UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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HYDRAULIC MODEL STUDIES ON COASTER GATES

By

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CHAPTER I - INTRODUCTION

Purpose of studies. Coaster gates will be used for emergency closure of the intakes of the penstocks for the main power units at Grand Coulee Dam; the penstocks at Shasta Dam; the 102-inch diameter outlets in the spillway section at Shasta Dam; the 110-inch diameter river outlets at Friant Dam; the 110-inch diameter Friant-Kern Canal outlets; the 91-inch diameter Friant-Madera Canal outlets; and the power penstocks at Davis Dam. These coaster gates operate on metal tracks and guides embedded in concrete on the upstream face of the dams and will be raised or lowered by mechanical or hydraulic hoists at the top of the dam. Although designed as emergency closure gates, they will normally be used for unwatering the penstocks and outlets to permit inspection and maintenance of the conduits, and the turbines and valves installed in them. For such use they will be opened and closed under conditions of balanced hydrostatic pressure on both sides of the gate and with no flow through the penstocks or outlets. Under emergency conditions, however, the gates may have to be closed with large, unbalanced hydrostatic heads on their upstream side and with maximum flow through the penstock or outlet.

The design of a coaster gate and its hoist is based largely upon forces acting on the gate due to the unbalanced pressures which will occur during an emergency closure. When the gate is closed sufficiently to become a definite control, the hydrostatic head on the upstream side of the gate will be supplemented by subatmospheric pressures on its downstream side. The frame of the gate must be sufficiently strong to resist the resultant force which pushes it against the face of the dam, and the rollers upon which the gate is mounted must have a low frictional resistance or the gate cannot be lowered into position. In addition to this force another termed the hydraulic downdraw force occurs. This downward pull on the gate is caused by the increase in velocity as the flow passes under the gate and into the penstock, thereby reducing the pressures on the gate bottom. Consideration of the downdraw in the design of the gate hoist is important, for this force increases the load on the hoist and may be equal to or greater than the weight of the gate.

Unfortunately, calculations of the hydraulic downdraw force only approximate its magnitude. Since the pressure reduction at any point on the gate bottom is equal to the velocity head at that point, calculations of downdraw must be based upon the velocity distribution underneath the gate. But the flow pattern under a gate describing the velocity distribution must be assumed, and will vary with the gate opening and the shape of the gate bottom. Nevertheless, an approximation of the downdraw was considered satisfactory in the design of the hoists for the penstock coaster gates at Grand Coulee Dam, the first large coaster gates built by the Bureau of Reclamation. At Shasta Dam, however, the estimated downdraw on the outlet coaster gates was so large that the total load on the hoist was about 30 tons in excess of the permissible load. The hoist was to be a 150-ton gantry crane operating on the bridge across the spillway section of the dam. The capacity of this crane was determined, not by the forces on the gate but by the strength of the bridge upon which it operated. Therefore, it became necessary to reduce the downdraw, for other forces on the hoist, such as the weight of the gate, could not be materially reduced. The accuracy of the estimated downdraw under such restrictions was questionable.

Hydraulic model studies were instigated to check the computed downdraw and to study the effect of the shape of the gate bottom on its magnitude. These tests showed the downdraw to be underestimated. By replacing the sloping bottom of the original design with a flatbottom with an extended lip below its downstream edge and placing a recess in the face of the dam above the outlet entrance, it was possible to reduce the downdraw to about 35 tons.

Since this revised bottom shape was structurally better than the sloping bottoms originally designed for the penstock coaster gates at Shasta and Davis Dams and the outlet coaster gates at Friant Dam, the model studies were continued. A flatbottom gate with an extended lip below its downstream edge was used in all designs. In addition, these studies were used to check the downdraw on the penstock coaster gates at Grand Coulee Dam to ascertain if temporary hoists of limited capacity could be used. The results of these model studies can be applied to future designs of similar coaster gates.

Description of coaster gates. Basically, a coaster gate is a bulkhead mounted on wheels or rollers so it can be lowered into position under unbalanced pressures. The term was first used to better describe the emergency gates for the main unit penstocks at Grand Coulee Dam and subsequently to describe the similar emergency gates at Shasta, Friant, and Davis Dams. All of these gates are lowered down the upstream face of the dams to close the entrances of the outlets and penstocks. A special designation was necessary because similar gates, lowered down the face of a dam, are used at many installations. However, few of these gates were designed to close under large unbalanced heads as were the coaster gates. Instead, the entrances of many penstocks and some outlets were purposely placed close to the water surface of the dam so the head would be low; at outlets where this was not possible, emergency slide gates were often placed in the conduit immediately upstream from the regulating valves. In either case, if a gate was lowered down the face of the dam to close the entrance of the outlet or penstock, it would be more simple in design than a coaster gate.

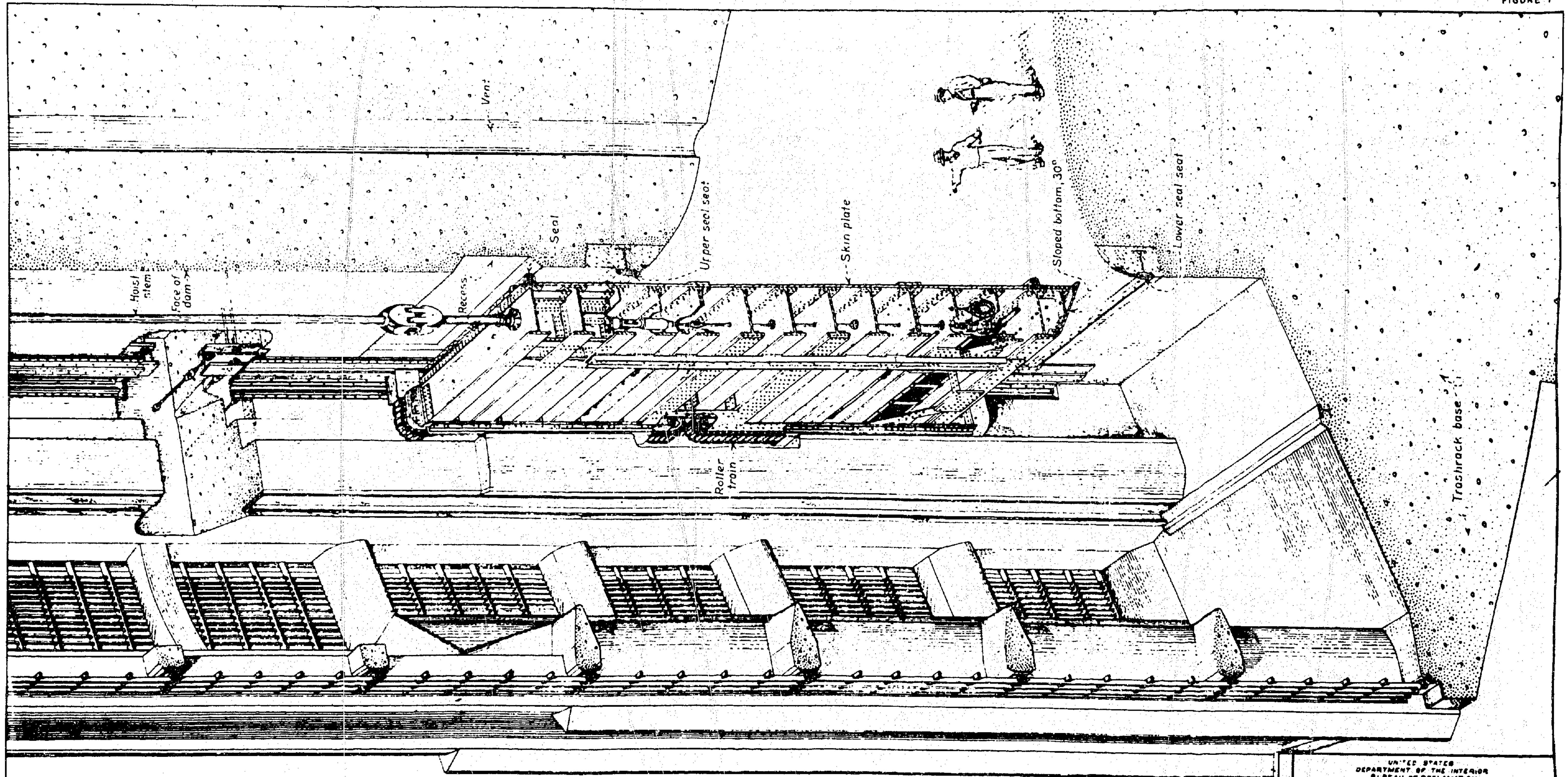
Since the coaster gates at Grand Coulee, Shasta, Friant, and Davis Dams are used at both power penstocks and at outlets, they were called penstock coaster gates and outlet coaster gates. This segregation of types was made because the form of the penstock entrances was different from that of the outlet entrances. The penstock entrances were rectangular, with a transition section immediately downstream to the circular penstock. The top and the bottom were bellmouth shaped, but the sides were square-edged. Massive concrete columns were placed at each side of the entrance in such a manner that they placed the gate in a slot. To reduce entrance losses, these columns formed streamlined lips in front of the gate in line with the square sides of the entrance (Figure 1).

The outlet entrances were simple in comparison, being circular bellmouths flush to the face of the dam. No massive columns were placed at the side of the gate, and, on the whole, there were comparatively few restrictions to the flow into the outlets. The difference in the entrance designs of the outlets and penstocks was based largely upon their size and function. The penstock entrances were rectangular with square sides so that the openings which the gates had to span would be as narrow as possible. This was necessary, since the penstocks are large. If the 18-foot diameter penstocks at Grand Coulee Dam had a bellmouth entrance similar to the entrance of the 102-inch (8-1/2-foot) diameter outlets at Shasta Dam, the coaster gates would have to span a 24-foot opening. By using a rectangular opening, the span was reduced to 15 feet. A rectangular opening was satisfactory at the penstock entrances since the flow into the penstocks was normally at low velocities so that pressure drops and loss in head through the penstocks would be slight. On the other hand, a rectangular entrance at the outlets would not be satisfactory because the flow through them is at high velocity, and the circular bellmouth entrance was necessary to prevent negative pressures from developing at the outlet entrance.

Although called penstock coaster gates and outlet coaster gates, the gates are similar. The frame of a gate consists of several horizontal beams placed between two vertical beams. A skinplate is attached to the downstream side of the frame. This frame is mounted on rollers linked together to form roller trains. These rollers lie between the tracks on the face of the dam and the skinplate of the gate; so the gate seals have to be projected to contact the seal-seats on the face of the dam. The coaster gates were originally designed with sloping bottoms.

Scope of tests. Initially, the investigations were concerned with the outlet coaster gates at Shasta Dam. Tests on a 1:17 scale model of the original design revealed the downdraw to be excessive. It was shown that if the sloping bottom of the gate were extended past the skinplate

FIGURE 1



UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT–WASHINGTON

GRAND COULEE DAM

15' x 28.68' PENSTOCK COASTER GATE
GATE INSTALLATION PERSPECTIVE

DRAWN... E.G.C. .... SUBMITTED ....
TRACED E.A.S. .... RECOMMENDED ....
CHECKED HBS .... APPROVED ....

DENVER, COLORADO

282-D-3526

to the face of the dam, the force could be reduced to a reasonable figure. However, this revision made the gate unsatisfactory structurally; so a flatbottom gate with a lip extending below the downstream edge was proposed. Tests showing the variation of downdraw with lip extension revealed this type to be practical, a satisfactory structural design which would not develop an excessive downdraw. Accordingly, in the final design for the outlet coaster gate at Shasta Dam this type of gate bottom was used.

The scope of the investigations was extended to include sufficient tests to estimate the downdraw on similar coaster gates at the outlets of Friant Dam and in the penstocks of Shasta and Davis Dams. A study of outlet coaster gates was made first, using the 1:17 Shasta model; then a study of penstock coaster gates was made, using a 1:30 model of a Shasta penstock and its coaster gate.

The tests on the outlet coaster gate at Shasta Dam included: (1) the development of the final design of the gate using a flat bottom with an extended lip; (2) a correlation of the downdraw obtained by both pressure and force measurements; (3) the effect upon downdraw of the gusset plates which support the extended lip; and (4) the effect of a recess in the face of the dam above the outlet entrance. The effects of (1) the outlet exit, (2) restriction of flow through the outlet, (3) the thickness of the gate, (4) the proximity of the trashrack base, (5) the length of the lip extension, and (6) the radius of the upstream edge of the bottom were studied in additional tests upon the downdraw on outlet coaster gates. Through these studies it is believed that the downdraw force can be estimated on any coaster gate with a flat bottom and extended lip which closes an outlet having a circular bellmouth entrance.

The penstock coaster-gate tests included: (1) the original design of the Shasta Dam installations; (2) a study of flatbottom, extended-lip type of gates; (3) the effect upon downdraw of holes in the gate bottom; and (4) the final design of the Shasta Dam coaster gate. The downdraw on the penstock coaster gates at Davis Dam and at Grand Coulee Dam was estimated from the model tests of the Shasta penstock coaster gate.

By comparing the behavior of a gate with a 45-degree sloping bottom used as a penstock gate with a similar installation as an outlet gate, it was shown that the two cases required separate treatment.

<u>Summary of tests</u>. The hydraulic downdraw force, acting on the gate hoist, is an important factor in the design of a coaster gate because it is large, sometimes exceeding the weight of the gate. This force, a pressure reduction on the gate bottom, is caused by flow passing under the gate and into the penstock or outlet. Although the pressure reduction at any point is equal to the velocity head at that point, estimates of downdraw cannot be precise because of the uncertainties of the velocity distribution under the gate. Therefore, when estimates indicated a downdraw of 160,000 pounds on the coaster gate for the outlets at Shasta Dam, which was excessive, hydraulic model studies were used to check the estimate and to revise the gate design to reduce the downdraw.

Pressure measurements on a 1:17 model indicated a downdraw of 260,000 pounds. However, the estimate of 160,000 pounds assumed a recess in the face of the dam to balance pressures on projected seals. As it was apparent that a recess alone was inadequate, the effect of the shape of the gate bottom on downdraw was first studied and the effectiveness of a recess determined after a final design was obtained.

In this test on the original design, the maximum downdraw was observed to occur at about the same opening where the gate became a definite control, that is, when pressures immediately downstream from the gate changed from positive to negative by a slight closing of the gate.

The spring point of the jet was at the downstream edge of the sloping portion of the gate bottom. On this sloping portion pressures were high, while pressures on an 8-3/8-inch space between the spring point and the face of the dam were low. To eliminate these low pressures, the sloping bottom was extended to place the spring point close to the face of the dam. The downdraw was reduced to 103,000 pounds, although the design was not structurally desirable. This revision demonstrated the importance of placing the spring point close to the face of the dam.

A flatbottom gate having an extended lip below its downstream edge was studied. The lip was supported by gusset plates. The upstream edge of the flatbottom was curved on a 9-inch radius to increase pressures on it, and the bottom of the lip was beveled at 45 degrees to place the spring point at its downstream edge. Later, this bevel was changed to 67 degrees 20 minutes. To have a maximum downdraw of 100,000 pounds, a lip extension of 17 inches would be necessary. This extension would be too great for the Shasta gate.

Nevertheless, the flatbottom, extended-lip type was so desirable structurally that other designs were tested. Design 3, having a lip extension of 10-3/4 inches and a radius of 7-1/2 inches at the upstream edge of the bottom, developed a downdraw of 130,000 pounds. Design 4, having a 12-inch extension and a 2-inch radius, developed a downdraw of 150,000 pounds. Design 5, the final design, having a 14-1/2 inch extension and a 9-inch radius, developed a downdraw of 113,000 pounds.

This force, obtained by pressure measurements, was closely checked by force measurements; however, on a second gate, designed for force measurements, the maximum was 139,000 pounds. This difference was due largely to lip clearance, for on the first gate the clearance was zero, while on the second gate the clearance was 0.85 inch. When a clearance of 0.50 inch was established for the prototype, the maximum downdraw was revised to 123,000 pounds for the first gate and 130,000 pounds for the second. Tests showed that a reasonable number of gusset plates could be used to support the extended lip without affecting downdraw.

The effectiveness of a recess in the face of the dam above the outlet entrance was studied. The purpose of the recess was to balance pressures on the upper projected seal because unbalanced pressures on this seal exerted a large downward force. It was found that a recess could be completely effective except when the gate was nearly wide open. It is recommended that the depth be at least three times the seal projection. A shallow recess, 1-1/3 times the seal projection, was made effective by using a curved edge above the seal. The use of a recess will reduce the downdraw on the outlet coaster gate for Shasta Dam to 70,000 pounds. However, it should be constructed so as not to be effective at small openings, to avoid an uplift force which would prevent the gate from closing. The effectiveness of using a recess suggests the possibility of designing a coaster gate which would have no downdraw.

To use the data from Shasta tests to estimate the downdraw on the coaster gates for Friant Dam, and for a general study, additional features effecting downdraw were studied. The effective head on the gate should include any drop in elevation between the entrance and the exit of the conduit.

The maximum downdraw is roughly proportional to the coefficient of discharge of the outlet. If the downdraw gate-opening curve is known for a constant velocity head, the maximum downdraw for an outlet having a given coefficient may be computed in a more precise manner by obtaining the velocity head under the gate for given gate openings. This is possible, since the velocity head is directly proportional to the downdraw.

It is important that the maximum possible discharge which may occur while the gate is closing be considered carefully. The maximum downdraw of 67,700 pounds on the coaster gate serving the river outlets at Friant Dam would be increased to 125,000 pounds if the needle valve at the exit were destroyed, permitting a large increase of discharge through the outlet.

The relationship of downdraw to gate thickness, other factors being unchanged, was roughly linear. By showing this relationship as a downdraw factor N to thickness, it was shown that the effect of thickness was nearly the same for gate openings from 40 to 75 percent.

Placing the trashrack base close to the outlet entrance increases the downdraw. This increase is negligible, unless the distance $\frac{C}{D}$ is less than 1, and $\frac{C}{D}$ must be less than 0.05 to increase the downdraw 10 percent.

Tests were made by varying the lip extension on a gate having a sharp corner at the upstream edge of the bottom. The results, and the data from the previous tests, to obtain a design for the outlet coaster gate at Shasta Dam, were presented as dimensionless curves, with the abscissa as the ratio of lip extension to gate thickness and the ordinate as the ratio of maximum to theoretical downdraw, the theoretical downdraw being the force that would occur if pressure on the gate bottom were zero, and the head on the gate including any drop in the conduit.

Various curves for constant ratios of radius over thickness and thickness over diameter may be drawn to apply to any flatbottom, extended-lip type of gate. However, the tests were limited.

By using the curves developed from these tests, the maximum hydraulic downdraw force on the coaster gates for Friant Dam was estimated. The force on the 11.92- by 11.92-foot gate was 67,700 pounds, and the force on the 9.86- by 9.86-foot gate was 25,600 pounds.

Penstock coaster-gate tests were made on a 1:30 model of the Shasta Dam penstock and gate. The maximum downdraw on the original design was 630,000 pounds by pressure measurements and 660,000 pounds by force measurements.

Since the original design of recess was effective for openings up to 50 percent, it had to be extended, for the maximum downdraw occurred at a gate opening of 75 percent. If this were not done the downdraw would be increased 117,000 pounds.

A flatbottom, extended-lip type of gate, having a sharp corner at the upstream edge of the bottom, was tested. With a 15-inch lip extension the downdraw was 660,000 pounds.

An attempt was made to reduce this force by cutting holes in the gate bottom, but to be effective the holes would cut away too much of the beam forming the bottom.

By curving the upstream edge on an 11-1/4-inch radius, the downdraw was reduced to 465,000 pounds. The final design was similar, except the radius was 9-1/4 inches. A design value of 500,000 pounds for the downdraw was believed to be conservative to account for the different radius.

Pressures were measured on a penstock coaster gate having a bottom similar to the outlet coaster gate at Shasta Dam. Pressure gradients on both gates were similar but those on the penstock gate relatively much less, indicating a larger downdraw, other conditions being equal. No relation between the two gates was found because it was believed to be more expedient to consider outlet and penstock coaster gates as separate problems.

The maximum hydraulic downdraw force on the penstock coaster gate at Davis Dam was estimated to be 110,000 pounds if the penstock were to discharge 5,000 second-feet under a 110-foot head. The maximum downdraw on the penstock coaster gate at Grand Coulee Dam was estimated to be 125,000 pounds for a discharge of 3,500 second-feet under a 250-foot head, or 170,000 pounds if the discharge were increased to 5,000 second-feet. These estimates were made from the Shasta tests by using the proper bottom shapes, correcting for velocity head, and other factors which were not similar.

The penstock coaster gates at Grand Coulee Dam. The first coaster gates designed by the Bureau of Reclamation were for the main unit power penstocks at Grand Coulee Dam (Figure 1). The coaster gates are necessary because the penstock entrances are near the bottom of the dam, as the demands for irrigation water will constantly change the water level in the reservoir. Eighteen 18-foot diameter penstocks are embedded in the concrete of the dam, nine for the right powerhouse and nine for the left. The entrances of these penstocks, rectangular, 15 feet wide by 29.5 feet high, are 249 feet below the maximum water surface elevation; so the coaster gates may have to close under heads as large as 250 feet.

The criterion for the design of these gates and their hoist was an emergency closure with a flow of 19,000 second-feet which would occur if the cover plates of the turbine were to burst when the reservoir was full. After a gate was closed sufficiently to become a definite control, subatmospheric pressures would act on its downstream face. To prevent these pressures from becoming too severe, a 30-inch vent was installed in the penstock near its entrance. Nevertheless, the gate was designed to resist an unbalanced head of about 280 feet on the assumption that the head of 250 feet on its upstream face would be supplemented by a vacuum of 30 feet on its downstream face.

To design the gate hoist, the weight of the gate, its frictional resistance, and the hydraulic downdraw force were required. The weight of the gate was computed from material lists; the frictional resistance was obtained by tests and coefficients; and the downdraw was estimated. To determine the frictional resistance of the roller trains, several rollers were moved between loaded parallel plates. Other frictional forces, such as the friction of the seals against their seats, were estimated from coefficients. The estimate of the hydraulic downdraw force was not so simply acquired. The flow under the gate does not follow any simple pattern so the pressure reduction on the bottom of the gate could not be accurately expressed by a formula. A careful approximation of this force in the case of the Grand Coulee penstock coaster gates was considered satisfactory, and model studies were not made until the question of the use of a temporary hoist was raised. The analytical design of the gates was made on the basis of minimizing the downdraw. The gate bottom was sloped at an angle of 30 degrees so that the flow pattern under it would converge as much as possible at the downstream edge of the bottom, which was to be the control. High velocities and low pressures were to exist at this control, but upstream from it the velocities would be less so that pressures on the gate bottom would be greater, tending to balance the static pressures on top of the gate, thus reducing the downdraw. This pressure increase on the bottom depended upon the degree of convergence of the flow pattern. An angle steeper than 30 degrees would result in even less downdraw, since the degree of convergence would be increased. However, the steeper angle was not structurally desirable. To aid in minimizing the pressure reduction on the bottom of the gate, the upstream edge of the bottom was curved.

To further reduce the downdraw, a recess was cut into the face of the dam above the penstock to eliminate the severe pressure differential between the top and the bottom of the upper projected seal (Figure 1). The resulting downward force on this seal without the recess would be as large as 100,000 pounds and must be considered as part of the downdraw force to be handled by the hoist. With a recess, however, this force was substantially reduced. As the gate is closing, water will flow through the recess, past the space between the skinplate and the upper seal-seat, into the penstock. The water in the recess is then under pressure, as the control is at the space between the skinplate and the upper seal-seat on the face of the dam. As shown in Figure 1, this recess was restricted in height and depth so that it was effective only when the gate was more than halfway closed, as it was anticipated that the maximum downdraw would occur when gate was nearly two-thirds closed.

<u>The coaster gates at Shasta Dam</u>. Coaster gates were designed for both the outlets and penstocks at Shasta Dam. The original design of the coaster gates at Shasta Dam was based largely upon the design of the penstock coaster gates at Grand Coulee Dam. Hydraulic model studies led to the change of the shape of the gate bottom in the final designs.

Five 15-foot diameter penstocks are embedded in the concrete of Shasta Dam. These penstocks pass through the dam and to the powerhouse approximately 500 feet downstream, with several hundred feet of the penstocks exposed. The entrances are 250 feet below the maximum water surface at elevation 1065.00. The gates were therefore designed to close under the same head as those at Grand Coulee Dam. The entrances were 15 feet wide and 19.05 feet high. Although not as high as those at Grand Coulee Dam, the penstock entrances were otherwise identical. The coaster gates, similar to those at Grand Coulee Dam, were designed to close while the penstock was discharging approximately 22,000 second-feet. This discharge would occur if an exposed portion of the penstocks were to burst while the reservoir was full.

A single 11.05- by 11.05-foot outlet coaster gate was designed to be used to close any of the eighteen 102-inch diameter outlets located in the spillway section of the Shasta Dam. Four of these outlets were at elevation 742.00, eight at elevation 842.00, and six at elevation 942.00. The maximum head on the lower outlets will be 323 feet. Originally, two ring-follower gates were to be placed in tandem in each outlet downstream from its entrance. The downstream gate was for regular service and the upstream gate for emergency use. A simple bulkhead was to be used to close the entrance of these outlets. Since a ring-follower gate is not satisfactory for purposes of regulation, especially under high heads, the downstream gate was replaced by a tube valve developed during a series of extensive tests in the hydraulic laboratory. Unbalanced forces on this tube valve would be slight in comparison with the unbalanced forces on ring-follower gates; so the expectancy of breakdowns and failure of the valves was reduced. Therefore, a single coaster gate was designed to replace the eighteen emergency ring-follower gates in the original plans.

This coaster gate was designed to be lowered over one of the lower outlets under an unbalanced head of 323 feet to stop a discharge of approximately 5,600 second-feet which would occur if the regulating tube valve had failed in an open position. To resist the resulting forces, the frame of the coaster gate consisted of 36-inch beams to which were attached a 1-1/4-inch skinplate. This gate was mounted on 5-inch rollers forming roller trains around the vertical beams of the frame.

To move the gate from one outlet to another and maneuver it into place, a 150-ton gantry crane was provided on the bridge above the spillway section. As stated, the model studies were begun because the permissible load on this hoist was less than the estimated load. It therefore became necessary to reduce the downdraw.

The outlet coaster gates at Friant Dam. The outlet coaster gates at Friant and Shasta Dams were quite similar, the gates closing over circular bellmouth entrances geometrically similar at both installations. At first thought, it appeared that the downdraw forces on the Friant gates could be estimated from the results of the Shasta tests. However, the Friant outlets were sufficiently different from the Shasta outlets to require additional coaster gate studies.

The outlets at Friant Dam include four 110-inch river outlets, two 91-inch outlets into the Friant-Madera Canal, and four 110-inch outlets into the Friant-Kern Canal. The four 110-inch river outlets, approximately 200 feet long, were placed to the left of the spillway near the center of the dam with their entrances at elevation 380.00 and their exits at elevation 330.00. To control the flow through these outlets, two 110- by 105-inch needle valves and two 110- by 102-inch tube valves will be placed at their exits. The maximum head at the entrance will be 198 feet.

The two 91-inch Friant-Madera Canal outlets, approximately 103 feet long, are near the right abutment of the dam. These outlets were placed horizontally at elevation 446.00. Two 91- by 87-inch needle valves will control the flow through these outlets with a maximum head of 132 feet.

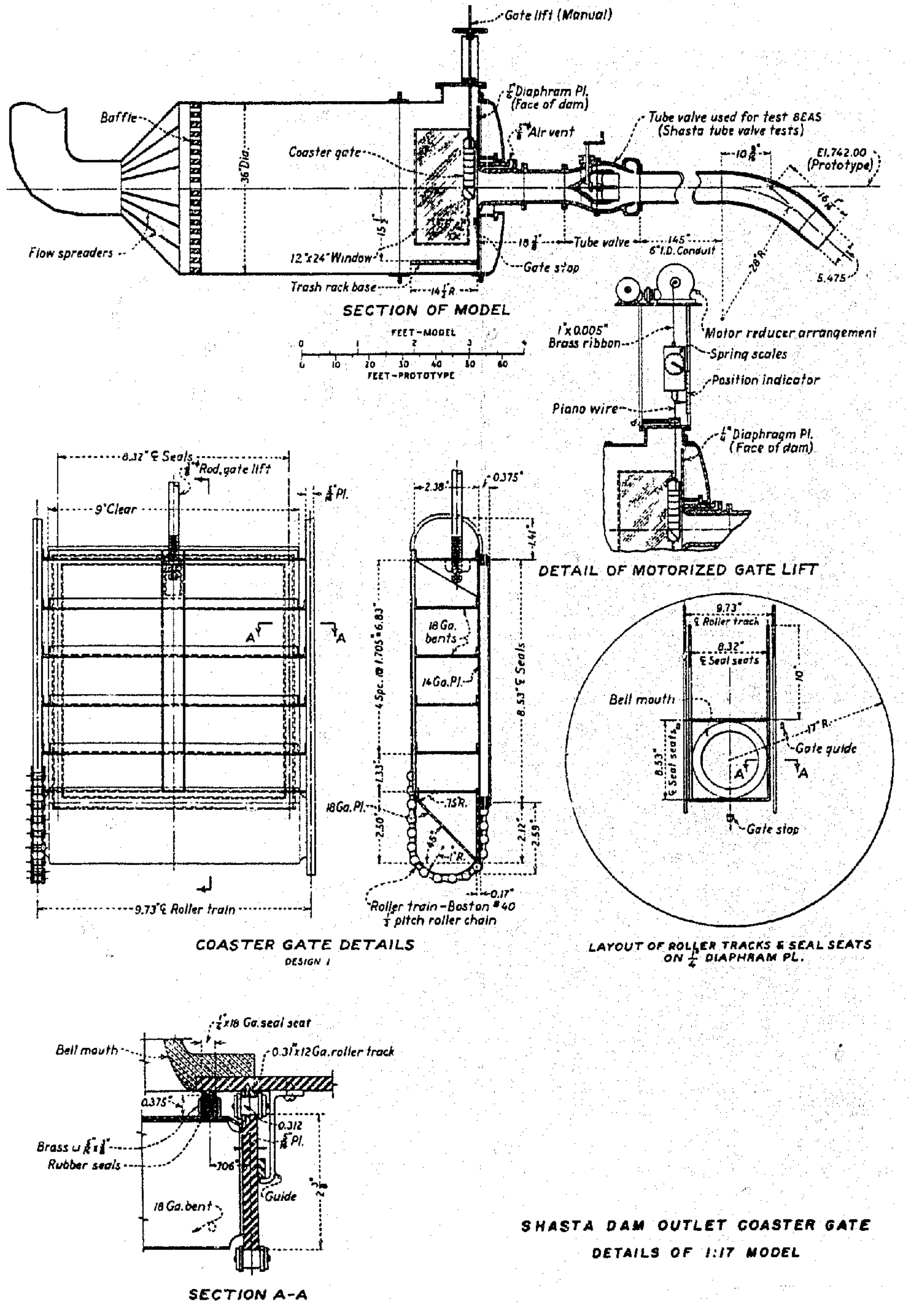
The four Friant-Kern Canal outlets, approximately 89 feet long, are near the left abutment of the dam. These outlets were placed horizontally at elevation 464.00. Two 110- by 105-inch needle valves and two 110- by 102-inch tube valves will be placed at their exits to control the flow. The maximum head will be 114 feet.

A single 11.92- by 11.92-foot coaster gate will close any of the river outlets or the Friant-Kern Canal outlets, while a 9.86- by 9.86-foot coaster gate will close the Friant-Madera Canal outlets. These gates will be operated by gantry cranes at the top of the dam. The larger gate was designed to close one of the river outlets under an unbalanced head of 198 feet while the regulating needle or tube valve was wide open. It was also designed to close one of the Friant-Kern Canal outlets under similar conditions. The smaller gate was designed to close one of the Friant-Madera Canal outlets under an unbalanced head of 132 feet while the regulating needle valve was wide open.

The penstock coaster gates at Davis Dam. Both the penstock entrances and the coaster gates at Davis Dam were originally designed similar to those at Grand Coulee Dam, although larger. Five 22-foot diameter penstocks will furnish power water to the main unit turbines at Davis Dam. The penstock entrances will be rectangular, 17.5 feet wide and 34.66 feet high. The maximum head at the center line of the penstocks will be approximately 110 feet.

A 17.5- by 34.66-foot coaster gate will be installed in each of these penstocks. The gates - to be operated by hydraulic hoists attached to the face of the dam - are designed to close the penstocks under a head of 110 feet with a discharge of 5,000 second-feet through the turbines. These gates will be mounted on wheels instead of rollers, since the unbalanced head of 110 feet will not be sufficient to require a roller train as in the case of Grand Coulee and Shasta Dams. In addition, it is not expected that the hydraulic downdraw force would be large, for the discharge of 5,000 second-feet was relatively small and the gate would be almost closed before the gate became a control.

The model. A 1:17 scale model of the original design of the outlet coaster gate for Shasta Dam was first constructed (Figure 2). Sheet metal of several gages was used in its construction to represent the thickness of prototype plates, and a roller chain was used for the roller trains. This gate was placed in a 36-inch diameter head tank of an existing 1:17 model of a Shasta Dam outlet which was ideally suited to accommodate the gate, since the outlet entrance was attached to a diaphragm plate representing the face of the dam. Roller tracks and seal-seats were placed on this diaphragm plate. The head tank was lengthened to permit installation of two 12- by 24-inch windows for observation of the gate in operation and to provide a flanged opening through which the gate could be lowered. A manual gate lift was first used consisting of a 3/8-inch lift rod attached to the top of the gate and passed through the head tank by a packing gland. The rod was raised or lowered by turning a wheel threaded to the rod and attached to a yoke above the packing gland. Later this manual gate lift was replaced by a mechanized gate lift designed primarily to measure the forces on the gate. In place of the rod, the gate lift consisted of a



SHASTA DAM OUTLET COASTER GATE
DETAILS OF 1:17 MODEL

length of piano wire, scales, and a 1-inch bronze ribbon. The bronze ribbon wound on the slow-speed shaft of a motor reducer which raised or lowered the gate at a uniform speed of about 1-1/2 inches per minute.

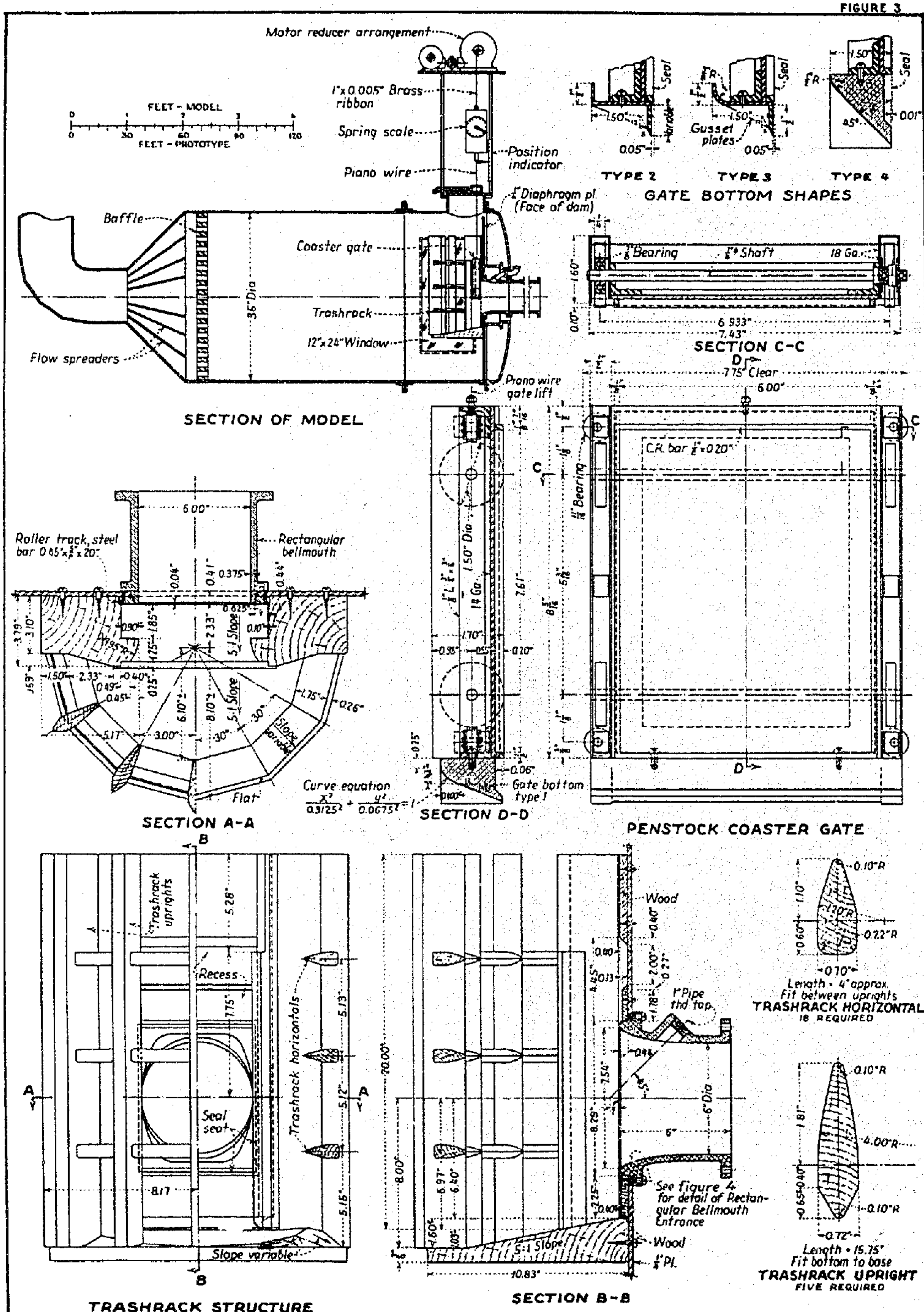
The trashrack and trashrack base were omitted in the model, since previous tests on the outlets at Grand Coulee Dam indicated that these features as situated at Shasta Dam were sufficiently far from the outlet entrance to not affect the pressures. Some minor features, such as the roller-train shields, were omitted because it was considered that their presence or absence would not have an effect upon the downdraw. The recess in the face of the dam was not installed originally.

Additional tests to study the Friant outlets were made on the same model by changing the outlet conduit downstream from the bellmouth entrance and replacing the Shasta tube valve with a model of one of the Friant needle valves. This 1:17 model of the Shasta tube valve had a conduit diameter of 6 inches; so a scale ratio of 1:18.33 was established for the Friant River and Friant-Kern Canal outlets and a scale ratio of 1:15.17 for the Friant-Madera Canal outlets. The model was quite flexible in that the necessary revisions to suit a particular test upon the outlets were made easily.

However, the model had to be completely revised for the penstock coaster-gate tests. A 1:30 model of the upstream section of a Shasta penstock was designed for the existing head tank (Figure 3). It was not necessary to consider the lower portion of the penstocks in this model as it was assumed that the penstocks had burst.

A new diaphragm plate was required to fit the rectangular bellmouth entrance (Figure 4). The columns at the sides of the gate and trashrack structure were made of redwood, lacquered and waxed to avoid warping and swelling. The penstock entrance included a recess in the face of the dam as shown in the original design, but the model recess was wider than the prototype recess. In the prototype this recess lies between the vertical seal-seat bars which extend above the penstock entrance, while in the model the recess lies between the roller tracks, and the vertical seal-seat bars above the entrance were omitted. This omission was to facilitate the model construction and was at first not considered important in the tests.

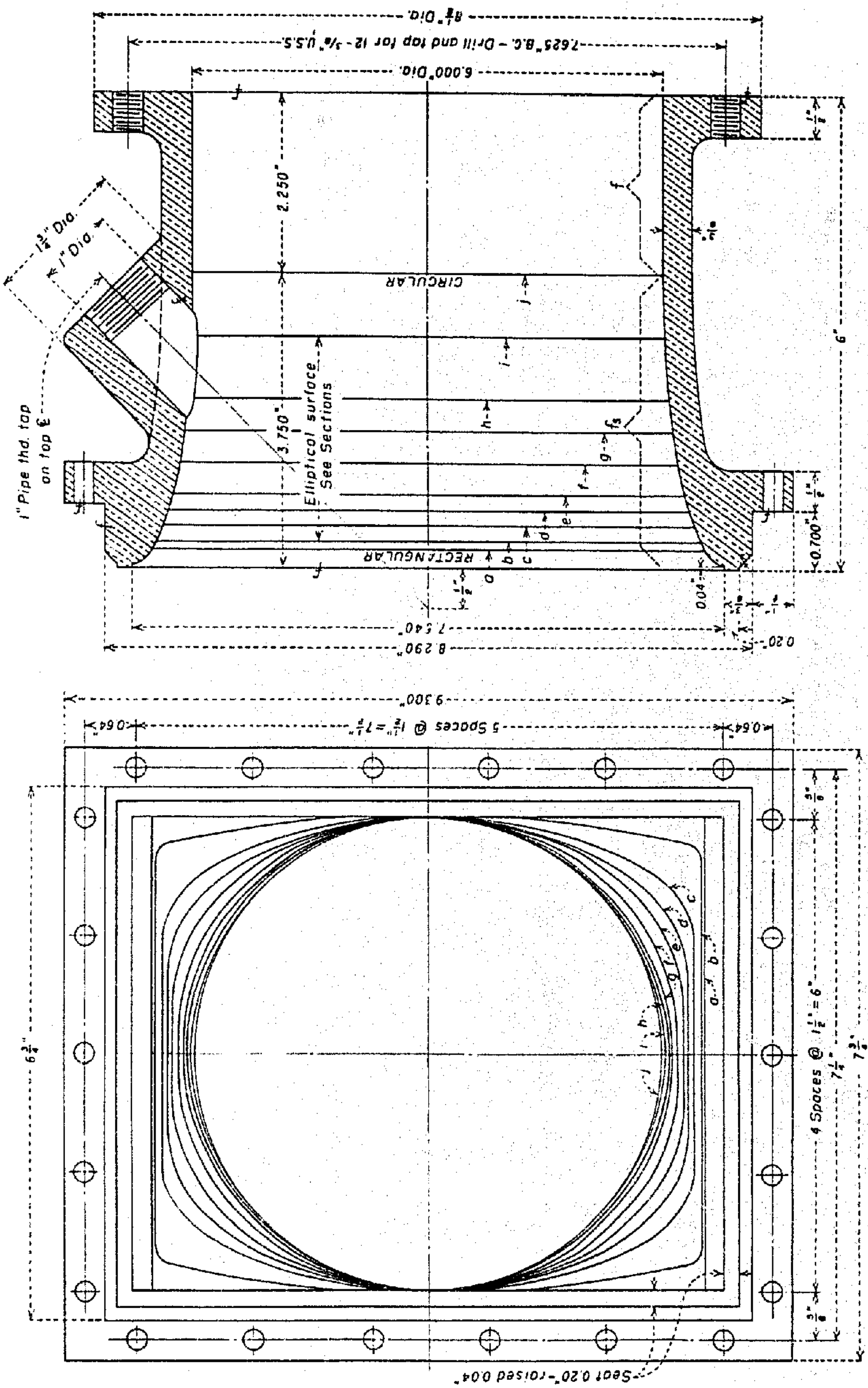
FIGURE 3



SHASTA DAM PENSTOCK COASTER GATE

DETAILS OF 1:30 MODEL

FIGURE 4



SECTIONS

SECTION	a	b	c	d	e	f	g	h	i	j
DIST. FROM FACE	.235	.350	.550	.750	.950	1.350	1.750	2.150	2.950	3.750
HEIGHT	7.051	6.993	6.770	6.643	6.539	6.372	6.247	6.153	6.037	6.000
SEMI-MINOR AXIS	0	0.520	1.458	1.994	2.333	2.691	2.860	2.941	2.991	3.000

SHASTA DAM PENSTOCK COASTER GATE

DETAIL OF RECTANGULAR BELLMOUTH ENTRANCE

F.C.L. 1-20-43

The model gate was simplified, duplicating only the basic features which would affect the hydraulic downdraw force, for the outlet coaster-gate tests indicated that a simple gate would be satisfactory. A 12-gage skinplate, reinforced by angles, formed the frame. Projected seals were attached to the downstream side. The gate was moved on ball bearing wheels instead of a roller train. The gate bottom was made from a babbitt casting which formed a true, smooth profile.

The testing procedure. The nature of the hydraulic downdraw force was such that it could be found either by pressure measurements on the gate or by force measurements on the hoist. Pressure measurements were used to compare different types of gate bottoms, while force measurements were used to study the downdraw of a given gate design under various conditions. In addition, a correlation of both methods insured reasonably accurate results for the final designs.

To obtain the downdraw force by pressure measurements, three rows of piezometers were installed on the bottom of the gate; one row at the center, one at the quarter-point, and one near the edge. Additional piezometers were installed at other points on the gate and in the outlet. The downdraw on the gates was measured at various heads and gate openings, depending upon the requirements of the individual test.

A measurement consisted of placing the gate at a given opening and recording the pressures on the piezometers while the pressure head in the head tank remained constant. The difference between the head and the pressure gradients on the gate bottom was then integrated over an area represented by a vertical projection of the gate upon a horizontal plane. As the recorded pressures were referred to a common datum and the integration measured only the pressure reduction on the bottom of the gate, the effect of buoyancy of the gate was not included in these measurements.

The downdraw of the model was converted to prototype by multiplying by the cube of the scale ratio. The downdraw is essentially the weight of a column of water above the gate because of the pressure reduction underneath it. The laws of similitude require that the volume of this hypothetical water column of the prototype be related to that of the model by the cube of the scale ratio. The specific weight of the water being the same in both cases, the weight of the water column, or downdraw, of the prototype must also be related to that of the model by the cube of the scale ratio.

The pressure measurements were especially useful in the tests to improve the design of the outlet coaster gate at Shasta Dam, for the pressure gradients on the various types of gate bottoms could be analyzed and compared. However, in later tests where the same type of gate bottom was used, the downdraw was obtained by measuring the force on the gate hoist by the mechanized gate lift. The nature of the later tests was such that pressure measurements would become tedious, while force measurements could be made quickly and easily. The forces acting on the gate were the weight of the gate and its buoyancy; the friction of the gate against the face of the dam; and the hydraulic downdraw. Only the sum of these forces could be measured directly, but the first two could be determined separately and hydraulic downdraw force obtained, for it was equal to the measured force on the hoist minus the weight of the gate in water and the friction.

The model gate was weighed while submerged to eliminate the effect of buoyancy. It was not practical to measure the static friction of the gate; but the kinetic friction was determined by raising and lowering the gate past the desired gate opening. Since the direction of the frictional force was the opposite of the gate movement, the difference between the forces on the gate lift while it was moving up and then down was equal to twice the kinetic friction, while the average of the two forces represented the force that would exist if the friction were zero.

For a given gate opening, the force measurements were made at several heads and the data was plotted. As the downdraw was proportional to the load, the data formed a straight line which made possible the detection of erratic readings.

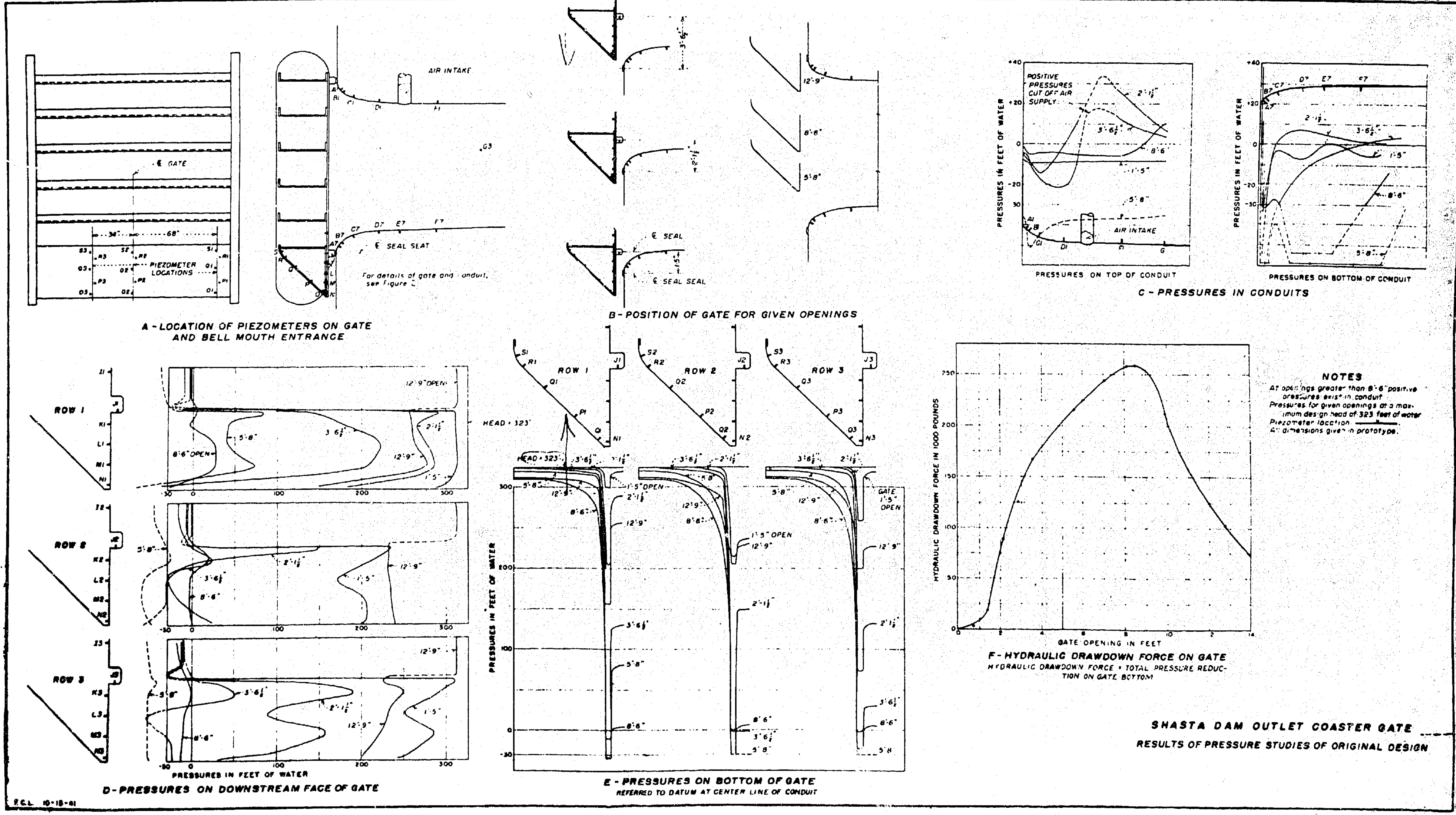
The first tests that were made using force measurements were none too satisfactory because difficulties were encountered in measuring the friction. The friction of the roller chains was so large that they had to be replaced with wheels. Flanged ball bearings that resembled miniature railroad wheels were used first. Under low heads they were satisfactory, but under heads larger than 10 feet the forces could not be measured easily for the wheels would stick in position and then release suddenly, obviously because they were overloaded.

Finally it was necessary to rebuild the gate, using wheels with diameter equal to the thickness of the gates. The diameter was as large as possible to minimize rolling and bearing friction. These wheels turned on ball bearings which were strong enough to withstand the forces imposed upon them. Nevertheless, the movements of the gate were still jerky, making the forces difficult to record, and it was found finally that the roller tracks on the face of the dam had to be glassy smooth before the jerking could be eliminated completely.

CHAPTER II - TESTS ON THE OUTLET COASTER GATE AT SHASTA DAM

<u>The original design</u>. Tests on the 1:17 model of the original design of the outlet coaster gate at Shasta Dam were begun with pressure measurements on the gate and in the outlet entrance (Figure 5A). The pressures were measured at several heads and gate openings. Since pressures were found to be nearly proportional to the head, the results of the tests are given for a maximum design head of 323 feet, prototype.

The relation of the hydraulic downdraw force to gate opening is shown in Figure 5F. With the gate in the full open position, the downdraw was approximately 75,000 pounds, prototype. As the gate closed the force first increased to a maximum of 260,000 pounds at an opening of about 8 feet 6 inches and then decreased, becoming zero with the gate closed. The maximum downdraw of 260,000 pounds apparently occurred as the gate became a definite control for, as the gate closed, pressures on its downstream face and in the outlet entrance changed from positive to negative when the gate was approximately 8 feet 6 inches open. The downdraw was less at larger gate openings because the control downstream from the gate maintained large positive pressures on the gate bottom. At gate openings less than 8 feet 6 inches, the control was at the downstream edge of the gate bottom where the pressures were a minimum, being zero or less. Elsewhere on the gate bottom, pressures were positive. As the gate was lowered, the pressures at the downstream edge of the bottom remained the same but the pressures on the gate bottom increased, reducing the downdraw. This was a logical result, as a closure of the gate decreased the discharge and hence decreased the velocities upstream from the control.



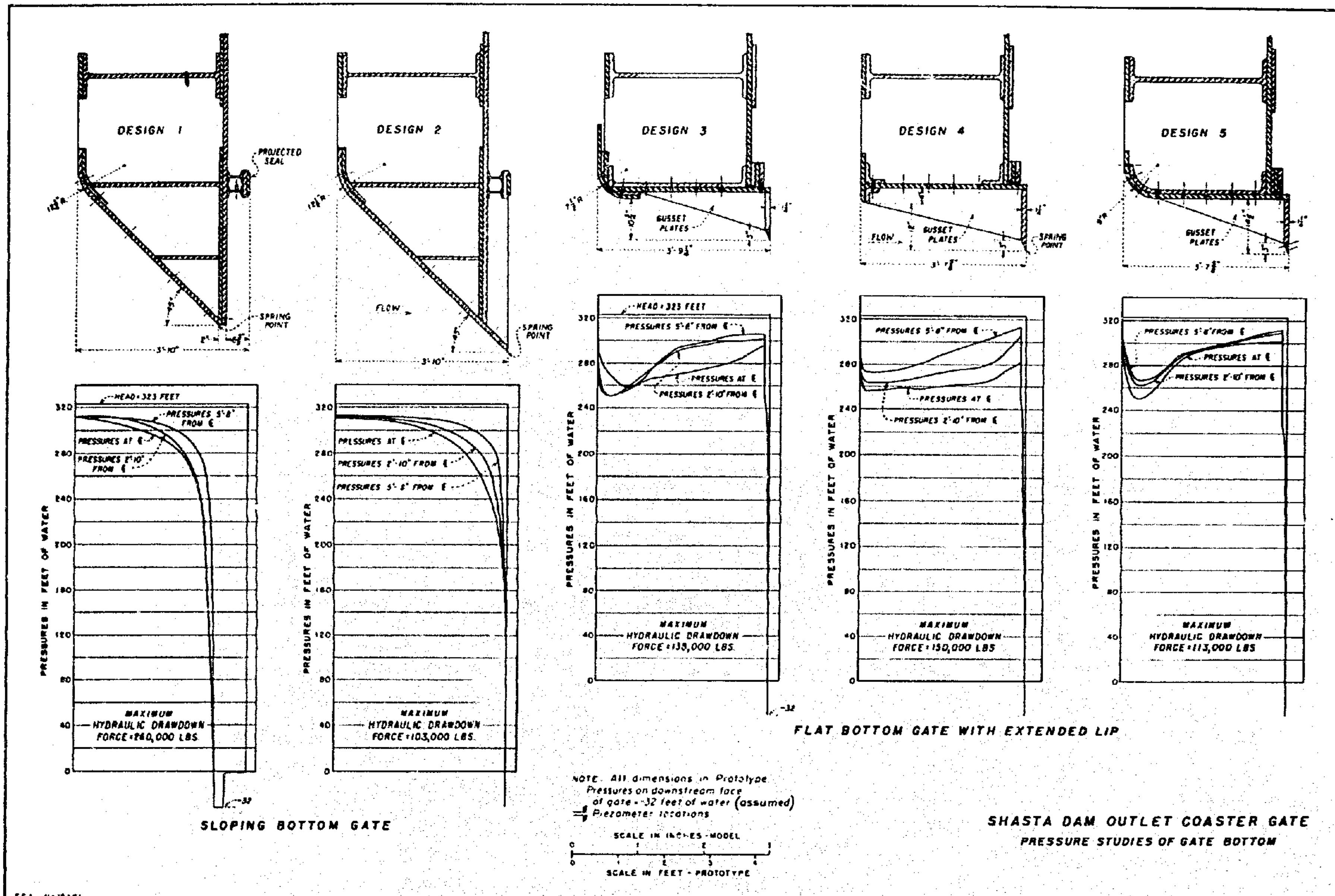
SHASTA DAM OUTLET COASTER GATE

RESULTS OF PRESSURE STUDIES OF ORIGINAL DESIGN

The pressures on the downstream face of the gate and in the outlet entrance at gate openings less than 8 feet 6 inches approached absolute zero in the prototype. In this respect, however, rigorous similitude between the model and prototype cannot exist, as the air entering the prototype vent would expand and afford slight relief. The vent was included to relieve the negative pressures sufficiently to prevent the severe vibration accompanying cavitation. However, when the gate was lowered in the range of gate opening between 2 and 3-1/2 feet, the jet under the gate impinged on top of the conduit and closed the vent. It was anticipated that this undesirable condition would be eliminated in later tests by changing the location of the vent, if necessary.

Reduction of downdraw in original design. The hydraulic downdraw force of 260,000 pounds, as determined by the pressure tests, did not agree with the original analytical estimate of 160,000 pounds. A review of the original calculations indicated that the figure of 160,000 pounds considered only the pressure reduction on the sloping portion of the gate bottom and apparently assumed that recess in the face of the dam above the outlet entrance would balance the pressures on the projected seals. The model test was made without a recess, and the unbalanced pressures on the top projected seal contributed at least 100,000 pounds to the total downdraw of 260,000 pounds. A recess in the model would tend to balance the pressures on the top seal, reducing the downdraw; and it was possible that a closer correlation might be obtained. However, the downdraw would still be excessive; so it was decided that the force should first be reduced by revision of the shape of the gate bottom and then, when a final gate design was obtained, to find the effectiveness of the recess in the face of the dam.

A study of the flow under the gate and of the pressure on its bottom demonstrated that it would be possible to obtain a large reduction of downdraw by an apparently simple revision of the bottom (Figure 6, Designs 1 and 2). The flow under the gate and into the outlet was studied by observing the movements of paper confetti in the head tank. The confetti approached the outlet from all directions, moving slowly until the paper particles were within a few inches of the outlet, where they appeared to be instantaneously drawn into it, indicating a rapid



SHASTA DAM OUTLET COASTER GATE
PRESSURE STUDIES OF GATE BOTTOM

FIGURE 6

increase in velocity close to the outlet entrance. This rapid increase in velocity was also shown by the pressure gradient across the 45-degree sloping portion of the bottom of the gate (Figure 6, Design 1). At the upstream edge the pressures were high. On approaching the outlet the pressure drop was at first gradual, but it became rapid close to the downstream edge. At the point where the 45-degree slope ended, the pressures became a minimum. This point was observed to be the spring point of the gate, that is, the point where the water normally sprang free of the gate bottom to form a jet in the conduit.

Between the spring point and the face of the dam was a space 8-3/8 inches wide, formed by the skinplate and reinforcing plate 2 inches thick and the projected seal 6-3/8 inches wide. The pressures on the bottom of the skinplate, the reinforcing plate, and the projected seal, being very low, did not balance the high pressures which were above these members at the top of the gate. As a result, this space between the spring point and the face of the dam contributed a large part of the downdraw. In contrast, the larger area of the 45-degree sloping portion of the bottom, upstream from the spring point, did not cause as much downdraw because pressures on most of this area were high, being low only near the spring point. Therefore, the original design was revised by extending the sloping portion of the gate bottom below the bottom of the skinplate and the projected seal. This revision placed the spring point close to the face of the dam, eliminating the effect of low pressures on those members (Figure 6, Design 2). The pressures on this revised gate bottom were similar to the original test; high near the upstream edge, dropping gradually at first, but more rapidly near the downstream edge with zero pressures occurring at the spring point. The maximum downdraw force was reduced from 260,000 to 103,000 pounds.

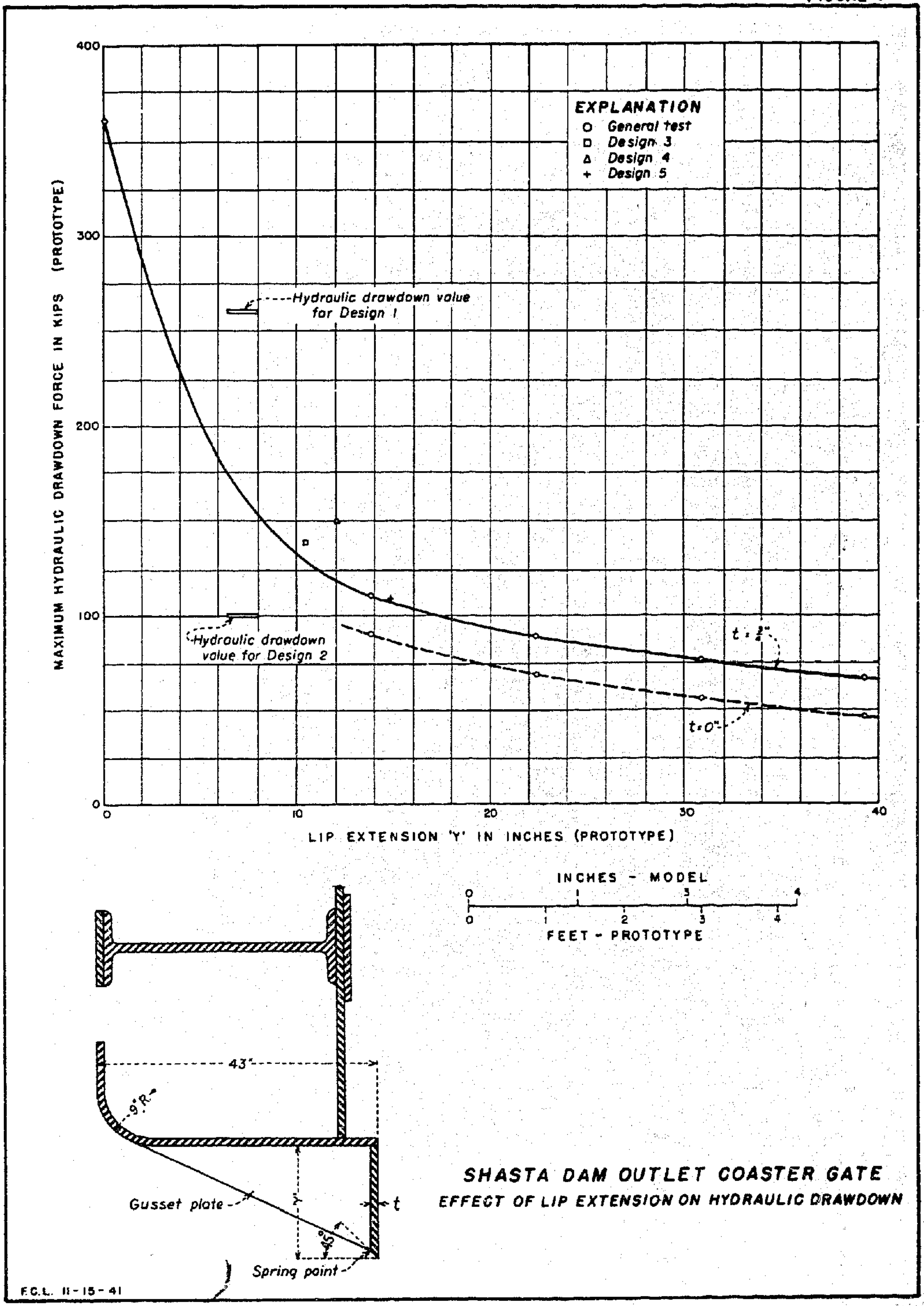
In contrast to the original design where the maximum downdraw occurred when the conduit was not completely filled with water, the maximum downdraw on the revised gate apparently occurred while the conduit was filled with water, just before a slight additional closure would lower the pressures so that the conduit would take some air through the vent.

Although the flow inside the conduit adjacent to the gate could not be observed, in similar models it had been noted that when the gate was partially closed and the conduit downstream from it was filled, a roller formed over the jet issuing from under the gate. This roller has a downward movement along the downstream face of the gate. Such a roller must have existed in the Shasta model for the pressures on top of the lower horizontal projected seal of the gate were greater than the pressures on the bottom of the upper projected seal, indicating that water must be impinging on the top of the lower seal. This condition caused a downward force estimated to be 5,000 pounds. However, this force was not of sufficient magnitude to be considered important. In addition to reducing the downdraw, this revised design changed the shape of the jet flowing into the outlet so that the jet at no time impinged on top of the conduit to close the air-vent, as was the case in the original design when the gate was open between 2 and 3-1/2 feet.

Effect of extended lip below downstream edge of flatbottom gate. The revised sloping-bottom gate reduced the downdraw from 260,000 to 103,000 pounds, which was desirable because the gate hoist would not be overloaded. However, the gate was not structurally desirable, for the sloping bottom was difficult to fabricate and heavy plates were required to withstand the loads on its downstream edge. Accordingly, further tests were made to develop some other type of gate which would have even less downdraw or at least a more acceptable structural design at the bottom.

The indications from the original tests were that a gate having a minimum downdraw would be one with a lip placed at the downstream edge of the bottom and extended vertically below the gate. This would place the spring point at a distance from the bottom, and the rapid drop in pressure which occurs near the spring point would be upon the vertical plane of the extended lip. To verify these indications a test was made to determine the effect of an extended lip by reducing the lip, in successive steps, from an extension nearly equal to the thickness of the gate to zero (Figure 7).

A flatbottom gate was selected for these tests, since it appeared most practical. The upstream edge of the bottom was curved on a 9-inch radius, prototype, to reduce the effect of the pressure on the bottom



SHASTA DAM OUTLET COASTER GATE

EFFECT OF LIP EXTENSION ON HYDRAULIC DRAWDOWN

F.C.L. 11-15-41

when the flow down the upstream face of the gate changes direction below the gate. The thickness of the extended lip was 3/4 inch (prototype), and its bottom was beveled at 45 degrees to place the spring point at the downstream edge of the lip and reduce the effect of its thickness upon the downdraw. The extended lip was supported by gusset plates attached to the bottom of the gate. These plates were in the plane of flow so that their effect upon the downdraw would be small and could be neglected.

The tests were made in the same manner as for the original design, that is, by measuring the pressures across the bottom of the gate to determine the downdraw. The pressure gradients were similar to those of Design 5, Figure 6, except that negative pressures occurred on the bottom of the lip. There was a reduction of pressure near the upstream edge, as was anticipated, since the flow down the upstream face of the gate had to change its direction. However, the pressure increased rapidly, becoming a maximum at the downstream corner where the lip joins the gate bottom. This condition indicated that not only does the extended lip keep the rapid reduction in pressure near the spring point on the vertical plane of the lip where it cannot cause downdraw but that it also tends to form a stagnation point in the downstream corner, noted by an increase of pressure at that point. The original gate tested had a large fillet in this corner; later tests indicated that its effect upon the downdraw was negligible.

Although the bottom of the lip was beveled at 45 degrees to place the spring point on its downstream edge, the contour of the jet was so steep that it flowed free from the bevel, and the spring point was on the upstream edge of the lip. The resulting negative pressures on the bottom of the lip would cause a downdraw of approximately 15,000 pounds when the lip was 3/4 inch thick, as indicated on Figure 7.

This curve of Figure 7 was plotted by finding the maximum downdraw force for different lip extensions. The maximum extension considered was approximately equal to the thickness of the gate, as a greater extension would be impractical structurally. This curve shows that an extension of 40 inches would reduce the downdraw to approximately 65,000 pounds. As the extension was decreased, the downdraw increased gradually until at a lip extension of 14 inches the downdraw was 110,000 pounds.

A further decrease in the extension caused a more rapid increase in downdraw which finally became 360,000 pounds when there was no extension.

Structural designs of flatbottom gate with extended lip. To build a flatbottom gate with an extended lip below its downstream edge which would develop a downdraw of 110,000 pounds, equalling that of the sloping-bottom gate of Design 2 (Figure 6), a lip extension of 17 inches would be necessary. But this was not practical, since the horizontal forces on it would be excessive. Nevertheless, a flatbottom gate having an extended lip was a simple design compared with the sloping bottom of Design 2; so further studies were proposed to see if a design involving a flat bottom and extended lip could be used, even though a slightly larger downdraw would result.

Design 3, Figure 6, was conservative from a structural viewpoint, having a lip extension of 10-3/4 inches which, from the curve of Figure 7, indicated a downdraw of approximately 130,000 pounds. The radius at the upstream edge of the bottom was 7-1/2 inches instead of 9 inches, prototype, as in the general test, and the thickness of the lip was 1-1/4 inches instead of 3/4 inch. It was anticipated that the smaller radius would increase the downdraw a small amount. The bottom of the lip was beveled at a steeper angle, 67 degrees 20 minutes, to place the spring point at its downstream edge to reduce the downdraw on the lip (Figure 6). The tests showed that the downdraw would be approximately 138,000 pounds. The steeper bevel on the lip placed the spring point at its downstream edge. Piezometers placed on the lip to determine pressures indicated that the downdraw on the 1-1/4-inch lip was nearly equal to that on the 3/4-inch lip of the general test in which the spring point was at its upstream edge. Accordingly, the curve of Figure 7 could be used to predict the downdraw of a gate having a 1-1/4-inch lip with a 67-degree bevel at its bottom.

In design 4, Figure 6, a simplification of the structural details was made by using flat plates and angles to eliminate the curved section at the upstream edge of the gate bottom. The end of the plate at the upstream edge was rounded to avoid a sharp corner at that point. A 1-1/4-inch lip having a steep bevel, similar to Design 3, was extended 12 inches below the upstream edge. The downdraw was 150,000 pounds, which represented a 25 percent increase over the downdraw that was obtained when using a 9-inch radius at the upstream edge of the gate bottom and a 12-inch lip extension, as on the gate in general test (Figure 7).

The final Shasta design. Neither Design 3 nor 4 was satisfactory for the Shasta Dam outlet coaster gates, for their downdraw of 135,000 and 150,000 pounds, respectively, was excessive. A careful analysis of the stresses on the bottom of a gate similar to the model used in the general test revealed that this gate would be practical if the lip extension did not exceed 14-1/2 inches; and the curve of Figure 4 indicated that the gate would develop a downdraw of 110,000 pounds. Since this downdraw was not excessive, Design 5 was constructed and tested (Figure 6). Design 5 differed from the gate of the general test in that a 1-1/4-inch lip having a 67-degree bevel at its bottom was used instead of a 3/4-inch lip having a 45-degree bevel. It was found previously that the downdraw on the 1-1/4-inch lip was nearly equal to that on the 3/4-inch lip with a 45-degree bevel. This downdraw of 112,000 pounds on Design 5 checked the downdraw predicted of 110,000 pounds. The gate of the final design was made an inch thicker than the gate tested; therefore the value of 112,000 pounds was rechecked and the estimate increased to 113,000 pounds.

It was apparent that any change of the gate to reduce the downdraw, such as extending the lip further, was not desirable; so this gate was selected as the final design. Three additional tests were made on it to conclude the studies of the outlet coaster gates at Shasta Dam: (1) the maximum downdraw of 113,000 pounds, obtained by pressure measurements, was checked by force measurements; (2) the effect of the gusset plates which supported the extended lip was checked; and (3) the effect upon downdraw of a recess in the face of the dam above the outlet entrance was studied to give the final design estimate of a maximum downdraw of 70,000 pounds.

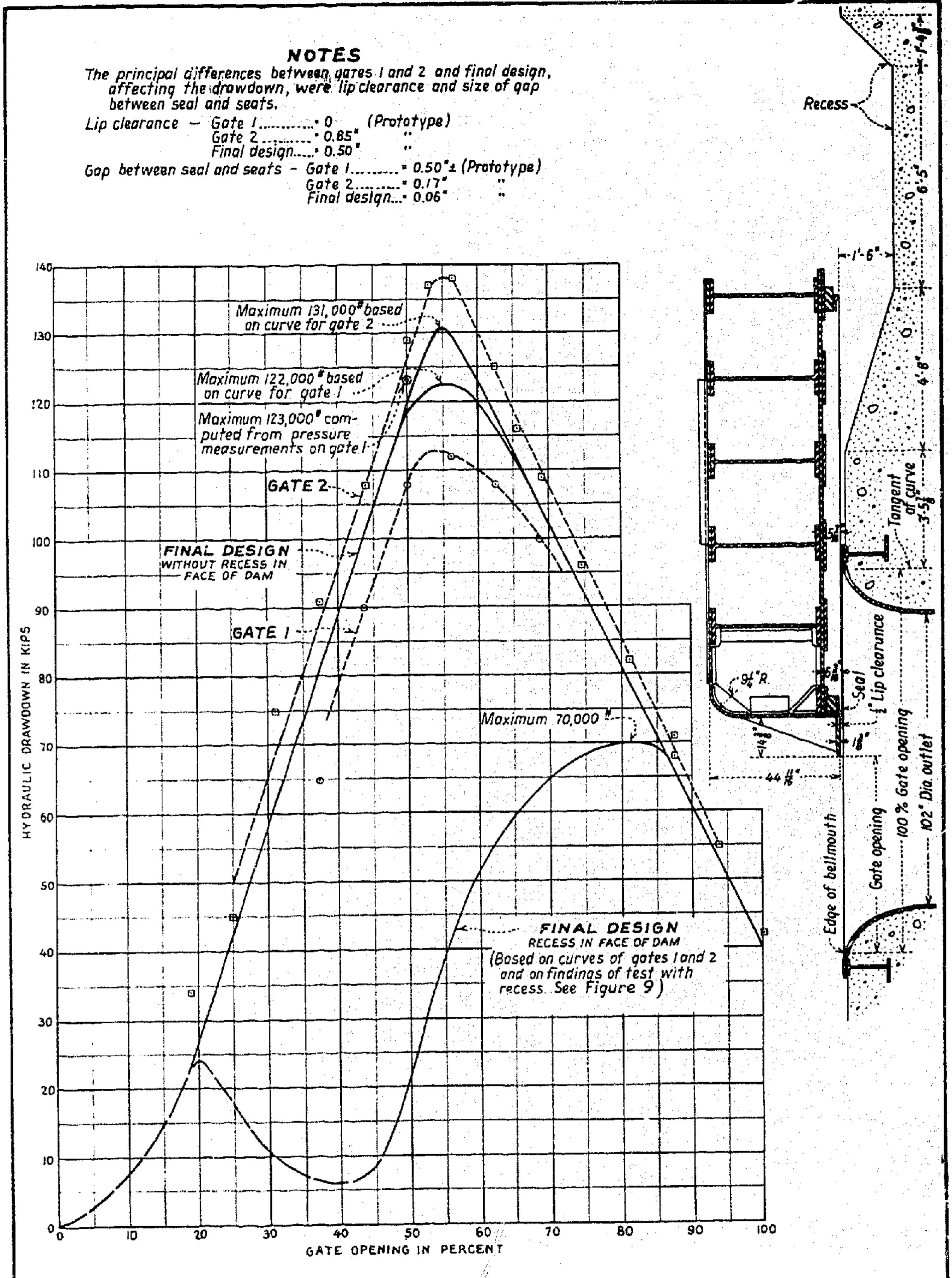
Correlation of downdraw by force measurements. Although the downdraw was estimated to be 113,000 pounds, a conservative allowance was necessary because the pressure measurements might be slightly in error due to unbalanced pressures existing on some portion of the gate not covered by piezometers during the tests. Therefore, the downdraw was checked by measuring the forces on the gate. The manual gate lift was replaced by a mechanized gate lift designed to measure the forces on the hoist while the gate was in motion, as described in Section 9.

Two gates were used for these correlation tests. Gate 1 was the same as used in the pressure tests, overhauled for the force measurements. Gate 2 was ostensibly the same as Gate 1, except it was designed specifically for force measurements.

To reduce the friction of Gate 1 the roller chains were replaced with flanged bearings, and the seals were reduced until they were flush with the downstream edge of the lip so they would not rub against the seal seats. The resulting gap between the seals and their seats was between 0.02 and 0.04 inch (model). At that time it was believed that the leakage through this gap would not affect the downdraw. The downdraw on Gate 1 was recorded over a range of gate openings (Figure 8), whereas the pressure measurements had been recorded only at maximum downdraw. The gate openings were based on the distance from the bottom of the lip to the lower edge of the bell-mouth (Figure 8).

The maximum downdraw of 113,000 pounds on Gate 1 recorded by force measurements checked closely the downdraw by pressure measurements of 112,000 pounds, indicating that the pressure measurements were reliable. The gate opening at which these maximum values occurred was 50 percent for the pressure measurements and 55 percent for the force measurements.

Gate 2, upon which the final measurements were made, was constructed more carefully than Gate 1 in that the gap between the seals and the seal-seats was at all points less than 0.17 inch (0.01 inch, model), while the gap on Gate 1 was about 0.50 inch (between 0.02 and 0.04 inch, model). The extended lip was set upstream from the face of the seals, forming a lip clearance of 0.85 inch (0.05 inch, model), while there was no lip clearance on Gate 1. Otherwise, the gate bottoms were identical. The maximum down-draw of Gate 2, occurring at a gate opening of 55 percent, was 139,000 pounds. Some discrepancy was expected between Gates 1 and 2, but not 24 percent. However, a study of the gates revealed that a large part of this difference was caused by the 0.05-inch lip clearance of Gate 2 and that some of the discrepancy might be caused by the larger gap between the seals and their seats on Gate 1.



SHASTA DAM OUTLET COASTER GATE

HYDRAULIC DRAWDOWN - FINAL DESIGN

F.C.L.-H.R.S.-M.T.Y.-1-23-43

The importance of the lip clearance was demonstrated in the tests to reduce the downdraw in the original design when it was necessary to place the spring point as close to the face of the dam as possible so that the lip clearance would be a minimum. An ideal gate would have the downstream edge of the extended lip touching the seal-seats. This is not possible; so a lip clearance is necessary. Since it was recommended that this lip clearance be as small as possible, it was felt that the unbalanced pressures on the portion of the seals over this lip clearance would not cause an appreciable increase in the downdraw. However, the tests on Gate 2 further emphasized its importance; and when the lip clearance of the final design was established as 1/2 inch, it was necessary to revise the maximum downdraw obtained from pressure measurements from 113,000 pounds to 123,000 pounds (Figure 8). In a similar manner the downdraw curve of Gate 1 was revised with a maximum downdraw of 122,000 pounds. The lip clearance of Gate 2 being 0.85 inch, prototype, the downdraw curve for Gate 2 was revised to a maximum downdraw of 131,000 pounds.

These revised curves of Gates 1 and 2 are in good agreement at all points except at their peak where a discrepancy of 7-1/2 percent exists. This discrepancy is probably due to the larger gap of 0.02 to 0.04 inch (model) between the seals and the seal-seats of Gate 1, which tended to reduce the downdraw. A test was made, by removing the seal-seats, to increase this gap to approximately 0.08 inch, and the downdraw was further reduced about 25 percent. Evidently water flowing through this gap formed pressures on the under side of the upper seal frame, producing an upward force. This test demonstrated the possibility of reducing the downdraw by increasing the clearance between the seals and seats. The same action was accomplished by placing a recess in the face of the dam above the outlet.

<u>Effect of the gusset plates supporting the extended lip</u>. Before tests upon the effect of a recess in the face of the dam were begun, the influence of the gusset plates supporting the extended lip was studied. These plates were placed vertically in the plane of flow so they would not cause downdraw. Piezometers on the bottom of the gusset plates indicated a pressure reduction on those members greater than on the gate bottom, but their contribution to the downdraw was not appreciable because the area on

the bottom of the gusset plates was small compared with the total area of the gate bottom. To confirm these findings force tests were made on Gate 1 with the gusset plates removed, but no difference in downdraw could be observed.

It was concluded that a reasonable number of gusset plates could be used to support the extended lip without increasing the downdraw. These gusset plates should end at the point where the bevel of the extended lip begins, approximately 3 inches above the spring point. It is suggested that any sharp curves on the bottom of these gusset plates be rounded by grinding.

Effect of a recess in the face of the dam. The maximum downdraw obtained from force measurements on Gate 2 was 131,000 pounds. It occurred at a gate opening of 55 percent. There were indications that this force could be substantially reduced by a recess in the face of the dam above the outlet entrance. When the gate was partially open, water would fill the recess and pressures on the under side of the upper, horizontal, projected seal would tend to balance the static pressure on top. Without a recess, pressures on the under side of the upper projected seal would be low, the same as pressures in the outlet entrance; so the static pressure on top of the upper projected seal would exert a downward force which becomes part of the downdraw.

The actual effectiveness of the recess was questioned. The water would flow continually from the portion of the recess above the gate, past the opening between the upper projected seal and the face of the recess into the portion of the recess below the top of the gate, thence past the opening between the skinplate and the upper seal-seat on the dam and into the outlet. If the jet of water flowing into the outlet were to impinge upon the top of the lower projected seal, the impact would create a downward force which would nullify the advantage gained by increasing pressures on the bottom of the upper seal frame. Where the depth of the recess is limited, the opening between the upper projected seal and the face of the recess may become a control, resulting in reduced pressures on the under side of the upper projected seal the same as if no recess existed. To be effective, the control has to be at the opening between the skinplate and the upper seal-seat; therefore the pressures in the lower portion of the recess, below the top of the gate, are nearly the same as the static pressures above the top of the gate.

Model studies were made to find the actual effectiveness of the recess, to observe whether the jet from the recess would impinge on the top of the lower projected seal, and to determine the minimum depth of recess which would be practical. To make the 1:17 model correspond with the prototype, the proposed recess, as determined analytically, would have to be at least 1 inch deep. Such a recess could not be used without major revision of the model. A recess 1/4 inch deep was possible and would be satisfactory if the tests were of a general nature rather than a specific study of the recess at Shasta Dam. Therefore, the results are shown only in model dimensions (Figure 9). The downdraw of the final design of the Shasta Dam outlet coaster gate with the recess was calculated from these findings.

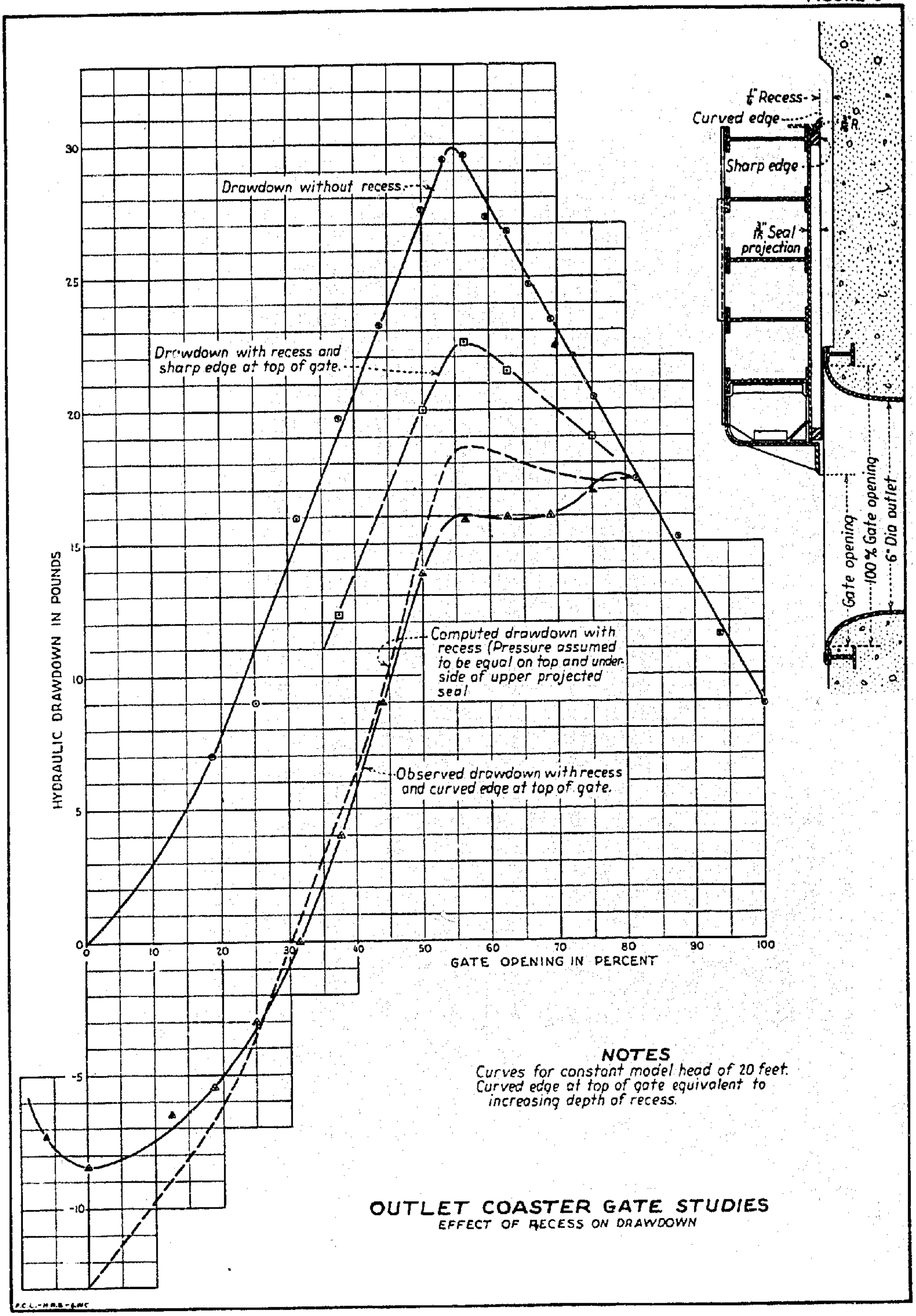
The model of the final Shasta Design, Gate 2, was used for the tests, and the relationship of the downdraw to the gate opening for this model, without a recess, was used as a basis for comparison (Figure 9). The seal projection of the model, about 3/8 inch to correspond with the final Shasta Design, was reduced to 3/16 inch when preliminary tests demonstrated that the projection must be less than the depth of the recess.

Two preliminary tests were made, one with a seal projection of 3/8 inch and one with a projection of 1/4 inch. With a seal projection of 3/8 inch the opening between the upper seal and the face of the recess was definitely a control and no reduction of downdraw was observed. With the projection of 1/4 inch the opening between the upper seal and the face of the recess was the same as the opening between the skinplate and the top seal-seat on the dam. So two controls might exist. Some reduction of downdraw was observed, but pressures on the under side of the upper projected seal were considerably less than the static pressure on top.

However, with the 3/16-inch seal projection, the control was at the space between skinplate and top seal-seat and a substantial reduction of downdraw was observed (Figure 9, curve with sharp edge at top of gate). The pressures on the under side of the upper horizontal seal frame were about half the static pressure on top, which indicated that a further reduction of downdraw could be obtained by a deeper recess, for the velocities past the upper seal would be less and the pressures on its under side greater.

As a deeper recess was difficult to install in the model, the same result was accomplished by placing a curved section on top of the upper seal. The square edges of the upper projected seal formed a contraction which increased the velocities around the projected seal and decreased the pressures under it. With a curved section on top of the projected seal, the flow was similar to the flow through a bellmouth orifice without contraction. This revision was effective, for the observed downdraw reasonably checked a calculated curve based upon the reduction of downdraw due to the recess, which assumed pressures on the top and the under side of the upper seal to be balanced. These curves checked closely between gate openings of 20 to 50 percent. Between openings of 0 to 20 percent the observed curve had larger values; but this was anticipated, for when the gate was nearly closed the recess would not be effective. Between gate openings of 55 to 70 percent the calculated values were larger than the observed values. In this region the flow conditions became complex and the values of the calculated curves were based upon conservative assumptions. When the gate was about 80 percent open, the recess was ineffective, for the bottom seal contacted the top seal frame. Under this condition no flow passed through the recess and static pressures on top of the lower projected seal exerted a downward force with the same effect as if no recess existed.

The agreement between the observed and the calculated curves between gate openings of 20 to 50 percent, where the calculations were reliable, was at first disconcerting because the pressures on the bottom of the upper projected seal were about 75 percent of the static head, and, if pressures on top of the seal were static, as first assumed, then the reduction of downdraw should be only 75 percent of the reduction obtained by assuming balanced pressures on the top and the bottom of the seal. However, pressures on the curved section on the top of the upper seal must be less than the static and would tend to balance the pressure on the bottom. No pressure measurements were made on the curved section above the upper seal; but other studies have indicated that a reduction in pressure will occur on any curved entrance similar to the arrangement of the model. Should it be necessary to use a shallow recess in a future prototype structure, a curved section similar to the section used in the model might be placed at the top of the upper seal. The radius should be at least equal to the projection of the seal and should be almost flush with the contact line of the seal, to be effective.



OUTLET COASTER GATE STUDIES
EFFECT OF RECESS ON DRAWDOWN

No such curved section was considered necessary on the Shasta outlet coaster gate because the recess was made 18 inches deep, approximately three times the depth of the seal projection. From the findings of the general test this was considered to be a reasonable depth, sufficient to balance the pressures on the top and the bottom of the upper seal. Figure 8 shows a curve of the probable downdraw on the Shasta gate with recess, calculated in the same manner as the calculated curve of Figure 9. These calculations were based upon the assumption that the pressures on the upper seal were balanced. The reduction in downdraw from the unbalanced condition (shown by the final design curve without recess in face of dam), will be equal to the product of the head differential between the top of the gate and the outlet entrance and the exposed area of the projected seal. Assuming a differential head of 323 feet, a seal projection of 5-7/16 inches, and a seal width of 11.05 feet, this reduction would be 101,000 pounds. This reduction would occur at gate openings from 0 to 50 percent when the pressures in the outlet entrance are atmospheric or negative.

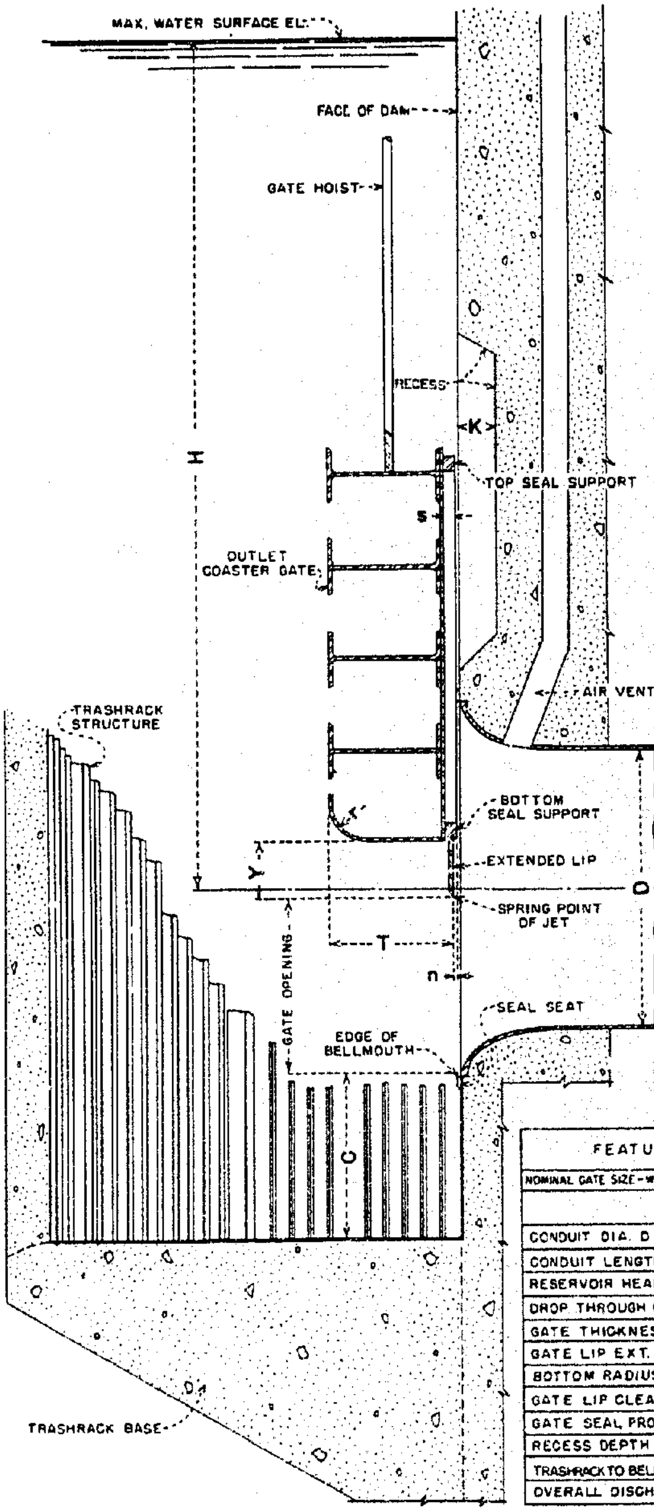
Negative downdraw or uplift forces would occur at gate openings less than 40 percent. As shown by the curves of Figure 9, an uplift force was observed on the model. During the tests it was demonstrated that this force could prevent the model gate from closing. To avoid this condition the prototype recess was tapered so that as the gate closed the recess would begin to lose its effectiveness at a gate opening of 45 percent and become completely ineffective when the gate was 20 percent open. The actual downdraw on the gate while it was being lowered from 45-percent to 20-percent openings would be uncertain, as shown by the dashed portion of the curve. At gate openings larger than 50 percent the head of 323 feet would be reduced by the pressure in the conduit then flowing full. Also, the reduction of downdraw would be lessened, since the top of the lower projected seal would be near the top of the circular bellmouth and only a portion of the seal width of 11.05 feet would be effective. It was assumed that only the portion of the top of the lower projected seal spanning the opening of the circular bellmouth was effective. From these calculations the maximum downdraw of 70,000 pounds was estimated to occur when the gate was 80 percent open.

CHAPTER III - ADDITIONAL OUTLET COASTER-GATE STUDIES

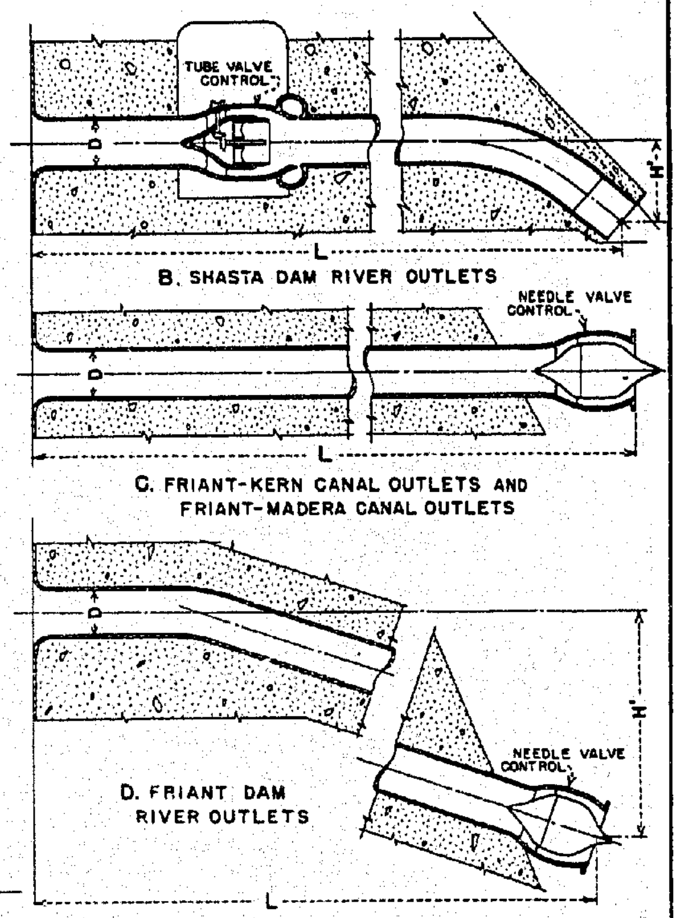
Comparison of outlet coaster gates. The outlet coaster-gate studies were continued to obtain sufficient data for estimating the downdraw on the gates at Friant Dam (Section 25) and on other similar outlet coaster gates. The various outlets and their coaster gates were studied and compared to determine the additional tests necessary so that the results of the tests on the outlet coaster gate at Shasta Dam could be applicable to other installations. Although the outlet entrances and gates were similar (Figure 10A), the outlets were of several types (Figures 10B, C, and D) and the dimensions of certain features which would affect the downdraw were not similar (Figure 10E).

Since the outlets varied in size, the diameter was used as a basis of comparison. If two outlets of different sizes were geometrically similar, such as a model and a prototype, the dimensions of their various features, such as the length of the conduit, would be the same when based upon the diameters; so their performance could be compared by principles of similitude. However, if two outlets were similar except for some dimension, as the conduit length, that dimension based upon their diameters would not be the same. Nevertheless, their performance could be compared if the effect of feature, such as a difference in length, were known. Moreover, the performance of two gates could be compared if they were different in several respects, providing the effect of all of the differences were known. Thus the effect on downdraw of the features shown in Figure 10E had to be determined before the results of the model studies on the Shasta Dam outlet coaster gates could be applied to the Friant Dam coaster gates.

The effect on downdraw of the following features was studied in the Shasta Dam outlet coaster-gate tests: (1) the reservoir head, H; (2) the gate lip extension, Y; (3) the bottom radius, r; (4) the gate lip clearance, n; (5) the gate seal projection, S; and (6) the recess depth, K. Additional outlet coaster-gate studies were necessary to find the effect on downdraw of: (1) the drop through the conduit, H'; (2) the resistance to flow through the conduit caused by the conduit length, L, and the regulating valves; (3) the thickness of the gate, T; and (4) the distance of the trashracks base from the edge of the bellmouth, C. Also, tests were



A. TYPICAL OUTLET ENTRANCE



OUTLET SECTIONS

E. TABLE OF DIMENSIONS

FEATURE	SHASTA DAM RIVER OUTLETS		FRIANT-KERN CANAL OUTLETS		FRIANT-MADERA CANAL OUTLETS		FRIANT DAM RIVER OUTLETS	
NOMINAL GATE SIZE-WIDTH W & HEIGHT	11.05' X 11.05' GATE		11.92' X 11.92' GATE		9.86' X 9.86' GATE		11.92' X 11.92' GATE	
		RATIO TO DIAMETER		RATIO TO DIAMETER		RATIO TO DIAMETER		RATIO TO DIAMETER
CONDUIT DIA. D (Inches)	102	1	110	1	91	1	110	1
CONDUIT LENGTH L (Ft.)	* 230	27	* 89	9.7	* 103	13.6	* 200	21.8
RESERVOIR HEAD H (Ft)	323	38	114	12.4	132	17.4	196	21.8
DROP THROUGH CONDUIT H' (Ft)	16.6	1.95	0	0	0	0	50	5.45
GATE THICKNESS T (in.)	44 11/16	0.438	* 40	0.364	29 1/4	0.321	* 40	0.364
GATE LIP EXT. Y (In)	14 3/8	0.141	* 15	0.136	12 1/4	0.120	* 15	0.136
BOTTOM RADIUS r (in)	9 1/4	0.091	9 1/4	0.084	9 1/4	0.091	9 1/4	0.084
GATE LIP CLEARANCE n (in.)	1/2		* 1/2		7/16"		* 1/2	
GATE SEAL PROJ. S (in)	6 7/16	0.060	* 4 1/8		4 1/8		* 4 1/8	
RECESS DEPTH K (In)	18	0.176	1/4		1/4"		1/4"	
TRASHRACK TO BELLMOUTH C (Ft.)	16.47	1.94	40	0.436	6.60	0.740	19.03	2.07
OVERALL DISCHARGE COEF. C_x	* 0.69		* 0.58		* 0.56		* 0.66	

* APPROXIMATE

OUTLET COASTER GATE STUDIES

DIMENSIONS AND NOMENCLATURE FOR OUTLETS OF SHASTA AND FRIANT DAMS

made to study further the gate lip extension and the radius at the upstream edge of the gate bottom. From these tests the downdraw on the outlet coaster gates at Friant Dam was estimated, as explained in Section 25.

Effect of drop in conduit. The downstream sections of the Shasta Dam outlets were curved downward to direct their jets along the face of the dam, making the centerlines of the exits approximately 16.6 feet below that of the entrances (Figure 10B). This drop through the conduit was normally part of the effective head acting on the outlet. Nevertheless, in the tests on the Shasta Dam outlet coaster gate the head was measured from the centerline of the outlet entrance and the drop, H', was not considered as part of the head. The effect upon downdraw of the drop, H', was not established clearly in those tests because the drop represented only 5 percent of the total head. However, the drop, H', was 50 feet at the Friant Dam River outlets, which was 25 percent of the head, H, above the gate. Therefore, it was necessary to determine the effect of the drop through the conduit.

The model was revised to represent a Friant Dam River outlet by changing the scale ratio to 1:18.33, filling the recess in the face of the dam, removing the regulating Shasta tube valve, installing an elbow in the conduit to produce a 2.73-foot drop (50 feet prototype), and placing a 1:18.33 scale model of a Friant needle valve at the exit. The model coaster gate, the final Shasta design, was not revised for this test. The hydraulic downdraw was measured at several heads and gate openings and compared with similar measurements on the same model with no drop in the conduit.

The tests were not completely satisfactory because the effect of the drop of the conduit was uncertain at gate openings between 48 and 58 percent where the downdraw was a maximum. Nevertheless, the effect of the drop was shown clearly for other gate openings. Until the gate was closed to a point where the pressures in the outlet entrance decrease rapidly with further closure, at about 58-percent opening, the drop H' increases the effective head on the gate, increasing the downdraw. When the gate became a definite control, openings less than 45 percent, the drop in the conduit had no effect upon the downdraw. With the gate as a control the pressures in the outlet entrance were negative, being relieved by aeration to the extent that the head on the gate was independent of the drop in the conduit.

From the tests it was concluded that the drop in the conduit would increase the downdraw only when the conduit was full of water with positive pressures in the outlet entrance. Since the maximum downdraw was observed to occur when the conduit was filled and with slight positive pressures at the entrance, it may be further concluded that the maximum downdraw would be increased by a drop in the conduit. It was conservative to base the downdraw on a head H + H'.

Effect of restricting outlet flow. The design of the outlet coaster gate at Shasta Dam was based upon the assumption that the regulating tube valve in an outlet might fail in an open position and that the gate would then have to close the outlet. Therefore, the tests to measure downdraw were made with the tube valve wide open, for it was apparent that closing the tube valve would restrict the flow and reduce the downdraw. The same premises were used in the design of the outlet coaster gates at Friant Dam although the downdraw was to be estimated from the results of the Shasta tests. However, the relative discharge of the Friant outlets was less than that of the Shasta outlets. So the flow through those outlets might be compared with the flow through a Shasta outlet when its valve was partly closed. No tests on the Shasta outlet were made with the valve partly closed; so it was necessary to study the effect of restricting the flow through the outlets.

The restriction of flow through outlets was expressed as an overall coefficient of discharge C_o obtained from the expression

$$Q = C_o A \sqrt{2 g H}$$

where

Q = discharge,

A = area of the outlet conduit, and

H = total head on the outlet.

C_o included all losses in the conduit and was related to the more common expression for the total head $H = (1 + K_1 + K_2 + K_3 \ldots) \frac{V^2}{2g}$ in the following manner:

$$Q = C_o A \sqrt{2 g H} = C_o A \sqrt{2g (1 + K_1 + K_2 + K_3 \ldots)\frac{V^2}{2g}}$$

or $$Q^2 = C_o^2 A^2 . 2g (1 + K_1 + K_2 + K_3 \ldots) \frac{V^2}{2g}$$

$$\frac{Q^2}{2g\ A^2} = C_o^2\ (1 + K_1 + K_2 + K_3)\ \frac{V^2}{2g}$$

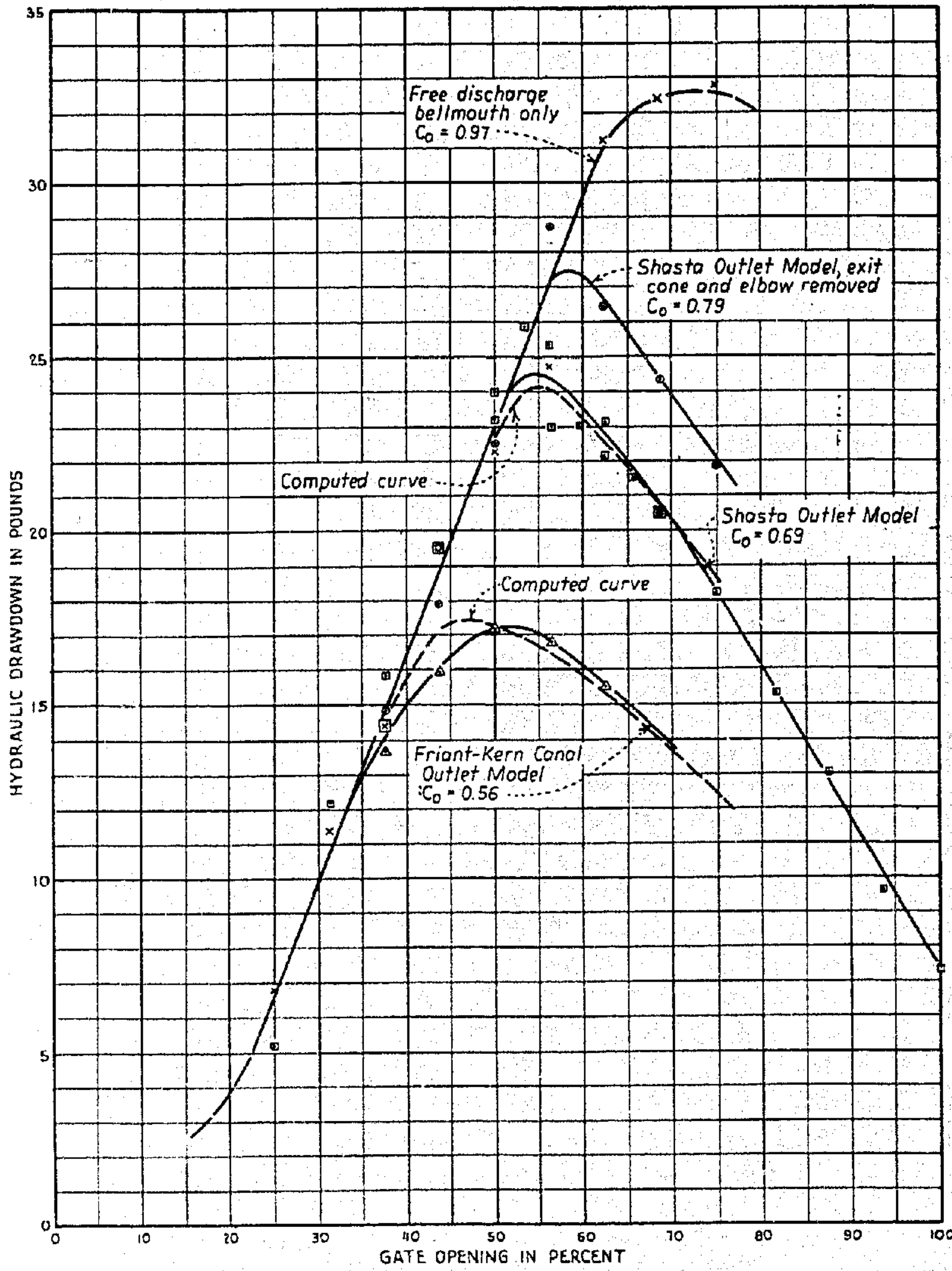
from which

$$C_o = \frac{1}{\sqrt{1 + K_1 + K_2 + K_3 \ldots}}$$

The downdraw on the Shasta outlet model with $C_o = 0.69$ was compared to the downdraw on a Friant-Kern Canal model with $C_o = 0.56$ and with two other arrangements made by removing the exit cone and elbow from the Shasta model with $C_o = 0.79$, and by removing all conduit downstream from the bellmouth to produce free discharge $C_o = 0.97$. The same model gate, the final Shasta design, was used for all tests. The results were corrected to a model head of 20 feet as shown on the gate opening versus head curves of Figure 11.

These curves show the maximum downdraw for the several outlets to be roughly proportional to the overall coefficient of discharge C_o. This relationship appears feasible to compare quickly the effect on downdraw of similar coaster gates used at outlets where the overall coefficient C_o is not the same. However, a more reliable method for computing an outlet having a given C_o is possible since downdraw is proportional to the velocity head under the gate. Such a procedure may be used to advantage if the downdraw curve for unrestricted discharge is known and the effect of a given restriction desired. The computed curves for the Shasta tube valve, Figure 11, and for the Friant needle valve were obtained from the curve for free discharge, $C_o = 0.97$. The method of obtaining these curves will be described, for the same procedure was used later to estimate the hydraulic downdraw forces on the penstock coaster gates at Davis and Grand Coulee Dams from basic data obtained on a model of a Shasta Dam penstock coaster gate tested for free discharge.

The free discharge curve $C_o = 0.97$ was selected as the basic curve because the velocity head for this curve was nearly constant. With a constant head of 20 feet on the gate, the velocity head was 20 feet at a 75-percent gate opening which increased to approximately 22 feet for gate openings between 30 and 60 percent, for negative pressures existed in the short bellmouth entrance. The curve $C_o = 0.97$ demonstrates that the downdraw was a maximum at a gate opening of 75 percent if the velocity head were



Restriction of flow through Outlet is expressed as a coefficient C_o which includes all losses, obtained from the expression $Q = C_o A\sqrt{2gh}$ where Q = discharge, H = total head, A = area of conduit. All data for constant model head of 20 feet. Shasta and Friant Models are shown on Dwg.

OUTLET COASTER GATE STUDIES

EFFECT ON DRAWDOWN OF RESTRICTING OUTLET FLOW

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not reduced. With restricted flow, shown by the other curves, the downdraw was the same as for free discharge as long as the gate was a control. The pressures in the outlet entrance were then negative. However, at wider gate openings, when the control was not at the gate, the downdraw was reduced. The maximum downdraw with the restrictions was considerably less than the downdraw for unrestricted flow and appeared to occur at a gate opening slightly larger than the opening where the gate became a definite control.

The nature of these curves suggested that the downdraw for any given restriction may be found from the curve of downdraw for free discharge by obtaining the velocity head under the gate over a range of gate openings. With the restrictions in the outlet, the velocity head will be reduced at wide gate openings when the gate is not a control. The downdraw will be reduced proportionately. The velocity head H_v may be expressed as $H_v = \frac{Q^2}{2g\,A_1^{\,2}}$ where Q equals the discharge and A_1 the area of the jet flowing under the gate at its point of contraction. The discharge may be estimated from the expression

$$Q = \sqrt{\frac{H_1\,A_2}{\frac{1}{2g\,A_2\,C_o} + \frac{1}{2g\,A_2} - \frac{1}{gA_1} + \frac{A^2}{2g\,A_1^{\,2}}}}$$

where H_1 = head on the gate (20 feet),

A_2 = area of the conduit, and

C_o = the overall coefficient of discharge.

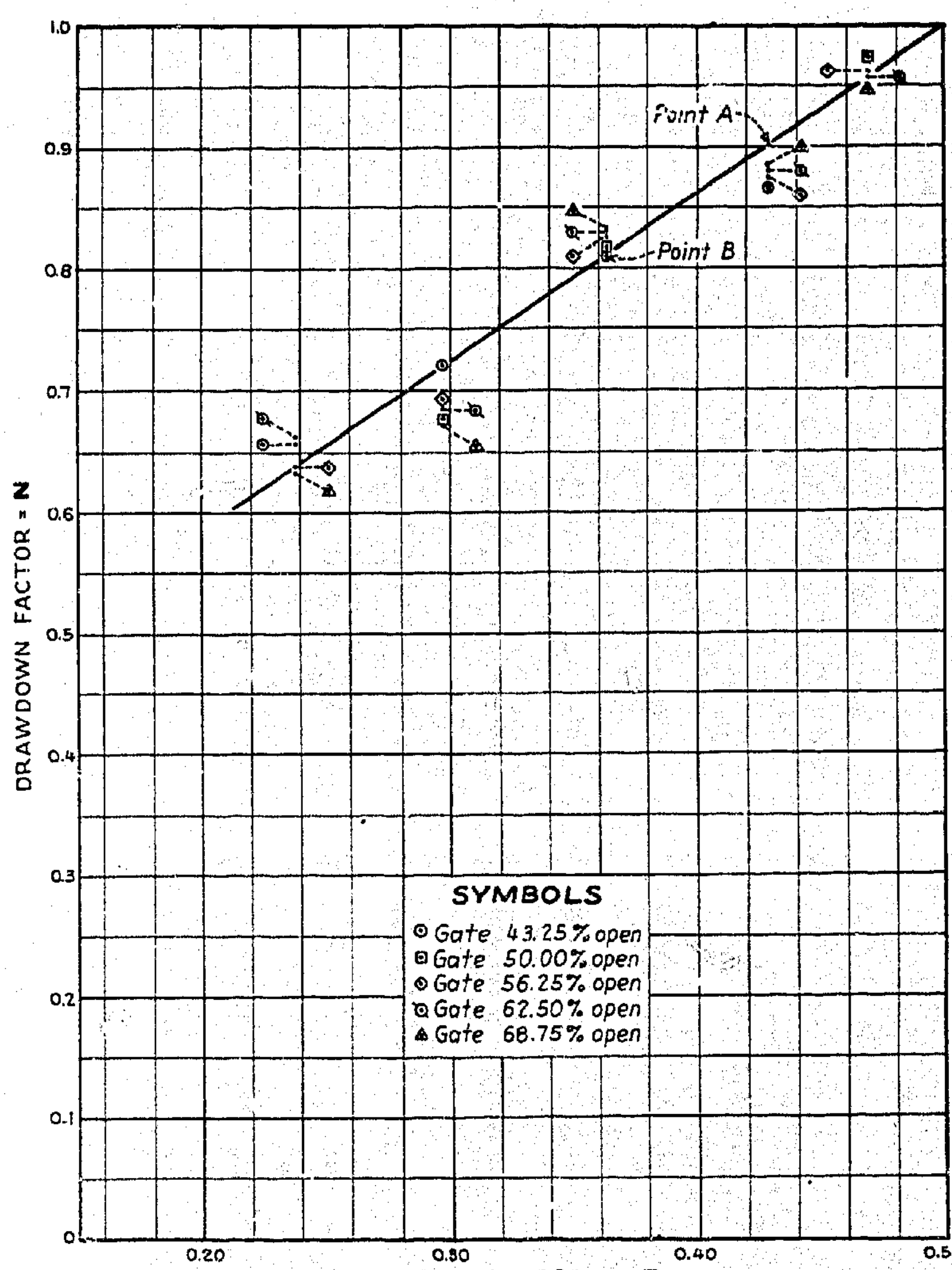
This formula for discharge was developed by using the principle of the conservation of momentum to determine the losses as the water passed under a partly closed gate and expanded into the outlet. A discharge curve based on this formula checked test data closely. It was found that the value of A_1, the area of the jet, at its contraction point was difficult to determine. If the area A_1 was expressed as 0.63 of the area of the outlet entrance beneath the gate, the computed curves for C_o= 0.56 and C_o= 0.69 agree closely with the test data. However, the contraction of a jet flowing under a partly closed gate was uncertain, and, with no other information available, it is often considered to be 0.60. If the value of 0.60 were used, the computed curves would be about 1-1/2 pounds larger than the test data shown for curves for $C_o = 0.56$ and $C_o = 0.69$, demonstrating that it is conservative to use a contraction factor of 0.60.

Effect of gate thickness. Perhaps no other basic dimension or factor which affects the downdraw will vary as much as the gate thickness, for the size of the beams which form the frame of the gate will depend upon the static head over the outlet. To compare the gate thickness T for different gates, a convenient ratio was the gate thickness to outlet diameter, $\frac{T}{D}$. The Shasta Dam outlet coaster gate, operating under a static head of 323 feet, has a $\frac{T}{D}$ ratio of 0.427, while the Friant-Madera Canal outlet coaster gate operating under head of 132 feet has a $\frac{T}{D}$ ratio of only 0.321.

The effect of gate thickness on downdraw was studied by revising the final design of the Shasta Dam outlet coaster-gate model so the thickness was changed from 2.57 to 2.81 inches, 2.18, 1.78, and 1.43 inches, respectively; thus the range of $\frac{T}{D}$ extended from 0.468 to 0.239. The data is presented in dimensionless form on Figure 12. The abscissa is the ratio of gate thickness to outlet diameter $\frac{T}{D}$, while the ordinate is a downdraw factor N, which is the ratio of downdraw for any value of $\frac{T}{D}$ to the downdraw for $\frac{T}{D} = 0.50$ for the same gate opening. The downdraw factor N was based on the ratio of $\frac{T}{D} = 0.50$, since that ratio was convenient to use, but the form of the curve would not be changed if the factor were based on some other ratio of $\frac{T}{D}$. As the data was not sufficient to show any consistent trend, it can be used only to estimate the effect on downdraw by changing the gate thickness and its use should be restricted to gates similar to the final design of the Shasta Dam outlet coaster gate.

Effect of trashrack base. To protect the outlets from debris, trashrack structures are placed in front of the entrances (Figure 10A). The frame of each trashrack consisted of five or six concrete columns surrounding the outlet entrance and extending to the top of the dam. These columns were supported on a trashrack base, either at the bottom of the dam or attached to the face of the dam as a bracket.

To avoid significant pressure disturbances at the outlet entrance, the concrete columns are streamlined and the floor of the trashrack base is placed at a reasonable distance below the outlet entrance. The effect of



NOTES

Tests were made by varying thickness of final design gate on Shasta dam Outlet model, figure 2.

The change in drawdown force, **F**, by a change in gate thickness from T_1 to T_2 may be expressed as

$$\frac{F_1}{F_2} = \frac{N_{\frac{T_1}{D}}}{N_{\frac{T_2}{D}}}$$

OUTLET COASTER GATE STUDIES
EFFECT OF GATE THICKNESS ON DRAWDOWN

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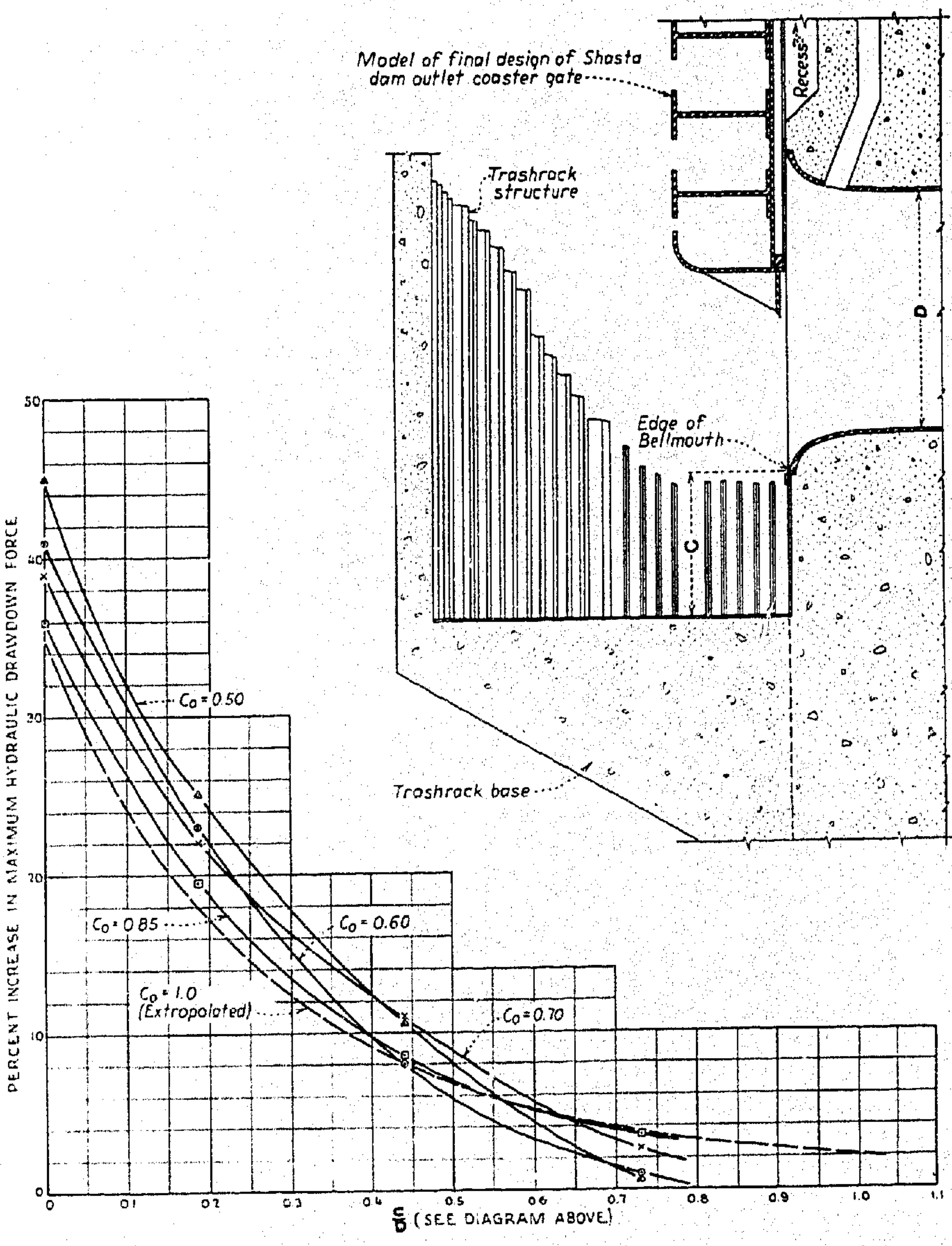
the trashrack and the trashrack base on downdraw was not considered in the design of the Shasta Dam outlet coaster gate because previous model studies indicated that these structures, as situated at Shasta Dam, were too far from the outlet entrance to affect the pressures. At Friant Dam, however, the entrance of the Friant-Madera Canal outlets and the Friant-Kern Canal outlets were close to the bottom of the dam; so their trashrack bases would have some effect upon pressures at the outlet entrance and tend to increase the downdraw on the gate, since the passage to flow under the gate would be restricted enough to increase velocities and reduce pressures on the gate bottom.

The locations of the trashrack bases at the different outlets were compared by using the ratio of the distance of the trashrack base below the outlet entrance C to the Diameter of the outlet D. This ratio $\frac{C}{D}$ was 1.94 at the Shasta Dam outlets but only 0.436 and 0.740 at the Friant-Kern and Friant-Madera Canal outlets, respectively (Figure 10E). To find the effect of the trashrack base, model studies were made by placing a trashrack base in several positions: C = 4-3/8 inches; C = 2-5/8 inches; C = 1-1/8 inches; and C = 0. Thus $\frac{C}{D}$ varied from 0.73 to 0, as the outlet diameter of the model was 6 inches. The downdraw on the gate was measured at several heads and gate openings for each position of the trashrack base and compared with the downdraw on the gate when the trashrack base was removed. The final design of the Shasta Dam outlet coaster gate was used for these tests, but the outlet was changed to simulate a Friant-Kern Canal outlet. This intermixing of models was not important for the gate would be similar at all outlets, and the type of outlet tested was immaterial since the downdraw was compared at different gate openings so that the results would be applicable to any outlet (Figure 13).

These results were plotted as a dimensionless curve with the ratio $\frac{C}{D}$ as the abscissa and the percent increase in downdraw as the ordinate. The curves were shown for different overall discharge coefficients of the outlets C_o. These curves are not exact, since they were obtained by comparing the increase of downdraw at the approximate gate opening where the downdraw becomes a maximum for the given values of C_o. If a recess in the face of the dam is used to reduce the downdraw, it is suggested that the curve $C_o = 1.00$ be used to estimate the increase in downdraw, for the maximum

FIGURE 13



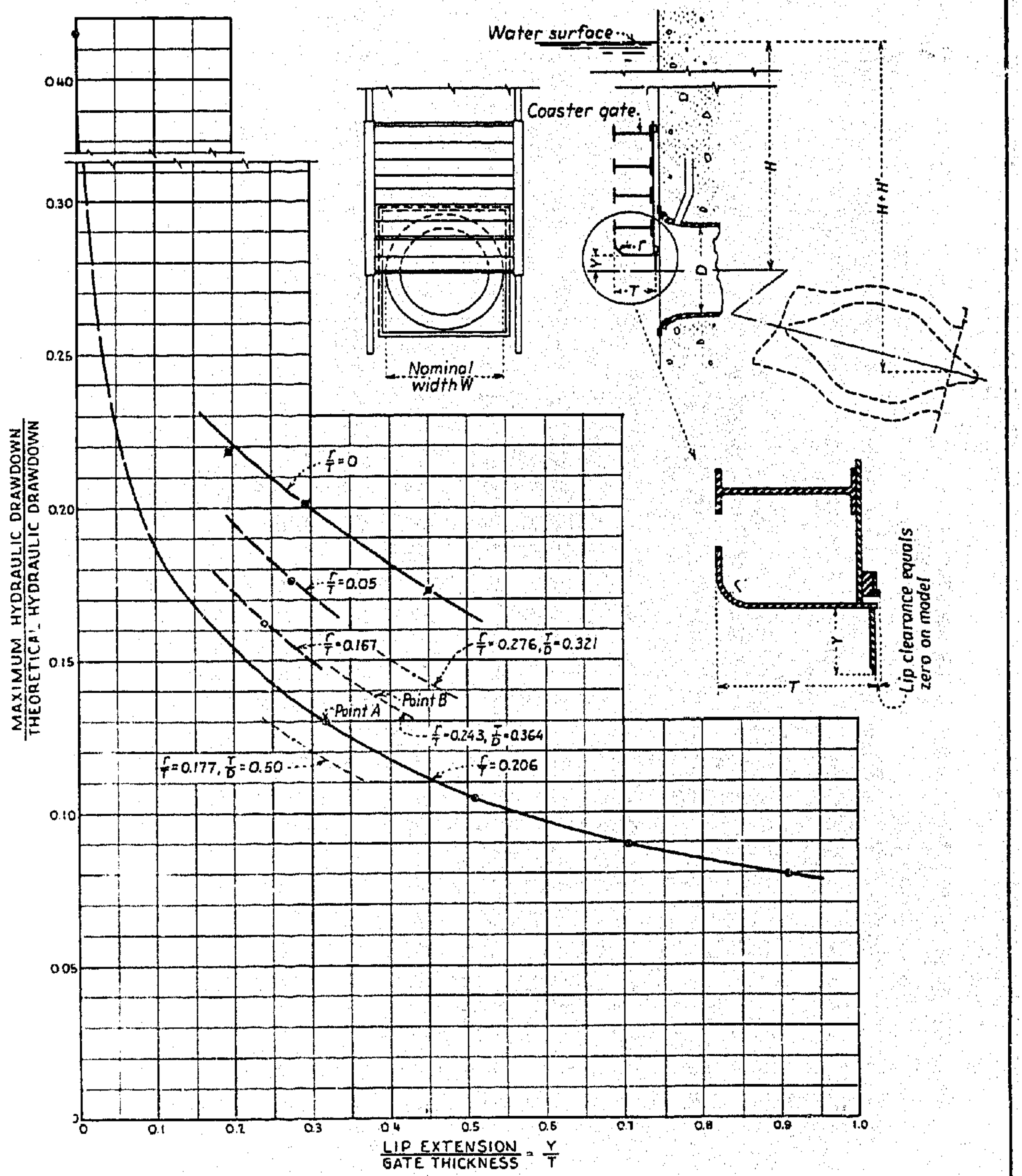
NOTES

C_o = Overall discharge coefficient of outlet.
With recess in face of dam, use curve, C_o = 1.00

OUTLET COASTER GATE STUDIES

EFFECT OF TRASHRACK BASE ON HYDRAULIC DRAWDOWN

P.C.L.-H.R.S.-E.W.C.



NOTES

The theoretical hydraulic drawdown is the product of the gate thickness T, the nominal gate width W, and the head above the outlet exit H+H'.
Heavy curves for constant gate thickness $\frac{T}{D} = 0.43$.
Light curves for gate thickness $\frac{T}{D}$ as noted.
All curves for overall coefficient of discharge $C_0 = 0.69$
All curves for gate with no recess and no lip clearance.

OUTLET COASTER GATE STUDIES

EFFECT OF LIP EXTENSION ON HYDRAULIC DRAWDOWN

F.C.L.-H.R.S.-E.W.C.

downdraw is then likely to occur with the gate nearly wide open (Figure 11).

The curves of Figure 13 will be satisfactory to estimate the effect of the location of the trashrack base on the downdraw. These curves show the increase of downdraw to be negligible where $\frac{C}{D}$ is larger than 1. The value of $\frac{C}{D}$ has to be less than 0.5 before the downdraw will be increased 10 percent.

Effect of lip extension and radius at upstream edge of gate bottom. The gate lip extension Y and the radius at the upstream edge of the gate bottom r were studied in tests to develop a design for the outlet coaster gate at Shasta Dam (Section 9). The results (Figure 7) were shown in prototype since the studies at that time were concerned only with the gate for Shasta Dam. For a general study, however, the results are presented in dimensionless terms (Figure 14). The abscissa is the ratio of the lip extension Y to the gate thickness T, and the ordinate is the ratio of the maximum hydraulic downdraw to a theoretical hydraulic downdraw. This theoretical downdraw is a force equal to the product of the gate thickness, T, the nominal gate width, W, and the head H + H' above the outlet exit. The nominal gate width, W, the span across the outlet entrance, was used rather than the total gate width because this dimension was also used to designate the size of the gate (Section 6).

In Figure 14 the tests to develop the gate for the Shasta Dam outlets are shown by the heavy curves labeled $\frac{r}{T} = 0.20$ (Design 5, Figure 6), $\frac{r}{T} = 0.167$ (Design 3), and $\frac{r}{T} = 0.05$ (Design 4). In additional tests a gate was studied which had a sharp corner at the upstream edge of the bottom, $\frac{r}{T} = 0$. These curves showed that increasing Y or the radius R reduced the downdraw. However, their scope was limited, the tests having been made on an outlet with a constant overall coefficient of discharge $C_o = 0.69$ and a constant thickness $\frac{T}{D} = 0.43$. As the maximum downdraw was roughly proportional to the coefficient C_o, the ratio of downdraw to theoretical downdraw would increase with an increase of the overall coefficient C_o or decrease with a decrease of C_o. The effect of changing the coefficient C_o can be computed as described in Section 21. The ratio of downdraw to theoretical downdraw will increase as the gate thickness decreases, as shown by the light curves of Fugure 14 for $\frac{r}{T} = 0.276$, $\frac{T}{D} = 0.321$, and $\frac{r}{T} = 0.177$, $\frac{T}{D} = 0.50$.

These curves were obtained by selecting values from the curve of studies on the effect of gate thickness (Section 22). The steps to be taken to obtain these points are outlined in Section 25.

To have complete, accurate data, it would be necessary to develop a series of curves similar to those of Figure 14 which would show the variation of $\frac{Y}{T}$ for different combinations of $\frac{r}{T}$, $\frac{T}{D}$, and C_o. A large number of tests would be required to obtain such curves. It being possible to make a reasonable estimate of downdraw of the gates at Friant Dam from the existing data, additional tests were not made. The basic design of gates at future installations may be changed, requiring further studies at that time.

Hydraulic downdraw on outlet coaster gates at Friant Dam. The maximum hydraulic downdraw force on the 11.92- by 11.92-foot coaster gate for the river outlets at Friant Dam was estimated to be 67,700 pounds. When this gate was used for the Friant-Kern Canal outlets the force was estimated to be 34,700 pounds. The maximum downdraw on the 9.86- by 9.86-foot gate for the Friant-Madera Canal outlets was estimated to be 25,600 pounds. These estimates were obtained from the results of the general tests, Sections 20 through 24. The actual steps to estimate these forces were similar in each case. Briefly, they consisted of finding the ratio of maximum to theoretical downdraw by curves of Figures 12 and 14. This ratio was corrected for C_o and the effect of the trashrack base. To the resulting downdraw, obtained by using the corrected ratio, the downdraw caused by lip clearance was added. If a recess in the face of the dam were used at the Friant outlets, another step would be to estimate the reduction of downdraw caused by the recess, Section 18.

The procedure for calculating the downdraw on the coaster gate for the river outlets at Friant Dam is outlined in detail in the following paragraph to suggest a method of using the data presented in Sections 20 through 24.

The curves of Figure 14, expressing the ratio of maximum to theoretical downdraw for given values of $\frac{Y}{T}$, were based on a $\frac{T}{D}$ ratio of 0.430 and $\frac{r}{T}$ ratios of 0, 0.05, 0.167, and 0.206. A curve for the Friant gate must be based on a $\frac{T}{D}$ ratio of 0.364 and an $\frac{r}{T}$ ratio of 0.231. Such a curve may be approximated by using the results of tests on gate thickness (Section 22). Point A of Figure 12 represents a gate of thickness $\frac{T}{D} = 0.430$, the same as the curves of Figure 14, while Point B represents a thickness $\frac{T}{D} = 0.364$, the same as the Friant gate. To further describe these gates, the gate represented by

Point A has an $\frac{r}{T}$ ratio of 0.206 and a $\frac{Y}{T}$ ratio of 0.322. Since the only change from Point A to Point B was in thickness, the gate represented by Point B has an $\frac{r}{T}$ ratio of 0.243 and a $\frac{Y}{T}$ ratio of 0.381.

The ratios of the Friant gate, $\frac{T}{D} = 0.364$, $\frac{r}{T} = 0.231$, and $\frac{Y}{T} = 0.375$ are nearly the same as those of Point B; so Point B may be used to estimate the downdraw on the Friant gate. This was possible since the downdraw of the gate represented by Point B was $\frac{N_B}{N_A}$ of the downdraw of the gate represented by Point A, which can be found from Figure 14. However, if the design of the Friant gate were changed so that values of $\frac{r}{T}$ and $\frac{T}{D}$ were no longer the same as those for Point B, a more complicated procedure would be necessary. Point B would have to be located on Figure 14 and a curve could be drawn through Point B to the desired value of $\frac{Y}{T}$ by assuming that the curve is similar to other curves of constant $\frac{r}{T}$. The effect of changing $\frac{r}{T}$ can be estimated from the test curves $\frac{r}{T} = 0$, 0.05, 0.167, and 0.206. Such a procedure should be reliable for estimating the effect of $\frac{r}{T}$ and $\frac{Y}{T}$ on gates which do not differ greatly from those tested.

The location of Point B on Figure 14 may be confusing because the ordinate is the ratio of maximum to theoretical downdraw. From Figure 12 the downdraw of Point B is $\frac{N_B}{N_A}$ of the downdraw of Point A. The theoretical downdraw of Point B is related to the theoretical downdraw of Point A by $\frac{T_B}{T_A}$, since only thickness of the gate changes. Therefore, the ratio of maximum to theoretical downdraw for Point B is $\frac{N_B}{N_A}\frac{T_A}{T_B}$ of the ratio of maximum to theoretical downdraw for Point A. Since this ratio for Point A was 0.130, the ratio for Point B will be $0.130 \frac{N_B}{N_A}\frac{T_A}{T_B} = 0.130 \frac{0.81 \times 0.430}{0.90 \times 0.364} = 0.138$.

For the estimate of maximum downdraw on the Friant gate this ratio was corrected to account for the difference of downdraw due to the different coefficients $C_o = 0.69$ and $C_o = 0.56$ (Figure 11). From the theoretical downdraw $(H + H') \cdot W \cdot T = (198 + 50) \times 40 \times 11.92 \times \frac{62.5}{12} = 616{,}000$ pounds (Figure 10), the resulting downdraw of 61,600 pounds was obtained. To this force the effect of lip clearance was added, $N \cdot W \cdot H$, of 6,100 pounds to make a total estimated downdraw of 67,700 pounds on the coaster gate for the river outlets at Friant Dam.

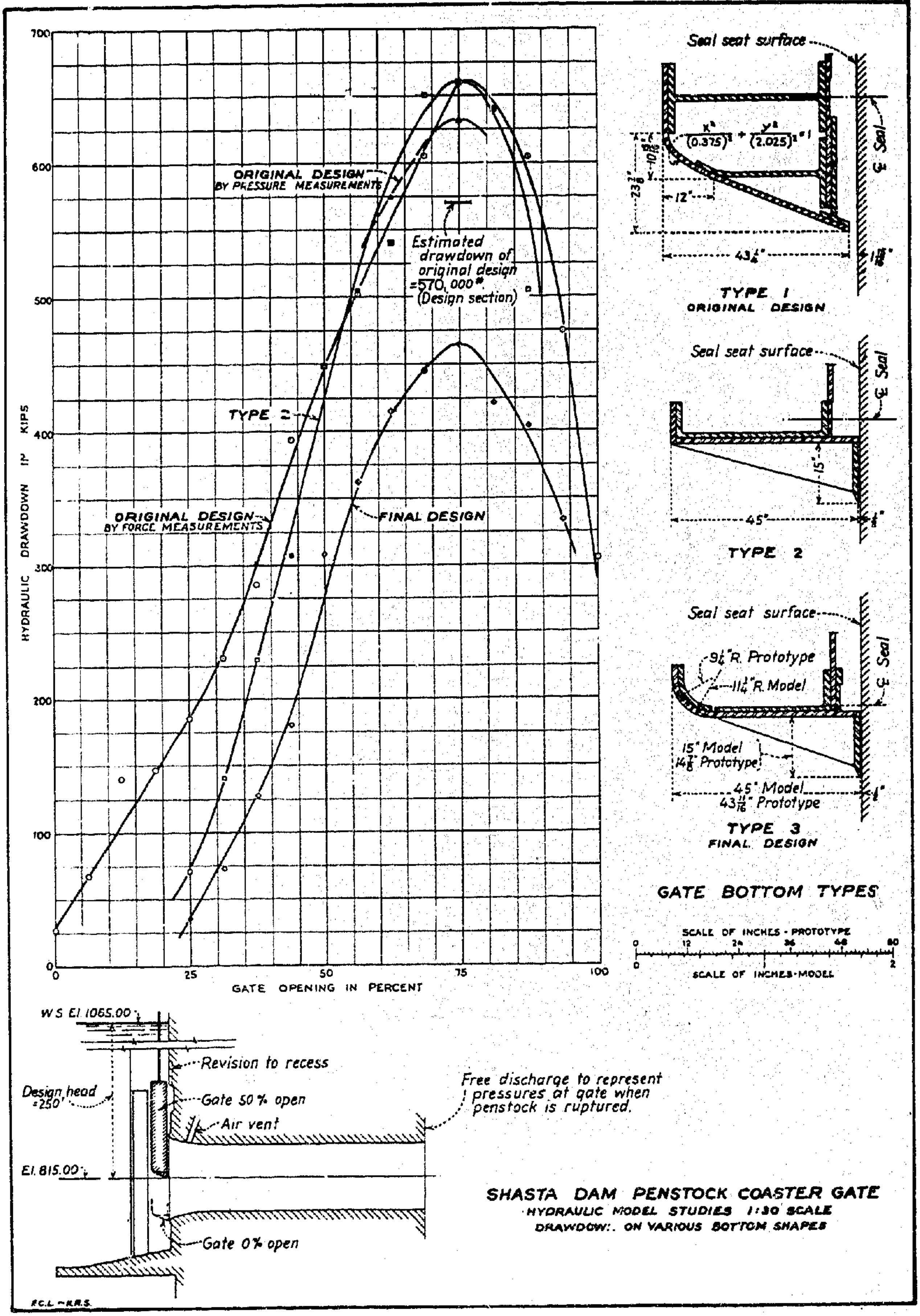
CHAPTER IV - PENSTOCK COASTER-GATE TESTS

The original design of the Shasta Dam penstock coaster gate. Although it was necessary to find the downdraw on penstock coaster gates at Shasta, Davis, and Grand Coulee Dams, the testing was done on the 1:30 model of a Shasta Dam penstock (Figure 3), and, as the entrances at all three dams dams were similar, the downdraw on the coaster gates for Davis and Grand Coulee Dams could be estimated from the results of the Shasta tests.

The original design of the coaster gate for the Shasta Dam penstocks had a sloping bottom (Type 1, Figure 15) patterned after the penstock coaster gates at Grand Coulee Dam. It was anticipated that the sloping bottom of the original Shasta design would be revised to a flatbottom with an extended lip similar to the Shasta Dam outlet coaster gate. Nevertheless, the original design was tested to check the accuracy of the original estimate of downdraw and to provide data to find the downdraw on the sloping bottom gates at Grand Coulee Dam.

Only a short length of conduit was placed downstream from the rectangular bellmouth entrance of the model; so the discharge was completely unrestricted. This was to assimilate the prototype should a portion of the exposed penstock below the dam burst, in which case the penstock would have to be closed by the coaster gate. Obviously this was the worst condition under which the gates would operate, as any flow through the powerhouse would be restricted at the turbines. The downdraw on the model was obtained for both pressure and force measurements, for several heads and over a complete range of gate openings. The results, in prototype, were for a maximum design head of 250 feet and were shown as a downdraw versus gate opening curve (Figure 15, original design). The maximum hydraulic downdraw force was 630,000 pounds by pressure measurements and 660,000 pounds by force measurements. This maximum occurred with the gate 75 percent open. The downdraw, based on estimates by the design department of 570,000 pounds, was reasonably close to the results of the model studies, although slightly low.

Revisions to recess at Shasta Dam penstocks. Since the maximum downdraw occurred with the gate 75 percent open, it was apparent that the recess in the face of the dam was improperly designed, for it was restricted in height and not effective after the gate was 50 percent open. Recommendations



SHASTA DAM PENSTOCK COASTER GATE
HYDRAULIC MODEL STUDIES 1:30 SCALE
DRAWDOWN ON VARIOUS BOTTOM SHAPES

were made to extend the recesses at Shasta Dam penstocks in height so that they would become effective as soon as the gate began to close. However, extending the recesses in the model to conform with the recommendations did not change the downdraw curves originally obtained. Investigation disclosed that the recess of the model was wider than the recess at the prototype. To facilitate construction in the model, the recess extended to the tracks and the frame for the vertical seal-seats extending above the outlet entrance was omitted. Omission of these frames permitted water to flow into the recess from the sides of the gate at any gate opening; so the recess on the model was effective at all gate openings.

This condition was corrected later, and a test was made to demonstrate the effect of eliminating the recess which was to increase the downdraw curve about 117,000 pounds. Action of recess in reducing downdraw on the coaster gate was discussed in Section 18. Throughout the remaining penstock coaster-gate tests on the model, the recess was used so that its effect would be included in the measurement of downdraw.

Use of flatbottom gate with extended lip, Type 2. A maximum downdraw of 660,000 pounds was larger than desired. Therefore a flatbottom gate with an extended lip was suggested (Figure 15, Type 2). To simplify its construction, the upstream edge of the bottom was made with a sharp corner although it was realized that the downdraw would be less if the upstream edge of the gate bottom were curved.

Two tests were made with this gate by changing the lip extension. With a lip extension of 22-1/2 inches (3/4-inch model), the maximum downdraw was 600,000 pounds; but with a lip extension of 15 inches (1/2-inch model), the downdraw was increased to 660,000 pounds. It was determined that a lip extension of 15 inches was the largest that was practical structurally. Therefore, this gate with the sharp corner at the upstream edge of its bottom was not satisfactory because the downdraw was too large.

Use of holes in gate bottom to reduce downdraw. It was suggested that holes in the bottom of the gate might materially reduce the downdraw by permitting flow to pass through the bottom, thus reducing the velocities under the gate and consequently the downdraw. However, no tests were made with holes in the gate bottom in the coaster-gate studies. As the beams forming the gate bottom would be fully stressed when the gate was closing under a maximum head, sufficient holes to be of any use were out of the question. Holes in the bottom of the penstock coaster gate were also considered impractical if a flatbottom, extended-lip type of gate were to be used. Nevertheless, tests were made to determine their effect.

Four 3/8-inch diameter (11-1/4 inches prototype) holes were drilled between the gusset plates along the centerline of the beam forming the gate bottom. These holes represented 5 percent of the area of the gate bottom. The downdraw was measured with a lip extension of 1/2 inch and 3/4 inch to compare with the previous tests (Section 28). With the 1/2-inch lip extension, the reduction of downdraw was approximately 7-1/2 percent. With the 3/4-inch lip extension, the reduction was approximately 9 percent.

These tests were not carried further because it was apparent that a large portion of the gate bottom would have to be removed to obtain a substantial reduction of downdraw. Even the 3/8-inch holes (11-1/4 inches prototype) were large compared with the thickness of the gate bottom.

The final design. When the flatbottom gate, Type 2, was proposed, it was realized that the downdraw would be less if the upstream edge of the bottom were curved. Nevertheless, the sharp corner at the upstream edge was simpler to build and would have been recommended if any substantial reduction of downdraw had been obtained by that revision. Since the downdraw was still excessive, another gate, Type 3, was proposed which was similar to Type 2 except the upstream edge of the gate bottom was curved on a 3/8-inch radius (11-1/4 inches prototype). A lip extension of 1/2 inch (15 inches prototype) was used since this was a practical structural limit. Force measurements indicated the maximum downdraw on this gate to be 465,000 pounds (Figure 15).

The final design of the penstock coaster gates at Shasta Dam was patterned after this model except that the radius at the upstream edge of the gate bottom was 9-1/4 inches instead of 11-1/4 inches. This smaller radius will increase the downdraw somewhat. Also, the extended lip of the final design was 14-7/8 inches instead of 15 inches. The increase of downdraw by these two factors would not be large, but the final estimate of downdraw was placed at 500,000 pounds, which included a conservative allowance for the differences between the model, Type 3, and the final design.

Comparison of outlet and penstock coaster gates. The similar design of the outlet and the penstock coaster gates suggested that results of the outlet coaster-gate tests could be used to estimate the downdraw on the penstock coaster gates. This was not done, for the massive concrete columns at the sides of the penstock coaster gates would restrict the passage of flow under the gates and the pressure reduction, and consequent downdraw force would be relatively larger than for the outlet coaster gates.

These facts were verified by pressure measurements made on a penstock coaster gate which had a 45-degree sloping bottom similar to the original design of the outlet coaster gate for Shasta Dam. Nevertheless, the form of the pressure gradients was similar, and a correction factor was suggested as a method of comparing the downdraw. As tests to find such a factor would have to be extensive to include several types of gates, it was more expedient to consider the outlet and the penstock coaster-gate studies as separate problems, although closely related.

The hydraulic downdraw force on penstock coaster gates at Davis and Grand Coulee Dams. The maximum hydraulic downdraw force on the penstock coaster gates at Davis Dam, estimated to be 110,000 pounds, would occur if the gate were lowered under a maximum head of 108 feet to make closure with a discharge of 5,000 second-feet. This force acted with the gate approximately 8 feet open. The maximum downdraw on the penstock coaster gates at Grand Coulee Dam, estimated to be 125,000 pounds, would occur if the gates were lowered under a maximum head of 250 feet to make a closure with a discharge of 3,500 second-feet. If the discharge were 5,000 second-feet, the maximum downdraw would be 170,000 pounds. Such forces would occur with the gate open approximately 3 and 4 feet, respectively. These estimates were made by modifying the results of the Shasta tests to account for different conditions of closure. In the estimate of downdraw on the coaster gate for Davis Dam, corrections were necessary to account for the differences in the size of the gates.

The steps required to estimate the downdraw on the gates at Davis Dam are explained in the following paragraphs, the procedure to estimate downdraw on the penstock coaster gates being different from that used on the outlet coaster gates (Section 25).

The bottom shape of final design of the Davis gate was basically similar to gate (Type 2) used in the Shasta tests, for the upstream edge of the gate was a sharp corner and the ratio of lip extension below this corner to gate thickness $\frac{Y}{T}$ was nearly the same as for gate Type 2, Figure 15. Therefore the downdraw curve, Type 2, was modified to apply to the Davis gate by making corrections to account for differences in lip clearance and seal extension, velocity head, gate thickness, gate width, and trashrack base.

The use of a recess at the Shasta Dam penstocks reduced the downdraw on the gates 117,000 pounds by balancing pressures on the top and the bottom of the upper seal which projected 5-7/16 inches. On the Davis gate the seals projected only 2-1/16 inches; so the reduction of downdraw would not be so large. Furthermore, a large lip clearance on the Davis gate, 2-1/16 inches, would tend to increase the downdraw the same amount that the seal projection would reduce it. The resulting effect would be the same as if no recess were used at Davis Dam. To compute the downdraw from the Shasta test, Type 2, the curve was therefore increased 117,000 pounds.

Since the downdraw was proportional to the velocity head under the gate, this curve was further corrected to correspond with the velocity head under the Davis gate. The curve, Type 2, represented a relationship of downdraw to gate opening for a constant velocity head of approximately 250 feet with pressures on the downstream side of the gate and in the penstock entrance being atmospheric or slightly negative. This condition was obtained on the Shasta tests by permitting the water to discharge freely, representing a burst penstock. The velocity head under the Davis gate was obtained for various gate openings by using discharges based on the formula

$$Q = \sqrt{\frac{HA_2}{\frac{1}{2g\,A_2\,(Co)^2} + \frac{1}{2g\,A_2} - \frac{1}{g\,A_1} + \frac{A_2}{2g\,A_1^2}}}$$

where

Q = discharge,

H = total head, the difference between the reservoir surface at elevation 625.00 and the tailwater at elevation 517.00,

$(Co)^2$ = an overall discharge coefficient based on the turbines discharging 5,000 second-feet with gate open and includes losses in the penstock,

A_1 = the contracted area of the jet under the gate,

A_2 = area of the penstock sections.

This formula for discharge was developed by using the principle of the conservation of momentum to determine losses as the water passed under a partly closed gate and expanded into the conduit. The velocity head was obtained from the formula $H_v = \frac{Q^2}{2g\,A_1^2}$. This procedure was checked in the outlet coaster-gate tests and found to be quite reliable if the correct value of A_1, the contracted area of the jet under the gate, can be obtained (Section 21). Since no other information was available, it was assumed that A_1 was 0.6 of the area of conduit under the gate. It was believed that the factor was actually larger than 0.6, but if this were the case, the use of the factor 0.6 was conservative.

The correction for velocity head was made for corresponding gate openings based on the relation of gate thickness to gate opening. This was logical since the rectangular opening of the penstocks with the columns at their sides to constrict the flow tended to make the flow patterns under the gate two-dimensional so that the flow under the gates would be similar for a given gate-opening gate-thickness ratio. This could not be done with a circular entrance such as was used in the outlet coaster-gate tests. By assuming such a two-dimensional flow pattern under the gate, the downdraw may be assumed to be proportional to the gate thickness and width. The effect of the differences in gate thickness and gate width were included in this manner.

Since the trashrack base was closer to the penstock entrance at Davis Dam than at Shasta Dam, the estimate of downdraw on Davis Dam was increased 7 percent to account for that factor.

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