UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDIES OF YELLOWTAIL DAM SPILLWAY AND OUTLET WORKS

(Preliminary Studies)*

Hydraulic Laboratory Report No. Hyd-414

DIVISION OF ENGINEERING LABORATORIES

OFFICE OF ASSISTANT COMMISSIONER AND CHIEF ENGINEER
DENVER, COLORADO

August 17, 1961

*see page i

HYD 414

PRELIMINARY STUDIES

Two separate designs for the Yellowtail Dam Spillway and Outlet Works were developed through hydraulic model studies of these structures. This report (Hyd-414) discusses the results of the initial studies which are designated "Preliminary." The designs developed from these "Preliminary Studies" were never built because changes in hydraulic requirements occurred before construction was started.

The second, or "Final Studies," brought about by the change in hydraulic requirements, concern the final design outlet works and spillway structures. The results of these studies are discussed in Hydraulic Laboratory Report Nos. Hyd-482 and Hyd-483.

CONTENTS

CONTENTS--Continued

CONTENTS--Continued

CONTENTS--Continued

CONTENTS--Continued

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Commissioner's Office--Denver
Division of Engineering Laboratories
Hydraulic Laboratory Branch
Hydraulic Structures and Equipment Section
Denver, Colorado
August 17, 1961

Laboratory Report No. Hyd-414
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Subject: Hydraulic model studies of Yellowtail Dam spillway and outlet works (Preliminary studies)*

THE SUMMARY

Hydraulic model studies of Yellowtail Dam spillway and outlet works, Figures 1 through 11, inclusive, were conducted on a 1:54 scale spillway model, Figures 12, 13, and 14, and a 1:28 scale outlet works model, Figure 15. The purpose of the study was to develop the hydraulic design of the tunnel spillway and the hollow-jet valve outlet works, and to obtain data useful in designing and operating the prototype structures.

Data and notes taken on the flow in the model structures showed that the general concept of the preliminary spillway structure, Figures 15 and 26, was satisfactory but that the preliminary concept of the outlet works, Figure 31, could be improved by the installation of a stilling basin, Figures 2, 3, 8, 9, 10, and 11.

As a result of this study the right bank of the spillway approach was reshaped, Figures 17, 18, 57, and 58, to improve the flow conditions in the approach channel. The spillway crest section, the spillway tunnel, and the spillway stilling basin were revised and recommended as shown in Figures 56 and 78 to reduce the construction cost of the prototype without sacrificing good hydraulic flow performance.

The spillway structure was calibrated, Figures 60 and 61, for both free flow and gate controlled flow for use in prototype operation of the spillway gates. Other design data concerning the recommended spillway crest and tunnel obtained from the model are shown in Figures 62 through 66. Other data concerning the recommended spillway stilling basin design are shown in Figures 76 through 79.

Tests on the preliminary outlet works structures, shown in Figures 31 through 35, showed the need for an outlet works stilling basin since the jets from the hollow-jet valves washed the riverbanks which, in

*see page i

the prototype, are covered with talus. The basin recommended for prototype use, Figure 55, was developed, Figures 39 through 54, inclusive, in the larger outlet works model and retested in the spillway model to be certain that the flow conditions in the river channel, Figure 80, were satisfactory for combined spillway and outlet works flows.

Motion pictures were taken throughout construction of the model, testing of the 1:54 scale spillway model, and testing of the 1:28 scale outlet works model. These pictures are assembled in a 16-mm film entitled "Hydraulic Model Studies of Yellowtail Dam Spillway and Outlet Works."

ACKNOWLEDGMENT

The final plans evolved from these studies were developed through the cooperation of the staffs of the Concrete Dams Branch and the Hydraulic Laboratory Branch. These studies were conducted during the period from November 1950 to January 1953. The final studies began in October 1960 and will be reported in Hyd-482 1/ and Hyd-483. 2/

INTRODUCTION

Yellowtail Dam is a part of the Missouri River Basin Project. It is located on the Big Horn River about 60 miles southeast of Billings, Montana, Figure 1. The dam, Figures 2 and 3, is a concrete arch-type dam approximately 1,300 feet long and 500 feet high above the riverbed. The discharge structures include a spillway, outlet works and powerhouse.

The spillway, Figures 4, 5, and 6, located in the left abutment, consists of two converging gate sections discharging into a concrete lined "horseshoe" tunnel. The spillway crest is at elevation 3593, 13 feet above the channel floor of the spillway approach and 64 feet below the maximum design reservoir elevation. The spillway tunnel consists of a transition section in which the tunnel changes from rectangular to horseshoe, a 45° inclined section in which the tunnel tapers from a 49-foot-diameter horseshoe to a 41-foot-diameter horseshoe, a 320.5-foot-radius bend, a nearly horizontal section, and a parabolic transition section that discharges into a stilling basin at the tunnel portal. Two 50- by 61.66-foot radial gates are provided at the spillway crest separated by a tapered concrete pier, Figure 7. The pier extends about halfway down the tunnel incline. The extra length is provided primarily for structural support of the tunnel roof.

The stilling basin apron is 448 feet below the spillway crest and 25 feet below the top of the end sill of the stilling basin and the level of the excavated discharge channel connecting the stilling basin to the river channel. The tunnel outlet portal is 1,771.5 feet downstream from the crest measured horizontally and 120 feet upstream from the end of the stilling basin.

1/Hyd-482 "Hydraulic Model Studies of Yellowtail Dam Outlet Works (Final Studies)" by T. J. Rhone
2/Hyd-483 "Hydraulic Model Studies of Yellowtail Dam Spillway (Final Studies)" by G. L. Beichley

The spillway is designed to discharge 173,000 second-feet at the maximum reservoir elevation 3657. Flows will exceed 12,000 second-feet, however, only when the reservoir elevation exceeds elevation 3640. When the reservoir is between elevation 3614 and 3640, releases of up to 20,000 second-feet will be required if a flood is approaching from upstream. In this case, the spillway would be required to discharge 12,000 second-feet, the outlet works 5,000 second-feet, and the powerhouse 3,000 second-feet. For spillway discharges up to 12,500 second-feet, the energy dissipator at the end of the spillway tunnel performs as a hydraulic jump stilling basin. For greater discharges the jump sweeps out and the basin performs as a flip bucket.

The outlet works, Figures 2, 3, 8, 9, 10, and 11, consists of two 84-inch-diameter outlets through the dam, controlled with hollow-jet valves, that discharge into a concrete stilling basin located adjacent to and to the right of the powerhouse at the toe of the dam. The outlets discharge a maximum of 2,500 second-feet each. In the preliminary plans the outlets discharged directly into the river channel, but model tests showed the need for a stilling basin. The basin developed for use is of a type which may be included in the powerplant structure.

The powerplant, Figures 2, 3, 8, 10, and 11, located at the toe of the dam accommodates four main generating units. Each unit is designed to discharge approximately 1,500 second-feet.

THE MODELS

Two models were used in the investigation. One was a 1:54 scale reproduction of the spillway and surrounding area, including the powerhouse and outlet works, Figures 12, 13, and 14. The other model was a 1:28 scale reproduction of the outlet works stilling basin and surrounding area, Figure 15.

The Spillway Model

The spillway model, Figure 12, consists of three main parts: (1) the reservoir area surrounding the spillway entrance; (2) the spillway structure consisting of the gate section, the tunnel, and the stilling basin; and (3) the tail water area consisting of the powerhouse, the outlets, and the river channel extending from the powerhouse to 1,000 feet downstream from the spillway portal. This model was constructed to a 1:54 scale.

PRELIMINARY STUDIES

The Reservoir

The reservoir was contained in a head box which allowed reproduction of the topography for 300 feet upstream from the spillway crest and approximately 300 feet to the right and 100 feet to the left of the spillway center line. Topography in the reservoir area was modeled of concrete mortar placed on metal lath which had been nailed over wooden templates shaped to the ground surface contours as shown in Figure 13A. The surface was given a rough finish to simulate the natural topography of the prototype.

Spillway Structure

Gate section. The gate section consists of the crest, gates, and center pier. The crest was molded in cement mortar, Figure 13D. Sheet-metal templates accurately cut and placed were used as guides, Figure 13B. Piezometers were installed in the spillway crest and consisted of 1/16-inch inside-diameter brass tubes soldered at right angles to the profile shape of the template and filed flush, Figure 13B.

The radial gates were constructed of 16-gage sheet metal. Threaded rods with a crank handle were provided for regulating the gate opening.

The center pier for the preliminary design was constructed of wood, Figure 14A. The pier was soaked in linseed oil to prevent warping. In the recommended design the portion of the pier extending over the crest section was constructed of sheet metal while that portion extending into the tunnel was constructed of transparent plastic.

Tunnel. In the preliminary design the upstream portion of the tunnel transition containing the center pier, shown in Figure 12, was formed of sheet metal, Figure 13C. The remainder of the tunnel, downstream to the transition section preceding the stilling basin, was molded in transparent plastic. Wood patterns, Figure 14B, were accurately shaped for use in molding the plastic tunnel sections. The plastic sections were then flanged and bolted together using waterproof grease between flanges to prevent leakage. Plastic piezometers having a 1/16-inch inside diameter were inserted at regular intervals along the invert and crown of the tunnel.

The tunnel transition section preceding the stilling basin in the preliminary design was molded in cement mortar similar to the method used for construction of the crest section. Piezometers were inserted along the invert in a like manner. The top of this section of tunnel was left open for observing flow conditions. In the recommended design this transition section and the upstream transition section containing

the pier were rebuilt of transparent plastic, the same as the remainder of the tunnel.

Hydraulic losses. Head losses due to friction in the model are usually greater, proportionately, than indicated by the model scale because surfaces sufficiently smooth to represent prototype surfaces to scale do not exist. Therefore, to maintain the scale velocity of the flow entering the stilling basin, it was necessary to either increase the slope of the tunnel or reduce the horizontal length. To maintain proper geometric similitude at the junction of the tunnel and the stilling basin, it was better to reduce the tunnel length than to increase the tunnel slope. For developing the design of the stilling basin, it was important that the velocity of the sweep-out discharge be correctly represented in the model. The model tunnel length reduction was, therefore, calculated for the anticipated maximum capacity of the stilling basin, 16,000 second-feet, at an entrance velocity of 81 feet per second. The reduction in length was computed to be 8.83 feet in the model or approximately 477 feet in the prototype. This reduction was based on a prototype roughness coefficient "n" of 0.014 in Manning's equation and a model roughness coefficient of 0.009, which represents a prototype roughness coefficient of 0.0175. Based on these coefficients, the tunnel would have been shortened to 10 feet to correct for 173,000 second-feet.

Spillway stilling basin. The preliminary basin had a concrete floor with sheet-metal sidewalls. Sheet-metal templates accurately cut and placed were used as guides in molding the floor to correct elevation. In the recommended design, the upstream portion of the basin was molded of transparent plastic while the downstream protion, which was open at the top, was constructed of wood presoaked in linseed oil.

The Tail Water Area

Outlet works. In the preliminary design, the outlet works consisted of two 90-inch hollow-jet valves discharging directly into the river channel from the valve house shown in Figure 12. No stilling basin was provided. Since the model valves were only 1.8 inches in nominal diameter, they were constructed of plastic with no provision for flow regulation. The valves thus operated in the 100 percent open position in the model. A recess was molded into the riverbed downstream from the outlet valves and filled with 3/8-inch crushed rock which provided a movable bed for erosion studies. In the recommended design, a stilling basin was installed along the right bank adjacent to the powerhouse.

Powerhouse. The model powerhouse training walls and draft tube outlets were constructed of wood as shown in Figure 12. Measured flows were introduced into the model, passed through a baffle system, and released through the draft tubes in such a way that the discharge and velocity leaving the structure represented prototype flow conditions.

PRELIMINARY STUDIES

River channel. A length of river channel extending from the powerhouse to approximately 1,000 feet downstream from the spillway portal was simulated in the model as shown in Figure 12. Topography was first molded in 3/4-inch gravel, then covered with a 3/4-inch layer of cement mortar.

Water Supply

Water was supplied to the model from the laboratory's permanent supply system. All flow entered the head box and was measured by calibrated Venturi meters. The portion of the flow to be passed through the powerhouse and outlet works entered a supply pipe connected to the head box and was measured by means of a bend meter calibrated in place and shown in Figure 12. The differential pressure between the inside wall of the bend and the outside wall was used to calibrate the bend meter for a range of discharges. To again divide the flow and measure the portion to be passed through the outlet works, a piezometer was installed 1 diameter upstream from one of the hollow-jet valves. The discharge pressure relationship at the piezometer was determined from calibration tests with the structure and piping in place. The valves could therefore be regulated so that proper division of the flow could be made between the spillway and the powerhouse and outlet works structures, then further divided between the outlet works and the powerhouse.

Water-surface Elevations

The reservoir water-surface elevation was measured by means of a hook-gage-in-well shown in Figure 12. Water-surface elevations in the river channel were controlled by a tailgate at the downstream end of the model. Two staff gages and a point gage were used to measure the elevation of the water surface in the river channel at three locations. Staff gages were used at the powerhouse and near the spillway stilling basin while the point gage, shown in Figure 12, was used near the downstream end of the model at about Station 24+00.

The Outlet Works Model

The outlet works model, Figure 15, constructed to a 1:28 scale, utilized two 3-inch hollow-jet valves to represent the two 84-inch valves of the prototype. The valves discharged into a stilling basin with an erodible bed downstream.

The 3-inch valves were operating models carefully machined of brass. The stilling basin was constructed of wood, however, the center wall and one training wall were covered with sheet metal. The other wall was the glass side of a test flume and provided means for observing the

flow throughout the depth of the basin. The river channel topography was molded in sand to provide a movable bed for studying erosion characteristics of the flow from the basin.

Water was supplied to the model from a portable vertical pump through an 8-inch line to a manifold where it was divided between the 3-inch pipes supplying the hollow jets. A portable 8-inch orifice Venturi meter was used to measure the discharge. The piezometric head on the valves was set in the model by opening or closing the hollow-jet valves and observing the pressure 1 diameter upstream from each valve where a piezometer and water manometer had been installed. Water-surface elevations in the river channel were regulated with a tailgate and measured by use of the tail water staff gage, shown in Figure 15.

THE INVESTIGATION

Purpose and Scope

The primary purpose of the investigation was to develop the hydraulic design of the spillway and outlet works structures and to determine the effect of operating the three discharge structures singly, in pairs, or all together. In developing the spillway design, it was necessary to study the characteristics of the flow as it approached and passed through the spillway as well as the characteristics of the flow as it entered and flowed through the river channel. Two spillways were tested; the preliminary spillway utilized a 45-foot-diameter horseshoe tunnel while in the recommended design the diameter was reduced to 41 feet. Each was tested with modifications to the entrances and exits.

In developing the outlet works stilling basin, after preliminary tests on the 1:54 model had shown the need for an energy dissipator, it was necessary to study the flow in the stilling basin and in the river channel. The stilling basin developed in the 1:28 scale model was then reconstructed in the 1:54 scale model and tested with and without the powerhouse and spillway operating.

Preliminary Spillway

The preliminary spillway tunnel had a 45-foot-diameter horseshoe cross section, Figure 16, and many of the features used in the recommended spillway were developed using the preliminary tunnel. The shape of the spillway approach, the general arrangement of the converging spillway bays, and the general concept of the spillway stilling basin were determined using the preliminary tunnel. Final developments were made using the recommended smaller tunnel.

PRELIMINARY STUDIES

Spillway Approach

The maximum design discharge is shown approaching the preliminary spillway in Figure 17A and B. Some disturbance occurred along the right wall of the excavated approach channel. The disturbance was less for smaller flows. To minimize this disturbance, the excavated right wall of the approach channel was reshaped, as shown in Figures 17 and 18. The recommended shape performed very well, as shown in Figure 17D.

A water-surface drawdown condition occurred around the nose of the center pier, as shown in Figure 19. To reduce the drawdown condition a pier nose more pointed than the preliminary one was used in the recommended design, as described later in "The Recommended Spillway" section of this report.

Crest Section

Calibration. The preliminary free discharge calibration test, Figure 20, showed that the spillway discharged the design flow of 173,000 second-feet at about 1.50 feet less head than the anticipated design elevation. Therefore, to reduce excavation costs, it was recommended that the approach floor be excavated only to elevation 3580 instead of elevation 3570 as preliminarily designed. With the approach floor elevation raised 10 feet the spillway still passed the design flow with the reservoir 0.6 foot below design elevation.

Coefficients of discharge for the spillway were computed from the equation

$$Q = CLH^{3/2}$$

where

Q is the discharge in second-feet
C is the discharge coefficient
L is the crest length between piers
H is the difference in elevation of reservoir and crest

With approach floor at elevation 3570, the coefficient for design flow is 3.48. With the floor at elevation 3580, it is 3.43.

Pressures. Pressures were measured on the spillway crest for a range of free flow discharges and gate controlled discharges using both gates. No subatmospheric pressures were recorded as shown in Figure 21.

Water surface. Water-surface profiles, shown in Figure 22, were measured along the left side of the center pier, along the right

training wall, and along the center line of the left bay for the design flow of 173,000 second-feet. The profile in the right bay was also obtained for discharges of 60,000, 125,000, and 173,000 second-feet by photographic record, as shown in Figure 23. The flow profiles were satisfactory.

Tunnel

Flow through the tunnel is shown in Figures 24 and 25 for discharges of 20,000, 60,000, 125,000, and 173,000 second-feet. A standing water fin occurred in the inclined tunnel and was most prominent for the smaller discharges. The fin was caused by flow convergence after passing the end of the center dividing pier. The pier, which extended well down into the inclined tunnel, could not be eliminated or shortened because it was needed for structural support of the tunnel roof. Pressures were measured at three piezometers located on the center line of the tunnel downstream from the pier, as shown in Figure 24. No subatmospheric pressures were found for any discharge. Flow through the entire tunnel, including the horizontal portion, was satisfactory. Observations of the flow in the converging section of the upstream transition suggested the possibility that the convergence angle could be increased to provide a shorter transition section and reduce the overall cost of this portion of the structure. Conferences with the designers indicated that they were of the same opinion. It was decided that the convergence angle could be increased from 4° to 6° or more.

Observations and measurements of the flow depth in the tunnel indicated that the tunnel flowed only about two-thirds full at maximum discharge. Since insufflation of air and bulking of the flow at this discharge would be negligible in the prototype, and since the most economical spillway possible was desired, it was suggested to the designers that the cross-sectional area of the tunnel be reduced. It was suggested, since the tunnel was open for ventilation at both ends and flow through the tunnel was unusually smooth and uniform, that the tunnel be designed to flow 0.8 full.

To determine the tunnel size that would produce the desired flow depth for the maximum discharge, the model discharge was increased until the depth of flow was 0.8 of the tunnel height. A discharge of 200,000 second-feet was required. Since 173,000 second-feet is the maximum design discharge and the scale of the model is 1:54, then

$$\left(\frac{200,000}{173,000}\right) = \left(\frac{54}{X}\right)^{5/2}$$

where X is the model scale if 200,000 second-feet is scaled down to 173,000 second-feet

$$X = 50.8$$

The revised height of tunnel cross section therefore is

$$\frac{50.8}{54}(45) = 42.3 \text{ feet}$$

Actually, 42.3 feet is still larger than required to produce the desired depth of flow because the head on the crest with the 200,000 discharge was not to proper scale by the ratio of 54 to 50.8. With the higher head, the velocity of flow would have been increased and the depth decreased for a given flow. Therefore, it was decided to construct and test a 41-foot-radius horseshoe tunnel and to increase the convergence angle of the spillway bays.

Spillway Stilling Basin

Preliminary basin. While the plastic tunnel for the revised spillway was being fabricated in the shop, the preliminary spillway stilling basin, Figure 26, was tested. In testing the stilling basin, the water-surface elevation in the reservoir was as shown in Figure 20. The water-surface elevation in the river channel was controlled to represent the expected prototype elevations at Station 24+00, Figure 27.

The stilling basin discharging is shown in Figure 28. For low flows a hydraulic jump formed in the stilling basin but at approximately 14,000 second-feet free discharge the jump swept out. For discharges over 14,000 second-feet, the basin performed as a flip bucket to project the jet of water downstream. The jet from the basin acted as an ejector, pushing the flow down the narrow river channel and tending to dewater the river channel upstream of the spillway. The concrete weir provided downstream from the powerhouse, shown in Figures 2 and 3, was necessary to maintain proper depths over the draft tubes. For discharges between 15,000 and 25,000 second-feet an eddy occurred in the river channel upstream from the jet and to the right of the basin which helped to hold some water in the powerhouse tailrace.

For the maximum design flow of 173,000 second-feet, the jet struck the river channel bottom approximately 460 feet downstream from the end of the basin. The diverging right hand wall of the stilling basin did not aid in spreading the jet.

For all high discharges the flow, after striking the channel floor, zigzagged from side to side, washing high on the canyon walls, as shown in Figures 12 and 28D. In the prototype the canyon walls are covered with talus material which would likely wash into and dam up the channel during periods of high discharge. This, of course, is an

undesirable condition since a dammed-up channel would probably reduce the powerplant head and, therefore, need to be cleaned out. However, it is intended, based on flood frequency curves, that the releases will seldom be more than 20,000 second-feet, part of which will be handled by the powerplant and outlet works. The spillway will seldom be required to discharge more than the stilling basin capacity. It should be realized, however, that when spillway flows exceed 14,000 second-feet, the basin will flip water into the river channel, and some cleanup of talus material might become necessary.

In the preliminary design, the stilling basin apron was constructed downstream from the exit portal of the tunnel. After the first tests it was suggested that the basin apron be moved upstream so that the tunnel itself could be used as part of the basin, resulting in a more economical structure with the overall length of the spillway structure reduced.

The distance that the basin apron could be moved upstream was dependent upon the water-surface profile in the basin. If the apron was moved too far upstream, the water surface would strike the roof of the tunnel portal. Therefore, water surface profiles were measured for the design flow of 173,000 second-feet and for the stilling basin capacity of 14,000 second-feet, Figure 29A, since for these two discharges the water surface would be higher than at any other time. The profiles show that it is possible to move the basin upstream; however, the basin was further developed before its location was changed in the model.

Modification of preliminary basin. To provide a more economical basin, the basin apron and the excavated discharge channel bottom were elevated 10 feet to elevations 3145 and 3170, respectively. This modification reduced the amount of excavation required and also reduced the length of the transition to the basin. The performance was similar to the preliminary basin even as to the quantity of flow required to sweep out the hydraulic jump. The jump remained in the basin for 13,900 second-feet but was swept out for 14,000.

Water-surface profiles, Figure 29B, were again measured, as for the preceding basin, to determine how far the basin could be moved upstream. It was found that even with the elevated floor the basin could be moved several feet upstream into the tunnel without risking closure at the exit portal.

Pressures were recorded along the invert of the tunnel-to-stilling-basin transition for a range of discharges as shown in Figure 30. Pressures were subatmospheric for only the higher discharges and these were not excessive. For maximum discharge the largest subatmospheric pressure recorded was 5.4 feet of water at Piezometer 3 located

approximately 40 feet downstream from the start of the transition. Pressures were therefore satisfactory.

Testing was continued with this basin moved upstream into the tunnel after the recommended tunnel was installed in the model. The final tests are discussed in "The Recommended Spillway" section of this report.

Powerplant Tailrace and Outlet Works

The preliminary design of the powerplant tailrace and outlet works is shown in Figure 31. The powerplant contains four turbines and the outlet works two 90-inch hollow-jet valves. The turbines are designed to discharge approximately 1,600 second-feet each and the hollow-jet valves approximately 4,000 second-feet each. The hollow-jet valves discharged directly into the river channel from a valve house on the right bank downstream from the powerplant. No stilling basin was provided. The powerplant tailrace contained a concrete weir to maintain the proper tail water depth above the draft tubes.

With reservoir elevation 3614 and the outlet valves discharging their combined maximum flow of 8,200 second-feet, the powerplant discharging 3,200 second-feet, and the spillway discharging 8,600 second-feet to produce a river discharge of 20,000 second-feet, as shown in Figure 32A, wave action along the right bank of the channel was rather severe. With the spillway not discharging, the jets from the valves washed high on the left bank, particularly when the powerhouse was not in operation, as shown in Figure 32B and C. Either case is undesirable for prototype operation because of the danger of washing talus material into the river channel and causing a rise in tail water elevation in the powerhouse tailrace. Reduction of head on the powerplant or frequent cleaning of the channel was not desirable.

Another undesirable flow condition existed when the spillway, outlets, and powerhouse were all operating as shown in Figures 32A and 33. A large unstable eddy occurred upstream and to the left of the valve jets. The eddy caused the water upstream of the weir in the powerplant tailrace to rise to elevation 3175. At this elevation the eddy ceased and water flowed downstream from the tailrace area until the water surface in the tailrace was lowered to elevation 3174 at which elevation the eddy began again. The cycle was repeated over and over again. This fluctuation in level at the draft tube outlets was considered undesirable for best powerplant performance.

A suggestion that the outlets be moved to the left, adjacent to the powerplant draft tubes, so that the valves could be aimed more

directly downstream could not be adopted because of structural reasons. A stilling basin was then suggested.

The idea was first explored in the model by preparing an erodible bed in which the jets from the horizontal outlet valves could scour a natural basin. The scour hole would, thereby, indicate the natural location and depth to which a basin could be excavated.

To determine the extent of the basin, two erosion tests were run as shown in Figures 34 and 35. Each began with the powerhouse discharging 3,200 second-feet and the tailrace water surface at the expected elevation 3179. The tail water control gate setting was not changed during each test, but the discharge in the channel was increased over a period of approximately 30 minutes to 20,000 second-feet by adding the outlet and spillway discharges in two probable operating sequences as furnished to the laboratory by the designers. For each test, the elevation of the bar of deposited material was also measured and found to be at elevation 3181. The average depth of scour was to elevation 3145. This occurred quite some distance downstream from the outlets. Toward the end of each test, as the scoured hole was formed, the appearance of the flow in the powerhouse tailrace and river channel was only slightly improved. It was, therefore, found that an excavated basin would need be very large and would still not quiet the flow very satisfactorily.

It was also noted that after the bar was formed and when only the powerhouse was discharging, the elevation of the water surface in the powerhouse tailrace was approximately 2 feet higher than the elevation at which the tests were begun. Thus, these tests also showed that it is important that a bar of deposited material does not form in the river channel. As a result of these tests, it was thought that tilting the valves downward might reduce the size requirement of the excavated basin, but that to quiet the flow satisfactorily in as small a space as possible an enclosed concrete basin similar to the one recommended for use at Boysen Dam[3] would be required. Such a basin was tested first in the spillway model and then in a larger scale outlet works model.

Outlet Works Stilling Basin

Preliminary Basin

At this stage of the investigation, the designers reduced the design capacity of the outlets from 8,000 to 5,000 second-feet and the size of the hollow-jet valves from 90 to 84 inches. For maximum reservoir elevation 3640 at which the valves are to operate, the head was computed to be 380 feet at the right valve and 368.6 feet at the left valve.

3/Hyd-283, "Hydraulic Model Studies of Boysen Outlets," by E. J. Rusho.

PRELIMINARY STUDIES

The plastic model hollow-jet valves in the 1:54 scale model were reused for these preliminary basin tests and, therefore, represented 90-inch valves fixed at 100 percent open.

The preliminary basin, shown in Figure 36, was first installed in the spillway model and operated as shown in Figure 37 for discharges of 8,000 and 5,000 second-feet. The roof of the basin was omitted in the model, and the top of the center and left training walls was at elevation 3184 instead of at elevation 3206, as shown in Figure 36.

For 5,000 second-feet, it appeared that the preliminary basin could be reduced in size but that the converging walls on the sloping floor appeared to be too low to completely contain the jets between them. The water surface was quite smooth, but, because the model valves were oversized and could not be regulated to produce the design head at the valves, the water surface in the model basin probably appeared to be smoother than if true model valves were used.

To develop the stilling basin design it was decided to construct a larger independent model with operating valves and a transparent side wall on the basin. The model constructed for this study is shown in Figure 15. In this model, too, the roof of the basin was omitted and the upstream portion of the center training wall did not extend to the full prototype height. The basin utilized two 3-inch model brass valves that were readily available in the laboratory. One wall of the basin was constructed with glass for observing flow characteristics throughout the entire depth of the basin.

Basin One

The design and construction of the model began before the designers had specified 84-inch valves to replace the 90-inch valves. The 3-inch model valves were to have provided a 1:30 model scale. However, because the prototype valve size was changed to 84 inches, the model scale became 1:28. Thus, the model dimensions of Basin One, shown in Figure 38, represented a prototype whose dimensions were 28/30 of those shown for the preliminary basin in Figure 36. The width of the basin became 18 feet 8 inches instead of 20 feet and the length 197.88 feet instead of 213 feet. However, the 12-foot-high converging walls in Figure 36 were increased to a height of 14 feet in Figure 38 because the 12-foot height in the 1:54 scale model was considered to be too low.

The elevation of the valve center line in Figure 36 was maintained in the 1:28 scale, Figure 38; therefore, it was necessary to change all other elevations. For example, the basin floor was changed from elevation 3144 to elevation 3146.4. However, the center training

wall was to extend to the roof of the basin at elevation 3206 in the prototype but extended only to elevation 3193 in the model.

Basin One discharging in the 1:28 scale model is shown in Figures 15, 39a and 40A. The basin appeared to be too small to handle the maximum capacity of 5,000 second-feet at a maximum operating head. The water surface leaving the basin was a little rough and the converging walls caused a fine spray.

Two 1-hour model erosion tests were conducted. In one of the tests both valves discharged a total of 5,000 second-feet with reservoir at elevation 3640. In the other test the right hand valve was closed while the left valve discharged 2,500 second-feet with the reservoir at elevation 3640. The scour pattern for each test was about the same and is shown in Figure 39. In each test approximately 5 feet of scour depth occurred at the downstream left hand corner of the basin. A sill at the downstream end of the basin would probably have improved the scour pattern.

The basin discharging 5,000 second-feet without the converging walls was tested to demonstrate the benefit of the walls, as shown in Figure 40. Without the wedges the basin was much too short and energy dissipation was poor.

The tests showed that the performance of Basin One could be improved by eliminating the spray at the converging walls and by utilizing the upstream portion of the basin to better advantage.

Basin Two

The walls were reinstalled at the toe of the slope, as shown in Figure 41A. The performance of the basin was improved over that of Basin One. The wall tops were submerged which eliminated the spray. The jet passing through the constriction followed along the floor of the basin for a greater distance downstream, practically eliminating the surface boil. The water surface was smoother than for Basin One and the energy-dissipating action was moved upstream slightly.

Basin Three

By narrowing the width of the gap at the downstream end of the walls from 7 feet 11 inches to 4 feet 8 inches in Basin Three, the performance of the basin was further improved. Exploratory tests showed that further reduction in the gap width offered little, if any additional improvement in performance. To compensate for the narrower gap, the height of the converging walls was increased from 14 feet to 22 feet in Basin Three.

PRELIMINARY STUDIES

Basin Three is shown discharging 5,000 second-feet with reservoir elevation 3640 in Figure 41B. Performance was very good. The upstream portion of basin was well utilized, and the water surface in the basin and leaving the basin was quite smooth. The energy-dissipating action was moved upstream sufficiently that the length of basin could be reduced. Further testing was done to reduce the amount of spray occurring at the converging walls.

Basin Four Recommended

Using the same height of converging walls and gap width as used in Basin Three, the walls were lengthened to provide a more gradual convergence starting at the top of the slope. The wall lengths were thus increased to 46 feet. The performance of the basin in dissipating energy was very good, as shown in Figure 42A, for the design discharge of 5,000 second-feet at reservoir elevation 3640. The spray at the converging walls was also eliminated. It appeared that this basin could be reduced 37 feet 3 inches in length. Note in Figure 42A that the bottom currents have left the floor well upstream from the end of the paved apron.

Pressures were measured along the downstream edge of the converging walls at the three piezometers shown in Figure 42A. For the design discharge, reservoir elevation and tail water elevation all pressures were above atmospheric.

Tests with the tail water below normal elevation were made to determine the factor of safety against sweep out if the tail water elevation in the prototype should be lower than expected. Figure 43A shows the basin to perform well if the tail water elevation is 2 feet below the expected normal elevation, and not until the tail water elevation reached 7 feet below the expected normal did the flow sweep out, Figure 43B. The factor of safety against sweep out was therefore satisfactory. This basin with the length reduced 37 feet 3 inches was recommended for prototype construction after Basins Five through Eleven had also been tested.

Basin Five

Experiments were continued in an attempt to move the energy-dissipating action even farther upstream so that the basin length could be further reduced. For Basin Five, a sill was added to the previously tested basin, as shown in Figure 42B. The sill extended across the full width of the basin, but tests showed the sill to be located too far downstream. The sill turned the flow immediately to the surface and caused a very high boil, as shown in Figure 42B.

Basin Six

The sill used in Basin Five was moved upstream to the toe of the slope, as shown in Figure 44A. The sill was too close to the converging walls and most of the flow passed over the sill, resulting in an unstable and wavy water surface leaving the basin, Figure 44A.

Basin Seven

The sill used in Basins Five and Six was relocated 5 feet 10 inches downstream from the toe of the slope, as shown in Figure 44B. Much of the energy was dissipated in the upstream portion of the basin so that the basin could probably be shortened about 70 feet. The water surface leaving the basin was very smooth; however, in the upstream portion of the basin a rather high boil occurred, as shown in Figure 44B. The boil was objectionable in that the basin roof beams in the prototype would probably be submerged and proper ventilation would be prevented.

Basin Eight

Basin Eight, shown in Figure 45A, utilized a shorter sill shown in Figure 46 that did not extend from wall to wall. The sill was placed on the center line of the basin at the same location used in Basin Seven. Basin Eight performed better than any other basin tested, and it appeared that the basin length could be reduced approximately 65 feet.

Most of the flow struck the sloping face of the sill, but part of the flow passed over the top to strike the floor of the basin downstream. Thus, the sill divided the flow into two parts. The upper layer of the flow passing over the sill prevented the boil that occurred in Basin Five, Figure 42B. The position of the sill was, therefore, critical in that when the sill was moved upstream or downstream the flow was turned upward to produce a violent boil.

A portion of the flow that struck the sloping face of the sill was dispersed toward the side walls. Part of the flow striking the side walls was turned downward to the basin floor and part of it was turned upward to fall backward into the basin while continuing downstream. No high boils were created, and the water surface leaving the basin was very smooth. Almost all of the action was contained in the upper end of the basin. The downstream 65 feet of the basin was not used to produce stilling action and therefore could be eliminated.

Pressures on the sill were recorded for a range of discharges at the piezometers shown in Figure 46. For 5,000 second-feet and less, with tail water at elevation 3179, and the reservoir at the normal expected elevation 3640, all pressures were above atmospheric.

PRELIMINARY STUDIES

Lowering the tail water elevation 1 foot for 5,000 second-feet reduced the pressure at Piezometer 2 to about 2.5 feet below atmospheric; other pressures were still above atmospheric. Maintaining the tail water at elevation 3179, but increasing the discharge to 6,000 and then to 8,000 second-feet reduced the pressures at Piezometers 2 and 3 to subatmospheric. For 8,000 second-feet with tail water elevation at 3179, the pressure at Piezometer 2 was 21 feet of water below atmospheric and for 6,000 second-feet was 3 feet of water below atmospheric. These, of course, are not contemplated operating conditions, but the tests indicate the pressure trends.

It was attempted to determine the tail water elevation at which the flow would sweep out of the basin. The tail water was lowered to elevation 3168, which was as low as possible in the model, but the flow would not sweep out. From a hydraulic standpoint this basin performs satisfactorily, and with the length reduced 65 feet would provide an economical structure. However, since the effectiveness of the basin is based on impact action on a small area, it was felt that at high heads the concrete walls and floor of the basin might rapidly deteriorate under continued operation.

Basin Nine

In Basin Nine, shown in Figure 45B, the sill used in Basin Eight was tilted upstream so that its upstream face was at an angle of 45° with the floor. More stilling action occurred above the sill than in Basin Eight, and it appeared that the basin could be made another 5 or 10 feet shorter than Basin Eight. The stilling action in the upstream portion of the basin created some water surface roughness there, but the water surface was smooth as it left the basin.

Basin Ten

In Basin Ten, Figure 47, the elevation of the floor was raised 6 feet and the length reduced 70 feet. The sill and sill location were the same as used in Basin Nine.

The basin performance for 5,000 second-feet with reservoir elevation 3640 was not quite as good as for some of the earlier basins since the water surface in the upstream portion of the basin was higher and rougher. However, the energy dissipation appeared to take place in a shorter length of basin, and the water surface leaving the basin was very smooth. The dissipating action appeared to occur in about the same manner as described for Basin Eight.

The basin performed very well in dissipating the energy of the design flow for tail water elevations below normal, as shown in Figure 48.

For tail water elevation 2 feet below normal and even for tail water elevation 7 feet below normal the flow did not appear ready to sweep out; instead, much energy dissipation still occurred in the upstream portion.

Pressures on the sill were measured at the piezometers, shown in Figure 49, for 5,000 second-feet over a range of tail water depths. The reservoir was at elevation 3640. For normal expected tail water elevation 3179, Piezometer 2 indicated approximately 1 foot of subatmospheric pressure. All others were about atmospheric. As the tail water was lowered, the subatmospheric pressure at Piezometer 2 increased until at tail water elevation 3173 the pressure was about 20 feet below atmospheric. All other piezometers still showed pressures to be above atmospheric.

Basin Eleven

In Basin Eleven, Figure 47B, the converging walls used in Basin Ten were relocated about 6 feet farther upstream on the sloping floor to provide more room for stilling action upstream from the sill and to reduce the height of the boil.

The height of boil was reduced from that in Basin Ten, as shown in Figure 47A and B, but the water surface leaving the basin was not as smooth. Also, greater subatmospheric pressures were measured on the sill. Basin Eleven did not perform as well, in general, as Basin Ten.

Comparison of Recommended Basin Four and Basin Ten

Of all the basin modifications tested, those incorporated in Basins Four, Eight, Nine, Ten, and Eleven produced the most satisfactory results. Basins Eight, Nine, Ten, and Eleven utilized a sill in addition to the long converging walls. Basin Eight appeared to perform slightly better than Basins Nine, Ten, and Eleven, but Basin Ten was more economical to construct. Basin Ten was therefore chosen to compare with Basin Four to determine whether or not the addition of a sill near the base of the slope was practical from the standpoint of possible maintenance costs versus first costs.

For the comparison tests, the basin lengths were reduced according to the observations made in the previously described tests. Basin Four was constructed 37.33 feet shorter than Basin One, while Basin Ten was constructed 68.83 feet shorter than Basin One. A sill was added at the downstream end of each basin for scour control. The basins, as constructed for the comparison tests, are shown in Figure 50.

At this time the designers were contemplating increasing the capacity of the outlet works to 6,000 second-feet for reservoir elevation

3640 and tail water elevation 3179. The basins were, therefore, tested for 6,000 as well as 5,000 second-feet. After completion of these tests, however, the designers decided to limit the maximum capacity of the outlet works to 5,000 second-feet.

Basin Four is shown discharging 5,000 second-feet in Figure 51A and 6,000 second-feet in Figure 51B. Performance of the basin was not as good for 6,000 as for 5,000 second-feet. The capacity of the basin appeared to be exceeded with 6,000 second-feet; and if the tail water elevation was lowered 2 feet below normal, the flow was on the verge of sweeping out of the basin, as shown in Figure 51C. Basin Four, therefore, is not recommended for flows exceeding 5,000 second-feet. Basin Four was also tested for other anticipated operating conditions. Tests were made for small flows and for 5,000 second-feet with the reservoir at elevation 3337. For these tests the basin was found to be very satisfactory, as previously described in the tests for Basin Four.

Basin Ten was tested for the same conditions described for Basin Four. Discharging 5,000 and 6,000 second-feet, Figure 52, Basin Ten performance was excellent, and the water surface of the flow leaving the basin was smoother than in Basin Four. Compare Figures 51 and 52. For 6,000 second-feet the tail water elevation could be lowered at least 6 feet below normal without the flow sweeping out. Figures 48 and 43 also show that Basin Ten performs better than Basin Four with below normal tail water. However, for low tail water, subatmospheric pressures occur on the sill of Basin Ten as previously pointed out in Figure 49.

For small discharges with high reservoir elevations, Basin Four performed better than Basin Ten. The sill produced some water-surface roughness that did not occur in Basin Four. However, this roughness was not considered to be objectionable since it did not persist downstream from the basin.

Pressures were measured in both basins at locations considered to be critical. Pressures on the sill for Basin Ten are recorded in Figure 49. A pressure head of 84 feet of water was recorded at Piezometer 1 on the upstream face of the sill for 5,000 second-feet with reservoir elevation 3640 and tail water elevation 3179. On top of the sill at Piezometer 2 a subatmospheric pressure of 1 foot was recorded for the same discharge condition. With lower tail water elevations, the subatmospheric pressures increased at Piezometer 2 as previously discussed.

Pressures were also measured at three piezometers, shown in Figure 50, along the downstream face of the walls to determine whether subatmospheric pressures might be present. None were found in either basin. Pressures on the glass wall side of the basins were also measured. The wall area was probed, using a movable piezometer, to

locate the area that was subjected to the highest pressure. The results for the design discharge of 5,000 second-feet with reservoir elevation 3640 and tail water elevation 3179 are recorded in the following table:

Basin	Maximum pressure on wall in ft of water	Location of wall area over which maximum pressure occurs	Approximate extent of area over which maximum pressure occurs
Four	30	Along floor 12 to 14 feet downstream from slope	1 by 3 feet
Ten	80	1 foot above floor about 10 feet downstream from slope	1 by 5 feet

Maximum pressures were therefore considerably less in Basin Four than in Basin Ten. It was for this reason that Basin Four is recommended for prototype construction. Even though Basin Ten was considerably shorter and probably less costly to construct, it was felt that the sill, side walls, and floor of Basin Ten might become damaged by erosive action of the jet and that difficult and expensive maintenance problems might result. On a future structure where the overall head is less, Basin Ten might prove to be entirely satisfactory.

To complete the comparison, erosion tests were made on each basin as shown in Figure 53. With each basin there was a tendency for erosion to undercut the sill at the downstream left hand corner of the basin. Erosion was deeper for Basin Ten than for Basin Four as evidenced by the fact that the scour depth for Basin Ten was 4 feet below the basin floor, whereas, for Basin Four it was only 2.6 feet. Therefore, Basin Four would not require as much riprap protection as would Basin Ten. Basin Four was, therefore, the better basin in this respect.

Based on these model data, Basin Four was recommended for use in the prototype, particularly since the designers specified that the outlets would never be required to discharge more than 5,000 second-feet and that either the present Indian Service Dam downstream, or, later an afterbay dam would always provide sufficient tail water for Basin Four to operate as intended. Therefore, the superior performance of Basin Ten in discharging 6,000 second-feet at normal tail water and 5,000 or 6,000 second-feet at very low tail water elevation can be disregarded.

One further modification was made to Basin Four in later tests. A curved fillet was added at the upstream end of the basin at the intersection of the basin floor and the sloping entry, as shown in Figure 10.

Long and short radii fillets were tested in the model, all of which performed satisfactorily. The purpose of the fillet was to reduce impact effects on the basin floor and to provide positive cleaning action of accumulated debris when the valves are first opened. In the model this fillet did not appear to be necessary to improve the cleaning action since gravel deliberately placed in the corners quickly washed out when the valves were opened. In the prototype, however, the fillets might aid in flushing out more densely packed debris and thereby reduce the possibility of abrasive erosion of the concrete.

Tests were then conducted to determine whether the valves might become submerged if it ever became necessary to discharge with above normal tail water conditions. The model was operated with extremely high tail water elevations, but in no case were the valves submerged. At all times the jets were open to the atmosphere and proper ventilation of the jets occurred.

It was evident, however, that the basin did not perform as well with high tail water as with normal tail water when the basin was discharging 5,000 second-feet, as shown in Figure 54. More air is entrained in the water in the basin and higher waves occur in the basin and downstream than when the tail water is at normal elevation 3179. Tail water elevation 3185.3, shown in Figure 54, will occur when the spillway and powerhouse are discharging in addition to the outlets to produce a total of 20,000 second-feet, Figure 27. Since tail water elevations higher than elevation 3179 will occur only occasionally, this characteristic of Basin Four was not considered objectionable.

The recommended Basin Four, Figure 55, was then installed in the 1:54 scale model along with the recommended 41-foot-diameter horseshoe spillway tunnel. Basin Four was found to operate as satisfactorily in the 1:54 model as in the 1:28 scale model. After completion of the model studies the recommended basin was altered slightly as shown on Figures 8, 9, and 10.

The Recommended Spillway

The entire spillway, including the crest section and the recommended 41-foot radius horseshoe tunnel, was redesigned as shown in Figure 56 and installed in the 1:54 scale model, replacing the crest section and preliminary 45-foot radius tunnel shown in Figure 16.

Redesign of the crest section and the converging transition was made on the basis of recommendations made after observing the preliminary structure. It was apparent that the convergence angle could be increased from 4° to approximately 6°, thereby shortening the transition and reducing the cost, without producing unsatisfactory flow conditions in the tunnel. Other modifications in the crest structure were made for

structural reasons and still further modifications were made after completion of the model study to simplify prototype construction as shown in Figures 5 and 6.

The outlet works basin developed in the 1:28 scale model tests, and most of the other modifications recommended during the preliminary tunnel tests were also incorporated in the model. The entire revised design was then tested, and further modifications were made before the structures were recommended for prototype use.

Spillway Approach

The spillway approach channel, as developed in Figures 17 and 18, was modified by the designers to provide clearance for construction of the right and left spillway piers. For construction reasons the designers found it was desirable to cut into the topography at both the right and left piers. These cuts as first designed, Figure 57, were installed in the model, Figure 58, and tested.

Flows up to about 100,000 second-feet were satisfactory, as shown in Figure 58B, C, and D, but for discharges of 100,000 to 173,000 second-feet a boil occurred in the cutout area on the right. Other flow characteristics along the right and left banks were satisfactory. To eliminate the boil, the extent of the cuts was reduced at both the right and left piers, as shown by the recommended revision in Figure 57.

The center pier nose shape in the preliminary design was also revised for the recommended design. The recommended pier nose was shaped as shown in Figure 59. This nose is more pointed than the preliminary one; and, therefore, reduces the water-surface drawdown effect that was experienced in Figure 19. The recommended nose performed very well as shown in Figure 58.

Spillway Crest Section

Calibration. The crest section of the recommended spillway, shown in Figure 56, was calibrated for both gate controlled and uncontrolled flow. The discharge calibration curves for both are shown in Figure 60. After the model study was completed the crest shape was redesigned as a warped surface, Figure 5, and the gates were redesigned to the size and position shown in Figure 6. Therefore, the calibration curves in Figure 60 can only be used in an approximate way for the prototype structure.

The coefficient of free discharge was computed from the equation

$$Q = CLH^{3/2}$$

where

Q is the discharge in second-feet
L is the crest length between piers
H is the difference in elevation of the reservoir and the crest
C is the discharge coefficient

Coefficients for the complete range of heads were computed and plotted as shown in Figure 60. For the design flow of 173,000 second-feet, the coefficient was found to be 3.38, which is less than the 3.43 value found for the preliminary design. However, the reservoir elevation for the design flow coincided with the anticipated design elevation 3657.

To obtain the gate controlled discharge curves shown in Figure 60, gate openings of 5, 15, 25, 35, 45, and 55 feet were calibrated. These data were then plotted in the form shown in Figure 61 from which the additional curves shown in Figure 60 were determined. The gate controlled discharge curves were obtained with both gates open an equal amount.

Pressures. The shape of the crest, shown in Figure 56, was not the same as in the preliminary design, shown in Figure 16; therefore, pressures were measured on the revised crest to be sure that severe subatmospheric pressure areas were not present. Pressures were measured on the center line of the right bay, and no subatmospheric pressures were found, as shown in Figure 62.

Water surface. Water-surface profiles were measured in the direction of flow over the crest, as shown in Figure 63, for the design flow. Water surfaces, in general, were higher in the left bay than in the right which indicated that the left bay might discharge a little more water than the right for free flow over the crest. The water surface was higher in the left bay because the flow approaches the crest along a curved path from the right. Deeper water in the left bay is, therefore, due to normal distribution of the flow in discharging around a curve. In the left bay it is necessary to raise the bottom of the gate to elevation 3648 to clear the water surface. The gate pins were well above the waterline for the design discharge.

Tunnel

The recommended tunnel is shown in Figure 56. In addition to having a smaller cross section than the preliminary tunnel, Figure 16, the transition convergence angle was increased from 4° to 6°10' and the

details of the crest section were modified to reduce the cost of the tunnel and simplify the prototype construction.

The performance of the tunnel transition section was very satisfactory for all discharges up to and including the design flow of 173,000 second-feet, as shown in Figure 64. Flow throughout the remainder of the tunnel including the lower bend, shown in Figure 65, was also very satisfactory.

Water surface. The water-surface profile for the design flow shown in Figure 66 was determined from the photographic record in Figures 64 and 65 and in the motion picture film entitled "Hydraulic Model Studies of Yellowtail Dam Spillway and Outlet Works." At the downstream end of the inclined tunnel, just upstream of the bend, the design flow utilizes more of the cross sectional area of the tunnel than at any other place. However, it is believed that the free area is sufficient to provide adequate ventilation of the tunnel.

Pressures. Subatmospheric pressures were not expected to occur along the tunnel crown since the tunnel was well vented at its entrance and a free passage for air was maintained throughout the tunnel length. However, pressures were measured along the crown and invert of the tunnel for the design flow of 173,000 second-feet. Pressures along the crown of the tunnel were atmospheric while those on the invert were above atmospheric. An air pocket formed downstream from the pier nose, but no subatmospheric pressures could be detected there.

Spillway Stilling Basin

Basin I. The first stilling basin installed with the 41-foot-diameter horseshoe tunnel is shown in Figure 67, Basin I. The upstream end of the basin was located upstream of the exit portal of the tunnel with the basin floor at elevation 3145 and the discharge channel at elevation 3170, as was recommended in the preliminary spillway tests. However, four further modifications not previously tested were made as follows: one, the basin width was reduced to 41 feet, the diameter of the recommended tunnel; two, the tunnel transition section joining the upstream end of the basin was reduced from 170 feet, as recommended in the preliminary tests, to 150 feet long; three, a 4:1 sloping sill from the basin apron to the discharge channel replaced the 2-1/2:1 slope that was used in the preliminary tests; four, the discharge channel was constructed so that 120 feet downstream from the end of the basin, the channel sloped upward 1 on 5 to the natural ground line which was at about elevation 3200.

Alteration number two was done primarily to reduce prototype construction costs. The invert trajectory curve, shown in Figure 67, was

obtained from simple curves rather than from the usual parabolic curve. Alterations three and four were made to provide a deeper pool at the discharge end of the tunnel so that the discharge channel could act as part of the stilling basin when the bucket was not operating as a flip bucket.

Operation with this basin was poor; the high downstream topography in the discharge channel prevented proper exit conditions for the flow. It was evident that better performance would be obtained if the 1 on 5 slope was replaced with a horizontal channel flow. Therefore, the slope was removed without further testing of Basin I.

Basin II. Basin II, shown in Figure 67, was the same as Basin I except that the topography in the discharge channel was removed to elevation 3170. This made it possible to perform tests on the basin itself which could not be made with the higher topography blocking the downstream flow.

The 4:1 sloping sill produced a clean jet; however, the flat sill slope did not project the flow downstream as far as was considered desirable and the basin did not hold the hydraulic jump in the basin as well as the 2-1/2 sloping sill in the preliminary basin tests. No further tests were made with the 4:1 slope.

Basin III. Basin III, Figure 67, was tested with a 2:1 sloping end sill. The jet leaving the sill appeared unstable and ragged for free flow with the basin acting as a flip bucket. The hydraulic jump swept out of the basin at about 14,000 second-feet which was the same as for the basin having the 2-1/2:1 slope in the preliminary basin. The sill appeared to be too steep, therefore, further tests were made using other sill types.

Basin IV. In Basin IV, Figure 67, a curved end sill was tested. It did not hold the jump in the basin as well as the sloping sill and, when acting as a flip bucket, the jet was very ragged, especially so for discharges near 40,000 second-feet, as shown in Figure 68. Note the flow patterns in the plan view photographs of Figure 68. The concentrations of flow originated in the tunnel to basin transition. Flow entered the tunnel transition section with uniform depth across its width but as the flow left the transition to enter the basin, the bulk of the flow was concentrated at the center line of the tunnel. After impinging on the basin floor which spread the flow toward the side walls of the basin, the sill again spread the flow toward the center. It was concluded that the steeper the slope the more abruptly the flow from the two sides came together, and, therefore, the more ragged the jet.

Basin V. To reduce the flow concentrations, a curved floor was placed at the intersection of the transition floor and the basin apron, Figures 67 and 69. Flow concentrations were still evident as previously described. The curved fillet was removed from the model before further tests were made.

Basin VI. The curved-face end sill in Basin V was replaced with a 2-1/2:1 sloping sill, and an additional 45° sloping sill 4 feet high at the downstream end of the 2-1/2:1 slope, Figure 67. The additional sill was added to extend the discharge limit for which the hydraulic jump would remain in the basin.

The jump remained in the basin for discharges up to approximately 15,000 second-feet. However, the 45° sill caused a boil on the water surface when the jump was in the basin; and the flow, after leaving the sill, appeared to pass through critical depth to form a second hydraulic jump. When the basin acted as a flip bucket the jet was clean, especially for the design flood of 173,000 second-feet. The jet arched high and spread to the full width of the river channel. Because of the poor performance with the jump in the bucket, the secondary sill was given no further consideration.

Basin VII. Basin VII was the same as Basin VI except that the 4-foot sill was removed, Figure 67. This basin produced a satisfactory jet when it acted as a flip bucket, as shown in Figures 70, 71, and 72, for discharges of 40,000, 100,000, and 173,000 second-feet, but the basin did not hold a jump for 13,000 second-feet as shown in Figure 73.

The basin design showed promise, however, and investigations were made upstream from the basin to improve the performance of the basin itself.

The transition section to the stilling basin was investigated for pressures along its invert. Since the flow entering the tunnel transition section was uniformly distributed across the width, and since the flow leaving the transition section was concentrated in the center of the tunnel as described for Basin IV, it was reasonable to suspect that subatmospheric pressures existed along the invert of the transition.

Pressure measured in the tunnel transition section, Figure 74, showed that the curvature of the invert was too sharp. Pressures at some points along the invert were below atmospheric for discharges of 10,000 to 15,000 second-feet and were about 35 feet of water below atmospheric for the design discharge. The transition was, therefore, redesigned before testing continued.

Concluding Tests to Develop the Recommended Basin

Basin VIII, shown in Figure 75, was used as a starting point in developing the recommended basin. The basin apron was at the preliminary design elevation 3135. The discharge channel was also lowered to the preliminary design elevation 3160. The invert of the tunnel transition section had the same parabolic shape and length as in the preliminary design, but the bottom and sides of the tunnel transition were modified as shown to reduce construction costs.

Transition pressure tests, Figure 76, along the invert and on the tunnel bottom 2-1/4 feet from the left hand corner showed no severe subatmospheric pressures for discharges up to 173,000 second-feet. Also, the flow depth was more uniform for the full width of the tunnel than in the previous transition. For 173,000 second-feet, a pressure of 9 feet of water below atmospheric pressure was recorded on the transition floor 5 feet downstream from beginning of the transition and 2-1/4 feet from the corner. The same pressure was also recorded on the invert 32 feet downstream from the beginning of the transition. Since other pressures were substantially higher, the transition was considered suitable for prototype use.

The 2-1/2:1 sloping sill at the downstream end of the basin produced a good appearing jet and performed satisfactorily when the basin retained the jump. The sill, therefore, was satisfactory. However, the length of the basin, the elevation of the apron, and the elevation of the discharge channel were yet to be established.

It was decided by the designers at this time that the smallest basin that would hold the hydraulic jump for 12,000 second-feet should be developed for prototype use. With the outlet works discharging 5,000 second-feet, the powerhouse approximately 3,000 second-feet, and the spillway 12,000 second-feet, the river discharge would be 20,000 second-feet with the jump retained in the spillway stilling basin.

Four combinations of basin length, apron elevation, and discharge channel elevation were tested, Figure 77, to determine the combinations of these dimensions that would meet the 12,000 second-feet limitation. In making these tests, the tail water elevation at Station 24+00, shown in Figure 27, was set for the spillway discharge plus 8,000 second-feet from outlets and powerhouse. Sweep out, therefore, occurs at a smaller discharge when only the spillway is discharging since the tail water elevation is lower. This is not an expected operating condition, however.

The model data in Figure 77 show that the longer and deeper the basin the more discharge it can handle before sweep out occurs.

A higher sill also provides more jump capacity as shown by the data. By interpolation between curves in Figure 77, the most economical basin to construct, having a jump capacity of 12,000 second-feet, is the one shown in Figure 78. The recommended basin is 130 feet long at apron elevation 3145 and has a sill at elevation 3170. A factor of safety of 500 second-feet was used so that the model data actually indicated that the jump for a flow of 12,500 second-feet would be retained in the basin. The average velocity of flow immediately downstream from the basin in the discharge channel was measured to be approximately 19 feet per second.

With the apron at elevation 3145, instead of at 3135, the required excavation was less and the length of the transition and trajectory curve was reduced by approximately 30 feet. However, with the basin apron at elevation 3145, it was desirable to raise the roof of the basin 4 feet to elevation 3196.

A water-surface profile measurement for 12,000 second-feet, Figure 79, showed that it was necessary for the top of the basin walls to be raised to elevation 3195 or higher to contain the waves within the basin. The clearance between the water surface and the portal roof was approximately 14 feet. It was felt that this clearance, or more, should be provided for adequate ventilation of the tunnel when the maximum water-surface elevation occurred with the hydraulic jump in the basin.

When the basin performed as a flip bucket, it was also necessary that the tunnel have free air passage from the gate section to the portal to reduce the possibility of subatmospheric pressures developing in the tunnel. The recommended design provides sufficient clearance for all flows up to and including the design flow of 173,000 second-feet.

Model photographs of the recommended spillway stilling basin discharging cannot be presented because the tunnel portal crown and the basin walls were never actually constructed to the recommended elevations. However, Figures 70 through 73 and Figure 80 show the discharge characteristics to be expected in the recommended design even though the portal crown and the basin training walls are at elevations 3192 and 3190, respectively, instead of 3196 and 3195, respectively.

The principal differences between the flow shown in these figures and that which will occur in the recommended prototype design are as follows: The clearance between the water surface and the basin roof will be 4 feet more than shown; the freeboard above the water surface on the basin training walls will be 5 feet more than shown; and the jet flow through the basin will not climb the basin walls as high a shown because of the longer transition. The transition 170 feet long

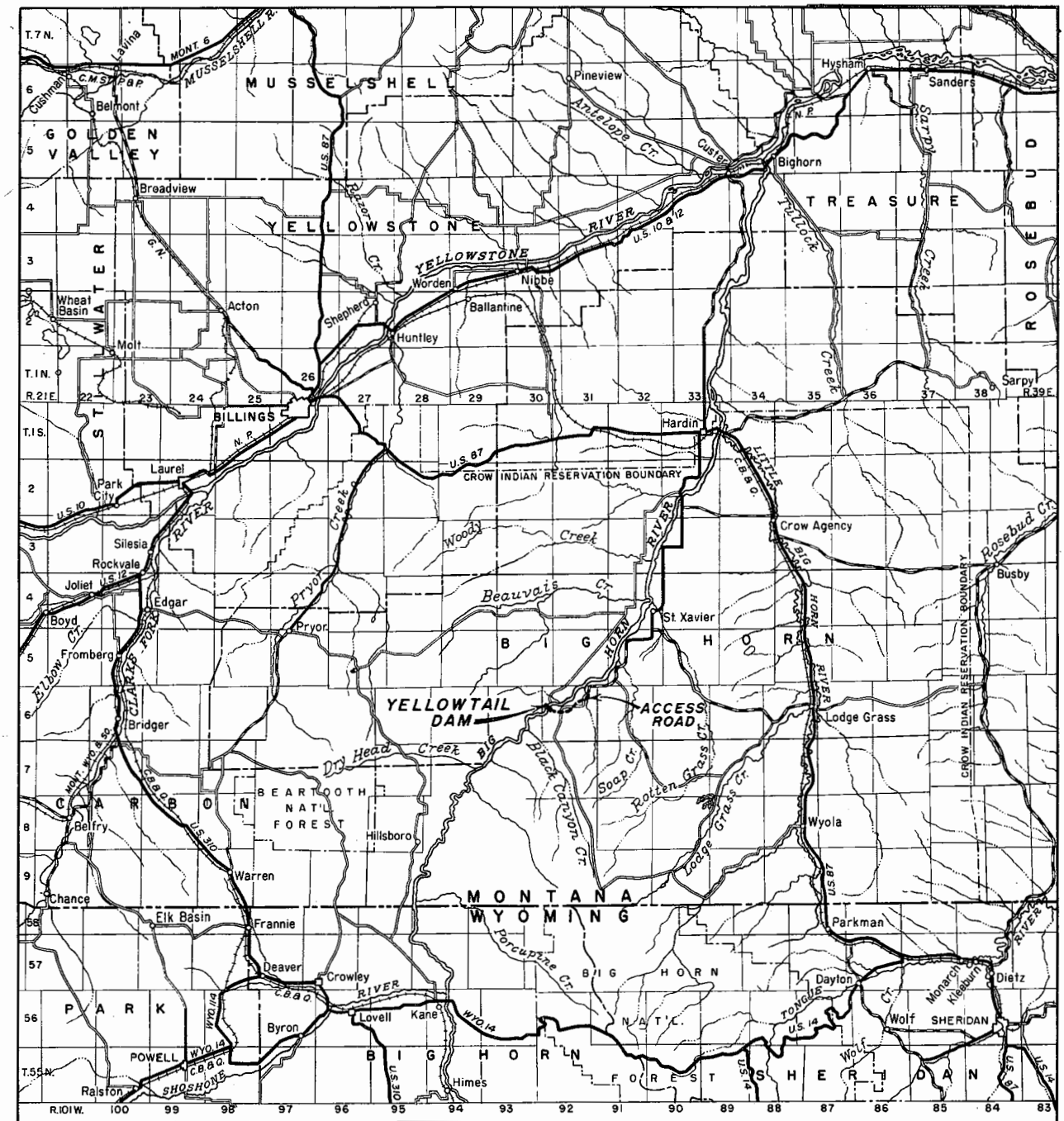
used with the recommended design provided better flow conditions at the basin entrance than the transition 150 feet long used with Basin VII.

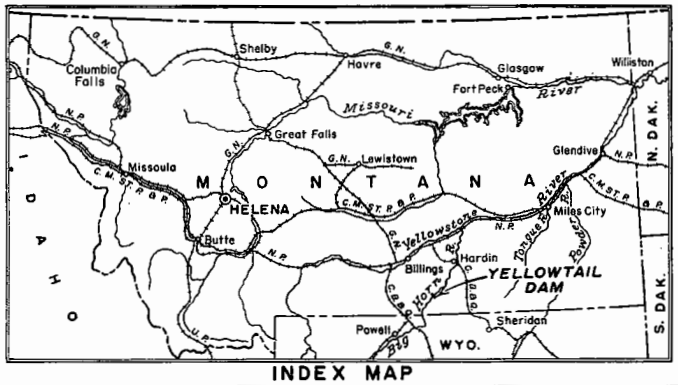
River Channel

The river channel discharging 20,000 second-feet in Figure 80, 12,000 through the spillway and 8,000 through the outlet works, shows the flow conditions to be expected in the river channel just before sweep out occurs in the spillway stilling basin. The basin shown varies from the recommended design in that the crown of the portal is at elevation 3192 instead of 3196, and the training walls are at elevation 3190 instead of 3195. The clearance between water surface and portal roof, therefore, would be 4 feet more than is shown and the freeboard on the training walls 5 feet more.

Flow downstream from the powerhouse and outlet works, shown in Figure 80, has a much rougher water surface than would be encountered in the prototype because 8,000 second-feet is being discharged by the outlets and none by the powerhouse, whereas, in the prototype the outlet works discharge will not exceed 5,000 second-feet. Normally, the powerhouse would discharge the additional 3,000 second-feet. The outlets discharging 5,000 second-feet produced good flow conditions in the channel either with or without the powerplant discharging.

Tests were also conducted to determine the effects of the spillway discharge in producing a drawdown in the powerhouse tailrace channel. With the spillway alone discharging 12,000 second-feet, the tail water surface at the powerhouse was at approximately elevation 3182. With an additional 8,000 second-feet discharged through the powerhouse and outlet works, the tail water surface at the powerhouse was at approximately elevation 3186. When the spillway discharge was increased to 13,000 second-feet, the jump swept out of the stilling basin and the tail water surface at the powerhouse dropped approximately 3 feet in approximately 1-1/4 to 1-1/2 model minutes, which in the prototype represents 9 to 11 minutes.





INDEX MAP

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MISSOURI RIVER BASIN PROJECT
LOWER BIGHORN DIVISION-YELLOWTAIL UNIT-MONTANA

YELLOWTAIL DAM AND POWER PLANT

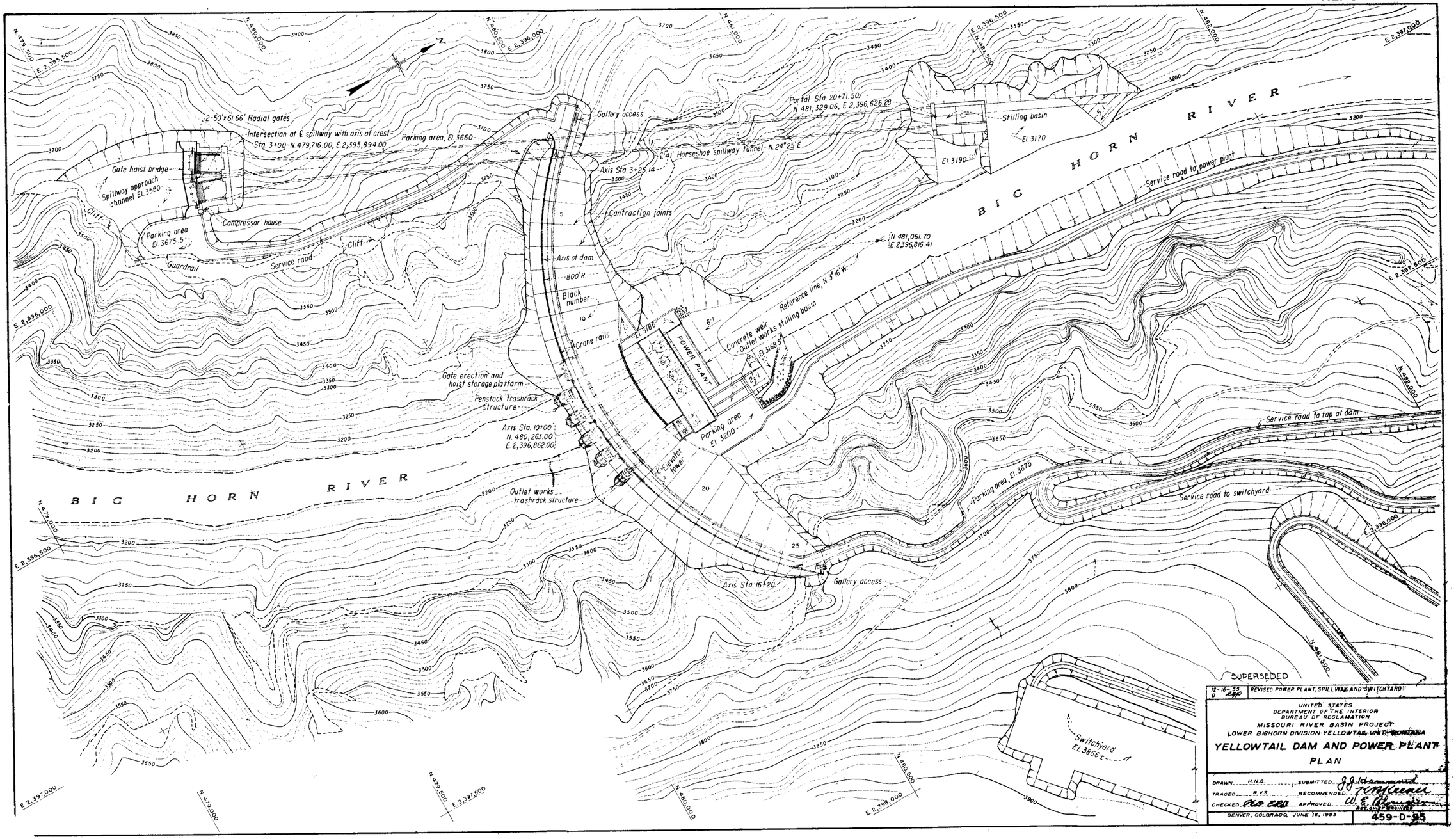
LOCATION MAP

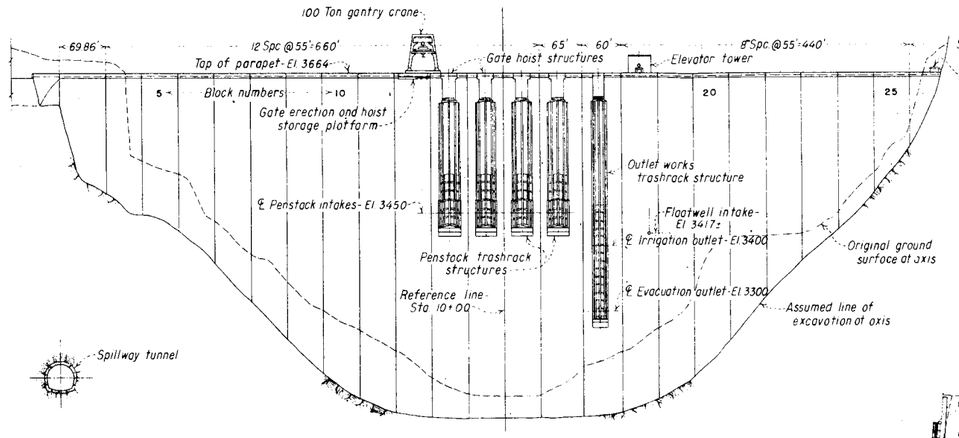
DRAWN G.F.S. SUBMITTED O. L. Rice
TRACED C.M.A. RECOMMENDED T. W. Lauer
CHECKED APPROVED Grant Blackford
ASSOC. CHIEF ENGINEER

DENVER, COLORADO, NOV. 21, 1955

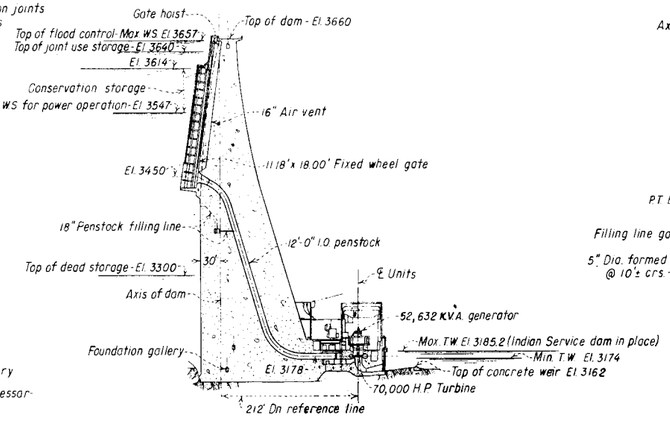
459-D-129

PRELIMINARY STUDIES
FIGURE NO. 2
REPORT HYD 414

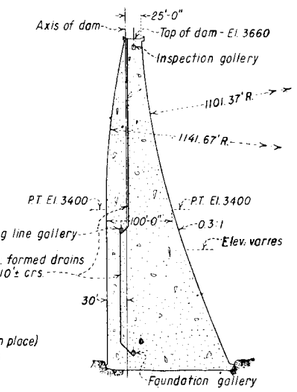




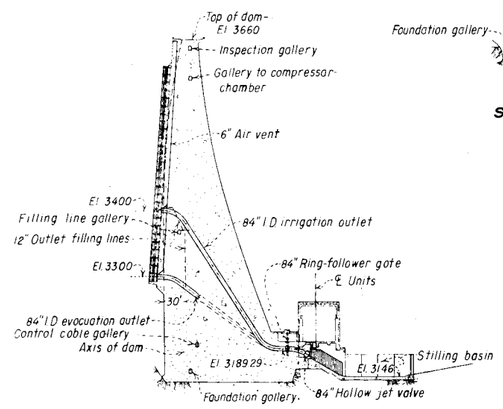
UPSTREAM ELEVATION
DEVELOPED ALONG AXIS



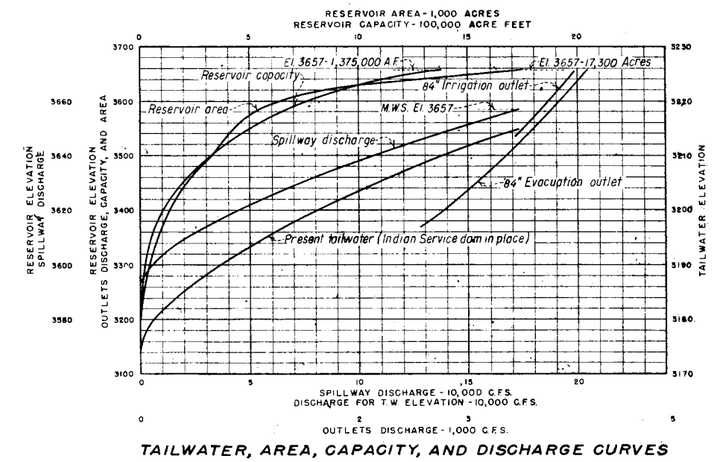
SECTION THRU PENSTOCK AND POWER PLANT



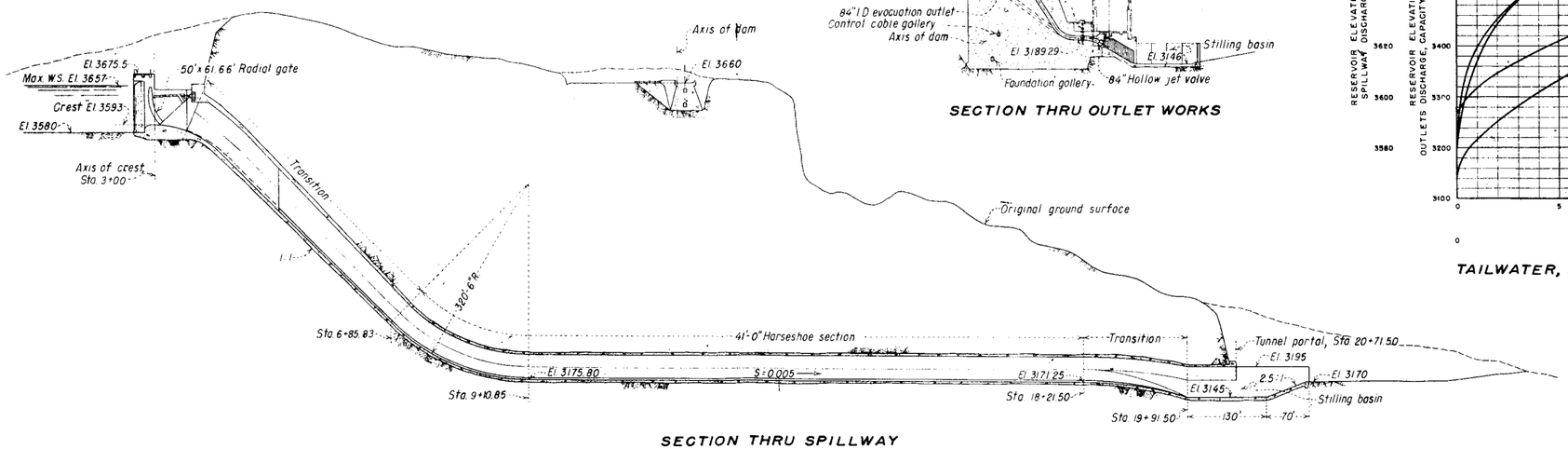
TYPICAL SECTION THRU DAM



SECTION THRU OUTLET WORKS



TAILWATER, AREA, CAPACITY, AND DISCHARGE CURVES



SECTION THRU SPILLWAY

SUPERSEDED

NOTE

Actual required foundation may vary widely from assumed excavation lines shown.

11-21-53	REVISED POWER PLANT AND SPILLWAY
0	

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

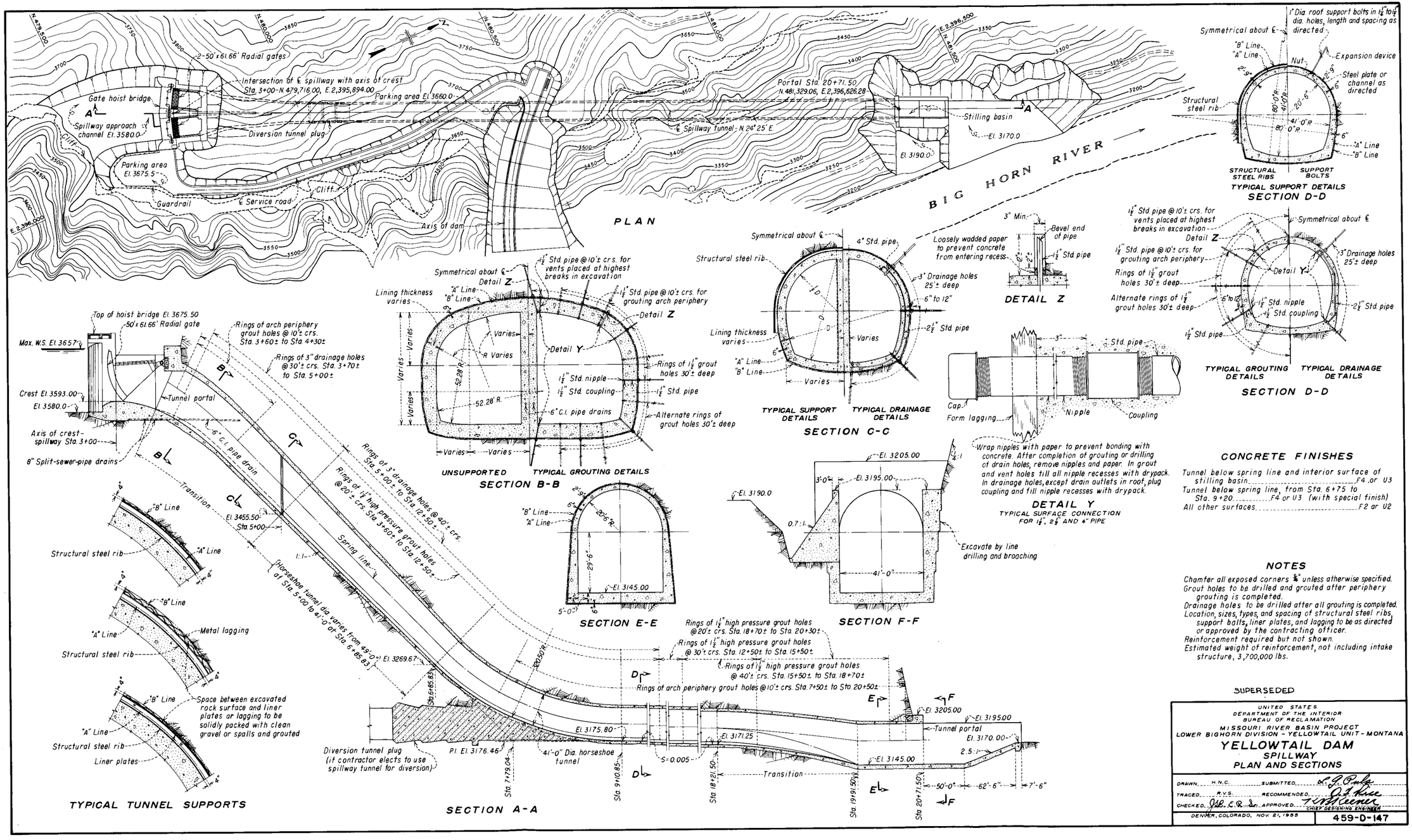
MISSOURI RIVER BASIN PROJECT
LOWER BIGHORN DIVISION-YELLOWTAIL UNIT-MONTANA

YELLOWTAIL DAM AND POWER PLANT

ELEVATION AND SECTIONS

DRAWN H.N.C. SUBMITTED J.J. Hammond
TRACED G.G.M. RECOMMENDED A.J. Wheeler
CHECKED APPROVED W. E. Glenn Jr. ASS. CHIEF ENGINEER

DENVER, COLORADO, JUNE 18, 1953 — 459-D-96



CONCRETE FINISHES

Tunnel below spring line and interior surface of stilling basin ..... F4 or U3
Tunnel below spring line, from Sta. 6+75 to Sta. 9+20 ..... F4 or U3 (with special finish)
All other surfaces ..... F2 or U2

NOTES

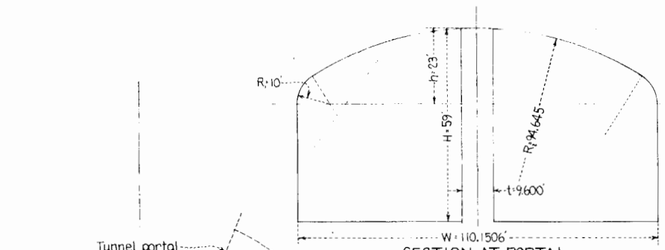
Chamfer all exposed corners ¾" unless otherwise specified.
Grout holes to be drilled and grouted after periphery grouting is completed.
Drainage holes to be drilled after all grouting is completed.
Location, sizes, types, and spacing of structural steel ribs, support bolts, liner plates, and lagging to be as directed or approved by the contracting officer.
Reinforcement required but not shown.
Estimated weight of reinforcement, not including intake structure, 3,700,000 lbs.

SUPERSEDED

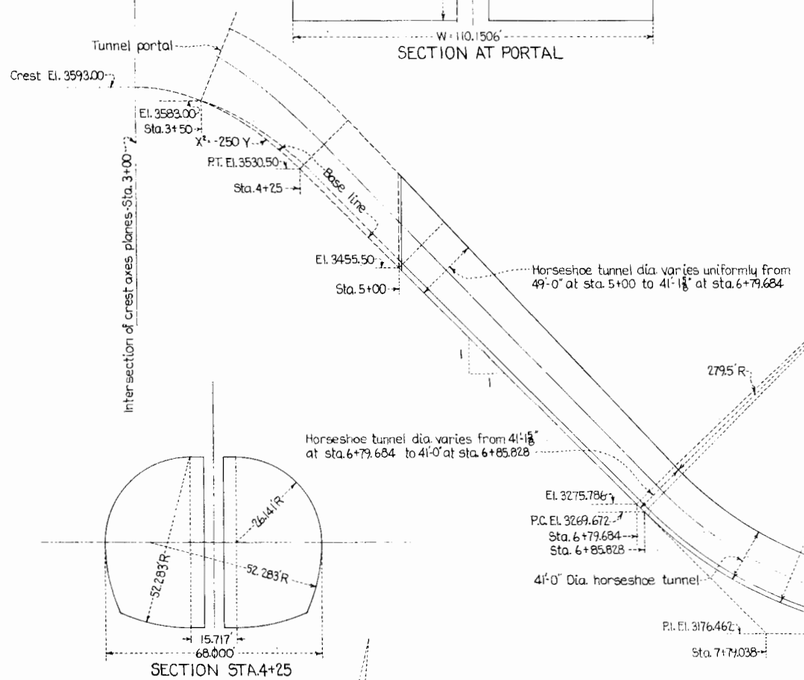
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
LOWER BIGHORN DIVISION - YELLOWTAIL UNIT - MONTANA

YELLOWTAIL DAM
SPILLWAY
PLAN AND SECTIONS

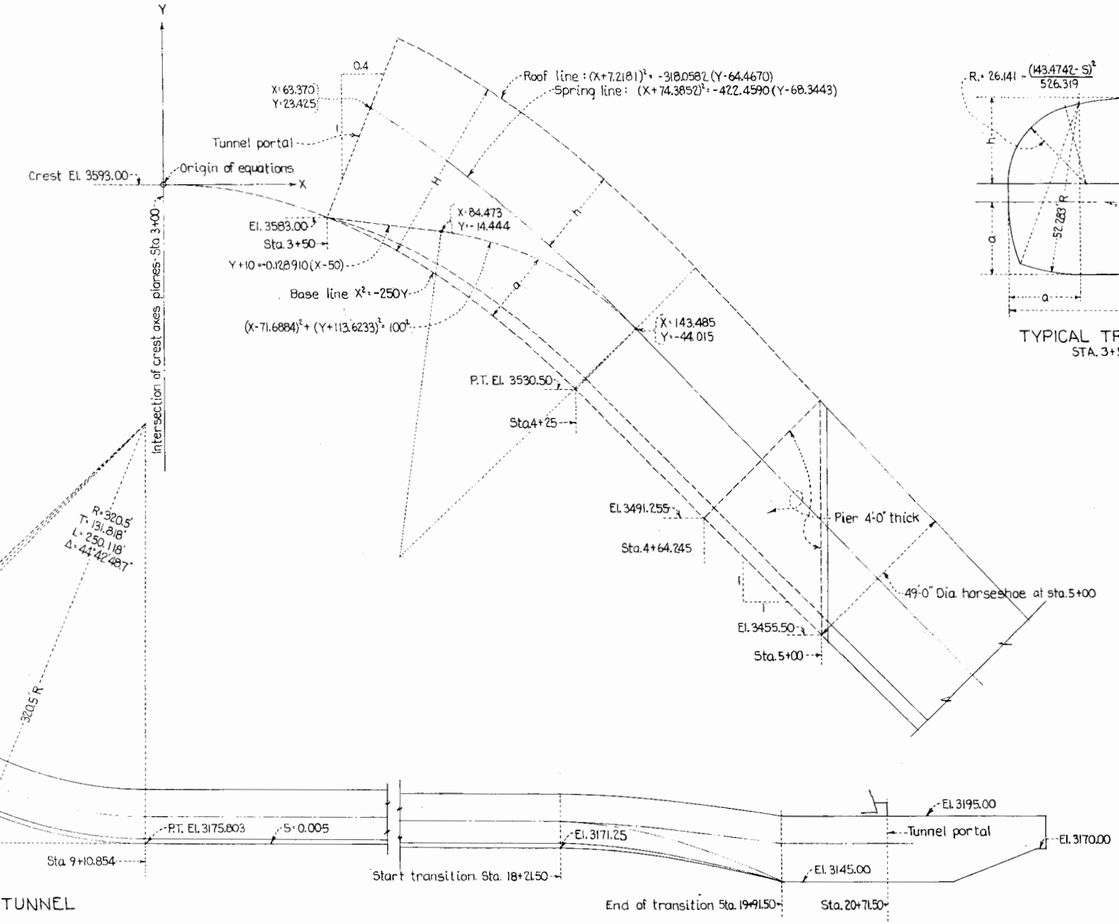
DRAWN H.N.C. SUBMITTED
TRACED R.V.S. RECOMMENDED
CHECKED APPROVED CHIEF DESIGNING ENGINEER
DENVER, COLORADO, NOV. 21, 1955
459-D-147



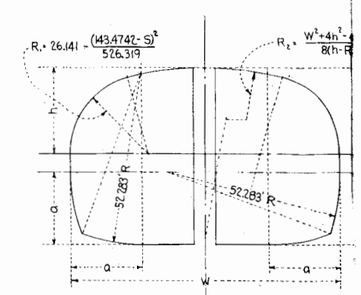
SECTION AT PORTAL



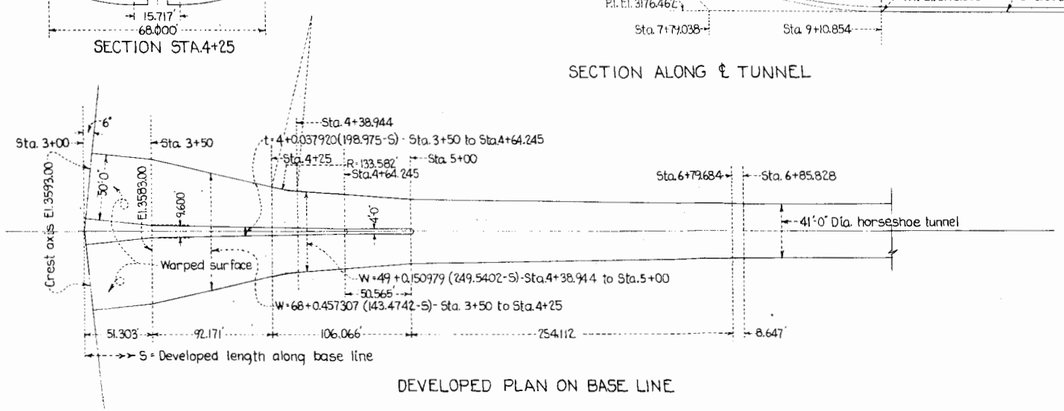
SECTION STA. 4+25



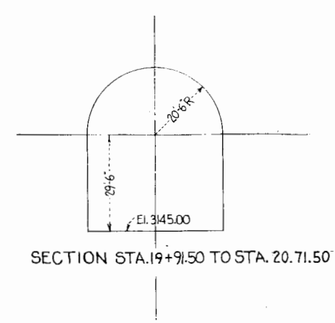
SECTION ALONG ℄ TUNNEL



TYPICAL TRANSITION SECTION
STA. 3+50 TO STA. 4+25



DEVELOPED PLAN ON BASE LINE

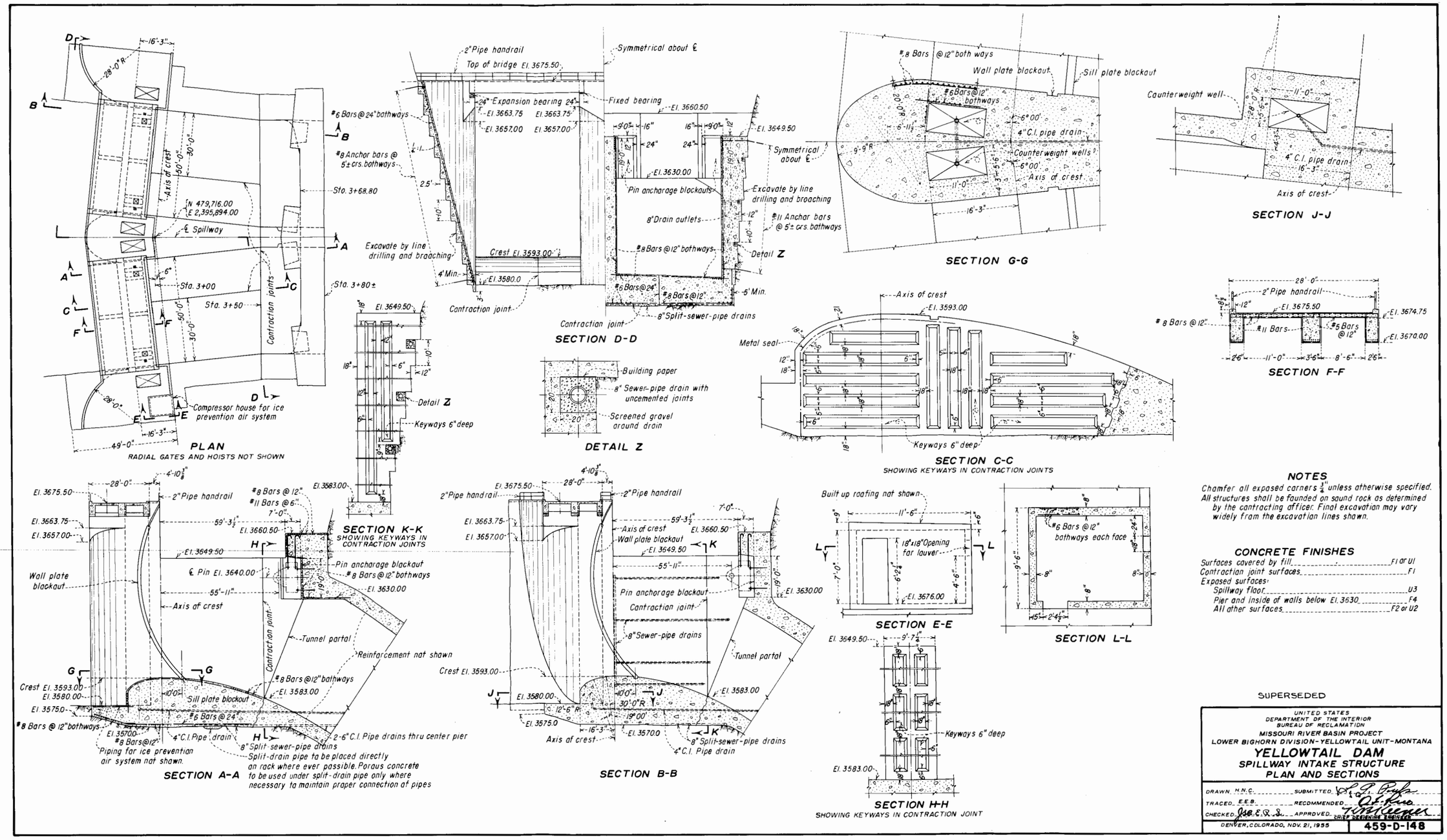


SECTION STA. 19+91.50 TO STA. 20.71.50

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
YELLOWTAIL DAM
SPILLWAY CREST
AND TUNNEL

DRAWN ..... SUBMITTED .....
TRACED ..... RECOMMENDED .....
CHECKED ..... APPROVED .....

DENVER, COLO. AUG 25, 1955 4



NOTES

Chamfer all exposed corners $\frac{3}{4}$" unless otherwise specified.
All structures shall be founded on sound rock as determined by the contracting officer. Final excavation may vary widely from the excavation lines shown.

CONCRETE FINISHES

Surfaces covered by fill	F1 or U1
Contraction joint surfaces	F1
Exposed surfaces:	
Spillway floor	U3
Pier and inside of walls below El. 3630	F4
All other surfaces	F2 or U2

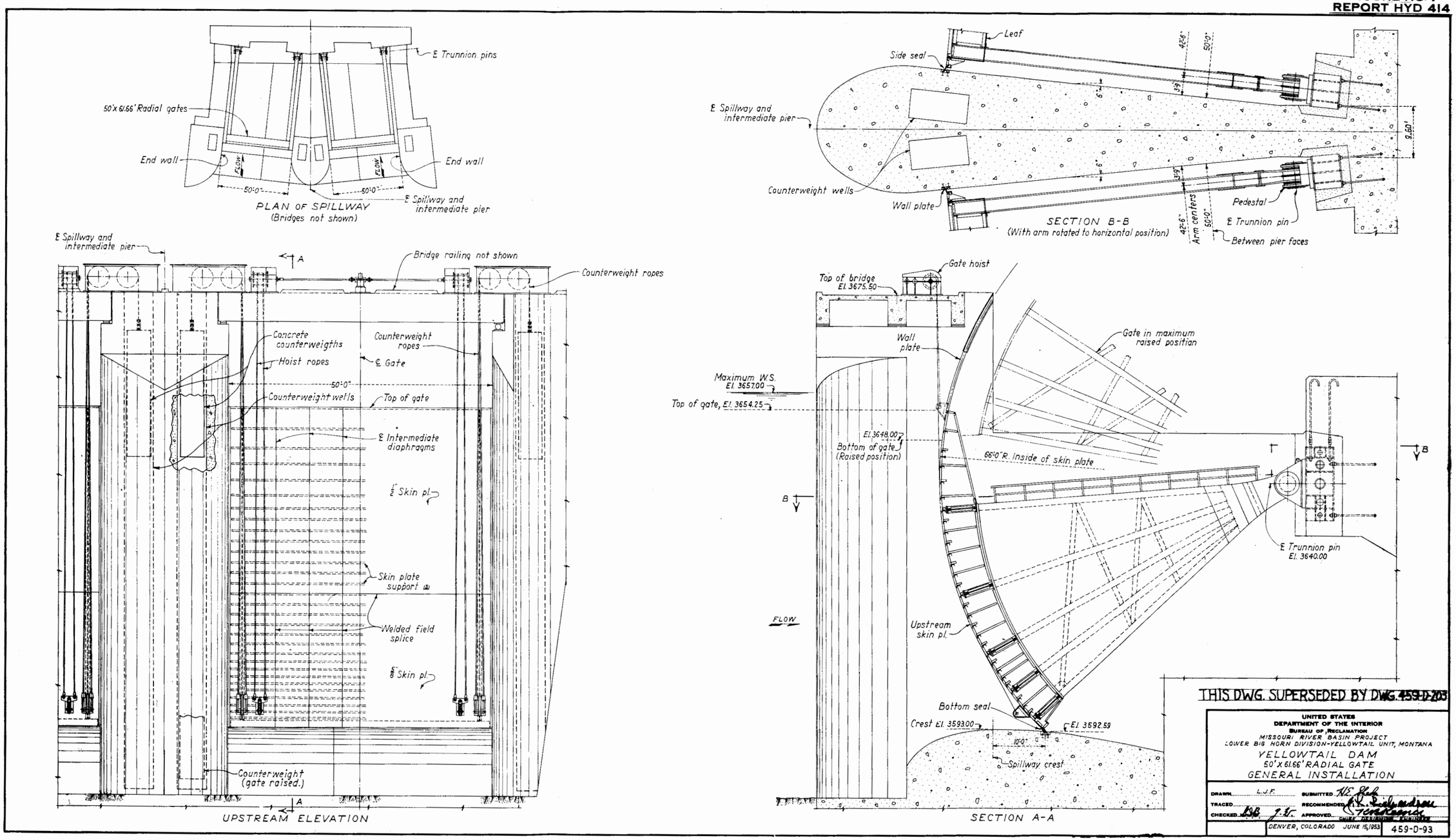
SUPERSEDED

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
LOWER BIGHORN DIVISION-YELLOWTAIL UNIT-MONTANA

YELLOWTAIL DAM
SPILLWAY INTAKE STRUCTURE
PLAN AND SECTIONS

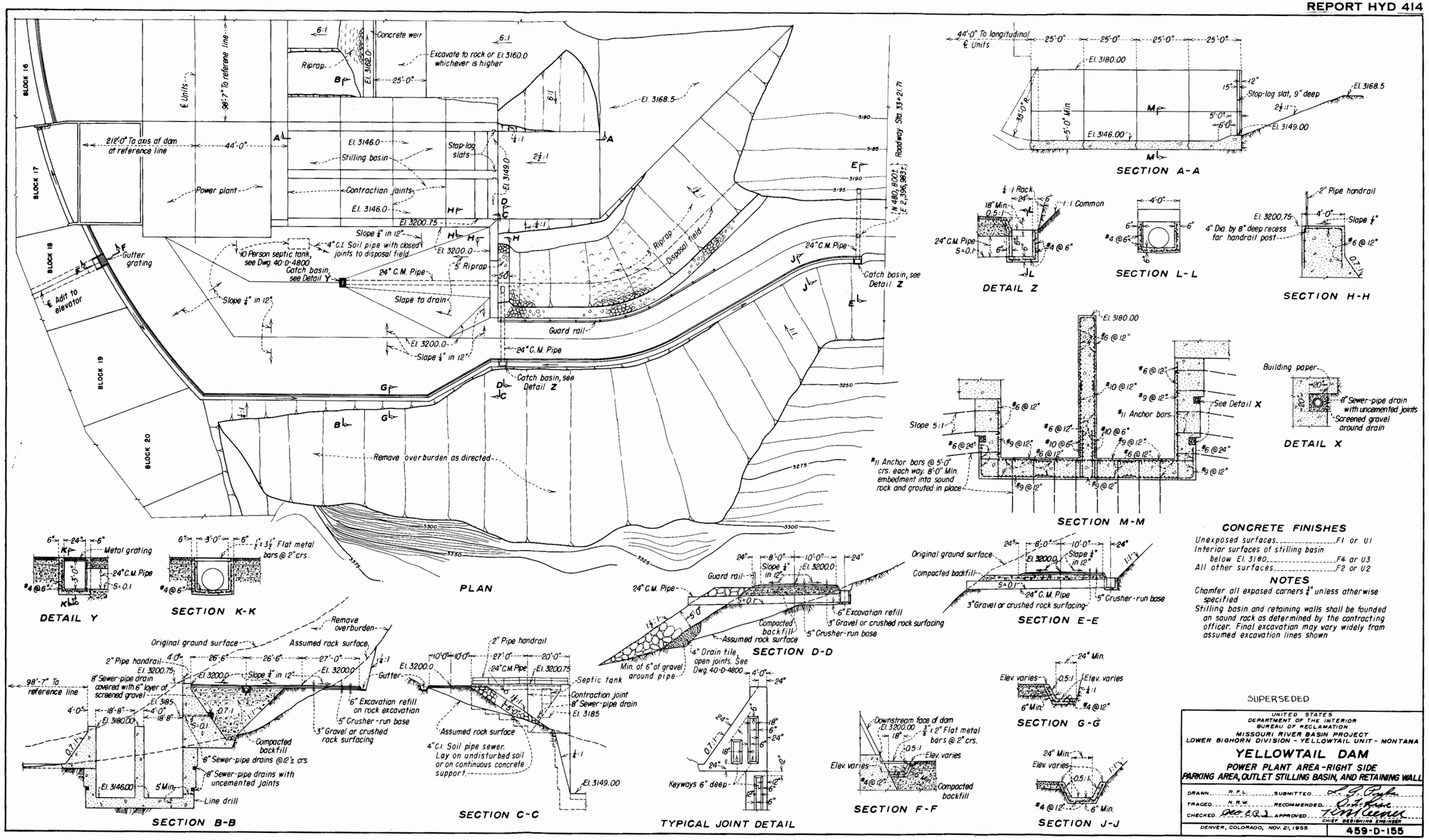
DRAWN H.N.C. SUBMITTED
TRACED E.E.B. RECOMMENDED
CHECKED APPROVED CHIEF DESIGNING ENGINEER
DENVER, COLORADO, NOV. 21, 1955

459-D-148


℄ Trunnion pins
50'x 61.66' Radial gates
End wall
FLOW
End wall
50'-0"
50'-0"
℄ Spillway and intermediate pier
PLAN OF SPILLWAY
(Bridges not shown)
Leaf
Side seal
42'-6"
50'-0"
℄ Spillway and intermediate pier
9.60'
Counterweight wells
Wall plate
Pedestal
℄ Trunnion pin
Between pier faces
Arm centers
SECTION B-B
(With arm rotated to horizontal position)
℄ Spillway and intermediate pier
A
Bridge railing not shown
Counterweight ropes
Concrete counterweights
Hoist ropes
Counterweight ropes
℄ Gate
50'-0"
Counterweight wells
Top of gate
℄ Intermediate diaphragms
℄ Skin pl.
Skin plate support
Welded field splice
℄ Skin pl.
Counterweight (gate raised.)
A
UPSTREAM ELEVATION
Gate hoist
Top of bridge
El. 3675.50
Wall plate
Gate in maximum raised position
Maximum W.S.
El. 3657.00
Top of gate, El. 3654.25
El. 3648.00
Bottom of gate
(Raised position)
66'-0" R. inside of skin plate
B
B
℄ Trunnion pin
El. 3640.00
FLOW
Upstream skin pl.
Bottom seal
Crest El. 3593.00
℄ El. 3592.59
10'-0"
Spillway crest
SECTION A-A
THIS DWG. SUPERSEDED BY DWG. 459-D-203
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
LOWER BIG HORN DIVISION-YELLOWTAIL UNIT, MONTANA
YELLOWTAIL DAM
50'x 61.66' RADIAL GATE
GENERAL INSTALLATION
DRAWN L.J.F.
SUBMITTED
TRACED
RECOMMENDED
CHECKED
APPROVED
CHIEF, DESIGNING ENGINEER
DENVER, COLORADO JUNE 15, 1953
459-D-93

PRELIMINARY STUDIES

FIGURE NO. 8
REPORT HYD 414



CONCRETE FINISHES

Unexposed surfaces.....F1 or U1
Interior surfaces of stilling basin below El. 3180.....F4 or U3
All other surfaces.....F2 or U2

NOTES

Chamfer all exposed corners ¾" unless otherwise specified

Stilling basin and retaining walls shall be founded on sound rock as determined by the contracting officer. Final excavation may vary widely from assumed excavation lines shown

SUPERSEDED

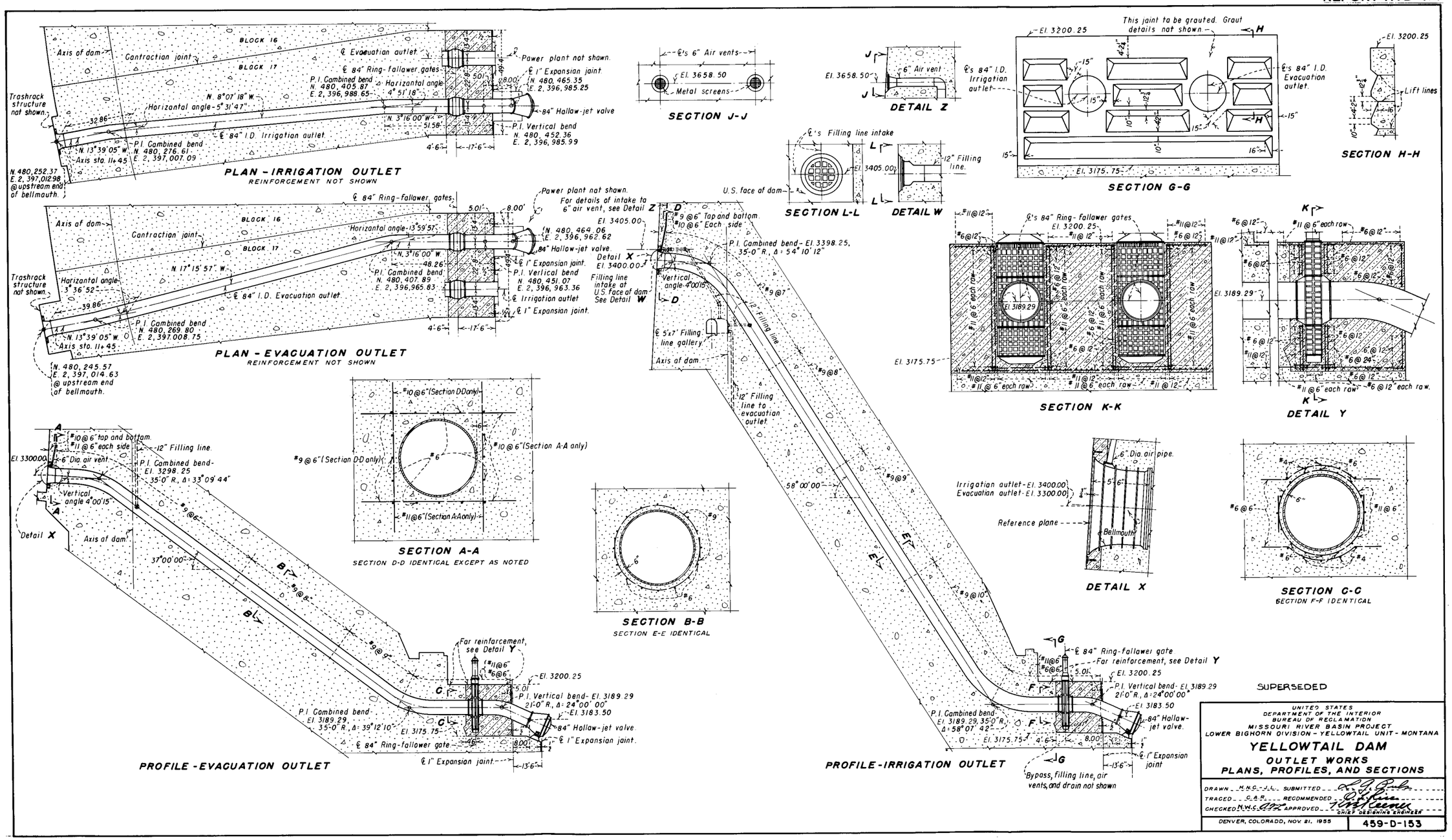
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
LOWER BIGHORN DIVISION - YELLOWTAIL UNIT - MONTANA

YELLOWTAIL DAM

POWER PLANT AREA - RIGHT SIDE
PARKING AREA, OUTLET STILLING BASIN, AND RETAINING WALL

DRAWN R.F.L. SUBMITTED L. G. Pyle
TRACED N.R.W. RECOMMENDED O. L. Rice
CHECKED [illegible] APPROVED [illegible]
CHIEF DESIGNING ENGINEER

DENVER, COLORADO, NOV. 21, 1955
459-D-155



SUPERSEDED

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
LOWER BIGHORN DIVISION - YELLOWTAIL UNIT - MONTANA

YELLOWTAIL DAM

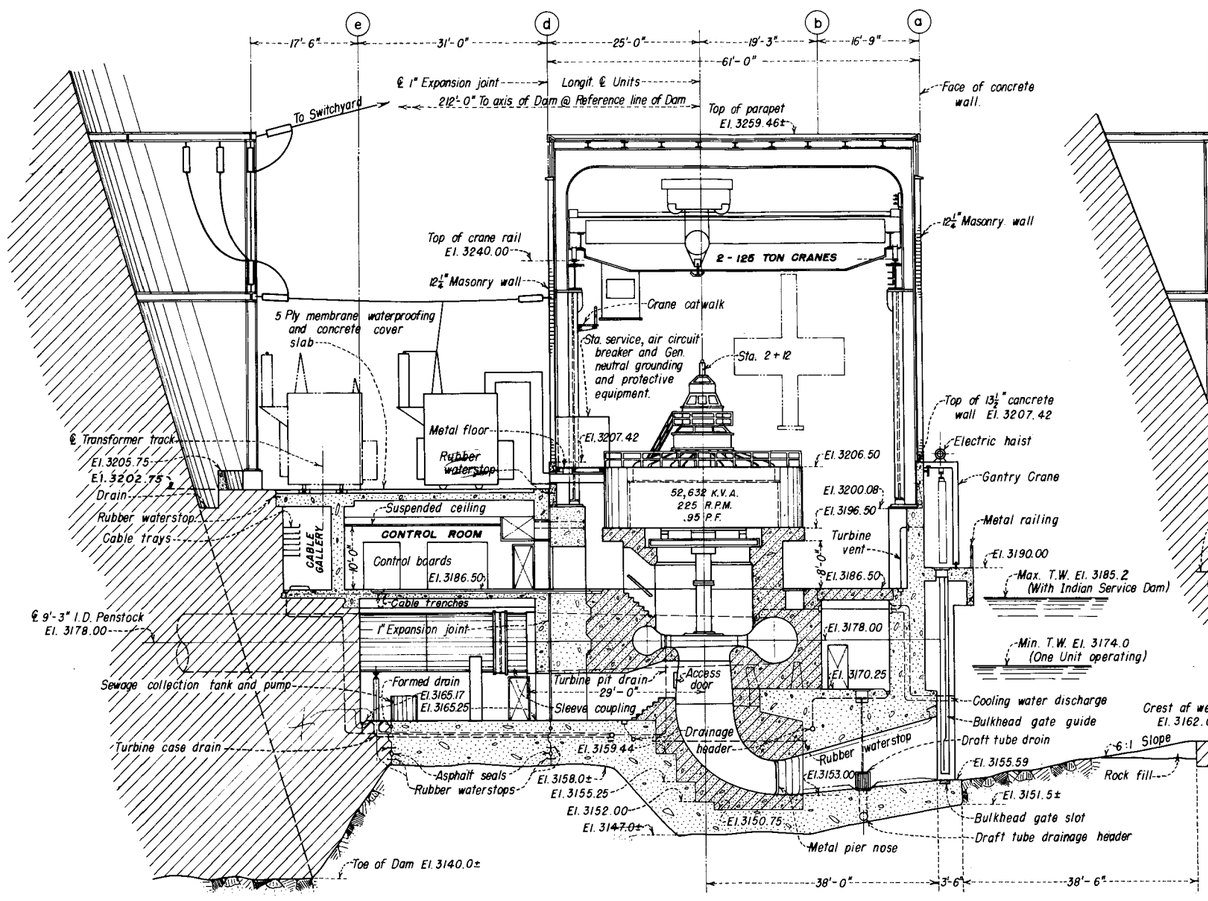
OUTLET WORKS

PLANS, PROFILES, AND SECTIONS

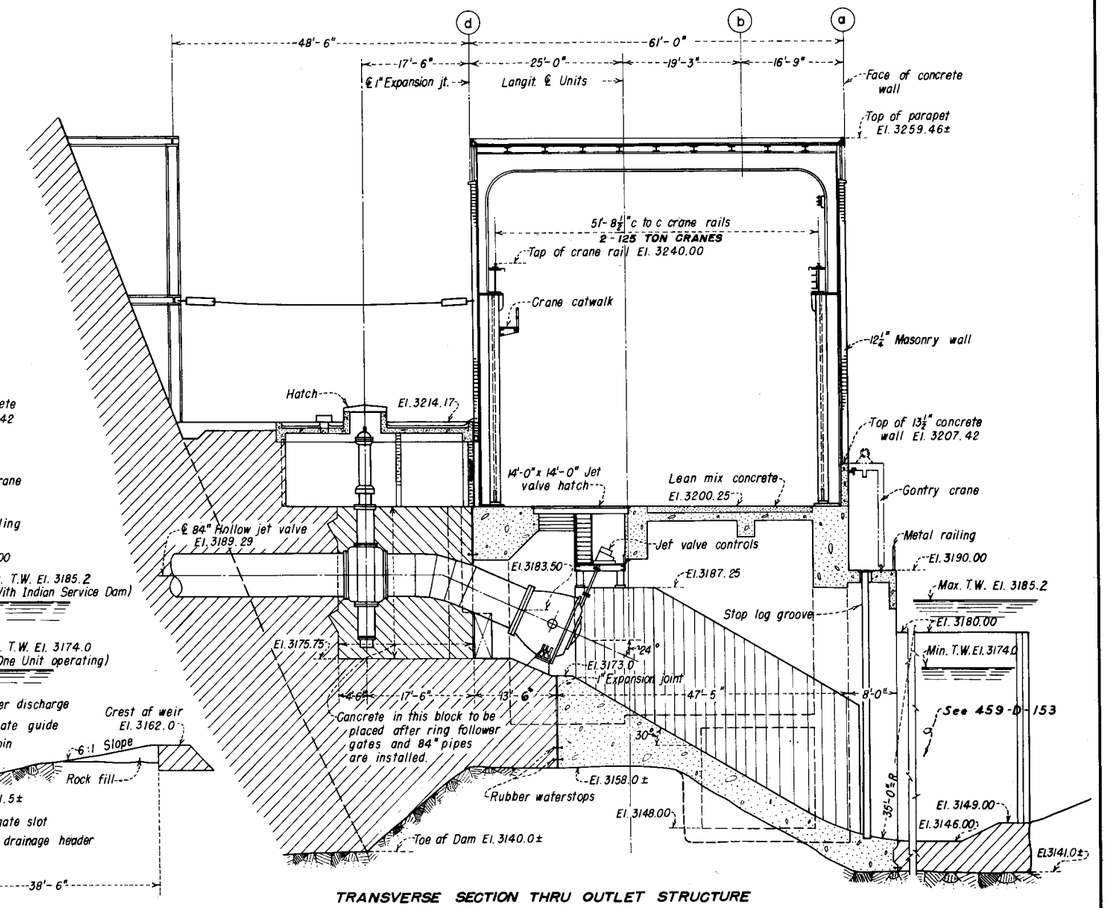
DRAWN M.N.G. - J.L. SUBMITTED
TRACED C.A.R. RECOMMENDED
CHECKED M.N.G. APPROVED
CHIEF DESIGNING ENGINEER

DENVER, COLORADO, NOV. 21, 1955

459-D-153



TRANSVERSE SECTION THRU ℄ OF UNIT
(UNIT No. 2)



TRANSVERSE SECTION THRU OUTLET STRUCTURE

NOTE
For. notes, see 459-D-102

5 0 5 10 15 20 25
SCALE OF FEET

THIS DRAWING SUPERSEDED BY DWG 459-D-286

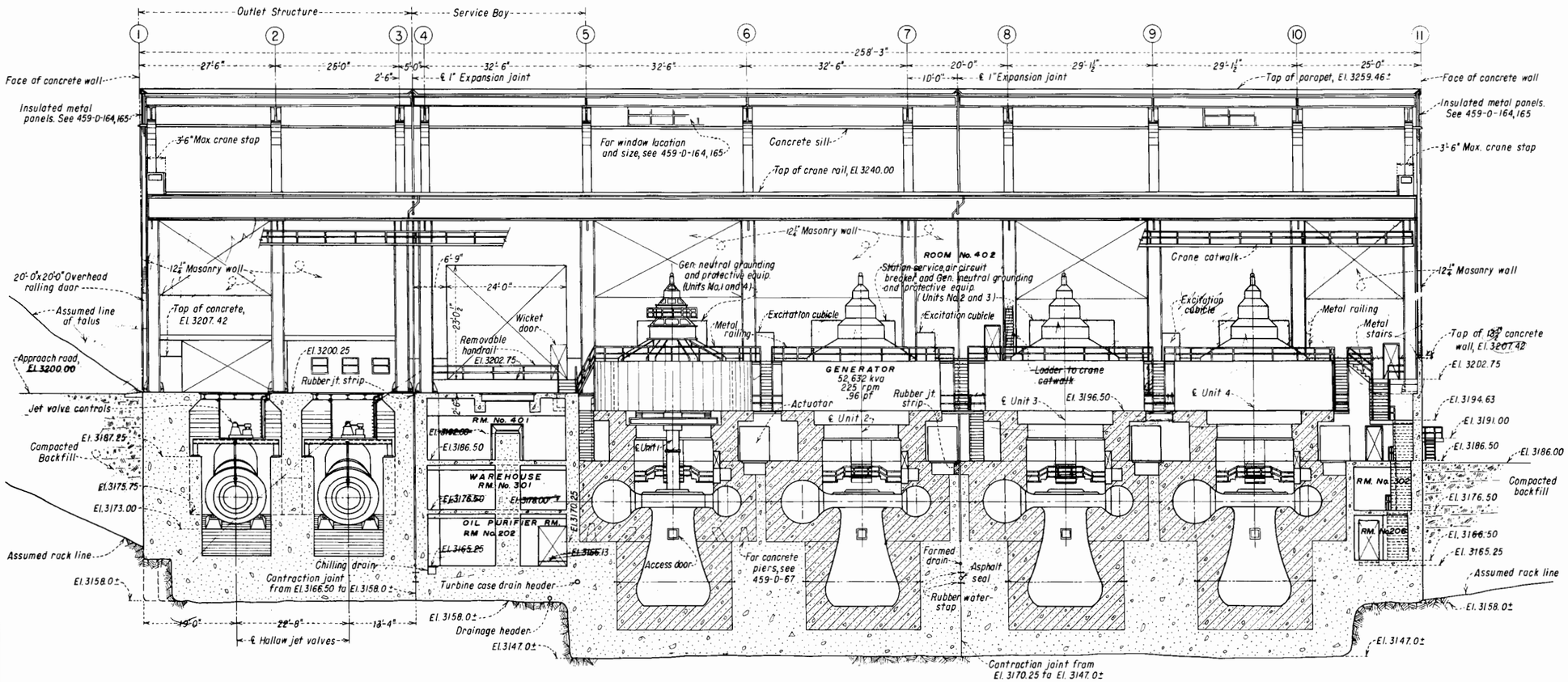
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
LOWER BIGHORN DIVISION - YELLOWTAIL UNIT - MONTANA

YELLOWTAIL POWER PLANT
GENERAL ARRANGEMENT
TRANSVERSE SECTIONS
℄ OF UNITS AND OUTLET STRUCTURE

DRAWN S.Z. SUBMITTED Samuel Gindel
TRACED R.T.G. RECOMMENDED T.W. Kelsey
CHECKED W.D.B. J.R. H. APPROVED Orm A. Blodgett
ASSOC. CHIEF ENGINEER

DENVER, COLORADO OCT. 21, 1958
SHEET 4 OF 8

459-D-105



LONGITUDINAL SECTION THRU ℄ UNITS

SCALE OF FEET

NOTE

For notes, see 459-D-102.

THIS DRAWING SUPERSEDED BY DWG 459-D-286

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

MISSOURI RIVER BASIN PROJECT
LOWER BIGHORN DIVISION - YELLOWTAIL UNIT - MONTANA

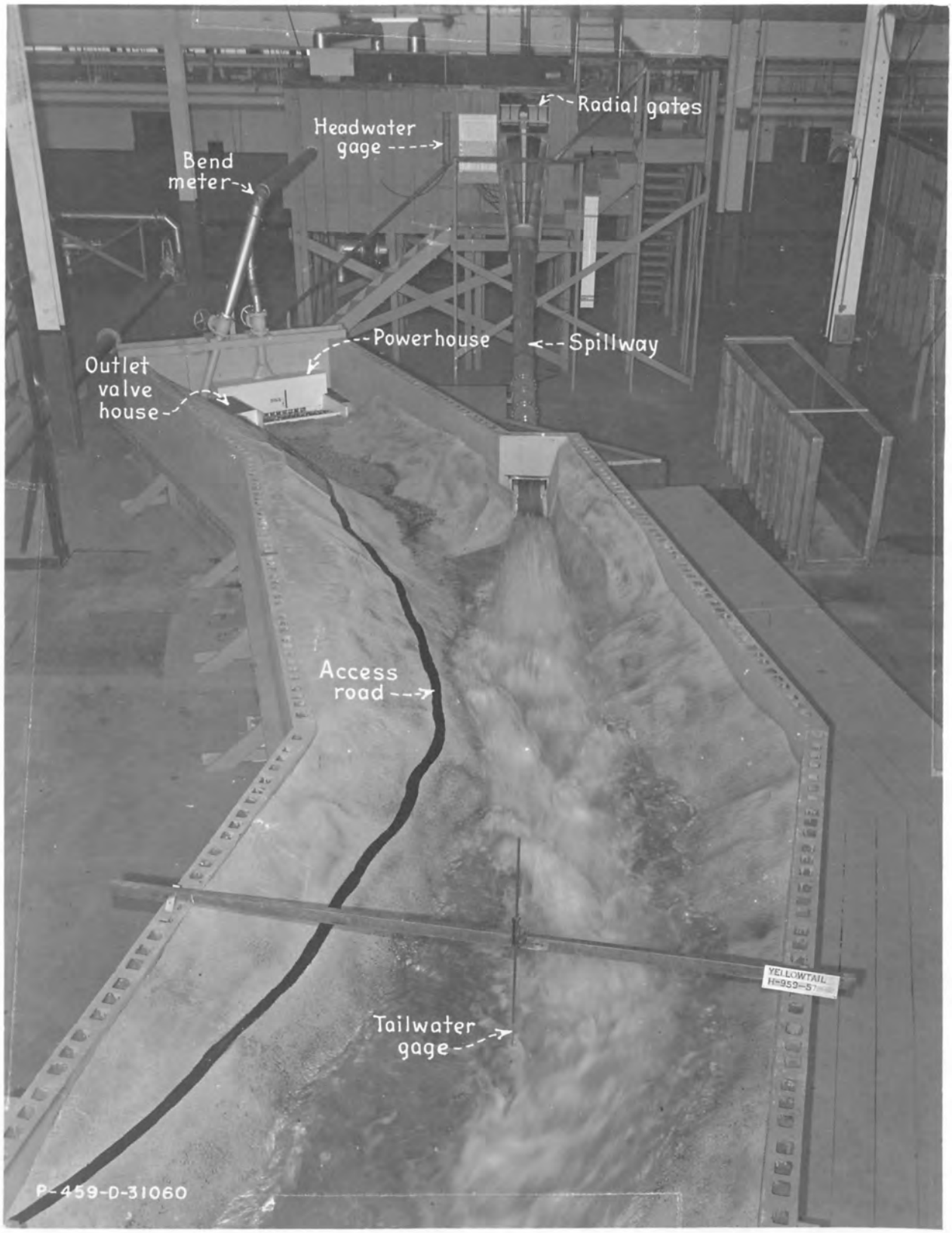
YELLOWTAIL POWER PLANT

GENERAL ARRANGEMENT
LONGITUDINAL SECTION THRU ℄ UNITS

DRAWN O.Z. SUBMITTED James L. Dodd
TRACED V.M.M. RECOMMENDED T. M. Keenan
CHECKED W.A.B. T.R. W.P. APPROVED Grant Blackwood
ASSOC. CHIEF ENGINEER

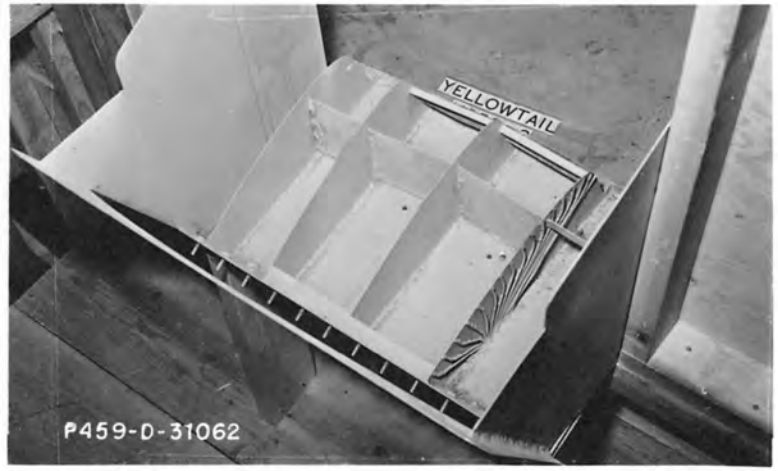
DENVER, COLORADO, OCT. 21, 1955
SHEET 5 OF 6

459-D-106

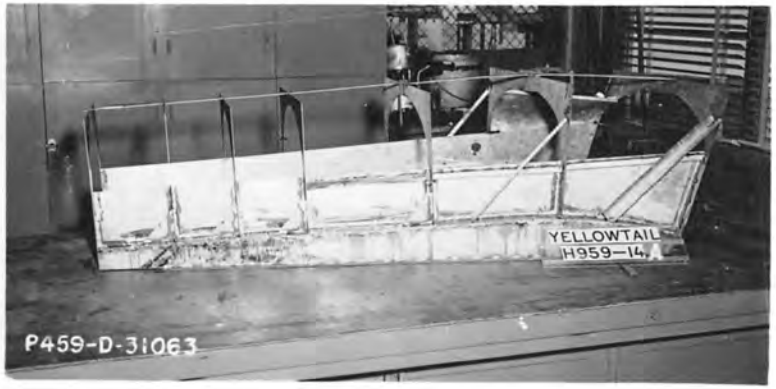


YELLOWTAIL DAM
SPILLWAY, OUTLETS, AND POWERHOUSE
1:54 SCALE MODEL

A. Approach area



B. Crest templates and piezometers



C. Tunnel transition

D. Crest

YELLOWTAIL DAM
SPILLWAY MODEL CONSTRUCTION
1:54 SCALE MODEL

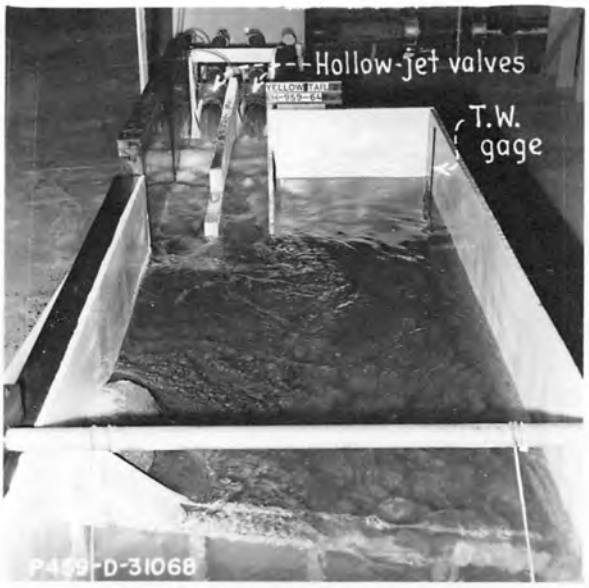
PRELIMINARY STUDIES
FIGURE 13
REPORT HYD 414

A. Spillway and tunnel pier

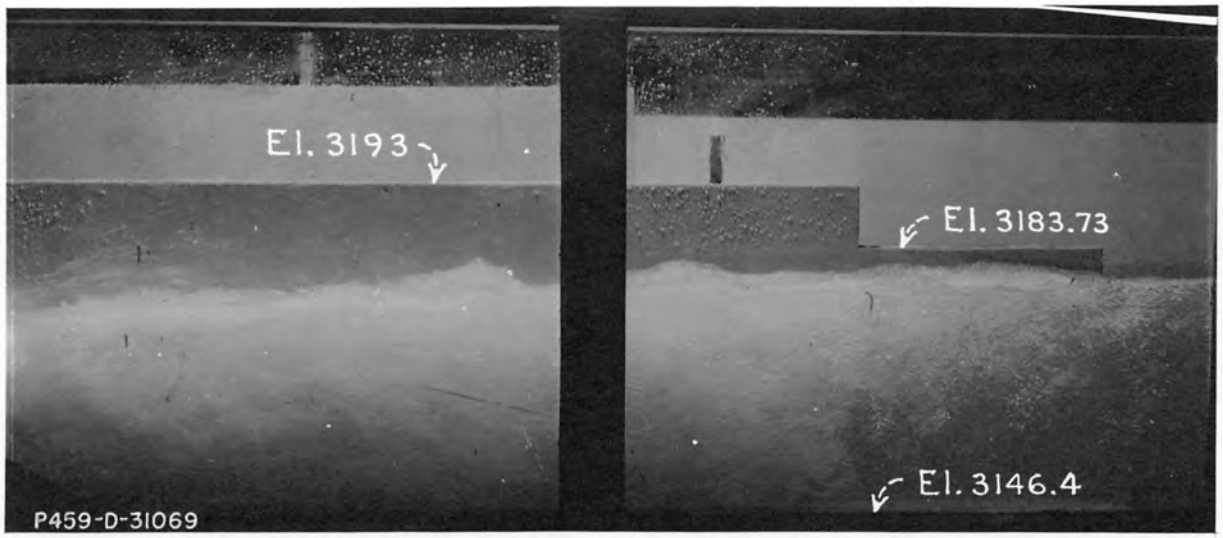
B. Wood pattern for tunnel transition

YELLOWTAIL DAM
SPILLWAY MODEL CONSTRUCTION
1:54 SCALE MODEL

A. Prepared for erosion test

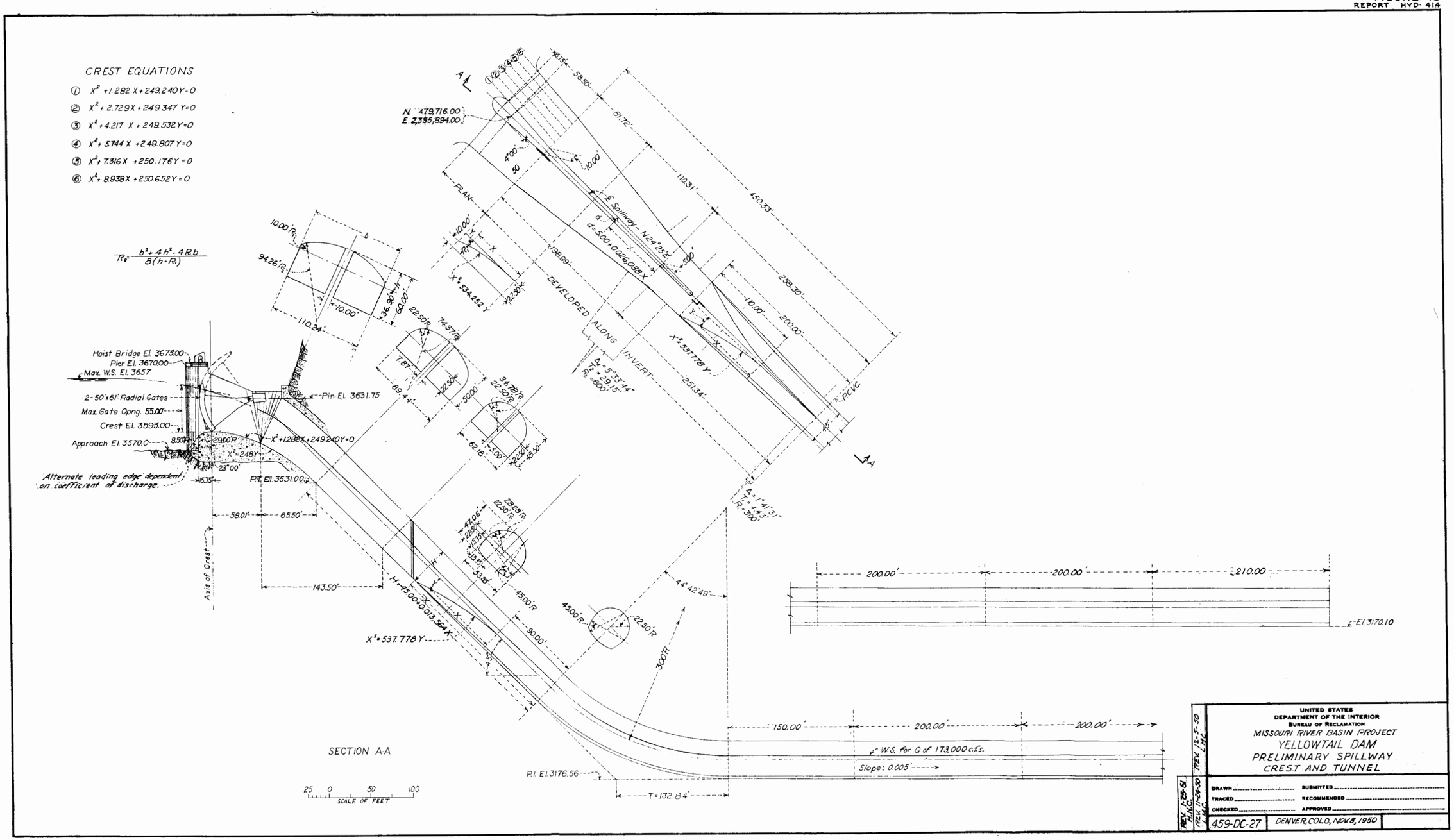


B. 5,000 second feet
Reservoir Elev. 3337



C. 5,000 second feet
Reservoir Elev. 3337

YELLOWTAIL DAM
OUTLET WORKS STILLING BASIN MODEL - BASIN ONE
1:28 SCALE MODEL


CREST EQUATIONS
① X² + 1.282 X + 249.240 Y = 0
② X² + 2.729 X + 249.347 Y = 0
③ X² + 4.217 X + 249.532 Y = 0
④ X² + 5.744 X + 249.807 Y = 0
⑤ X² + 7.316 X + 250.176 Y = 0
⑥ X² + 8.938 X + 250.652 Y = 0
PLAN
N 479,716.00
E 2,395,894.00
℄ Spillway - N24°25'E
d = 5.00 + 0.026,038 X
DEVELOPED ALONG INVERT
X² = 537.778 Y
X² = 534.232 Y
X² = 537.778 Y
X² + 1.282 X + 249.240 Y = 0
X² = 248 Y
H = 4.00 + 0.013,564 X
Hoist Bridge El. 367.00
Pier El. 367.00
Max. W.S. El. 365.7
2-50'x61' Radial Gates
Max. Gate Opng. 55.00
Crest El. 359.00
Approach El. 357.0
Pin El. 363.1.75
Alternate leading edge dependent on coefficient of discharge.
P.T. El. 353.1.00
Axis of Crest
SECTION A-A
P.I. El. 317.6.56
T = 132.84'
W.S. for Q of 173,000 c.f.s.
Slope: 0.005'
El. 317.0.10
P.C.V.C.
SCALE OF FEET
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT
YELLOWTAIL DAM
PRELIMINARY SPILLWAY
CREST AND TUNNEL
459-DC-27
DENVER, COLO., NOV. 8, 1950

A. Approach area - Preliminary

B. Preliminary right bank

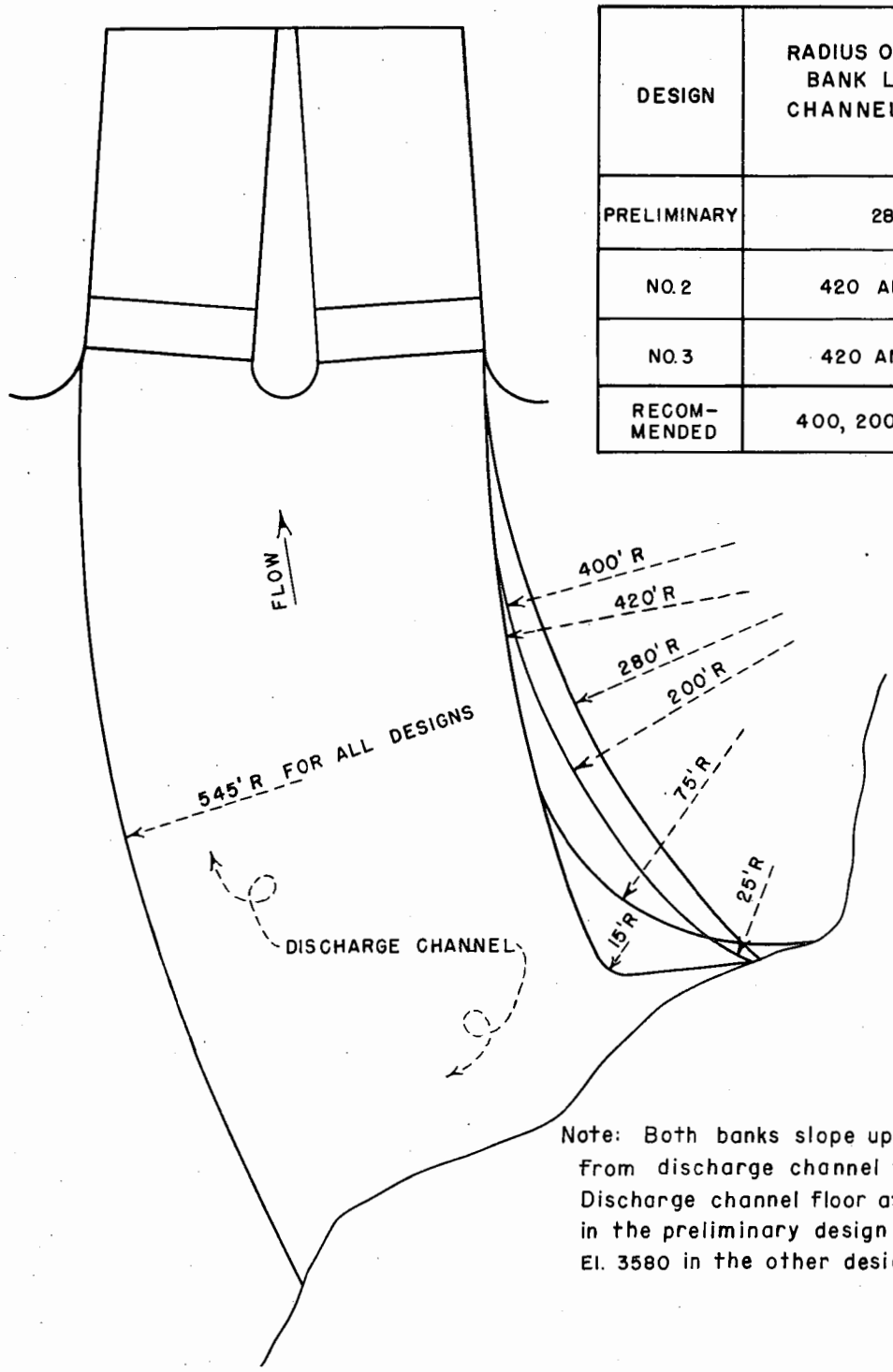
C. An unsatisfactory revision

D. Recommended

YELLOWTAIL DAM
PRELIMINARY SPILLWAY--APPROACH CHANNEL--DISCHARGE 173,000 SECOND FEET
1:54 SCALE MODEL

PRELIMINARY STUDIES
FIGURE 17
REPORT HYD 41

FIGURE 18
REPORT HYD. 414



DESIGN	RADIUS OF RIGHT BANK LINE AT CHANNEL FLOOR
PRELIMINARY	280
NO. 2	420 AND 15
NO. 3	420 AND 75
RECOM-MENDED	400, 200 AND 25

Note: Both banks slope up 4 on 1 from discharge channel floor. Discharge channel floor at El. 3570 in the preliminary design and at El. 3580 in the other designs.

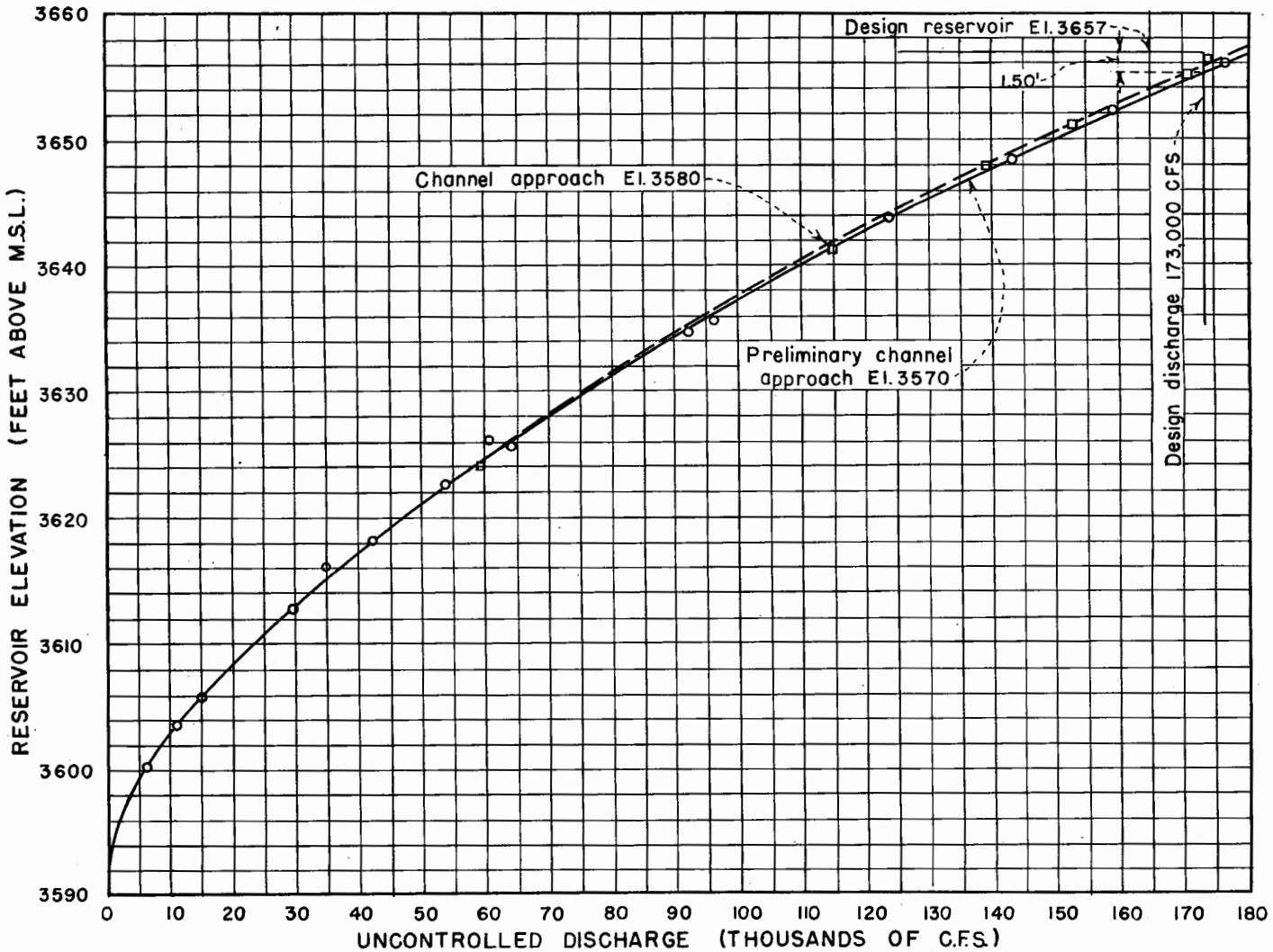
YELLOWTAIL DAM

PRELIMINARY SPILLWAY - APPROACH CHANNAL MODIFICATIONS

A. 60,000 second feet

B. 125,000 second feet

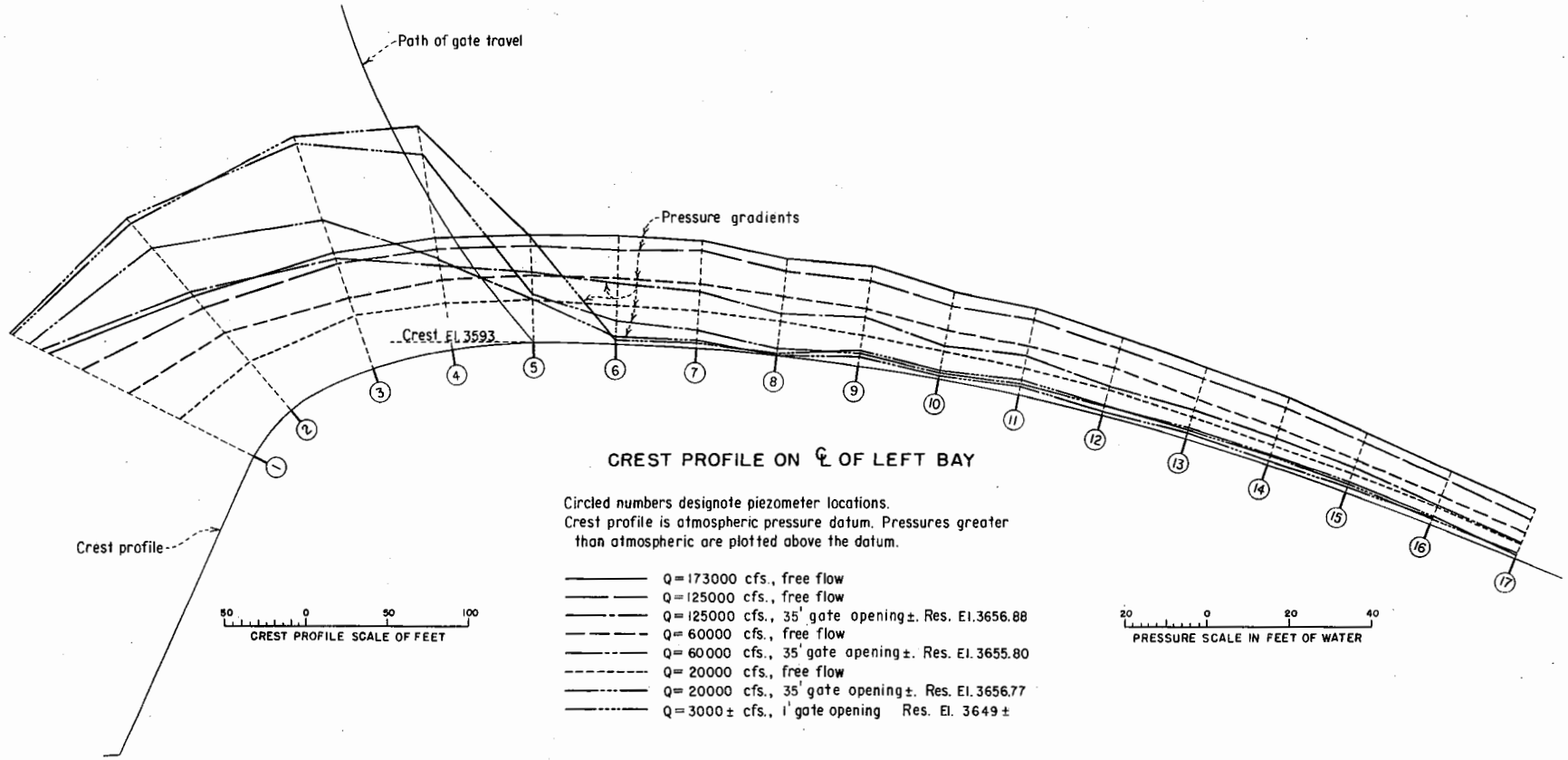
YELLOWTAIL DAM
PRELIMINARY SPILLWAY PIER NOSE AND GATE SECTION
1:54 SCALE MODEL



YELLOWTAIL DAM

PRELIMINARY SPILLWAY CAPACITY CURVES

1:54 SCALE MODEL



CREST PROFILE ON ℄ OF LEFT BAY

Circled numbers designate piezometer locations.
Crest profile is atmospheric pressure datum. Pressures greater than atmospheric are plotted above the datum.

- Q = 173000 cfs., free flow
- Q = 125000 cfs., free flow
- Q = 125000 cfs., 35' gate opening ±. Res. El. 3656.88
- Q = 60000 cfs., free flow
- Q = 60000 cfs., 35' gate opening ±. Res. El. 3655.80
- Q = 20000 cfs., free flow
- Q = 20000 cfs., 35' gate opening ±. Res. El. 3656.77
- Q = 3000 ± cfs., 1' gate opening Res. El. 3649 ±

YELLOWTAIL DAM

PRELIMINARY SPILLWAY - CREST PRESSURES

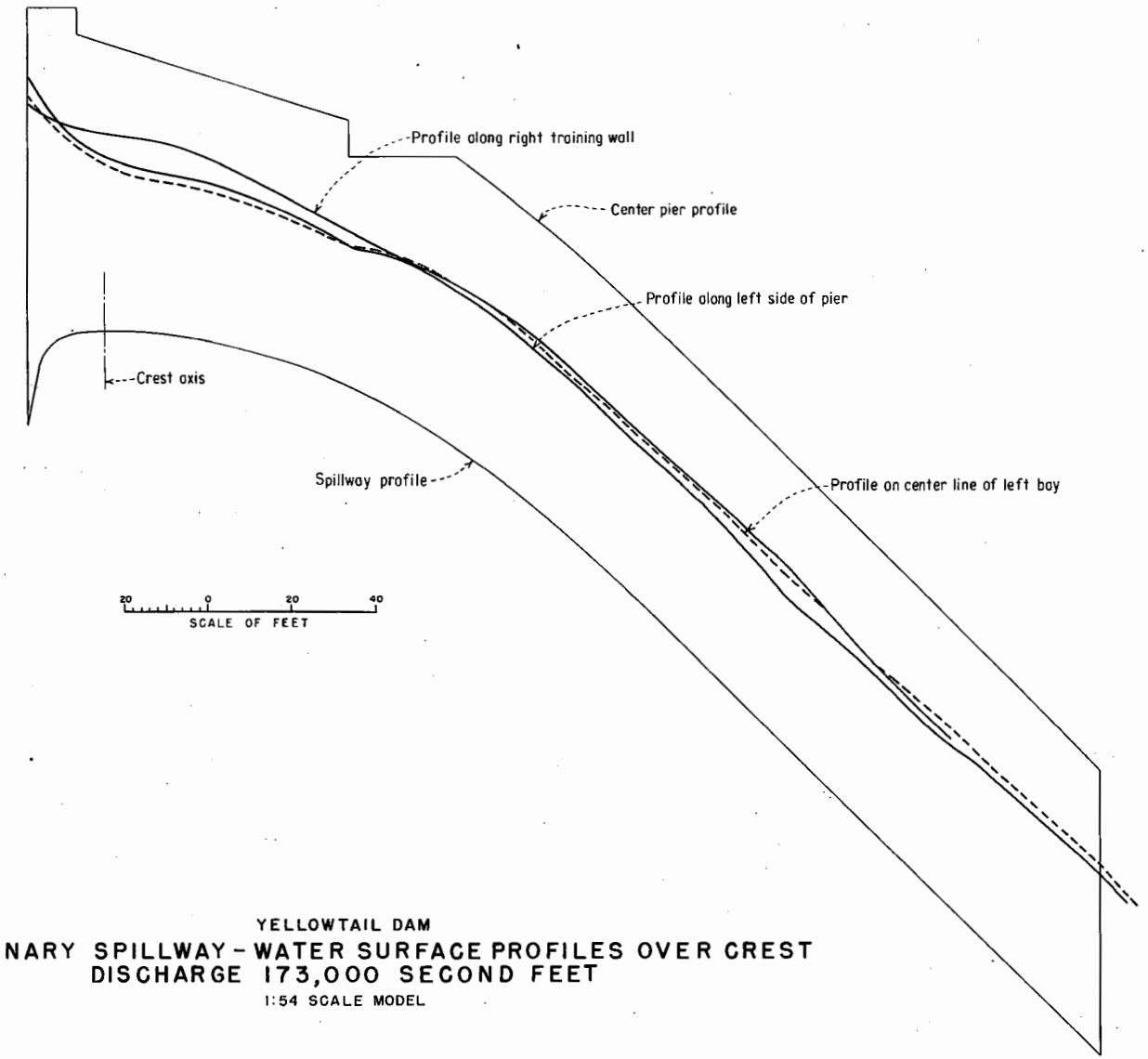
1:54 SCALE MODEL

PRELIMINARY STUDIES

FIGURE 21
REPORT HYD 414

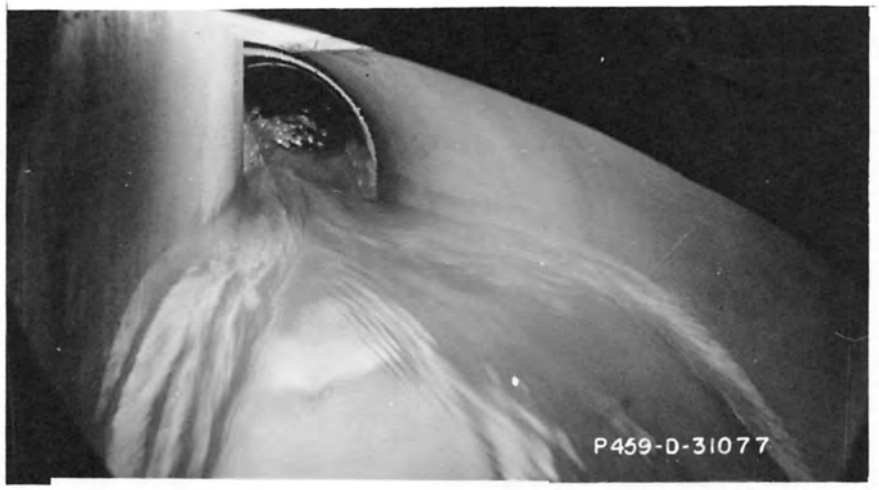
430

FIGURE 22
REPORT HYD. 414

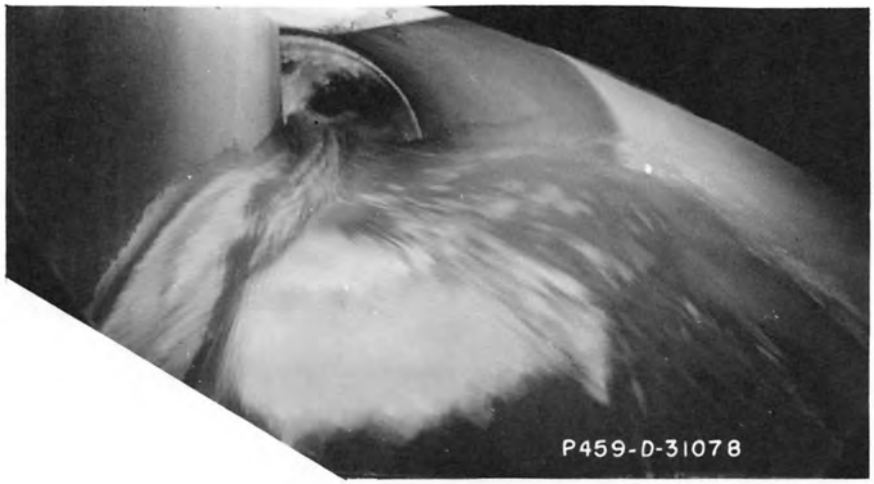


YELLOWTAIL DAM
PRELIMINARY SPILLWAY - WATER SURFACE PROFILES OVER CREST
DISCHARGE 173,000 SECOND FEET
1:54 SCALE MODEL

A. 60,000 second feet

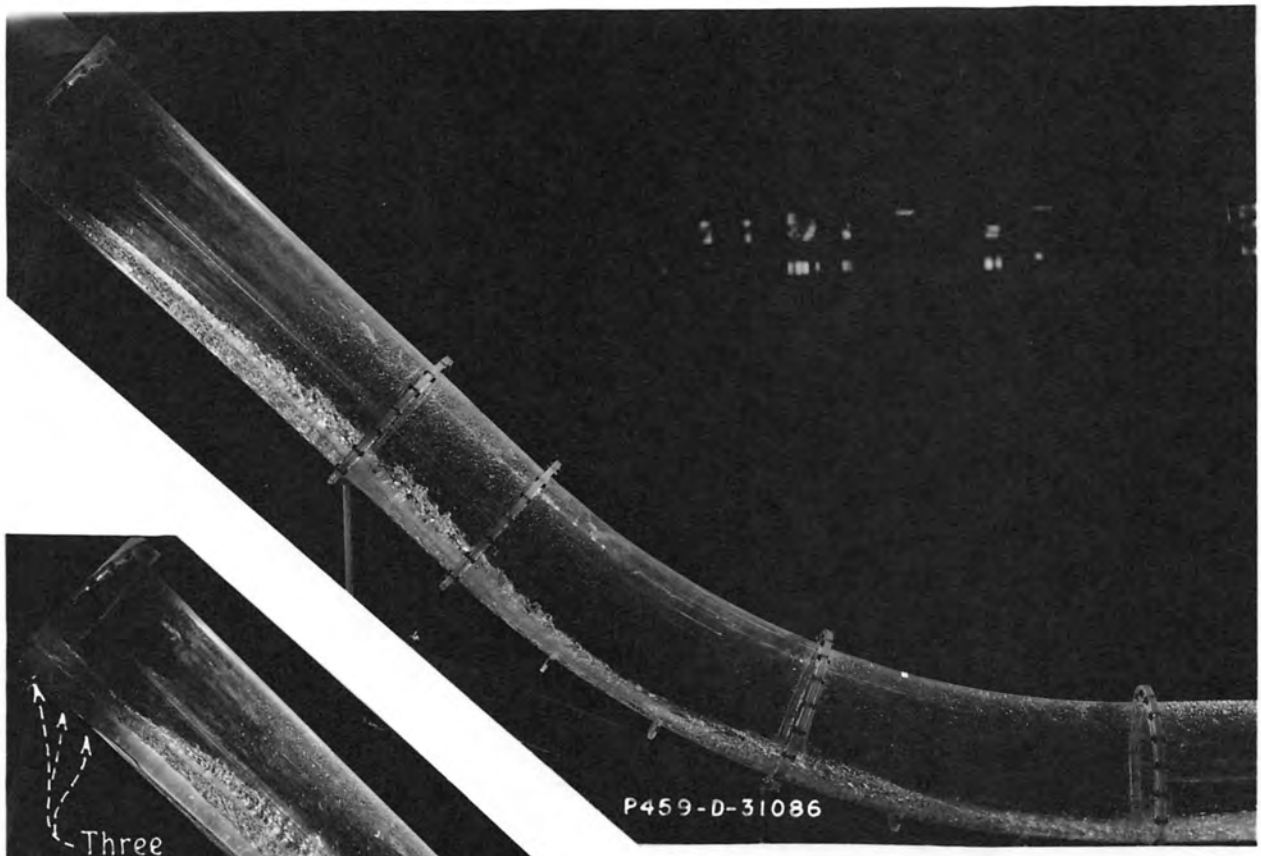


B. 125,000 second feet

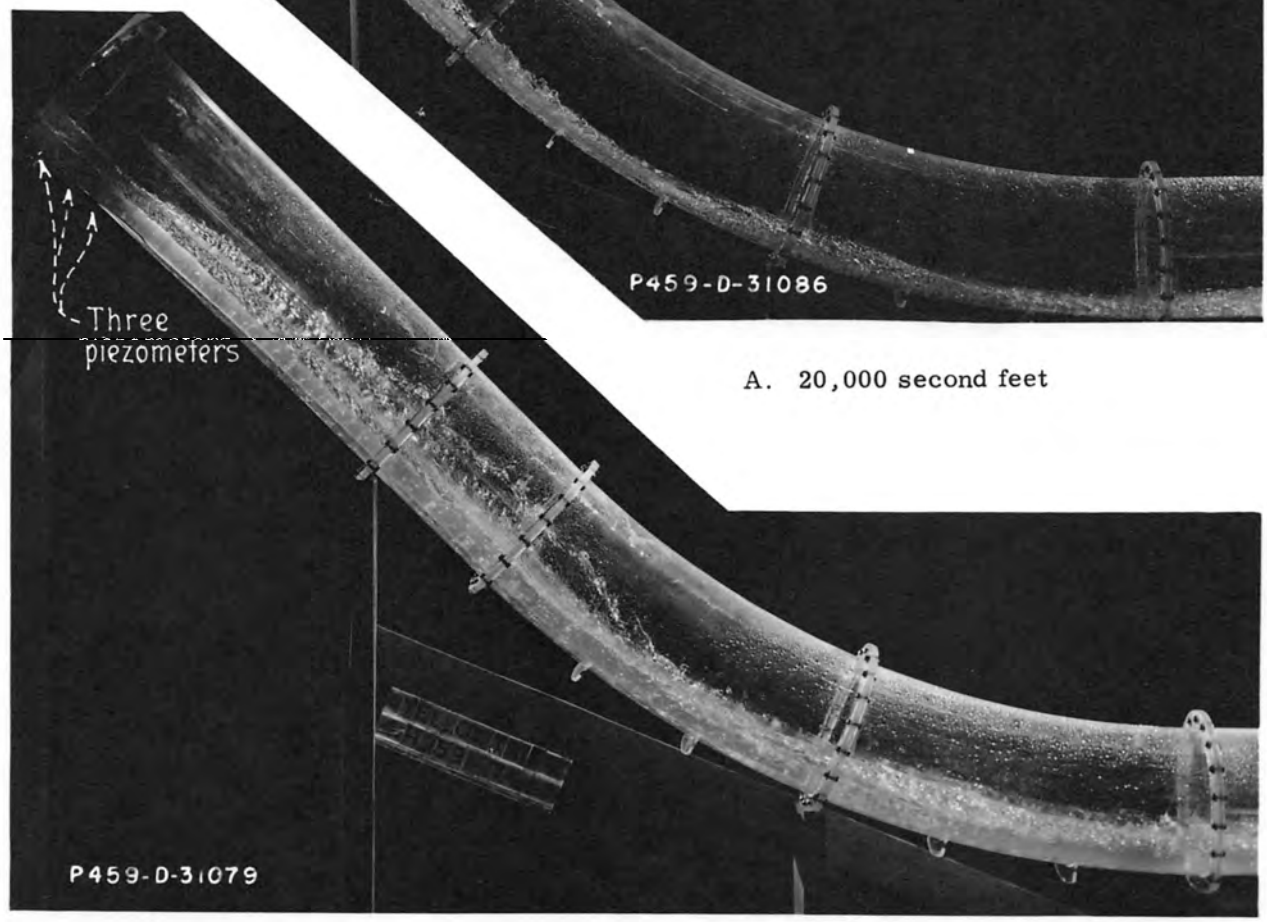


C. 173,000 second feet

YELLOWTAIL DAM
PRELIMINARY SPILLWAY--RIGHT BAY DISCHARGING INTO TUNNEL
1:54 SCALE MODEL



A. 20,000 second feet

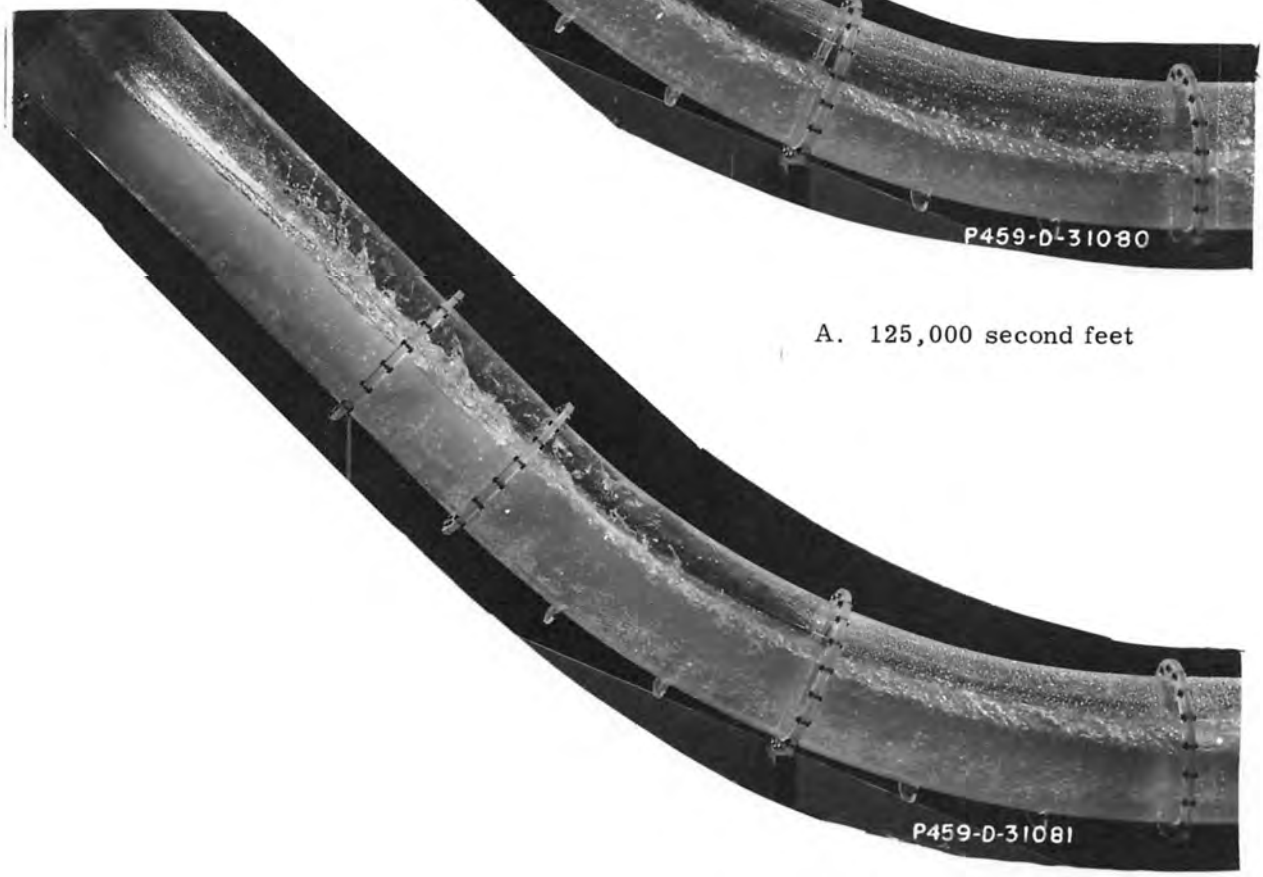


B. 60,000 second feet

Note standing water fin on centerline of tunnel caused by dividing pier.

YELLOWTAIL DAM
PRELIMINARY SPILLWAY--LOW DISCHARGES IN TUNNEL
1:54 SCALE MODEL

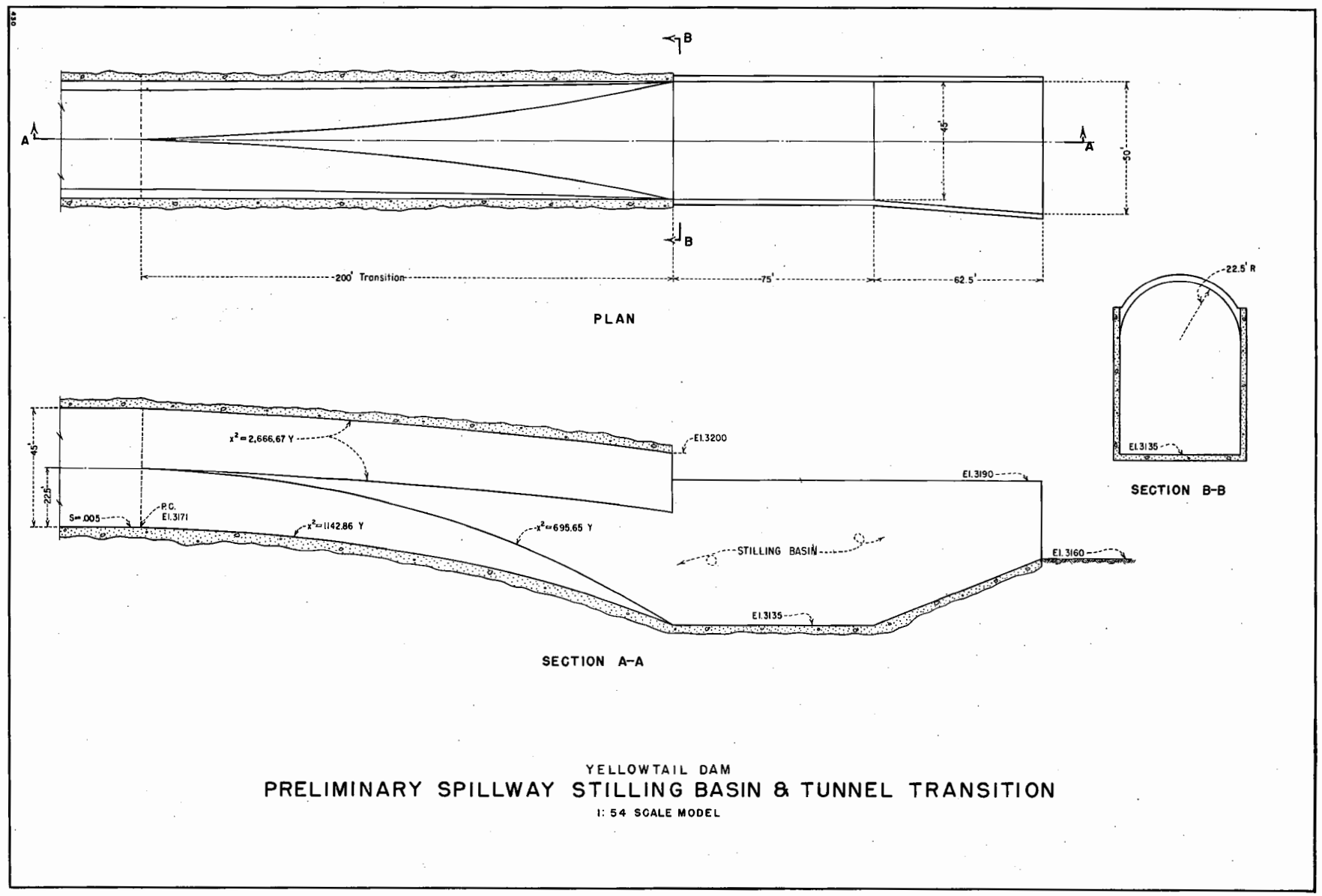
A. 125,000 second feet



Note standing water fin on centerline of tunnel caused by dividing pier.

B. 173,000 second feet

YELLOWTAIL DAM
PRELIMINARY SPILLWAY--HIGH DISCHARGES IN TUNNEL
1:54 SCALE MODEL



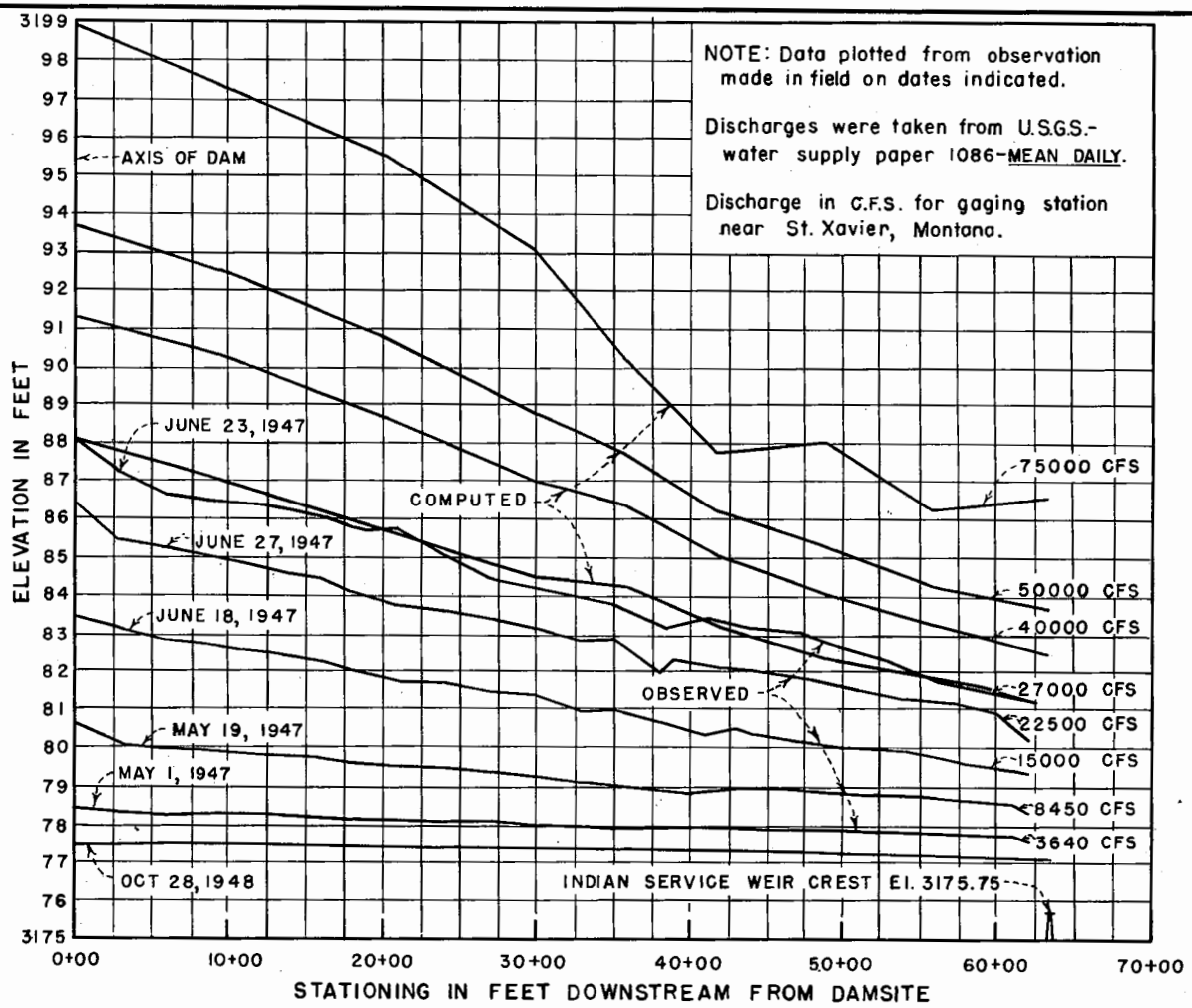
YELLOWTAIL DAM

PRELIMINARY SPILLWAY STILLING BASIN & TUNNEL TRANSITION

1: 54 SCALE MODEL

PRELIMINARY STUDIES

FIGURE 26
REPORT HYD 414



YELLOWTAIL DAM

BIG HORN RIVER SURFACE PROFILES

PRELIMINARY STUDIES

FIGURE 27
REPORT HYD. 414

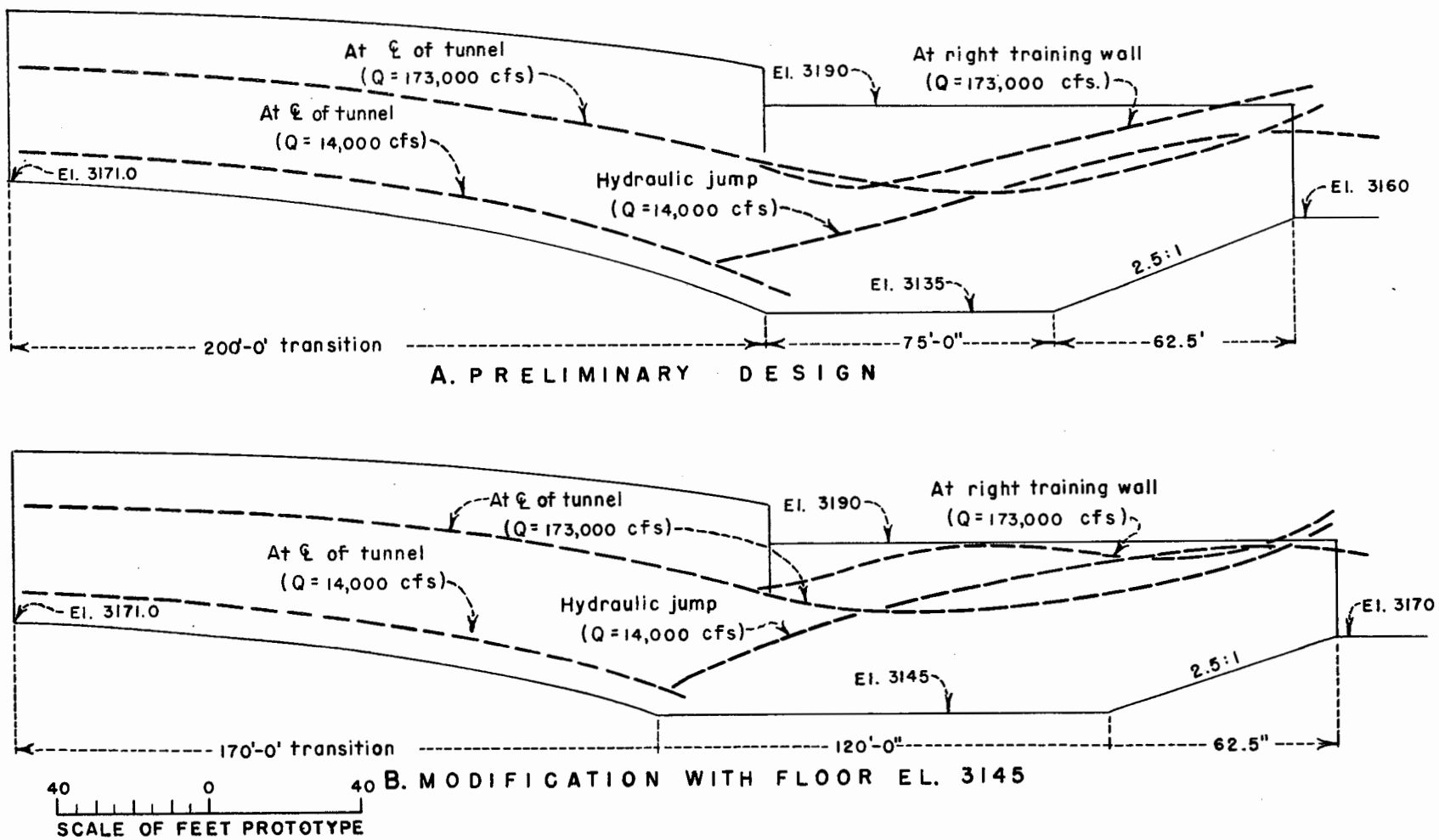
A. 14,000 second feet
just before sweepout

C. 173,000 second feet

B. 14,000 second feet
sweeping out of basin

D. Spillway - 167,000 second feet
Outlets - 8,400 second feet
Powerhouse - 3,200 second feet

YELLOWTAIL DAM
PRELIMINARY SPILLWAY--STILLING BASIN DISCHARGING
1:54 SCALE MODEL



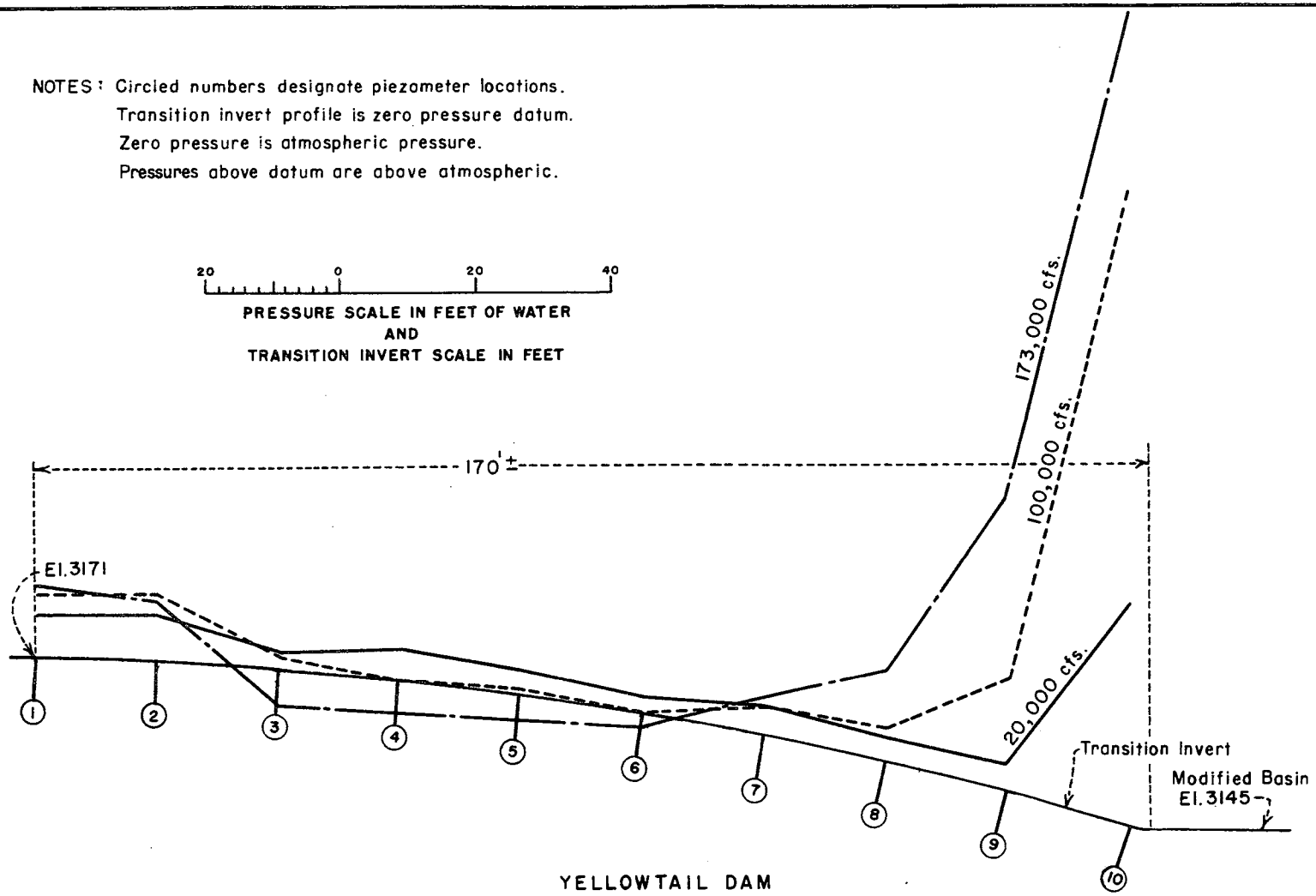
YELLOWTAIL DAM

PRELIMINARY SPILLWAY
STILLING BASIN WATER SURFACE PROFILES

1:54 SCALE MODEL

PRELIMINARY STUDIES
FIGURE 29
REPORT HYD. 414

NOTES: Circled numbers designate piezometer locations.
Transition invert profile is zero pressure datum.
Zero pressure is atmospheric pressure.
Pressures above datum are above atmospheric.

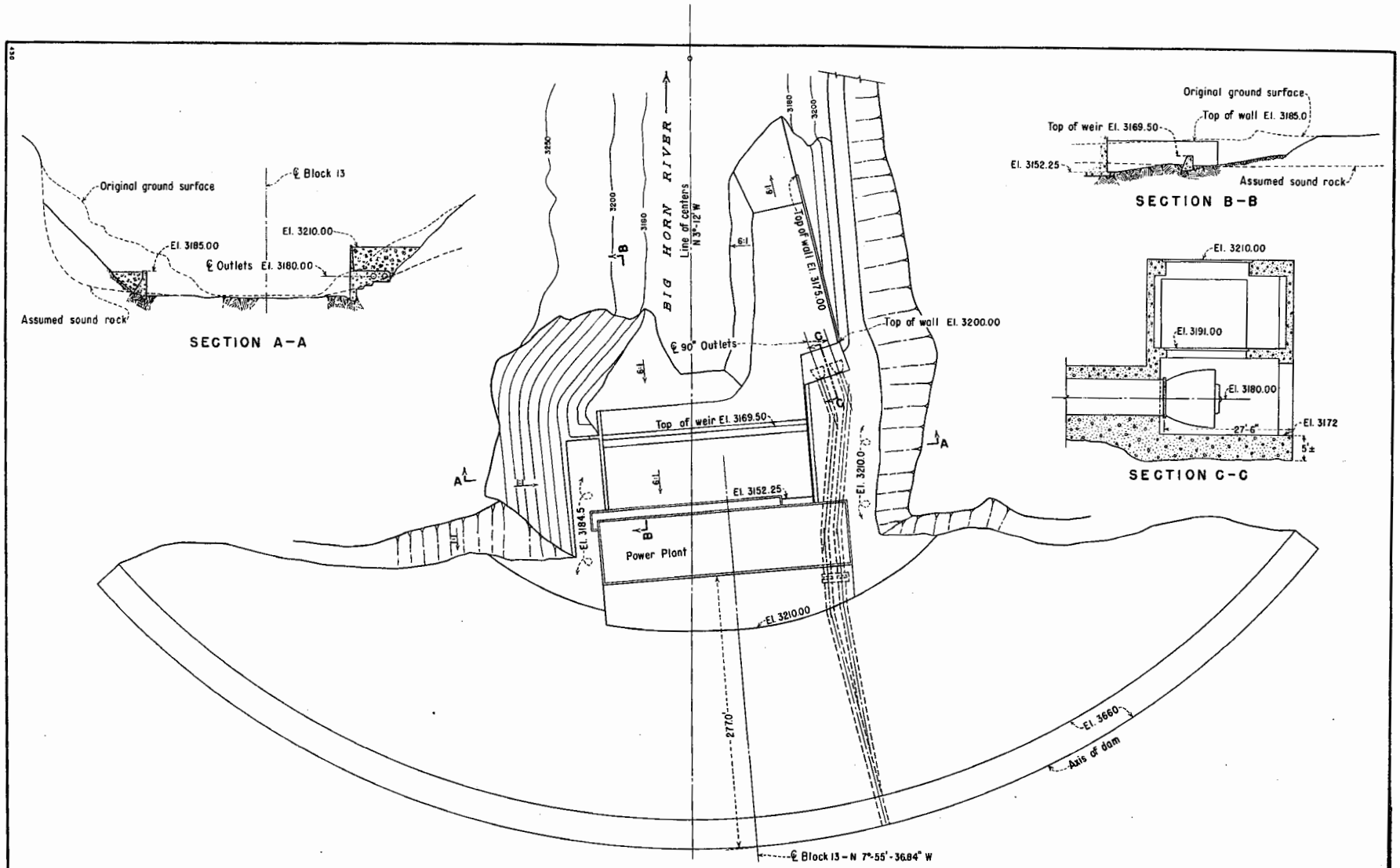


YELLOWTAIL DAM

PRELIMINARY SPILLWAY

PRESSURE IN TUNNEL TRANSITION TO BASIN

1:54 SCALE MODEL



YELLOWTAIL DAM

POWER PLANT TRAILRACE AND RIVER OUTLETS

FIGURE 31
REPORT HYD. 414

PRELIMINARY STUDIES

A. Outlets - 8,200 second feet
Powerhouse - 3,200 second feet
Spillway - 8,600 second feet
Reservoir Elev. 3614
Powerhouse tailwater fluctuates between elevations 3174 and 3175

B. Outlets - 8,200 second feet
Powerhouse - 3,200 second feet
Spillway - No flow
Reservoir Elev. 3614
Powerhouse tailwater Elev. 3174

C. Outlets - 8,440 second feet
Powerhouse - No flow
Spillway - No flow
Reservoir Elev. 3640

YELLOWTAIL DAM
PRELIMINARY OUTLETS DISCHARGING
1:54 SCALE MODEL

Outlets - 8,200 second feet
Powerhouse - 3,200 second feet
Spillway - 8,600 second feet
Reservoir Elev. 3614

YELLOWTAIL DAM
PRELIMINARY POWERHOUSE TAILRACE
1:54 SCALE MODEL

A. Outlets - 3,200 second feet
Powerhouse - 3,200 second feet

B. Outlets - 8,200 second feet
Powerhouse - 3,200 second feet

C. Outlets - 8,200 second feet
Powerhouse - 3,200 second feet
Spillway - 8,600 second feet

D. Scour after preceeding sequence of flows

Test required 30 minutes to complete sequence "A" to "C"

YELLOWTAIL DAM
PRELIMINARY OUTLETS EROSION TEST FOR RESERVOIR ELEVATION 3614
1:54 SCALE MODEL

A. Outlets - 3,000 second feet
Powerhouse - 3,000 second feet

Outlets - 8,400 second feet

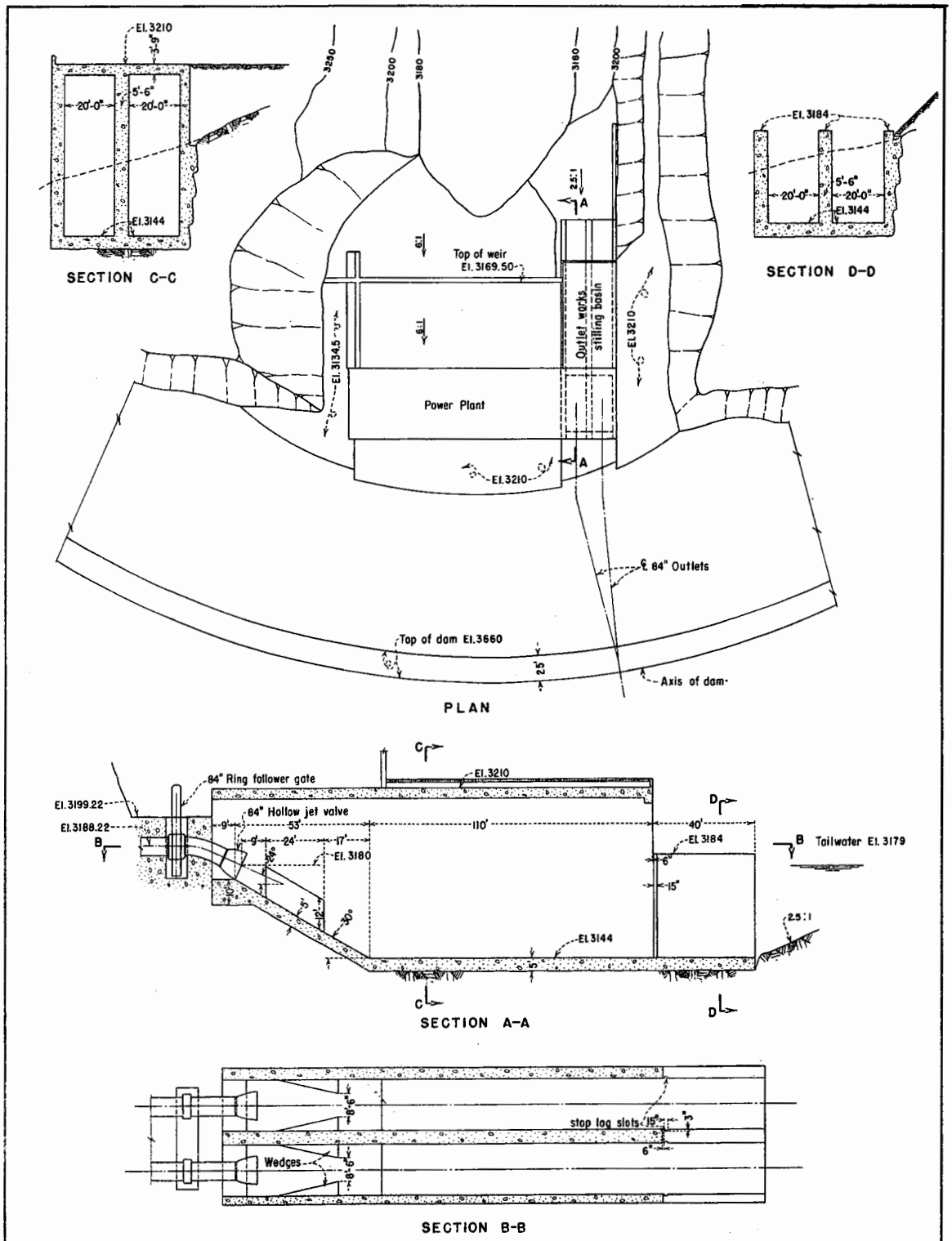
C. Outlets - 8,400 second feet
Spillway - 11,600 second feet

D. Scour after preceeding sequence of flows

Test required 30 minutes to complete sequence "A" to "C"

YELLOWTAIL DAM
PRELIMINARY OUTLETS EROSION TEST FOR RESERVOIR ELEVATION 3640
1:54 SCALE MODEL

FIGURE 36
REPORT HYD. 414



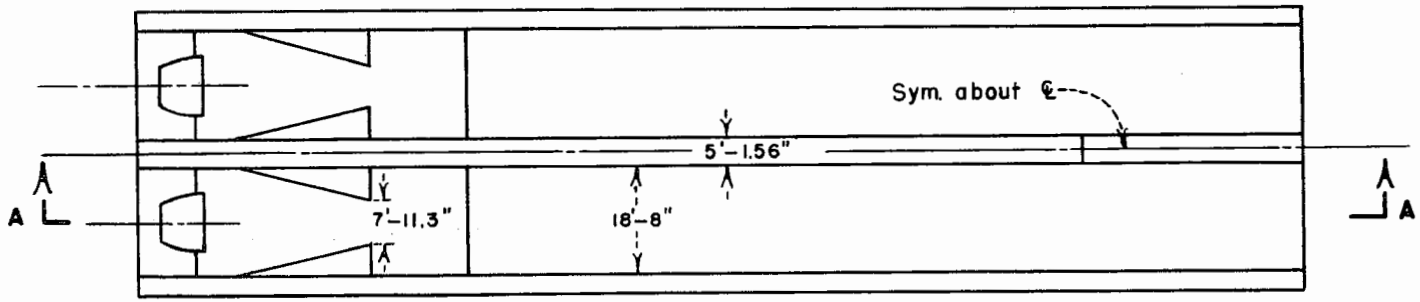
YELLOWTAIL DAM

PRELIMINARY OUTLET WORKS STILLING BASIN

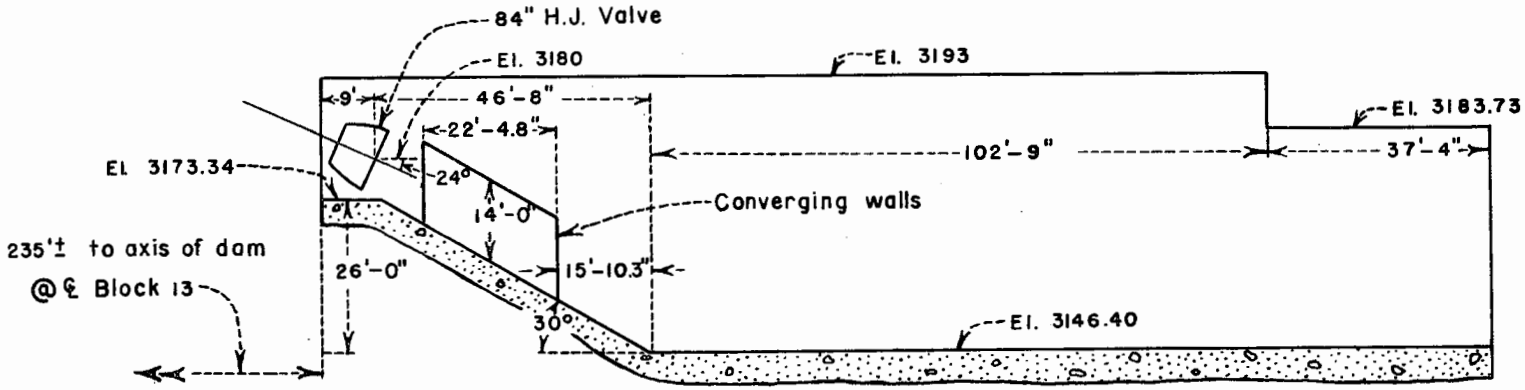
A. Outlets discharge 8,000 second feet. Reservoir elevation 3614. Tailwater elevation 3179.

B. Outlets discharge 5,000 second feet. Reservoir elevation 3614. Tailwater elevation 3179.

YELLOWTAIL DAM
PRELIMINARY OUTLET WORKS BASIN DISCHARGING
1:54 SCALE MODEL



PLAN VIEW



SECTION A–A

YELLOWTAIL DAM

OUTLET WORKS STILLING BASIN DESIGN I

PRELIMINARY STUDIES

FIGURE 38

REPORT HYD. 414

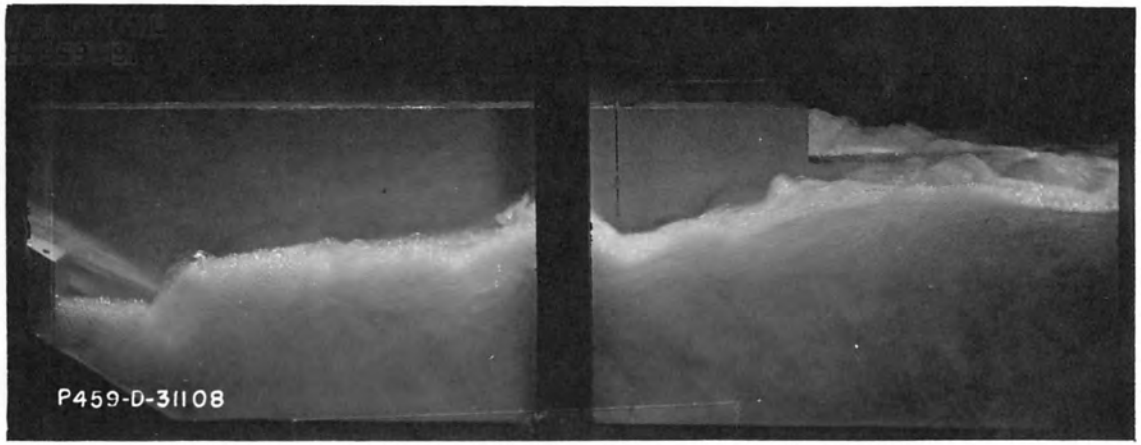
A. 5,000 second feet
Reservoir Elev. 3640
Tailwater Elev. 3179

B. Erosion after discharging 5,000 second feet for one hour in model

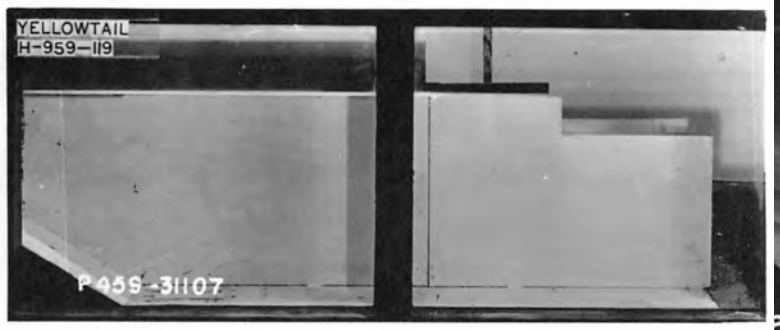
C. 2,500 second feet
Reservoir Elev. 3640
Tailwater Elev. 3177.6

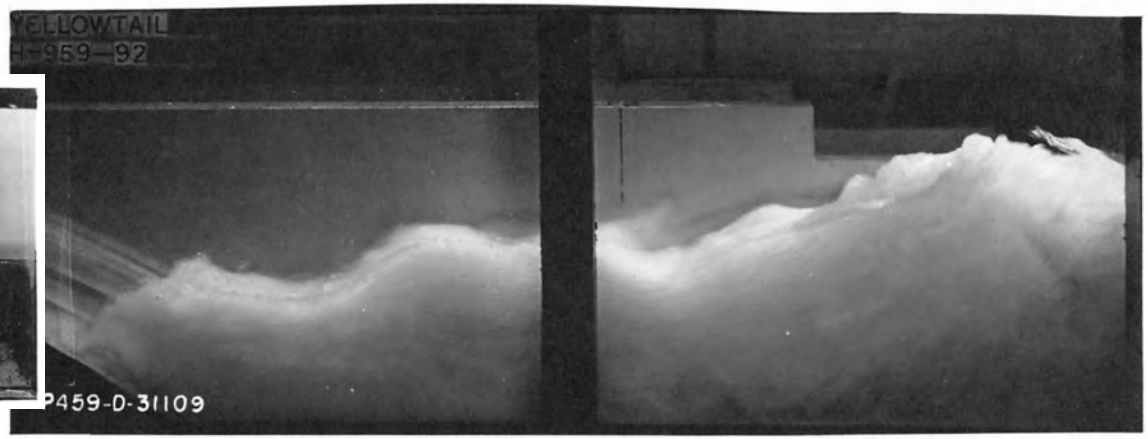
D. Erosion after discharging 2,500 second feet through left valve for 1 hour in model

YELLOWTAIL DAM
OUTLET WORKS BASIN ONE--EROSION TEST
1:28 SCALE MODEL



A. Basin One--The basin is too short for complete energy dissipation within it. Spray forms at converging walls.





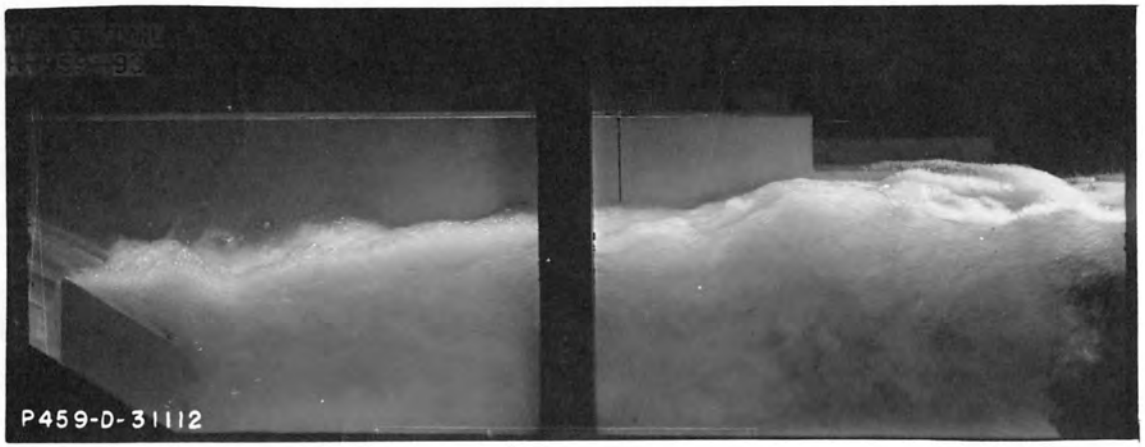
B. Basin One with walls removed--Energy dissipation is violent and not completely contained within the basin. The basin is much to short.

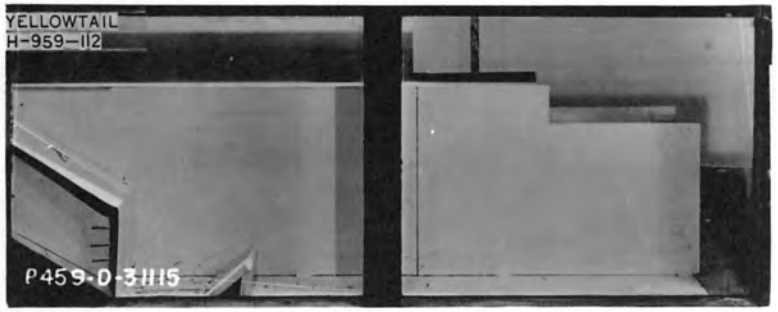
5,000 second feet, reservoir elevation 3640, tailwater elevation 3179

YELLOWTAIL DAM
OUTLET WORKS BASIN ONE DISCHARGING WITH AND WITHOUT CONVERGING WALLS
1:28 SCALE MODEL

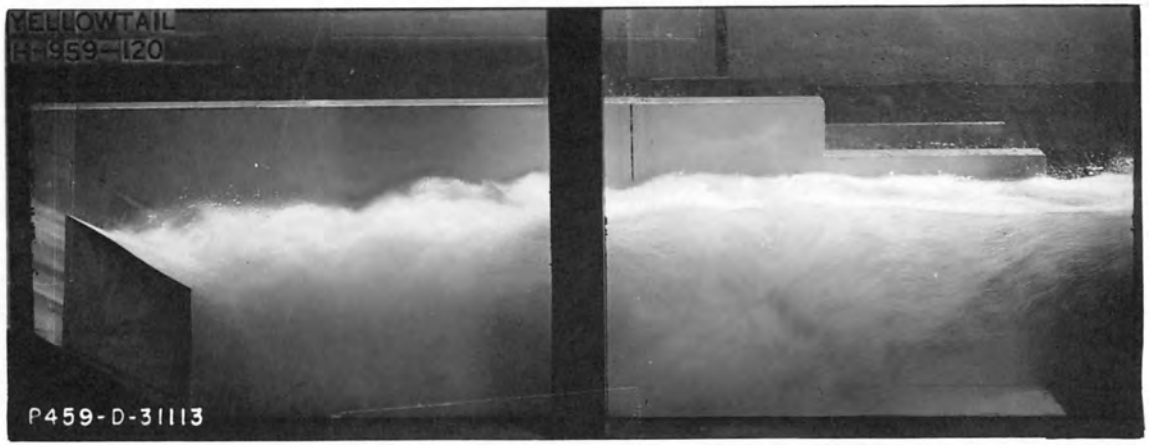
PRELIMINARY STUDIES
FIGURE 40
REPORT HYD 414

A. Basin Two--Walls are at toe of slope. Energy dissipation is better than in Basin One, and action occurs farther upstream in the basin. No spray.





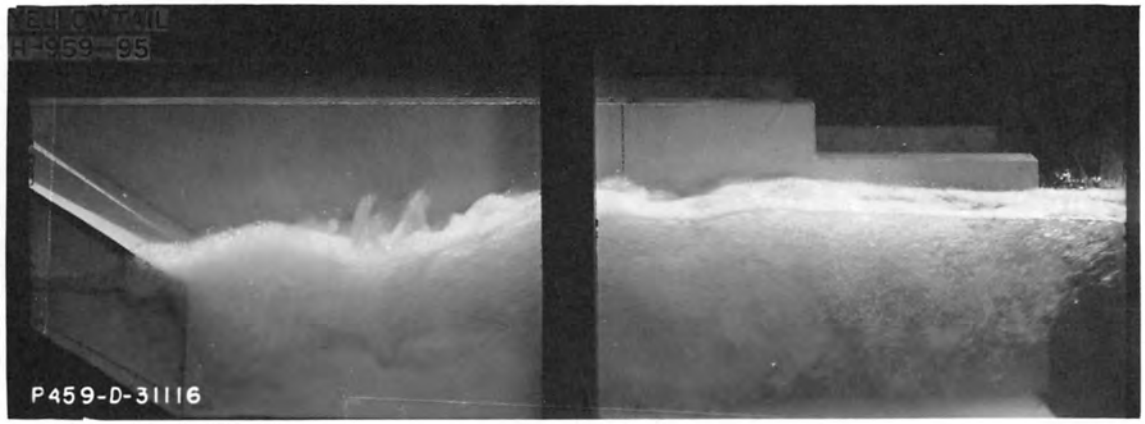
B. Basin Three--Walls are taller and gap is narrower than in Basin Two. Energy dissipation is well upstream and produces smooth water surface. Much spray.



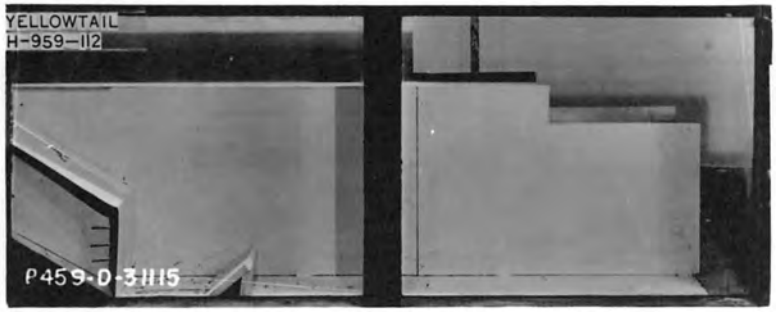
5,000 second feet, reservoir elevation 3640, tailwater elevation 3179

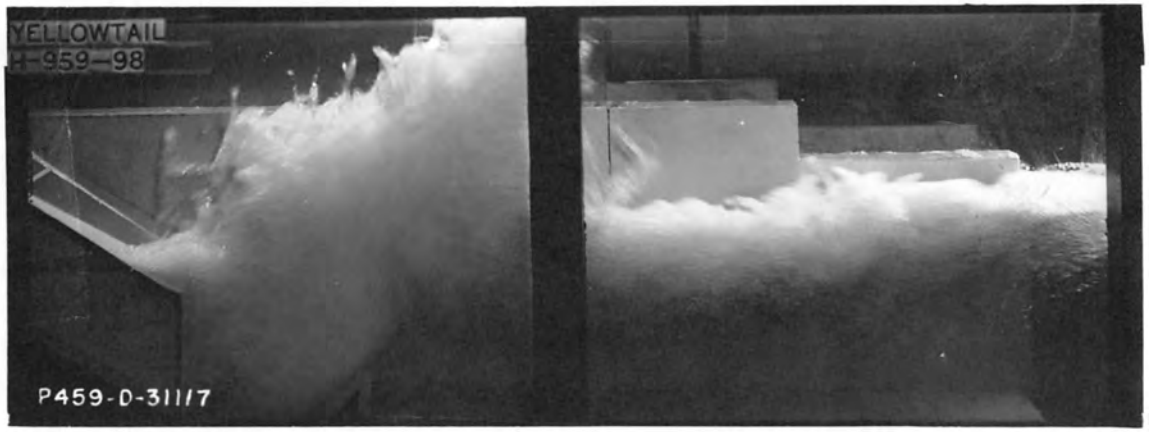
YELLOWTAIL DAM
OUTLET WORKS BASINS TWO AND THREE DISCHARGING
1:28 SCALE MODEL

PRELIMINARY STUDIES
FIGURE 41
REPORT HYD 414



A. Basin Four--Long tall walls with narrow gap. Energy dissipation is well upstream. Smooth water surface. No spray. Basin could be shortened 37 feet.



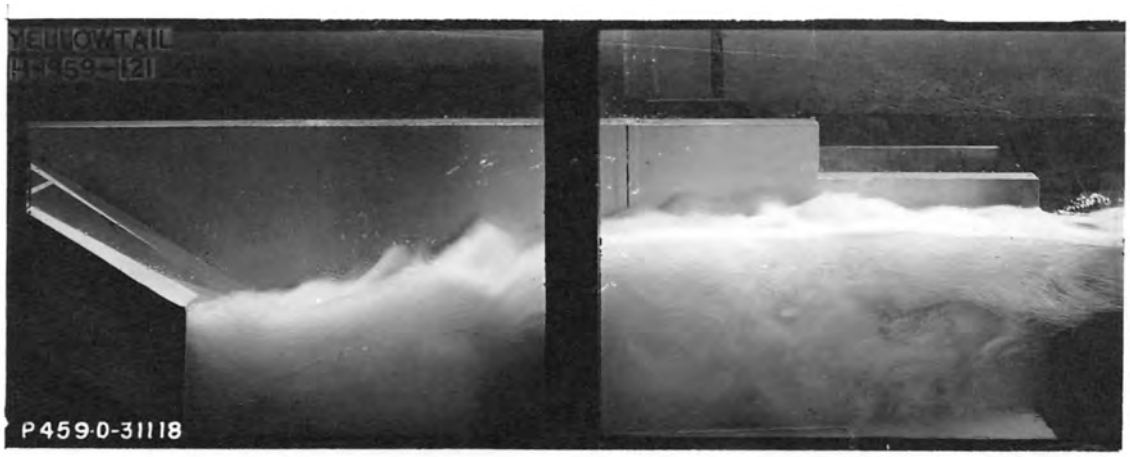


B. Basin Five--Sill added to Basin Four. Sill directs flow to the surface. Operation poor.

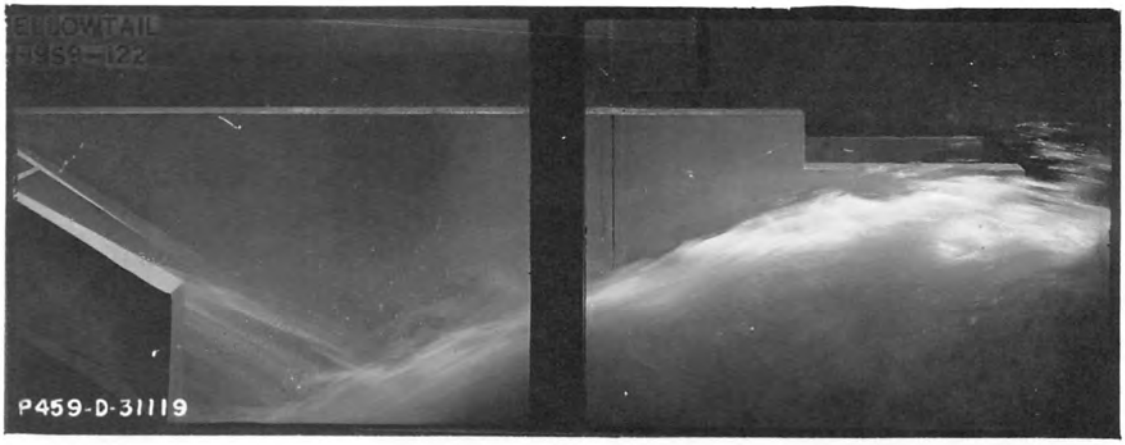
5,000 second feet, reservoir elevation 3640, tailwater elevation 3179

YELLOWTAIL DAM
OUTLET WORKS BASINS FOUR AND FIVE DISCHARGING
1:28 SCALE MODEL

PRELIMINARY STUDIES
FIGURE 42
REPORT HYD 414



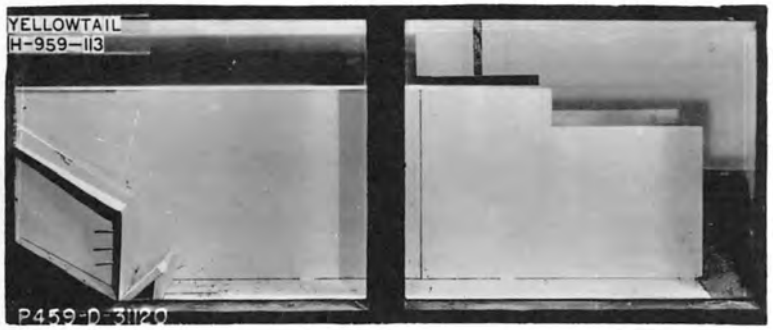
A. 5,000 second feet, tailwater elevation 3177, two feet below normal



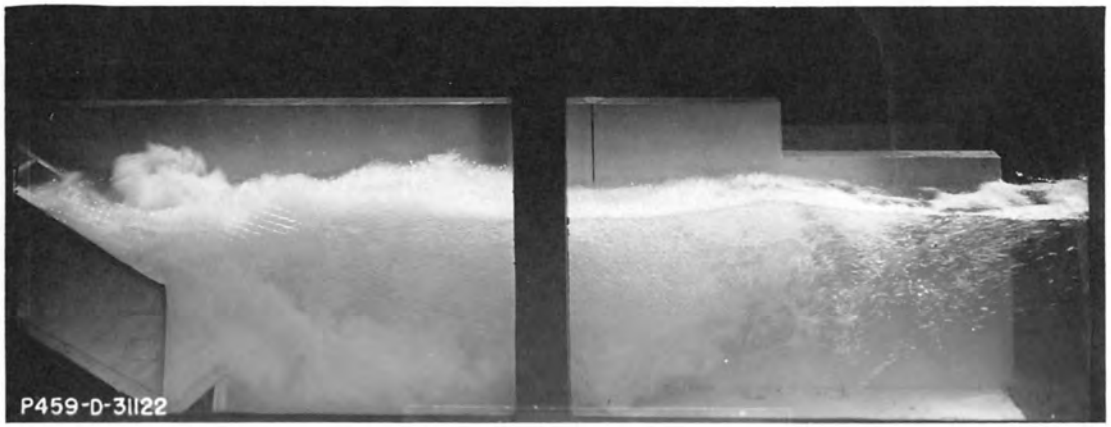
B. 5,000 second feet, tailwater elevation 3172, seven feet below normal

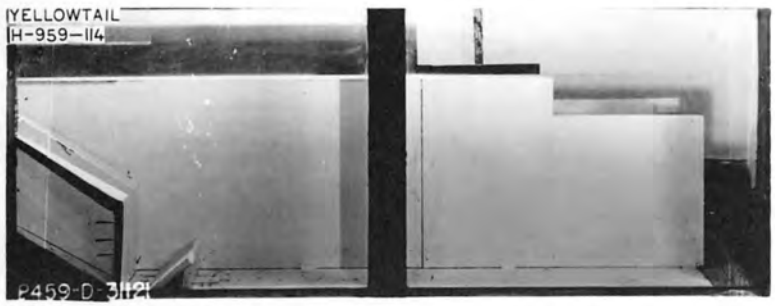
Reservoir Elev. 3640

YELLOWTAIL DAM
OUTLET WORKS BASIN FOUR DISCHARGING WITH LOW TAILWATER
1:28 SCALE MODEL

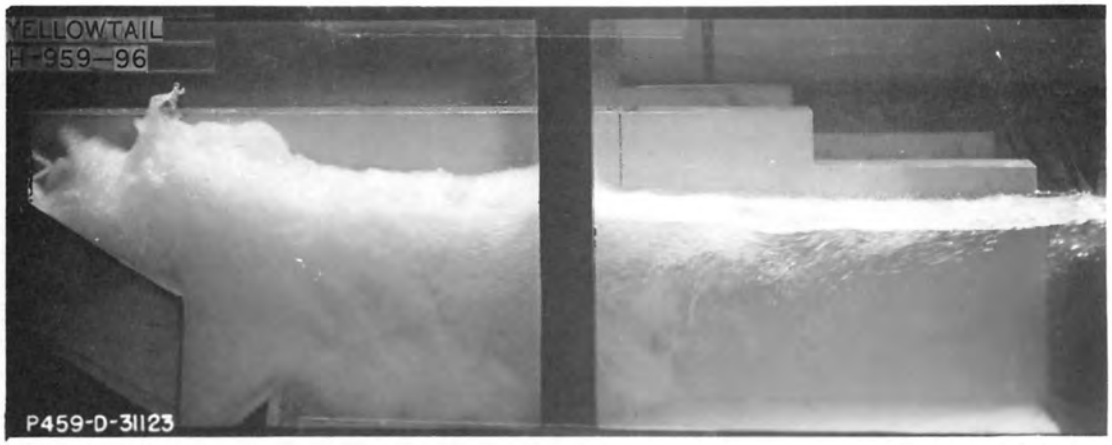


A. Basin Six--Sill placed at toe of slope. Performance not good because water surface leaving basin is unstable and wavy.





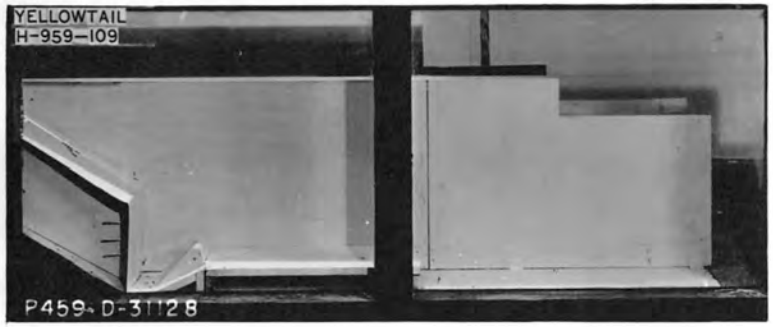
B. Basin Seven--Sill placed 5' 10" downstream from wedges. Downstream water surface very smooth but upstream surface very rough. Basin could be shortened about 70 feet.



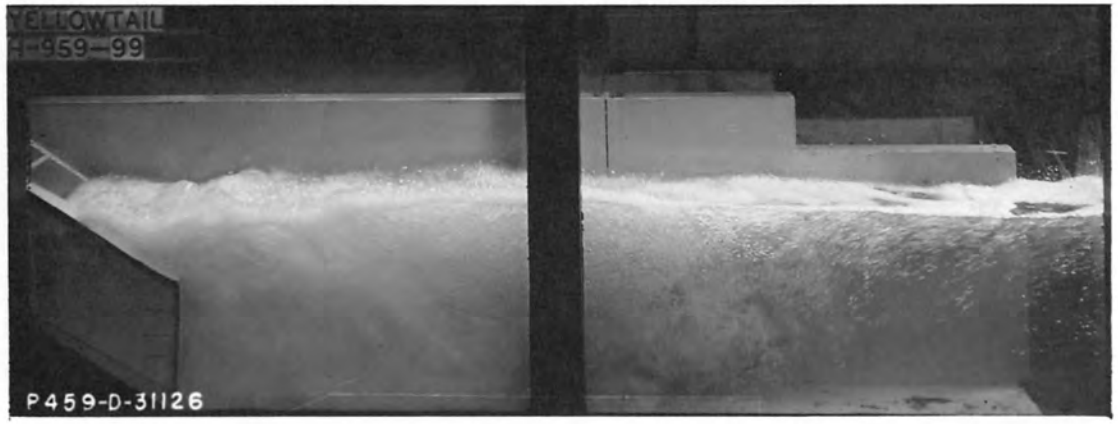
5,000 second feet, reservoir elevation 3640, tailwater elevation 3179

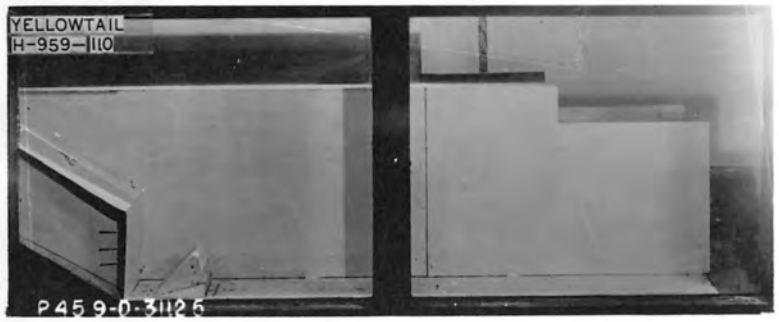
YELLOWTAIL DAM
OUTLET WORKS BASINS SIX AND SEVEN DISCHARGING
1:28 SCALE MODEL

PRELIMINARY STUDIES
FIGURE 44
REPORT HYD 414

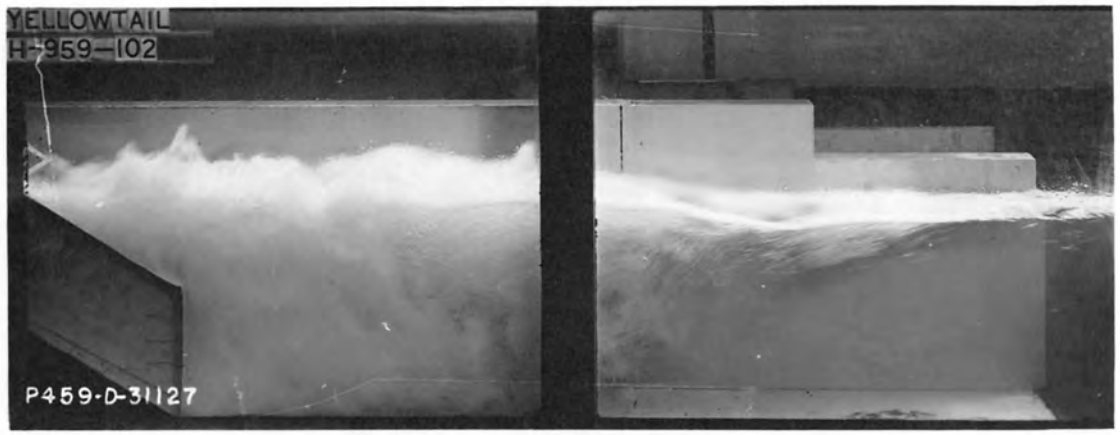


A. Basin Eight--Sill in center portion only. Water surface in and leaving basin very smooth. Basin could be shortened 65 feet.





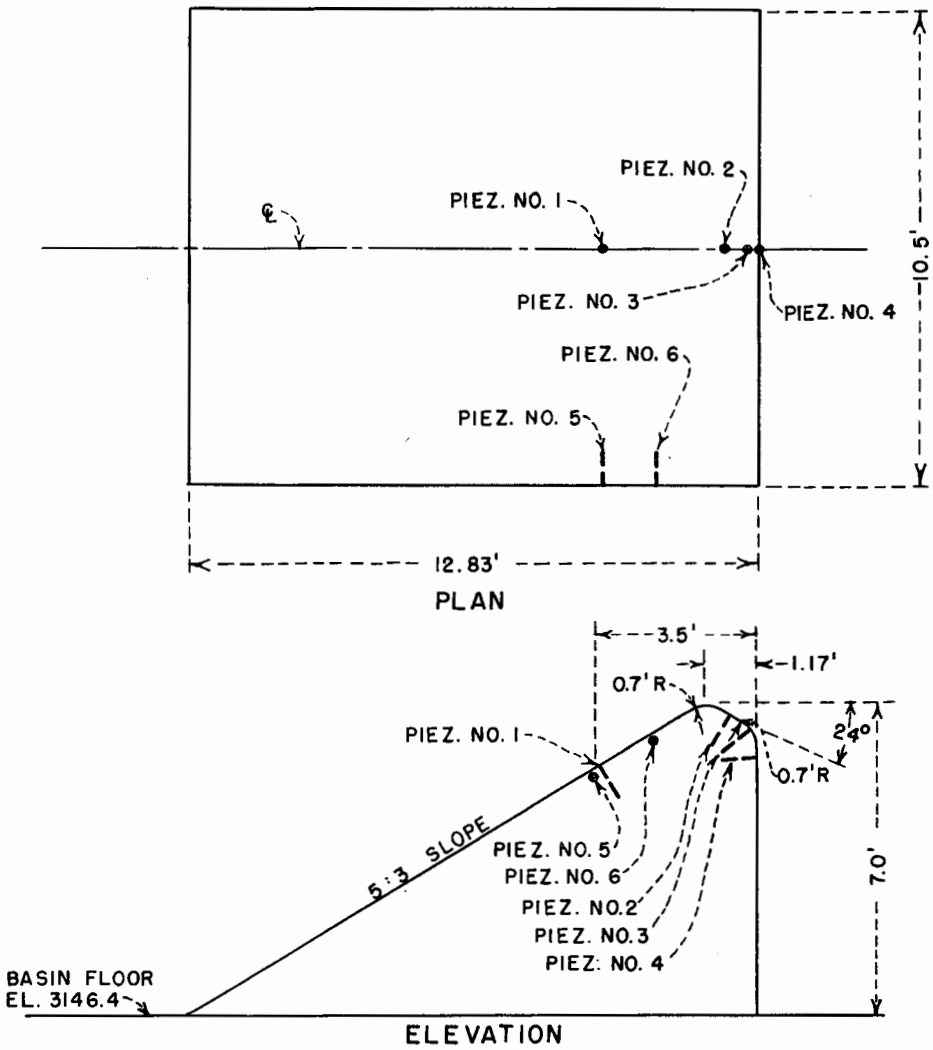
B. Basin Nine--Sill slope increased to 45 degrees. Water surface leaving basin is smooth. Basin could be shortened 70 feet.



5,000 second feet, reservoir elevation 3640, tailwater elevation 3179

YELLOWTAIL DAM
OUTLET WORKS BASINS EIGHT AND NINE DISCHARGING
1:28 SCALE MODEL

PRELIMINARY STUDIES
FIGURE 46
REPORT HYD 414



DISCHARGE IN CFS	4,000	5,000	6,000	8,000
RESERVOIR ELEVATION (FEET)	3640	3640	3640	3640
TAILWATER ELEVATION (FEET)	3179	3179	3179	3179
PRESSURE HEAD AT PIEZ. NO. 1	49	93	119	168
PRESSURE HEAD AT PIEZ. NO. 2	10	5	-3	-21
PRESSURE HEAD AT PIEZ. NO. 3	11	8	5	-3
PRESSURE HEAD AT PIEZ. NO. 4	13	10	8	1
PRESSURE HEAD AT PIEZ. NO. 5	11	10	7	0
PRESSURE HEAD AT PIEZ. NO. 6	11	10	8	0

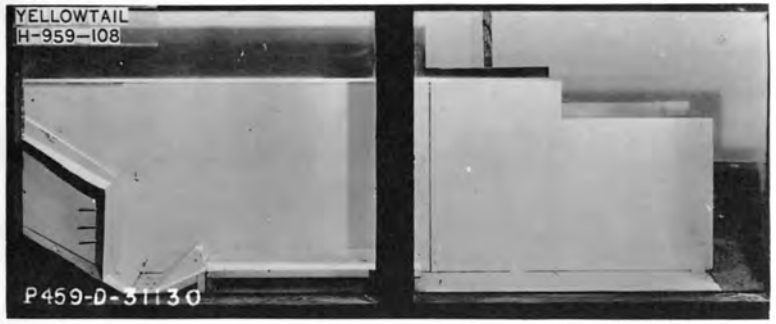
Pressure head is in feet of water. Zero pressure head is atmospheric.

YELLOWTAIL DAM

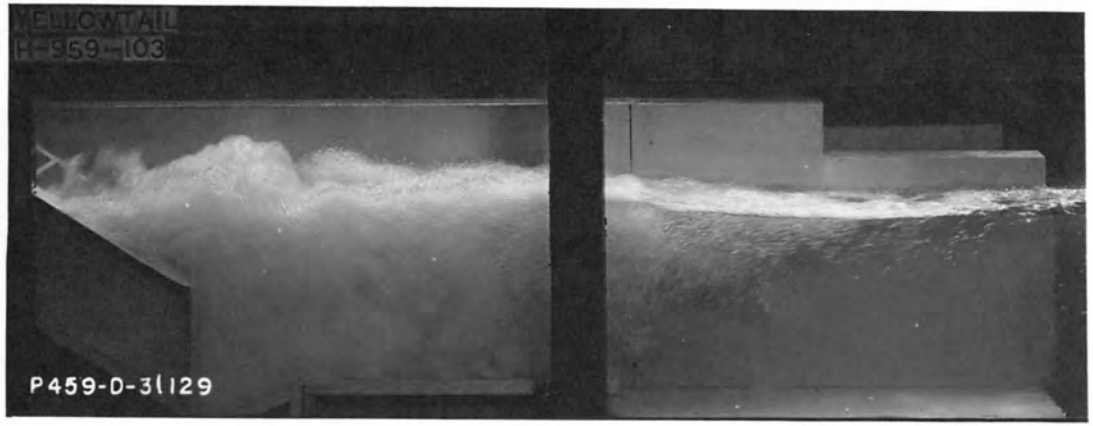
PRESSURES ON SILL OF OUTLET WORKS BASIN VIII

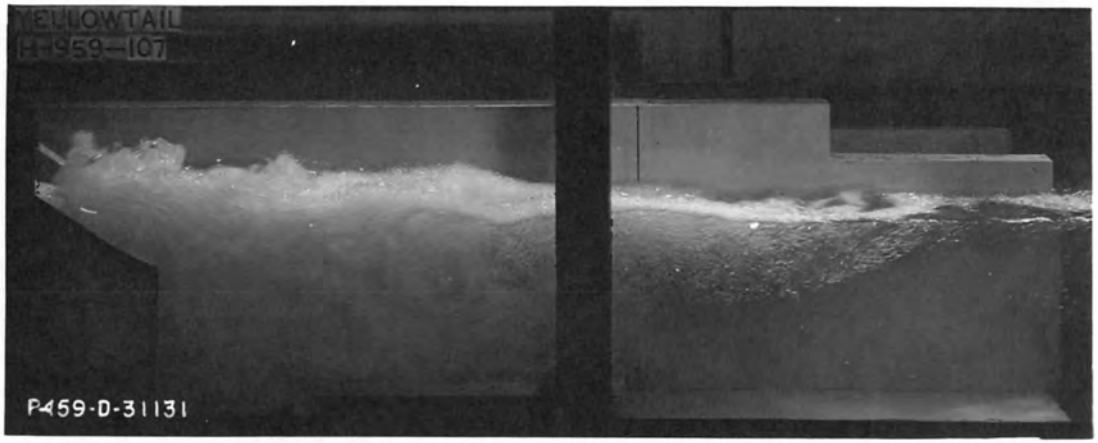
1:28 SCALE MODEL

A. Basin Ten--Floor elevated 5.6 feet and shortened 70 feet. Stilling action occurs within the reduced length. Water surface is smooth.



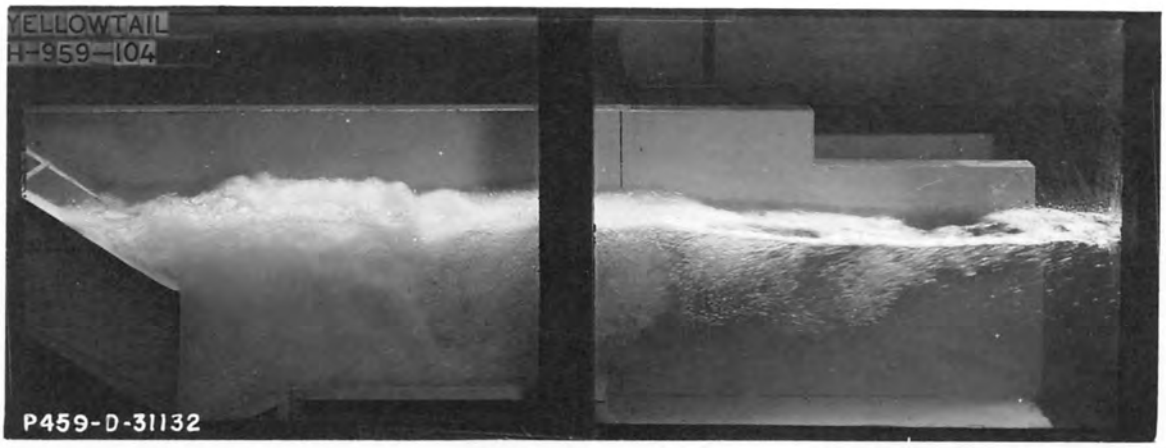
B. Basin Eleven--Walls are moved upstream. Water surface boil is lower but water surface downstream not as smooth.



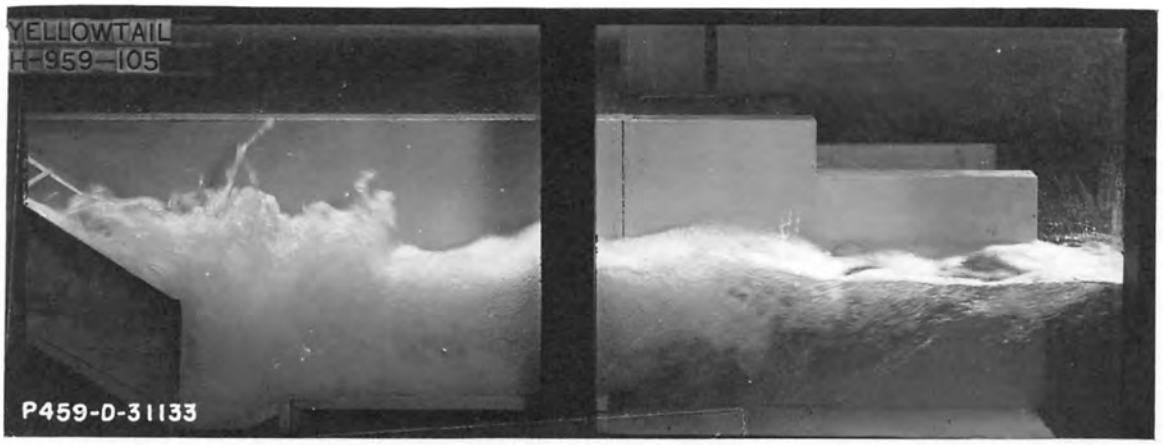


YELLOWTAIL DAM
OUTLET WORKS BASINS TEN AND ELEVEN DISCHARGING
1:28 SCALE MODEL

PRELIMINARY STUDIES
FIGURE 47
REPORT HYD 414



A. 5,000 second feet, tailwater elevation 3177, two feet below normal

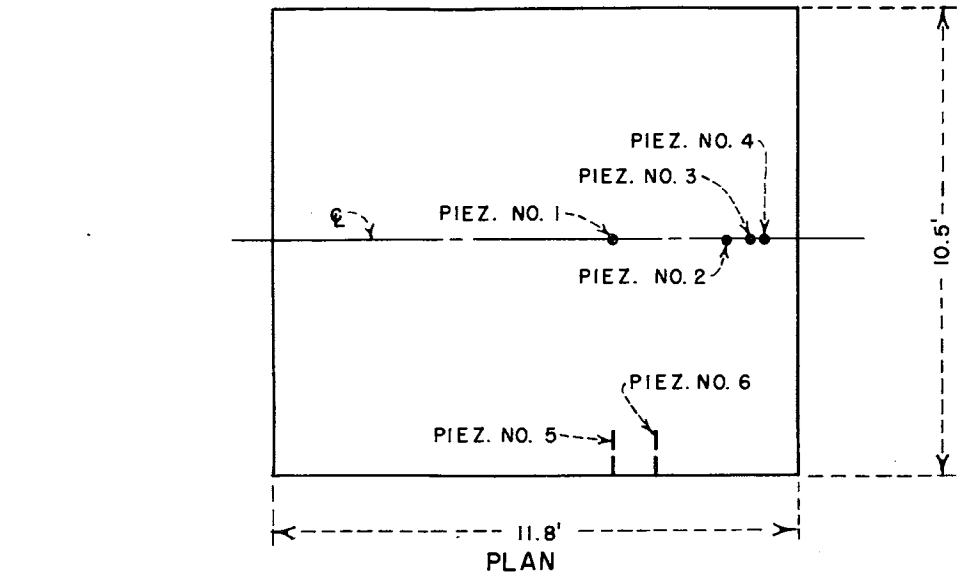


B. 5,000 second feet, tailwater elevation 3172, seven feet below normal

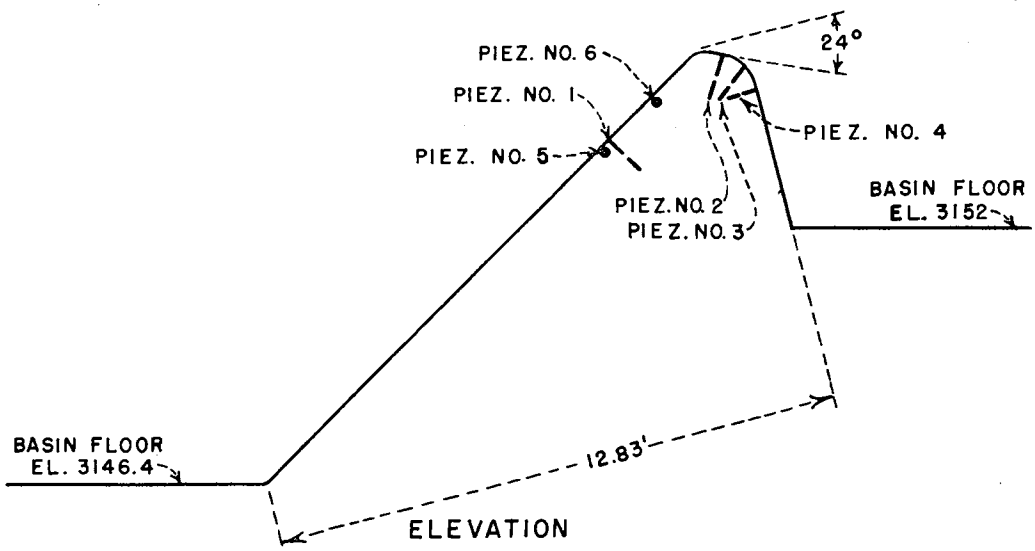
Reservoir Elevation 3640
Compare with Figure 43

YELLOWTAIL DAM
OUTLET WORKS BASIN TEN DISCHARGING WITH LOW TAILWATER
1:28 SCALE MODEL

FIGURE 49
REPORT HYD. 414



PLAN



ELEVATION

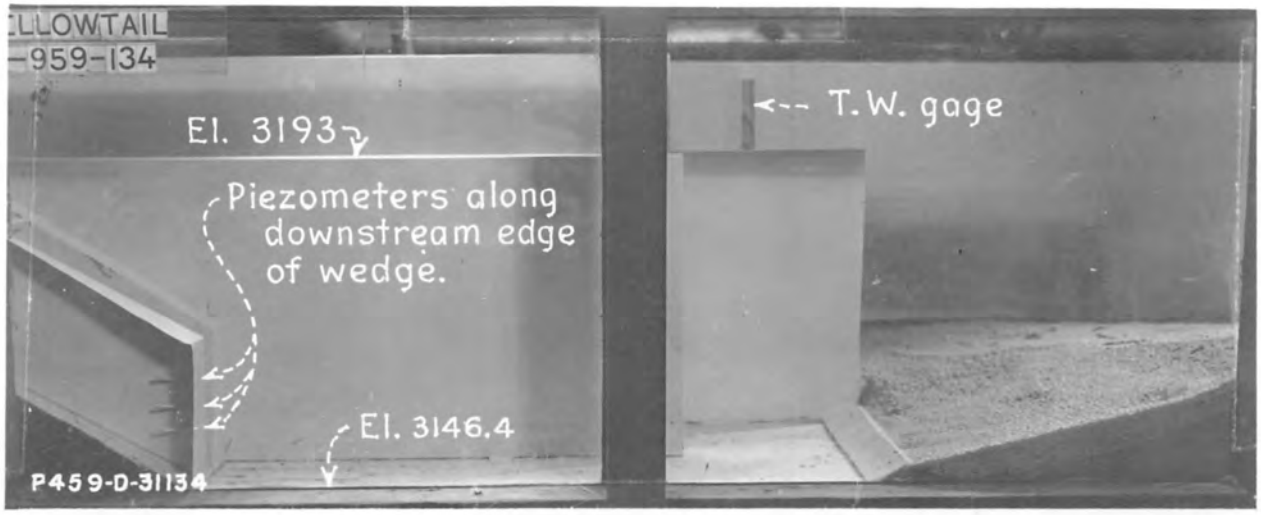
DISCHARGE IN CFS	5000	5000	5000	5000
RESERVOIR ELEVATION (FEET)	3640	3640	3640	3640
TAILWATER ELEVATION (FEET)	3179	3177	3175	3173
PRESSURE HEAD AT PIEZ. NO. 1	56	88	115	137
PRESSURE HEAD AT PIEZ. NO. 2	-1	-5	-12	-20
PRESSURE HEAD AT PIEZ. NO. 3	9	8	8	1
PRESSURE HEAD AT PIEZ. NO. 4	12	10	10	4
PRESSURE HEAD AT PIEZ. NO. 5	7	9	9	8
PRESSURE HEAD AT PIEZ. NO. 6	4	12	12	13

Pressure head is in feet of water. Zero pressure head is atmospheric.

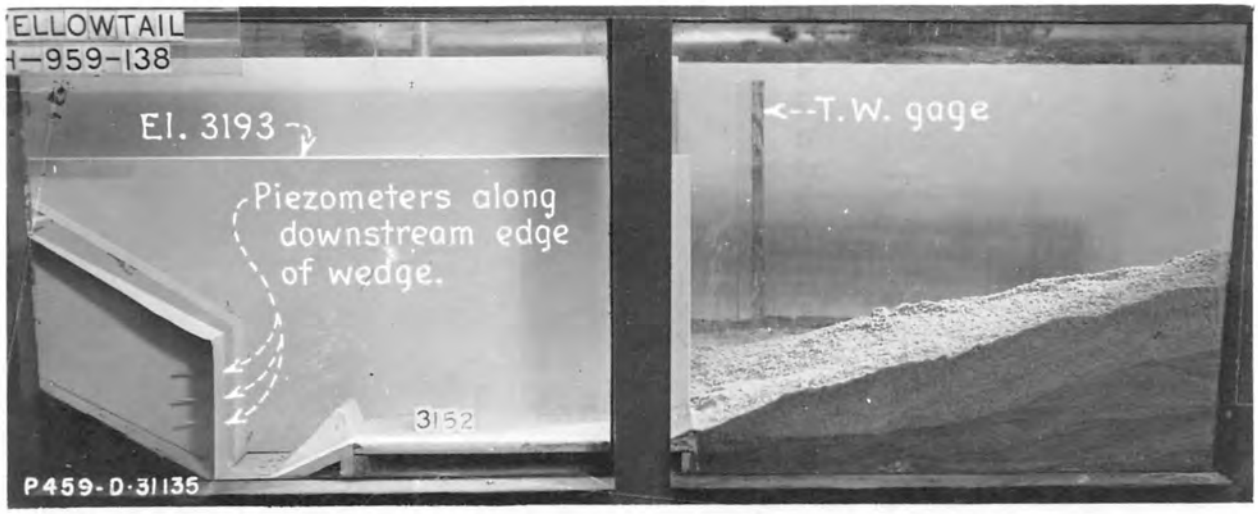
YELLOWTAIL DAM

PRESSURES ON SILL OF OUTLET WORKS BASIN X

1:28 SCALE MODEL



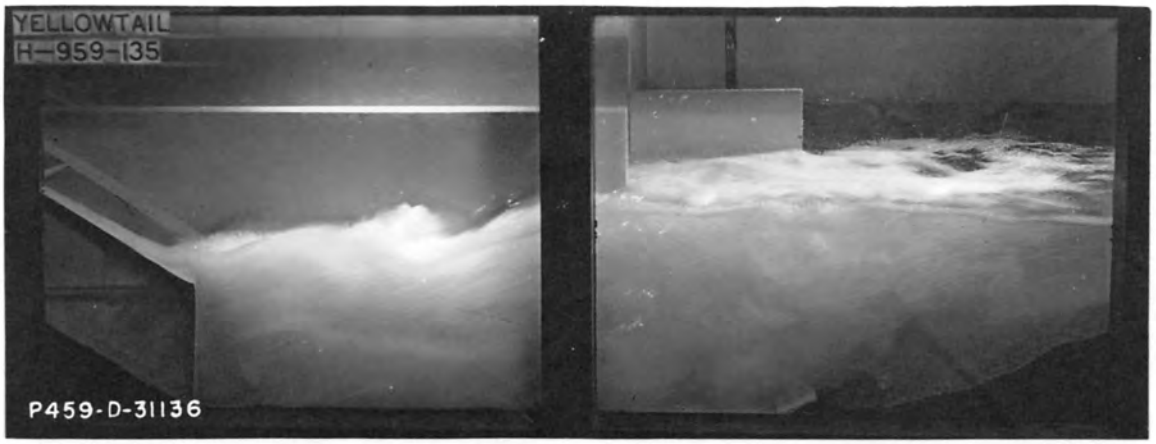
Basin Four--Recommended



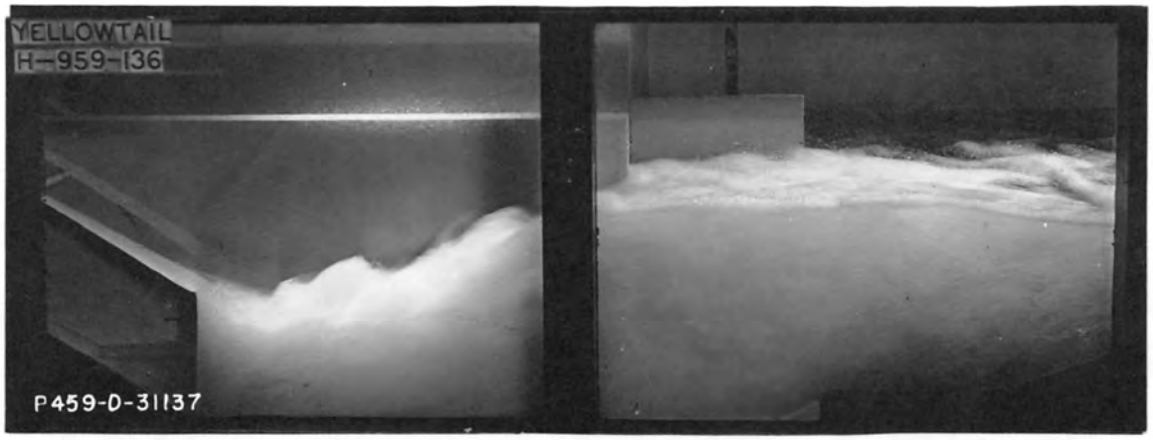
Basin Ten

The three piezometers are spaced 4 feet apart.
The lower one is 10 feet above the floor.

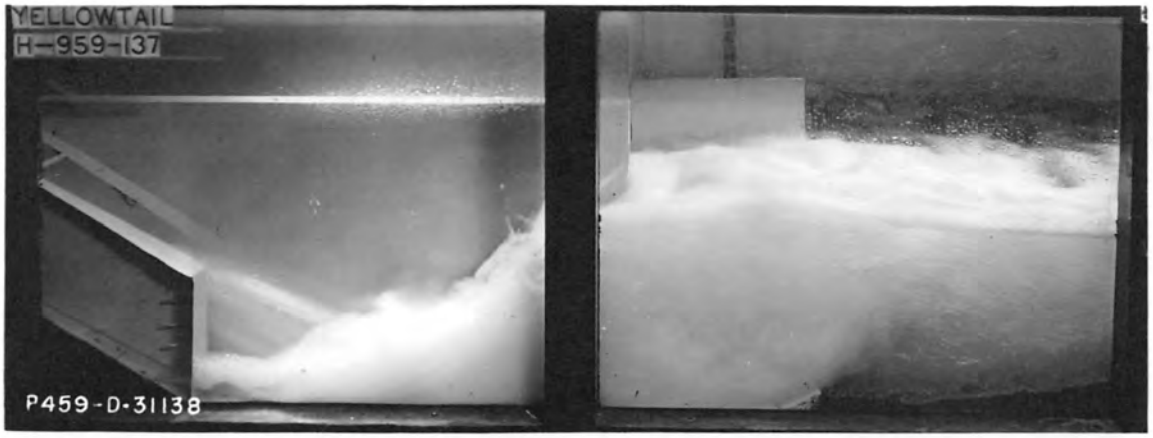
YELLOWTAIL DAM
OUTLET WORKS BASINS FOUR AND TEN
1:28 SCALE MODEL



A. 5,000 second feet - Res. Elev. 3640 - Normal T.W. Elev. 3179

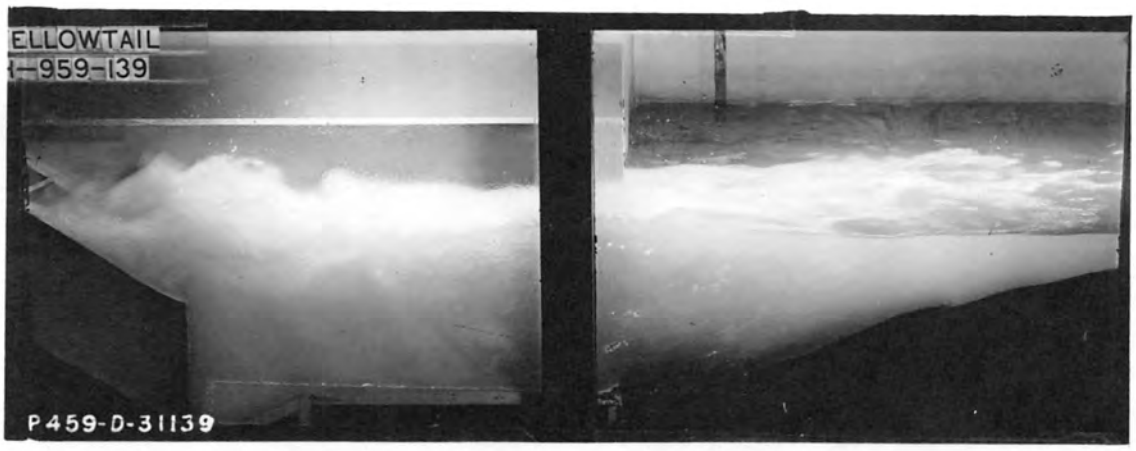


B. 6,000 second feet - Res. Elev. 3640 - Normal T.W. Elev. 3179

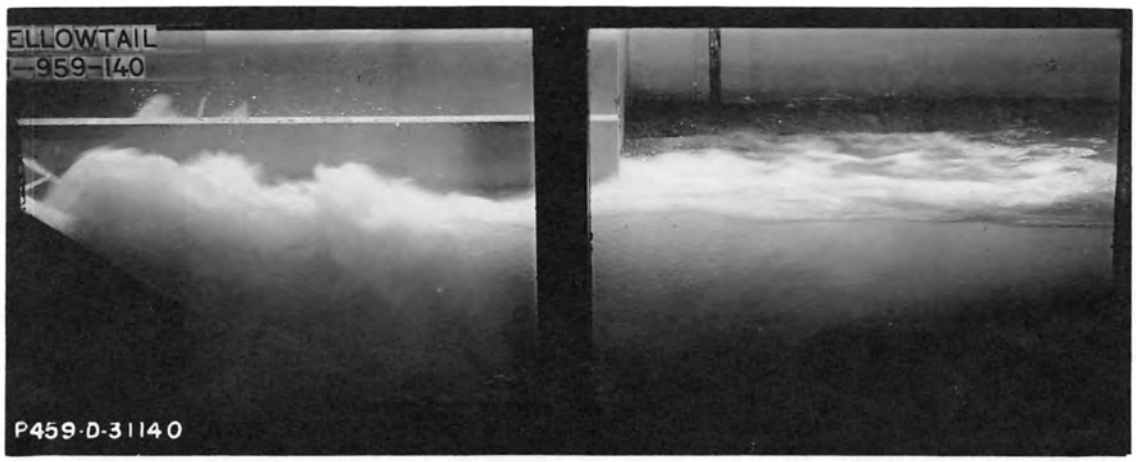


C. 6,000 second feet - Res. Elev. 3640 - T.W. Elev. 3177, two feet below normal

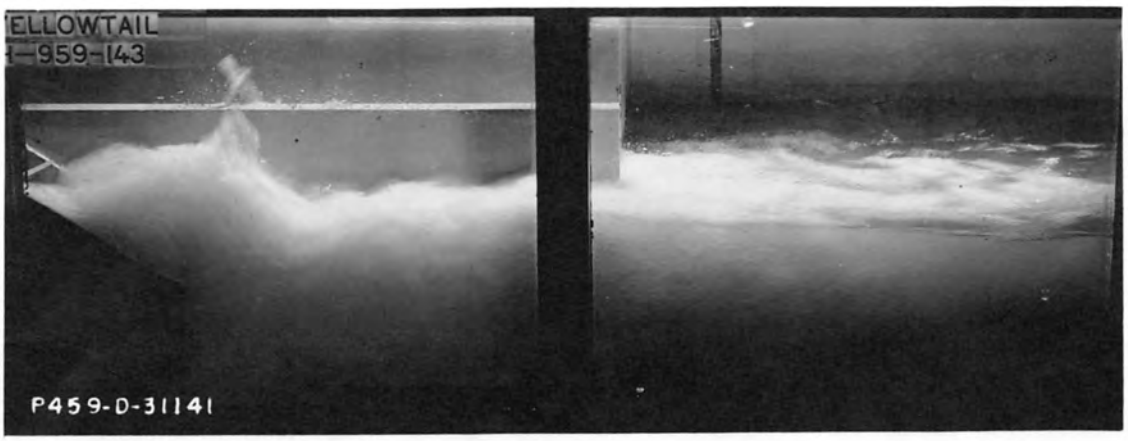
YELLOWTAIL DAM
RECOMMENDED OUTLET WORKS BASIN FOUR DISCHARGING
1:28 SCALE MODEL



A. 5,000 second feet - Res. Elev. 3640 - Normal T.W. Elev. 3179



B. 6,000 second feet - Res. Elev. 3640 - Normal T.W. Elev. 3179



C. 6,000 second feet - Res. Elev. 3640 - T.W. Elev. 3177, two feet below normal

YELLOWTAIL DAM
OUTLET WORKS BASIN TEN DISCHARGING
1:28 SCALE MODEL

Basin Four--Recommended

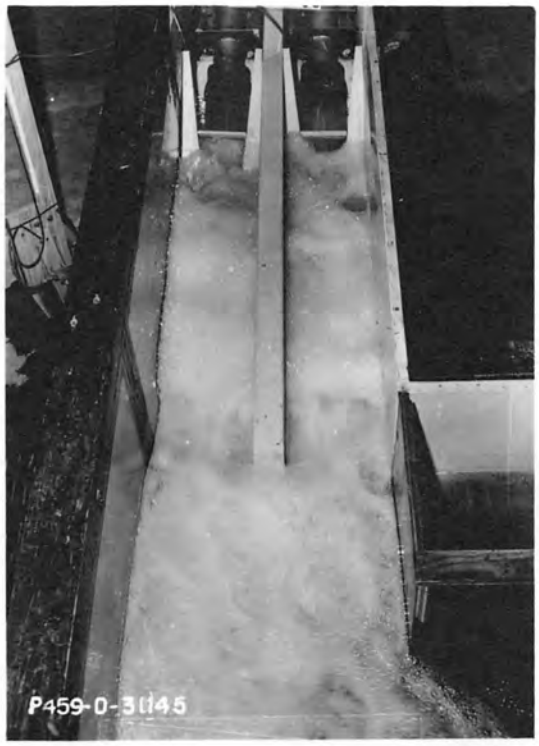
Basin Ten

Erosion Pattern after 5,000 second feet discharged for one hour in the model with reservoir at elevation 3640

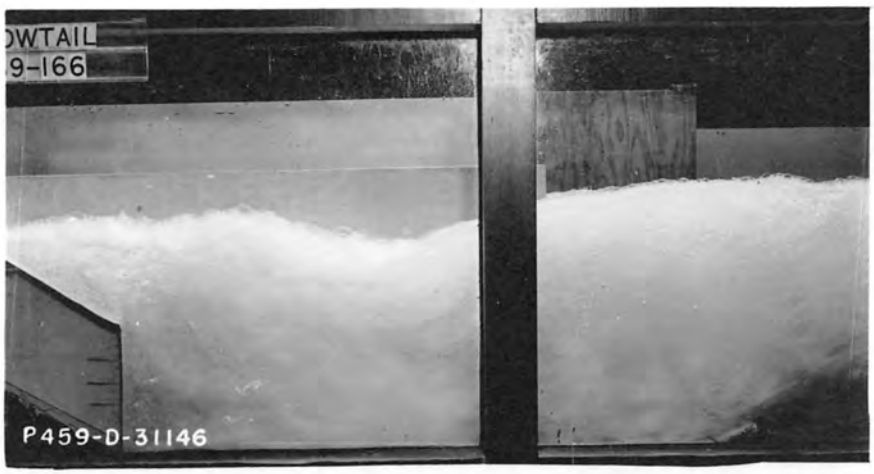
YELLOWTAIL DAM
OUTLET WORKS BASINS FOUR AND TEN--EROSION TESTS
1:28 SCALE MODEL

PRELIMINARY STUDIES
FIGURE 53
REPORT HYD 414

A. 5,000 second feet. Normal tailwater elevation 3179

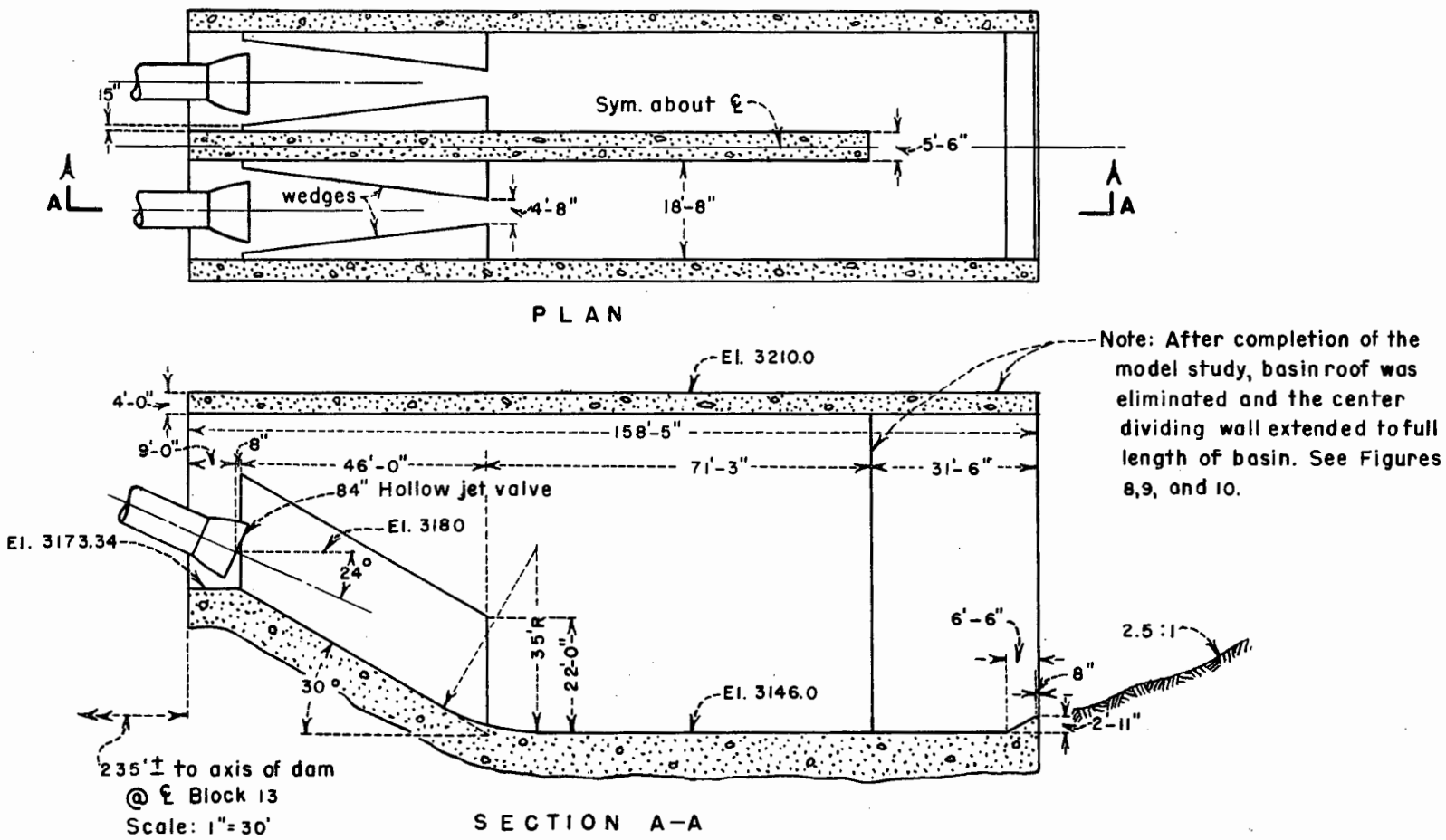


B. 5,000 second feet. Tailwater elevation 3185.3; 6.3 feet above normal



C. Same as "B"

YELLOWTAIL DAM
OUTLET WORKS BASIN FOUR DISCHARGING WITH
NORMAL AND HIGH TAILWATERS
1:28 SCALE MODEL



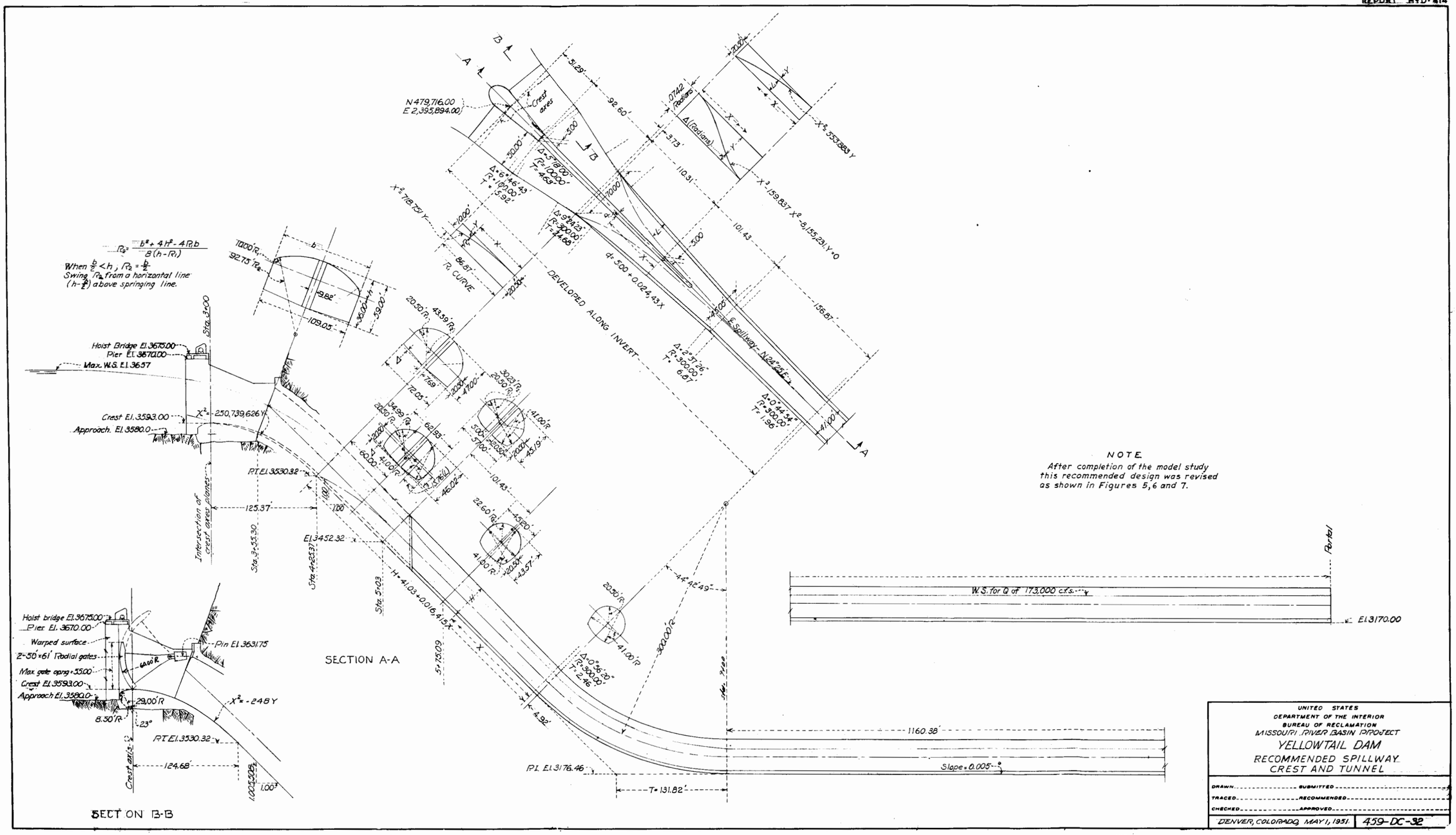
YELLOWTAIL DAM

RECOMMENDED OUTLET WORKS STILLING BASIN

PRELIMINARY STUDIES

FIGURE 55

REPORT HYD. 414

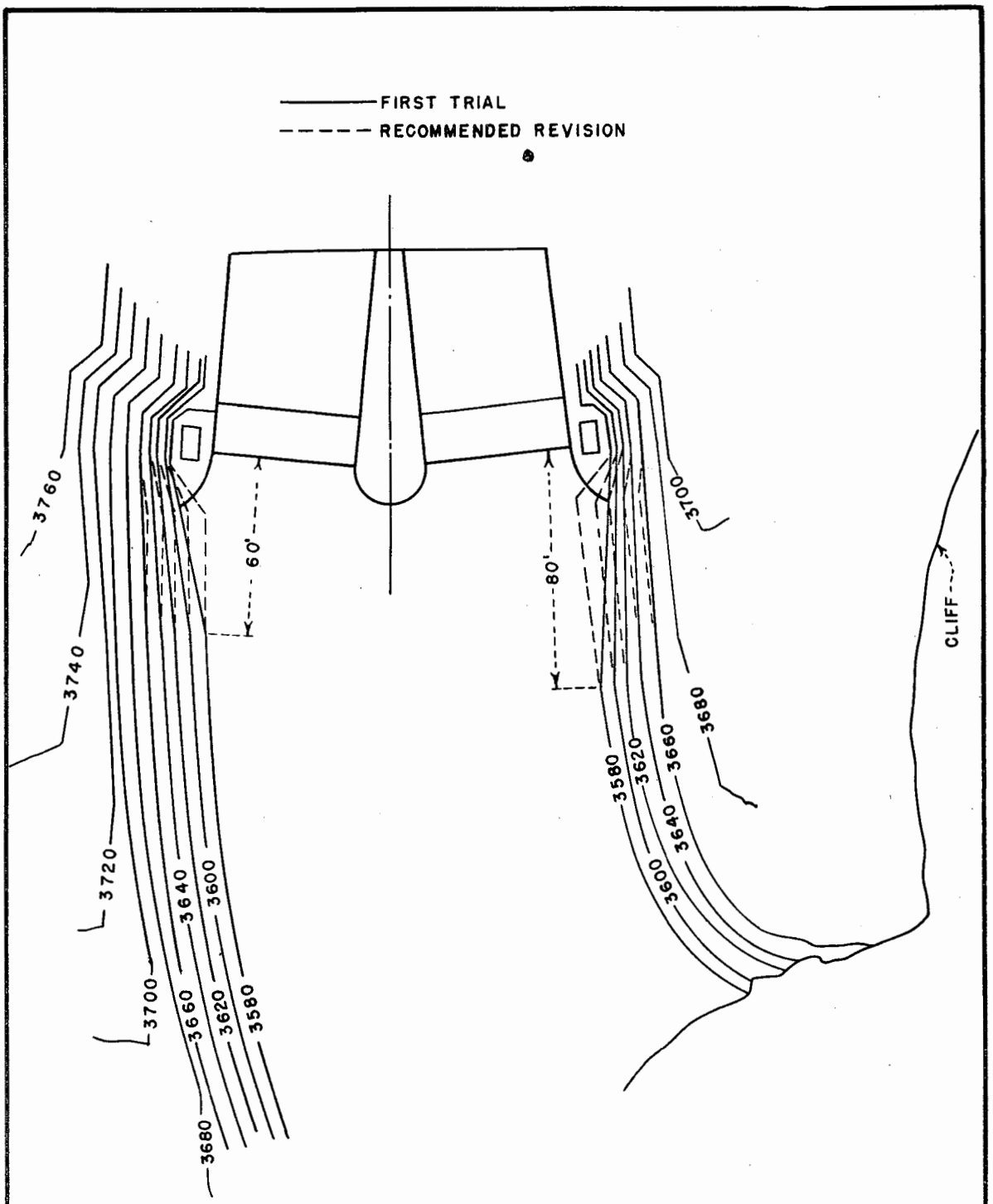


UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
MISSOURI RIVER BASIN PROJECT

YELLOWTAIL DAM
RECOMMENDED SPILLWAY
CREST AND TUNNEL

DRAWN ---- SUBMITTED ----
TRACED ---- RECOMMENDED ----
CHECKED ---- APPROVED ----

DENVER, COLORADO, MAY 1, 1951. 459-DC-32



YELLOWTAIL DAM

RECOMMENDED SPILLWAY
APPROACH CHANNEL TOPOGRAPHY

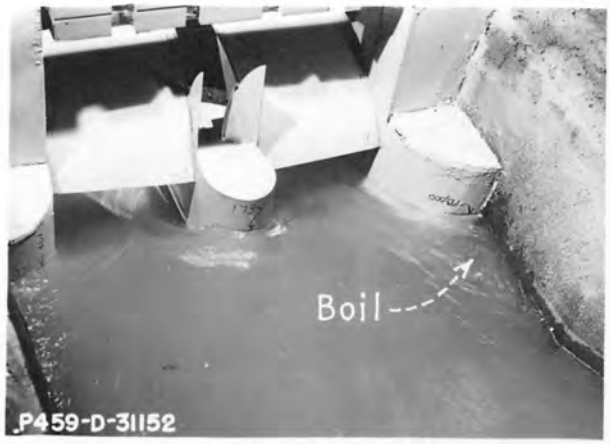
A. Approach channel (See Figure 57 for recommended revision)

B. 12,000 second feet

C. 40,000 second feet

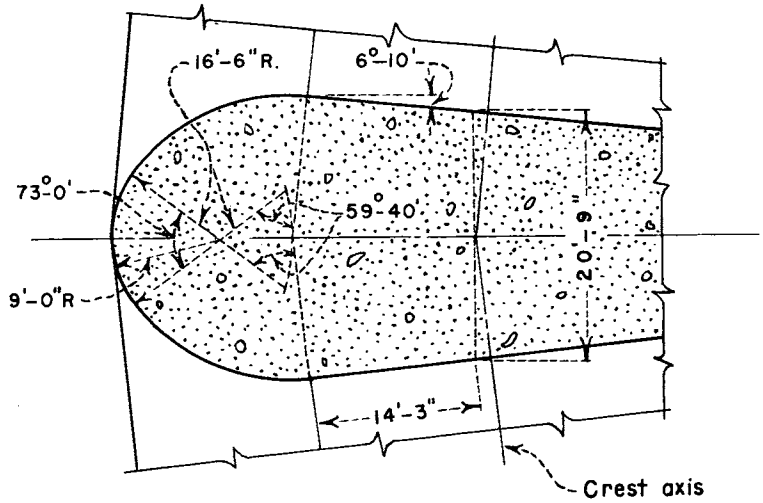
D. 100,000 second feet

E. 173,000 second feet

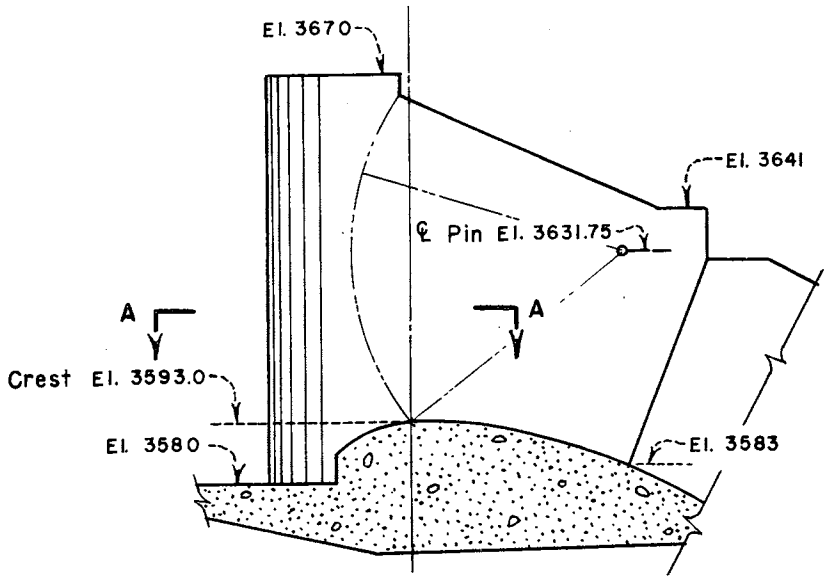


F. 173,000 second feet

YELLOWTAIL DAM
RECOMMENDED SPILLWAY
APPROACH CHANNEL FLOW
1:54 SCALE MODEL



SECTION A–A

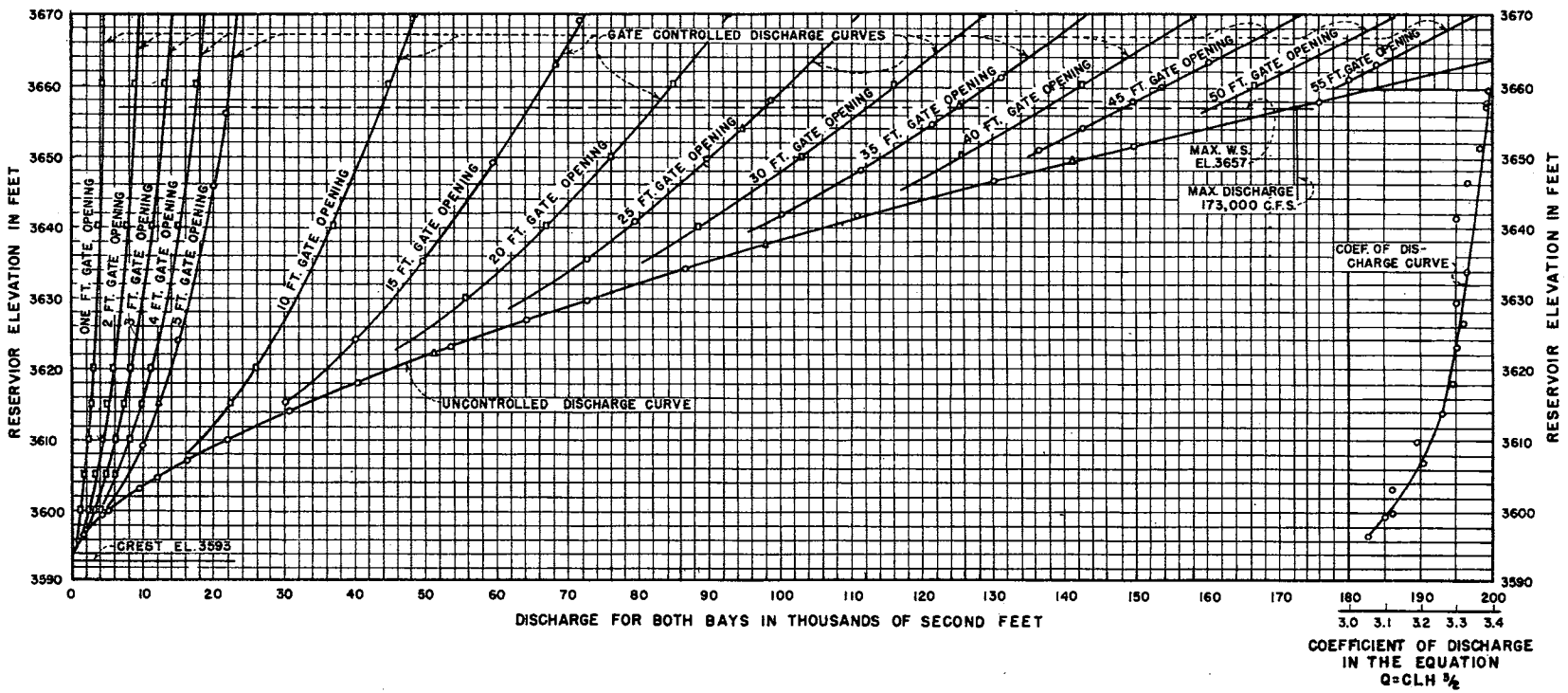


CREST SECTION

Note: After completion of the model study, crest section was revised and gate was relocated. See Figures 5,6,7, and 56.

YELLOWTAIL DAM

RECOMMENDED SPILLWAY PIER NOSE



EXPLANATION

- ○ Model test data points
- ▫ Interpolated points from Figure 61
- △ Model check points

NOTE

See Figures 56 and 59 for recommended design

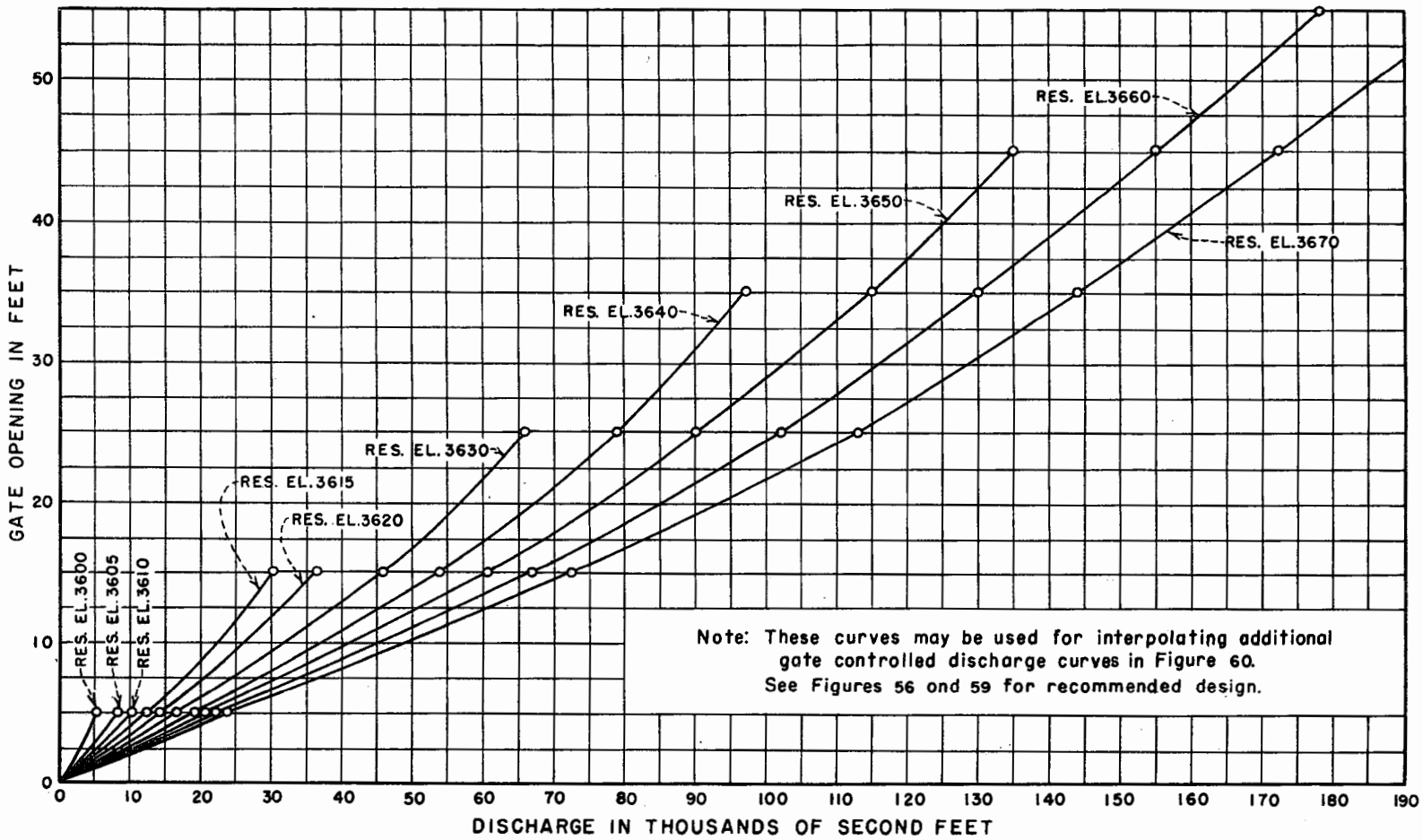
YELLOWTAIL DAM

RECOMMENDED SPILLWAY
DISCHARGE AND COEFFICIENT OF DISCHARGE CURVES

1:54 SCALE MODEL

PRELIMINARY STUDIES

FIGURE 60
REPORT HYD. 414



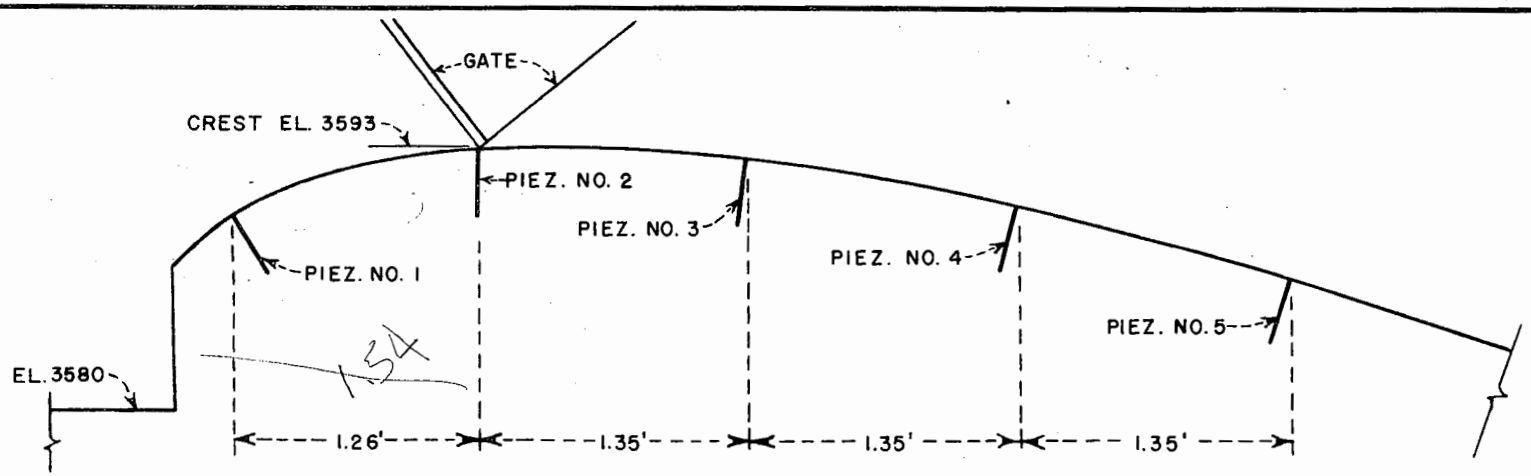
YELLOWTAIL DAM SPILLWAY

RECOMMENDED SPILLWAY GATE OPENING VS. DISCHARGE

1:54 SCALE MODEL

PRELIMINARY STUDIES

FIGURE 61
REPORT HYD. 414



PIEZOMETER PRESSURES						
DISCHARGE IN C.F.S.	12,000	98,700	149,500	86,700	130,100	173,000
HEAD ON CREST IN FEET	62.26	57.8	64.6	40.72	53.4	64.0
GATE OPENING IN FEET	APPROX. 2	25	45	FREE FLOW	FREE FLOW	FREE FLOW
PIEZOMETER NO. 1	64.8	42.3	27.9	29.7	34.6	40.5
PIEZOMETER NO. 2	10.8	12.6	23.0	19.3	23.0	26.5
PIEZOMETER NO. 3	1.1	8.5	19.8	18.4	22.5	25.6
PIEZOMETER NO. 4	0.5	4.0	13.5	14.8	18.0	21.1
PIEZOMETER NO. 5	1.6	5.4	12.6	13.0	16.2	19.3

NOTES: Pressures are at centerline of right bay in feet of water.
Zero pressure is atmospheric pressure.
See Figures 56 and 59 for recommended design.

1.35
1-40

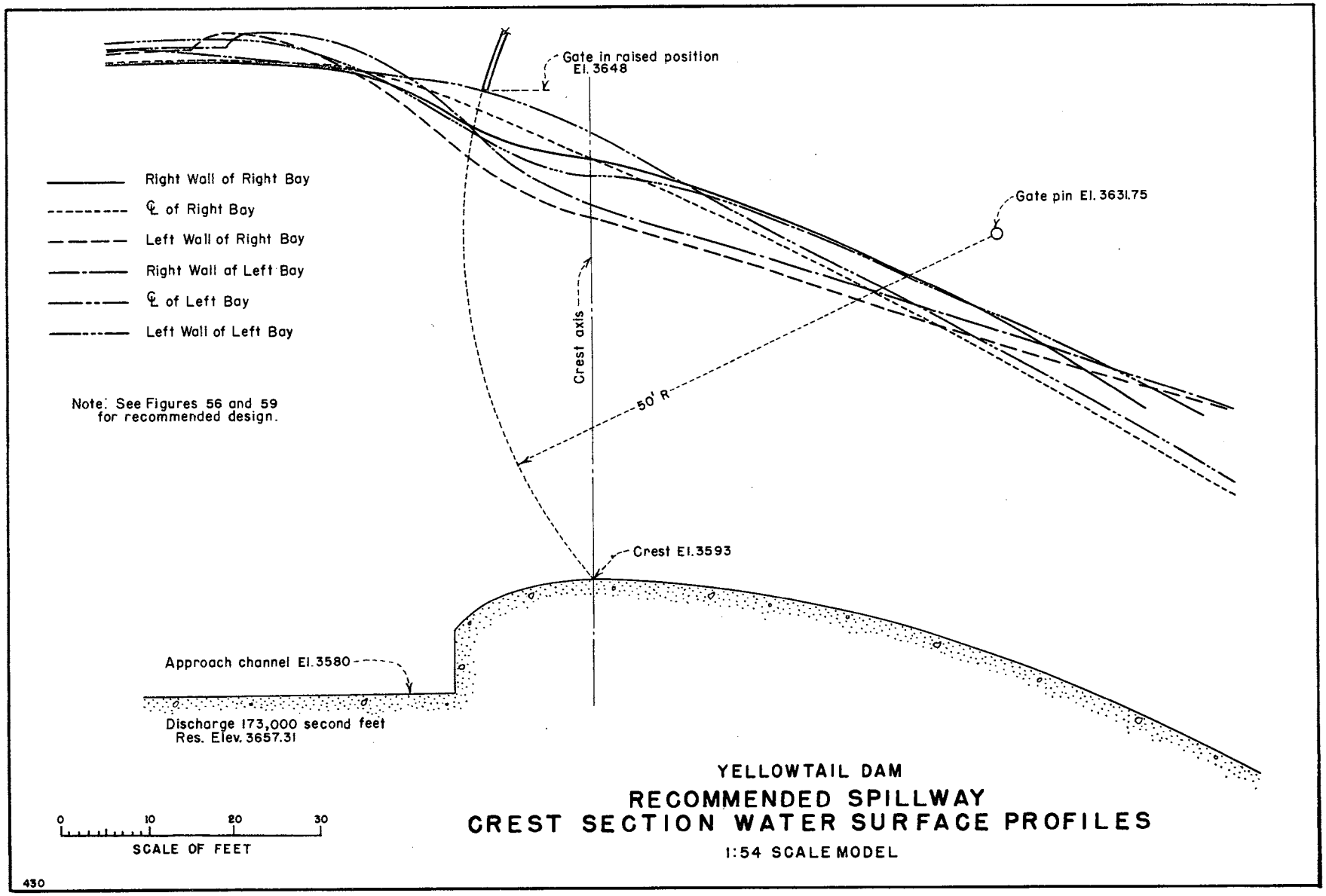
YELLOWTAIL DAM

PRESSURES ON RECOMMENDED SPILLWAY CREST

1:54 SCALE MODEL

PRELIMINARY STUDIES

FIGURE 62
REPORT HYD. 414



YELLOWTAIL DAM

RECOMMENDED SPILLWAY

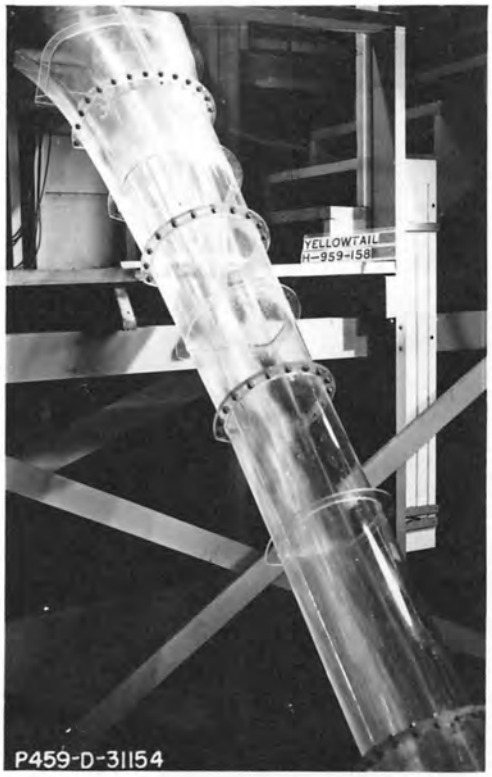
CREST SECTION WATER SURFACE PROFILES

1:54 SCALE MODEL

PRELIMINARY STUDIES

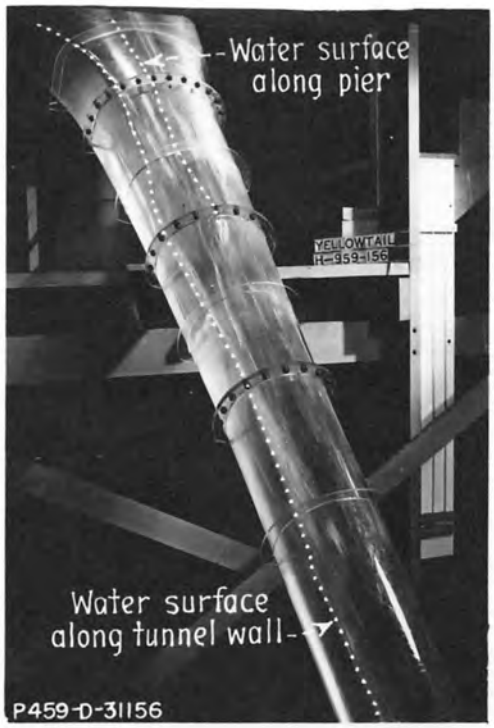
FIGURE 63
REPORT HYD. 414

12,000 second feet



40,000 second feet

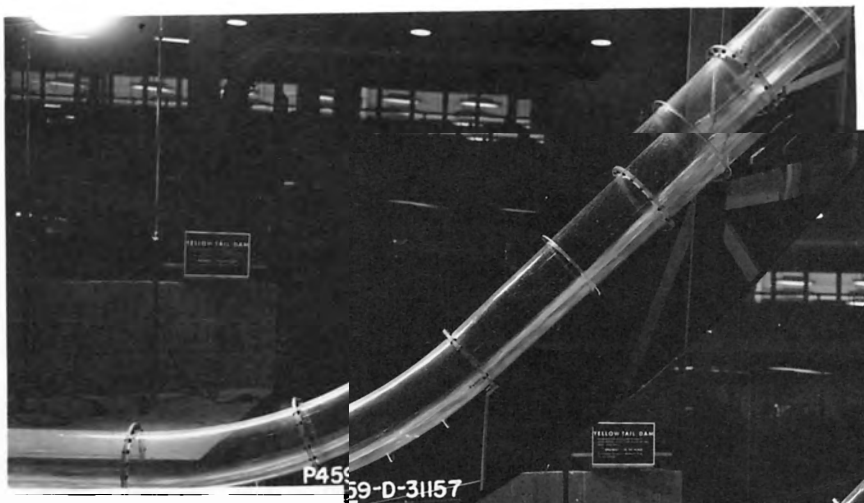
100,000 second feet



173,000 second feet

Note: Flow over crest is uncontrolled

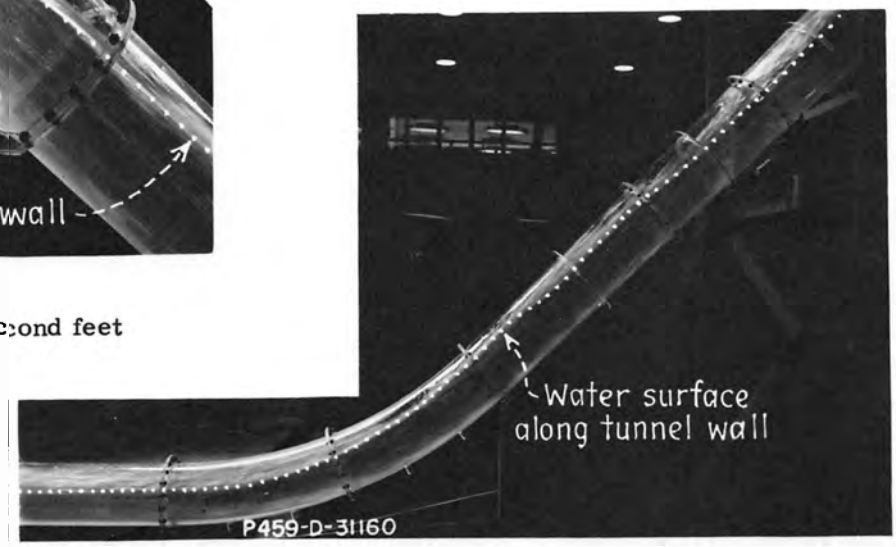
YELLOWTAIL DAM
RECOMMENDED UPPER PORTION OF TUNNEL DISCHARGING
1:54 SCALE MODEL



40,000 second feet

100,000 second feet

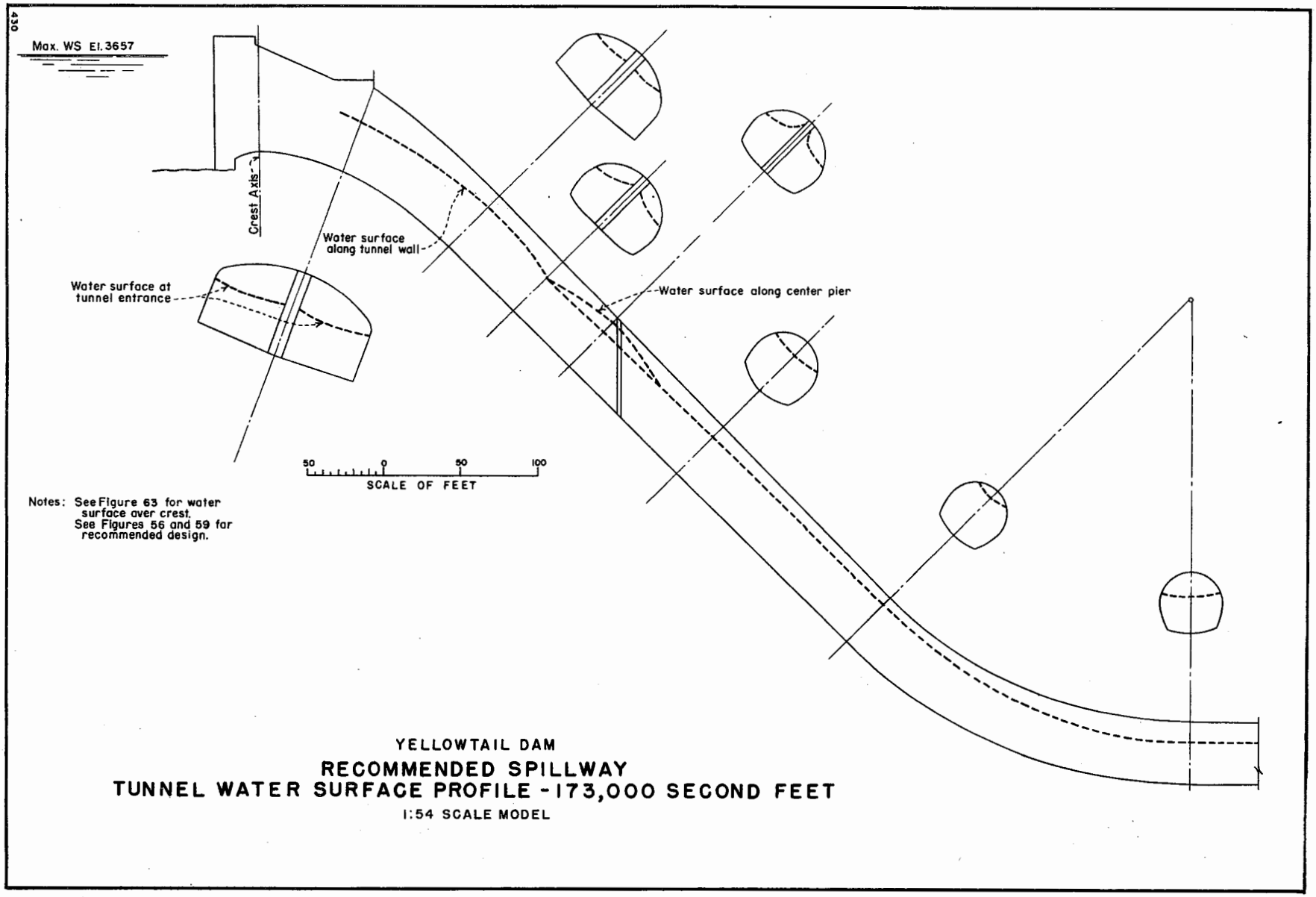
173,000 second feet



Note: Flow over crest is uncontrolled

173,000 second feet

YELLOWTAIL DAM
RECOMMENDED LOWER PORTION OF TUNNEL DISCHARGING
1:54 SCALE MODEL



YELLOWTAIL DAM

RECOMMENDED SPILLWAY

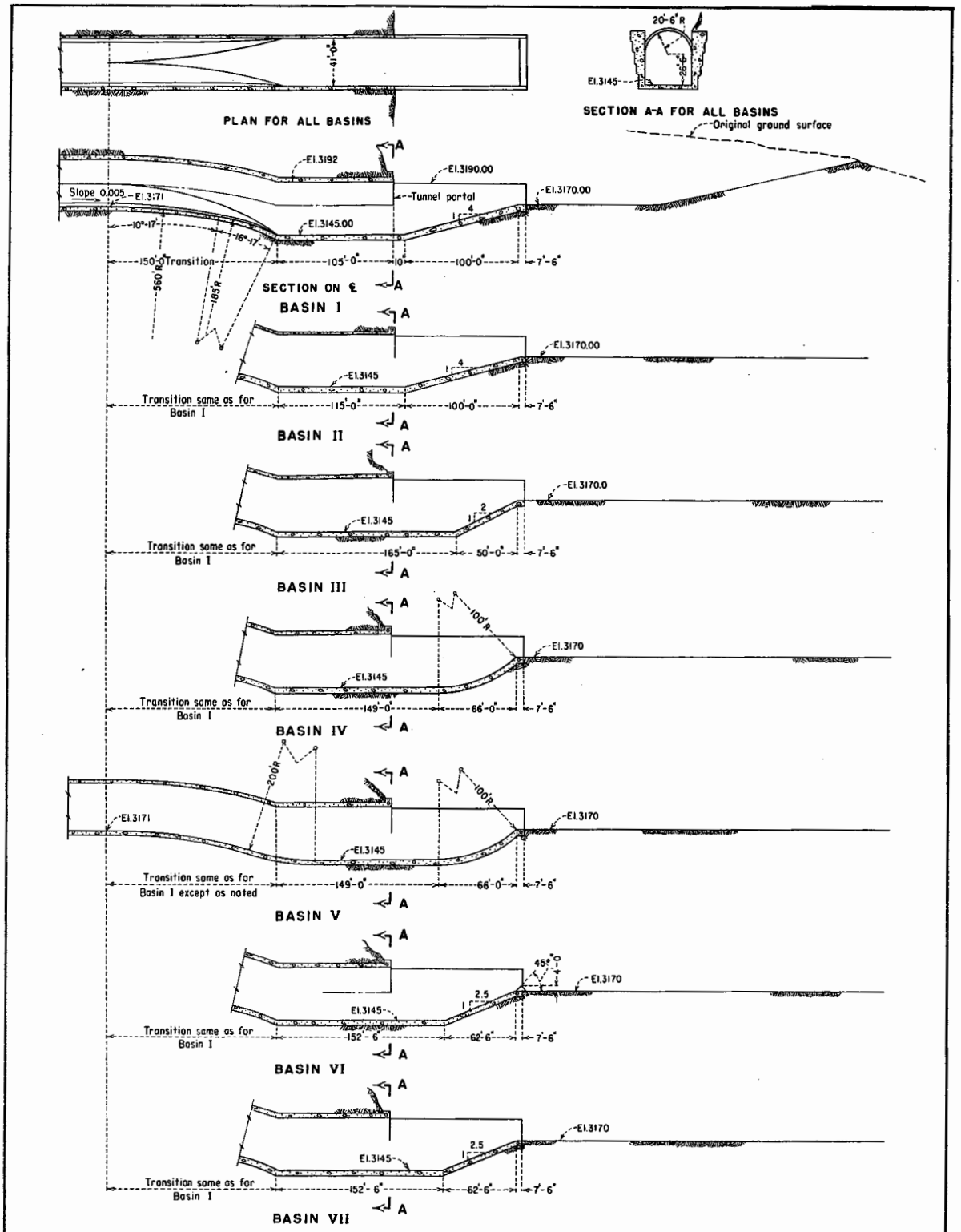
TUNNEL WATER SURFACE PROFILE - 173,000 SECOND FEET

1:54 SCALE MODEL

PRELIMINARY STUDIES

FIGURE 66
REPORT HYD. 414

FIGURE 67
REPORT HYD. 414



YELLOWTAIL DAM

SPILLWAY

STILLING BASIN DESIGNS I THROUGH VII AND TUNNEL TRANSITION

1:54 SCALE MODEL

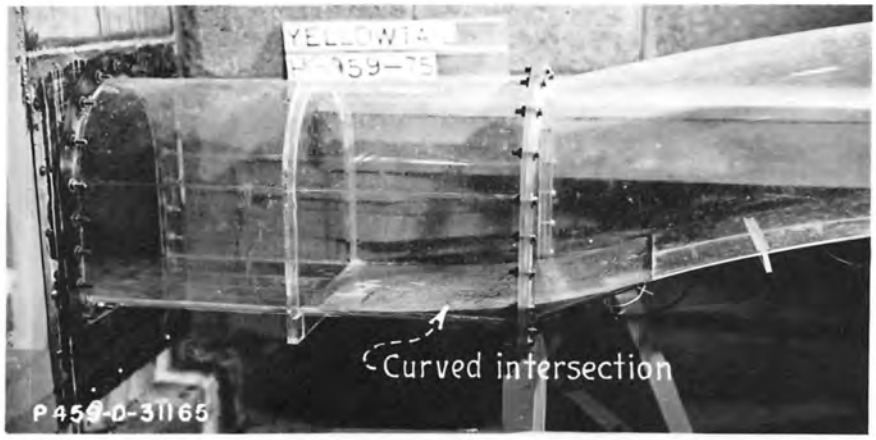
430

40,000 second feet

40,000 second feet

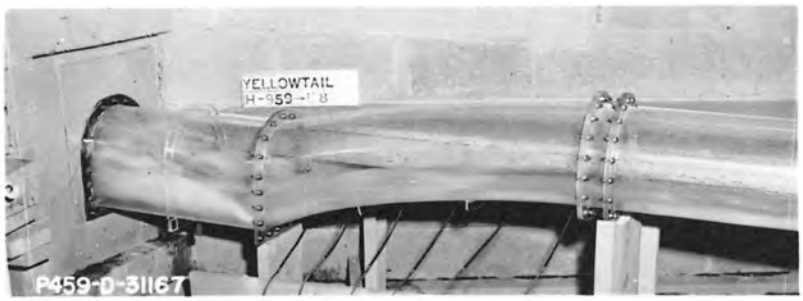
14,000 second feet

YELLOWTAIL DAM
SPILLWAY
BASIN IV DISCHARGING
1:54 SCALE MODEL

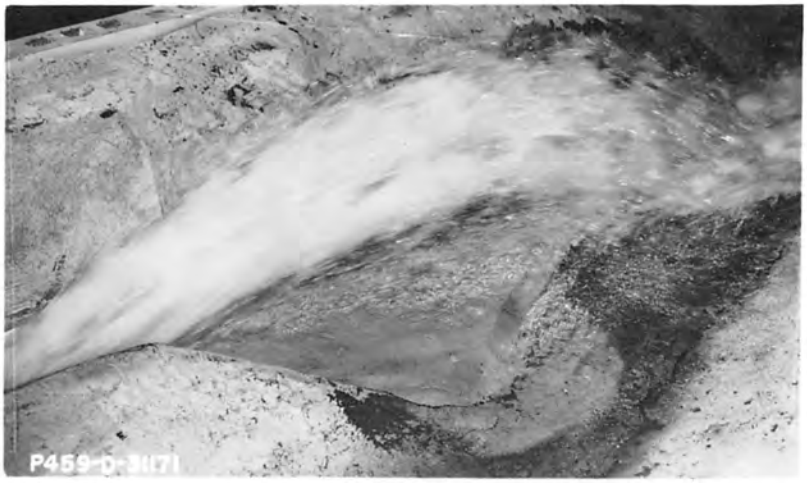


40,000 second feet

YELLOWTAIL DAM
SPILLWAY
BASIN V DISCHARGING
1:54 SCALE MODEL

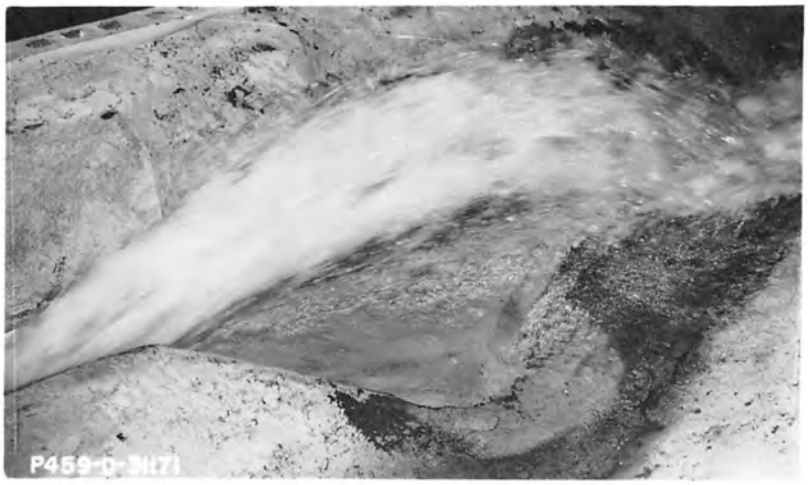


YELLOWTAIL DAM
SPILLWAY
BASIN VII DISCHARGING
40,000 SECOND FEET
1:54 SCALE MODEL



YELLOWTAIL DAM
SPILLWAY
BASIN VII DISCHARGING
100,000 SECOND FEET
1:54 SCALE MODEL

FIGURE 72
REPORT HYD 414

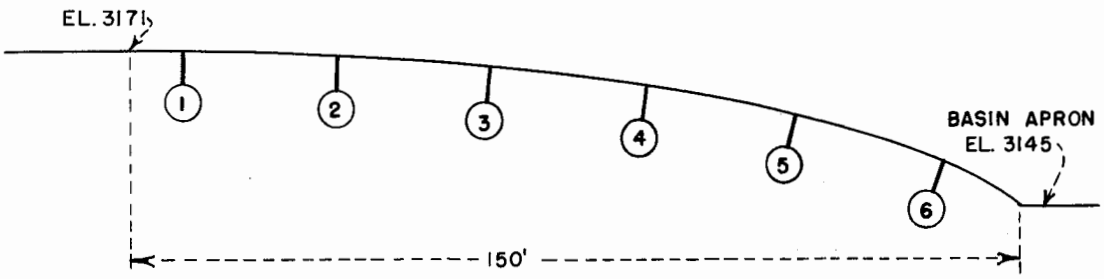


YELLOWTAIL DAM
SPILLWAY
BASIN VII DISCHARGING
173,000 SECOND FEET
1:54 SCALE MODEL

13,000 second feet sweeps out

YELLOWTAIL DAM
SPILLWAY
BASIN VII DISCHARGING
1:54 SCALE MODEL

(NO) Designates piezometer locations.



PROFILE ALONG TRANSITION INVERT *

PRESSURES

DISCHARGE CFS	RESERVOIR ELEVATION IN FEET	PIEZOMETERS					
		1	2	3	4	5	6
15,000		2.3	3.6	3.6	-2.7	-3.2	2.7
20,000	3608.82	1.8	3.6	3.6	-4.5	-5.0	5.4
40,000	3617.62	0.5	3.6	5.0	-9.5	-10.8	18.9
60,000	3625.00	-0.5	2.2	5.4	-14.0	-15.3	3.2
100,000	3637.85	-2.25	-9.0	5.0	-21.2	-25.6	69.3
140,000	3648.70	-4.5	-4.0	2.7	-28.4	-28.4	103.5
173,000	3657.00	-6.3	-7.6	-0.9	-34.6	-22.5	123.4

NOTES: Pressures are in feet of water.
Zero pressure is atmospheric pressure.

* See figure 67 for design shape

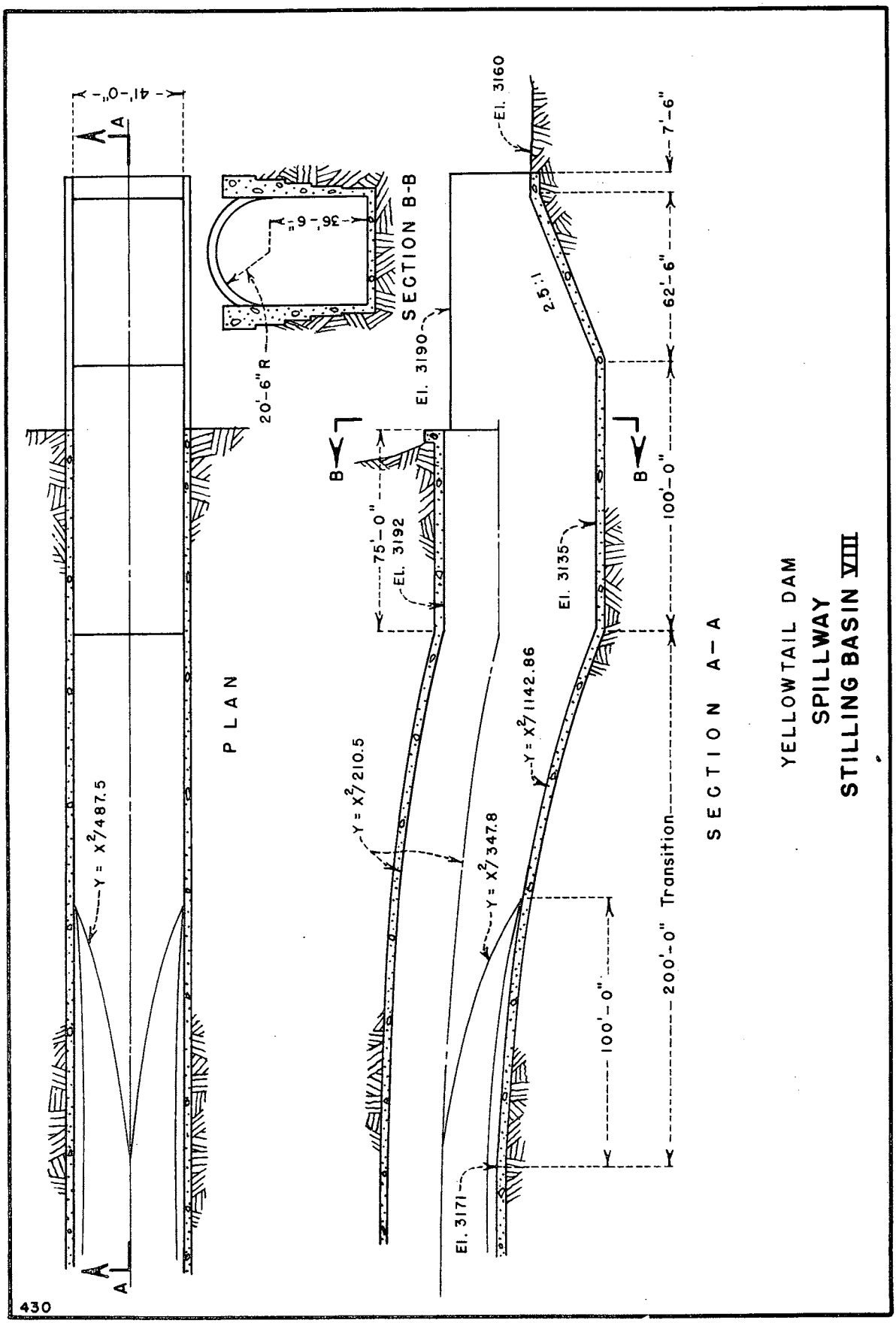
YELLOWTAIL DAM

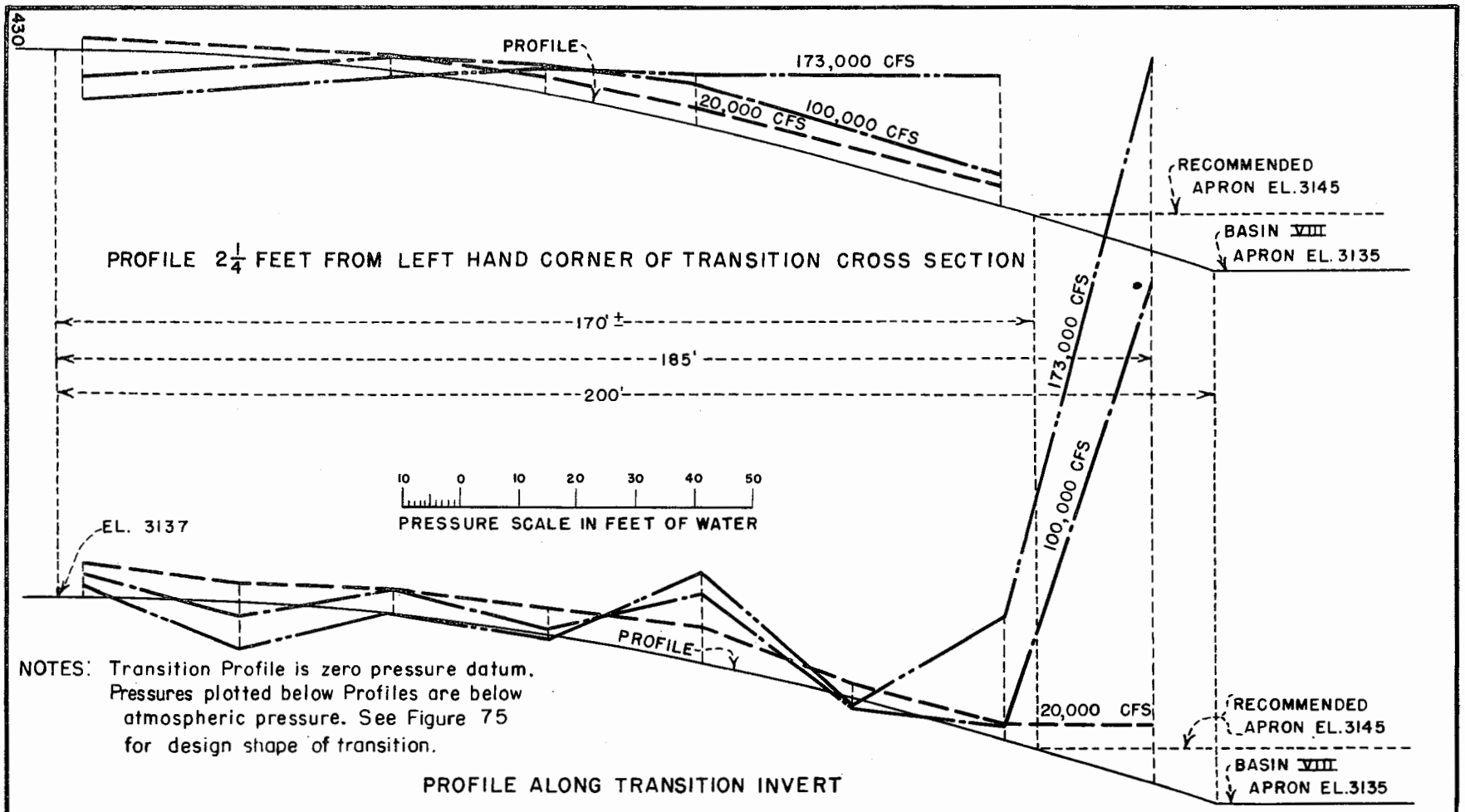
SPILLWAY

PRESSURES IN TUNNEL TRANSITION TO BASIN VII

1:54 SCALE MODEL

FIGURE 75
REPORT HYD. 414





NOTES: Transition Profile is zero pressure datum. Pressures plotted below Profiles are below atmospheric pressure. See Figure 75 for design shape of transition.

PROFILE ALONG TRANSITION INVERT

YELLOWTAIL DAM

SPILLWAY

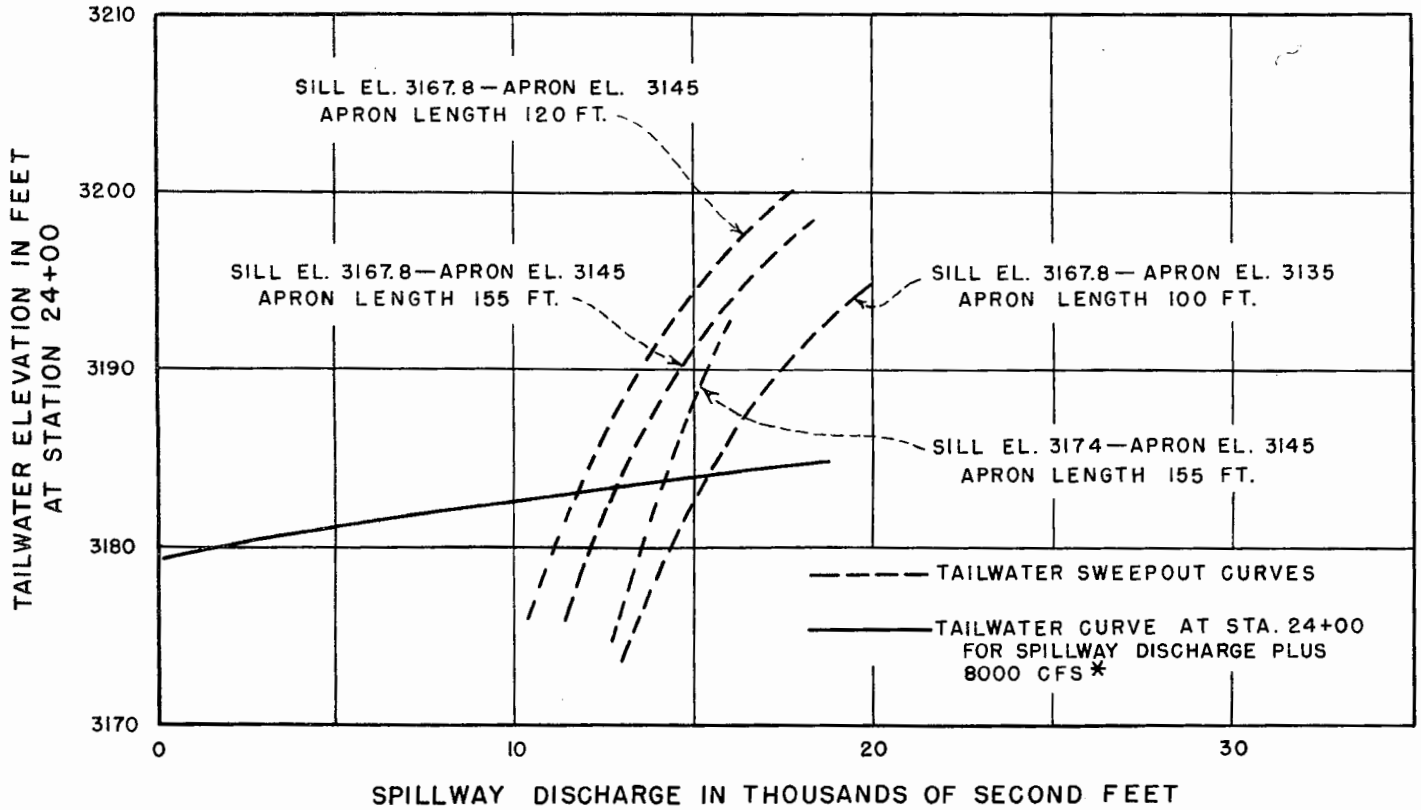
PRESSURE GRADIENTS IN TUNNEL TRANSITION TO STILLING BASIN VIII

1:54 SCALE MODEL

PRELIMINARY STUDIES

FIGURE 76

REPORT HYD. 414



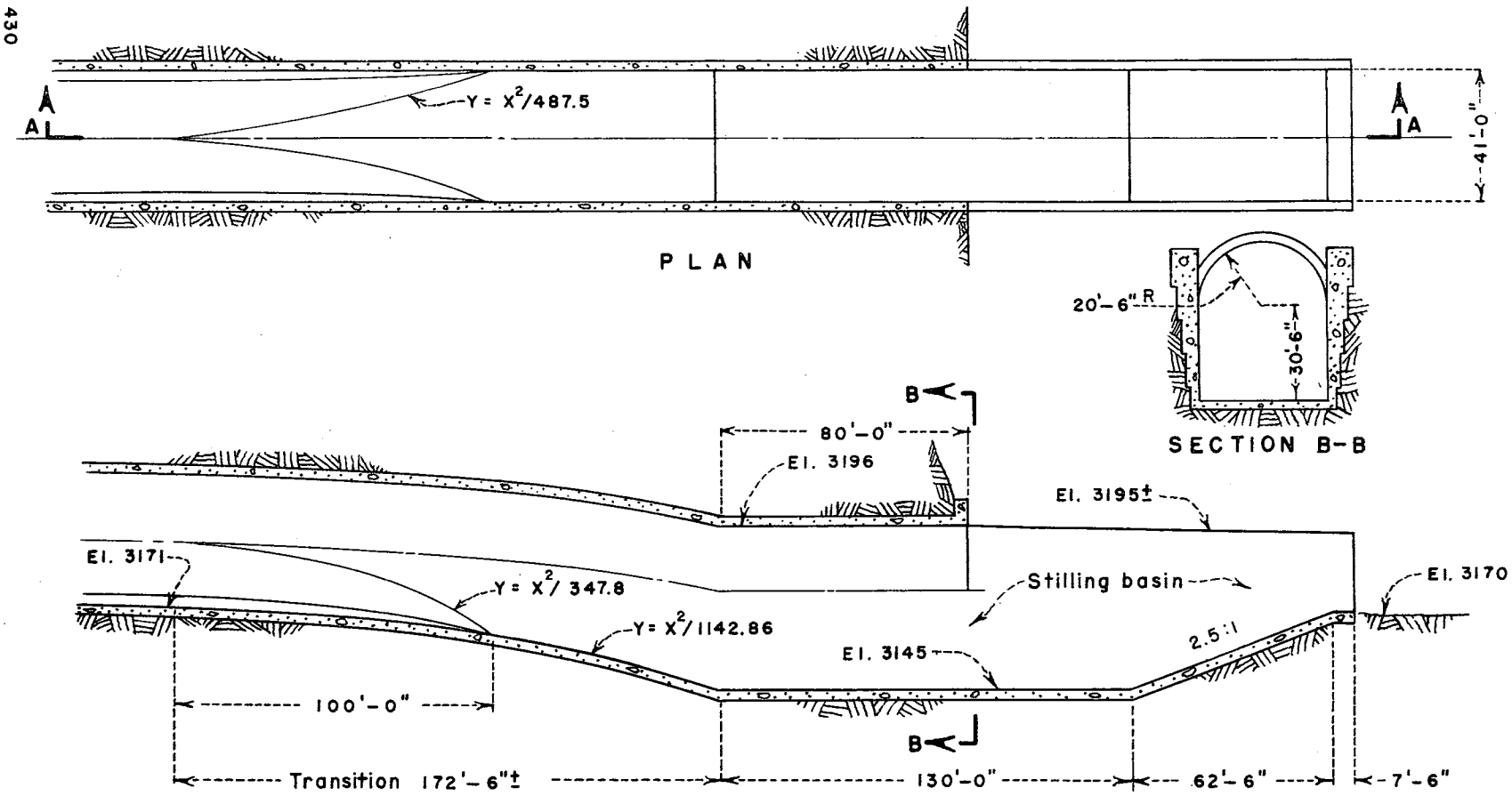
*8000 second feet is from power house and outlets.

YELLOWTAIL DAM

SPILLWAY

TAILWATER SWEEPOUT IN THE STILLING BASIN

1:54 SCALE MODEL



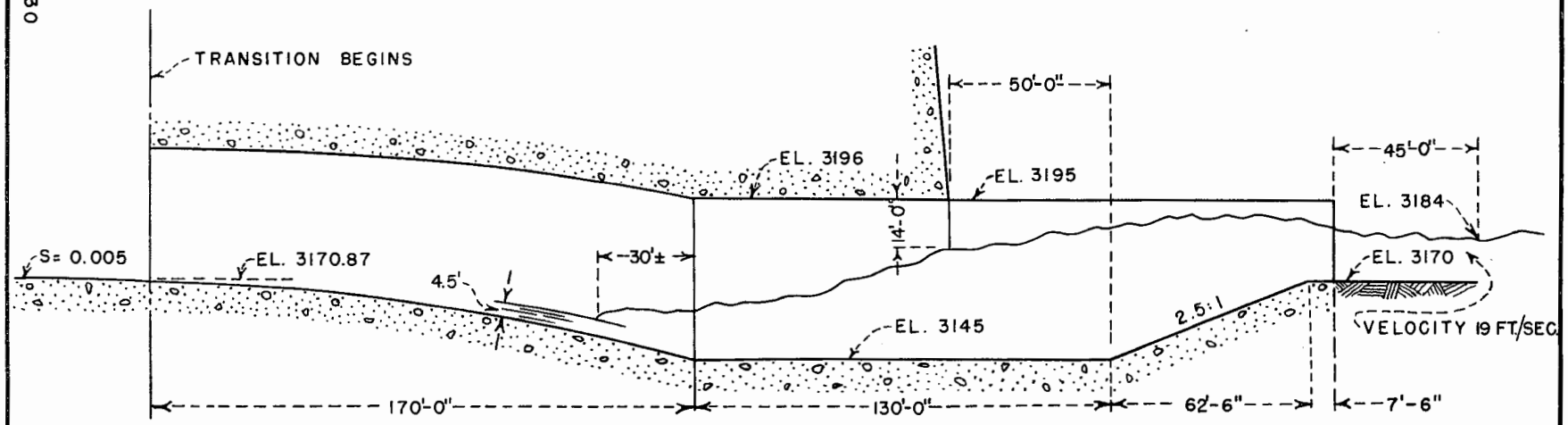
YELLOWTAIL DAM

RECOMMENDED SPILLWAY STILLING BASIN & TUNNEL TRANSITION

PRELIMINARY STUDIES

FIGURE 78

REPORT HYD. 414



AVERAGE MAXIMUM WATER SURFACE PROFILE FOR 12,000 SECOND FEET

Note: Total discharge in river channel is 20,000 second feet.
Tailwater is at elevation 3183 at station 24+00 in river channel.
Basin is 41 feet wide.

YELLOWTAIL DAM

WATER SURFACE PROFILE IN THE RECOMMENDED SPILLWAY STILLING BASIN

1:54 SCALE MODEL

PRELIMINARY STUDIES

FIGURE 79
REPORT HYD. 414

RECOMMENDED SPILLWAY BASIN DISCHARGING EXCEPT THAT BASIN WALLS AND CROWN OF PORTAL ARE AT ELEVATION 3195 and 3196, RESPECTIVELY, IN THE RECOMMENDED DESIGN.

YELLOWTAIL DAM
RECOMMENDED SPILLWAY AND OUTLET WORKS--DISCHARGING INTO RIVER CHANNEL
1:54 SCALE MODEL