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HYDRAULIC LABORATORY REPORT NO. 107

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HYDRAULIC MODEL STUDIES OF DIVERSION TUNNEL COASTER GATES, SHASTA DAM, CENTRAL VALLEY PROJECT.

By

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Denver, Colorado

March 11, 1942

UNITED STATES
DEPARTMENT OF THE INTERIOR
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Branch of Design and Construction
Engineering and Geological Control
and Research Division
Denver, Colorado
March 11, 1942

Laboratory Report No. 107
Hydraulic Laboratory
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Subject: Hydraulic Model Studies of Diversion Tunnel Coaster Gates, Shasta Dam, Central Valley Project.

INTRODUCTION

The diversion tunnel, Specifications No. 771, now used by the Southern Pacific Railroad, will, beginning early in 1942, by-pass the flow of the Sacramento River until the construction of Shasta Dam is completed (figure 1). A service coaster gate (figure 2) will be installed in this tunnel to regulate the flow of the river so the reservoir can be filled as the work progresses, enabling the generation of power sooner than originally planned. The maximum operating head on the gate will be 190 feet. Upon completion of Shasta Dam, this service gate will be closed and the diversion tunnel filled at the tunnel-plug section (figure 1). Should the service gate fail to close completely, an emergency closure will be necessary. A stop-log structure downstream from the gate was first proposed for this purpose, but was later abandoned in favor of an emergency gate, because the behavior of stop-logs in the prototype structure would be too uncertain.

Hydraulic model studies were utilized in the design of this structure to assist in developing a satisfactory gate. Pressures on the model gates were measured to determine the relative hoist capacities, and visual observations of the flow conditions around each gate were made to detect any adverse operating conditions. In addition, discharge calibration curves were obtained for various heads and gate openings.

SUMMARY OF TESTS

The design of the fixed-wheel gates for the diversion tunnel at Shasta Dam, Specifications No. 1009, involved a study of the down-pull forces on the gates to determine the required hoist capacities. The down-pull forces consisted of the weight of the gate, the dynamic frictional resistance, and the hydraulic drawdown force. While the weight of the gate and its dynamic frictional resistance could be estimated, the hydraulic drawdown force could be obtained only by tests, for this force was caused by the difference in pressures on the top and the bottom of the gate. Electrical analogy studies were first made on the original design, but the resulting hydraulic drawdown forces did not agree with the results of later hydraulic model studies. This disagreement resulted from assuming the cross section of the tunnel in the electrical analogy studies to be rectangular instead of horseshoe-shaped (figure 2). In the original design of the gate with a 45-degree bottom (figure 2), the hydraulic drawdown forces were not excessive (figures 8A and G), and with the aid of model studies a desirable arrangement of the service and emergency gates was obtained placing both gates in the same well structure (figure 7). To do this, the upstream gate sealed on its upstream face while the downstream gate sealed on its downstream face.

Improvements in the design of the gates were necessary. The bottom of the gates sloped at 45 degrees, which was not completely desirable structurally. Impact of flow on the downstream gate held it open at the full open position. Studies made by changing the shape of the gate bottom eliminated these adverse features. However, the hydraulic drawdown force was excessive in the service gate of the revised design (figures 8E and G), so large, in fact, as to require excessively large hoisting equipment.

In contrast, the upstream emergency gate had no hydraulic drawdown forces. Because this gate sealed on its upstream face the flow

passing underneath was free of the bottom, and the gate well was vented to the atmosphere. The pressures on the top and bottom of this gate were thus atmospheric, and no hydraulic drawdown force could exist. Accordingly, a new design using gates with seals on their upstream faces was proposed. It was necessary to place the gates in separate well structures located at stations 4775+20 and 4776+17, since both sealed on their upstream faces. This arrangement was satisfactory. As a final revision, the size of these gates was reduced by using transitions to change the 23- by 25-foot horseshoe-shaped tunnel to an equivalent 19.5- by 25-foot rectangular section at the gates (figures 3, 14, and 15).

DESCRIPTION OF MODEL

A 1:30 scale model was built and tested in the hydraulic laboratory of the Bureau of Reclamation, Denver, Colorado (figures 4, 5, and 6). The model consisted of a head box to which the diversion tunnel was attached. The tunnel, gate, and gate-well structure were constructed of sheet metal, except where pyralin sections were used to permit observation of flow conditions (figure 5). To measure the head and pressures, piezometers were installed in the head box, at selected points in the tunnel, and on the gate.

DIFFERENCES BETWEEN MODEL AND PROTOTYPE

While the principal features of the gate and tunnel were incorporated in the model, some differences existed between the model and prototype which had to be considered in analyzing the results of these tests. In measuring the forces necessary to lift the model gate, it was realized that the frictional resistance encountered in the model was not the same as that of the prototype. In predicting the prototype discharge from the results of the model studies, it was necessary to account for two factors: (1) the tunnel section upstream from the gate was not similar to the prototype as it was shortened, due to laboratory space limitation, and the irregular entrance shown in figure 1 was changed to the rounded entrance shown in figure 4; and (2) the hydraulic friction factors of the tunnel walls were not the same. The comparative friction factors in the formula

$$H_f = f \frac{L}{D} \frac{V^2}{2g}$$

were estimated as $f = 0.014$ for the model and $f = 0.008$ for the prototype. These computations are discussed in section 15.

ORIGINAL DESIGN - SERIES A

The tests were divided into two groups, series A and B. In series A the original design and a revised arrangement were tested with the service and emergency gates in the same well. Studies were then made to improve the individual gates. Additional observations and checks upon the final design concluded this series of tests. Throughout series A, a maximum design head of 165 feet was used in contrast to the final design head of 190 feet. Series B tested two gates with seals on their upstream faces and placed in separate wells, which led to the final design. In the original design a service gate was located at station 4776+00 with a stop-log structure 80 feet downstream for an emergency closure (figures 4 and 5).

In discussing the design features in this report the main consideration will be the hydraulics, the structural viewpoint being considered only when the hydraulic solution is restricted by structural limitations. The outstanding hydraulic features of the gate were the shape of its bottom and the location of the seals. The features of the stop-log structure will not be discussed, as the design of the structure was abandoned before any tests or observations were made because of the uncertainty of operation and the hydraulic forces which would be encountered.

The pressures on the 45-degree bottom of the original service gate were positive and were therefore considered favorable. In contrast to favorable positive pressures recorded elsewhere on the gate, under certain conditions adverse negative pressures would develop on its downstream face and also in the tunnel below. When the gate was approximately 75 percent open a hydraulic jump would form, causing the tunnel to flow full and producing slight negative pressures on the downstream face of the gate. This is a natural condition, and not adverse;

however, should the gate then be lowered slightly, the tunnel would remain full of water and prohibitive negative pressures would develop. This condition was a direct result of no aeration in the tunnel downstream from the gate. The negative pressures could only be relieved by adequate tunnel aeration. The stop-log well was considered as an aeration duct, for it leads directly to the atmosphere (figure 5), but it was too far downstream to be of any value. Two 1-inch pipes (30 inches prototype) were installed immediately downstream from the service gate to admit air from the ground surface to the tunnel (figure 5). This revision proved satisfactory, since the negative pressures with the pipes open did not exceed 2 feet prototype for any operating condition.

SERVICE AND EMERGENCY GATES IN SAME STRUCTURE

From tests on the original design it was evident that the stop-log structure should be abandoned in favor of an emergency gate and that it would be necessary to introduce air into the tunnel to eliminate negative pressures on the service gate. The stop-log structure was replaced by an emergency gate installed in the same gate well as the service gate. In the original tests on this arrangement, the upstream gate was considered as the service gate. On this gate the seals were on the upstream side, while the emergency gate seals were on the downstream side (figure 7). By having the seal of the service gate on its upstream face, the well shaft provided tunnel aeration, making it unnecessary to use the two 1-inch pipes installed in the first arrangement insofar as the service gate was concerned. Elimination of these pipes, however, caused negative pressures on the emergency gate in a manner similar to conditions of the original design.

Several faults of this arrangement were immediately obvious. The edges of the stream of water under the service gate impinged on the gate slots, producing rough flow conditions in the tunnel. The flow under the downstream gate was much smoother, indicating that it was better suited as a service gate. The downstream gate was subjected to hydraulic uplift forces produced by impact of the rough flow emerging from under the service gate. This made the gate difficult to close, a condition

undesirable especially in an emergency gate. Furthermore, as there was no provision for venting the downstream gate, when it was closed quickly a water hammer occurred with such intensity that several joints in the model tunnel were ruptured. Accordingly, the suggestion that vent pipes could be excluded was wrong.

The two 1-inch air vents which proved successful in the original design were reinstalled. The downstream gate was designated as the service gate because it produced a smoother flow in the tunnel, and the upstream gate was designated as the emergency gate because it would close more easily. The performance with this arrangement was satisfactory except, as before, the downstream gate would not close easily because of hydraulic uplift forces produced by the impact of the flow against the bottom of the gate. Any force on either of the two gates, tending to prevent them from closing, was undesirable. If these forces could not be entirely eliminated, it was anticipated that the prototype gates would be loaded with concrete to insure a closure. To estimate the amount of concrete that would be necessary in the prototype, the model gates were loaded with lead shot until they would close easily. While the upstream emergency gate required only enough shot to overcome the kinetic friction, the downstream service gate required approximately 15 pounds of shot because of the hydraulic uplift forces. This weight, in terms of the prototype, would be excessive and not practical because sufficient concrete could not be placed within the gate.

IMPROVEMENT OF GATE DESIGN

With gates placed in one well, the service gate downstream sealing on its downstream face and the emergency gate upstream sealing on its upstream face, and with the air vents installed to prevent excessive negative pressures on the downstream face of the service gate, the general arrangement was satisfactory; but during the operation of the gates they would not close by their own weight. Hydraulic uplift forces prevented the service gate from starting to close when it was wide open, and frictional resistance due to the high static pressure prevented both gates from closing as they approached the gate seat. In addition, their

structural design was undesirable because the thin section produced by the 45-degree bottom required an excessive amount of steel to attain sufficient strength. Further tests in Series A were made to improve the design of the downstream service gate to facilitate its operation. It was anticipated that the design obtained for this gate could be used for the upstream emergency gate.

The 45-degree bottom was replaced with a horizontal one, which is ideal structurally (figures 8A and B). Adverse negative pressures were recorded on the horizontal bottom for the various heads and gate openings. Also, the force required to lift this revised model gate was considerably more than the force required to lift the original. This increase in the lifting forces was due to an increased hydraulic drawdown force on the flat bottom. These forces were calculated by integrating the vertical components of pressures on the respective gates for various openings. The maximum force on the 45-degree bottom gate was approximately 342,000 pounds (prototype), while on the flat bottom gate it was of the order of 1,300,000 pounds (figure 8C).

A gate with a 15-degree bottom was then tried, but negative pressures were steel recorded (figure 8C), giving a drawdown in excess of 1,200,000 pounds. This procedure of changing the angle of the bottom was abandoned, as it was apparent from visual study that the revised gates were not shaped correctly to permit the flow lines to follow the given shape. Consequently, the flow tended to separate from the bottom of the gates, creating negative pressures. The gate bottom was curved to these flow lines. The drawdown force, with this design, was the maximum observed (figure 8D and 8G); but the flow lines followed the bottom of the gate at most openings and the negative pressures appeared to occur because the curvature of the upstream edge of the bottom was too severe.

Since a number of gates had to be tested before a satisfactory bottom shape could be obtained, a method of expediting these tests was necessary. It was noted in the visual studies on the curved bottom gate that small air bubbles would stick to the gate in regions of negative pressures.

Using this as a criterion, observations were quickly made on wooden gates (figure 9). Fifteen shapes were tested with bottom R-15 being selected for further tests.

Bottom shape R-15 was incorporated in the model gate and tested by recording pressures and observing the flow at various heads and gate openings (figure 8E). As a result of changing the shape of the bottom of the gate from the 45-degree bottom to the curved bottom, shape R-15, the structural aspect of the bottom was improved, the excessive uplift forces which would prevent the gate from starting to close due to impact of the flow on the bottom of the gate were eliminated, and positive pressures were obtained for all gate openings. However, some adverse features still existed: (1) The gate would vibrate at openings greater than 20 feet (80 percent); (2) the hydraulic drawdown forces were greater than those on the 45-degree bottom gate; and (3) frictional resistance still prevented the gate from closing as it was about to seat. For these reasons, two additional tests were made on the downstream service gate to determine, if possible, the cause and frequency of the vibrations and to check the accuracy of the computed hydraulic drawdown forces by direct measurement of the forces acting on the gate. The problem of determining the magnitude of the frictional resistance in the gate, which appeared to prevent the gate from closing, was also considered in the second test.

VIBRATION OF GATE

While recording pressures on the final curved-bottom gate, it was observed that the gate would start to vibrate at openings greater than 80 percent. The vibrations occurring at these openings were of such a nature that the very top of the gate would remain fixed, forming an axis or hinge about which the rest of the gate would vibrate. Frequently the axis of vibration would change to the bottom of the gate, and sometimes it was nonexistent. The amplitude of these vibrations was restricted by the guide tracts in the gate-well structure (figure 2). When the gate was 100 percent open, the frequency of vibration was low, but as the

gate was lowered, the frequency increased, reaching a maximum when the gate was approximately 75 percent open. Upon further lowering of the gate the vibration ceased, as the pressures on the upstream face of the gate became sufficient to hold it against the seat.

A diaphragm was installed in the skin plate of the model gate to record these vibrations. The movements of the diaphragm were transferred by a lever arm to an electric cell and oscillograph. Vibrations were never recorded because when all was ready, the gate refused to vibrate. Despite many attempts to start the gate vibrating, no revision or change had any influence upon its performance, and the tests had to be abandoned.

These tests were not fruitless because during the attempts to make the gate vibrate, a condition was observed which had been overlooked. The pyralin guide tracks shown in figure 7 could be sheared from the frame in the normal operation of the gate. When the vibration tests were started, the pyralin guide tracks sheared, and, at that time, it was thought this was due to wear from previous testing. Two additional sets of guides were installed and they also sheared. When the gate was raised, an opening was reached where the gate would move upstream in the slot, exerting force upstream upon the pyralin guides. This upstream movement of the gate indicated that the pressures on its downstream face were greater than those on the upstream face. This increase of pressure was attributed to impact created by the edges of the jet impinging on the downstream side of the gate slot. The importance of preventing such a condition in the prototype can be shown by a comparison of stresses in the gate guides. Since the guides in the model were geometrically similar to the prototype and the pyralin guides had a shear strength of 1,000 pounds per square inch, it follows that stresses as great as 30,000 pounds per square inch would occur in the prototype. To minimize this expansion of flow through the gate-well structure and to reduce the pressure between the gate and the gate-well structure, an arch was placed between the gates (figure 7). This arch reduced the impact of flow on the downstream face of the gate, but the upstream swing of the

gate could not be eliminated. If this arrangement is used in any installation, the gate should never be operated at openings greater than 22 feet (88 percent).

DRAWDOWN STUDIES

To conclude the tests on the downstream service gate, the forces acting on it were computed for various openings and for a head of 165 feet prototype. Since the sum of these forces was equivalent to the force on the hoist cable, it could be checked by operating the model gate at a head equivalent to 165 feet prototype, and at the same time measuring the force with a spring scale attached to the hoist cable. The forces acting on the gate were (1) the weight of the gate; (2) the kinetic friction; and (3) the hydraulic drawdown. Only the sum of these forces could be measured directly on the model, but the first two forces could be determined separately and the hydraulic drawdown force obtained for any given gate opening, since it was equal to the measured force on the hoist cable minus the weight of the gate and the kinetic friction. This test was made to determine the accuracy of the hydraulic drawdown forces computed in the previous tests from pressures measured at the center of the gate only. In the previous tests it had been assumed that the pressures near the sides of the gate were the same as at the center. It was necessary to check this assumption, since the magnitude of the hydraulic drawdown was such as to make a correct prediction from the model studies essential.

A separate study was made to evaluate the weight of the gate and the kinetic friction. The gate was weighed and a correction made for the effect of buoyancy. The weight was found to correspond closely with the estimated prototype weight of 300,000 pounds. The principal cause of the frictional resistance was the horizontal force due to water pressure on the upstream face of the gate. This pressure was practically constant over the face of the gate and equal to the static pressure, measured in the gate well. The frictional resistance was expressed as the product of the pressure on the gate, the area bounded

by the gate seals, and a coefficient of kinetic friction. This coefficient was determined by loading the gate and measuring the force required to move the gate along a horizontal surface. A coefficient of 0.125 was obtained (figure 10) which is believed to be slightly large, as some water will flow under the seals when the gate is operating, a condition which could not be duplicated in the tests to determine the coefficient. A coefficient of kinetic friction of 0.10 was selected, making this method of determining a coefficient of friction a matter of judgment rather than precision. However, it was possible to check this assumed coefficient. Since the force of resistance is opposite to the gate movement, the difference between the force required to raise the gate and that to lower it is equal to twice the frictional resistance of the gate. During the tests to check the hydraulic drawdown, the gate was operated through a cycle of closing and opening, successfully checking the frictional resistance based on a coefficient of 0.10. Additional tests were made to determine (1) whether the frictional resistance which tended to hold the gate as it approached the closed position would be overcome when the model gate was filled with concrete (figure 11), (2) the force necessary to close the gate with the concrete removed, and (3) the effect on drawdown of a skin plate attached to the upstream face of the gate (figure 12).

Figure 11 shows the results of the drawdown tests made on the gate filled with concrete. The ordinate represents the drawdown forces on the gate. The abscissa represents the gate opening in feet, the gate being wide open at 25 feet. The individual forces acting on the gate are shown by the light curves. Its weight, shown by a horizontal line, is independent of gate openings. The frictional resistance to movement is a maximum when the gate is closed and acts in the opposite direction to the gate movement. The hydraulic drawdown force was obtained from the data shown on figure 80. The sum of these forces is shown by the heavy solid curves. When the gate was being opened, the maximum force occurred at an opening of 12 feet. In the prototype this force would

be 1,800,000 pounds. During the closing cycle, the critical point was at an opening of about 3 inches prototype. The drawdown forces reduced to zero, and a downward force was required to close the gate due to the frictional resistance of the model gate being greater than its effective weight.

This total force curve was checked by measuring the forces actually required to operate the gate while maintaining the head at 165 feet. This check, shown by the heavy dashed curve, agrees reasonably well with the computed curve over the major portion of the cycle of operation. From these results, it would appear that the hydraulic drawdown force computed from the pressures recorded at the center of the gate is reasonably reliable. Of particular interest in this check was the agreement at the two critical points, the maximum load on the hoist and the point at which the frictional resistance prevents the gate from closing. Both of these points were checked satisfactorily, which indicates that a prototype design, similar to the model, would not close by its own weight and would need also a hoist capacity of 1,800,000 pounds. However, the coefficient of kinetic friction of 0.10 in the model will not be the same in the prototype. Better material for the wheels and shafts will be used and the coefficient of friction of the seals, high in the model, will be slight in the prototype. Unfortunately, this prototype coefficient cannot be obtained from the results of model studies, and the adverse figures given above are only an indication of the prototype forces and are apt to be misleading if their limitations are not realized.

This high frictional resistance in the model was the cause of some concern, and a test to estimate the actual force required to close the gate was desired. The concrete, not very effective because of its buoyancy, was removed and a 3/8-inch rod installed in the gate in place of the hoist cable, enabling the gate to be pushed closed. The procedure on this test was similar to the test made on the gate filled with concrete. The forces acting on the gate were computed, and their sum was checked by operating the gate, providing an additional check of the

computed hydraulic drawdown forces. The results of this check tests, shown in figure 12, were plotted as circled points to compare with the computed curve. Difficulties were encountered in opening the gate and the results do not agree as well as in the former test. It was found that should the frictional resistance on the prototype be as great as that of the model, a force of 180,000 pounds would be necessary to close the gate (figure 12).

The final test was made to determine the effect of a skin plate on the upstream face of the gate. As some turbulence existed between the beams of the gate, it was thought that by smoothing the flow around the gate, some effect upon the hydraulic drawdown forces could be noticed. This test was similar to that made to find the force required to close the gate, excepting the skin plate was added to its upstream face. The results are also shown on figure 12, plotted as crossed points in comparison with the circled points of the previous test. The conditions of testing were identical to the former test, and the agreement of the crossed points with the circled points indicates that the skin plate was of no value in reducing the hydraulic drawdown forces.

GATES WITH SEATS ON UPSTREAM FACE - SERIES B

The final design of the service and emergency gates developed in series A was at first considered satisfactory, for the advantage of having both gates in the same well appeared to offset the disadvantage of the large drawdown forces in the downstream service gate. These forces were estimated to be 2,000,000 pounds under a maximum head of 190 feet. Inasmuch as it would be difficult to obtain hoist machinery having the required capacity, it was necessary to reduce the hydraulic drawdown forces on the gate. Three methods were proposed: (1) reduce the size of the gates; (2) change the shape of the bottom of the service gate; or (3) replace the service gate with one having seals on its upstream face. Each change had its disadvantages. Reducing the size of the gates involved changing the cross section of the tunnel. Changing the

shape of the bottom would probably result in a structurally undesirable shape similar to the original 45-degree bottom. Replacing the service gate with one having seals on its upstream face required two separate gate wells. The service gate was replaced with one having seals on its upstream face and placed in a separate well. The elimination of the hydraulic drawdown forces which the tests verified was a distinct advantage. This new arrangement was considered better than that of series A even though two separate gate wells were required. The proposal to reduce the size of the gates was also acceptable when it was demonstrated that the cross section of the tunnel could be changed advantageously without reducing the area.

REVISIONS TO MODEL

The single gate-well structure of series A, containing both the service and the emergency gates, was replaced by two structures, each containing one gate only. These wells (figure 13) will be located at stations 4775+20 and 4776+17. Two identical model gates having upstream seals were constructed to be placed in these wells. To obtain a flow beneath each gate which would spring free from its bottom, the skin plate on the upstream face of the gates protruded below the last structural beam a distance equivalent to one-half the beam spacing. The lower beam could, therefore, be considered as the bottom of the gate. This was a simpler design than the emergency gate of series A, which employed a sloping bottom. In that gate, the sloping bottom appeared to create the turbulent flow which was observed in the tests; and it was anticipated that the turbulence of flow passing under the new gates would be reduced by the protruding skin plate.

PERFORMANCE OF GATES

In testing the new arrangement, study was made of the pressures on the gates, the drawdown and frictional forces, provisions for aeration, the flow under the gates and through the well, and the simultaneous operation of both gates to determine which functioned better as a service gate.

As anticipated, the pressures on the top and bottom of the gates were atmospheric under normal operating conditions. However, when the gate was open 80 percent or more and the tunnel filled with water, air could not reach the bottom of the gate, and the pressures became slightly negative. As the gate opened further, the larger discharge increased the pressures in the tunnel and under the gate in the manner described in the tests of series A.

The atmospheric pressures on the top and the bottom of the gate indicated that no hydraulic drawdown existed. The operation of the gates confirmed this fact since only enough force was required to overcome the kinetic friction.

Although a downward force was still required to close the gate, the placing of the seals on the upstream face was an advantage, for the gate was out of the water and the effective weight available to overcome the friction was not reduced by buoyancy. It was thought that the gate would close by its own weight if the sliding friction between the guide tracks and the guides were eliminated. These guides were replaced by ball-bearing races, which reduced the frictional resistance but not sufficiently to permit the gate to close by its own weight. However, the prototype structure should close easily, for its frictional resistance to movement will be less than in the model. If the kinetic friction in the prototype is too large a closure can be made by operating both gates at the same time. No matter how great the resistance to movement, the downstream gate will close a little farther than the other, and when it does the pressure forces on the upstream gate are reduced, permitting it to close a little farther than the first. The model gates were successfully operated in this manner.

Adequate aeration was necessary to prevent subatmospheric pressures and to vent the tunnel downstream from each gate. By using a gate that sealed on its upstream face, it was possible to aerate the tunnel below by the gate well. However, the clearance between the downstream face of

the gate and the wall of the well had to be sufficient to aerate the tunnel and at the same time drain water that flows around the gate when the seals were not seated. In the design of the upstream emergency gate of series A the clearance was over five feet. In the new design this clearance was two feet, which was adequate under all conditions tested.

The flow emerging under the gates was smooth, indicating that a better gate resulted by extending the skin plate and eliminating the sloping bottom of series A. While the flow under the gate was satisfactory, eddies at the sides of the gate well similar to figure 15 indicated possible negative pressures. In series A this condition was not given any attention because the downstream service gate formed a control at the downstream side which kept the pressures in the gate well positive. However, in series B the control was on the upstream face of the gates, so the eddies could indicate negative pressures in the gate well. Since these eddies could not be eliminated, their intensity was reduced by curving the downstream face of the gate-well structure. Pressure tests to determine their effect were delayed until later (see paragraph 13).

Observations were made on both gates to determine which was more suited to be the emergency gate. The procedure was to set one gate at a particular opening to represent a fouled service gate; the other, representing the emergency gate, was then closed slowly. Using the downstream gate as the fouled service gate, it was the control when the upstream gate was open and the upstream gate well was partially filled with water. As the upstream gate closed, a point was reached when the control shifted to it and the column of water in the upstream well drained and normal aeration occurred. In this test no adverse drawdown forces existed on the upstream gate, even when the gate well was filled with water and the control was at the downstream gate. However, should the upstream gate be closed too rapidly, the column of water in its well would not have sufficient time to drain, resulting in a downward force.

When the upstream gate represented the service gate fouled at a given opening, it was necessary to lower the downstream gate into the rapid flow emerging from underneath the upstream gate. This flow impacted on the face of the downstream gate, and while no adverse conditions were apparent in the model, in the prototype the jet striking the gate might cause vibration. The downstream gate was closed rapidly several times. This rapid closure caused a sudden increase in pressure upstream, evidenced by a rush of water through the upstream gate well which was powerful enough to wash out the upstream gate. In the prototype the gates must be lowered slowly so that this condition will not occur. The tests indicated that either gate could be operated as the service gate; and its selection should depend mainly upon the fact that the downstream gate will be accessible for repairs when the upstream gate is closed.

REDUCTION OF GATE SIZE

By eliminating the hydraulic drawdown forces, the hoist capacity required to operate the gates was reduced approximately 50 percent. Nevertheless, the weight of the gate and the kinetic friction may be as great as 500,000 pounds; and to reduce these forces, the use of a smaller gate was suggested. This required a change in the cross section of the tunnel at the gates, a change limited by the requirement that the cross-sectional area throughout the tunnel be the same to prevent any constriction which might reduce the quantity of flow through the tunnel. A transition 25 feet long was used to change the 23- by 25-foot horseshoe shape of the tunnel to a 19.5 by 25-foot rectangular section which has the same area but permits the use of a narrower gate (figures 14 and 15A).

The diversion tunnel model was revised to include this change. In the new gates ball-bearing races were used in place of the brass wheels with steel shafts used in the former tests. This eliminated the frictional resistance, permitting the gate to close easily. As it was anticipated that this would be the final design, piezometers were installed in the gate, in the gate slot, and in the transition sections of the

tunnel. Since the pressures were fluctuating, a sensitive electric pressure gage was used instead of water manometers.

The pressures on the gate bottom were atmospheric. In the gate slot where eddies occurred (figure 15B), the pressures fluctuated considerably, and, while they were usually positive, negative pressures as great as 10 feet (prototype) were recorded. Negative pressures were also observed on the downstream side of the seals. However, no pressures less than -10 feet were recorded, for the air entering the gate-well structure vented this region. The transition sections, both upstream and downstream from the gates, were free from negative pressures.

A clearance of 2 feet, prototype, was provided between the downstream face of the gates and the wall of the well to permit aeration of the tunnel below. Both gates acting together behaved in the manner described in section 12, although the gates closed easily. The ball-bearing races had only a slight resistance compared with the brass wheels with steel shafts which were used in previous tests.

Only one adverse condition was observed. When the gates were wide open they moved upstream. This movement was caused by the flow underneath the gate, in a manner similar to the action of a jet pump, which removed the water between the upstream face of the gate and the gate-well structure. Consequently, the pressures on the downstream face of the gate were greater than those on its upstream face. The resulting force, which moved the model gate upstream, was estimated to be 300,000 pounds, sufficient to damage the seals in the prototype. If the gates are never opened more than 24 feet, 10 inches of the full gate opening of 25 feet, this upstream movement will not occur. This small closure does not noticeably reduce the maximum discharge capacity.

A final check on the hydraulic drawdown forces was made at openings from 90 to 100 percent. When the gate was 90 percent open, water filled the tunnel and rose into the gate well, preventing aeration on the bottom of the gate. It was feared that under this condition negative pressures would occur, causing a hydraulic drawdown force. Slight negative pressures

did exist; but, as the gate well filled with water, the uplift due to buoyancy more than overcame any resulting drawdown force.

DISCHARGE STUDIES

When the diversion tunnel is in use, regulation of the flow of the Sacramento River will be made at the service gate. One of the purposes of the model studies was to provide discharge diagrams showing the relation between discharge and reservoir elevation for various gate openings (figure 17). Discharge studies were made on the original design to obtain preliminary rating curves. When the final design was evolved, corrected and revised rating curves were obtained. Although discharge calibrations were made only on the original and final design, checks were made to be certain that the several revisions of the gates did not materially reduce the total capacity.

The final rating curves were corrected and revised to eliminate the dissimilitude between the model and the prototype as noted in section 4. The method of correcting the model data was to establish similitude at the service gate by correcting the energy head for a given discharge. For any given gate opening and discharge, the corresponding reservoir head was equal to the sum of the energy head at the gate and the hydraulic losses upstream. It was unnecessary to consider the types of flow in the model and prototype since their Reynolds' numbers, R_d, were well above the critical region.

It was necessary to correct the energy head at the gate only when it was wide open, since the gate acted as a control at partial openings. This correction was made by changing the slope of the tunnel.

The hydraulic losses in the prototype upstream from the gate, necessary to determine the reservoir head, were estimated to be $0.59 \frac{V^2}{2g}$ which included an entrance loss, H_e, of $0.40 \frac{V^2}{2g}$ and a frictional loss H_f of $0.19 \frac{V^2}{2g}$. The entrance loss, H_e, was an estimate,

based upon the coefficients by King; and the frictional loss was calculated from the formula $H_f = f \frac{l}{d} \frac{V^2}{2g}$ where d was assumed to be four times the hydraulic radius of the horseshoe-shaped tunnel section. The friction factor f selected from curves based upon the values of Reynolds' number R_d was 0.008 for the prototype and 0.014 for the model. Tests showed the friction factor of the model to be 0.014.

The rating curves, figure 17, are more accurate at small gate openings, for the hydraulic losses upstream from the gate will be small compared with the total head and errors in the computation of these losses are negligible.

- - -

F. C. Lowe.

FIGURE 1

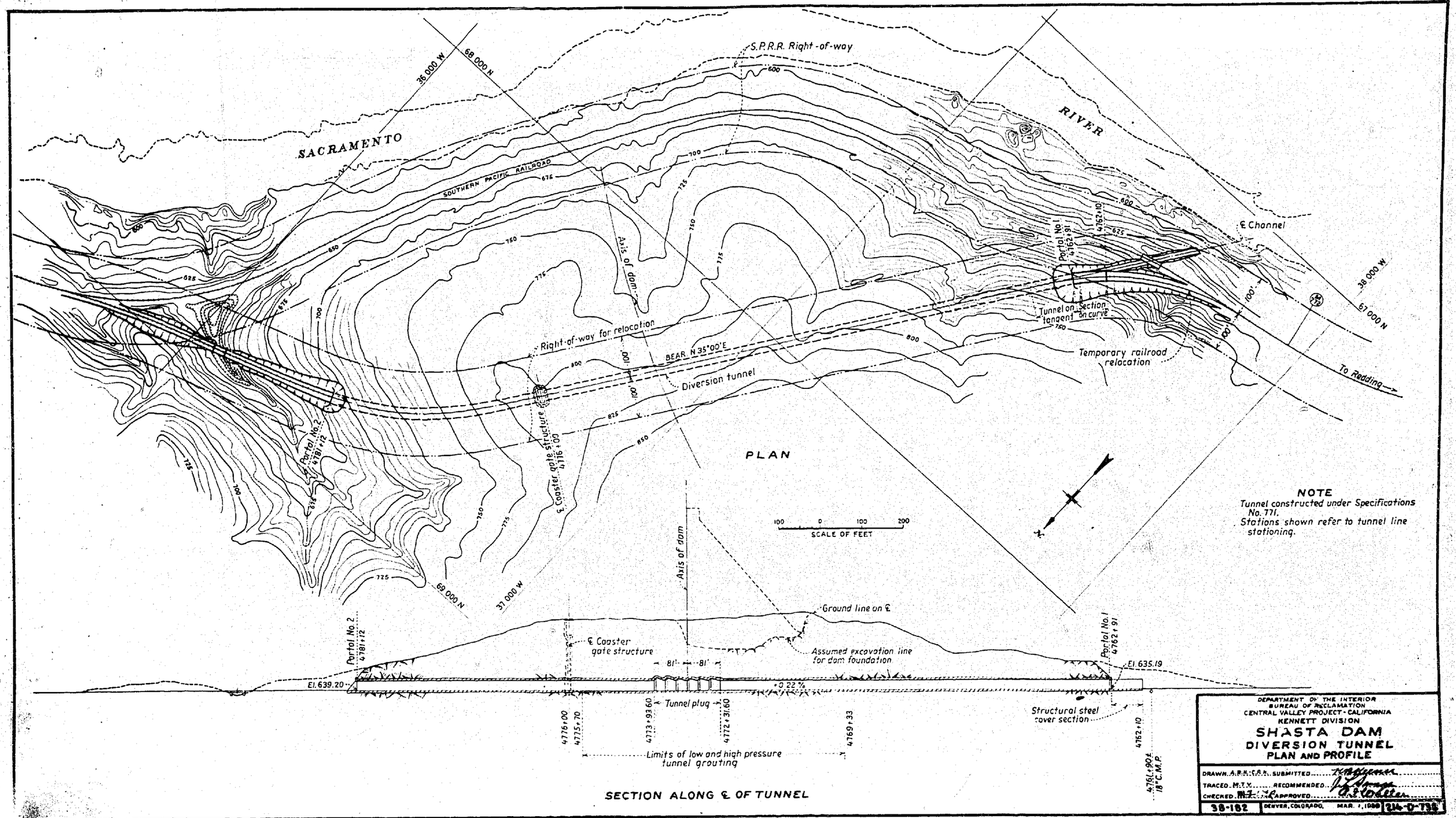
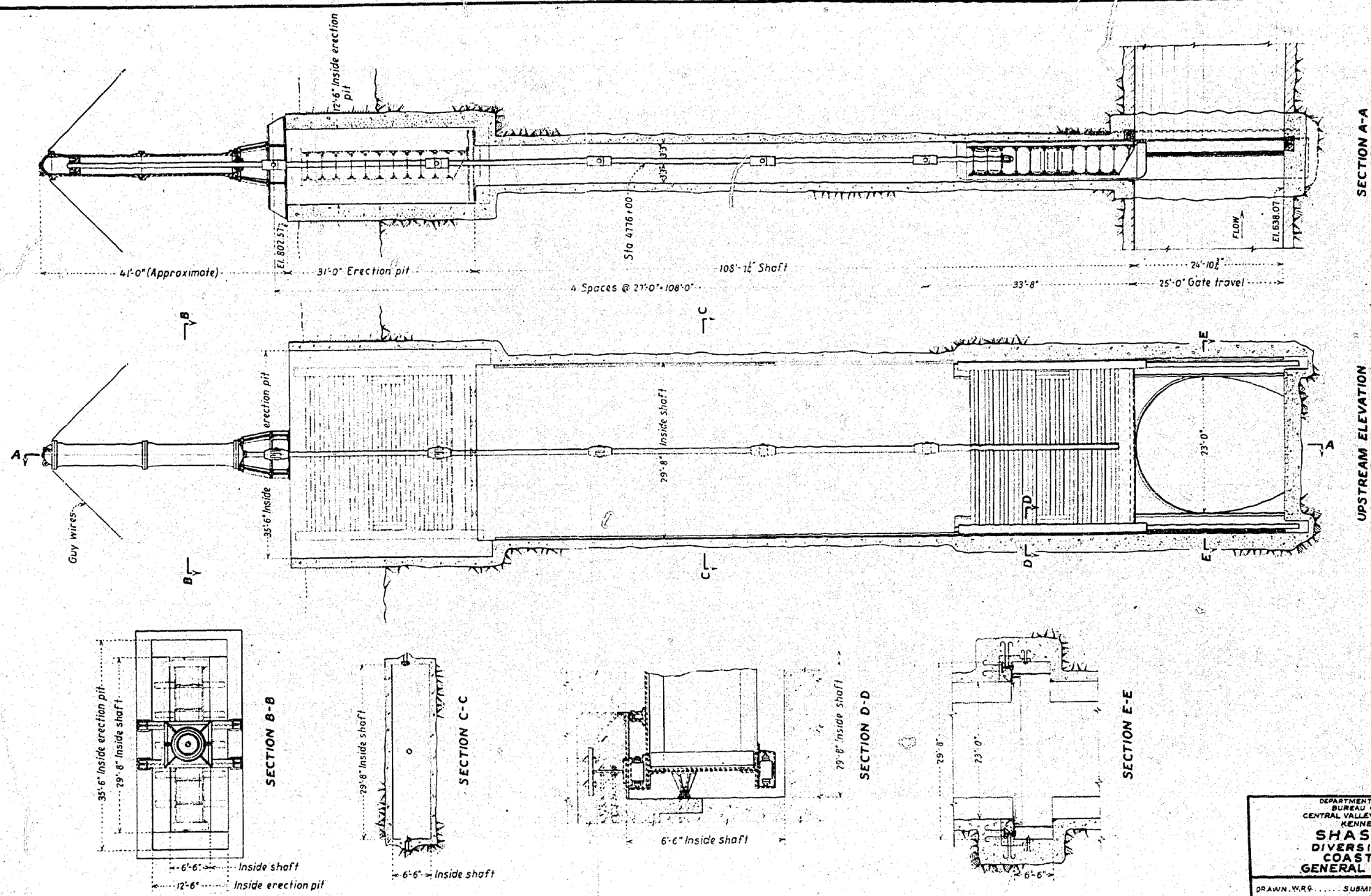

SACRAMENTO
RIVER
S.P.R.R. Right-of-way
SOUTHERN PACIFIC RAILROAD
36 000 W
68 000 N
38 000 W
67 000 N
69 000 N
37 000 W
℄ Channel
Portal No. 1
4762+91
4762+10
Tunnel on tangent
Section on curve
Temporary railroad relocation
To Redding
Right-of-way for relocation
BEAR N 35°00'E
Diversion tunnel
Axis of dam
℄ Coaster gate structure
4776+00
Portal No. 2
4781+12
PLAN
SCALE OF FEET
100 0 100 200
NOTE
Tunnel constructed under Specifications No. 771.
Stations shown refer to tunnel line stationing.
Ground line on ℄
℄ Coaster gate structure
Assumed excavation line for dam foundation
El. 639.20
El. 635.19
+0.22%
Tunnel plug
Structural steel cover section
4776+00
4775+70
4773+93.60
4772+31.60
4769+33
4762+10
4761+90±
18" C.M.P.
Limits of low and high pressure tunnel grouting
SECTION ALONG ℄ OF TUNNEL
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT - CALIFORNIA
KENNETT DIVISION
SHASTA DAM
DIVERSION TUNNEL
PLAN AND PROFILE
DRAWN A.B.N. C.A.R. SUBMITTED
TRACED M.T.V. RECOMMENDED
CHECKED M.T. APPROVED
38-182
DENVER, COLORADO, MAR. 1, 1939
214-D-735

FIGURE 2



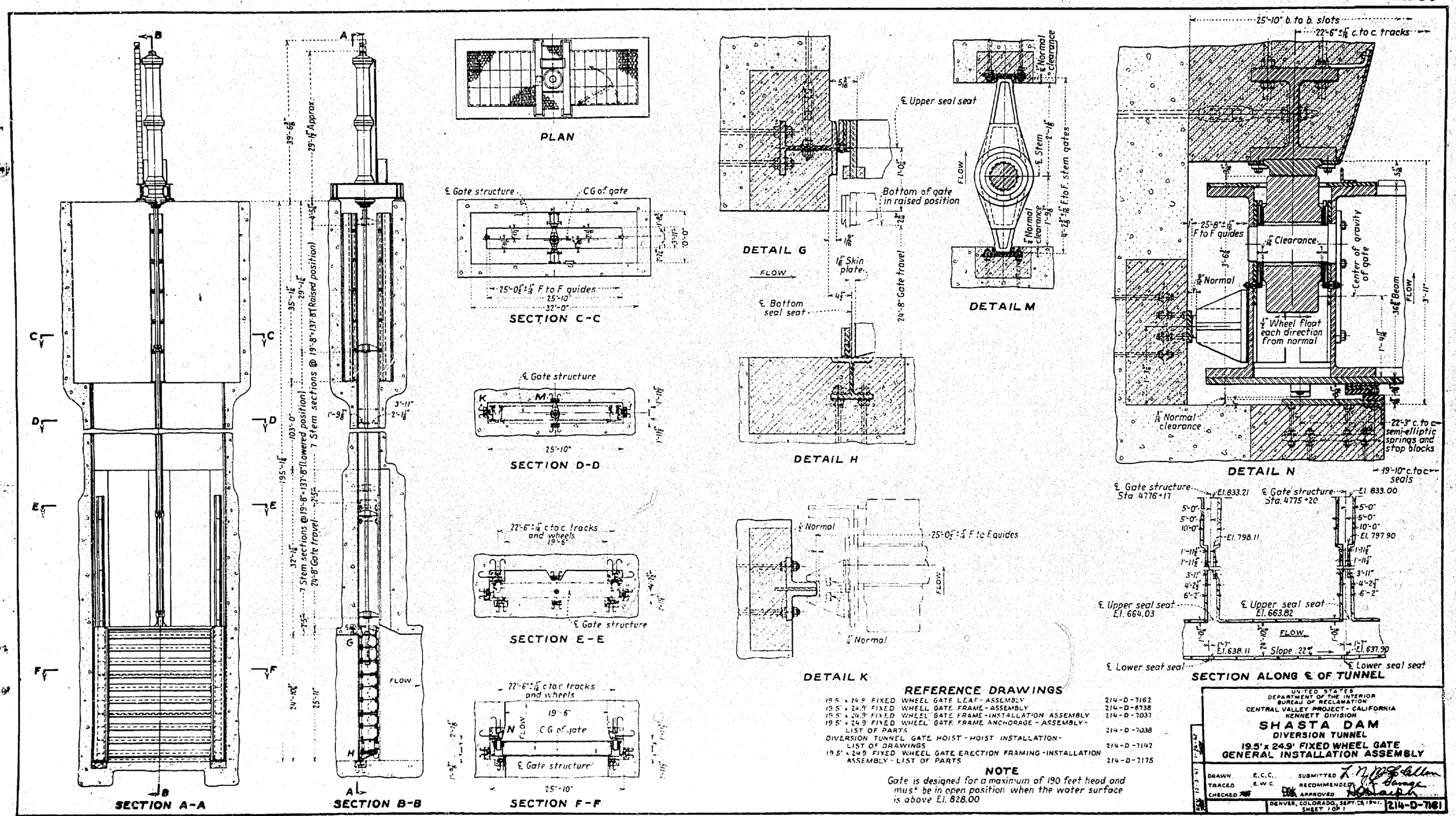
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT - CALIFORNIA
KENNETT DIVISION

SHASTA DAM
DIVERSION TUNNEL
COASTER GATE
GENERAL INSTALLATION

DRAWN W.R.G. SUBMITTED L. N. McClellan
TRACED N.P.C. - F.H.C. RECOMMENDED J. Stone
CHECKED M.L.P.B. APPROVED A. J. Wirth

38-184 | DENVER, COLORADO | MAR. 1, 1938 | 214-D-740

FIGURE 3



REFERENCE DRAWINGS

19.5' x 24.9' FIXED WHEEL GATE LEAF - ASSEMBLY	214-D-7162
19.5' x 24.9' FIXED WHEEL GATE FRAME - ASSEMBLY	214-D-6738
19.5' x 24.9' FIXED WHEEL GATE FRAME - INSTALLATION ASSEMBLY	214-D-7031
19.5' x 24.9' FIXED WHEEL GATE FRAME ANCHORAGE - ASSEMBLY - LIST OF PARTS	214-D-7038
DIVERSION TUNNEL GATE HOIST - HOIST INSTALLATION - LIST OF DRAWINGS	214-D-7142
19.5' x 24.9' FIXED WHEEL GATE ERECTION FRAMING - INSTALLATION ASSEMBLY - LIST OF PARTS	214-D-7175

NOTE

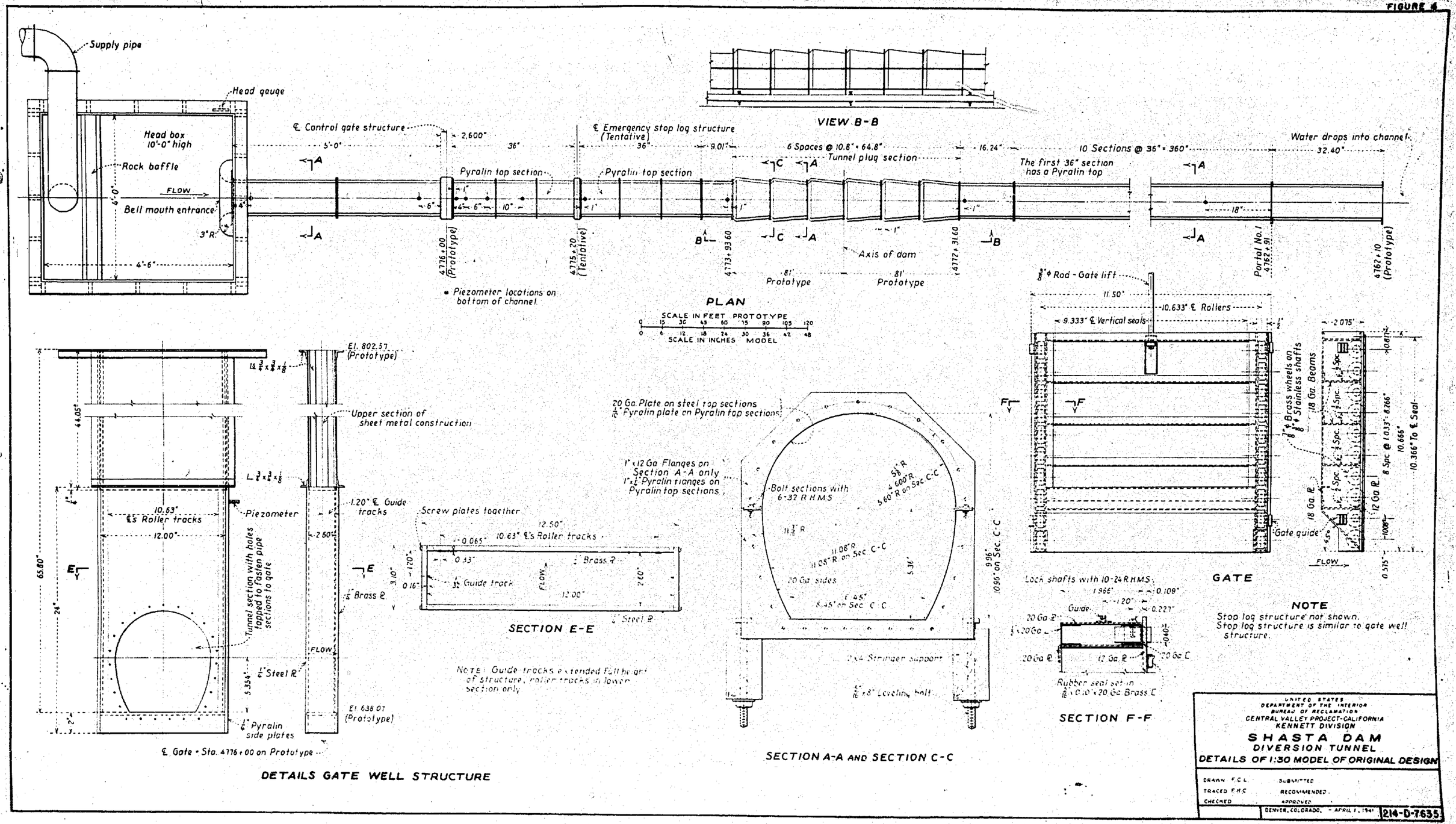
Gate is designed for a maximum of 190 feet head and must be in open position when the water surface is above El. 828.00

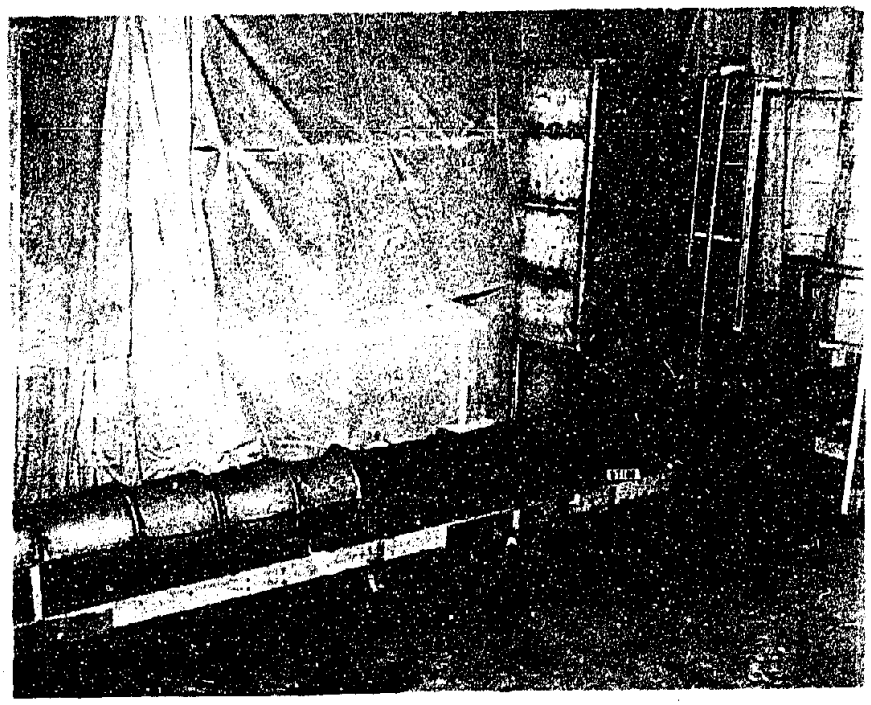
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT - CALIFORNIA
KENNETT DIVISION

SHASTA DAM
DIVERSION TUNNEL
19.5' x 24.9' FIXED WHEEL GATE
GENERAL INSTALLATION ASSEMBLY

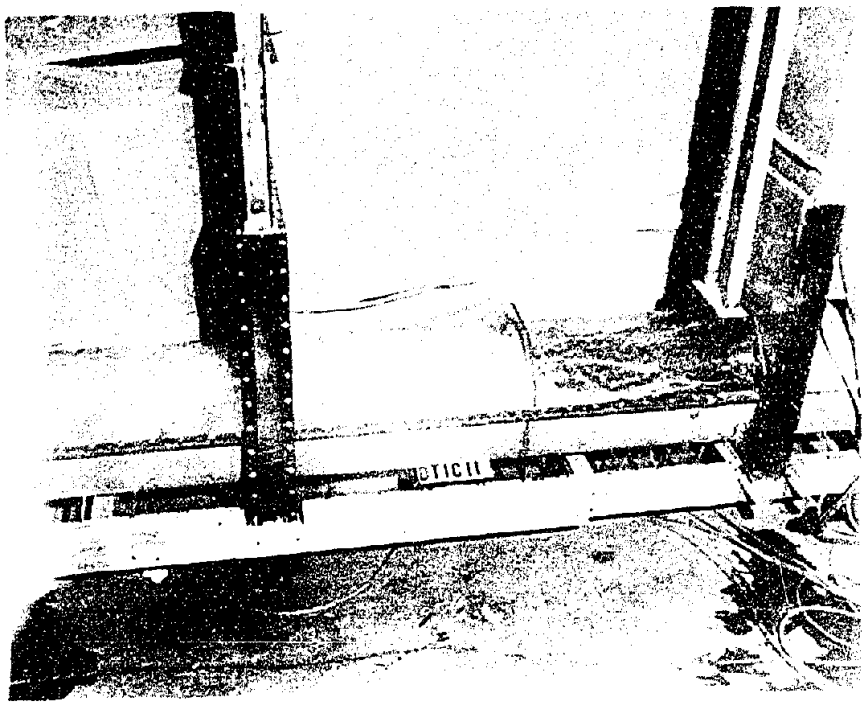
DRAWN E.C.C. SUBMITTED
TRACED E.W.C. RECOMMENDED
CHECKED APPROVED
DENVER, COLORADO, SEPT. 28, 1961
SHEET 1 OF 1
214-D-7161

FIGURE 4


Supply pipe
Head gauge
Head box 10'-0" high
Rock baffle
FLOW
Bell mouth entrance
3"R
4'-6"
℄ Control gate structure
2.600"
5'-0"
36"
℄ Emergency stop log structure (Tentative)
36"
9.01"
6 Spaces @ 10.8" = 64.8"
Tunnel plug section
16.24"
10 Sections @ 36" = 360"
Water drops into channel
32.40"
Pyralin top section
Pyralin top section
The first 36" section has a Pyralin top
4776+00 (Prototype)
4775+20 (Tentative)
4773+93.60
4772+31.60
Axis of dam
81' Prototype
81' Prototype
Portal No. 1 4762+91
4762+10 (Prototype)
• Piezometer locations on bottom of channel
PLAN
SCALE IN FEET PROTOTYPE
SCALE IN INCHES MODEL
VIEW B-B
El. 802.57 (Prototype)
Upper section of sheet metal construction
1.20" ℄ Guide tracks
Piezometer
10.63" ℄s Roller tracks
12.00"
Tunnel section with holes tapped to fasten pipe sections to gate
Brass R
Steel R
Pyralin side plates
El. 638.07 (Prototype)
℄ Gate = Sta. 4776+00 on Prototype
DETAILS GATE WELL STRUCTURE
Screw plates together
12.50"
10.63" ℄s Roller tracks
Guide track
Brass R
Steel R
SECTION E-E
NOTE: Guide tracks extended full height of structure, roller tracks in lower section only.
20 Ga. Plate on steel top sections
1/8" Pyralin plate on Pyralin top sections
1" x 12 Ga Flanges on Section A-A only
1" x 1/2" Pyralin flanges on Pyralin top sections
Bolt sections with 6-32 R.H.M.S.
20 Ga. sides
2x4 Stringer support
1/2" x 8" Leveling bolt
SECTION A-A AND SECTION C-C
3/8" ϕ Rod - Gate lift
11.50"
10.633" ℄ Rollers
9.333" ℄ Vertical seals
Brass wheels on Stainless shafts
18 Ga. Beams
Gate guide
FLOW
GATE
Lock shafts with 10-24 R.H.M.S.
Guide
20 Ga R
20 Ga
12 Ga R
20 Ga C
Rubber seal set in 1/8" x 0.10" x 20 Ga Brass C
SECTION F-F
NOTE
Stop log structure not shown.
Stop log structure is similar to gate well structure.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT-CALIFORNIA
KENNETT DIVISION
SHASTA DAM
DIVERSION TUNNEL
DETAILS OF 1:30 MODEL OF ORIGINAL DESIGN
DRAWN F.C.L.
TRACED F.H.C.
CHECKED
SUBMITTED
RECOMMENDED
APPROVED
DENVER, COLORADO, - APRIL 1, 1941
214-D-7635



A. TUNNEL PLUG SECTION, STOP LOG STRUCTURE, AIR PIPES AND GATE STRUCTURE

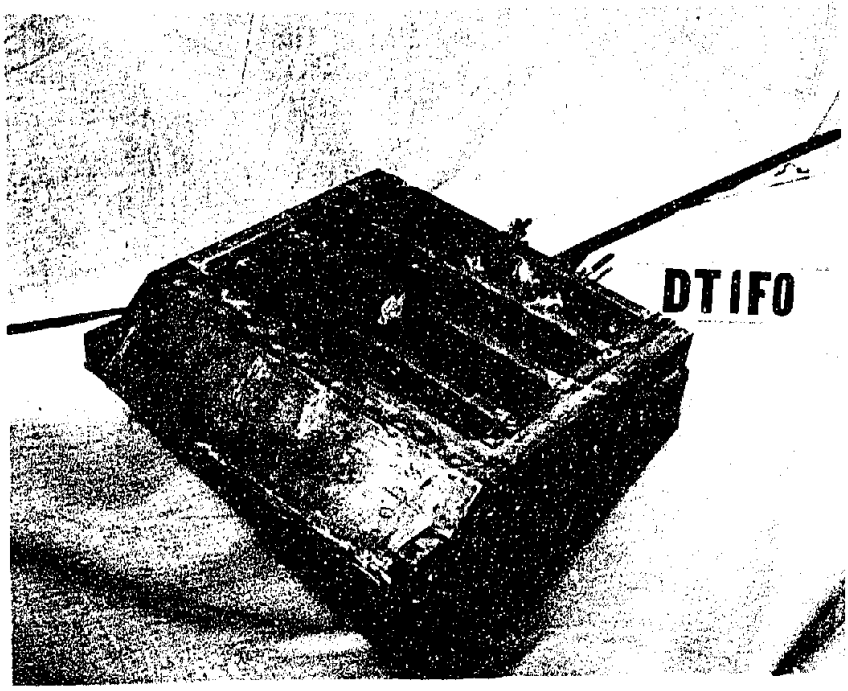


B. DISCHARGE WITH GATE 60 PERCENT OPEN WHEN NO AIR IS ADMITTED THROUGH AIR PIPES

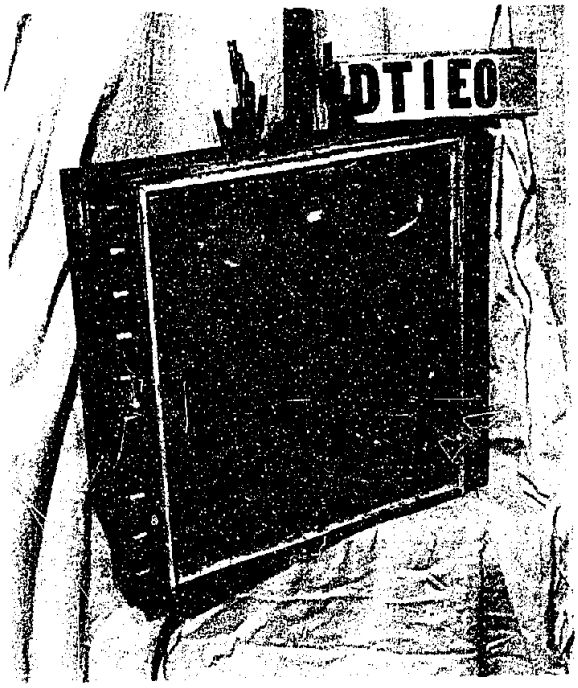
1:30 SHASTA DAM DIVERSION TUNNEL MODEL

ORIGINAL DESIGN

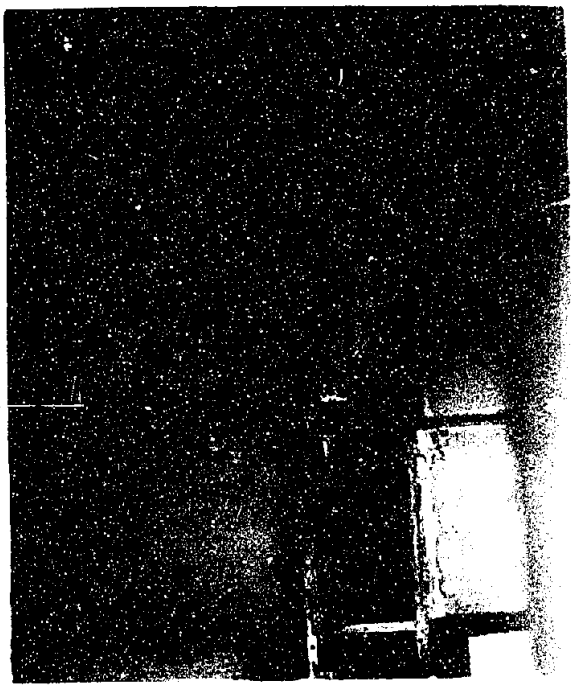
FIGURE 6



A. UPSTREAM SIDE OF GATE



B. DOWNSTREAM SIDE OF GATE

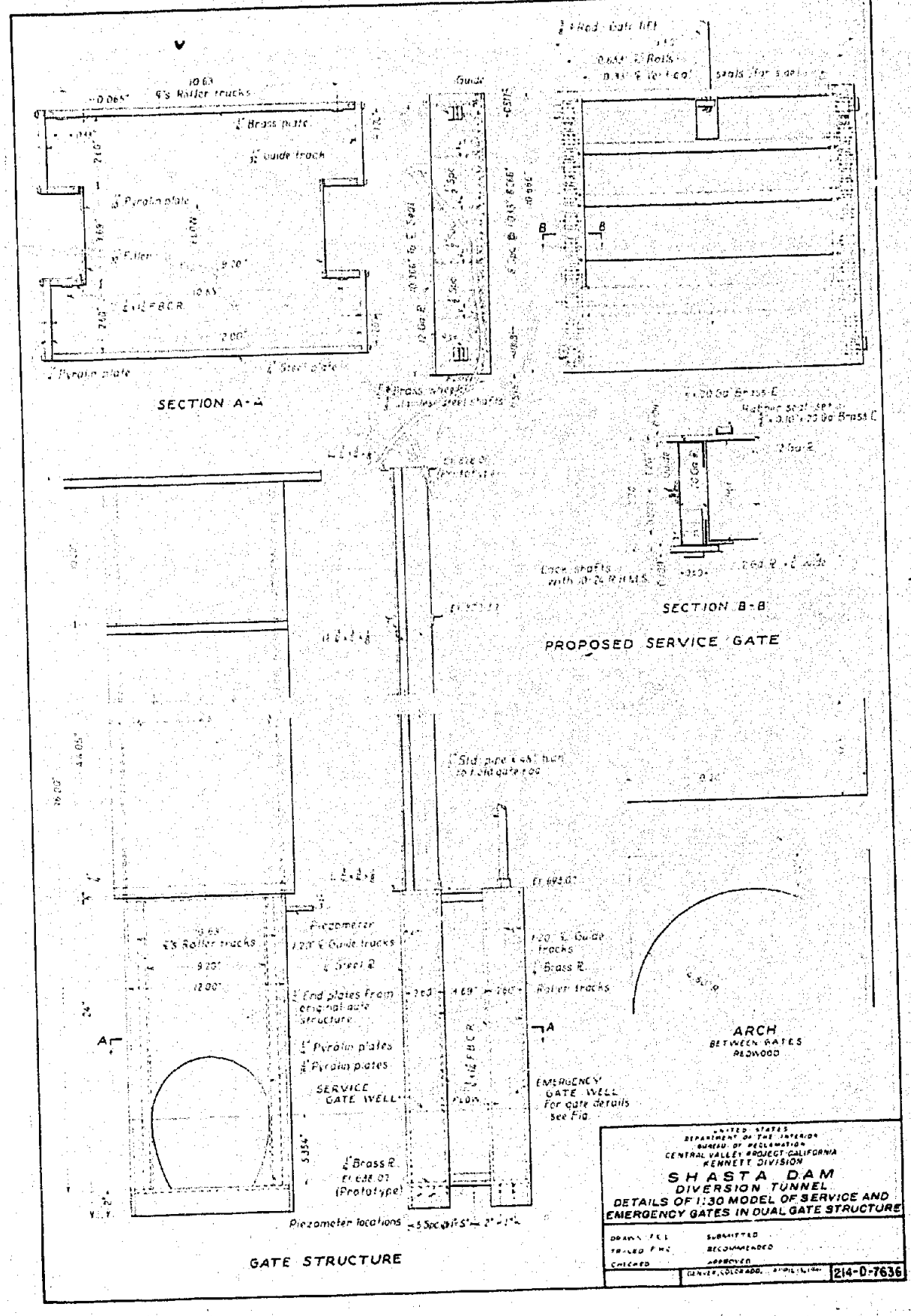


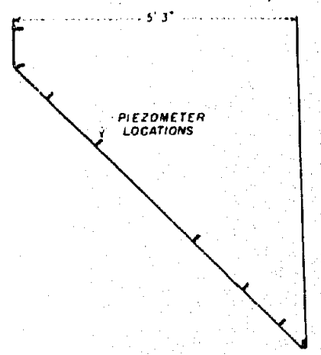
C. GATE IN POSITION

1: 30 SHASTA DAM DIVERSION TUNNEL MODEL

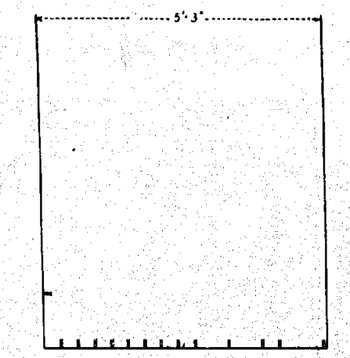
ORIGINAL DESIGN

FIGURE 7

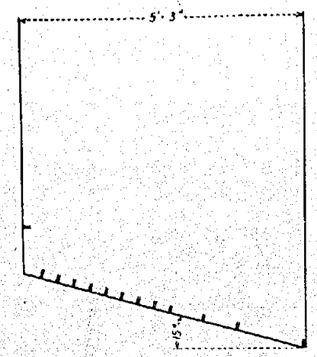

SECTION A-A
SECTION B-B
PROPOSED SERVICE GATE
GATE STRUCTURE
ARCH
BETWEEN GATES
REDWOOD
SERVICE
GATE WELL
EMERGENCY
GATE WELL
For gate details
see Fig.
Piezometer
Piezometer locations
(Prototype)
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT-CALIFORNIA
KENNETT DIVISION
SHASTA DAM
DIVERSION TUNNEL
DETAILS OF 1:30 MODEL OF SERVICE AND
EMERGENCY GATES IN DUAL GATE STRUCTURE
SUBMITTED
RECOMMENDED
APPROVED
DENVER, COLORADO
214-D-7636



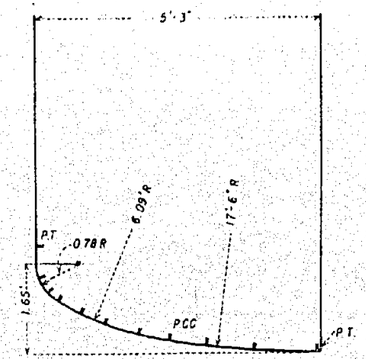
A- 45° BOTTOM GATE
FLOW



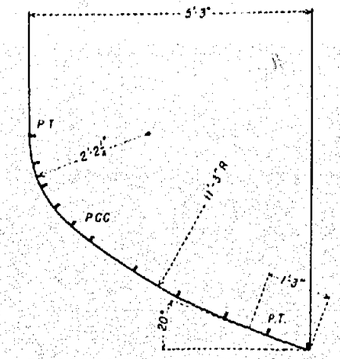
B- FLAT BOTTOM GATE
FLOW



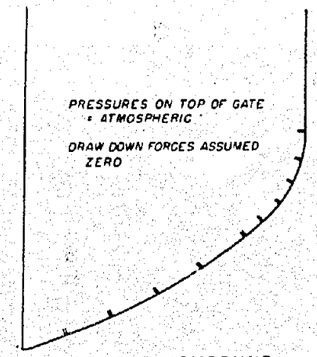
C- 15° BOTTOM GATE
FLOW



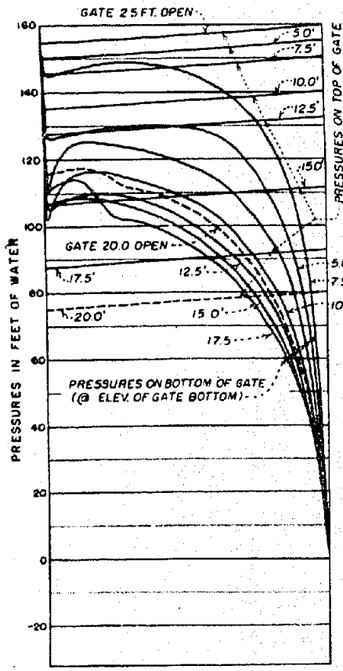
D- FLAT ANGLE COMPOUND CURVE GATE (SHAPE R1)
FLOW

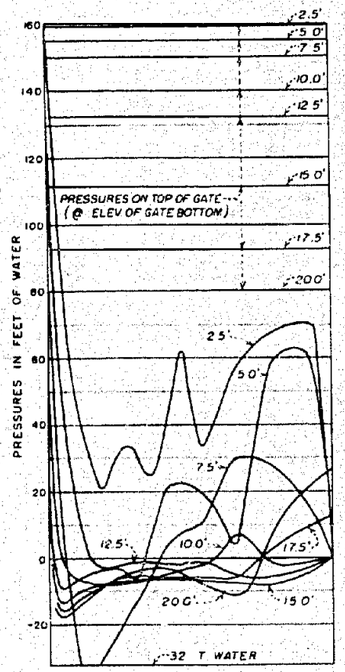


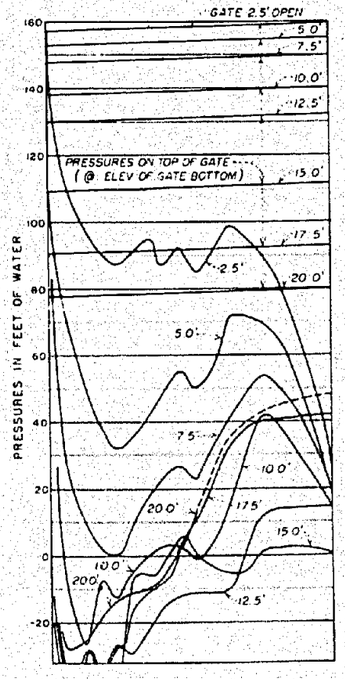
E- 20° ANGLE COMPOUND CURVE GATE (SHAPE R15)
FLOW

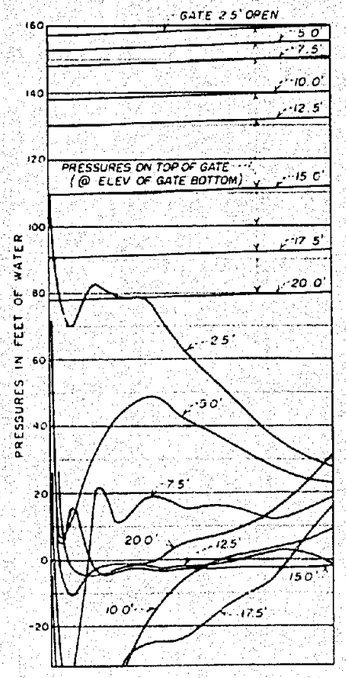


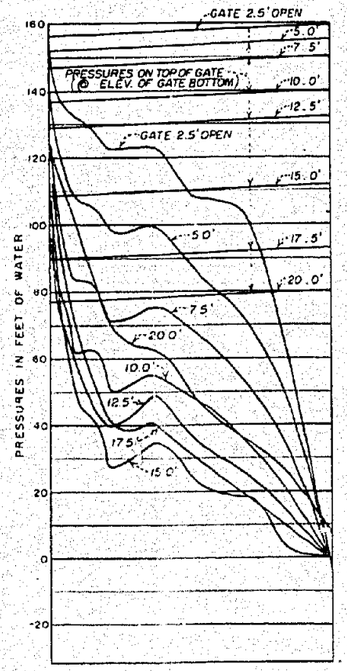
F- 20° ANGLE COMPOUND CURVE ANGLE REVERSED
FLOW

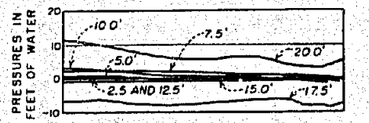


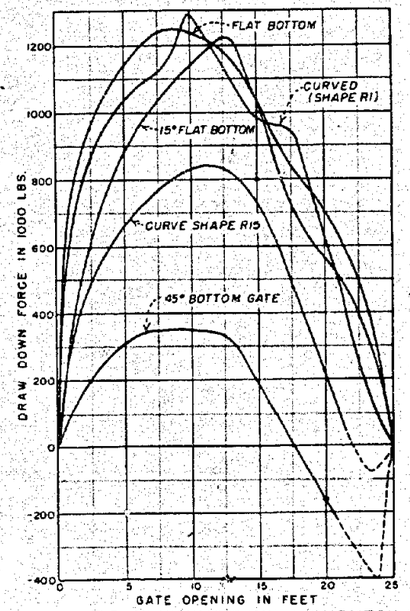












G- HYDRAULIC DRAW DOWN CURVES FOR GATES TESTED

NOTES
THE UPLIFT (NEG DRAW DOWN) FORCE HOLDS GATE OUT OF WATER
NOTE THE GATE DEPTH IS ASSUMED TO BE 26'-4"

NOTE
PRESSURES ON TOP OF GATE FLUCTUATED; THUS THESE PRESSURES AS SHOWN FOR EACH GATE ARE OBTAINED FROM A STUDY OF ALL TESTS

PRESSURES ON BOTTOM OF GATES TESTED FOR MAXIMUM DESIGN HEAD OF 165 FEET AND GATE OPENINGS OF 2.5, 5.0, 7.5, 10.0, 12.5, 15.0, 17.5, AND 20.0 FEET
(ALL DIMENSIONS CONVERTED TO PROTOTYPE)

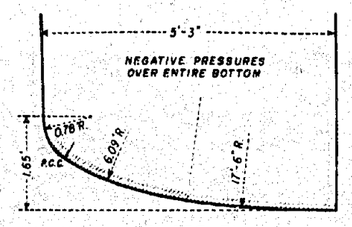
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT-CALIFORNIA
KENNETT DIVISION

SHASTA DAM
DIVERSION TUNNEL
PRESSURE STUDIES OF GATE BOTTOM

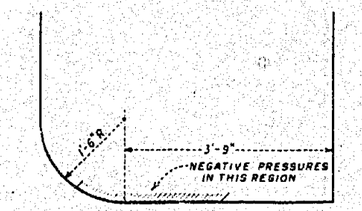
DRAWN	F.C.L.	SUBMITTED	
TRACED	E.F.J.-H.E.	RECOMMENDED	
CHECKED		APPROVED	

DENVER, COLORADO MAY 27, 1941 — 214-D-7637

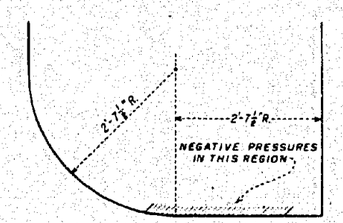
FIGURE 9



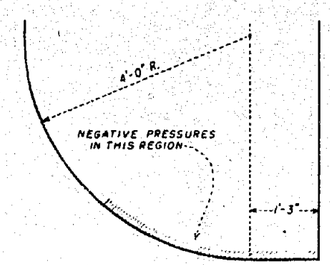
SHAPE R1



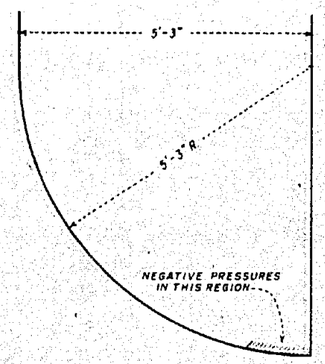
SHAPE R2



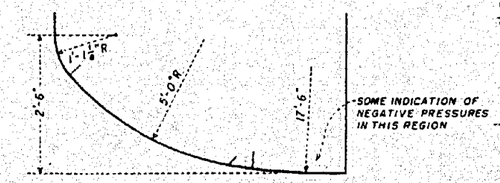
SHAPE R3



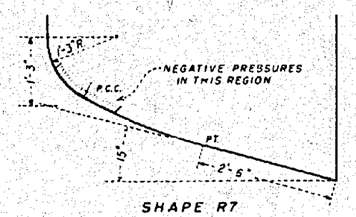
SHAPE R4



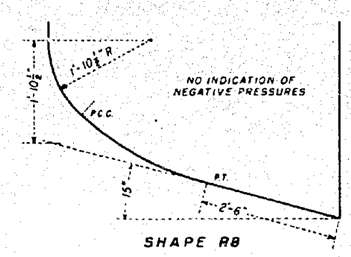
SHAPE R5



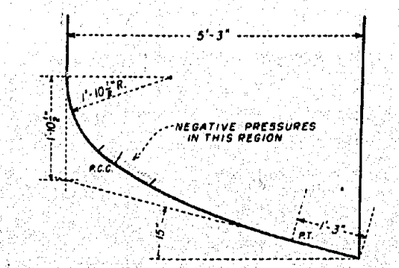
SHAPE R6



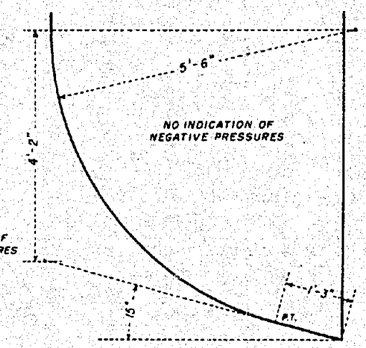
SHAPE R7



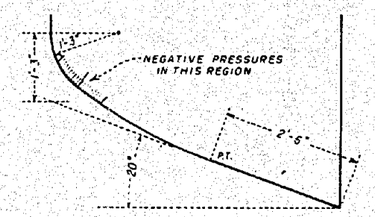
SHAPE R8



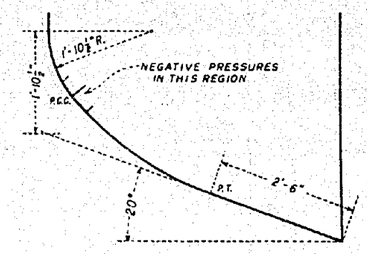
SHAPE R9



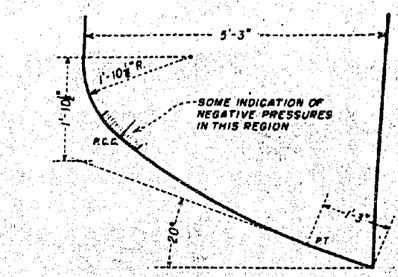
SHAPE R10



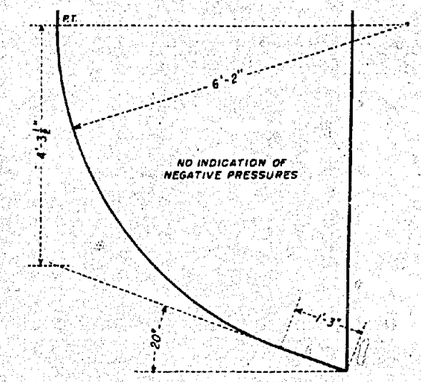
SHAPE R11



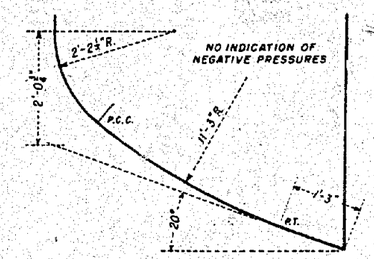
SHAPE R12



SHAPE R13



SHAPE R14



SHAPE R15
REVISED SHAPE R13

DIRECTION OF FLOW

NOTES

Negative pressure areas were indicated by segregation of small air bubbles.
All dimensions in prototype.

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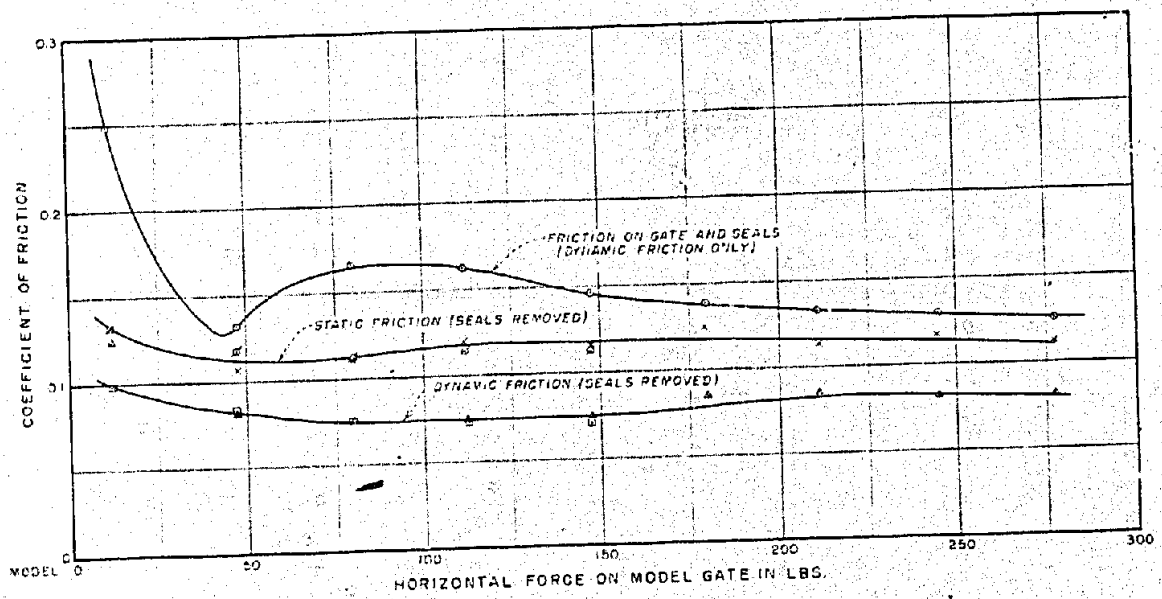
CENTRAL VALLEY PROJECT-CALIFORNIA
KENNETT DIVISION

SHASTA DAM
DIVERSION TUNNEL
VISUAL STUDIES OF GATE BOTTOM

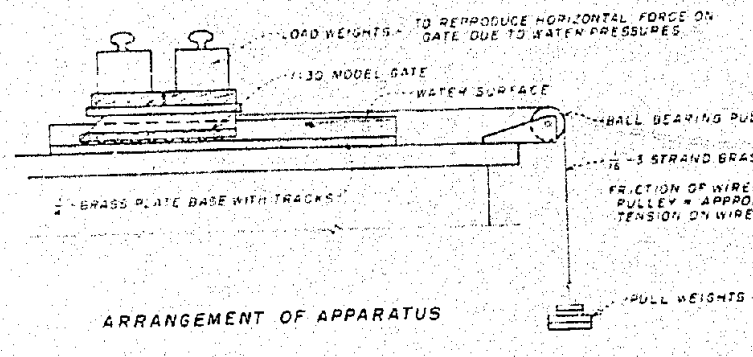
DRAWN F.C.L. SUBMITTED
TRACED R.T.R.-R.E.K. RECOMMENDED
CHECKED APPROVED

DENVER, COLORADO — JUNE 8, 1961 214-D-7838

FIGURE 10



Note: To obtain force in prototype multiply model force by 27,000



ARRANGEMENT OF APPARATUS

$$\text{FRICTION COEFFICIENT} = \frac{\text{PULL WEIGHTS}}{\text{LOAD WEIGHTS} + \text{WEIGHT OF GATE}}$$

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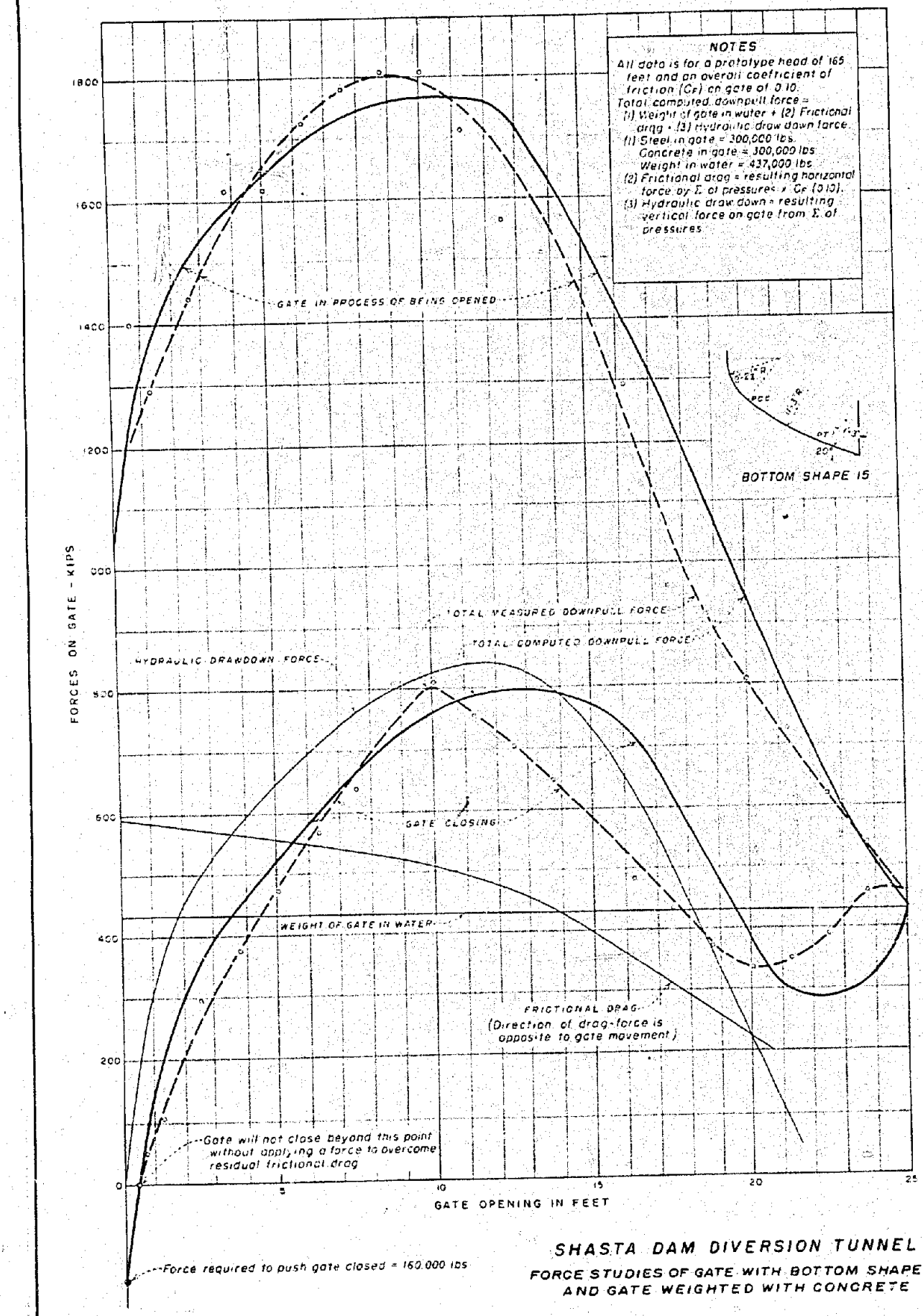
CENTRAL VALLEY PROJECT-CALIFORNIA
KENNETT DIVISION

SHASTA DAM
DIVERSION TUNNEL
MODEL GATE FRICTION COEFFICIENTS

DRAWN	SUBMITTED
TRACED	RECOMMENDED
CHECKED	APPROVED
DENVER, COLORADO — JUNE 12, 1941	214-D-7639

FIGURE 11

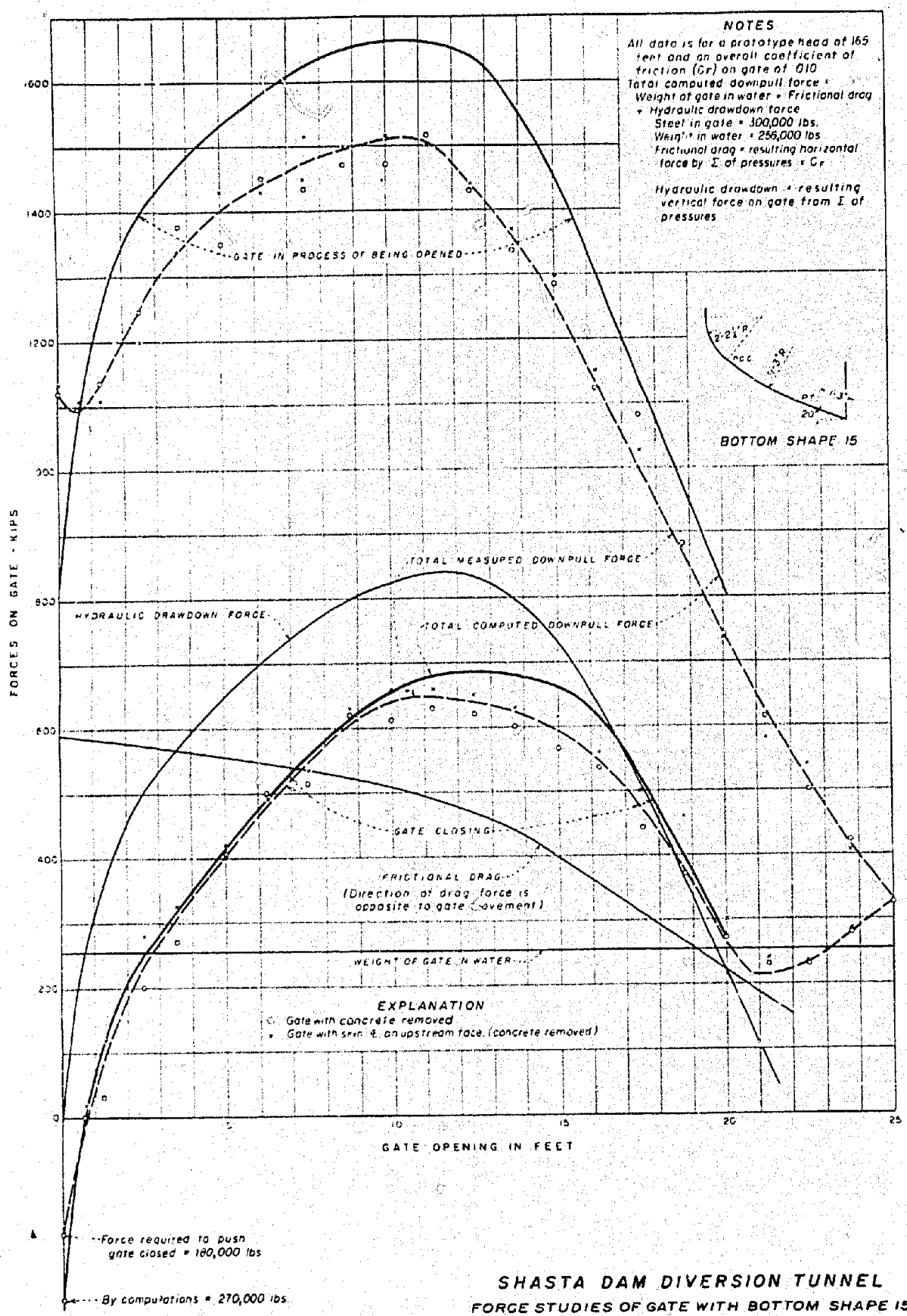


SHASTA DAM DIVERSION TUNNEL

FORCE STUDIES OF GATE WITH BOTTOM SHAPE 15 AND GATE WEIGHTED WITH CONCRETE

214-D-7640

FIGURE 12



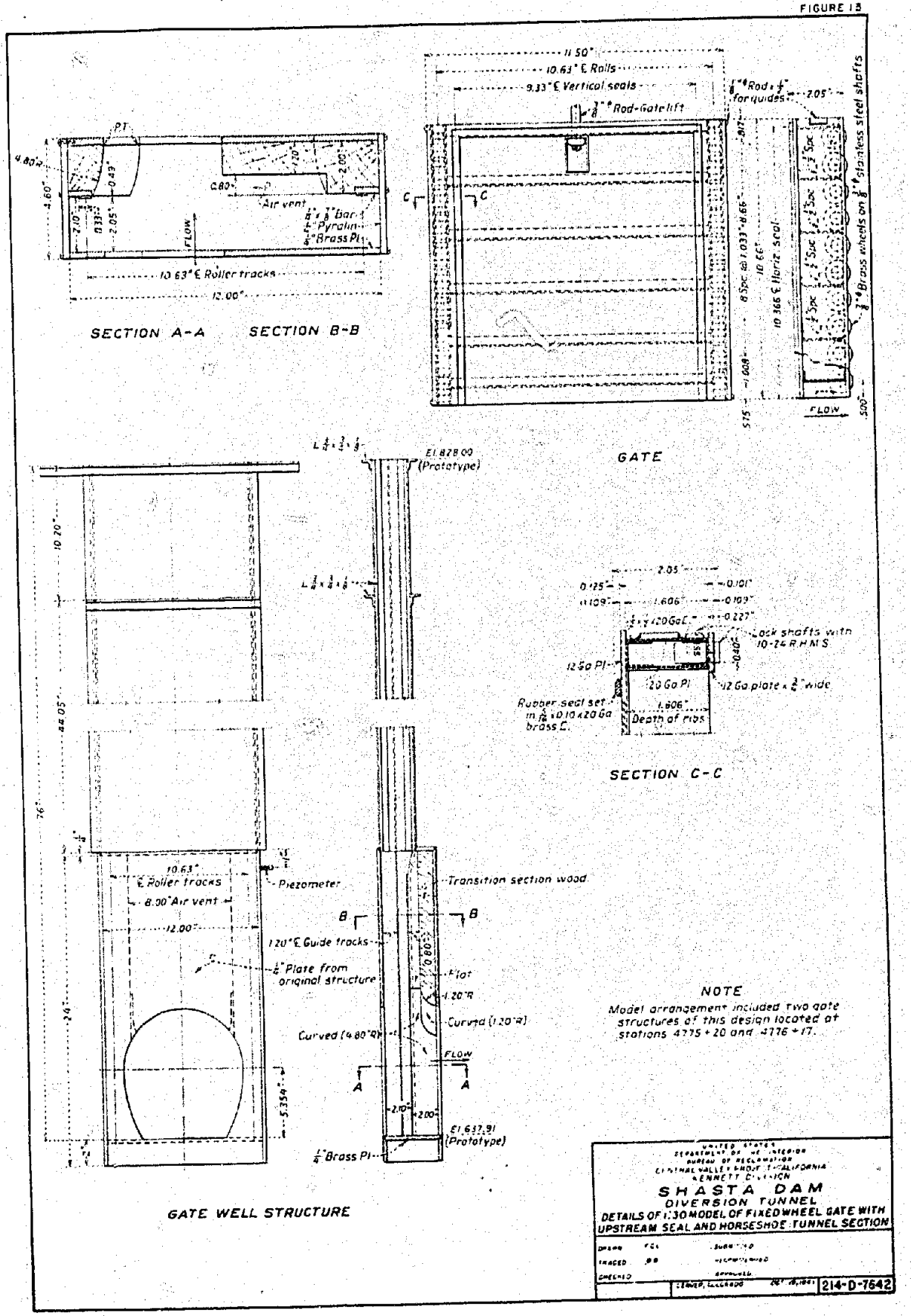
SHASTA DAM DIVERSION TUNNEL

FORCE STUDIES OF GATE WITH BOTTOM SHAPE 15 AND UPSTREAM SKIN PLATE

8-15-41

214-D-7631

FIGURE 13


SECTION A-A
SECTION B-B
GATE
SECTION C-C
GATE WELL STRUCTURE
10.63" ℄ Roller tracks
12.00"
Air vent
FLOW
11.50"
10.63" ℄ Rolls
9.33" ℄ Vertical seals
Rod-Gate lift
Rod for guides
Brass wheels on stainless steel shafts
10.66" ℄ Horiz. seal
El. 878.00 (Prototype)
Lock shafts with 10-24 R.H.M.S.
Rubber seal set in
Depth of ribs
Piezometer
Transition section wood
1.20" ℄ Guide tracks
Plate from original structure
Flat
Curved (1.20" R)
Curved (4.80" R)
El. 637.91 (Prototype)
Brass Pl.
NOTE
Model arrangement included two gate structures of this design located at stations 4775 + 20 and 4776 + 17.
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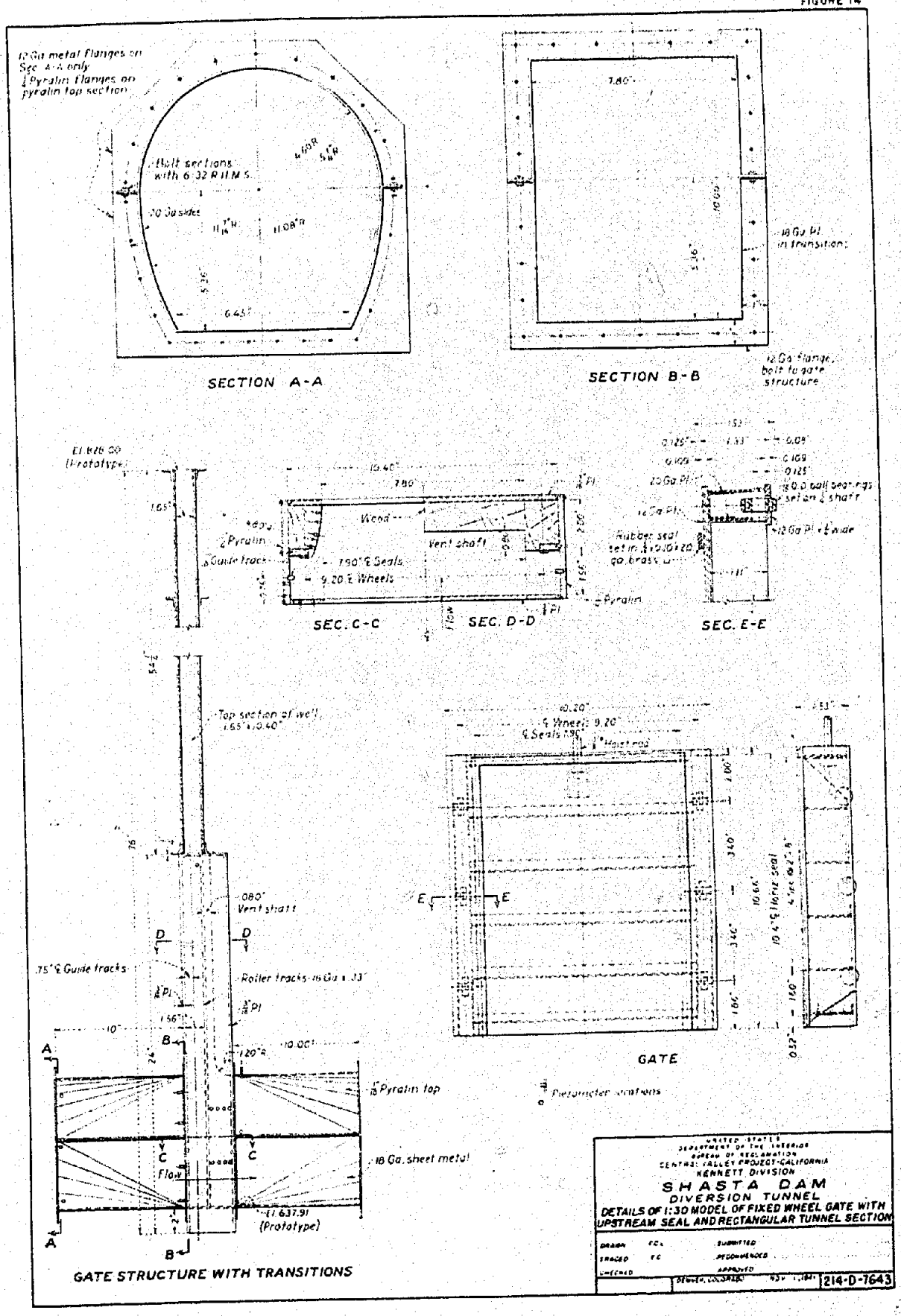
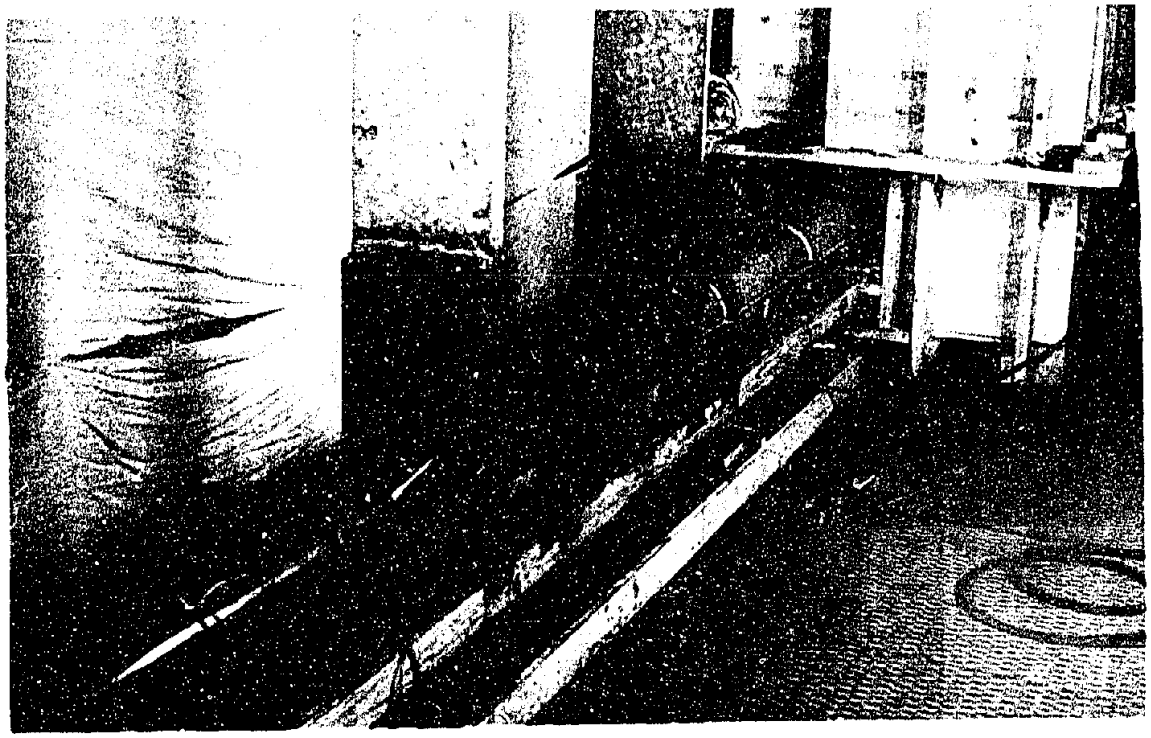
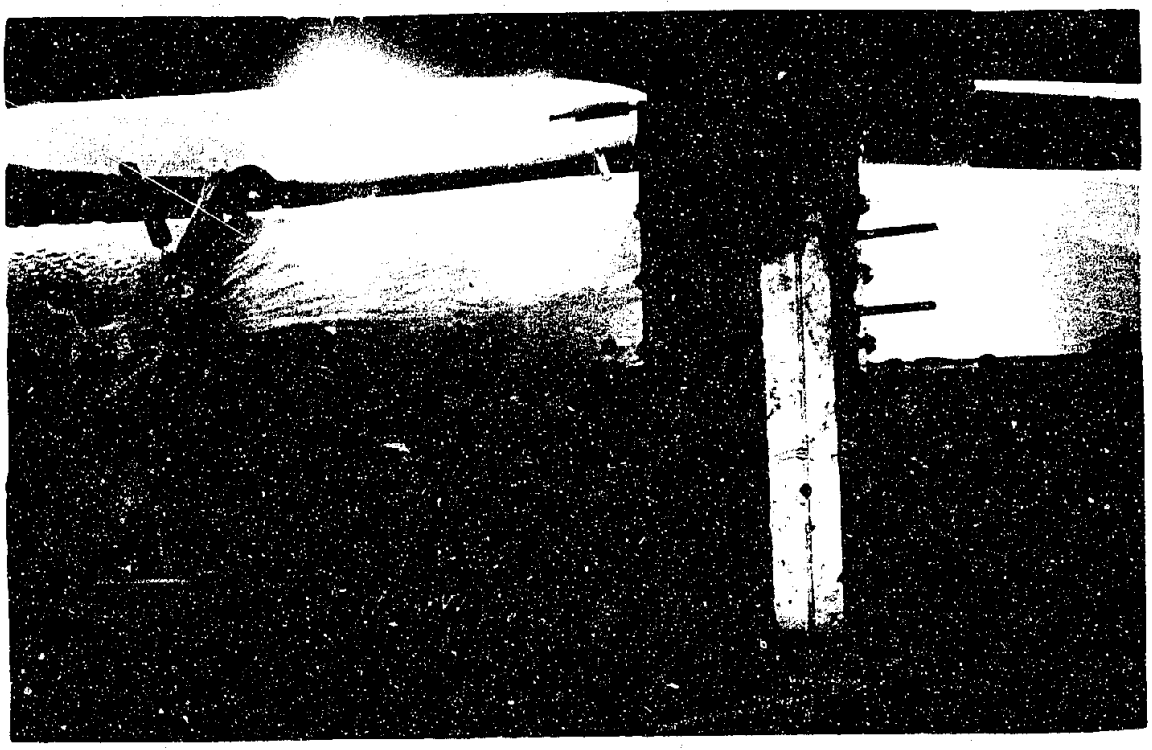
CENTRAL VALLEY PROJECT, CALIFORNIA
KENNETT DIVISION
SHASTA DAM
DIVERSION TUNNEL
DETAILS OF 1:30 MODEL OF FIXED WHEEL GATE WITH UPSTREAM SEAL AND HORSESHOE TUNNEL SECTION
214-D-7642

FIGURE 14


12 Ga metal flanges on Sec. A-A only
Pyralin flanges on pyralin top section
Bolt sections with 6-32 RHMS
SECTION A-A
SECTION B-B
18 Ga Pl in transition
12 Ga flange, bolt to gate structure
SEC. C-C
SEC. D-D
SEC. E-E
Wood
Vent shaft
Pyralin
Guide track
Rubber seal
Top section of well
Vent shaft
Guide tracks
Roller tracks
Pyralin top
18 Ga. sheet metal
Flow
(Prototype)
GATE STRUCTURE WITH TRANSITIONS
GATE
Piezometer locations
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
CENTRAL VALLEY PROJECT-CALIFORNIA
KENNETT DIVISION
SHASTA DAM
DIVERSION TUNNEL
DETAILS OF 1:30 MODEL OF FIXED WHEEL GATE WITH UPSTREAM SEAL AND RECTANGULAR TUNNEL SECTION
214-D-7643



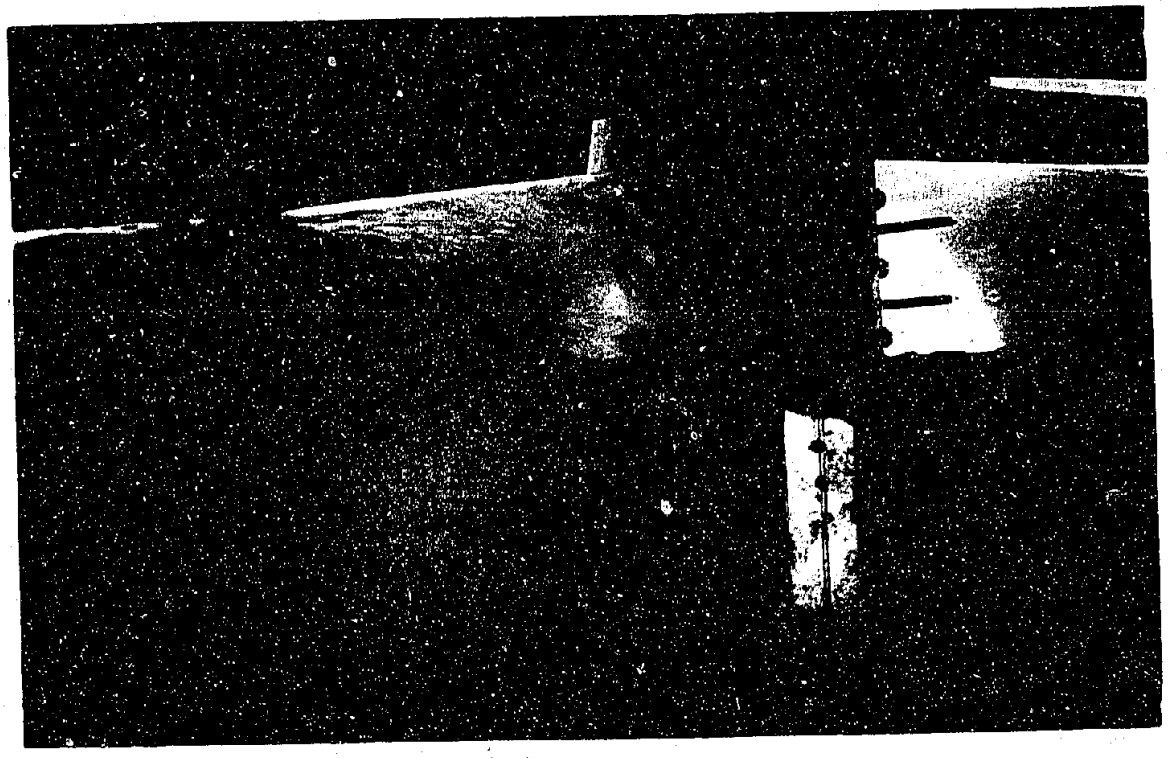
A. THE MODEL



B. GATE IN DIVERSION [illegible]

1:30 SHASTA DAM DIVERSION TUNNEL MODEL

FINAL DESIGN



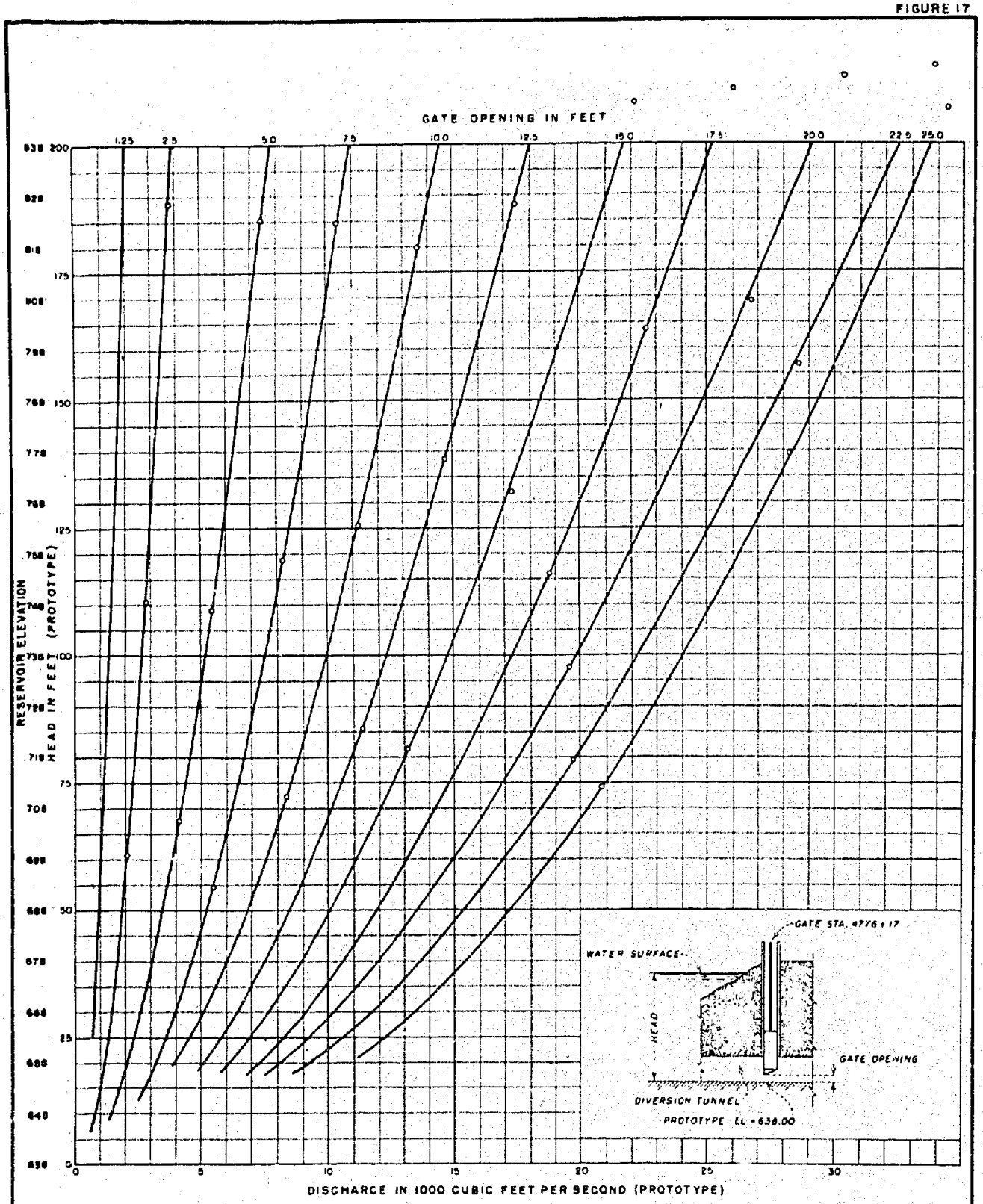
A. GATE 60 PERCENT OPEN

B. GATE 20 PERCENT OPEN

1:30 SHASTA DAM DIVERSION TUNNEL MODEL

FINAL DESIGN

FIGURE 17



SHASTA DAM DIVERSION TUNNEL

RELATION OF HEAD TO DISCHARGE FOR DIFFERENT GATE OPENINGS

10-1-41

214-D-7644