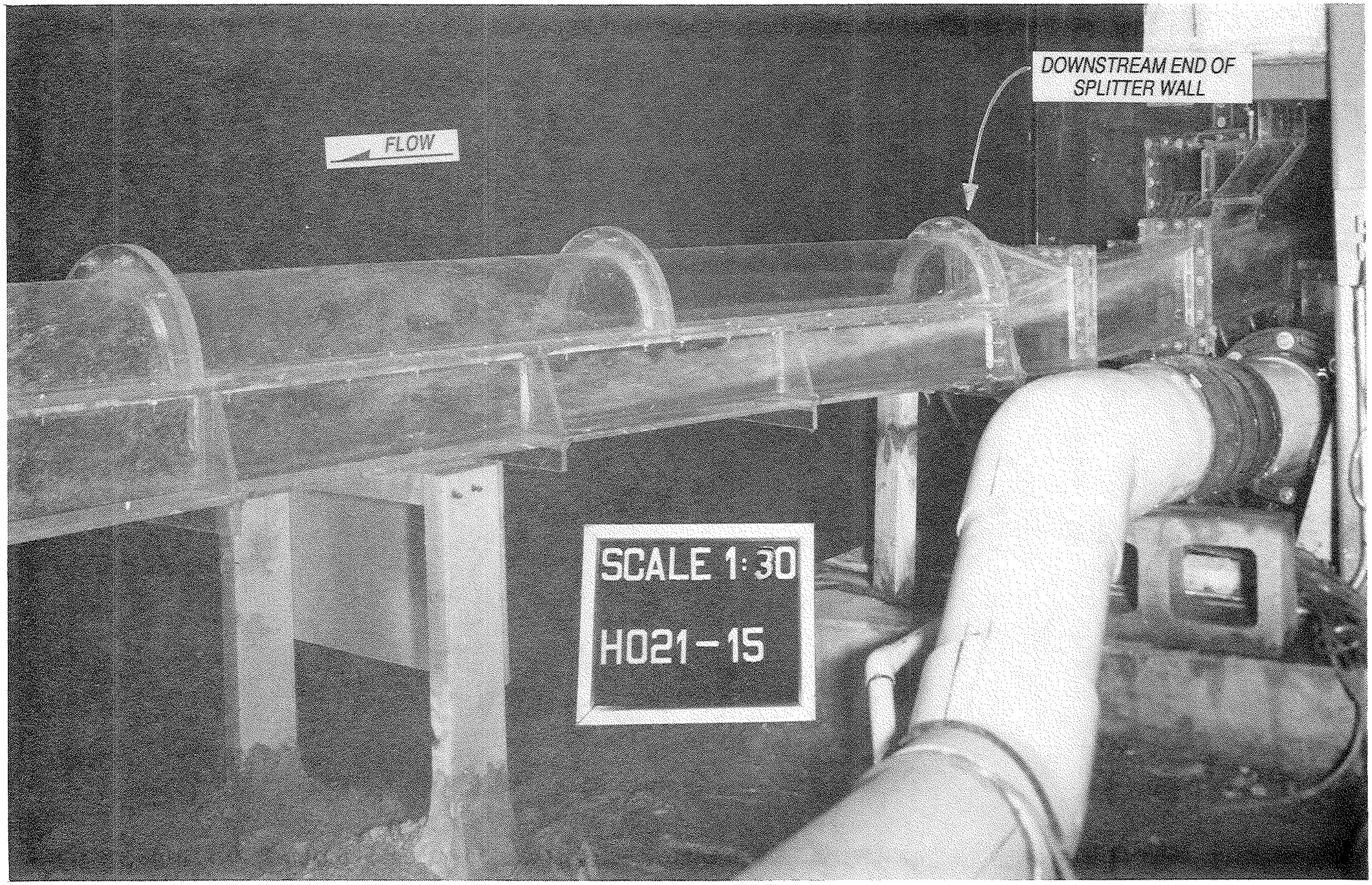


Photo 7. Flow through fully open gate 1 at pool el 1215, original design, discharge 10,400 cfs, sta 3+65 to sta 5+00

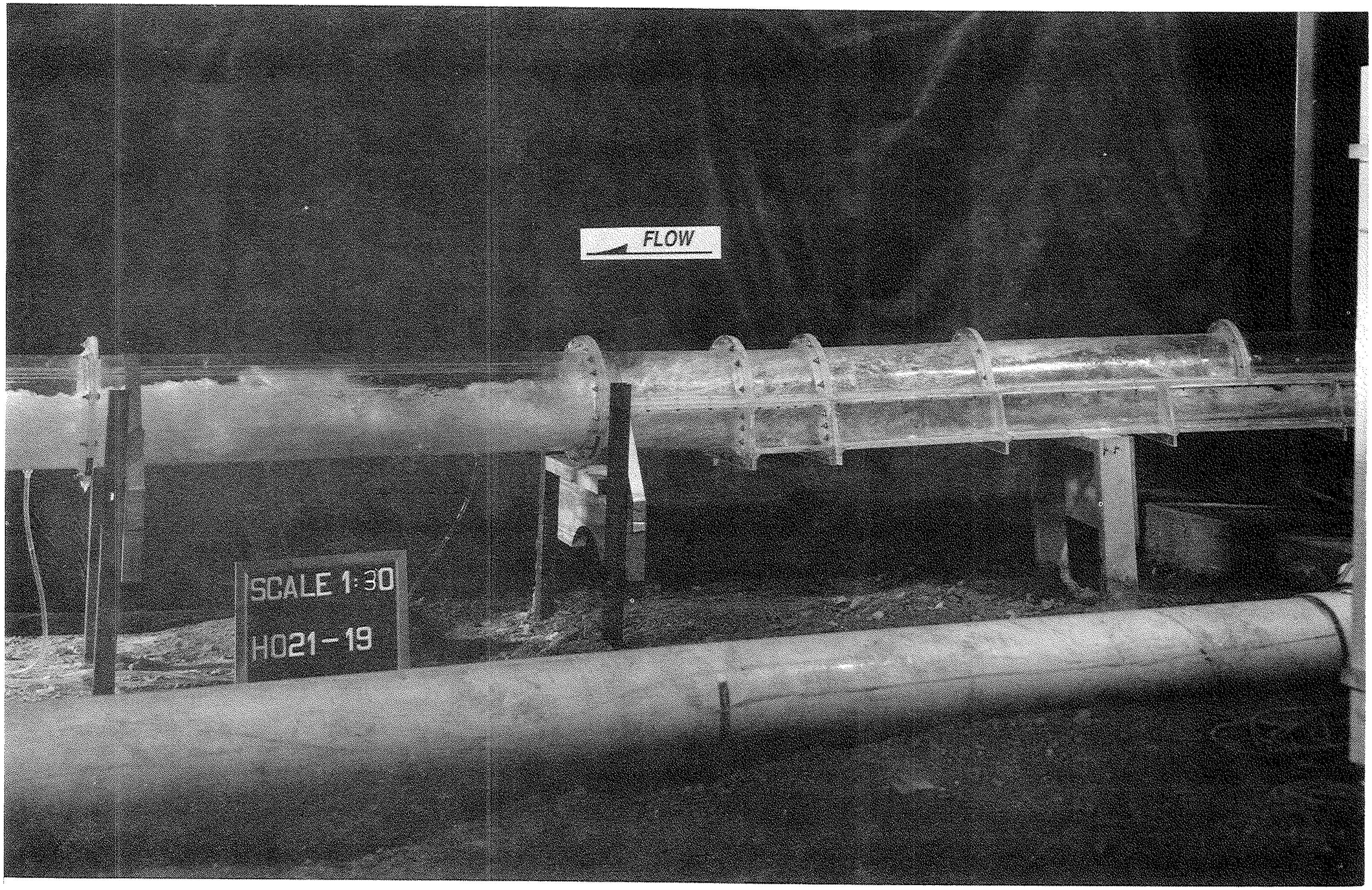


Photo 8. Flow through fully open gate 1 at pool el 1215, original design, discharge 10,400 cfs, sta 5+00 to sta 8+50

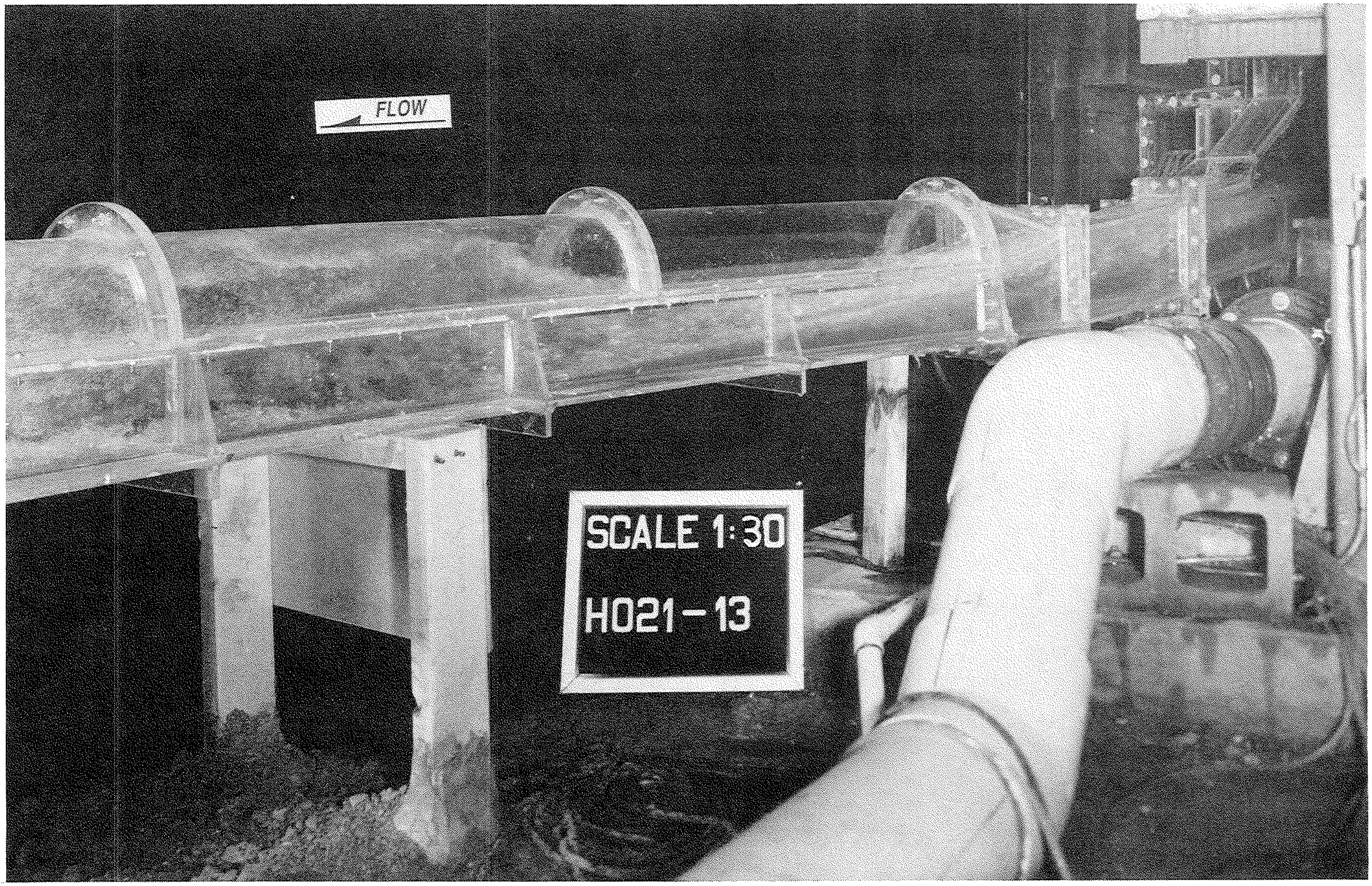


Photo 9. Flow with both gates fully open, pool el 1215, original design, discharge 19,500 cfs, sta 3+65 to sta 5+00

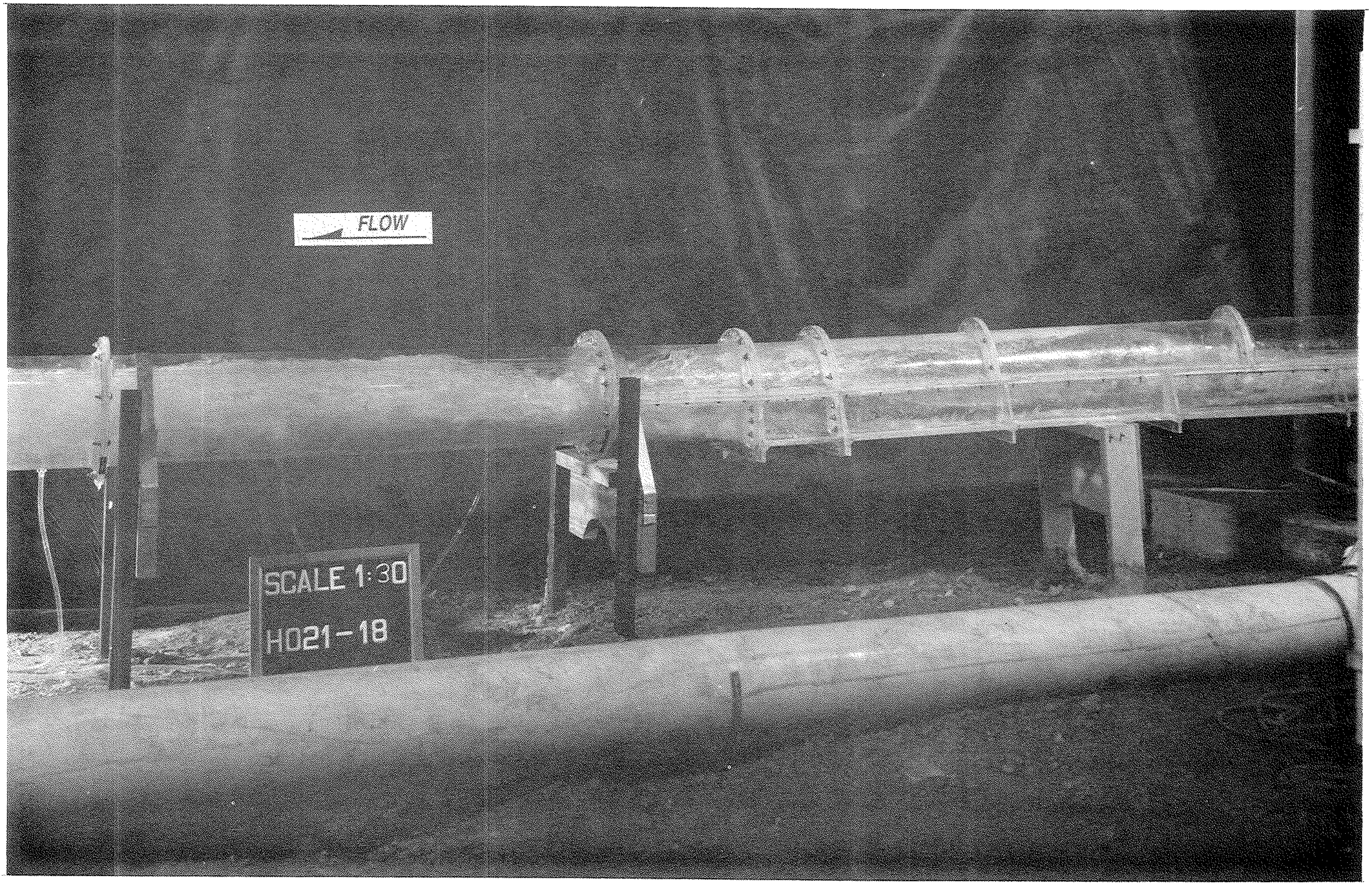


Photo 10. Flow with both gates fully open, pool el 1215, original design, discharge 19,500 cfs, sta 5+00 to sta 8+50

Photo 11. Exit flow conditions for original design with both gates fully open, pool el 1215, prototype tailwater not simulated, n = 0.018, discharge 19,500 cfs

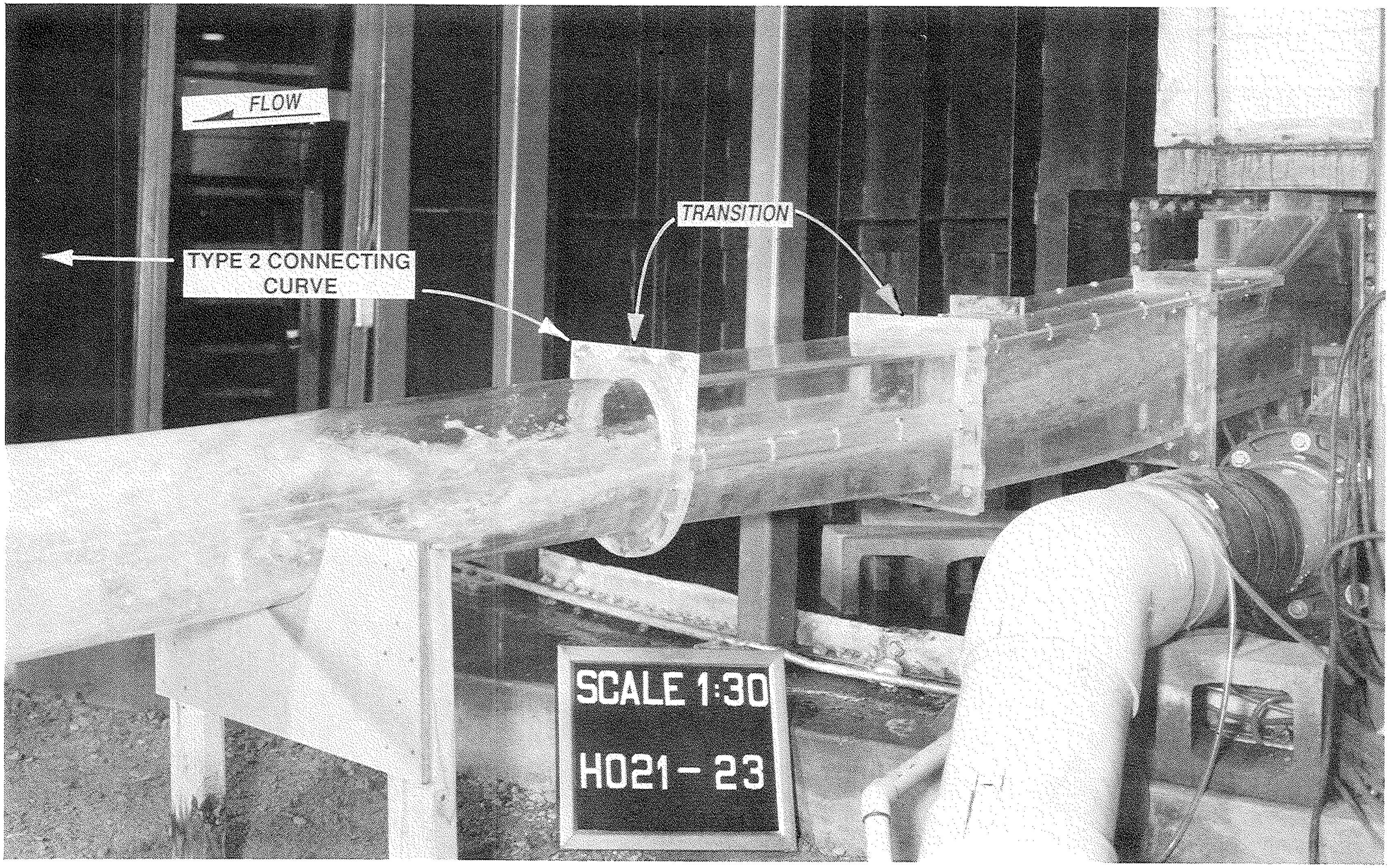


Photo 12. Maximum discharge condition, flow through fully open gates at pool el 1215, type 2 design connecting curve, discharge 19,500 cfs, sta 3+65 to sta 5+00

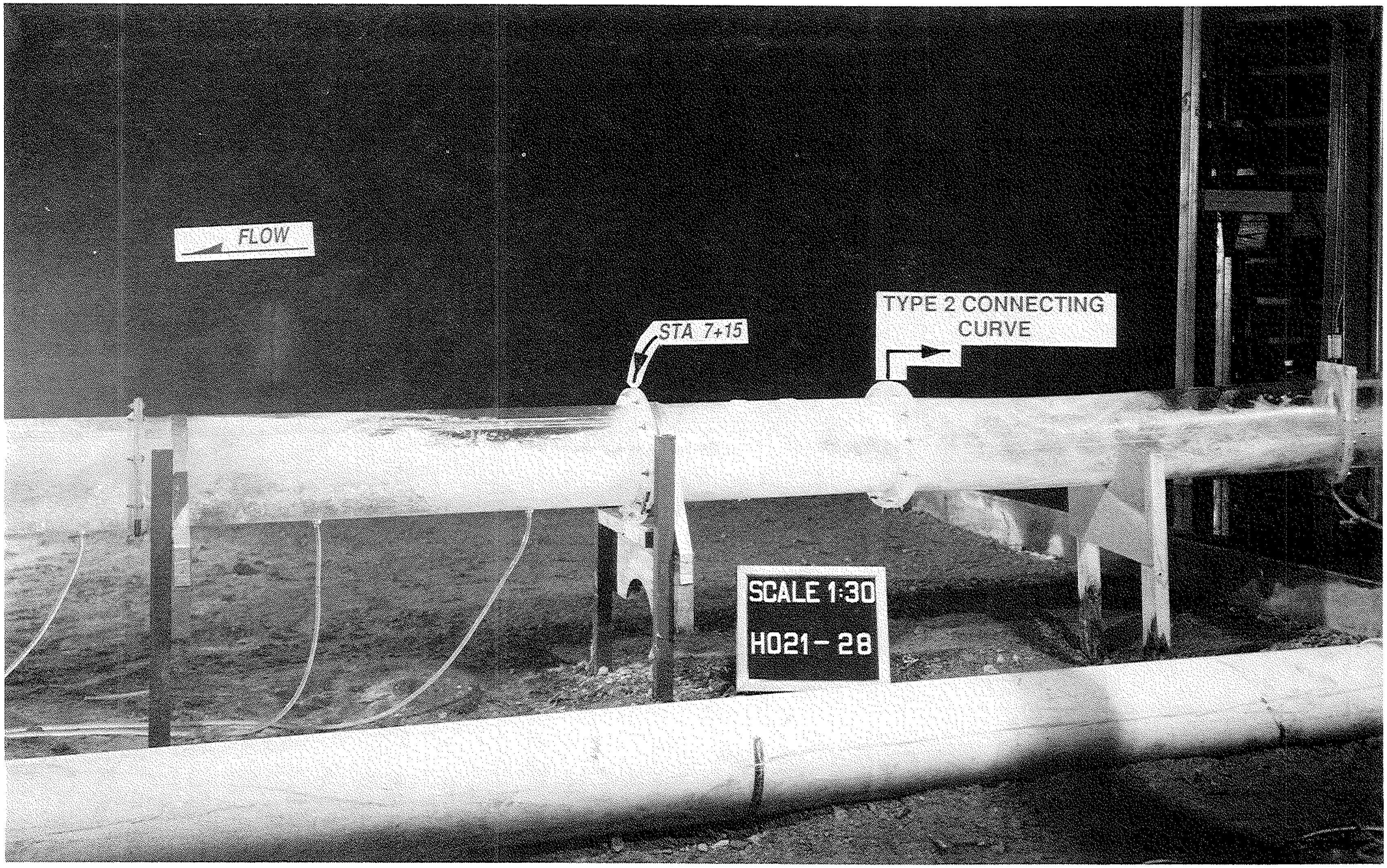


Photo 13. Maximum discharge condition, flow through fully open gates at pool el 1215, type 2 design connecting curve, discharge 19,500 cfs, sta 5+00 to sta 8+50

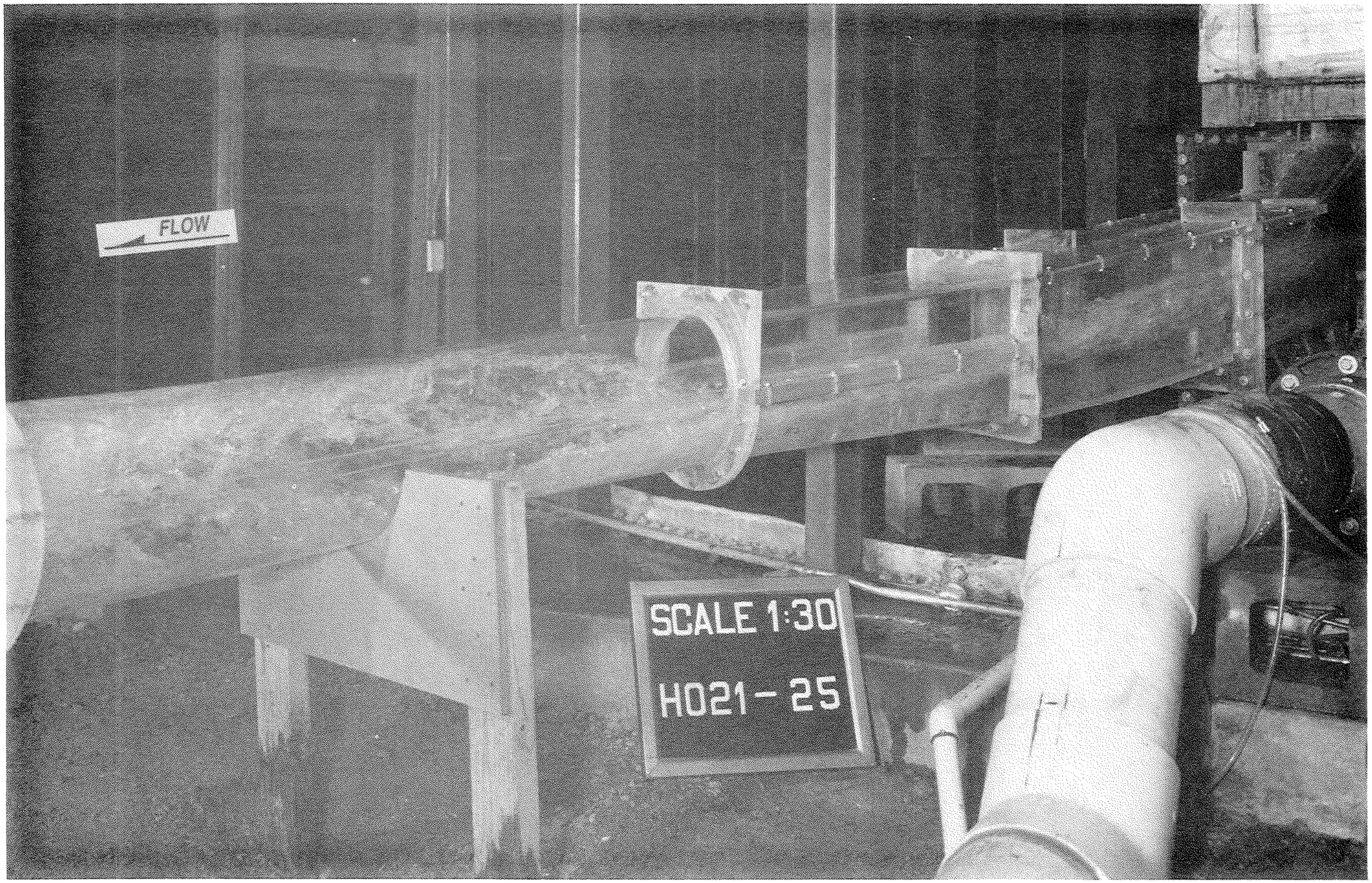


Photo 14. Flow through fully open gate 1 at pool el 1215, type 2 connecting curve, discharge 10,400 cfs, sta 3+65 to sta 5+00

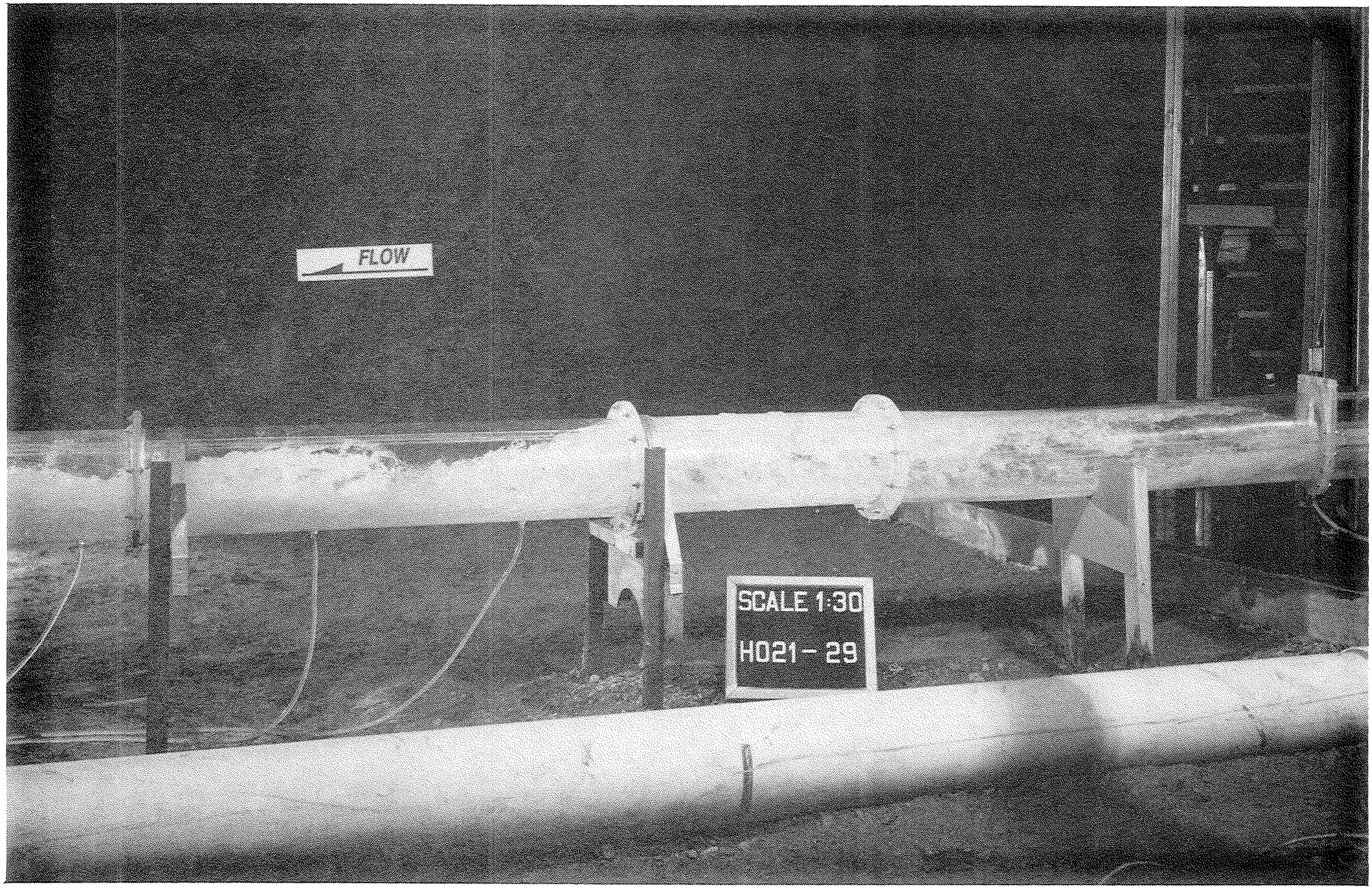


Photo 15. Flow through fully open gate 1 at pool el 1215, type 2 connecting curve, discharge 10,400 cfs, sta 5+00 to 8+50

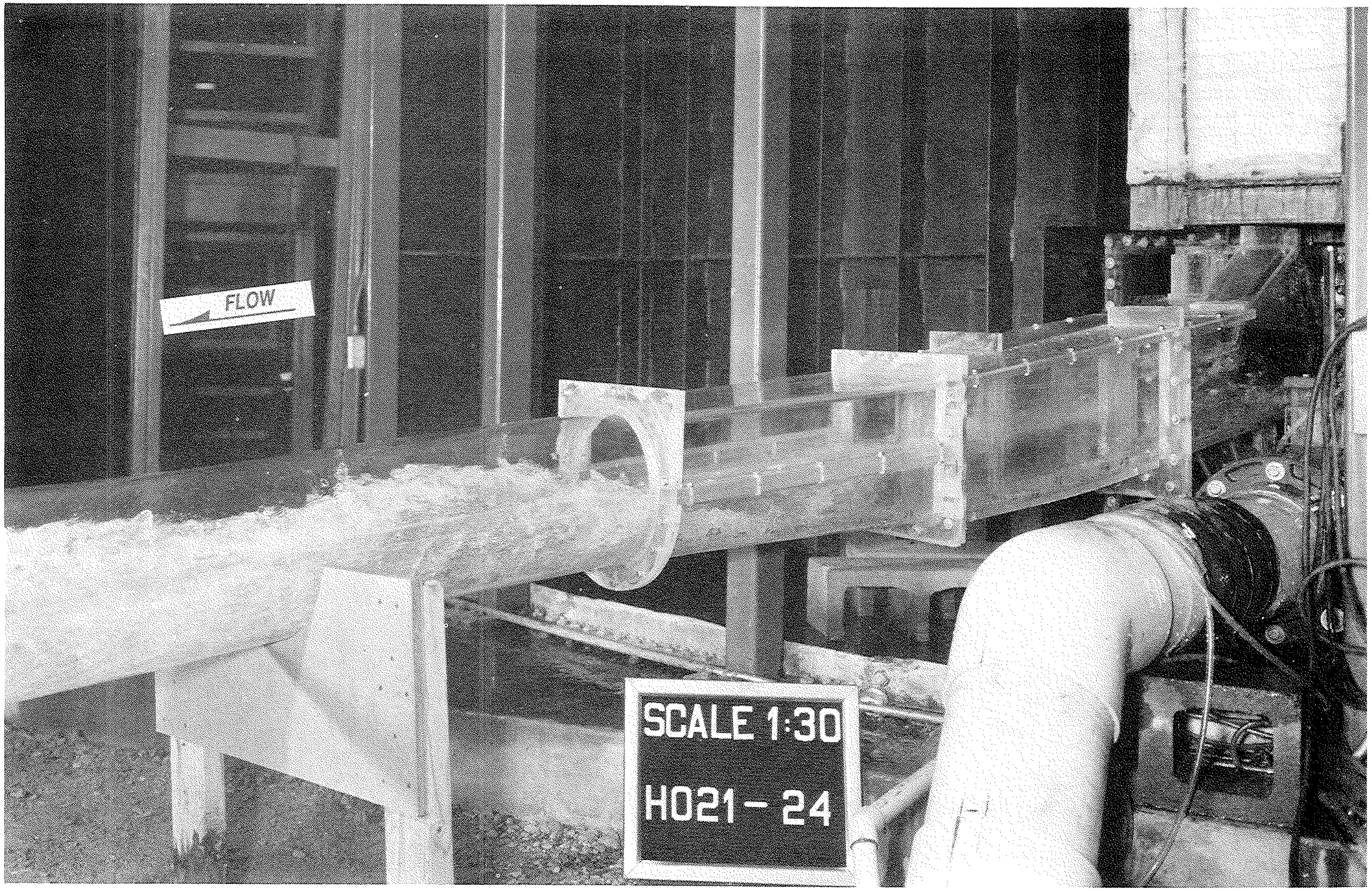


Photo 16. Flow through fully open gate 2 at pool el 1215, type 2 connecting curve, discharge 10,200 cfs, sta 3+65 to sta 5+00

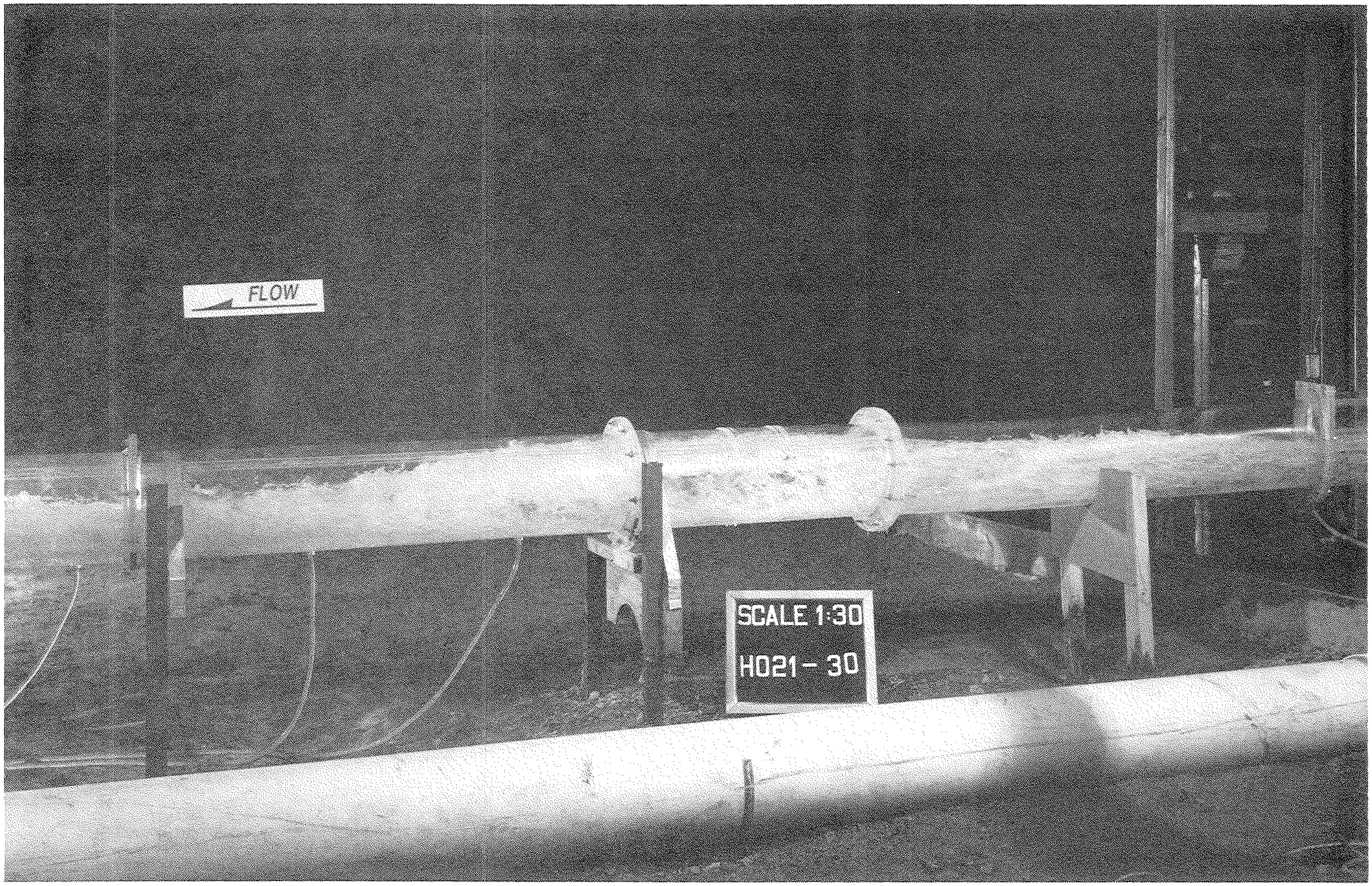


Photo 17. Flow through fully open gate 2 at pool el 1215, type 2 connecting curve, discharge 10,200 cfs, sta 5+00 to sta 8+50

Photo 18. Design condition, 13,000-cfs flow through equal gate openings at pool el 1215, type 2 connecting curve, sta 3+65 to sta 5+00

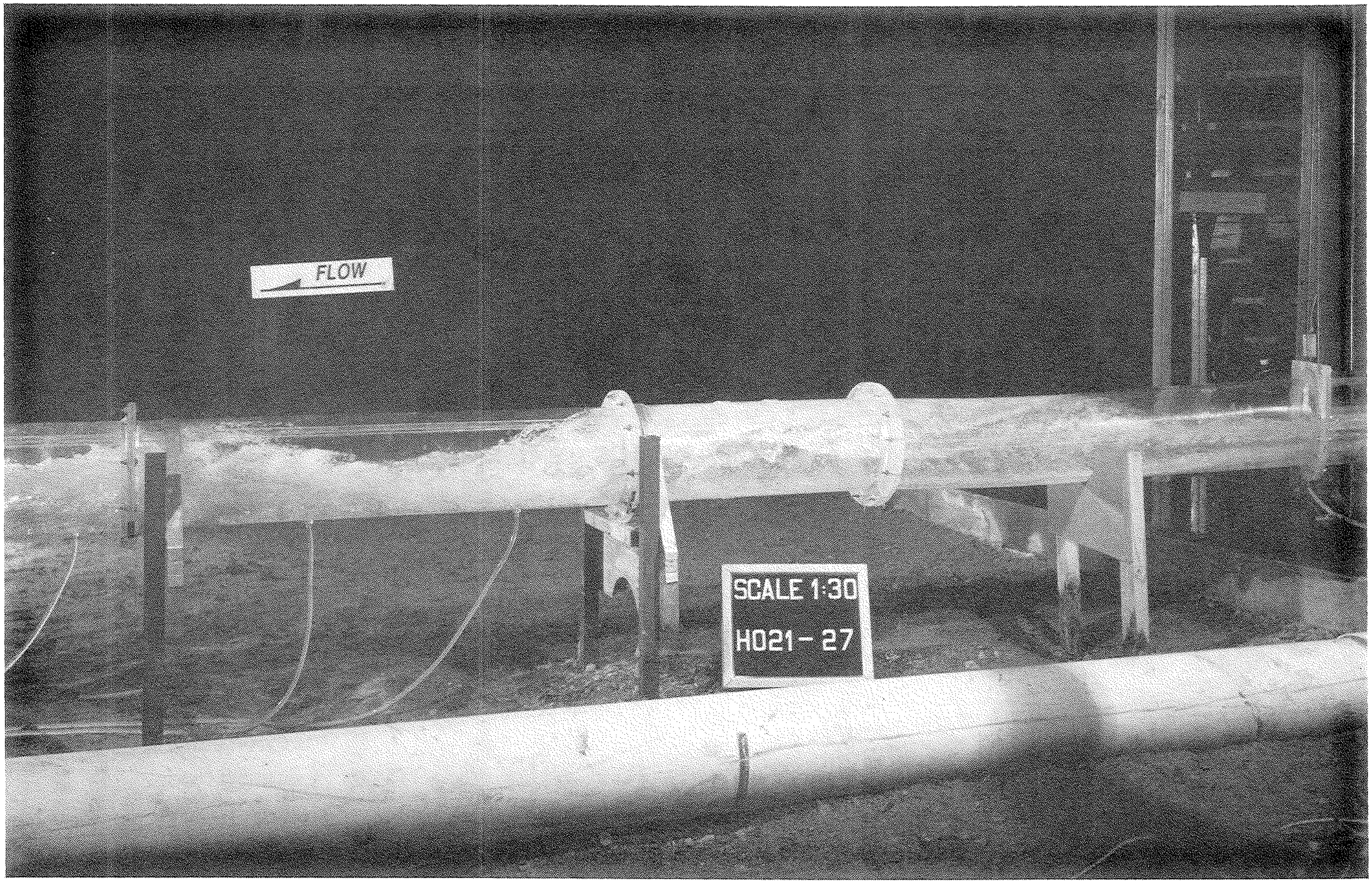


Photo 19. Design condition, 13,000-cfs flow through equal gate openings at pool el 1215, type 2 connecting curve, sta 5+00 to sta 8+50

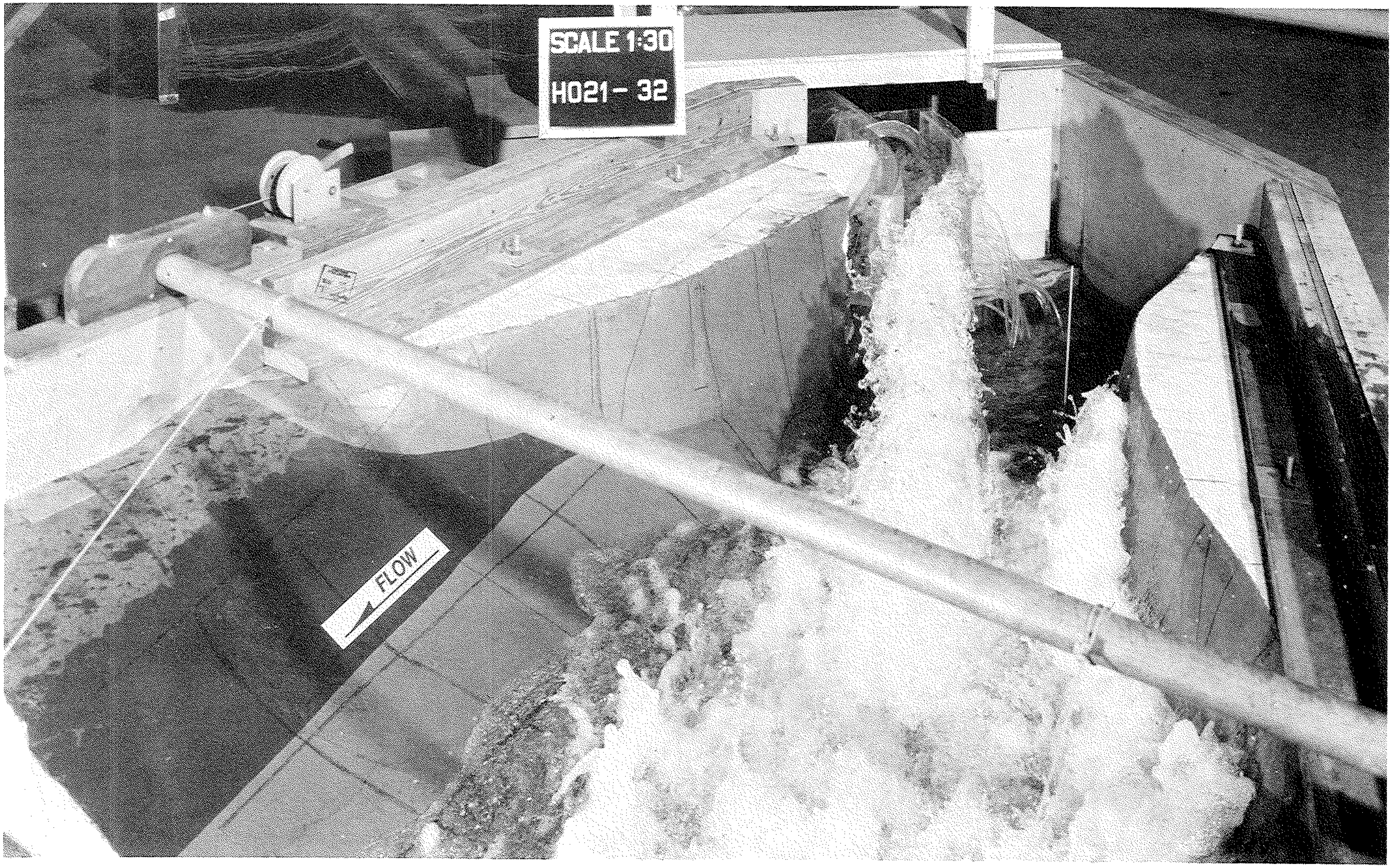


Photo 20. Maximum discharge condition, flow through fully open gates at pool el 1215, type 7 exit structure, prototoype tailwater not simulated, n = 0.018, discharge 19,500 cfs, looking upstream

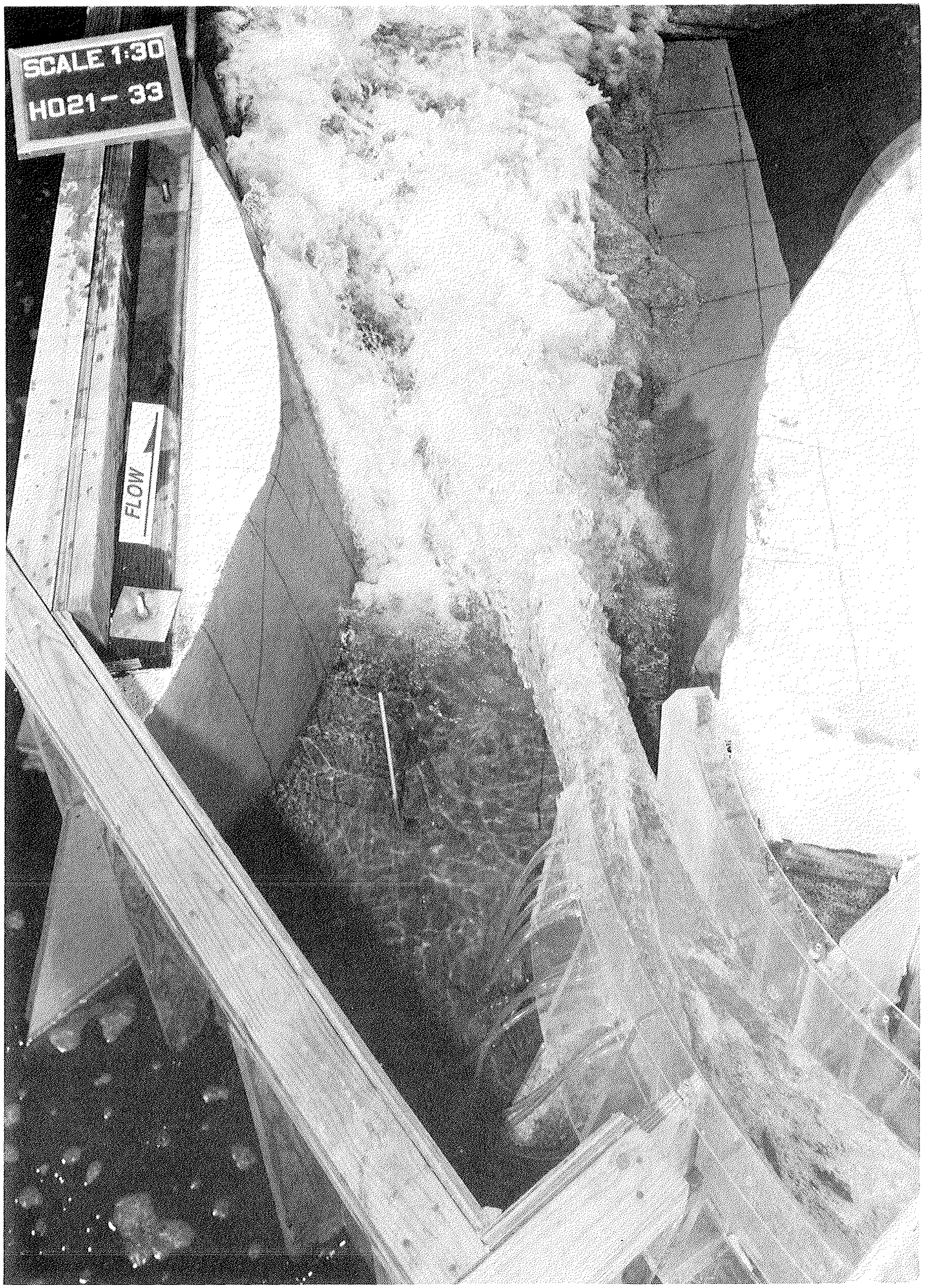


Photo 21. Maximum discharge condition, flow through fully open gates at pool el 1215, type 7 exit structure, prototype tailwater not simulated, n = 0.018, discharge 19,500 cfs, looking downstream

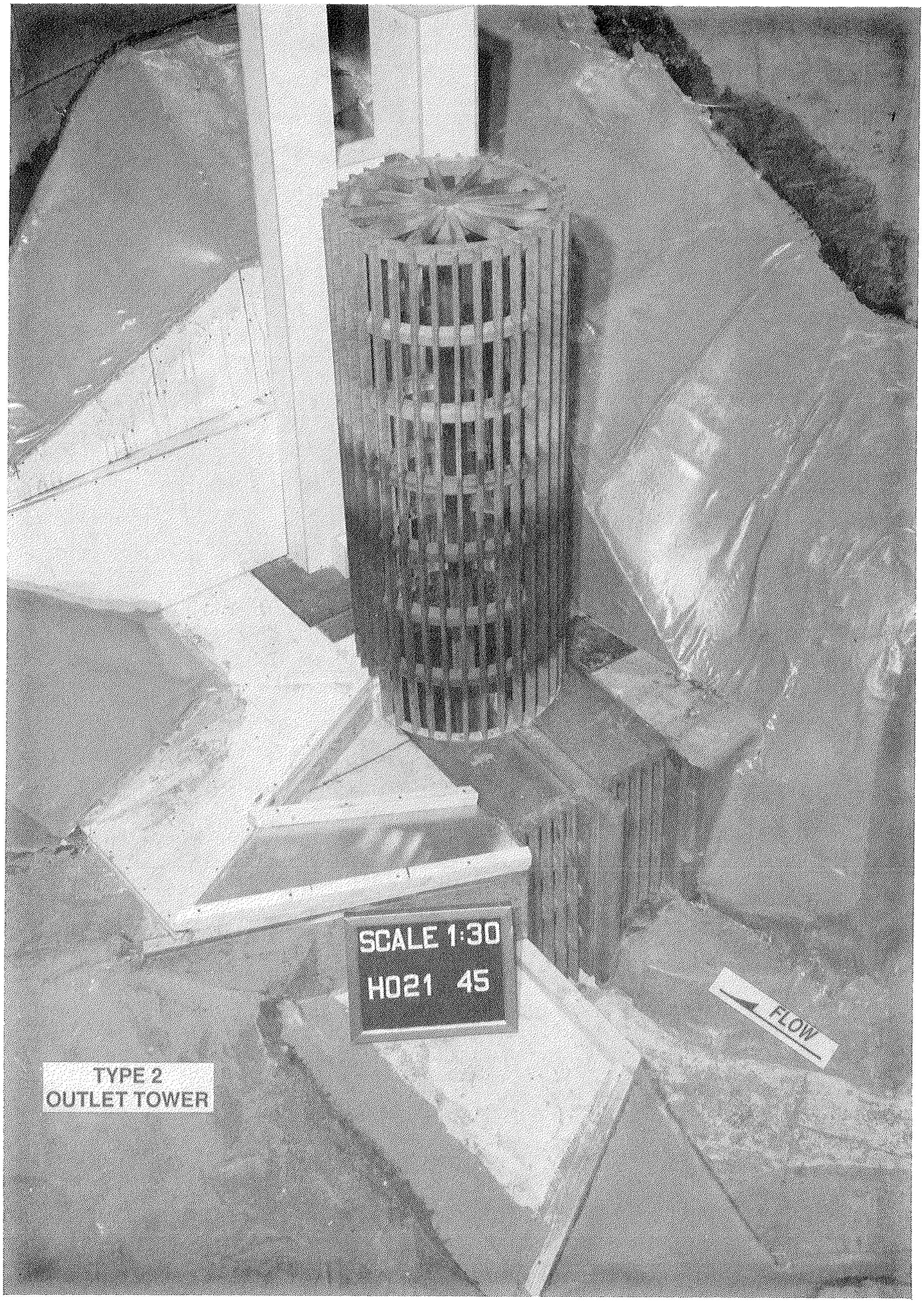


Photo 22. Type 2 design outlet tower

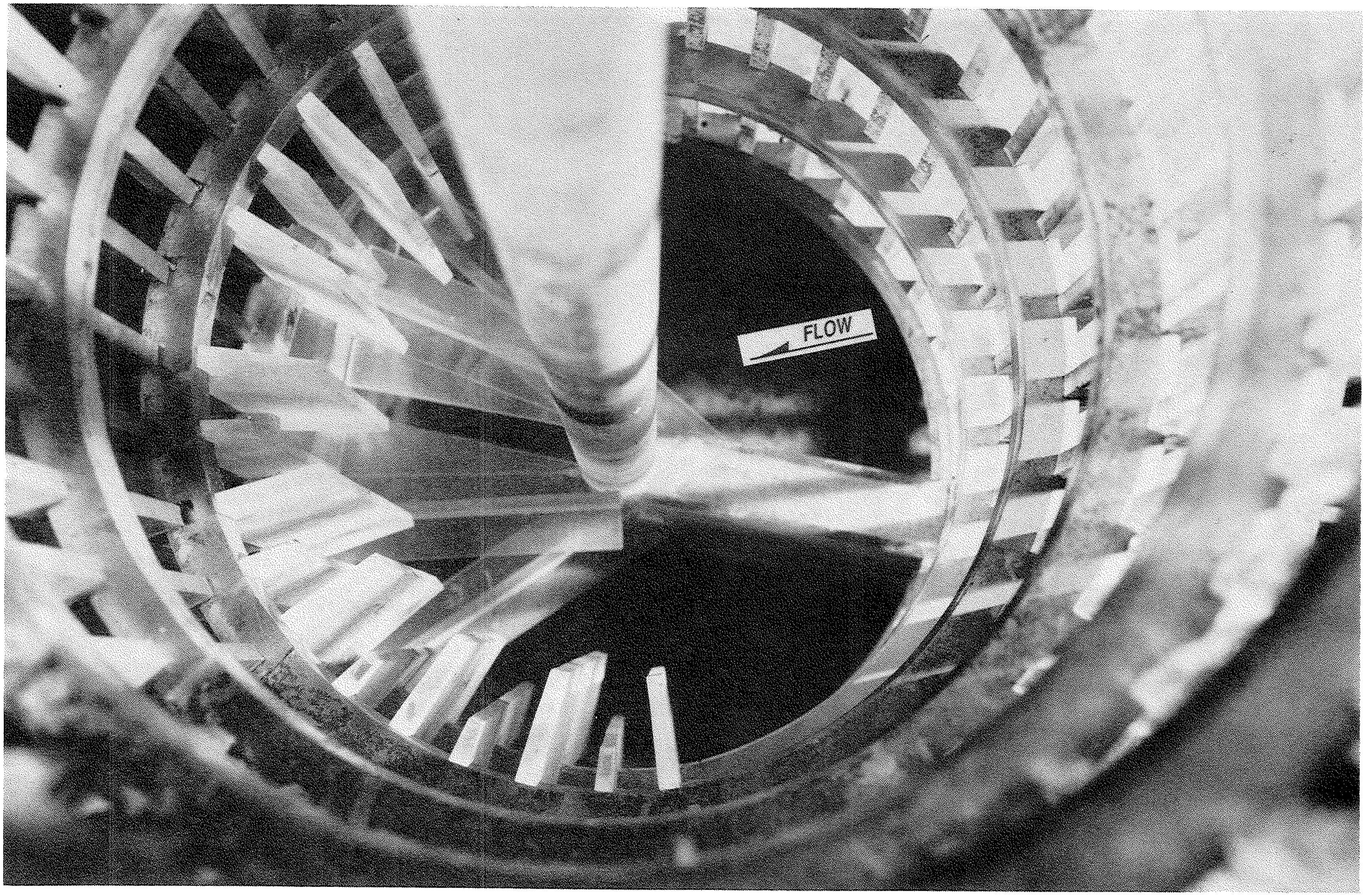


Photo 23. Type 7 design vortex suppression baffle, looking down the outlet tower

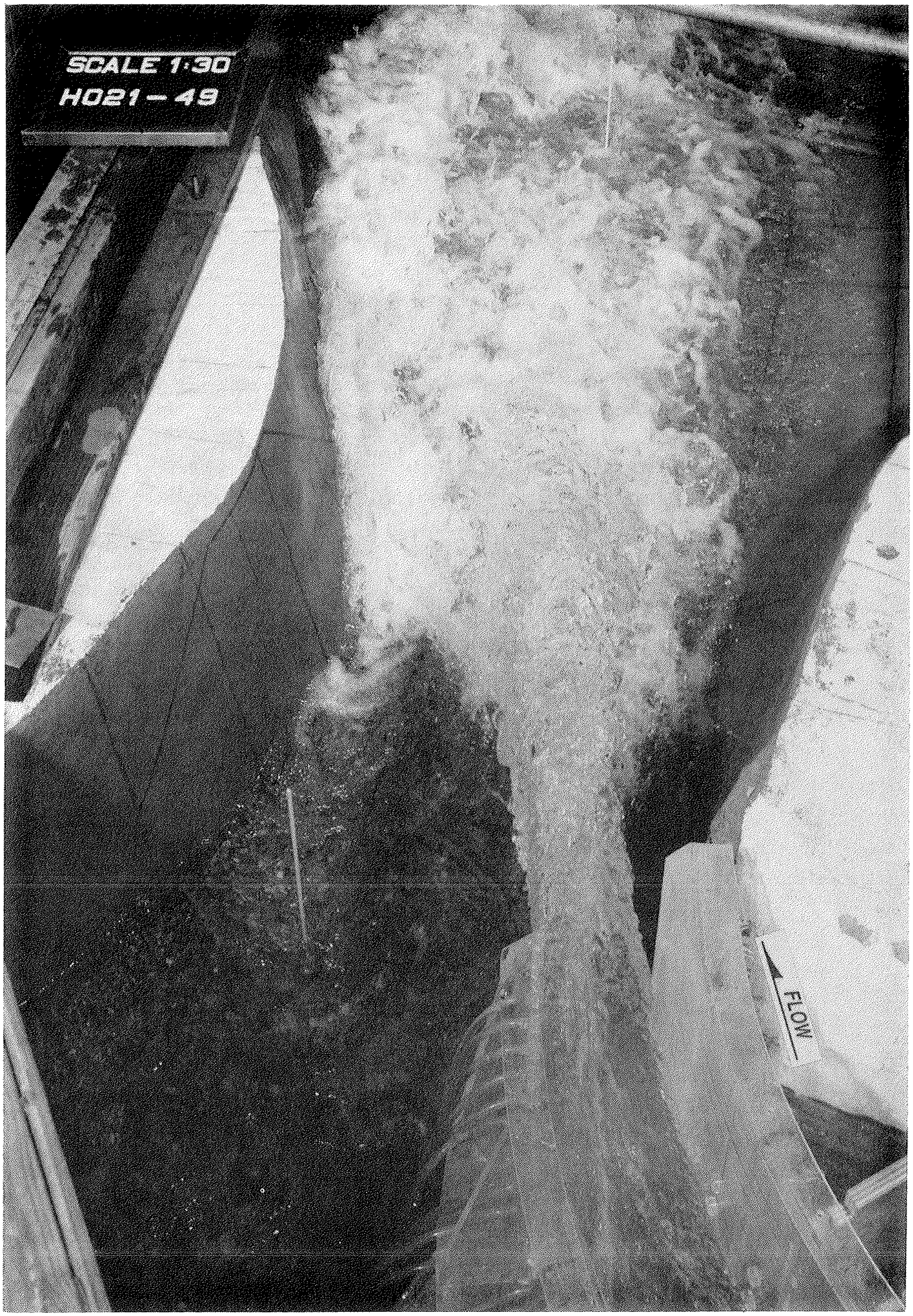


Photo 24. Flow through equal gates at pool el 1215, discharge 17,600 cfs, type 7 exit structure, no tailwater, n = 0.013

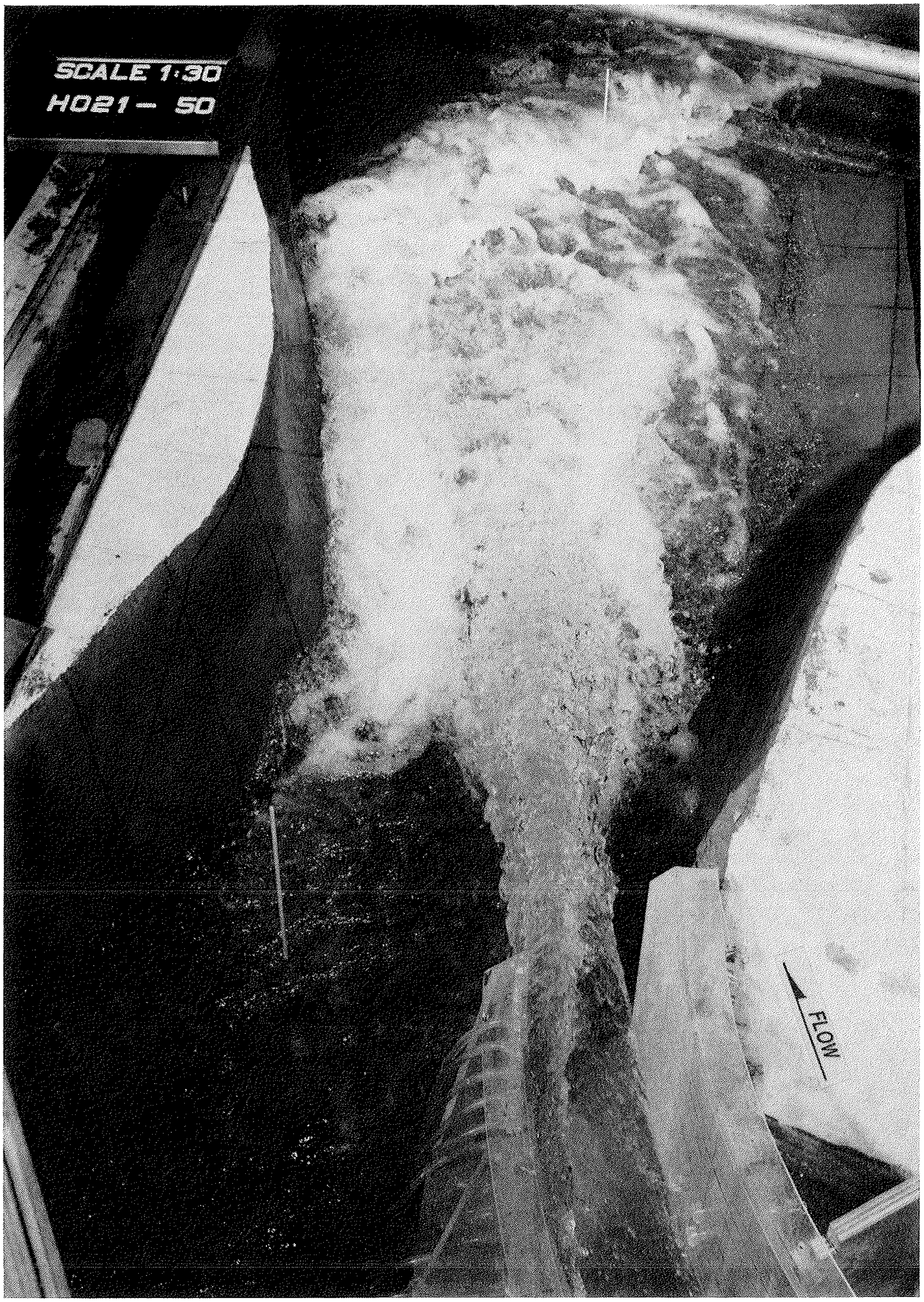


Photo 25. Design condition, 13,000-cfs flow through equal gates at pool el 1215, type 7 exit structure, prototype tailwater not simulated, n = 0.013

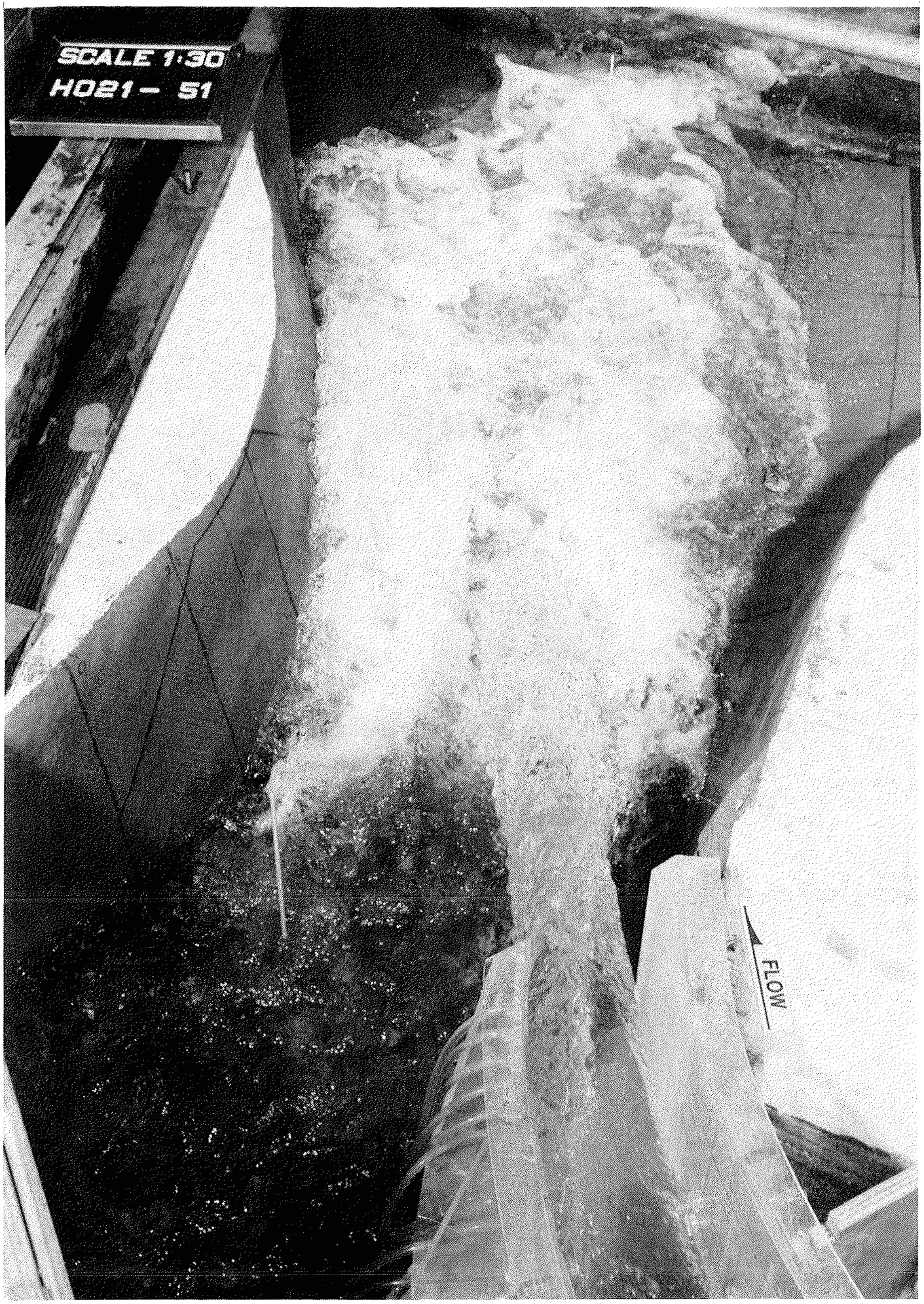
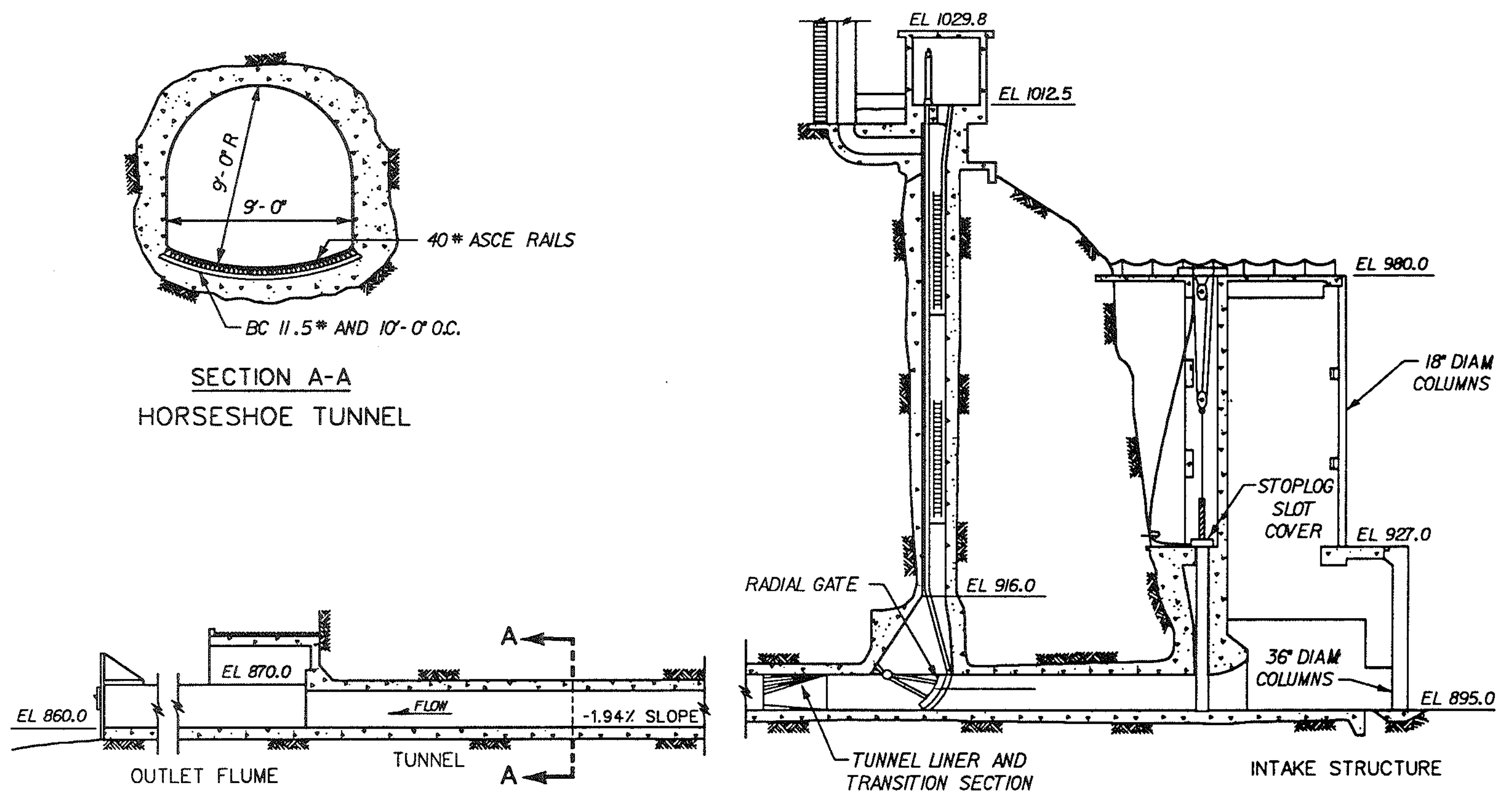


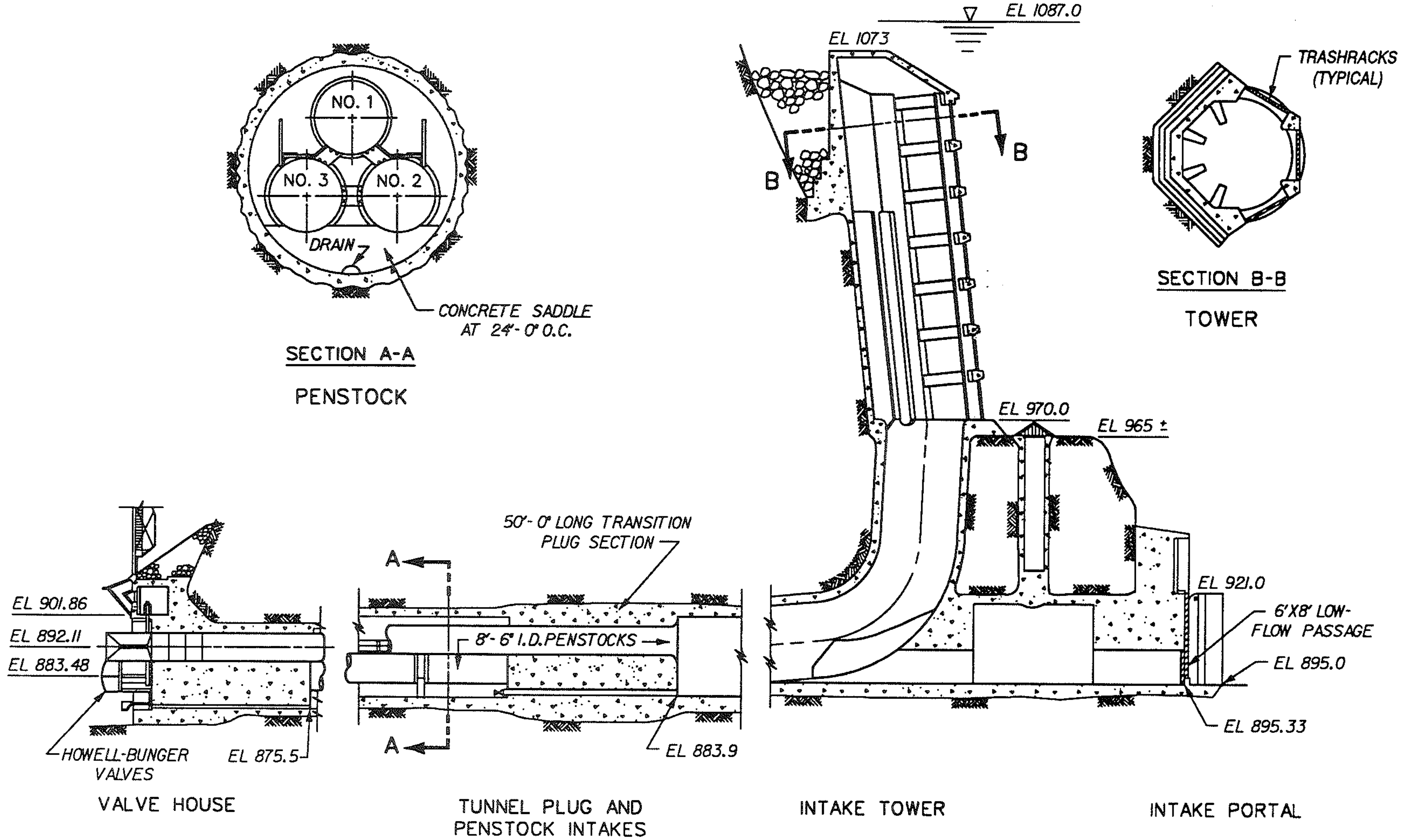
Photo 26. Flow through fully open gates at pool el 1050, discharge 14,300 cfs, type 7 exit structure, prototype tailwater not simulated, n = 0.013

Photo 27. Flow with fully open gates at pool el 925, type 7 exit structure, prototype tailwater not simulated, n = 0.013, discharge approximately 1,500 cfs (estimated by sponsor)

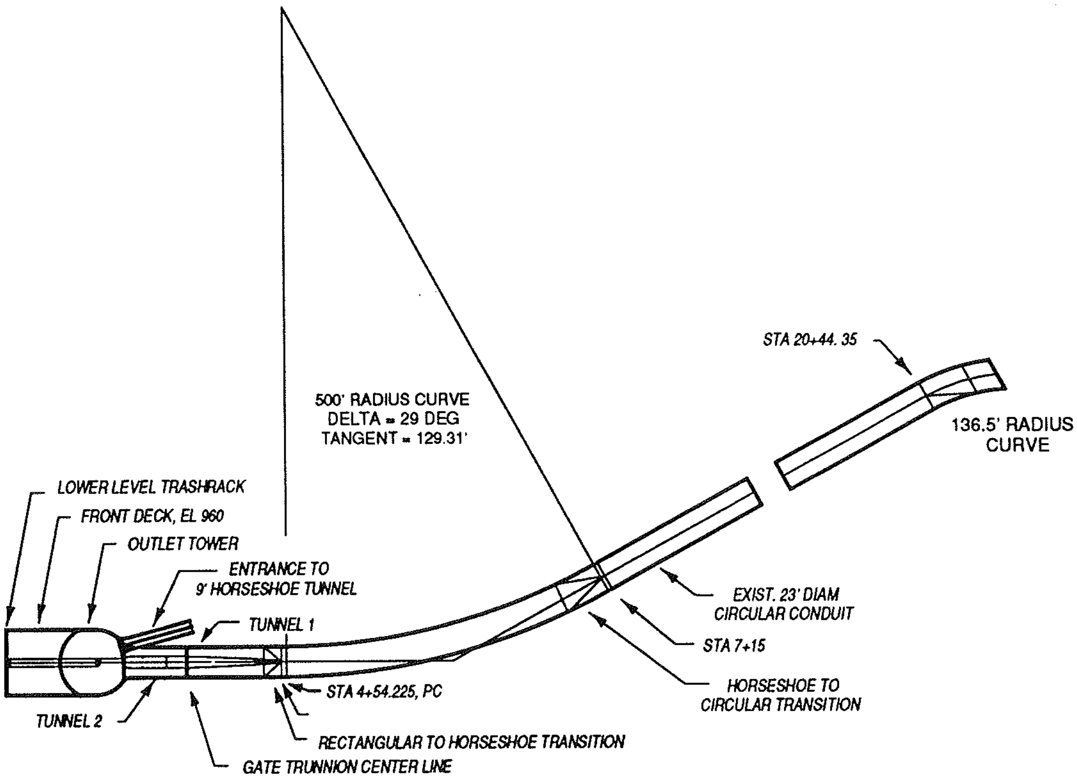


9-FOOT TUNNEL

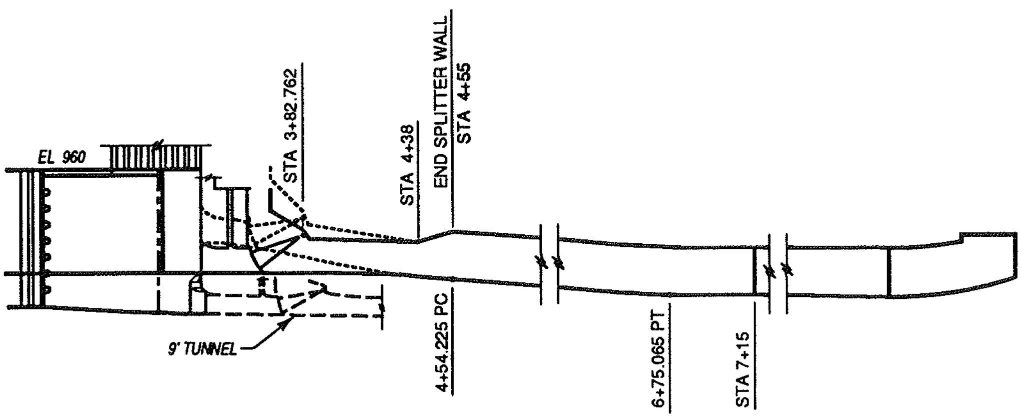
Plate 2



23-FOOT TUNNEL

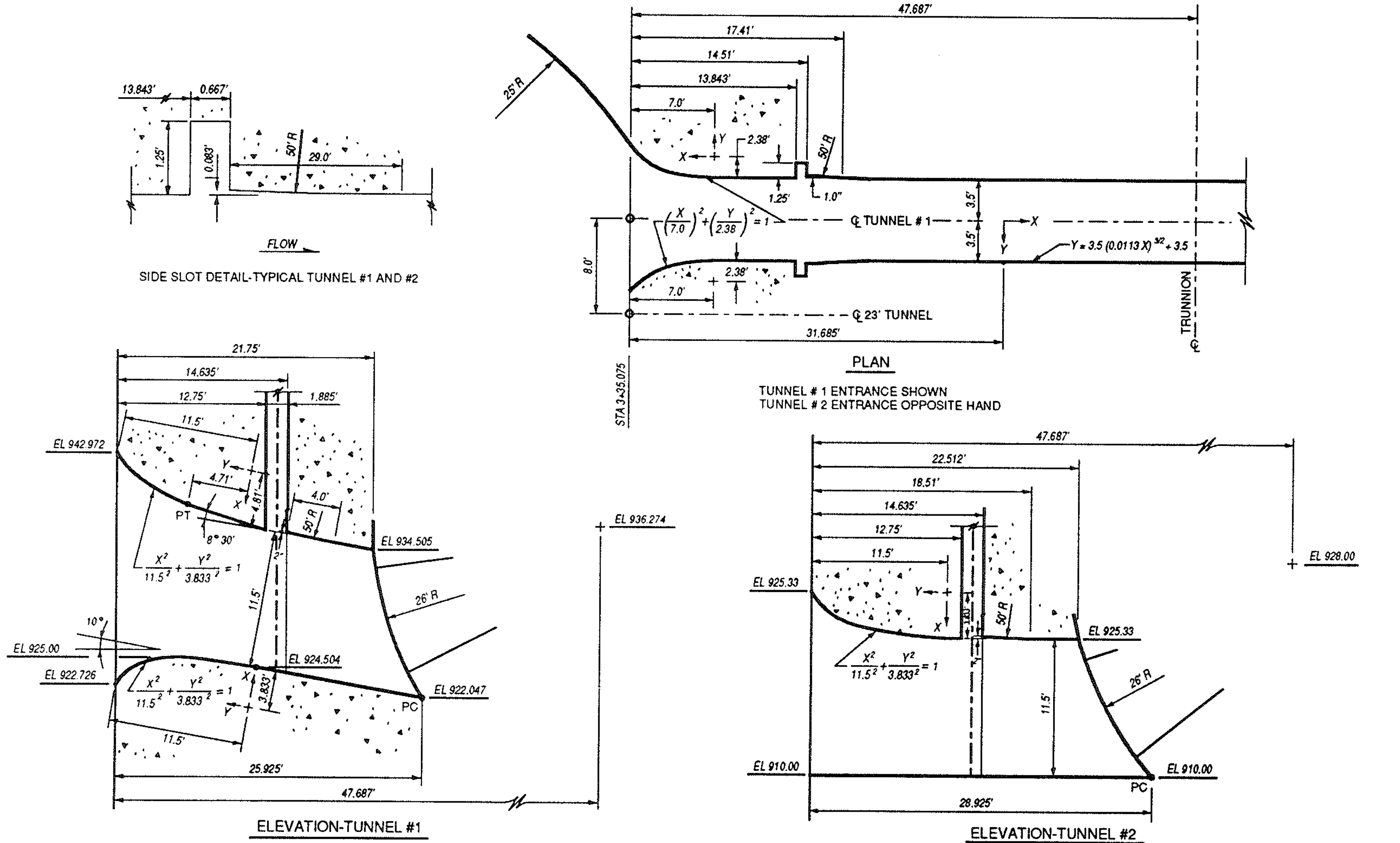


PLAN



ELEVATION

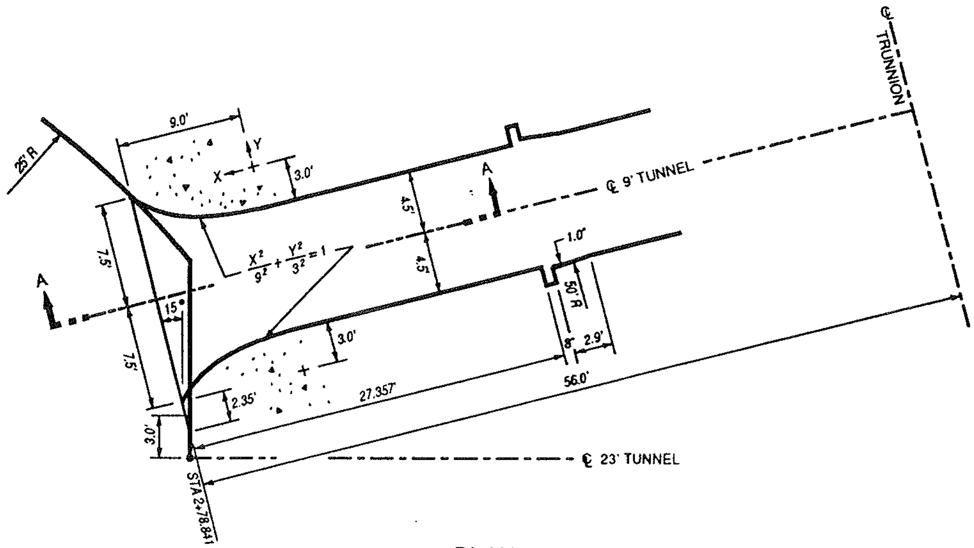
ORIGINAL DESIGN



$$\left(\frac{X}{7.0}\right)^2+\left(\frac{Y}{2.38}\right)^2=1$$

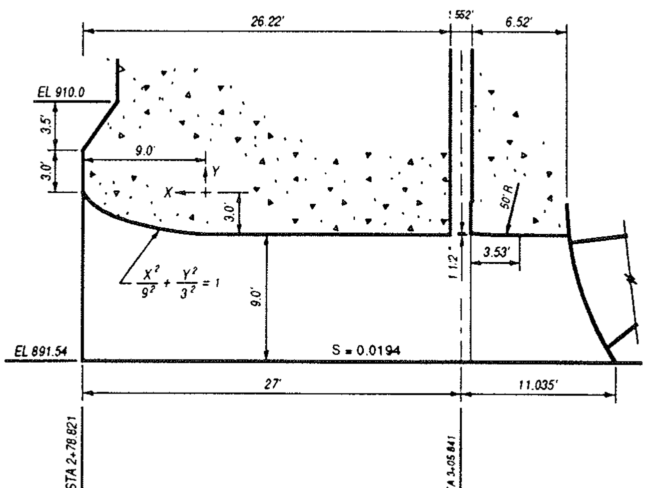
$$\frac{X^2}{11.5^2}+\frac{Y^2}{3.833^2}=1$$

23-FT TUNNEL ENTRANCES
ORIGINAL DESIGN



PLAN

9-FT TUNNEL ENTRANCE

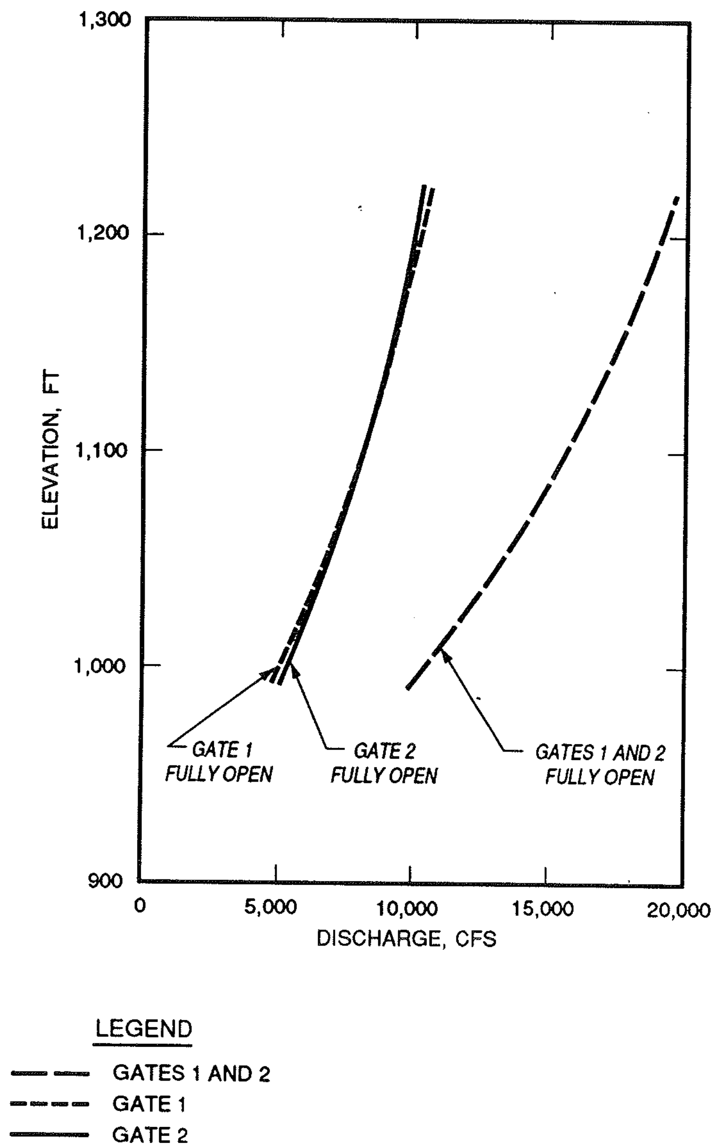


ELEVATION

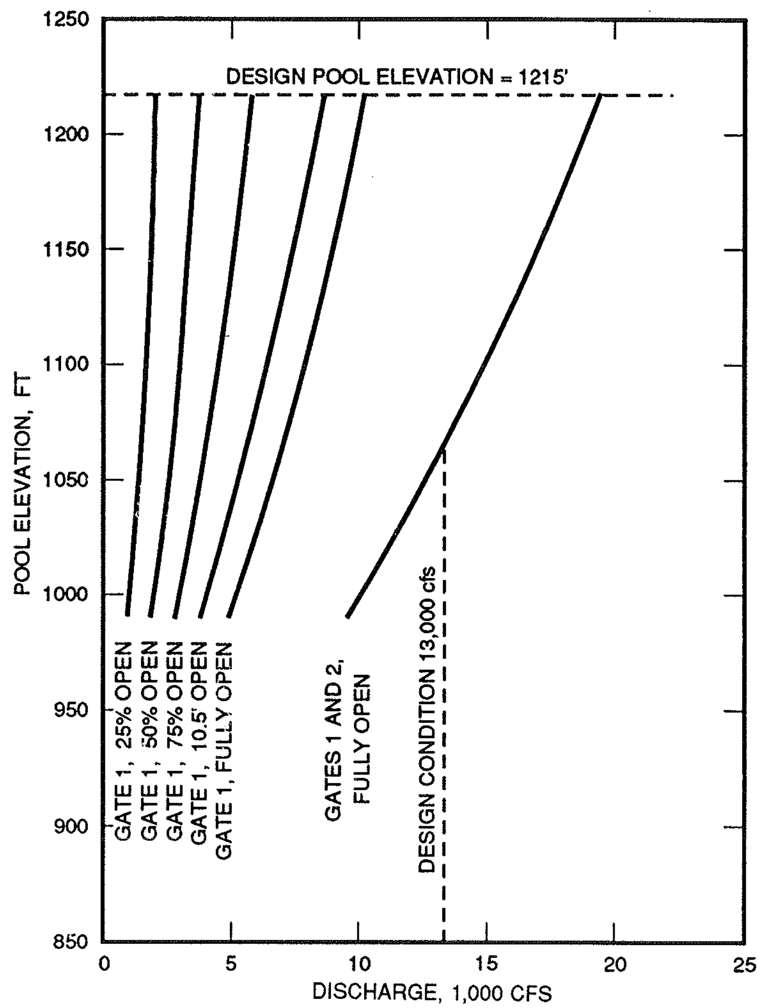
9-FT TUNNEL ENTRANCE

9-FT TUNNEL ENTRANCE

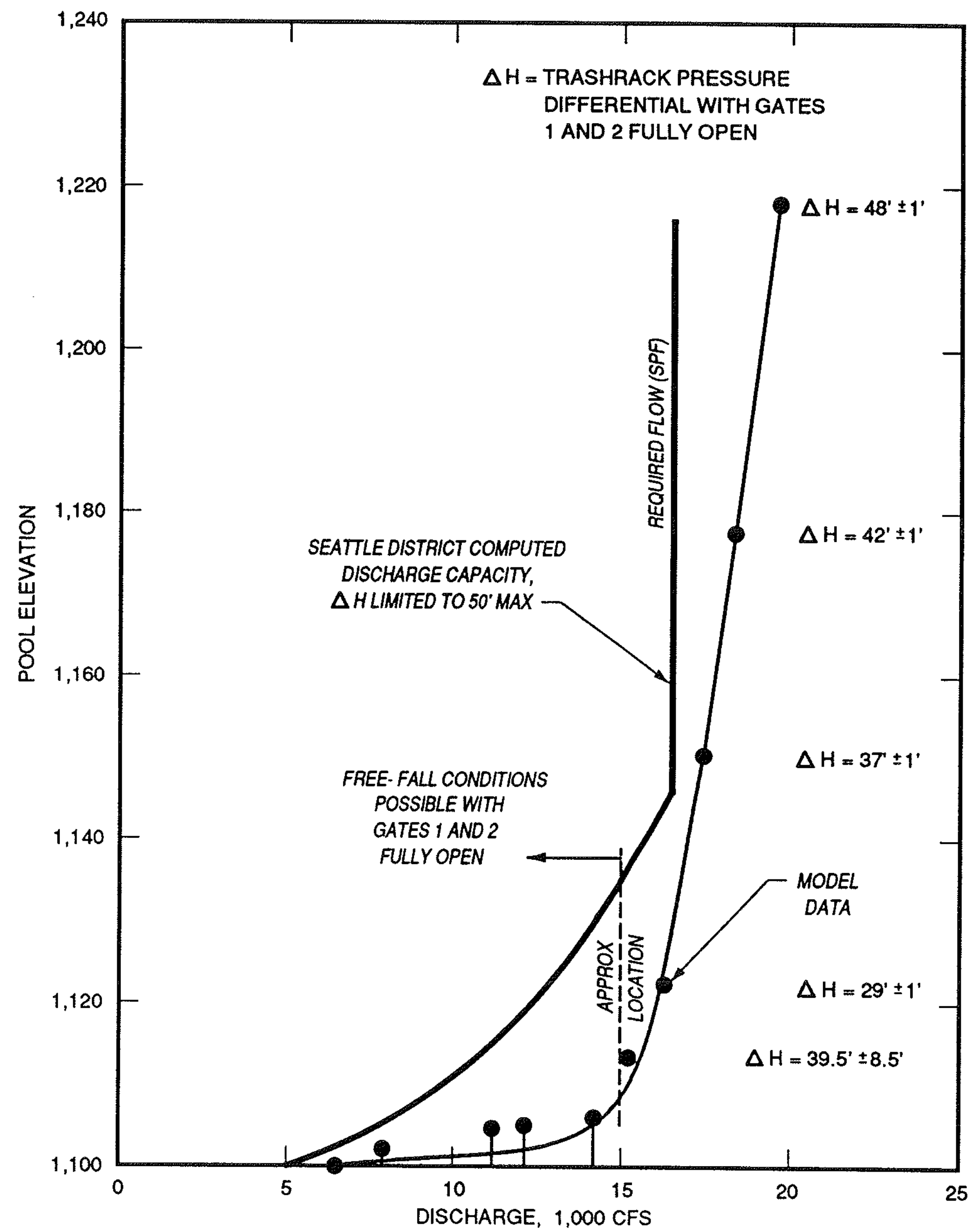
ORIGINAL DESIGN



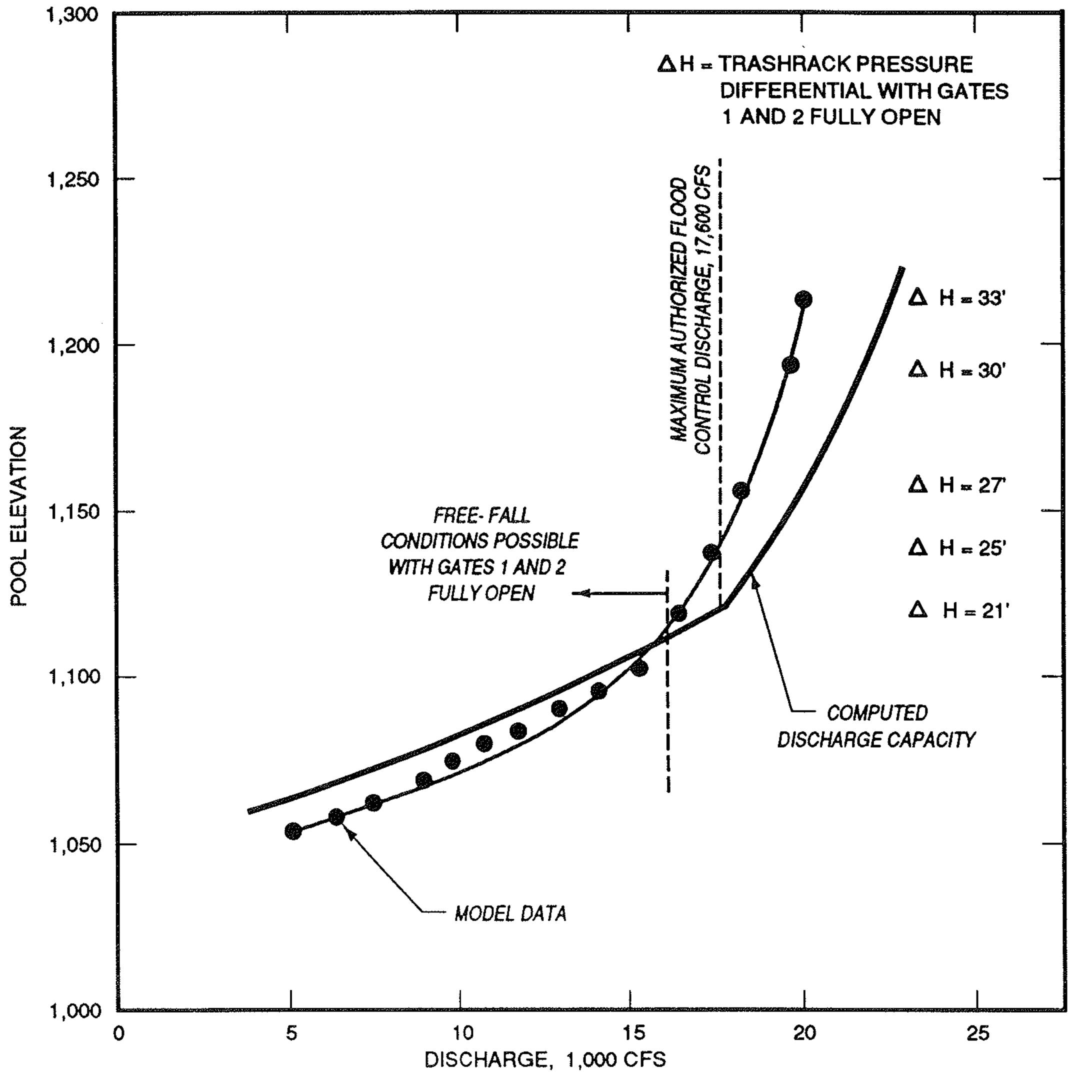
POOL ELEVATION VERSUS DISCHARGE
FULL GATE OPENINGS
23-FT TUNNEL
ORIGINAL DESIGN



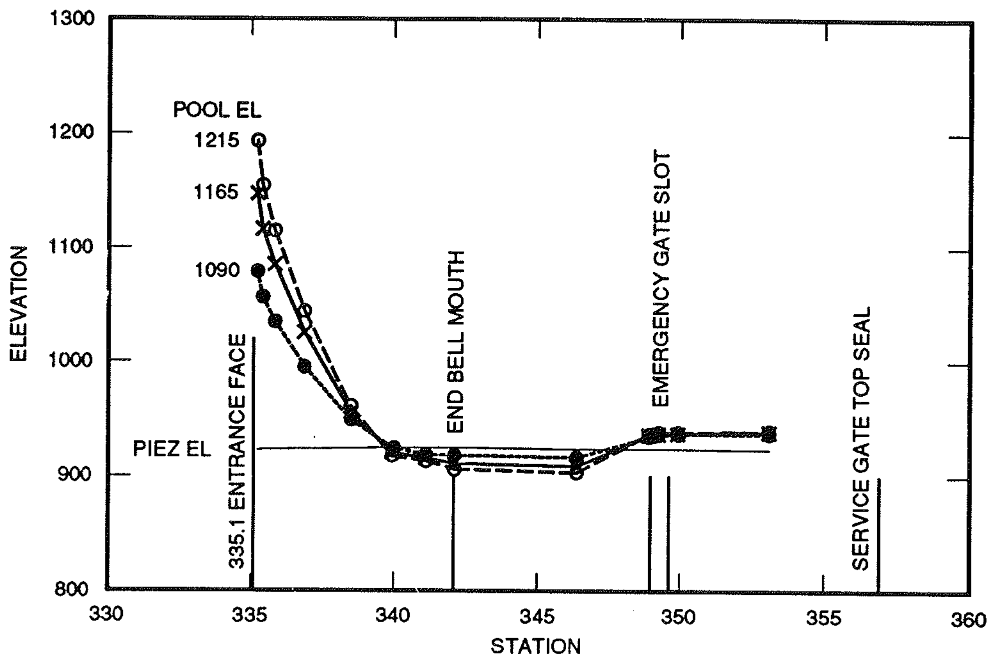
POOL ELEVATION VERSUS DISCHARGE
PARTIAL GATE OPENINGS
23-FT TUNNEL
ORIGINAL DESIGN



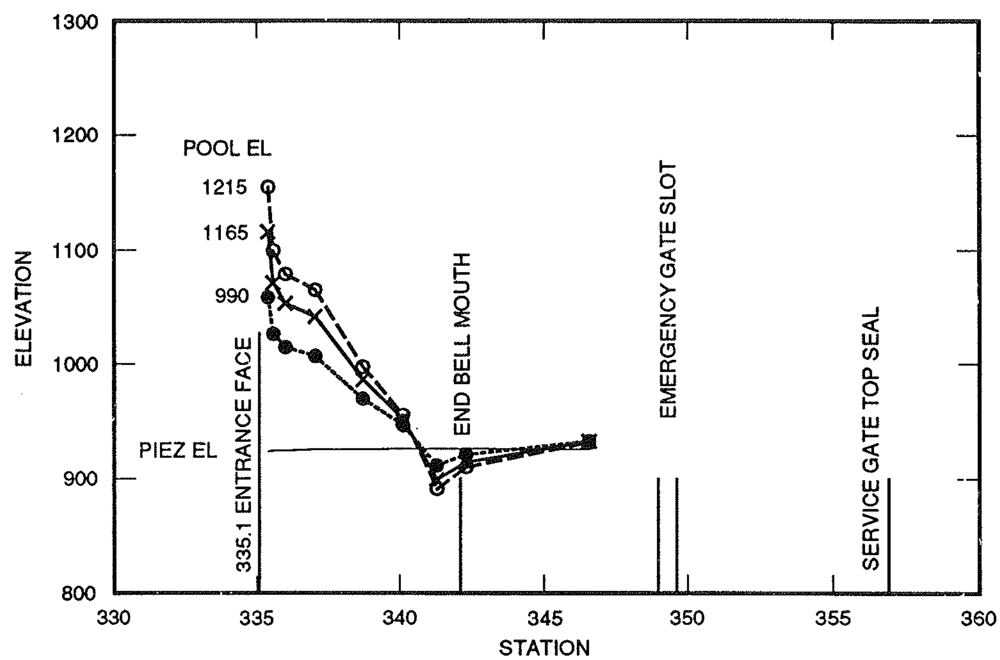
INTAKE TOWER BLOCKAGE TESTS
SPILLWAY DESIGN FLOOD BLOCKAGE
BLOCKED 100% EL 895-1080
BLOCKED 75% EL 1080-1100
GATES 1 AND 2 FULLY OPEN
ORIGINAL DESIGN



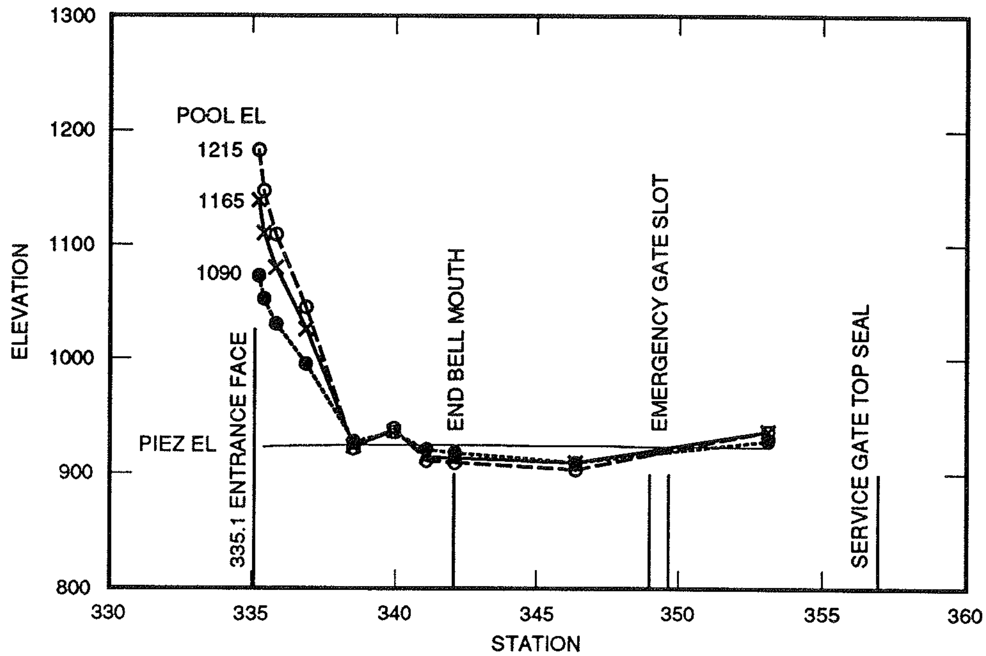
INTAKE TOWER BLOCKAGE TESTS
PROJECT DESIGN FLOOD BLOCKAGE
BLOCKED 100% EL 895-1015
BLOCKED 90% EL 1015-1100
GATES 1 AND 2 FULLY OPEN
ORIGINAL DESIGN



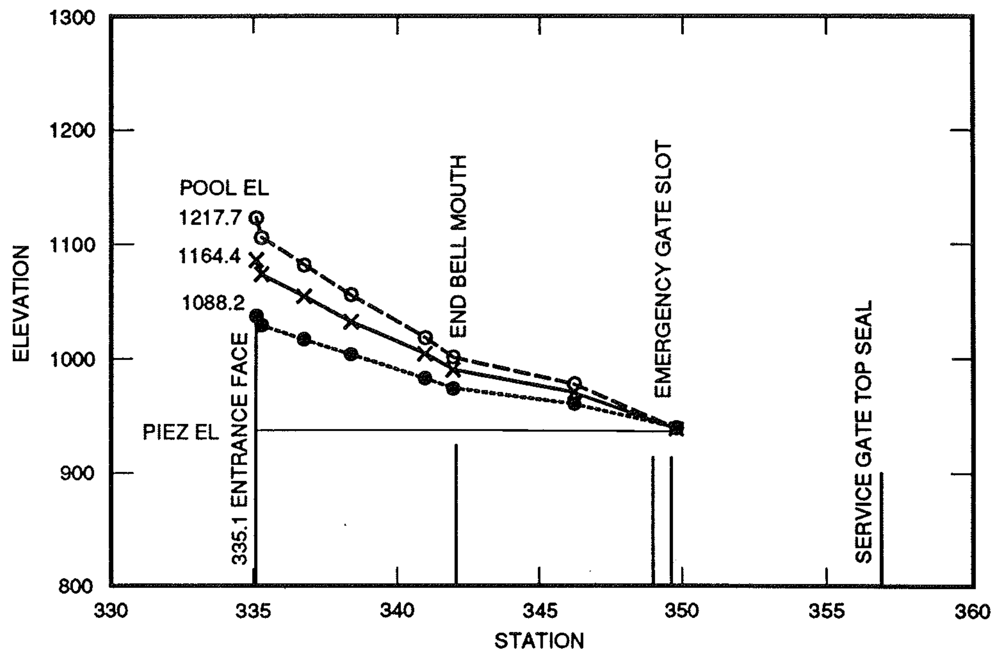
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
LEFT-BOTTOM CORNER
GATE 1 FULLY OPEN
ORIGINAL DESIGN



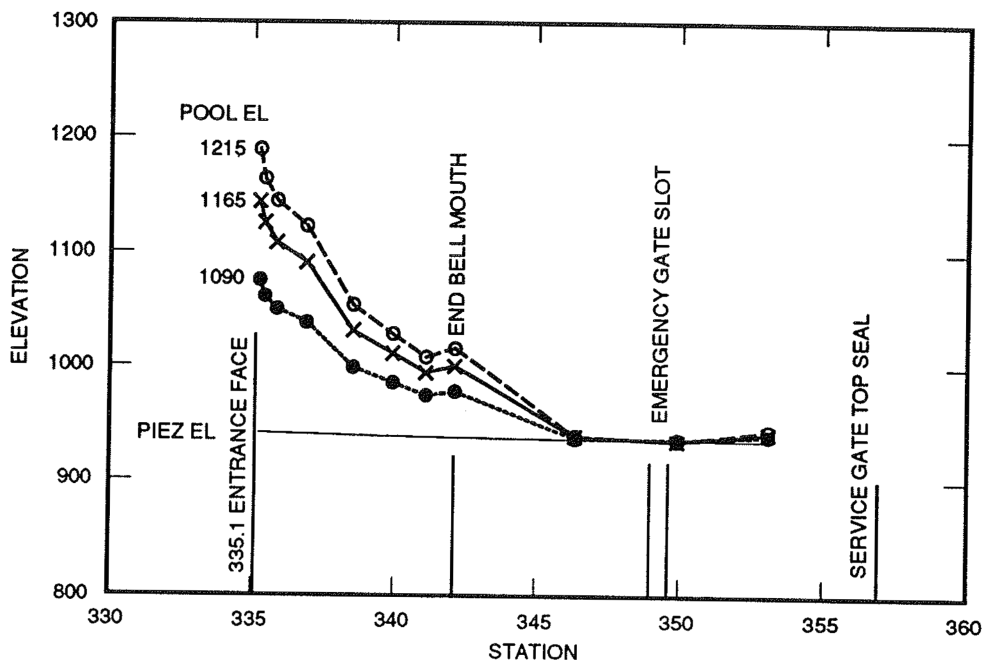
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
CENTER-BOTTOM
GATE 1 FULLY OPEN
ORIGINAL DESIGN



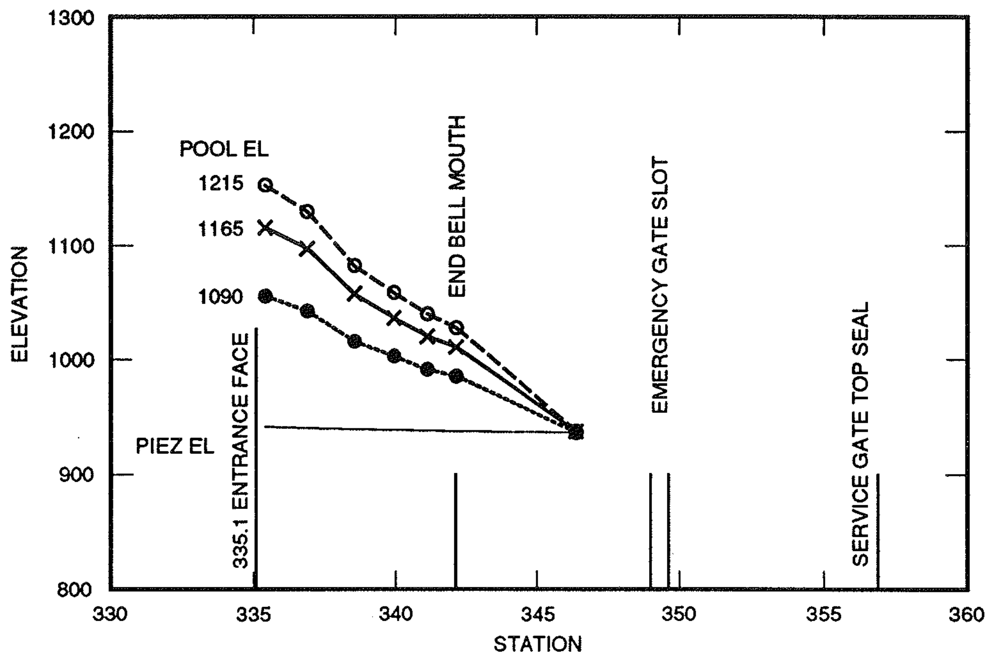
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
RIGHT-BOTTOM CORNER
GATE 1 FULLY OPEN
ORIGINAL DESIGN



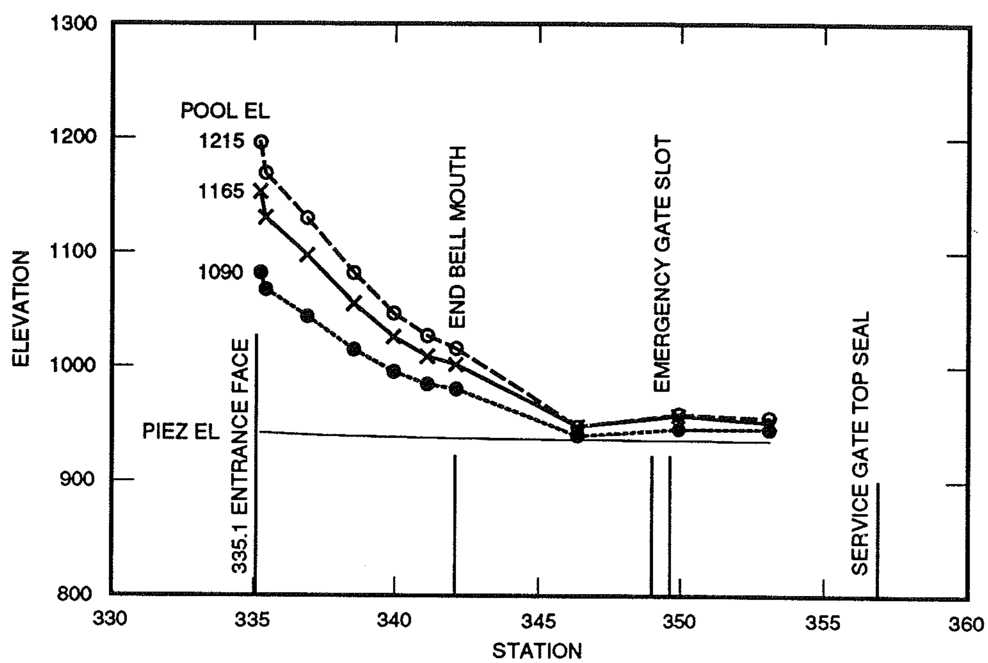
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
CENTER-RIGHT SIDE
GATE 1 FULLY OPEN
ORIGINAL DESIGN



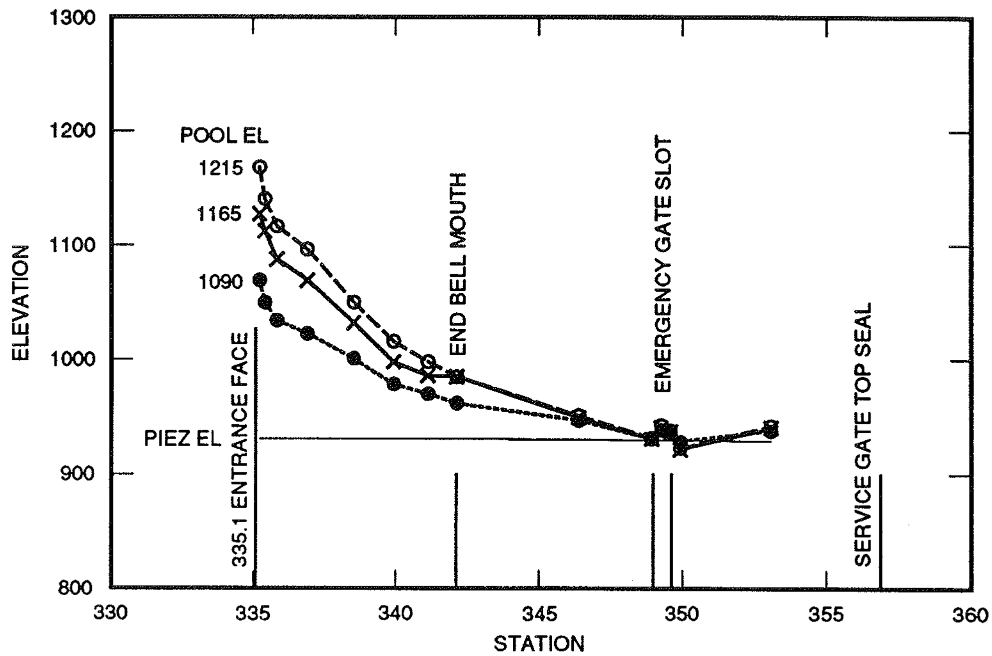
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
RIGHT-TOP CORNER
GATE 1 FULLY OPEN
ORIGINAL DESIGN



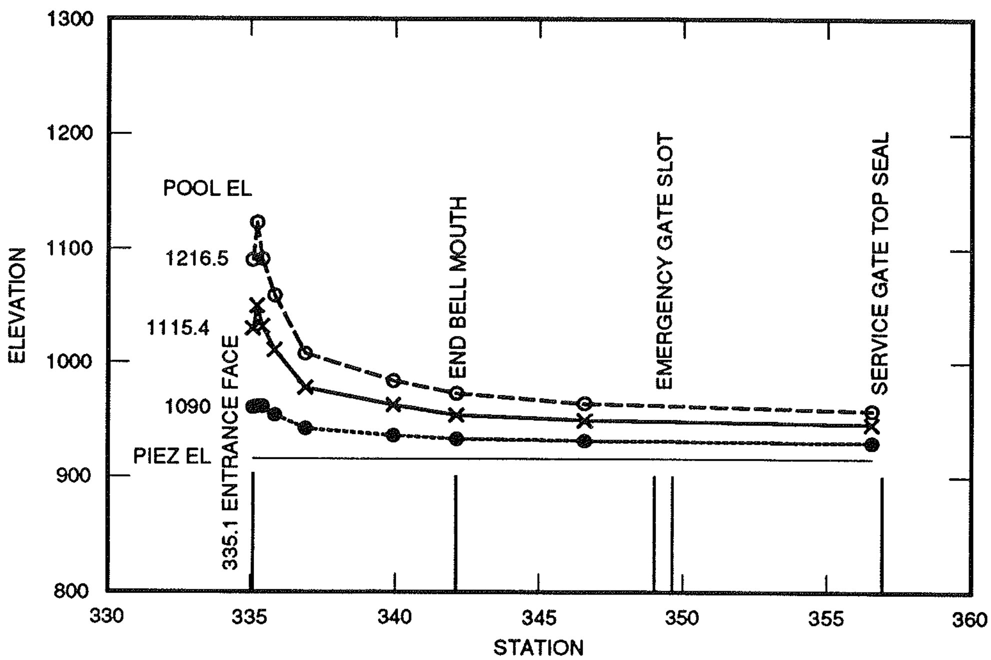
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
CENTER-TOP
GATE 1 FULLY OPEN
ORIGINAL DESIGN



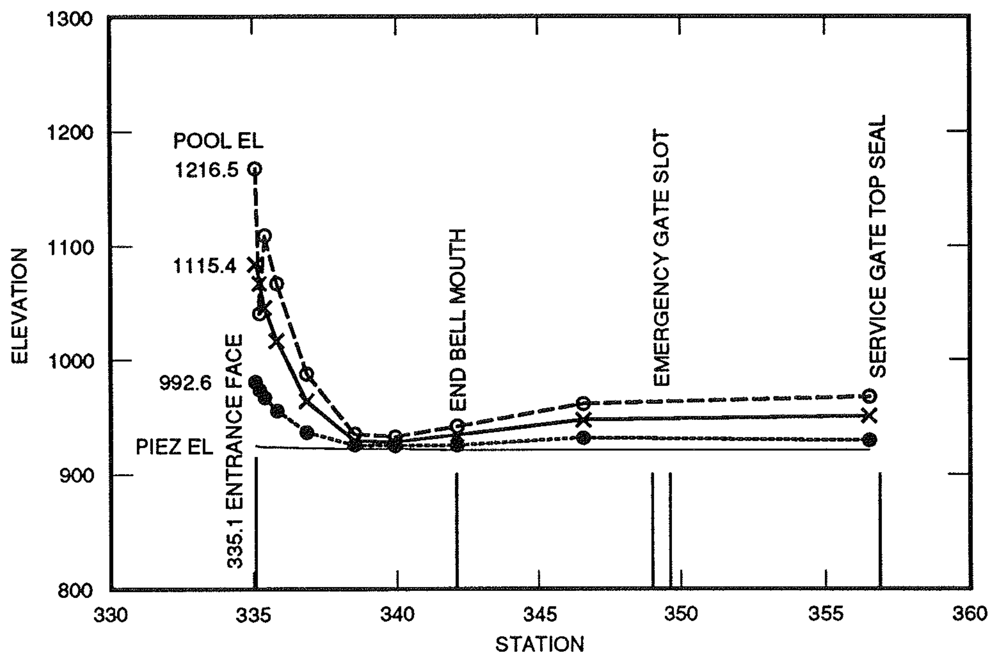
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
LEFT-TOP CORNER
GATE 1 FULLY OPEN
ORIGINAL DESIGN



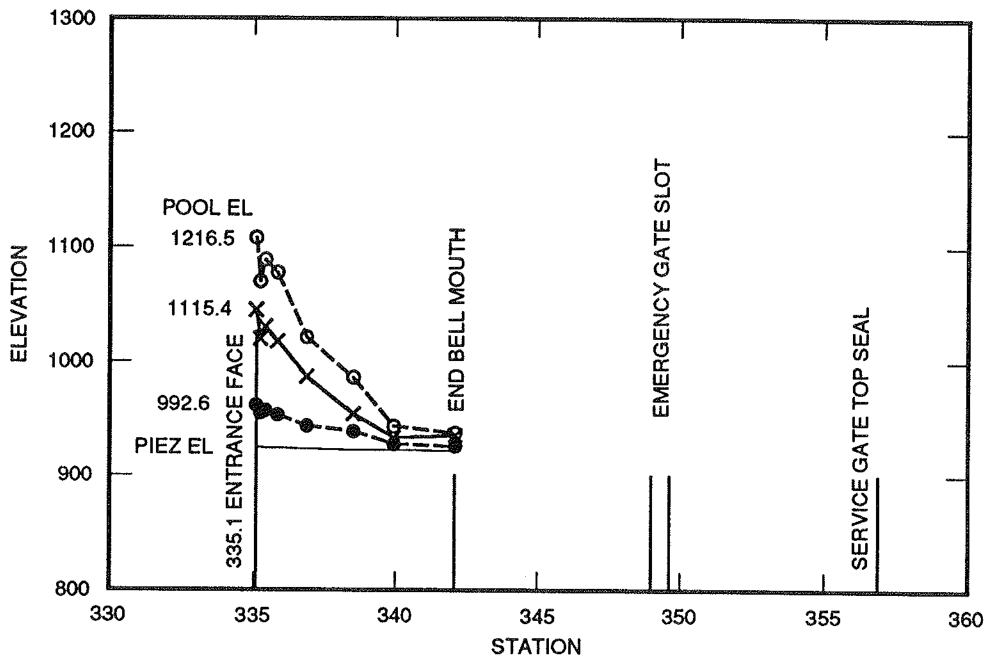
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
CENTER-LEFT SIDE
GATE 1 FULLY OPEN
ORIGINAL DESIGN



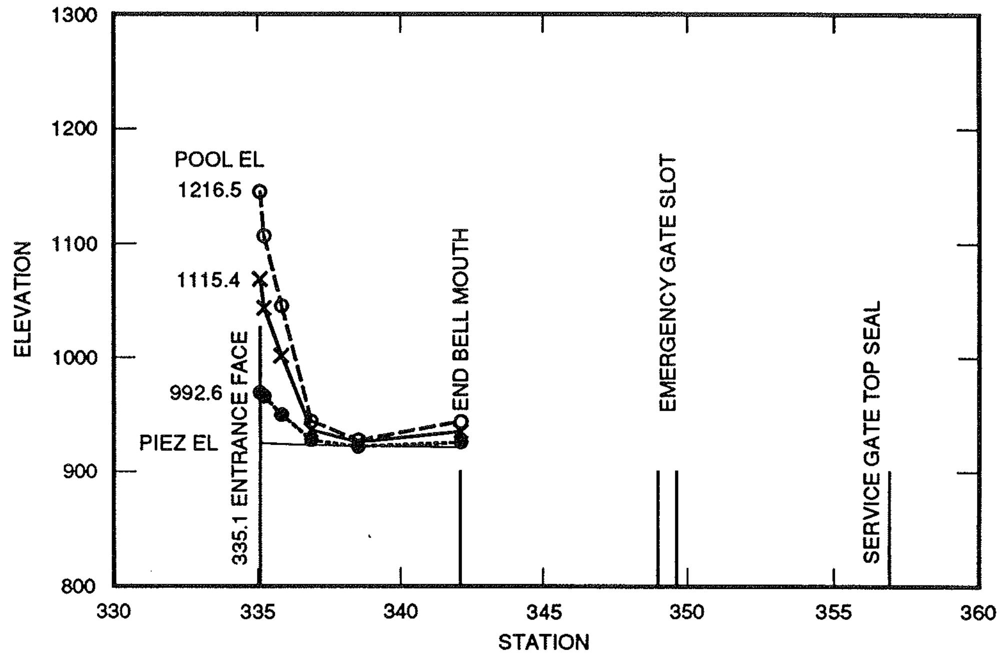
TUNNEL 2 ENTRANCE
AVERAGE PRESSURES
CENTER-RIGHT SIDE
GATE 2 FULLY OPEN
ORIGINAL DESIGN



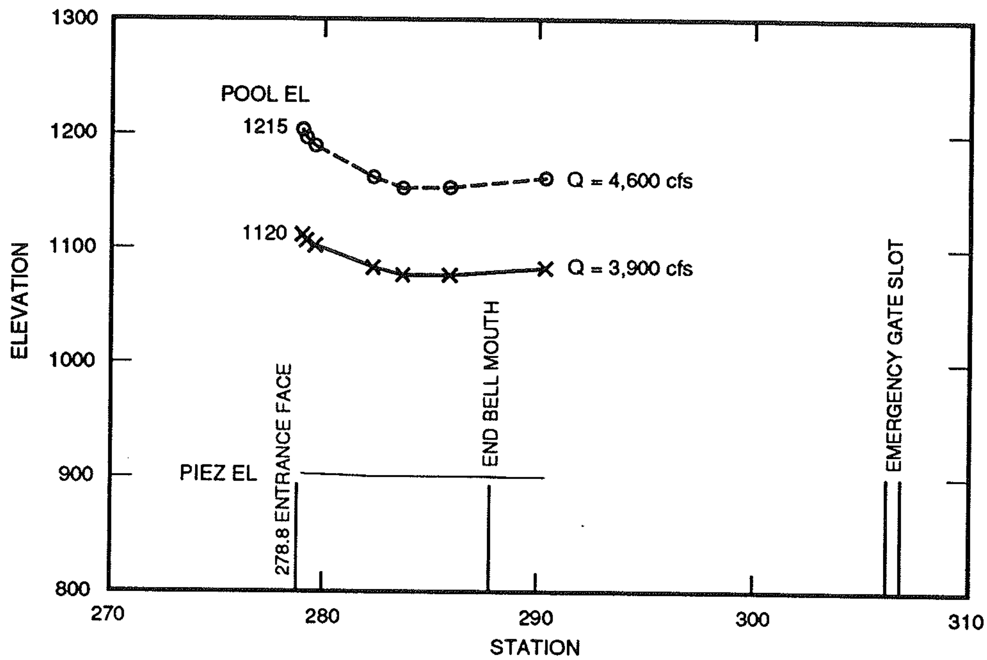
TUNNEL 2 ENTRANCE
AVERAGE PRESSURES
TOP-RIGHT CORNER
GATE 2 FULLY OPEN
ORIGINAL DESIGN



TUNNEL 2 ENTRANCE
AVERAGE PRESSURES
TOP-CENTER
GATE 2 FULLY OPEN
ORIGINAL DESIGN

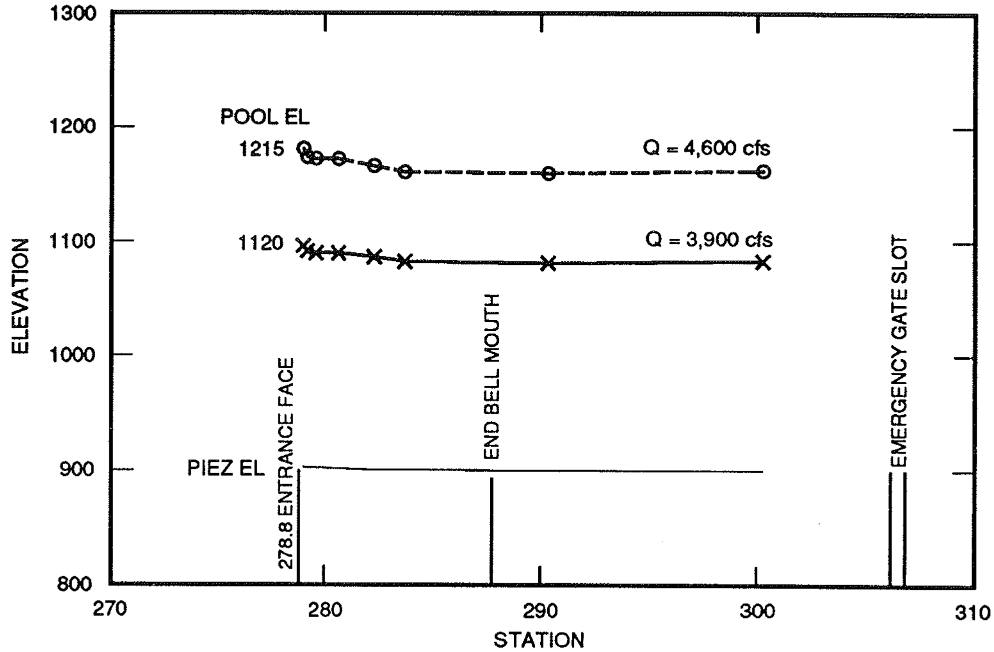


TUNNEL 2 ENTRANCE
AVERAGE PRESSURES
TOP-LEFT CORNER
GATE 2 FULLY OPEN
ORIGINAL DESIGN



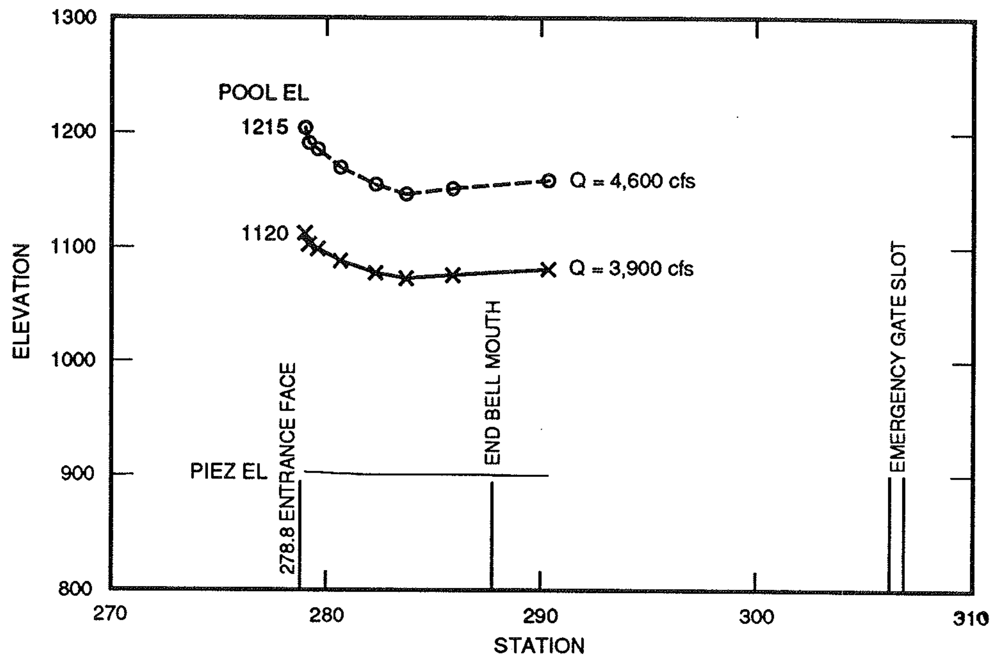
NOTE: 9-FT TUNNEL FLOWS FULL WITH Q > 2,200 cfs

9-FT TUNNEL ENTRANCE
AVERAGE PRESSURES
RIGHT-TOP CORNER
9-FT TUNNEL GATE FULLY OPEN
ORIGINAL DESIGN



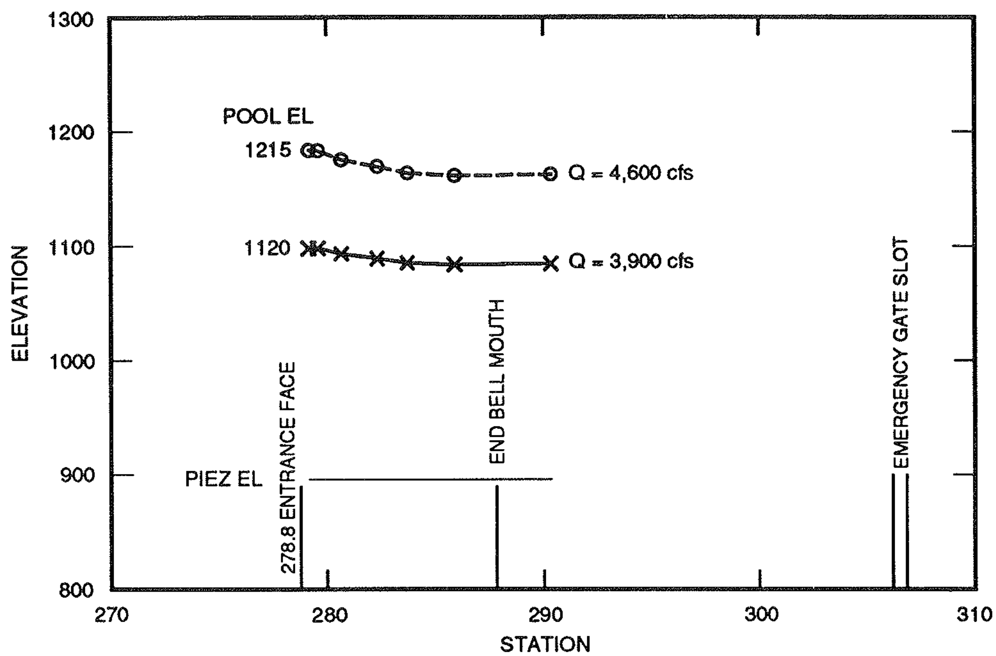
NOTE: 9-FT TUNNEL FLOWS FULL WITH Q > 2,200 cfs

9-FT TUNNEL ENTRANCE
AVERAGE PRESSURES
TOP-CENTER
9-FT TUNNEL GATE FULLY OPEN
ORIGINAL DESIGN



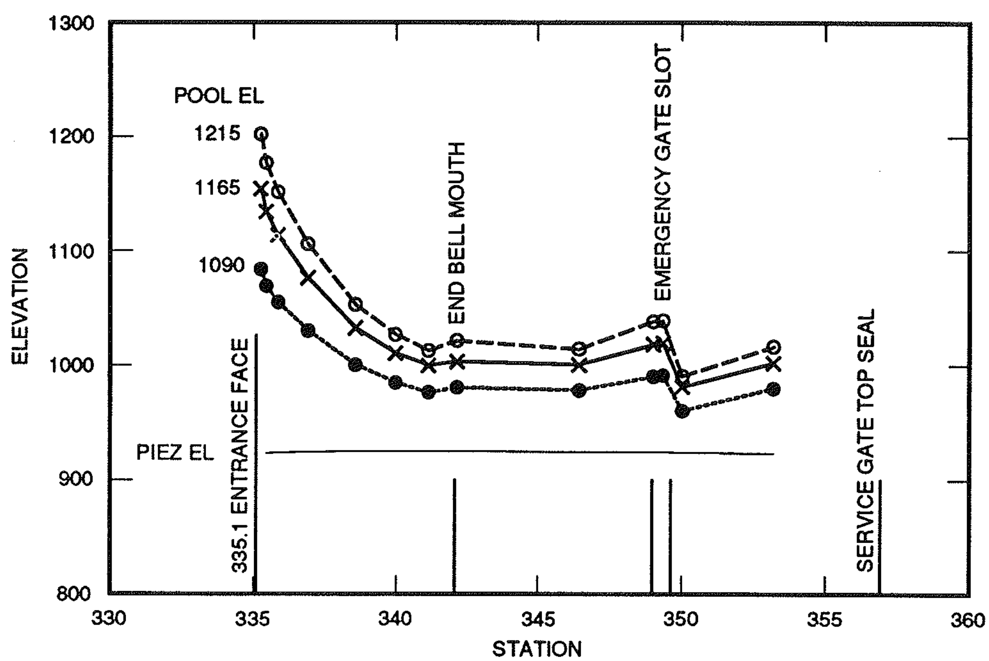
NOTE: 9-FT TUNNEL FLOWS FULL WITH Q > 2,200 cfs

9-FT TUNNEL ENTRANCE
AVERAGE PRESSURES
LEFT-TOP CORNER
9-FT TUNNEL GATE FULLY OPEN
ORIGINAL DESIGN

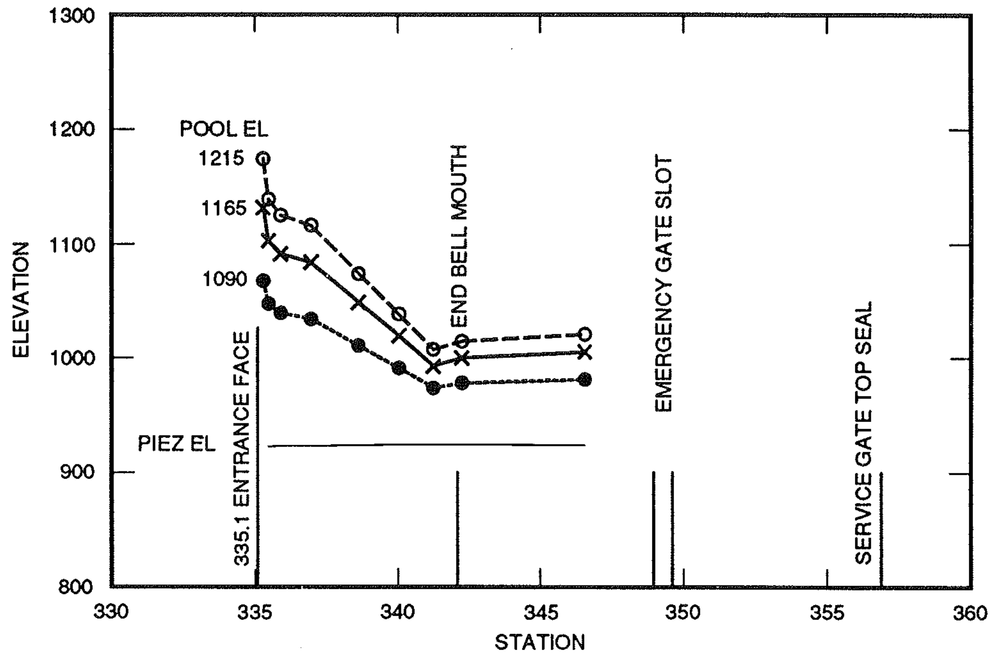


NOTE: 9-FT TUNNEL FLOWS FULL WITH Q > 2,200 cfs

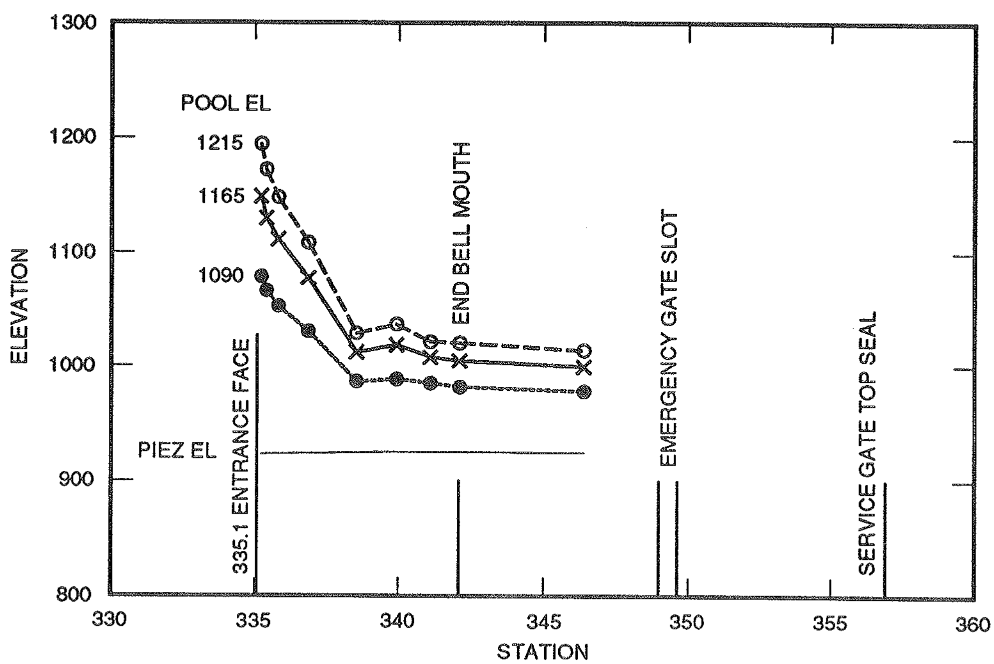
9-FT TUNNEL ENTRANCE
AVERAGE PRESSURES
CENTER-LEFT SIDE
9-FT TUNNEL GATE FULLY OPEN
ORIGINAL DESIGN



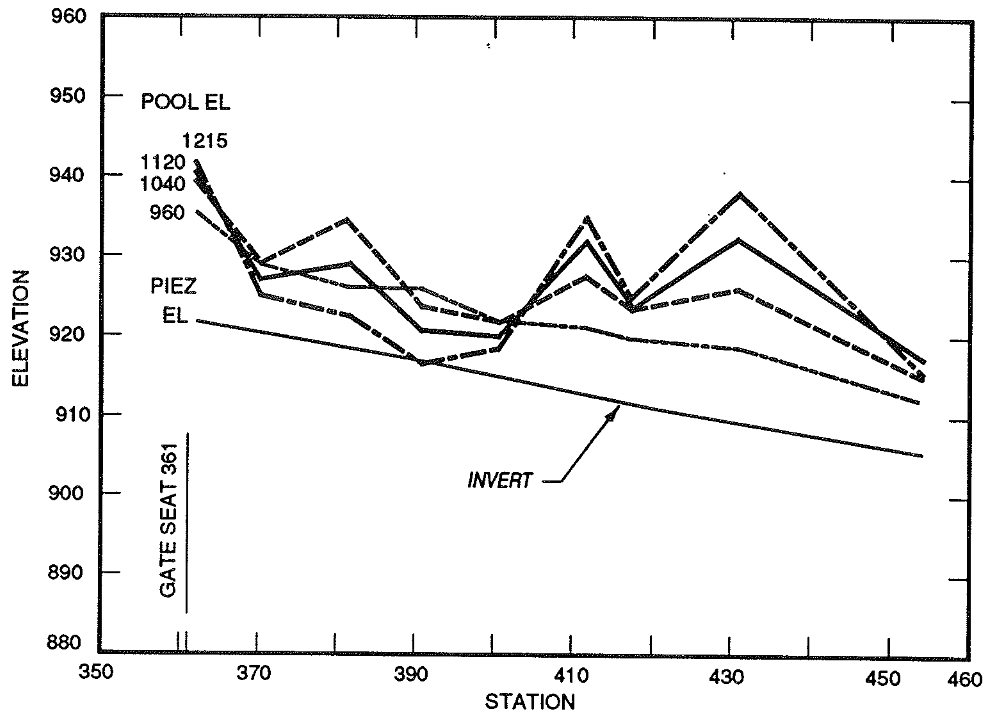
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
BOTTOM-LEFT CORNER
GATE 1, 10.5' OPEN
ORIGINAL DESIGN



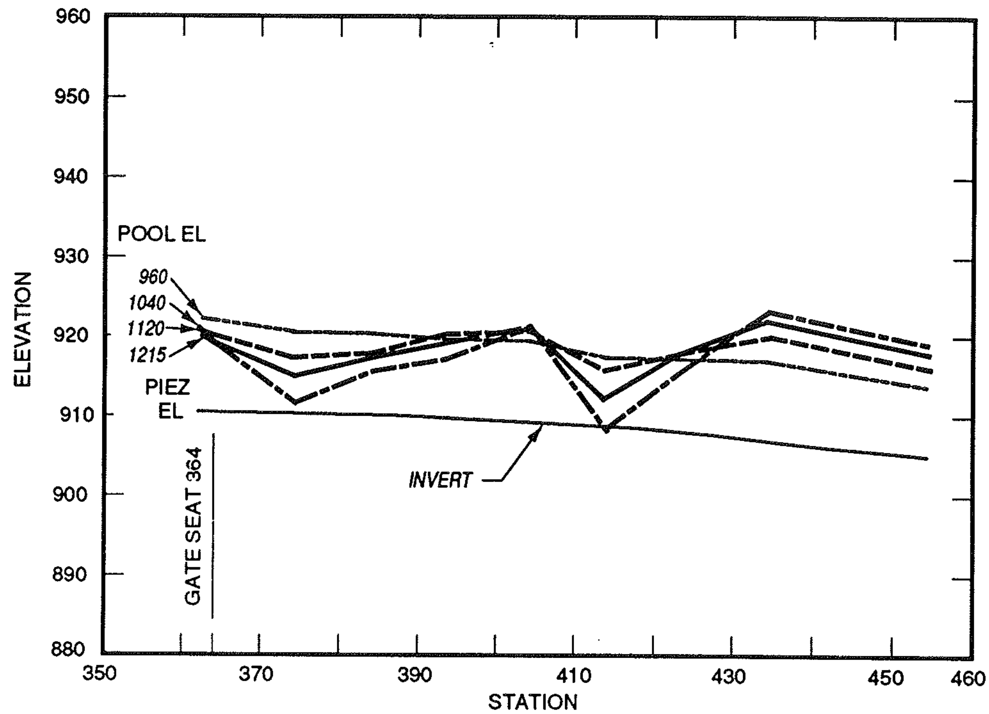
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
CENTER-BOTTOM
GATE 1, 10.5' OPEN
ORIGINAL DESIGN



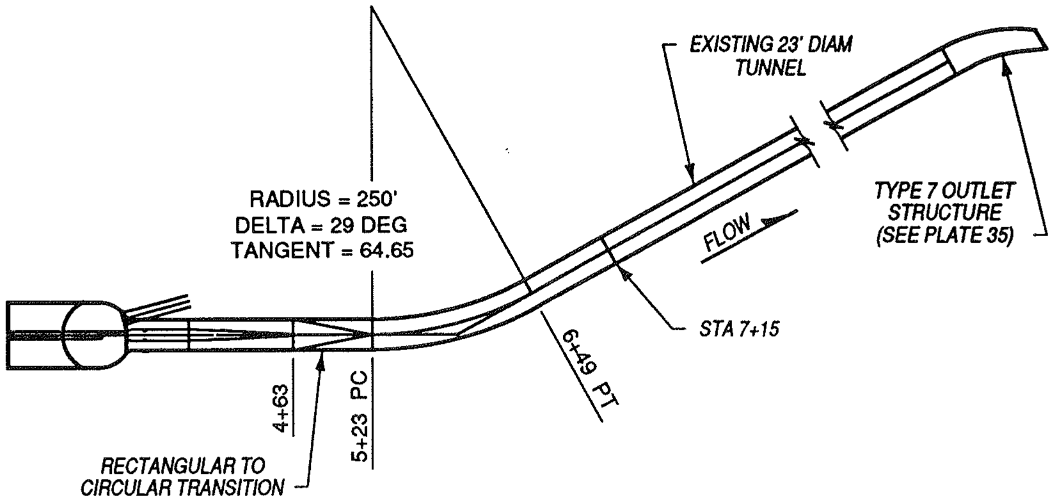
TUNNEL 1 ENTRANCE
AVERAGE PRESSURES
BOTTOM-RIGHT CORNER
GATE 1, 10.5' OPEN
ORIGINAL DESIGN



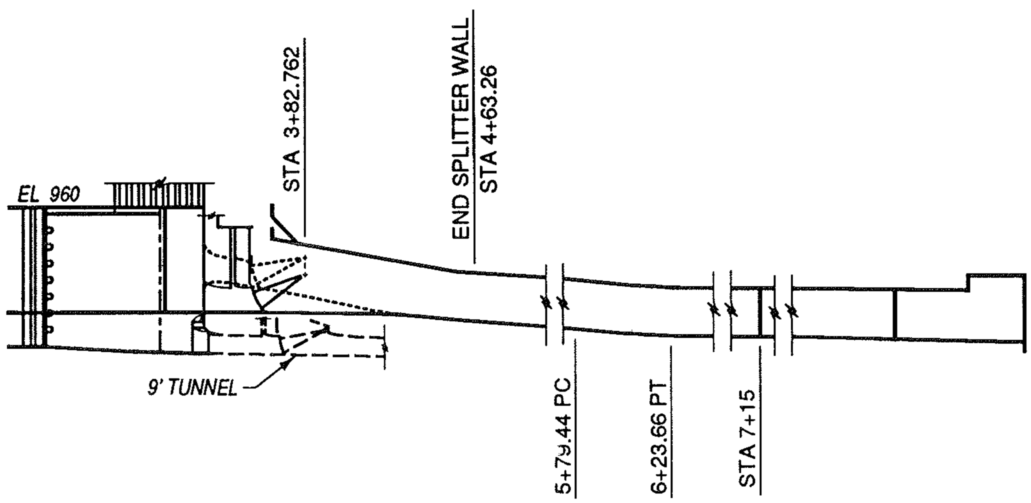
AVERAGE CENTER-LINE
INVERT PRESSURES
TUNNEL 1
ORIGINAL DESIGN



AVERAGE CENTER-LINE
INVERT PRESSURES
TUNNEL 2
ORIGINAL DESIGN

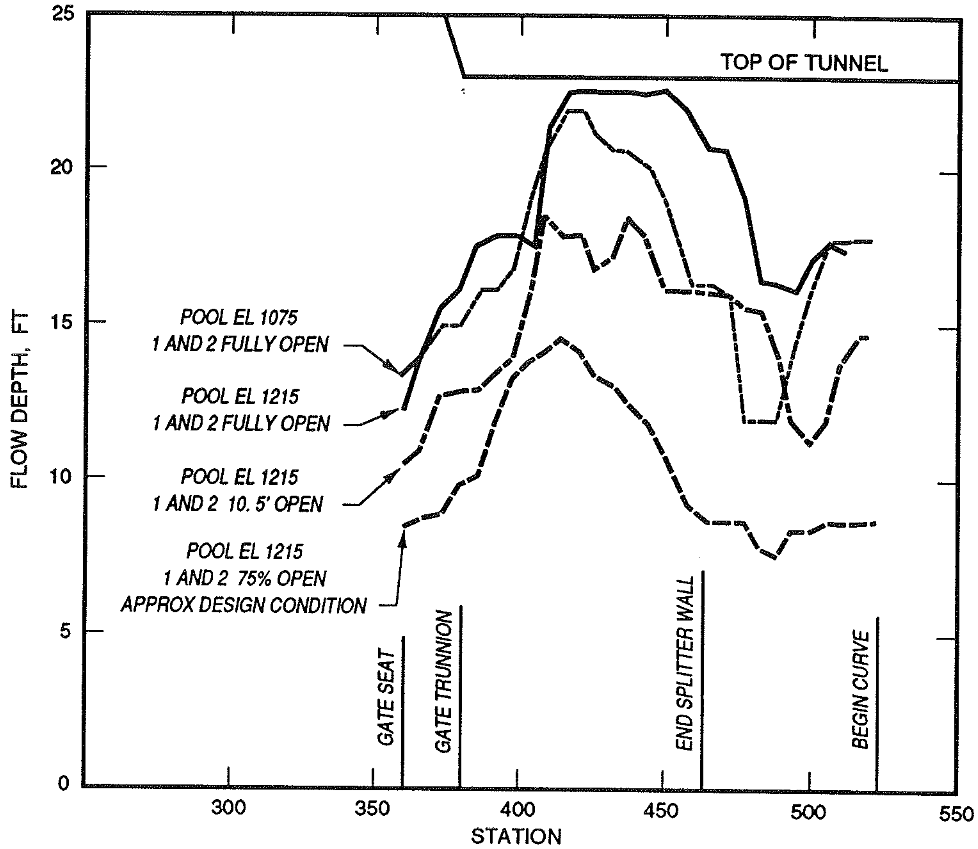


PLAN



ELEVATION

TYPE 2 DESIGN CURVE AND
TYPE 7 DESIGN EXIT STRUCTURE



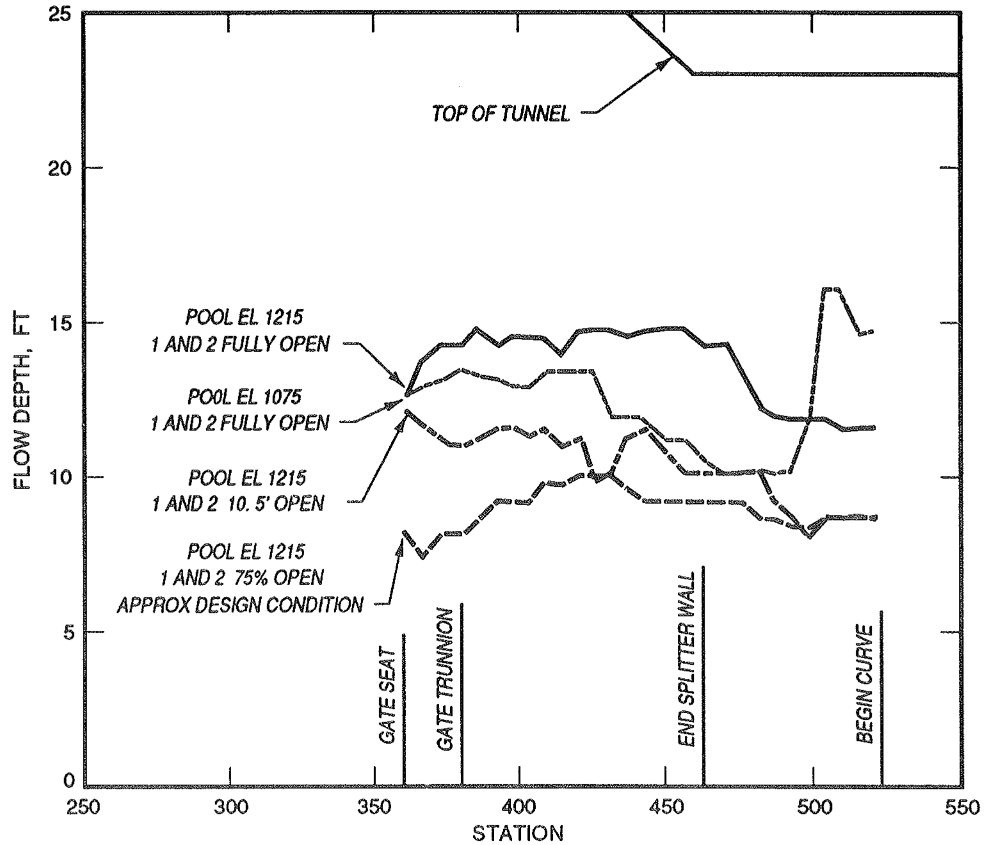
TUNNEL FLOW DEPTH

TUNNEL 1, LEFT WALL

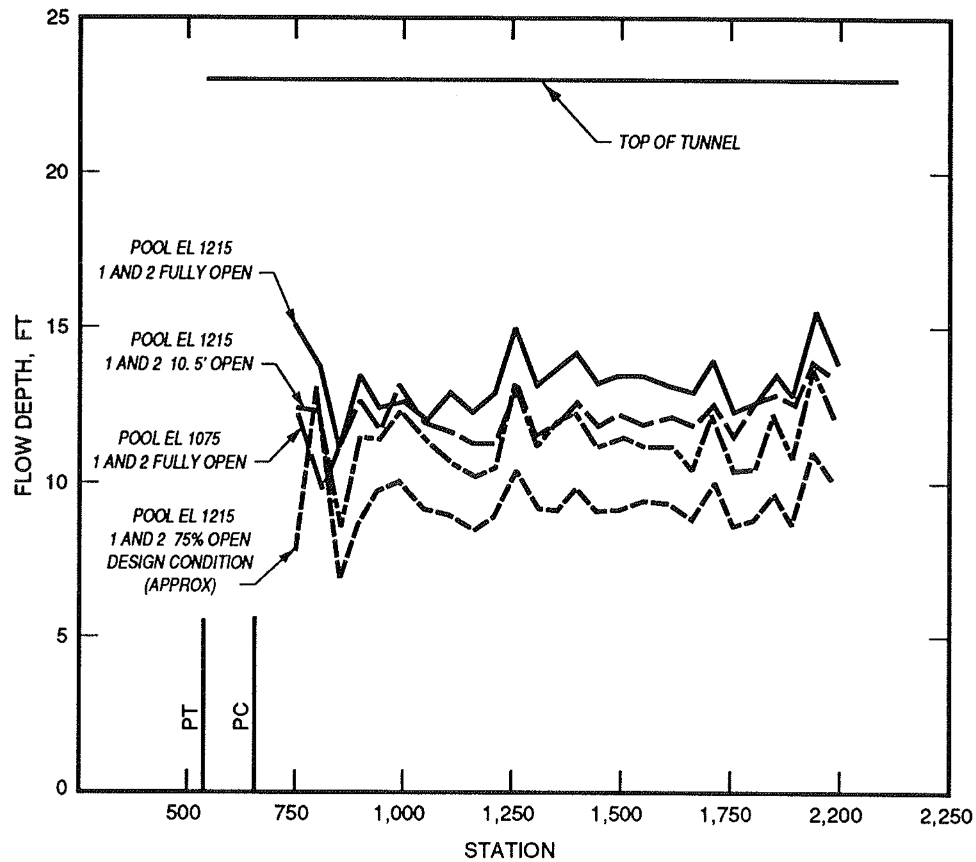
MAXIMUM DEPTH

TYPE 2 DESIGN CONNECTING CURVE

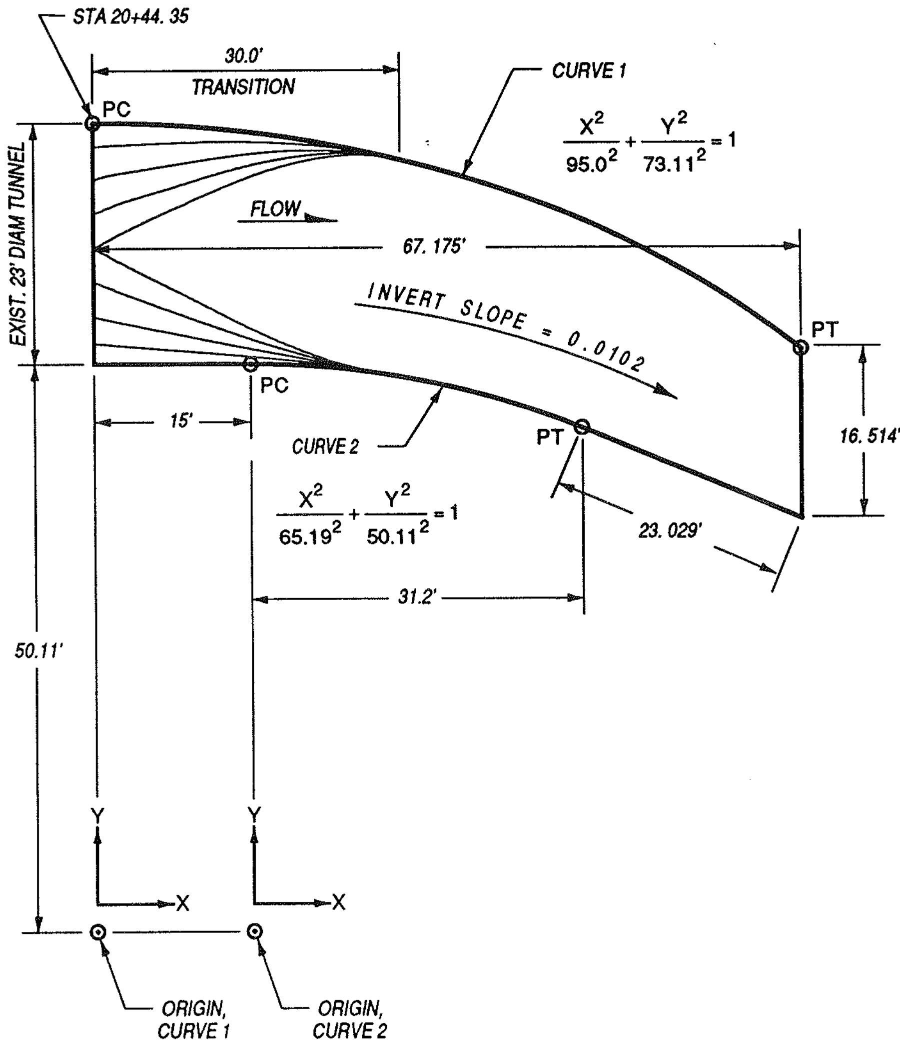
ORIGINAL DESIGN INTAKE TOWER



TUNNEL FLOW DEPTH
TUNNEL 2, RIGHT WALL
MAXIMUM DEPTH
TYPE 2 DESIGN CONNECTING CURVE
ORIGINAL DESIGN INTAKE TOWER



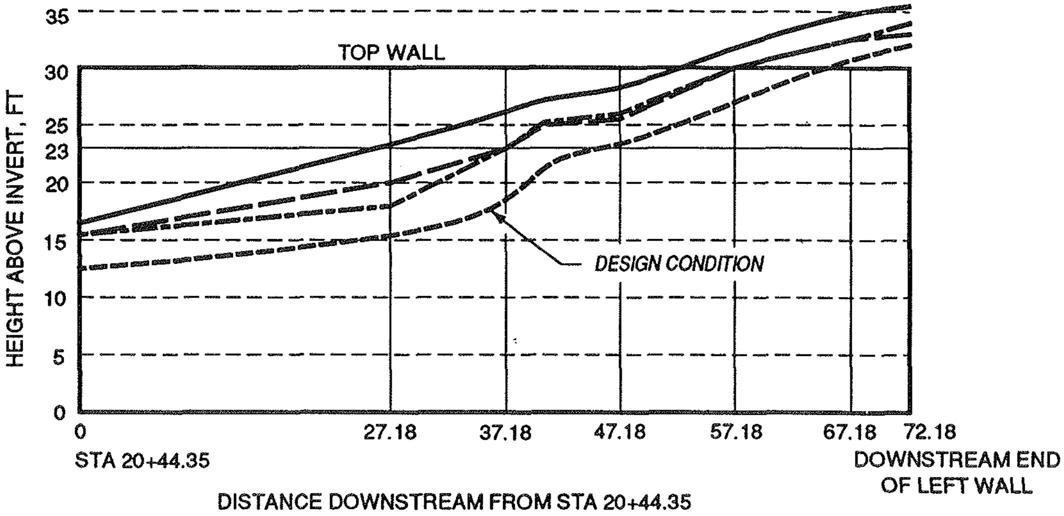
CONDUIT FLOW DEPTH
TYPE 2 DESIGN CONNECTING CURVE
TYPE 3 DESIGN INTAKE TOWER
23-FT TUNNEL HYDRAULIC
GRADE LINE
n = 0.018



PLAN VIEW

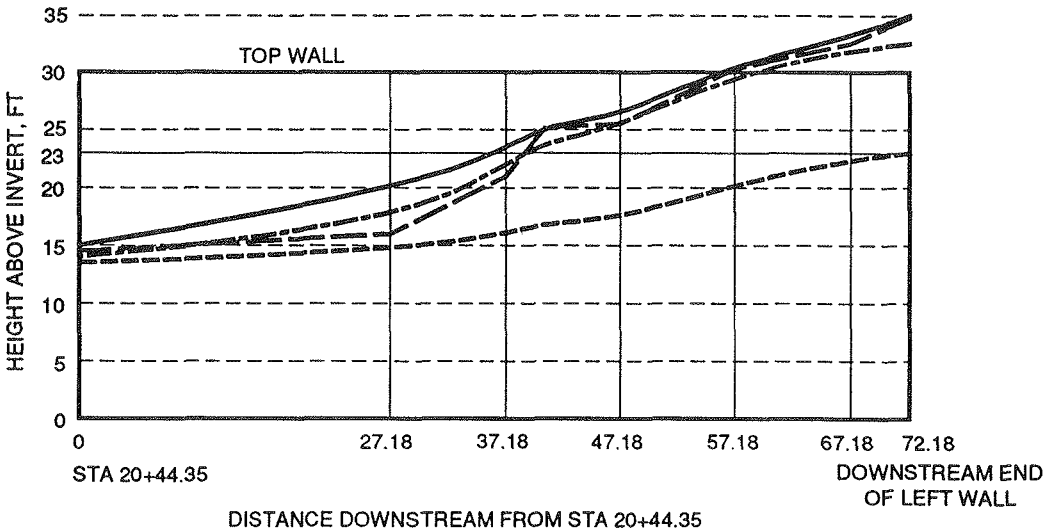
NOTE : 23' DIAM TO RECTANGULAR TRANSITION FILLETS ONLY INCLUDED IN BOTTOM QUADRANTS OF MODEL

TYPE 7
DESIGN EXIT STRUCTURE



	POOL EL	FLOW, CFS	GATE SETTINGS
———	1215	19,500	EQUAL, FULLY OPEN
— - — -	1215	17,100*	EQUAL AT 10.5 FT
— —	1215	17,600	EQUAL
— — -	1215	13,000	EQUAL

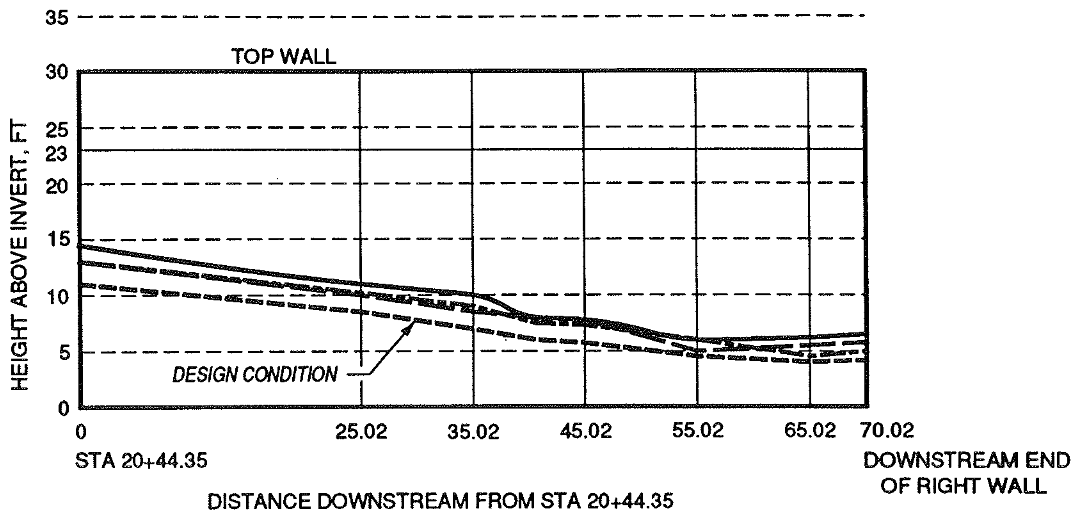
* ESTIMATE ONLY



	POOL EL	FLOW, CFS	GATE SETTINGS
———	1215	16,300	EQUAL, FULLY OPEN
— - — -	1215	14,000	EQUAL AT 10.5 FT
— —	1075	14,200	EQUAL, FULLY OPEN
— — -	980	NOT EST	EQUAL, FULLY OPEN

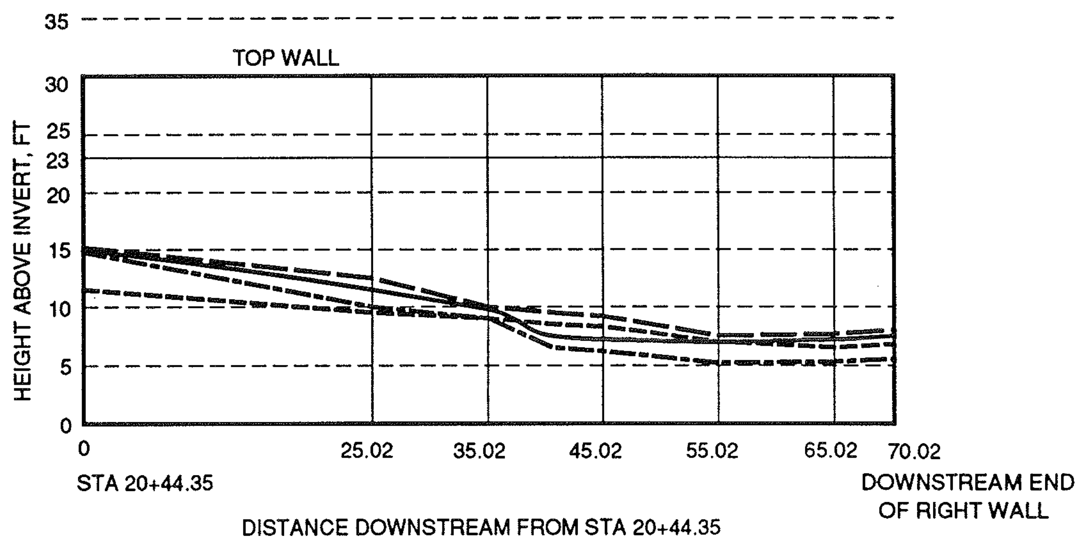
NOTE : DISCHARGES SHOWN ARE ESTIMATES ONLY

WATER-SURFACE PROFILES
LEFT WALL OF TYPE 7 DESIGN
EXIT STRUCTURE
n = 0.018



	POOL EL	FLOW, CFS	GATE SETTINGS
(solid line)	1215	19,500	EQUAL, FULLY OPEN
(dash-dot line)	1215	17,100*	EQUAL AT 10.5 FT
(long dash line)	1215	17,600	EQUAL
(short dash line)	1215	13,000	EQUAL

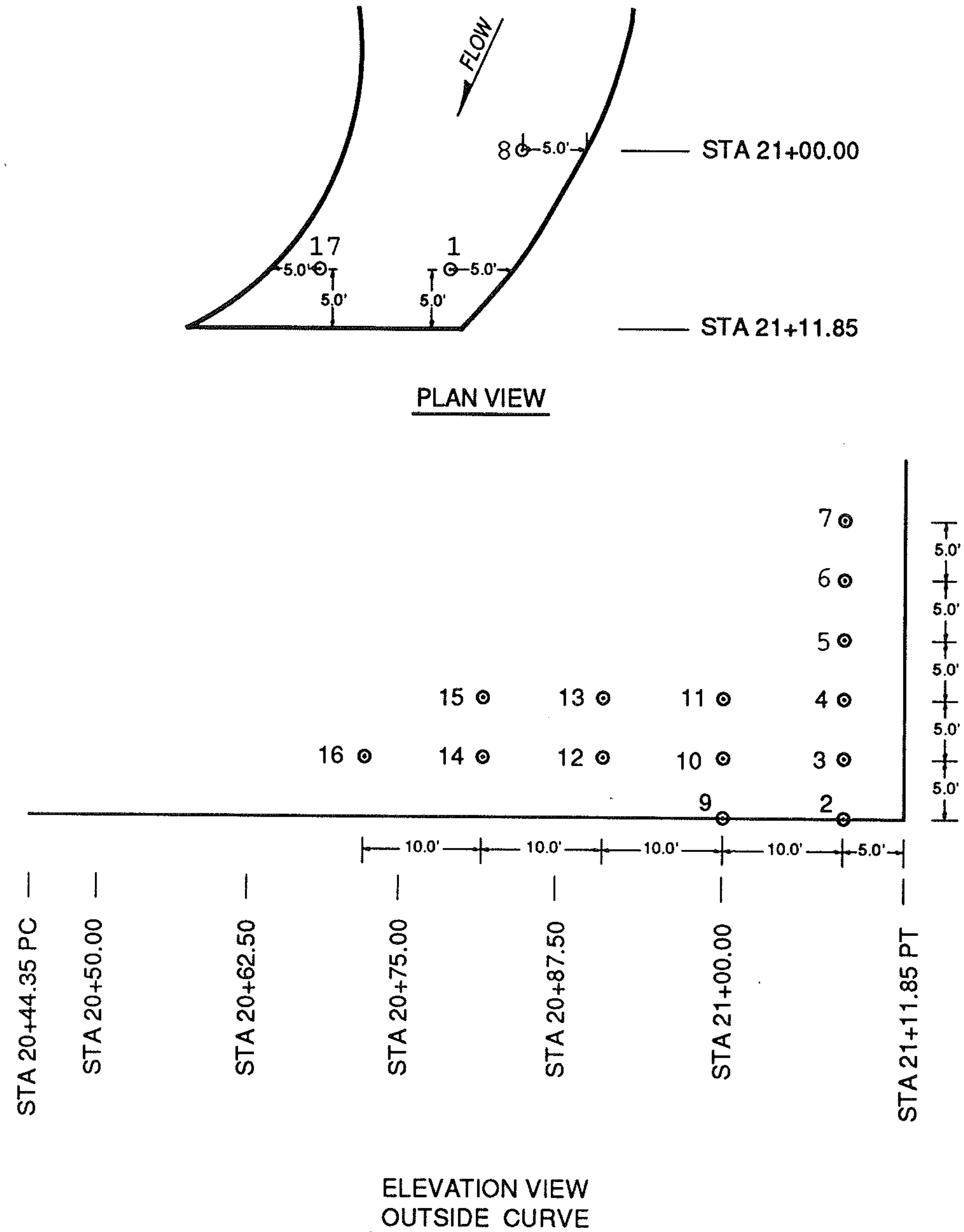
* ESTIMATE ONLY



	POOL EL	FLOW, CFS	GATE SETTINGS
(solid line)	1215	16,300	EQUAL, FULLY OPEN
(dash-dot line)	1215	14,000	EQUAL AT 10.5 FT
(long dash line)	1075	14,200	EQUAL, FULLY OPEN
(short dash line)	980	NOT EST	EQUAL, FULLY OPEN

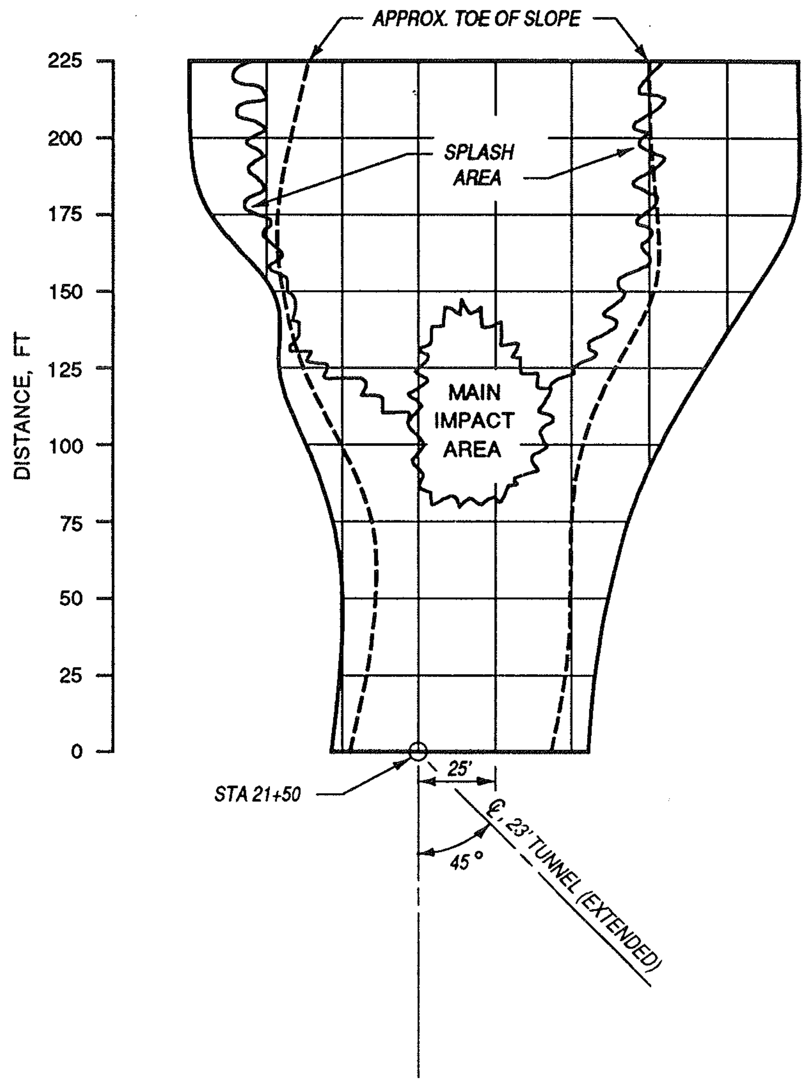
NOTE : DISCHARGES SHOWN ARE ESTIMATES ONLY

WATER-SURFACE PROFILES
RIGHT WALL OF TYPE 7 DESIGN
EXIT STRUCTURE
n = 0.018

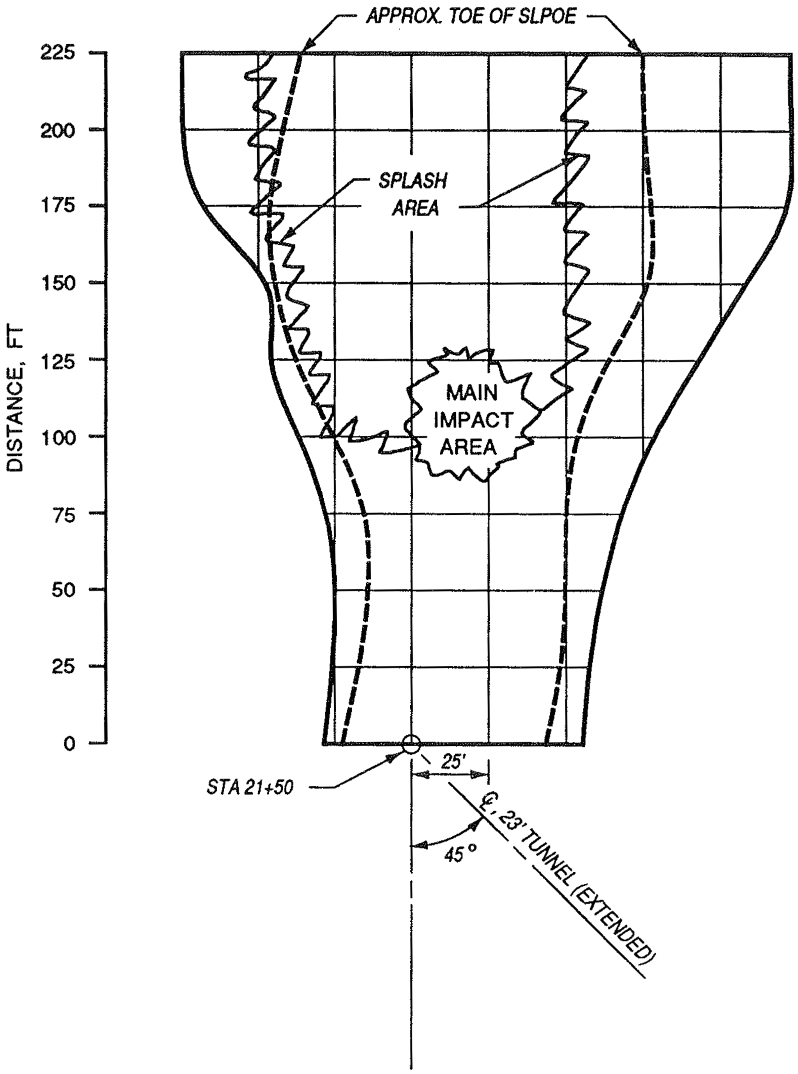


NOTE: HORIZONTAL SCALE SKEWED TO REFLECT OUTSIDE CURVE

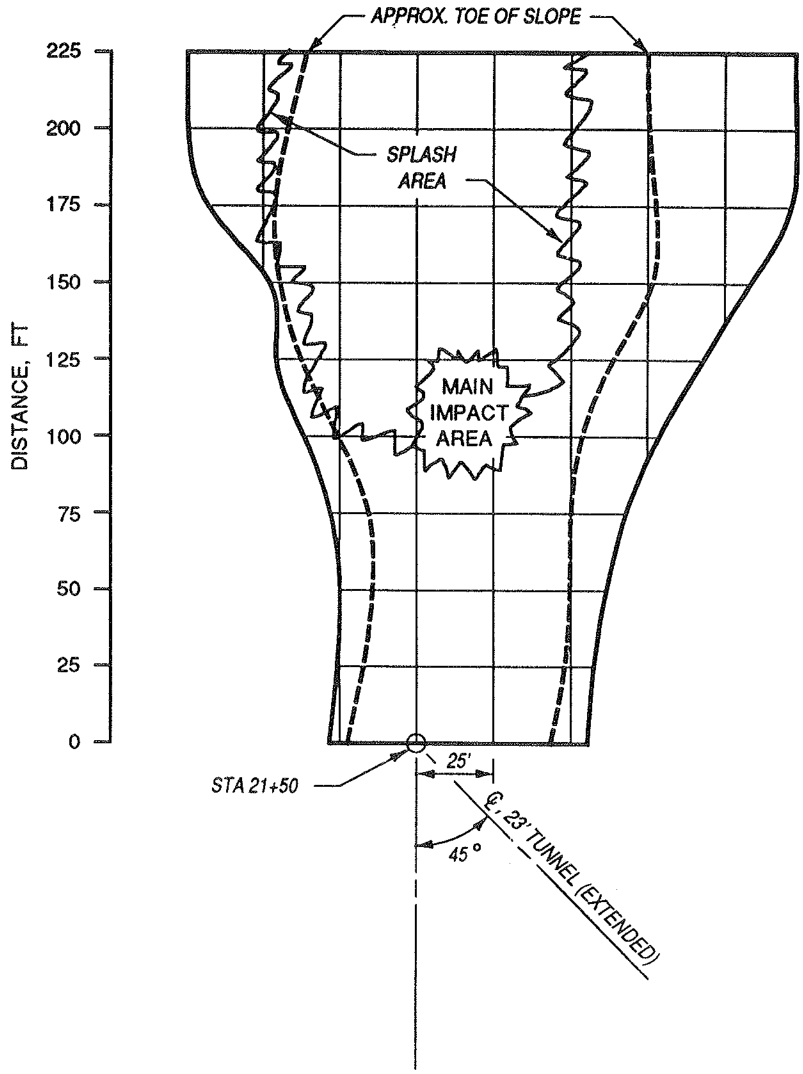
PIEZOMETER LOCATIONS
TYPE 7 DESIGN
EXIT STRUCTURE



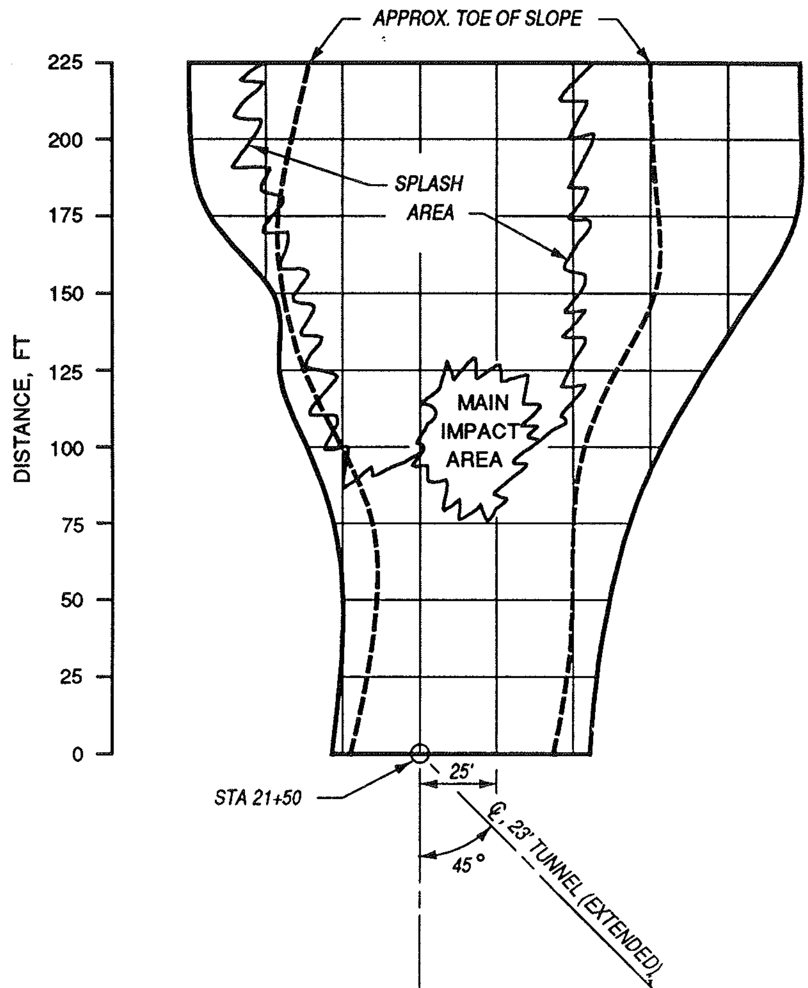
PLAN VIEW OF EXIT CHANNEL
TYPE 7 DESIGN EXIT STRUCTURE
POOL EL 1215
BOTH GATES OPEN FULL
DISCHARGE 19,500 cfs
n = 0.018
MAXIMUM DISCHARGE CONDITION



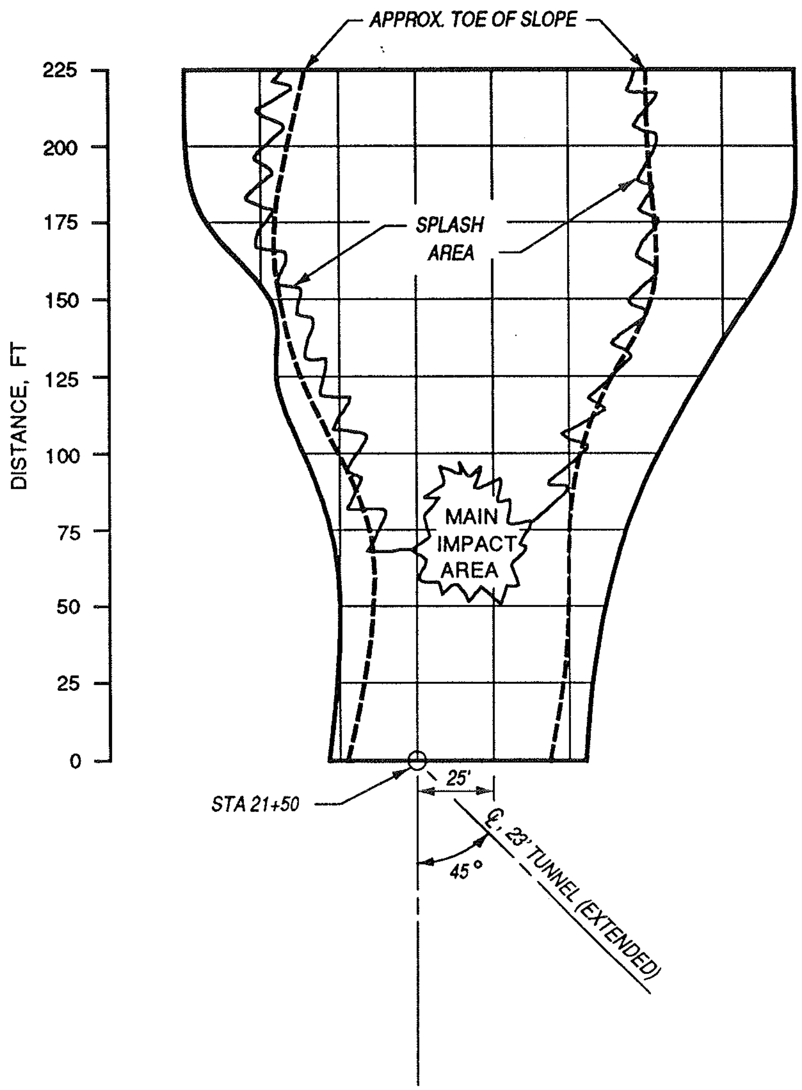
PLAN VIEW OF EXIT CHANNEL
TYPE 7 DESIGN EXIT STRUCTURE
POOL EL 1215
EQUAL GATE OPENINGS
DISCHARGE 17,600 cfs
n = 0.018
MAXIMUM AUTHORIZED PROJECT FLOOD
CONTROL DISCHARGE CONDITION



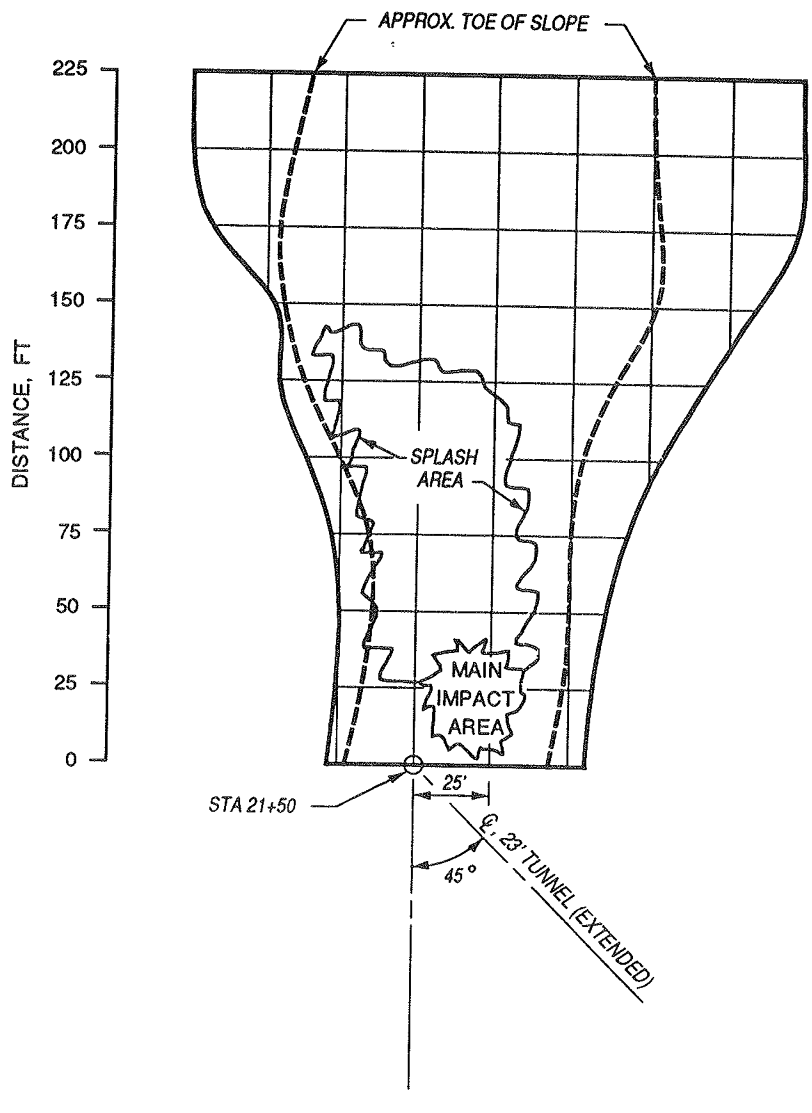
PLAN VIEW OF EXIT CHANNEL
TYPE 7 DESIGN EXIT STRUCTURE
POOL EL 1215
EQUAL GATE OPENINGS
DISCHARGE 13,000 cfs
n = 0.018
DESIGN CONDITION



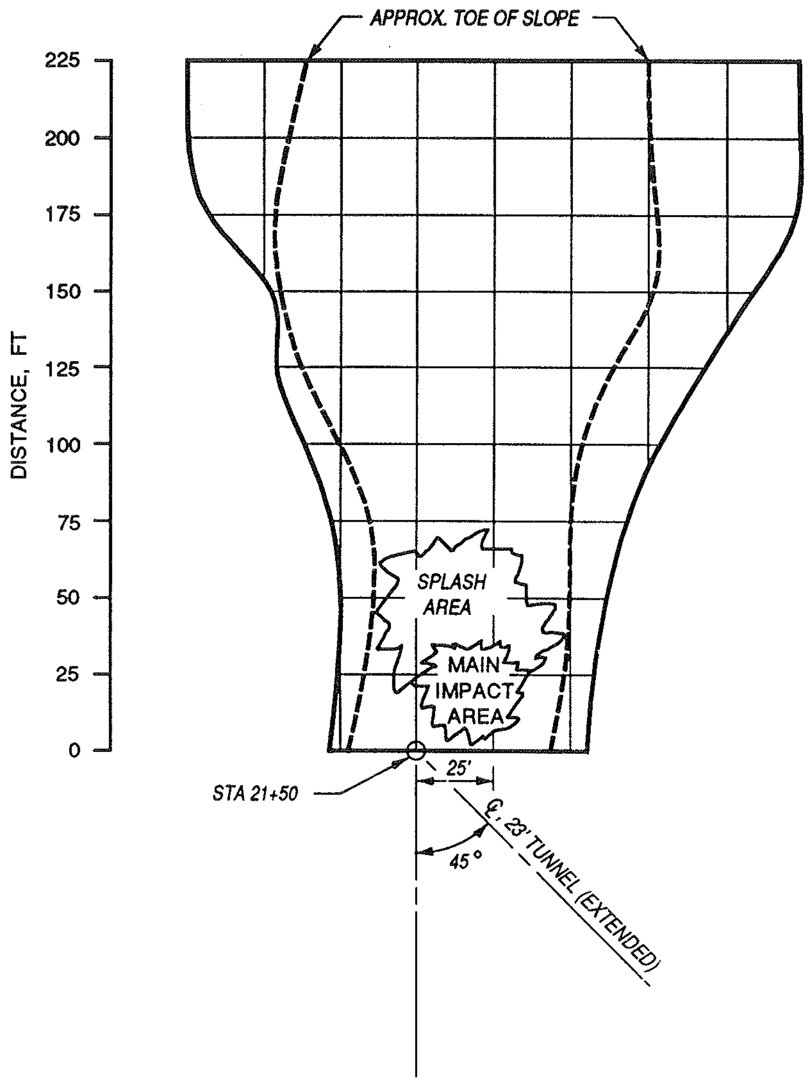
PLAN VIEW OF EXIT CHANNEL
TYPE 7 DESIGN EXIT STRUCTURE
POOL EL 1125
BOTH GATES OPEN FULL
DISCHARGE 16,300 cfs (ESTIMATED)
n = 0.018



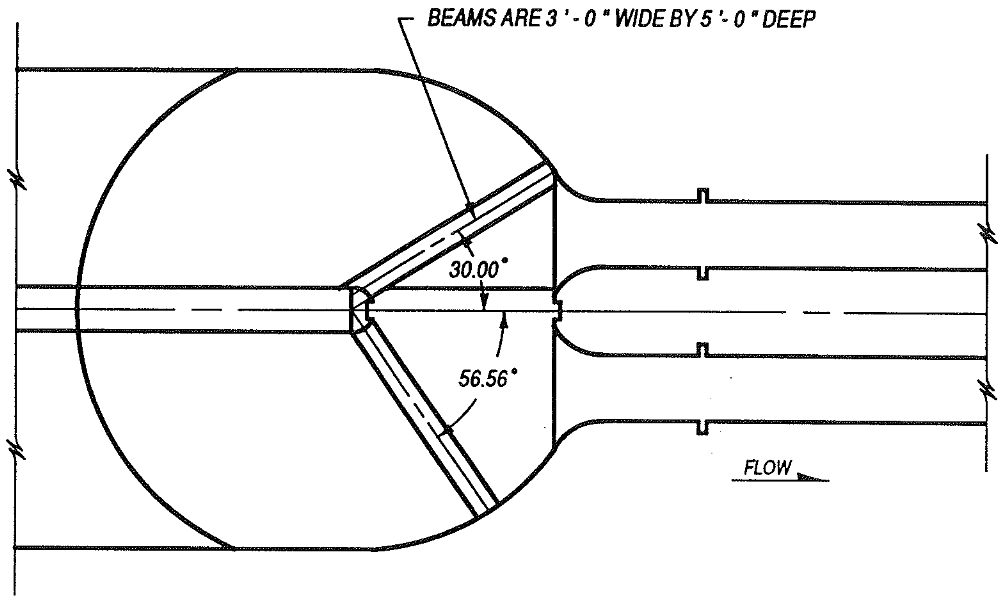
PLAN VIEW OF EXIT CHANNEL
TYPE 7 DESIGN EXIT STRUCTURE
POOL EL 1075
BOTH GATES OPEN FULL
DISCHARGE 14,200 cfs (ESTIMATED)
n = 0.018



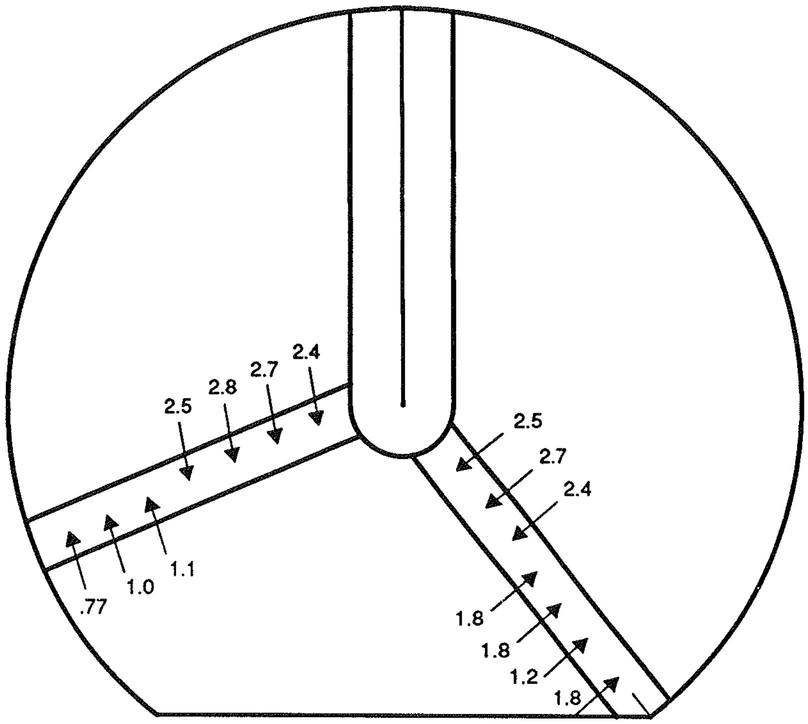
PLAN VIEW OF EXIT CHANNEL
TYPE 7 DESIGN EXIT STRUCTURE
POOL EL 950
BOTH GATES OPEN FULL
DISCHARGE 6,000 cfs (ESTIMATED)
n = 0.018



PLAN VIEW OF EXIT CHANNEL
TYPE 7 DESIGN EXIT STRUCTURE
POOL EL 925
BOTH GATES OPEN FULL
DISCHARGE 1,500 cfs (ESTIMATED)
n = 0.018

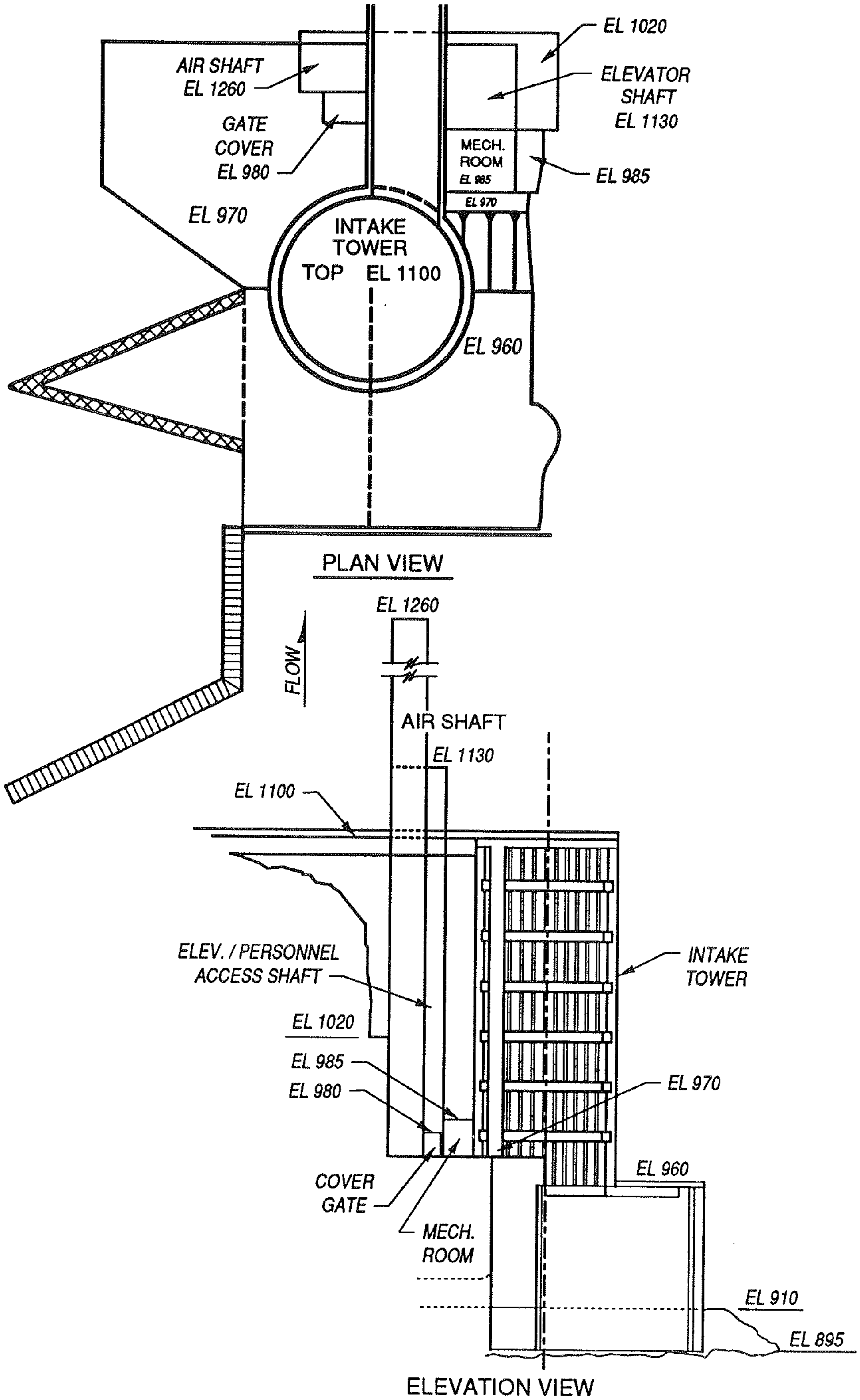


TYPE 4 DESIGN BAFFLE
ORIGINAL DESIGN OUTLET TOWER

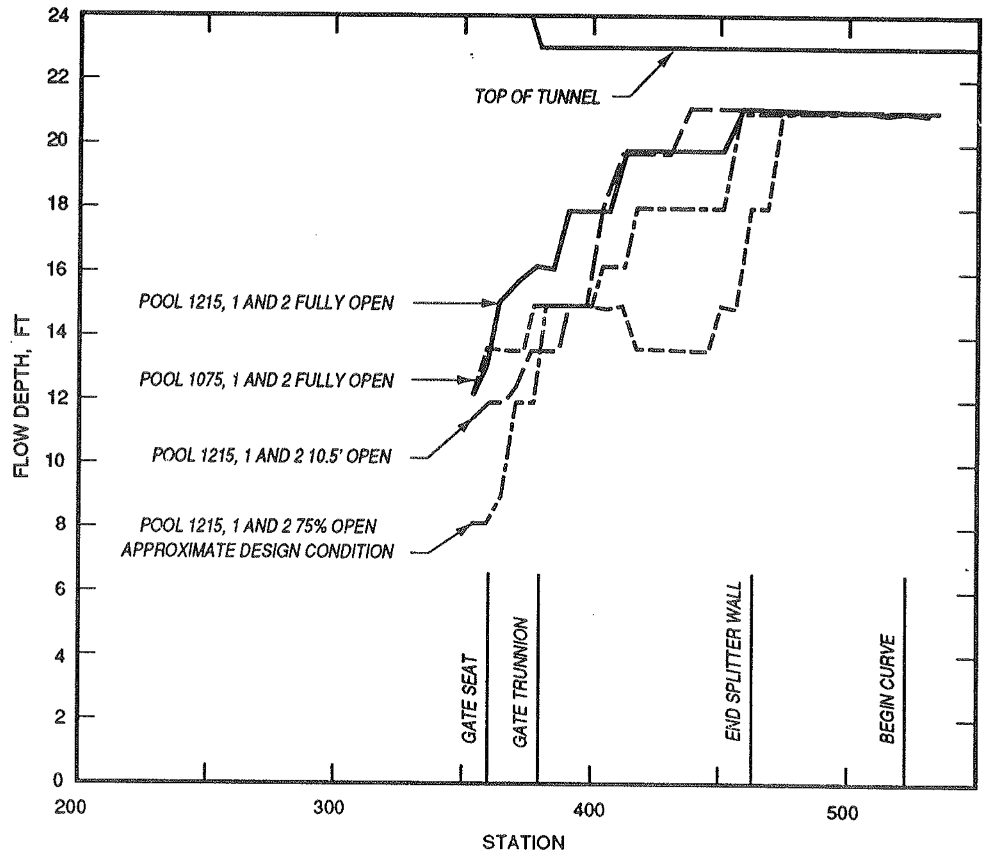


NOTE: TOP OF BAFFLE EL 960
VELOCITIES TAKEN 1 FT ABOVE BAFFLE
VELOCITIES ARE IN FT/SEC

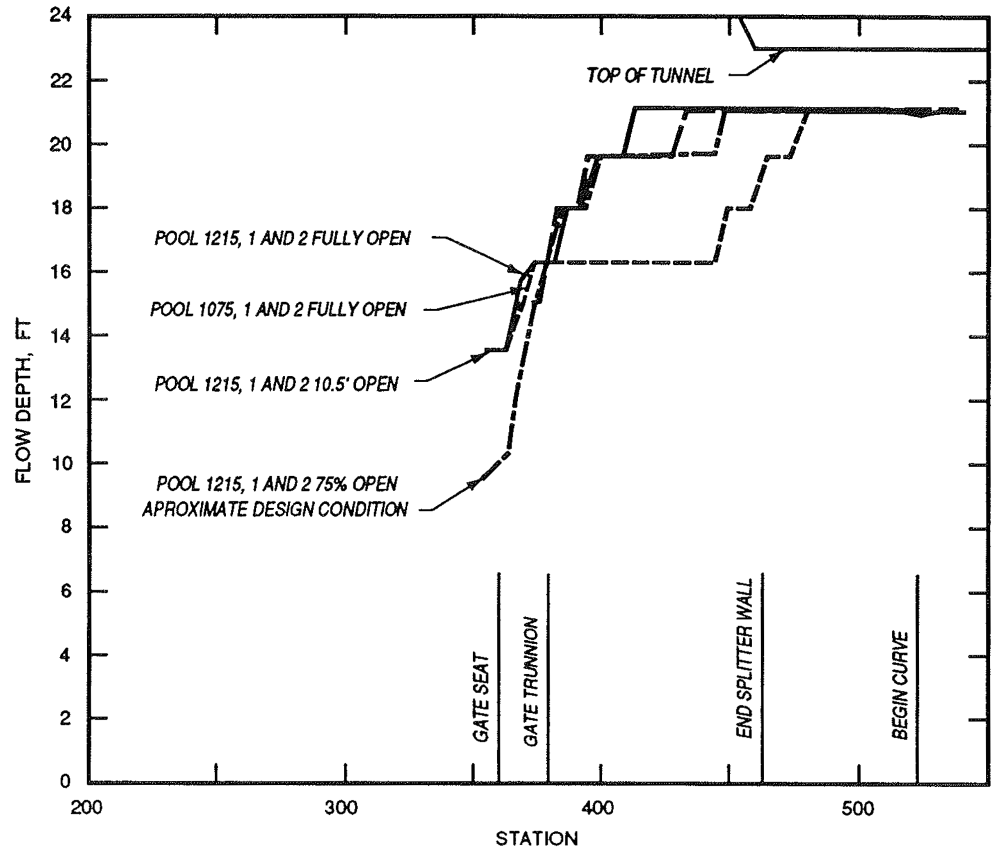
MAXIMUM VELOCITIES
TYPE 4 DESIGN BAFFLE
POOL EL 1008
BOTH GATES OPEN FULL
DISCHARGE 11,650 cfs



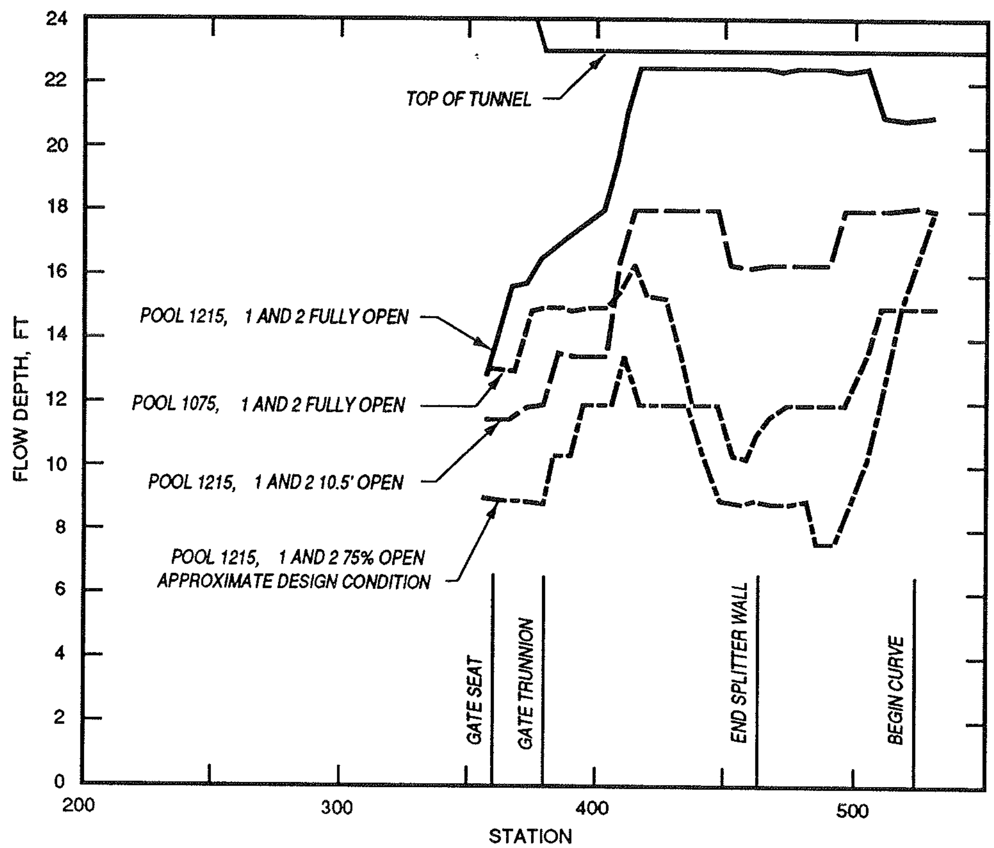
TYPE 2 DESIGN INTAKE TOWER



TUNNEL FLOW DEPTH
TUNNEL 1, LEFT WALL
MAXIMUM DEPTH
TYPE 2 DESIGN CONNECTING CURVE
TYPE 3 DESIGN INTAKE TOWER



TUNNEL FLOW DEPTH
TUNNEL 2, RIGHT WALL
MAXIMUM DEPTH
TYPE 2 DESIGN CONNECTING CURVE
TYPE 3 DESIGN INTAKE TOWER



TUNNEL FLOW DEPTH

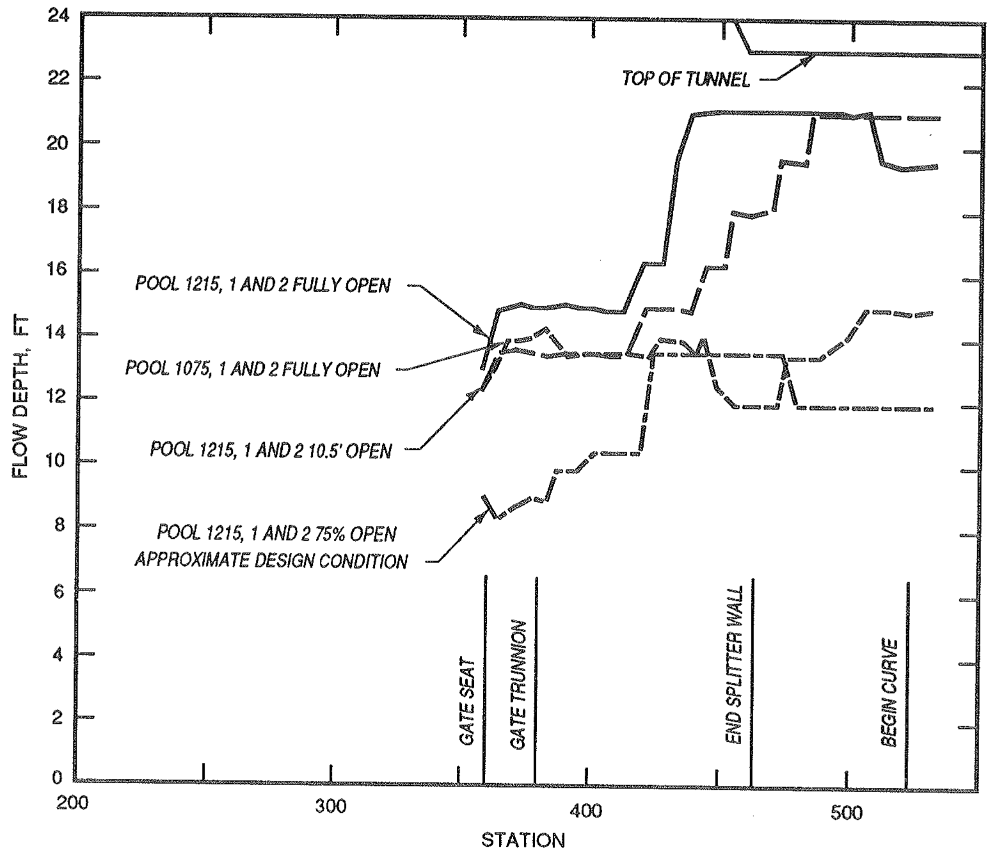
TUNNEL 1, LEFT WALL

MAXIMUM DEPTH

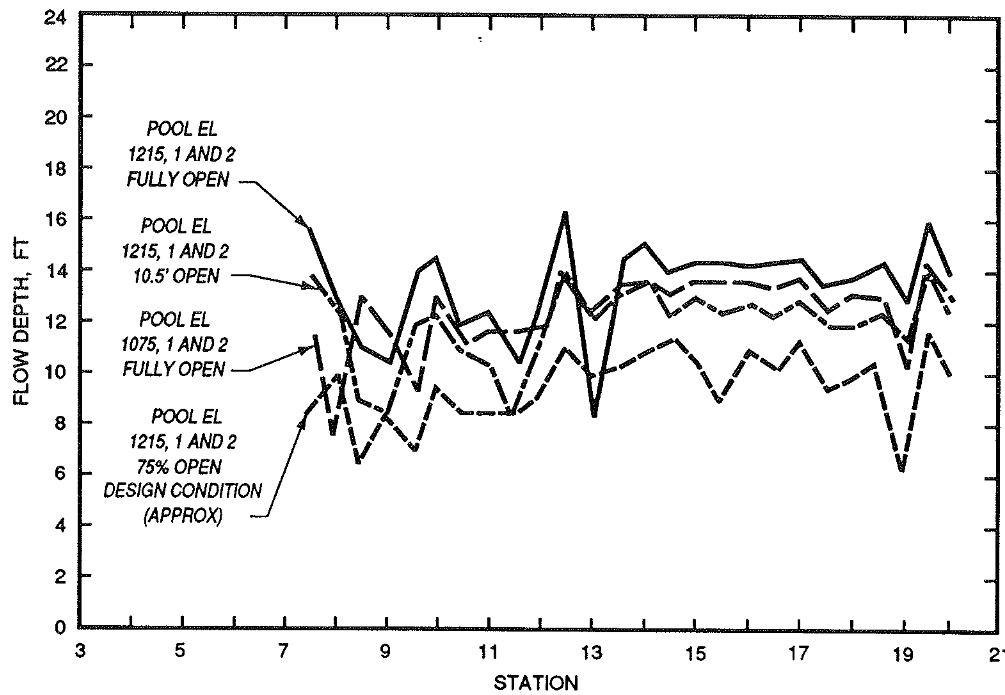
TYPE 2 DESIGN CONNECTING CURVE

TYPE 3 DESIGN INTAKE TOWER

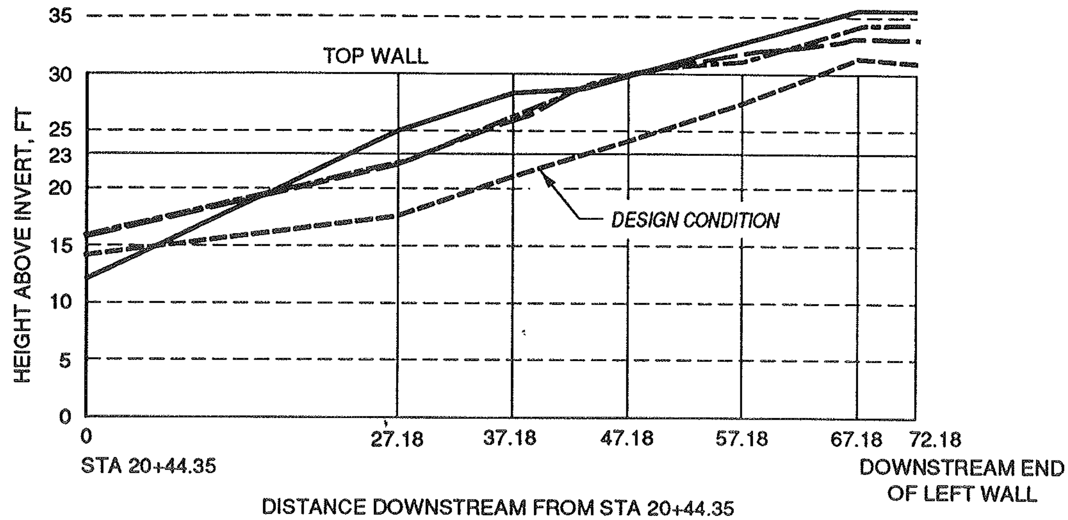
TYPE 7 DESIGN BAFFLE



TUNNEL FLOW DEPTH
TUNNEL 2, RIGHT WALL
MAXIMUM DEPTH
TYPE 2 DESIGN CONNECTING CURVE
TYPE 3 DESIGN INTAKE TOWER
TYPE 7 DESIGN BAFFLE

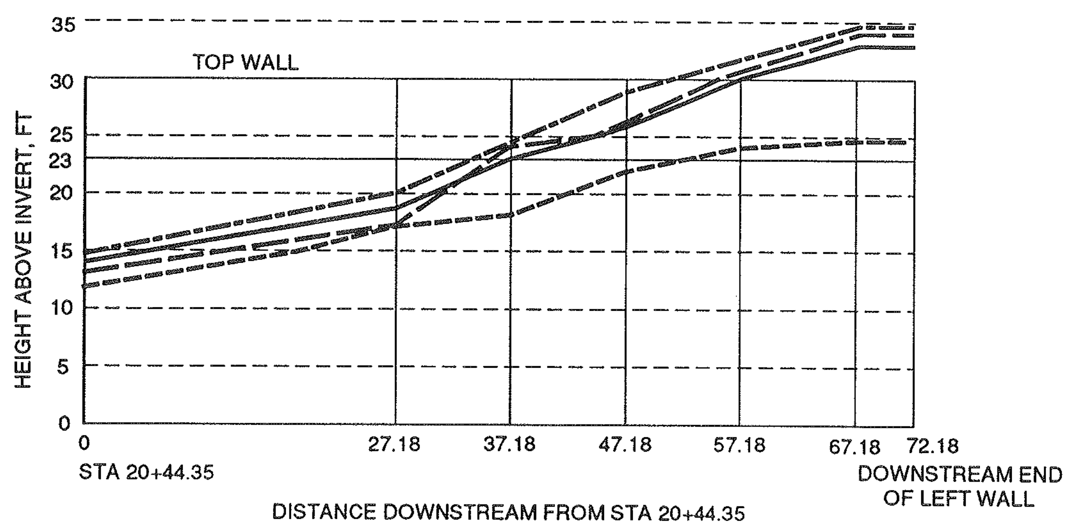


CONDUIT FLOW DEPTH
TYPE 3 DESIGN INTAKE TOWER
23-FT TUNNEL HYDRAULIC
GRADE LINE
n = 0.013



POOL EL	FLOW, CFS	GATE SETTINGS
1215	20,500	EQUAL, FULLY OPEN
1215	17,100 *	EQUAL AT 10.5 FT
1215	17,600	EQUAL
1215	13,000	EQUAL

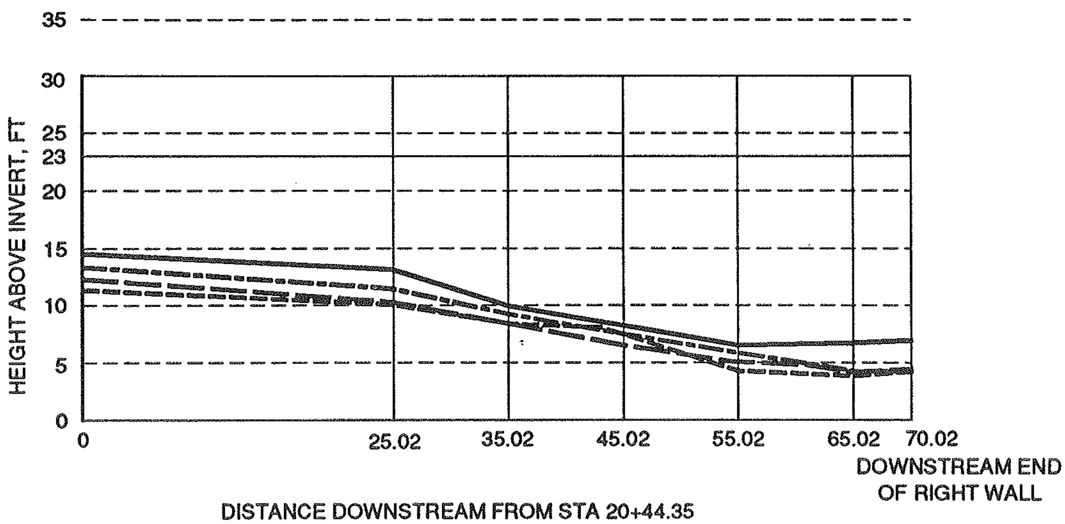
* ESTIMATE ONLY



POOL EL	FLOW, CFS	GATE SETTINGS
1125	16,300	EQUAL, FULLY OPEN
1125	14,000	EQUAL AT 10.5 FT
1075	14,200	EQUAL, FULLY OPEN
980	NOT EST	EQUAL, FULLY OPEN

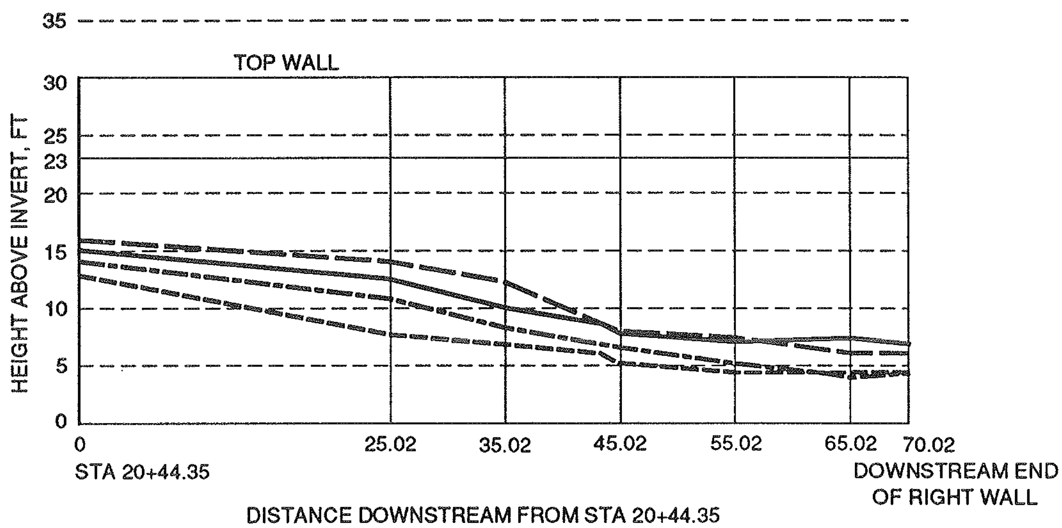
NOTE : DISCHARGES SHOWN ARE ESTIMATES ONLY

WATER-SURFACE PROFILES
LEFT WALL OF TYPE 7 DESIGN
EXIT STRUCTURE
n = 0.013



	POOL EL	FLOW, CFS	GATE SETTINGS
	1215	20,500	EQUAL, FULLY OPEN
	1215	17,100 *	EQUAL AT 10.5 FT
	1215	17,600	EQUAL
	1215	13,000	EQUAL

* ESTIMATES ONLY



	POOL EL	FLOW, CFS	GATE SETTINGS
	1125	16,300	EQUAL, FULLY OPEN
	1125	14,000	EQUAL AT 10.5 FT
	1075	14,200	EQUAL, FULLY OPEN
	980	NOT EST	EQUAL, FULLY OPEN

NOTE : DISCHARGES SHOWN ARE ESTIMATES ONLY

WATER-SURFACE PROFILES
RIGHT WALL OF TYPE 7 DESIGN
EXIT STRUCTURE
n = 0.013

REPORT DOCUMENTATION PAGE

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Charles H. Tate, Jr.

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Modifications to the outlet works at Mud Mountain Dam have been proposed to meet dam safety criteria. As part of the project, a new intake tower is proposed that will contain the entrances and transitions to the 9-ft-horseshoe and the 23-ft-diam flood control tunnels. The three fixed-cone flow control valves on the existing 23-ft-diam tunnel will be replaced with upstream tainter gates, and the tunnel will have open channel flow.

A 1:30-scale model of the proposed 23-ft-diam tunnel was constructed to determine the flow conditions associated with the proposed intake tower and the 23-ft-diam tunnel exit structure. The intake tower was modified several times based on value engineering suggestions and seismic constraints. Vortex conditions were documented for the various designs, and vortex suppression devices were developed for the worst conditions. Pressures were measured in the three bell-mouthed intakes to the tunnels. Flow conditions downstream of the tainter gates were documented, and the original design connecting curve between the new and existing sections of the 23-ft-diam tunnel was modified for improved flow conditions and a significant construction savings. Flow through the existing tunnel was documented. The exit structure was modified to direct the flow into the center of the exit channel. Pressures and water-surface profiles were documented through the recommended exit structure.

14. SUBJECT TERMS
Bell mouth intake pressures
Hydraulic models
Mud Mountain Dam, Washington State
Outlet works

15. NUMBER OF PAGES
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16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		