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UNITED STATES
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HYDRAULIC LABORATORY REPORT NO. 103

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SPILLWAY AND OUTLETS FOR GRAND COULEE DAM

By

Jacob E. Warnock

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Denver, Colorado

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SPILLWAY AND OUTLETS FOR GRAND COULEE DAM

By

Jacob E. Warnock, Engineer, U. S. Bureau of Reclamation.

(Prepared to be included in the illustrative examples in the proposed manual on hydraulic models to be published by the American Society of Civil Engineers.)

The principal feature of the Columbia Basin Project[1] in the State of Washington is the Grand Coulee Dam[2] in the Columbia River. It has as important hydraulic features an overfall spillway and 60 river outlet conduits, all situated in its central portion.

The spillway for conveying surplus flow from the reservoir to the river bed downstream, without endangering the structure or surroundings, has a gross length of 1,650 feet. Its crest, having an ogee profile made up of a parabolic segment and circular arcs, is controlled by 11 hydraulically operated drum gates 28 feet high and 135 feet long, separated by piers supporting the roadway across the dam. Two training walls on the downstream face of the dam, one downstream from each end-pier, confine the spillway flow and direct it to the roller-bucket stilling pool at the toe of the dam. When operating at the design capacity of 1,000,000 second-feet, it is essential that this pool reduce to non-destructive form, energy amounting to 31,800,000 horsepower.

The sixty river outlets, 102 inches in diameter, arranged in three tiers, each differing in elevation by 100 feet, pass through

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1 A comprehensive description of the project may be found in:
Columbia Basin Project Reported Feasible. Engineering News-Record, June 30, 1932, pages 907-11.
Facts and Figures on Grand Coulee. Power, October, 1938, pages 78-80, inclusive.

2 A discussion of the general plans for the Grand Coulee Dam and drawings may be found in:
Grand Coulee High Dam. Engineering News-Record, December 23, 1937. Pages 1021-24.

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the right two-thirds of the spillway section. Each tier contains twenty outlets arranged in pairs located directly above or below those of the other tiers. Each conduit is provided with a belled-entrance to prevent destructive action due to cavitation and each is supplied with control and emergency gates. All emerge from the downstream face of the dam and direct their flow downward along the face to the stilling pool. Under normal conditions the head on the lower outlets will be excessive and only those in the intermediate and upper tiers will be useful in regulating the outflow from the reservoir during the period of low stream flow.

Hydraulic features of unprecedented proportions, such as these, introduce new problems in design and intensify the usual ones. Both require extensive and diversified investigations to insure dependable designs, which prompted a comprehensive program of hydraulic model studies for the design of the spillway and river outlets. These studies, conducted intermittently with those on other projects, extended over a period of several years. They were comprehensive and productive of results, which, though unanticipated in many cases, produced designs superior to any which might have been based on precedent alone. Fourteen models, representing designs from the embryonic to the final stage, were utilized in evolving the adopted designs.

In most cases the models were of the sectional type, representing a particular part or section of the structure, such as a cross-section of the spillway, a section of the spillway crest, the spillway piers, the river outlet, the outlet entrance, or the outlet control gate. The model scale varied, depending on the laboratory facilities and the purpose of the model. These models proved useful for preliminary designs where expeditious, economical changes were desired or in studies where the size of the feature on a model of the complete structure was too small to yield dependable data. Moreover, this type of model is suited to the use of glass panels, which are invaluable for observing flow phenomena. A glass panel makes possible a visual concept of

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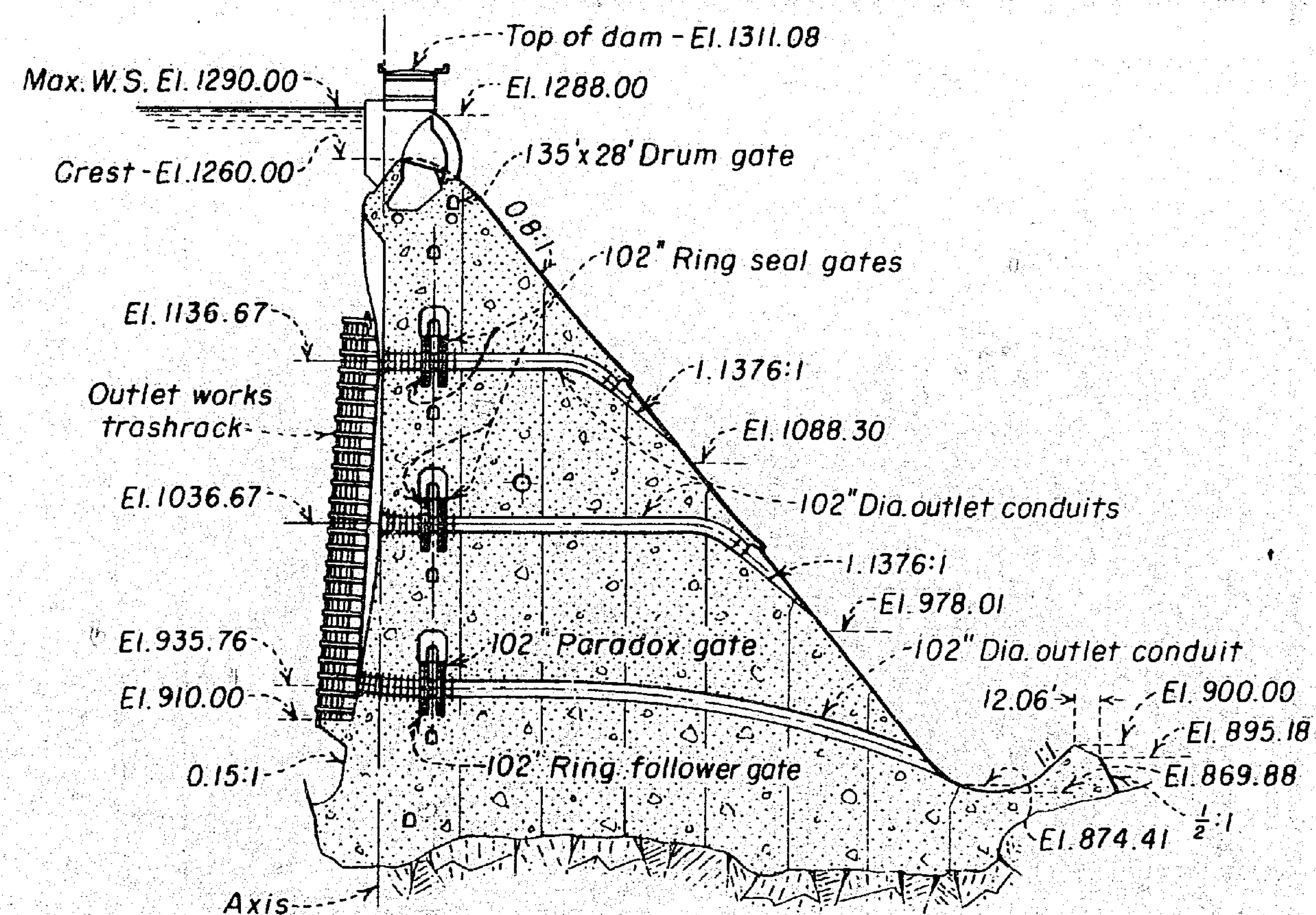

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SPILLWAY SECTION - GRAND COULEE DAM

the hydraulic characteristics of a design. Regardless of the data obtained by other devices, none is so effective as a visual image of the true behavior of water in the spillway bucket of Grand Coulee Dam.

The use of the sectional model, however, does not eliminate the necessity of studies involving the structure as a whole, for it is only from a model containing all the pertinent features in respective locations that it is possible to study the performance of each singly and collectively under various operating conditions. Two of the models were of this type, one representing the ultimate structure and the other, its various construction stages. Both were on a scale of 1 to 120, the largest possible with available laboratory facilities. A scale of 1 to 100 or 1 to 80, permitting the study of more details, would have been more desirable and would have reduced the number of sectional models. The advantages of the larger model, however, would, no doubt, be offset by the inaccessibility of certain features and the inconvenience of making tests. Moreover, it would not be susceptible to rapid changes or suitable for using the glass panel for visual studies. Though the complete models were quite small and limited in their purpose, they served admirably for what they were intended. They were naturally of little use for study of preliminary designs, thus were not constructed until a tentative design of the important features had been determined from tests on the sectional models.

Operation of the outlets singly, collectively, and in conjunction with the spillway, the performance of the spillway with various flood flows, the flow conditions in the tailrace with the powerhouses, outlets and spillway operating individually and collectively, the effect of various operating procedure on the river bed below the dam, the feasibility of fish ladders for migrations during early construction stages, and the flow conditions in flood season for various construction stages, were the important factors studied on the complete models. Those studied on sectional models included the shape, elevation

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and dimensions of the spillway stilling pool bucket, the profile of the crest and gate, calibration of the spillway crest, the shape of the crest pier nose, the size and shape of the spillway training walls, the shape of the entrance to the river outlet conduits, the effect of the trash racks on the pressures in the outlet entrances, improvement of the design of the outlet control gates, the profile of the outlet conduits, the shape of the outlet exit, the shape of deflectors over the outlet exits, the aeration of the outlet conduit with spillway only operating, calibration of the river outlets, and the design of air nozzles to prevent ice from forming adjacent to the structure and on the outlet and power penstock trash racks.

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When the hydraulic investigations for the design of the Grand Coulee spillway and river outlets were instigated the program was complicated by plans providing progressive development of the project in two stages, requiring two dam heights. The initial development was to be a low dam for power generation, while the ultimate development, a high dam, was to have the added purposes of controlling floods and storing irrigation water.

From the inception of the testing program it was realized that the hydraulic features of these two structures would be interdependent and that the studies on both should be conducted simultaneously. As a result, tentative designs for the high dam had been ascertained when those for the initial development were completed. The general shape and dimensions of the spillway were known and studies for the river outlets and specific parts of the spillway were in progress.

A small sectional model of a low buttress-type dam, on a scale of 1 to 125, constructed of sheet metal and angle iron, was used for the preliminary studies on the initial development. Although encouraging results were obtained from this model, the design was discarded in favor of one utilizing a low gravity structure as an integral part of the high dam. From these tests was evolved a low dam design, embodying the base of the high dam. This design eliminated costly

FIGURE 2

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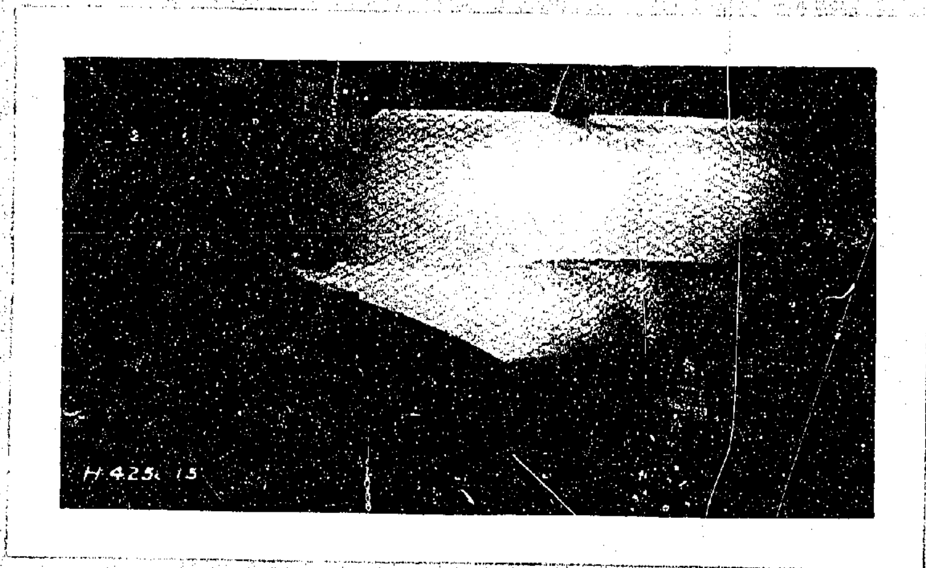
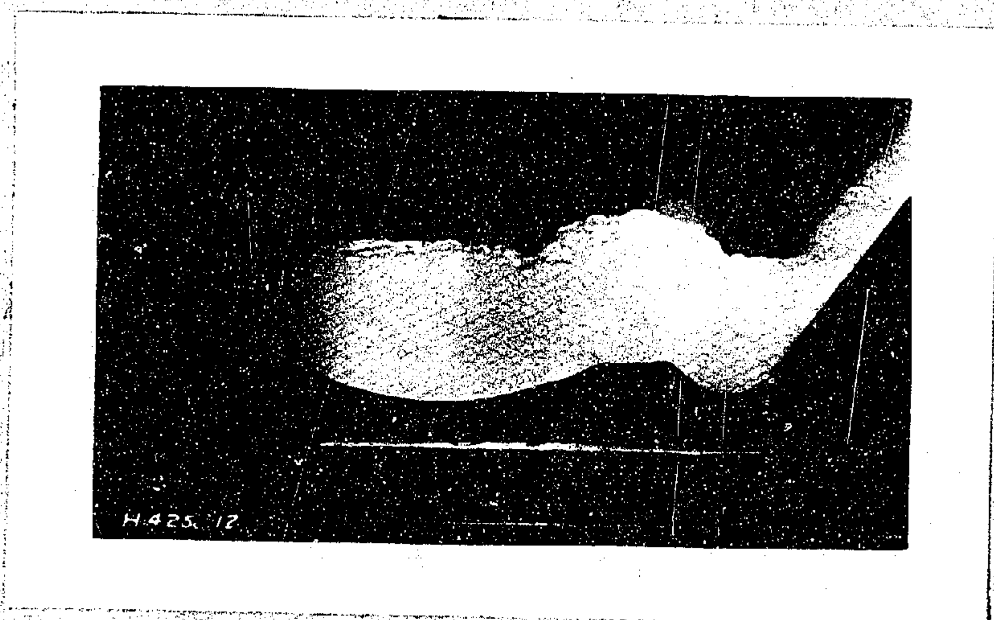
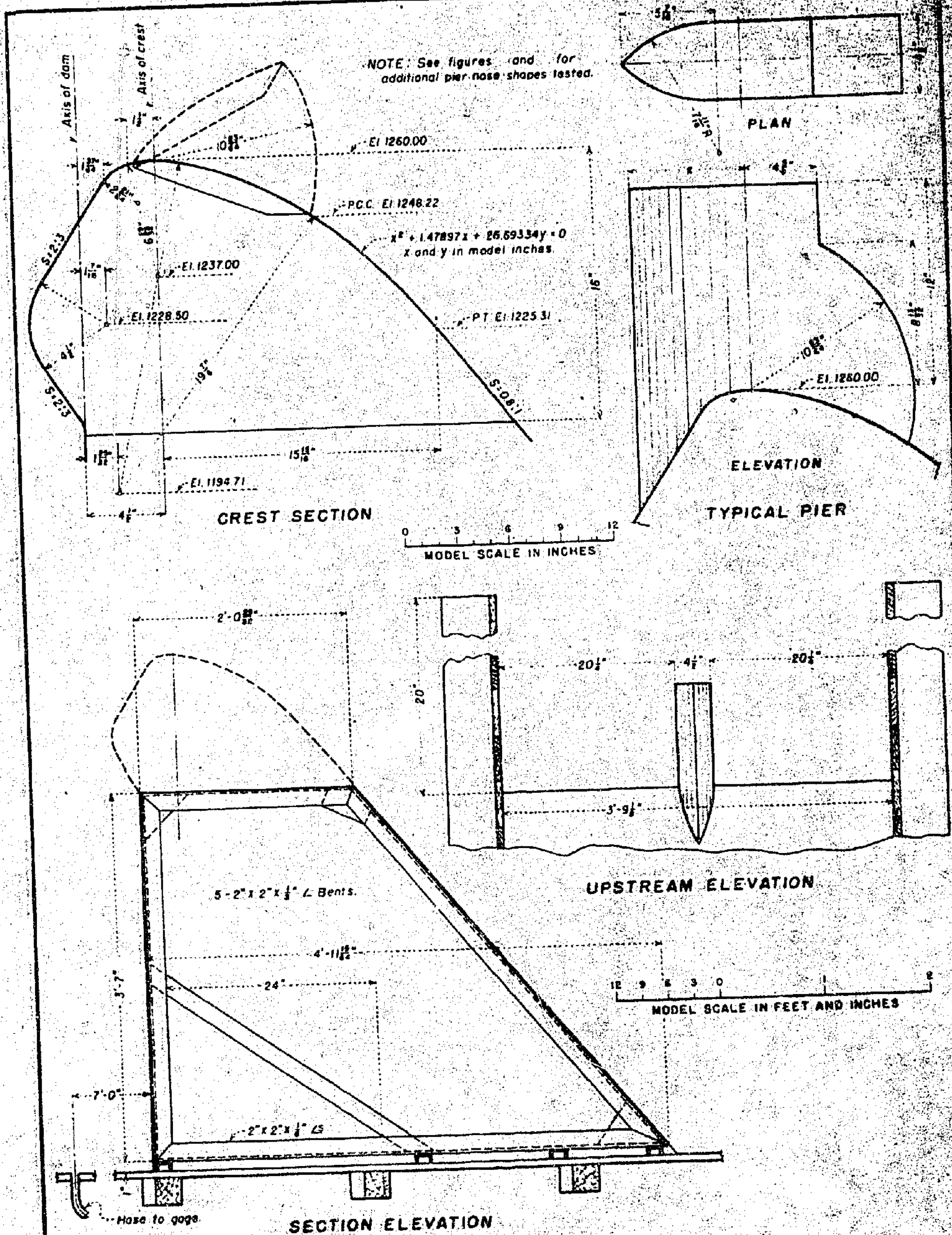


Flow conditions in roller-bucket stilling pool.



Flow conditions in rectangular stilling pool.

FLOW PHENOMENA VIEWED THROUGH GLASS PANEL.



GRAND COULEE DAM
HYDRAULIC MODEL STUDIES-SCALE 1:40
MODEL DETAILS

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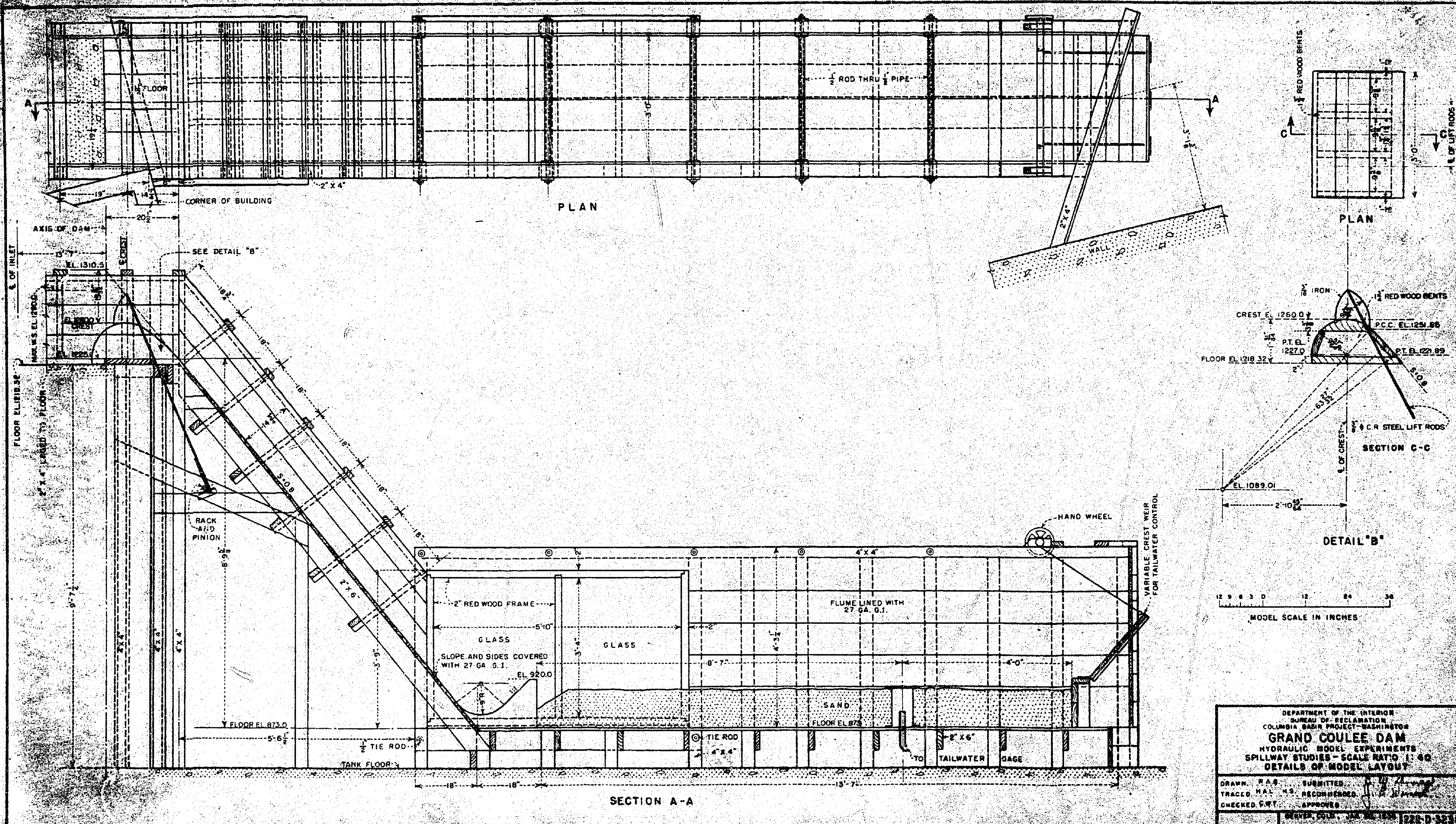
PLAN
CORNER OF BUILDING
AXIS OF DAM
SEE DETAIL "B"
½" ROD THRU ¾" PIPE
WALL
SECTION A-A
RACK AND PINION
2" RED WOOD FRAME
GLASS
SLOPE AND SIDES COVERED WITH 27 GA. G.I.
EL. 920.0
FLOOR EL. 873.0
½" TIE ROD
TANK FLOOR
FLUME LINED WITH 27 GA. G.I.
SAND
FLOOR EL. 873
TIE ROD
TO TAILWATER GAGE
HAND WHEEL
VARIABLE CREST WEIR FOR TAILWATER CONTROL
SECTION C-C
DETAIL "B"
CREST EL. 1260.0
FLOOR EL. 1218.32
EL. 1089.01
C.R. STEEL LIFT RODS
MODEL SCALE IN INCHES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT—WASHINGTON
GRAND COULEE DAM
HYDRAULIC MODEL EXPERIMENTS
SPILLWAY STUDIES – SCALE RATIO 1:40
DETAILS OF MODEL LAYOUT
DRAWN R.A.S. SUBMITTED
TRACED H.A.L. RECOMMENDED
CHECKED C.W.T. APPROVED
DENVER, COLO.
228-D-3238

excavation and unwatering for subsequent construction and proved of value when construction of the ultimate development was approved before the initial development was completed. It not only simplified the transition from the smaller to the larger structure, but allowed construction to proceed with minimum interruption. The design also confined subsequent investigations to specific parts of the ultimate structure and to its construction stages.

The major problem in connection with the design of the ultimate spillway was protection against scour at the toe of the dam to insure its safety. With the design capacity of 1,000,000 second-feet and a difference in head of 280 feet, the energy to be dissipated or reduced to non-destructive form, was 31,800,000 horsepower, 19,300 horsepower per foot of gross crest length. Four different models were tested to develop a method of protection that would satisfy this requirement. Each was constructed with definite limitations and for a definite purpose. The first model, of metal and wooden construction with a glass panel side, was built to a scale of 1 to 184. Space limitations dictated the size, which although too small to give accurate quantitative results, served admirably for the study of suggested designs and for the elimination of undesirable ones quickly and economically.

Preliminary studies of the stilling pool utilized the hydraulic jump. The design was expensive because it required an apron (pool floor) of enormous thickness with a parabolic profile to obtain the proper downstream depth relationship for all flows. The hydraulic properties as indicated by the model were unsatisfactory.

The model indicated that a bucket, curved in section and at a very low elevation, was best suited to the topography and tailwater relationship existing at the dam site. All succeeding tests concerned the refinement of this design. Improvement of flow and scour conditions resulted from the addition of a dentated lip on the downstream edge of the bucket. The modified design eliminated both the impingement of the jet directly on the river bed and the scouring effect of the turbulent flow. However, the behavior of

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the water in and around the teeth of the dentated lip led to the belief that sub-atmospheric pressures existed, a serious condition considering the possibility of cavitation and consequent destruction of the teeth.

Since the 1 to 184 model was too small for the detailed study of these pressure conditions, a sectional model was constructed on a scale of 1 to 40, which included one drum gate with a half pier at each end and the downstream face of the spillway, including the bucket at the toe. It was sheet metal lined wooden construction, with a glass panel on one side to permit study of the flow conditions in the bucket. Piezometers were installed in the exposed surfaces of two teeth to measure pressures. The existence of sub-atmospheric pressures on certain surfaces of the teeth was substantiated. Efforts were made to reduce or eliminate them by streamlining the sharp corners. Although substantial reductions were made, varying with the degree of streamlining, they were accomplished only at the expense of the effectiveness of the dentated lip, which was appreciably reduced by each successive degree of streamlining.

Since very little was known concerning the similarity of vacuum conditions in model and prototype, a third and larger model, with a scale of 1 to 15, was constructed for further studies.

A direct comparison of data obtained from similar tests on the two models proved the performance of the dentated lip was impaired by streamlining, but gave little clue as to the model-prototype relationship of sub-atmospheric pressures. The design was considered impracticable after an incidental test disclosed that the edges of the teeth would be rapidly abraded by ice or other materials which might be carried into the bucket during the operation of the spillway gates. Cakes of paraffin and short lengths of weighted wooden dowel rods, assimilating ice and water-soaked logs, were used in this test.

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After the bucket design with a smooth curved profile had been chosen, more detailed information was sought concerning the pressures and velocities in the bucket and the extent of scour of the river bed. Piezometers were placed in the bucket at such intervals that there was no possibility of a change in pressure occurring unobserved. Pitot tube traverses were made at representative sections in both models.

The pressure measurements supplied data for the structural design of the downstream part of the bucket and to relieve the concern expressed regarding the possibility of the formation of sub-atmospheric pressures directly downstream from the crest of the bucket lip.

A clear picture of the behavior of the internal mechanism by means of which the roller accomplished the dissipation of energy, was obtained from the velocity traverses. The descending sheet of water plunged into the tailwater and diverged. This divergence can best be described as a process of raveling due to contact with the roller. After the stream enters the bucket it is diverted with a practically constant velocity to the crest of the lip. The effect of the lip is to divide the jet into two parts, one deflected upward to form the elliptical surface roller with its major axis in a horizontal plane above the bucket, and the other downstream to form a ground roller.

These two rollers are the fundamental factors governing the dissipation of energy and the prevention of scour. The upstream surface roller was primarily effective in dissipating the energy which might otherwise prove destructive to the river bed, while the direction and intensity of the ground roller determined the extent of the erosion immediately below the bucket. A slope steeper than 1 to 1 on the upstream face of the lip produced a too nearly vertical deflection of the jet, with the result that the

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ground roller dipped sharply and produced excessive scour and the surface roller was rendered ineffective. For slopes flatter than 1 to 1, the surface roller tended to sweep out of the bucket and the ground roller was obliterated by a downstream current which again produced excessive scour.

A significant fact, brought out by the Pitot tube traverses, was that the actual maximum velocities in the curved part of the bucket were materially less than might be expected from theoretical considerations. For example, it was found that with a spillway discharge of 500,000 cubic feet per second, the maximum velocity measured at the point where the descending sheet entered the pool was 133 f.p.s. This was a reasonable agreement with the calculated velocity of 141 f.p.s. At the point of tangency of the downstream face of the dam with the curve of the bucket the maximum measured velocity was 55 f.p.s.

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In making observations on the erosion of the bed below the bucket, care was exercised before each run to restore the surface of the bed to a predetermined profile selected to facilitate comparison. From the downstream toe of the bucket the bed material was placed on a 1 to 1 slope to stimulate the condition that probably existed following construction. It was found that as the discharge was raised gradually to capacity, the river bed material was carried back against the bucket, completely filling the trench and forming a deposit parallel to the lip and roughly parabolic in section. This deposit was quite stable and not materially affected by subsequent variations in the discharge.

Model buckets representing prototype radii of 30, 50, 75, and 100 feet were tested. The circular roller of the 30-ft. bucket was much less effective than the elliptical roller of the 50-ft. bucket. The use of a 75 or 100-ft. radius resulted in only slight further improvement, insufficient to justify the additional cost.

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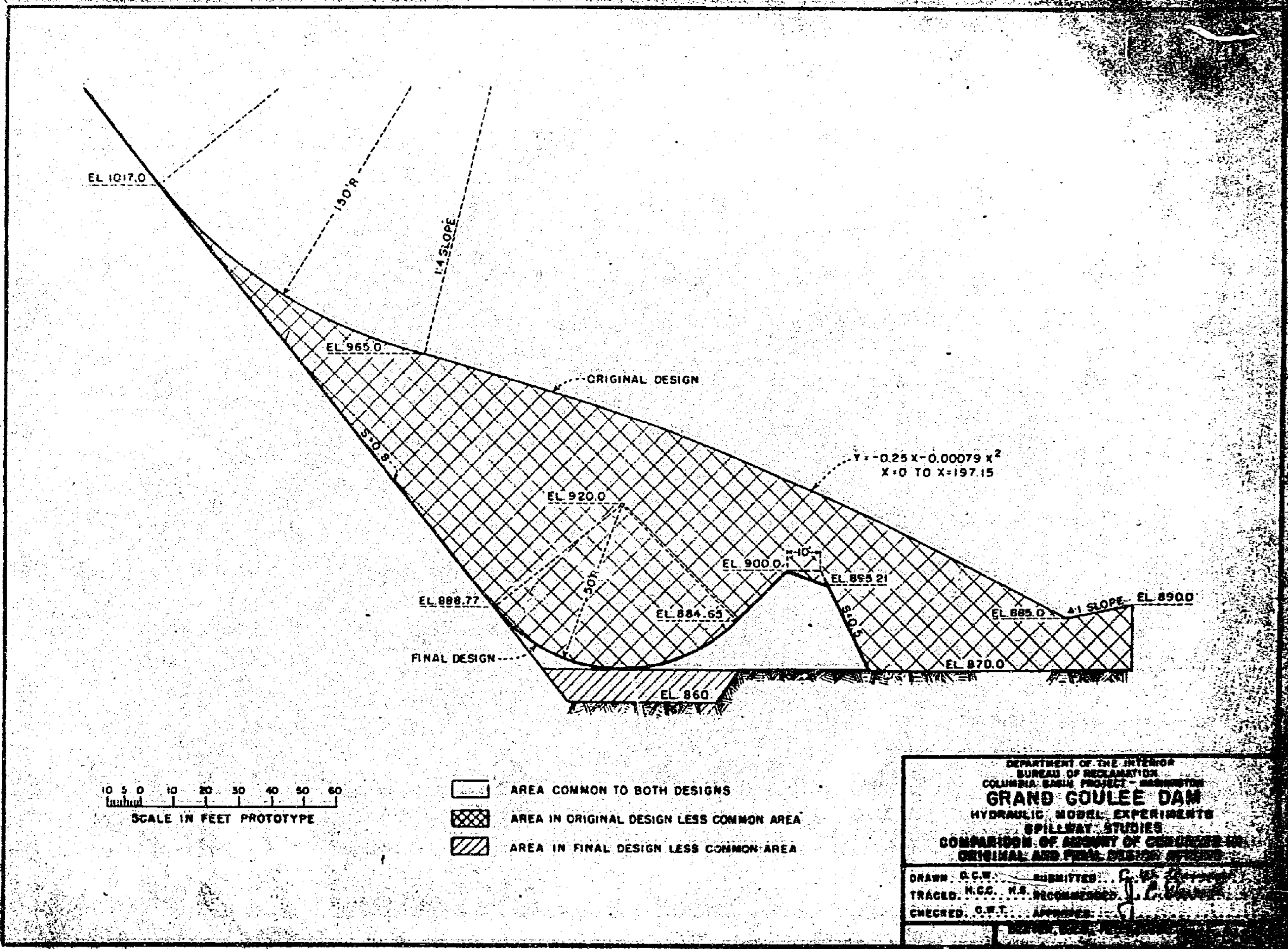

EL 1017.0
150'R
1:4 SLOPE
EL 965.0
ORIGINAL DESIGN
S=0.8
$Y = -0.25X - 0.00079X^2$
X=0 TO X=197.15
EL 920.0
50'R
EL 900.0
10
EL 895.21
S=0.5
EL 888.77
EL 884.65
FINAL DESIGN
EL 860
EL 870.0
EL 885.0
4:1 SLOPE
EL 890.0
10 5 0 10 20 30 40 50 60
SCALE IN FEET PROTOTYPE
AREA COMMON TO BOTH DESIGNS
AREA IN ORIGINAL DESIGN LESS COMMON AREA
AREA IN FINAL DESIGN LESS COMMON AREA
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT - WASHINGTON
GRAND COULEE DAM
HYDRAULIC MODEL EXPERIMENTS
SPILLWAY STUDIES
COMPARISON OF AMOUNT OF
ORIGINAL AND FINAL DESIGN
DRAWN D.C.W. SUBMITTED
TRACED N.C.C. H.S. RECOMMENDED
CHECKED C.W.T. APPROVED

At this point it was desired to ascertain the conditions obtaining in the complete structure with these designs. Accordingly, a 1 to 120 model of comparatively permanent material, described in detail at the conclusion of this discussion, Figure   was constructed.

As the studies on this model proceeded, it was observed that the pool action in the vicinity of the powerhouse tailraces was less violent than had been anticipated. It was noted, furthermore, that the removal of one gate on the extreme left end of the spillway resulted in material improvement in the behavior in the tailrace. As a consequence the spillway was shortened from twelve gates with a gross length of 1,800 feet, to eleven gates, with a gross length of 1,650 feet. The resulting increase in head on the spillway crest fortunately had no adverse effect. This change permitted the shifting of the left powerhouse to a position 150 ft. nearer the river, a more favorable location, with less excavation, effecting an appreciable reduction in construction cost.

To study the erosion of the river bed it was first necessary to select the material that would suitably represent the natural alluvium and to determine a method which the river bed profile could be reproduced expeditiously. The bed material of the Columbia River at the Grand Coulee Dam site is a combination of clay, sand, and gravel, closely interspersed with larger rock fragments all intimately associated in a cohesive mass. To find an accurately analogous material was quickly seen to be a practical impossibility, but it was felt that satisfactory qualitative results could be obtained by the use of cohesionless and less stable sand, since comparative rather than absolute data was desired. A design based upon conditions found to be satisfactory in this sand would be amply conservative when constructed in the tenacious material present at the site.

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To facilitate the reproduction and recording of river bed topography, a profilograph was developed with a simple horizontal and vertical gear ratio substituted for the more cumbersome pantograph. Field data were plotted to scale on the profilograph sheet and transferred in proper proportions to the model bed. Similarly, the measurement of the model bed after erosion had occurred was recorded on the profilograph sheet in prototype terms. Experiments on the 1 to 120 model resulted in the improvement of the design of the spillway training walls. The amount of scour around the downstream end of the walls as originally designed, was reduced to a satisfactory minimum in a relatively small number of tests.

In approaching the structural design of these walls no information, either theoretical or experimental, was available as to the intensity of the unbalanced hydrostatic pressures to be expected. To provide the required information, one of the walls of the model was equipped with 64 piezometers so located as to give the pressure distribution at six vertical sections. The tests showed that pressure differences were much less than assumed and the subsequent redesign resulted in material saving in concrete and reinforcing steel.

Separate tests were made to assist in the design of the spillway crest and drum gates. An unusually heavy vertical cantilever section, definitely limiting the shape of the crest was essential to support the large drum gates. It was desired to determine a profile which would coincide with the trajectory of a freely falling jet, thus giving the maximum efficiency without the presence of subatmospheric pressures. A preliminary design was based upon the Bazin experiments for a 2 to 3 approach slope. A model of the upstream portion of the crest with a sharp-crested weir at elevation 1266.18 was constructed to a scale of 1 to 30. The profile of the lower nappe of the jet as measured with a coordinometer, agreed to an excellent degree with that according to Bazin. The measured trajectory, as closely approximated by a compound curve with three radii was incorporated in the model and pressure measurements made with various discharges.

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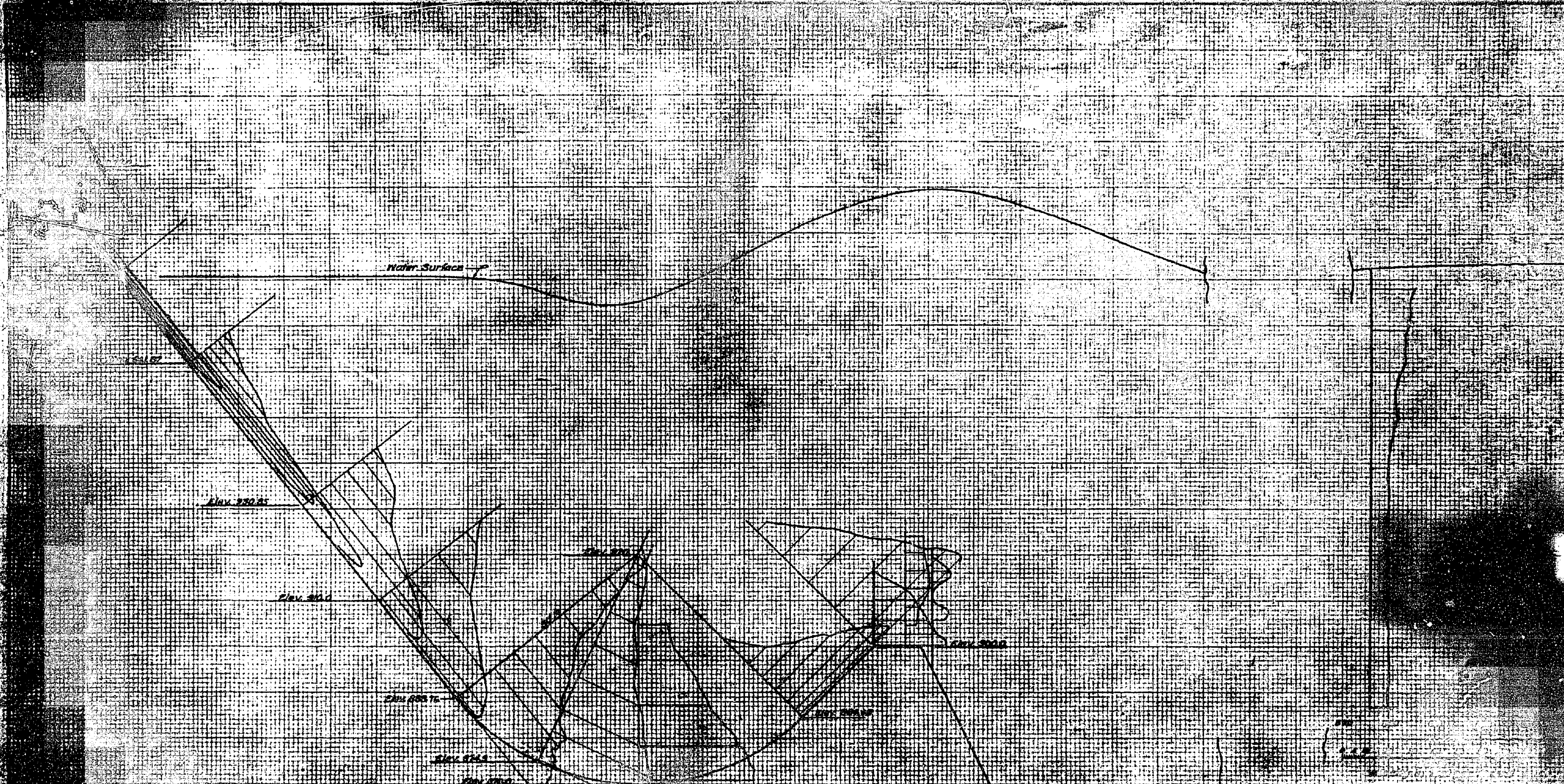

DEPARTMENT OF THE [illegible]
BUREAU OF [illegible]
COLUMBIA BASIN [illegible]

GRAND COULEE DAM

HYDRAULIC MODEL [illegible]
SPILLWAY STUDIES – SCALE [illegible]
VELOCITY STUDIES [illegible]

DRAWN A.H.S.	[illegible]
TRACED A.H.S.	[illegible]
CHECKED R.O.	[illegible]

The pressure curve for the original design showed a region of sub-atmospheric pressure under all flow conditions which indicated the slightly excess curvature near the downstream edge of the drum gate. The radius of the downstream section of the curve was lengthened, the axis of the crest moved upstream, and a parabolic curve introduced to connect the 66.25 foot arc to the 0.8 downstream slope of the spillway. Subsequent testing showed that the low-pressure zone no longer existed. After the revised design had been found satisfactory with the drum gate in the lowered position, additional measurements were made with the gate raised to provide pressure data for the structural design of the gate.

With the shorter spillway crest length, it was essential that all resistance affecting its capacity be reduced to a minimum. A source of resistance was the contractions at the upstream nose of the bridge piers. A 1 to 40 model of a section of the crest containing one pier, and two half-gates was constructed entirely of sheet metal for these tests. Several shapes with the nose placed at various distances upstream from the crest axis were studied. In the shape selected, considering structural limitations, the nose was formed by two arcs with radii equal to 5/6 of the pier thickness. The nose was placed coincident with the extreme upstream edge of the crest.

A model, sufficiently flexible to represent poured lifts of construction stages, was built to ascertain the conditions obtaining during the flood seasons. This model, with scale of 1 to 120, consisted of metal forms filled with a mixture of sand and cement. Alteration from one stage to the next was effected by adding the necessary forms, representing the finished surfaces, filling them with the mixture and finishing the surface level with the tops of the forms.

In the early construction stages, it was necessary to provide for passing salmon through the construction area during the yearly

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migration upstream. Extensive measurements were made on this model, to determine the velocity distribution in the flood passages for different river flows. Water surface elevations above, below and through the structure were obtained for each flow. Flow and scour conditions below the structure were also noted. After investigations on the early stages, which in some cases indicated changes in schedules for pouring concrete on the prototype to be necessary, these studies furnished little information other than the assurance that no major difficulties would be encountered in the proposed construction program.

In the original design of the Grand Coulee Dam, outlets in two tiers of 20 each, were provided to release 220,000 second-feet of water. On preliminary drawings the outlets were rectangular in cross-section, 5 ft. 8 in. wide by 10 ft. 6 in. high, longitudinal in plan, horizontal in section, and unlined.

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Severe splash and erosion was noted when this design was tested in the 1 to 120 model representing the ultimate development. All the jets impinged on the water surface downstream from the spillway bucket, causing severe scour in the river. The destructive conditions were extreme, particularly along the riprap bank of the right powerhouse tailrace. As a result the outlets with horizontal inverts were abandoned.

The outlets were next changed from rectangular to circular in cross-section and placed on parabolic paths through the dam so that the jet would plunge into the spillway stilling pool. The invert of the lower conduit was placed tangent to the spillway bucket and pairs of outlets were made to diverge in plan to spread the flow and to improve the energy dissipation in the pool. This became the final design of the lower tier at Grand Coulee except for a later entrance refinement to avoid erosion by cavitation. A series of investigations were made of the pressure conditions in the outlet entrances. A sharp-edged orifice was placed at the downstream end of a pressure tank and a detailed survey made of the jet from this orifice. The slope of the upstream face of the dam and the position of the control gates for the outlets had been established previously. With these limitations and with the surveyed shape of the free jet, a bell-mouth entrance with a converging elbow was developed. A 1 to 17 model of this shape was installed in the tank in place of the orifice. Detailed measurements showed the pressures to be above atmospheric throughout the bell-mouth and convergent section.

Since the trashrack structure might affect the entrance pressures in the lower outlet because of its proximity to the base, a replica was installed in the model. The test revealed that the position of the bottom of the trashrack had the most influence, while the effect of rib placement was negligible. A decrease in pressure along the top of the entrance resulted when the bottom of the trashrack was moved toward the opening. A position was chosen that gave positive pressures in the entrance and satisfactory velocity distribution downstream.

The control gates for the lower outlets at Grand Coulee are of two types. The upstream or emergency control is a ring follower gate operated by hydraulic pistons. The downstream or service control is a paradox roller gate operated by motor and gear train connected to the gate stem. The gate leaves in the two types are fundamentally alike in that each has at the bottom a follower ring which comes into position when the gate is fully opened, making the conduit an unbroken passage through the gate section.

Models of these gates were placed in the 1 to 17 outlet model to study the excessive downward forces discovered in previous tests on a similar gate. In operating the model gate it was found that the force required to lift it at small openings was greatly in excess of the dead weight of the gate. When reversed in position, with the normally upstream face turned downstream, the gate leaf floated and

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required a downward force to close it. Analysis of the pressure data showed that as the gate leaf normally descended toward the closed position its top was subjected to practically full reservoir pressure over its projected area. At the same time the high velocity jet passing through the constricted area between the partially closed leaf and the oppositely curved lower surface of the conduit produced a sub-atmospheric pressure over an area essentially equivalent to that subjected to static pressure above. These two produced a downward force, known as down-pull, upon the leaf and stem. Hydraulic balance was reestablished to a large degree by providing a vertical intercommunicating passageway behind the leaf in the gate bonnet and frame. This allowed the excess pressure above the leaf to escape into the top of the conduit downstream from the gate and alleviated a condition which in the operation of the prototype would have been a source of grief.

A pipe of the correct inside diameter and formed to the proper profile for the lower outlet was installed on the 1 to 17 model of the entrance and control gate. The pressure gradients throughout the conduit with the correct tailwater were above atmospheric pressure as expected. However, when the model was operated without the tailwater, to simulate conditions in the upper tiers, the results were startling. Sub-atmospheric pressures which would have caused absolute zero pressure through a considerable length of the prototype conduit, prevailed in the model. Severe cavitation would have resulted, hampering or even completely preventing successful operation. The fact that the frictional losses in the conduit were insufficient to overcome the accelerating force introduced by the slope of the conduit had apparently been overlooked.

Another condition that required further study was the formation of spray on the face of the dam. The canyon wall outlets at Boulder Dam had demonstrated that the friction of a jet with the surrounding

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FIGURE 7

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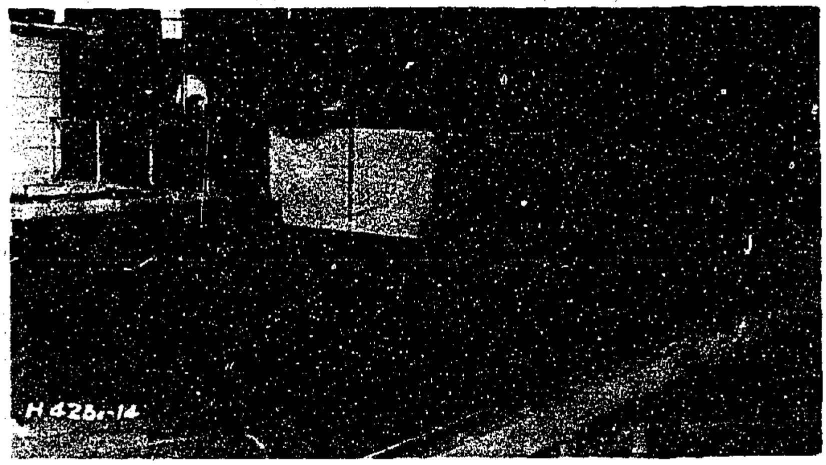
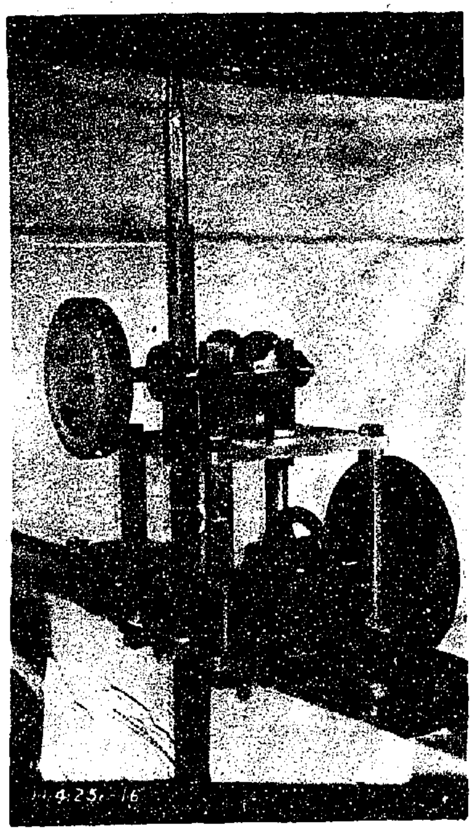


Placing model topography with profilograph.



Profilograph gearing.

air created a dense spray which was carried up the canyon toward the powerhouse, causing undesirable conditions and some damage.

The subsequent redesign of the conduits for the intermediate and upper tiers at Grand Coulee was therefore based on three objectives, (1) prevention of sub-atomospheric pressures within the conduits, (2) minimizing the formation of spray, and (3) minimizing the river bed erosion.

It was realized that there would be some difficulty in obtaining a design fulfilling all three requirements - at least one would have to be sacrificed to attain the others. After much consideration a preliminary design was selected, in which the conduit downstream from the control gate had a horizontal profile to a point near the downstream face of the dam where an elbow curved downward to a cone connecting to a trough in the face of the dam. With this arrangement the outlet jet flowing down the face of the dam was less conducive to the formation of spray than one falling freely through the air. Also the river bed erosion was minimized since the bucket at the toe functioned as an energy dissipator for the outlets as well as for the spillway. Furthermore, the cone at the end assured positive pressures within the conduit under normal operating conditions. Regardless of the desirability of this design, a large number of tests were necessary to obtain the required refinements.

The reduction in exit area in the first trial was effected by converging the crown of the elbow toward the invert. The invert of the open trough portion of the outlet was made circular in cross-section and tangent to that of the elbow. Pressures in the elbow were above atmospheric but the discharge was materially decreased. In addition, fins of water formed on both sides of the jet in the upper end of the open trough. The fins were objectionable because of spray and because of the unpleasant appearance.

To prevent the formation of these fins a long succession of revisions in the shape of the open channel were undertaken. The

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solution finally obtained comprised a conical constriction equal to 85 percent of the conduit cross-sectional area, symmetrical about the centerline. This formed a slight but definite break at the intersection of the frustrum with the trough, but the pressures throughout the conduit were positive for all heads in excess of 40 ft. (prototype) on the centerline of the entrance. Since the outlets were to operate under the low heads only for a short time during construction, this condition was not considered serious. Furthermore, the conduits would receive air from vents located downstream from the control gates; thus the sub-atmospheric pressures would not be excessive.

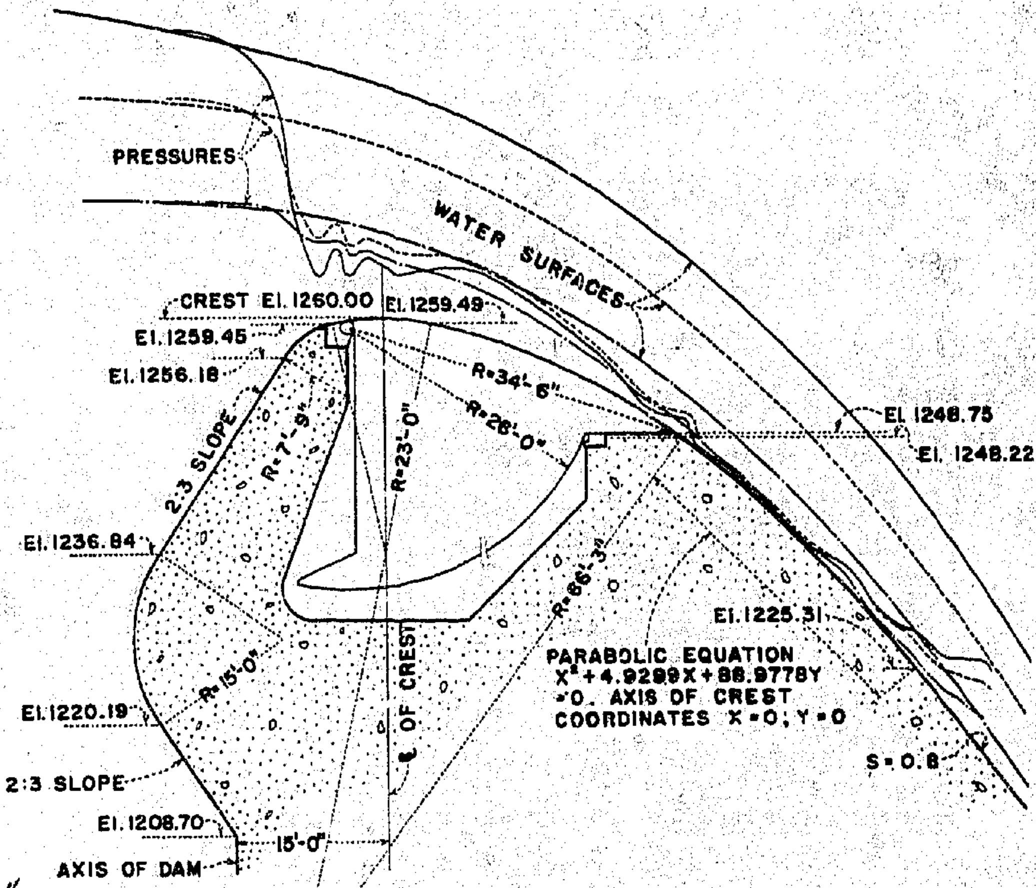
The outlet trough presented a problem of greater magnitude than originally anticipated. The slight but distinct break between the inverts of the cone and trough and that between the trough and the face of the dam produced pressures contrary to expectations. Slight positive pressures existed immediately downstream from the cone while, excessive negative pressures were present upstream from the intersection of the trough with the face of the dam.

A number of changes in curvature and profile were made in attempting to solve this problem - none were successful. When the solution was found it was quite by accident. While changing the connection on one of the piezometers in this region, it was noted that the pressure downstream was raised nearer atmospheric pressure; the low pressure region had been aerated by air flowing through the disconnected tube. A system of vents solved the problem.

A complete set of 60 outlets of this design were installed on the 1 to 120 model to ascertain their feasibility under various operation conditions. The results were satisfactory except for the splash resulting from the spillway flow dropping into the outlet trough. Little concern was felt regarding this condition until the phenomena was viewed on a model of similar design having a scale

HYD103

HYD 103



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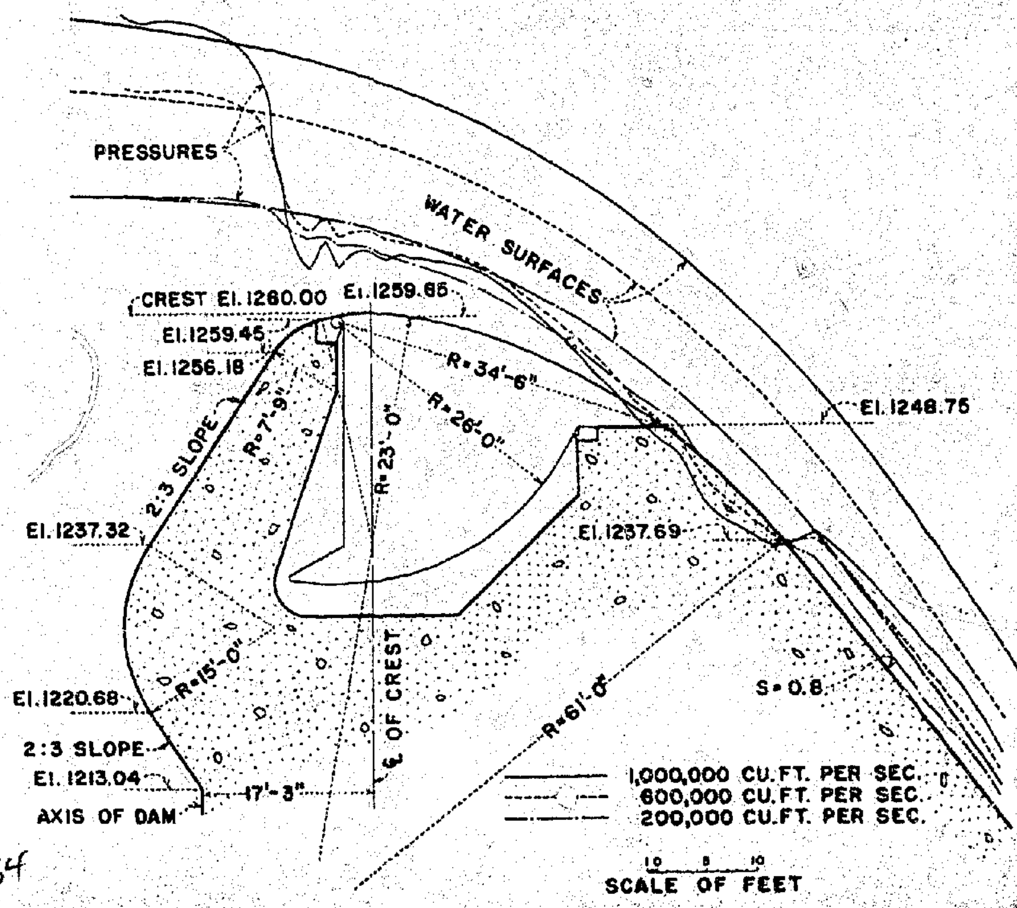

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Plan view.

Side view.

FLOW AROUND PIER NOSE FORMED BY CIRCULAR ARCS.

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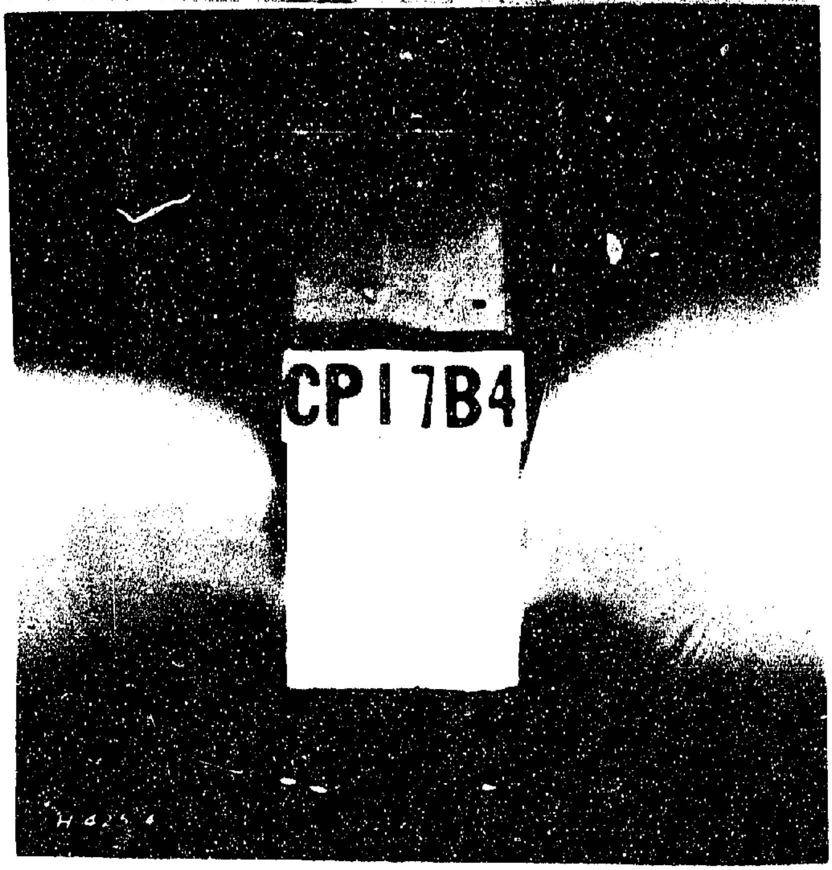
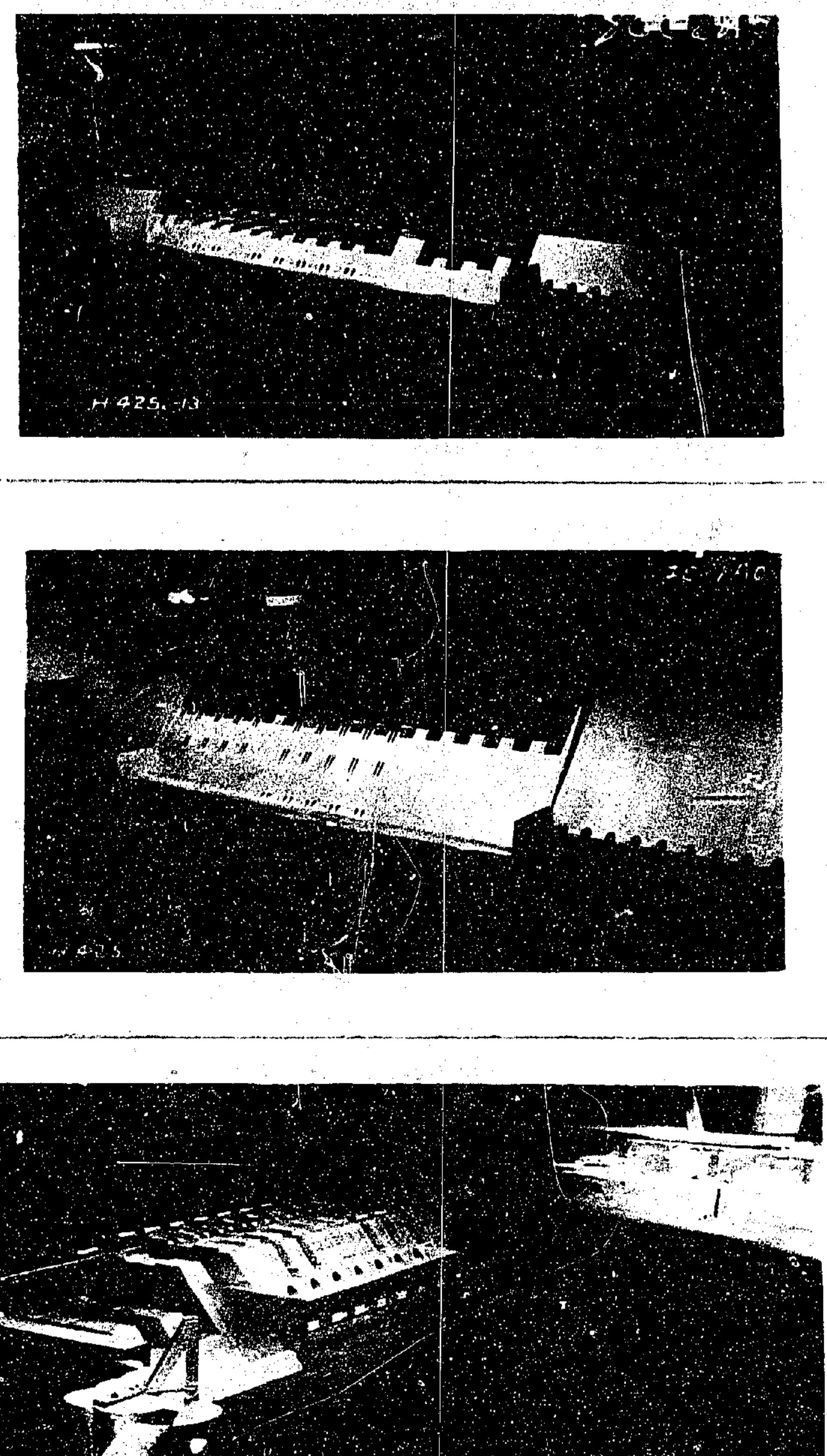


Plan view.

Side view.

FLOW AROUND PIER WITH FLAT NOSE.

FIGURE 11



MODEL OF CONSTRUCTION STAGES.

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of 1 to 68. The condition was termed critical thereafter and tests were made to remedy it.

The tentative final design for the intermediate outlets at Grand Coulee Dam, which was developed under extreme urgency because of the progress of construction, did not have deflectors over the outlets, although consideration had been given to the excessive spray from the spillway flow dropping into the trough of the outlet.

To eliminate this, the trajectory of the spillway jet was deflected above the opening in the face of the dam. The raised portion or deflector was made parabolic in the direction of flow and was blended into the spillway face by reverse curves.

With the addition of the deflector over the outlet, the thickness of concrete between the cone and the face of the deflector was increased considerably beyond the minimum of 3 feet established at the beginning of the studies as necessary for the reinforcing steel. Advantage was taken of these projections to move the elbow and cone 3 ft. horizontally downstream. This change moved the point of intersection between the invert of the channel and the face of the dam up the slope 13 ft. reducing the exposed opening. Construction progress prevented any change in the intermediate outlets at Grand Coulee except the addition of the deflector, but the shortened opening and the deflector were adopted for the upper tier.

A laboratory study was made concerning nozzles for an air-lift de-icing system for maintaining an ice-free water surface adjacent to the dam and trashracks to prevent damage during the cold winter months. In this system compressed air is forced through nozzles into the reservoir adjacent to a structure at a depth at which the water temperature is at or near that corresponding to the maximum density. The stirring and mixing action of the rising air induces an upward flow of relatively warm currents of water which either melt the ice or prevent its formation.

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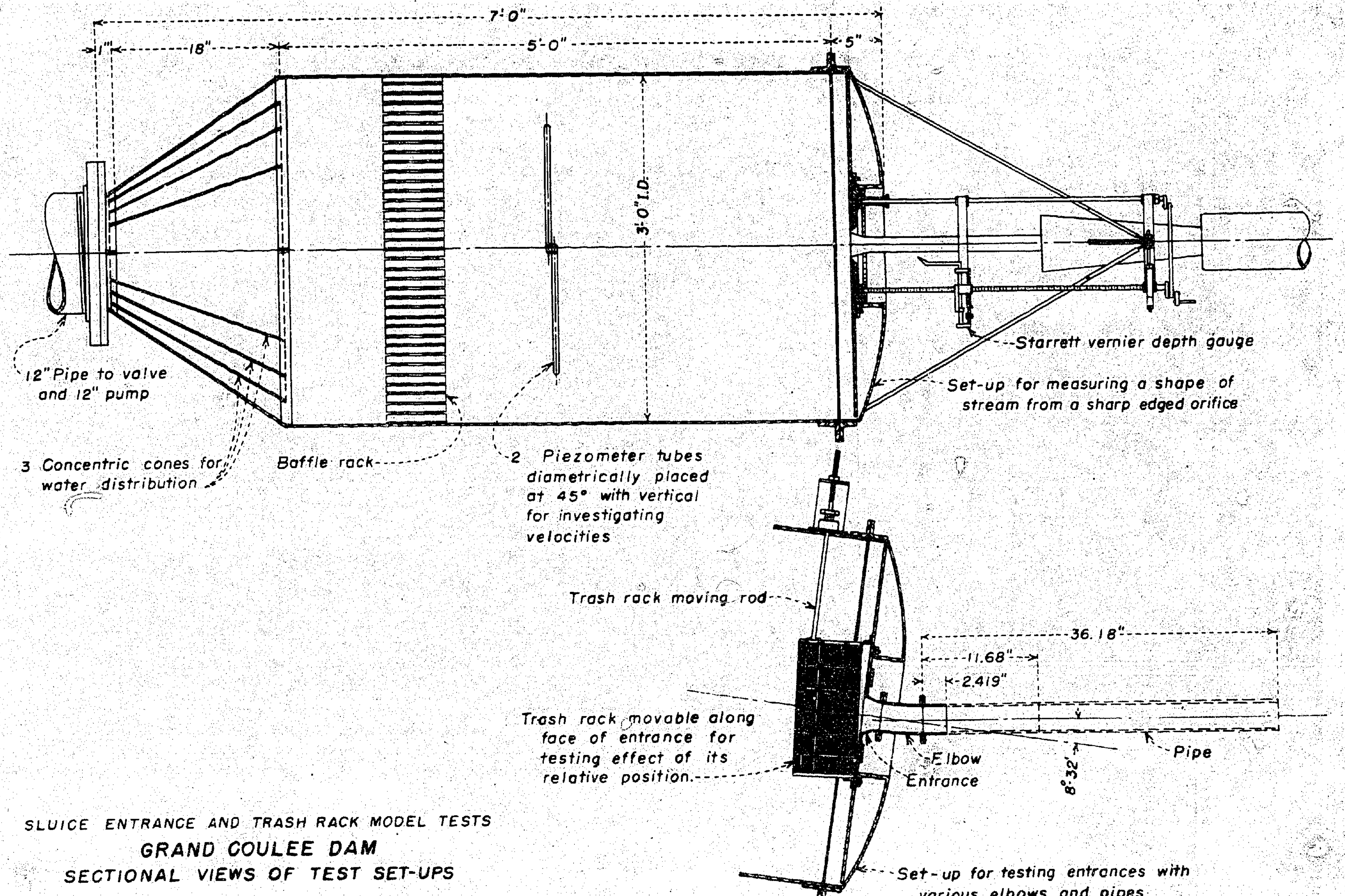
The problems of determining the best size, the best shape, the most satisfactory direction of discharge of the nozzle, and the cooling effect due to expansion of the air at the nozzle exit were studied in a 1 to 1 scale model. The model was contained in an insulated tank to enable studies under near-freezing water temperatures. The study embraced testing of single and multiple-hole nozzles. In addition to evolving a satisfactory nozzle for Grand Coulee Dam, valuable data from which to design nozzles for air-lift de-icing systems subjected to various temperature conditions were obtained from these studies.

Though the model studies for the design of the Grand Coulee spillway and river outlets have been discussed in detail, no mention has been made of the problems in the design of the models themselves. This is an important phase since the success or failure of the investigation may, in many cases, depend on the consideration given these problems. Oftentimes, these problems are more numerous than those to be studied concerning the prototype structure. The construction elements of the 1 to 120 model of the Grand Coulee Dam are herewith described to illustrate the model construction problems.

As the final design of the spillway was approached, a model on a scale of 1 to 120 was developed to include all design changes and to make possible the duplication of every possible flow condition which might conceivably exist in the future. The model was constructed so as to be maintained in usable shape until the prototype was complete and no further use for it existed. The fact that the model was maintained for a long period of time does not mean that it was in constant use, but that it was held ready to answer any problem arising before completion of the project. Actually, the studies could have been completed in a much shorter time.

Since approach conditions on any model should represent as near as possible those on the prototype, considerable thought was given to the arrangement of the head tank. The problem was simplified

FIGURE 12



SLUICE ENTRANCE AND TRASH RACK MODEL TESTS

GRAND COULEE DAM

SECTIONAL VIEWS OF TEST SET-UPS

E.S.G. 1-26-38

somewhat by the branching of the laboratory supply system, such that the flow was delivered to two widely separated points in the head tank. This divided flow required less baffling in the 6 x 23-foot head tank than would have been necessary had the water entered at one point.

The head tank was a framework of 2 x 4-inch timbers lined with 1-inch sheathing and 27-gage galvanized iron. One-half inch tie rods were placed across the box and a section of the downstream side was omitted in which to install the spillway model. A baffle made of a framework of 2-inch lumber covered with hardware cloth and filled with 1 to 2-inch rock was used to distribute the water uniformly in the tank upstream from the model. This baffle was placed sufficiently far upstream to allow measuring of the water surface without including the drawdown caused by flow over the crest. The minimum distance from model to head gage inlet was taken as five times the maximum head on the model crest. The baffle was placed to give smooth flow at this point.

The headwater and tailwater tanks were constructed separately to give access to the under side of the model. Additional space to facilitate making changes and operating various model parts was obtained by placing these boxes on a platform 4 feet above the floor of a concrete-lined laboratory tank. A steel beam support for the model proper was constructed immediately downstream from the head tank. Flexible strips of thin sheet metal between this model and tank allowed slight movements without disturbing the model.

The tailwater tank was of the same construction as the headwater tank but its size was governed by the extent of river bed required for the model studies. It was necessary to include a bridge located about 1/4 mile below the dam so the tailwater box was made to represent a length of river somewhat in excess of this, or about 1/2 mile. The depth was sufficient to conduct tests pertaining to erosion of the river bed below the dam and to contain all

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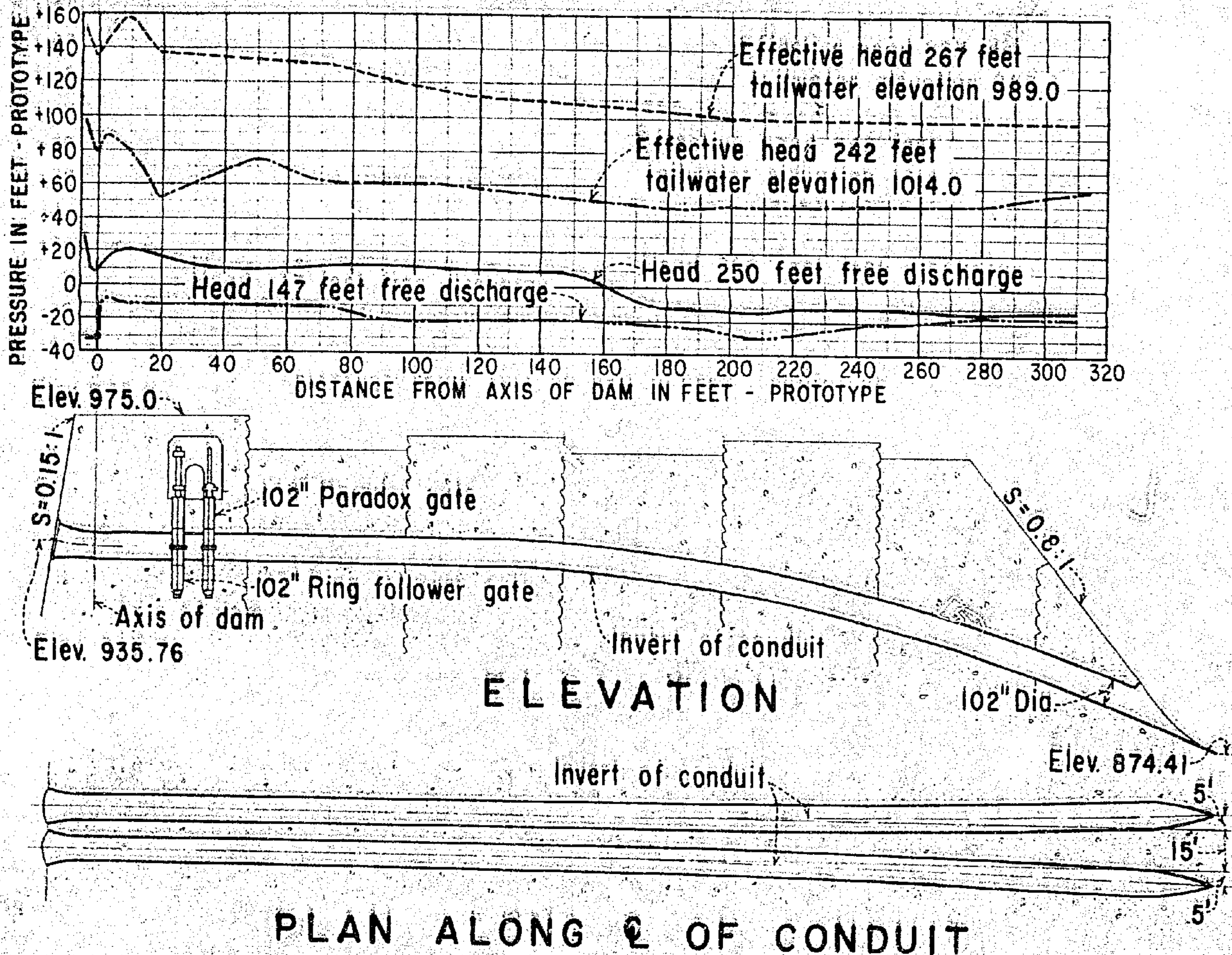

PRESSURES IN LOWER OUTLET - FINAL DESIGN
GRAND COULEE DAM

topography to an elevation slightly above the maximum tailwater.

A tailwater regulator of the variable width weir type made of angle iron and 16-gage sheet metal, was placed at the downstream end of the tailwater box. Gage wells mounted on concrete walls adjacent to the model were connected by hose to piezometer openings in the floor of the tank. The water surface elevations in the gage wells were measured with hook gages.

To properly design the model, it was necessary to distinguish between the permanent parts and those susceptible to change. Insofar as feasible the latter were installed with provision for removing without disturbing the more permanent sections.

Alteration of the cross-section of the model dam excluding the crest and stilling pool seemed unlikely, so bents of 2 x 2 x 1/8-inch angle iron faced with 16-gage sheet metal were used to form the base. The angle iron was cut to length and welded while held in position in a jig. Allowance was made for the thickness of the metal faces. Flat head brass machine screws were used to fasten the sheet metal to the bents. A smooth, water-tight surface was obtained by countersinking, soldering and filing the screwheads.

The heavy, galvanized facing was used to reduce the sag between the bents and to prevent distortion by heating when soldering. Strips of light-weight metal soldered to the facing and tank lining prevented leakage.

Besides being permanent, this type of construction provided space for installing and operating the gate mechanism, installing the river outlets and operating the outlet gates. The crest which was subject to change in subsequent studies, was constructed of three short wooden timbers, obtained by gluing 2-inch redwood together. The finished shape was obtained by planing and sanding to accurate outside templates of heavy gage iron. After recessing for the spillway gates and rabbeting for joining the crest to the base of the

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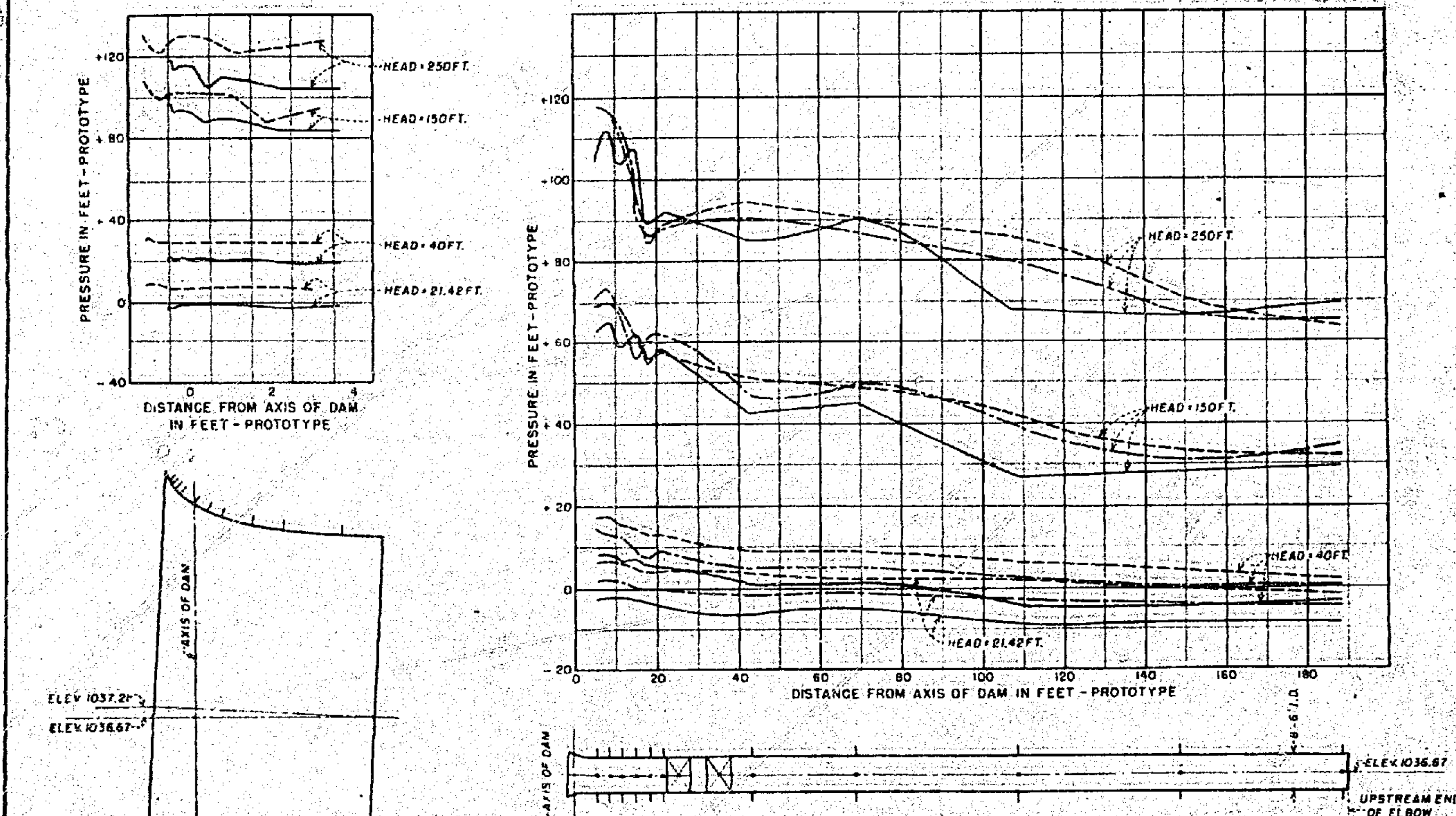
FIGURE 15



GRAND COULEE DAM

OUTLET STUDIES

PRESSURES IN CONDUIT
FINAL DESIGN

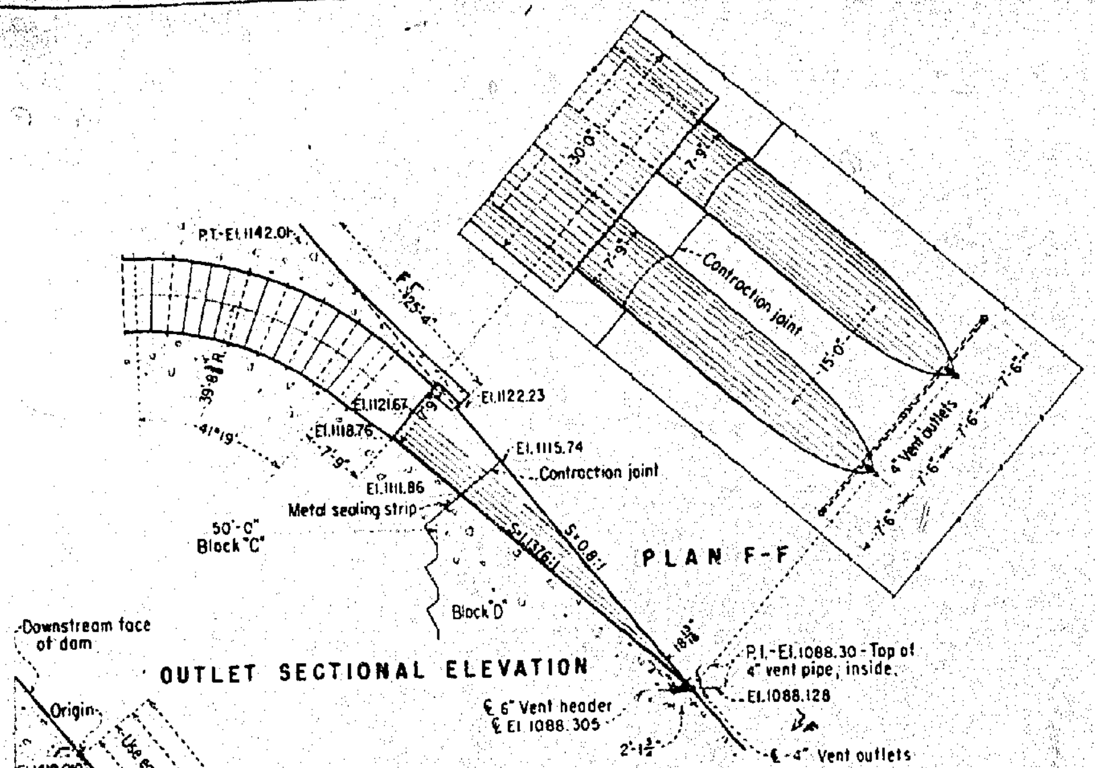
NOTE

The head indicated on the pressure diagrams is the distance of the water surface above the center line of the entrance and is not the total static head.

EXPLANATION

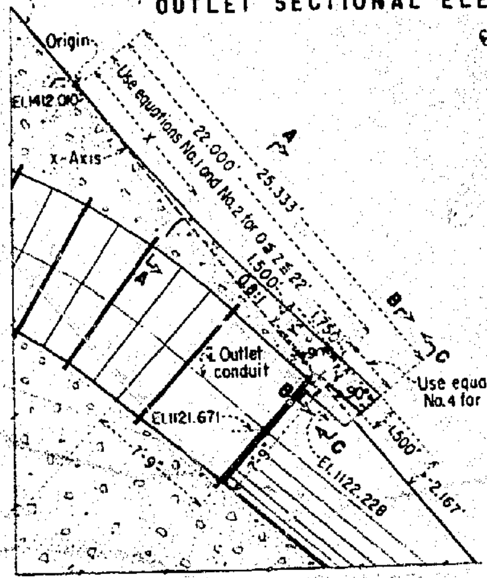
- ———— Pressures on crown.
- – – – – Pressures on invert.
- —·—·— Pressures on side.

D.M.L. 3-12-40

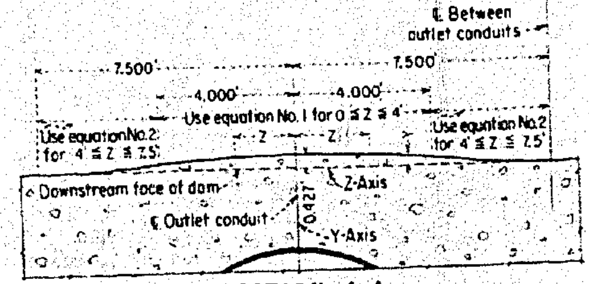


PLAN F-F

OUTLET SECTIONAL ELEVATION



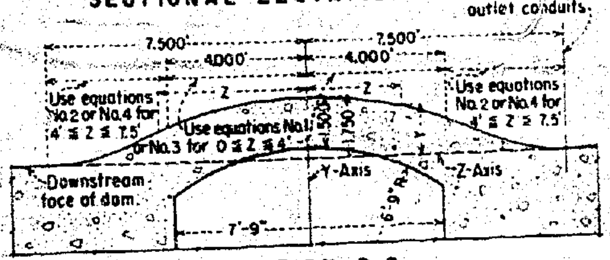
SECTIONAL ELEVATION



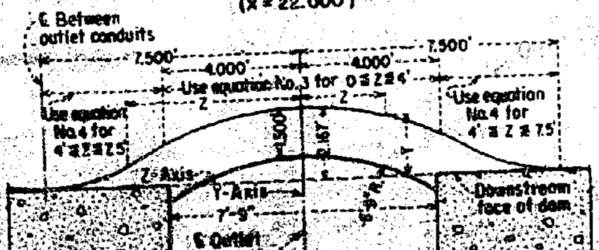
SECTION A-A
(x = 10.000')

DEFLECTOR COORDINATES FOR SECTIONS

SECTION A-A			SECTION B-B			SECTION C-C		
X	Y	Z	X	Y	Z	X	Y	Z
10.000'	0.427'	0	22.000'	1.750'	0	25.333'	2.167'	0
10.000'	0.417'	1.000'	22.000'	1.709'	1.000'	25.333'	2.116'	1.000'
10.000'	0.386'	2.000'	22.000'	1.582'	2.000'	25.333'	1.959'	2.000'
10.000'	0.332'	3.000'	22.000'	1.360'	3.000'	25.333'	1.684'	3.000'
10.000'	0.255'	4.000'	22.000'	1.045'	4.000'	25.333'	1.293'	4.000'
10.000'	0.142'	5.000'	22.000'	0.583'	5.000'	25.333'	0.722'	5.000'
10.000'	0.054'	6.000'	22.000'	0.223'	6.000'	25.333'	0.276'	6.000'
10.000'	0.006'	7.000'	22.000'	0.025'	7.000'	25.333'	0.032'	7.000'
10.000'	0	7.500'	22.000'	0	7.500'	25.333'	0	7.500'



SECTION B-B
(x = 22.000')



SECTION C-C
(x = 25.333')

NOTES

Equation No.1: $Y = 0.875\left(1+\frac{Z^2}{46}\right)\left(1+\cos\frac{\pi Z}{7.5}\right)\left(1-\cos\frac{\pi X}{44}\right)$

Equation No.2: $Y = 1.167\left(1+\cos\frac{\pi Z}{7.5}\right)\left(1-\cos\frac{\pi X}{7.5}\right)$

Equation No.3: $Y = 0.500\left(0.125X-1\right)\left(1+\frac{Z^2}{46}\right)\left(1+\cos\frac{\pi Z}{7.5}\right)$

Equation No.4: $Y = 0.667\left(0.125X-1\right)\left(1+\cos\frac{\pi Z}{7.5}\right)$

Origin: Point in downstream face of dam @ El.1142.010 on vertical ℄ of outlet conduit.

Z-Axis: A horizontal line in the downstream face of dam passing thru origin.

Y-Axis: Line normal to downstream face of dam passing thru origin.

X-Axis: Line in downstream face of dam, normal to Z-Axis and passing thru origin.

Consider "Z" positive either to right or left of origin.

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GRAND COULEE DAM

EL. 1130 - CONDUIT OPENING

model, the wood was treated with hot linseed oil. The crest segments were then provided with holes for the spillway gate operating mechanism, and fastened to the angle iron bent with wood screws. Water-tight joints between the metal faces of the base and the crest were made by placing white lead between the surfaces and fastening with screws into the rabbet. The bridge piers, also of redwood, were bolted to the crest.

Gates of 12-gage galvanized iron were rolled to shape and hinged by pins into brass blocks set into the crest under the piers. A forked rod of 3/8-inch round steel and 1/8-inch pipe fittings was used to operate the gate. A threaded mechanism served to propel the forked rod when raising or lowering the gate. Since the water pressure on the gates lowered them when the fork was withdrawn, it was only necessary to have positive action upwards, so the mechanism was not attached to the gates. More recent construction of an all-metal crest enabled positive control of the gate by use of racks and pinions, and provided space for including the drum of the gate.

That portion of the training wall between the crest and stilling pool was constructed of redwood and bolted to the base of the model after applying white lead compound to the contact surface. The lower part of the training wall was made of galvanized iron to facilitate the installation of piezometers.

The bottom of the stilling pool or bucket was shaped by covering 16-gage galvanized iron bents with light-weight sheet metal. The bucket was leveled and spot soldered to the downstream face of the model base. The soldered spots were filed smooth and the joints filled with melted beeswax which was dressed with a steel template after it had cooled. This method of joining the metal parts prevented warping by heat and saved considerable time and labor necessary to obtain a smooth soldered joint.

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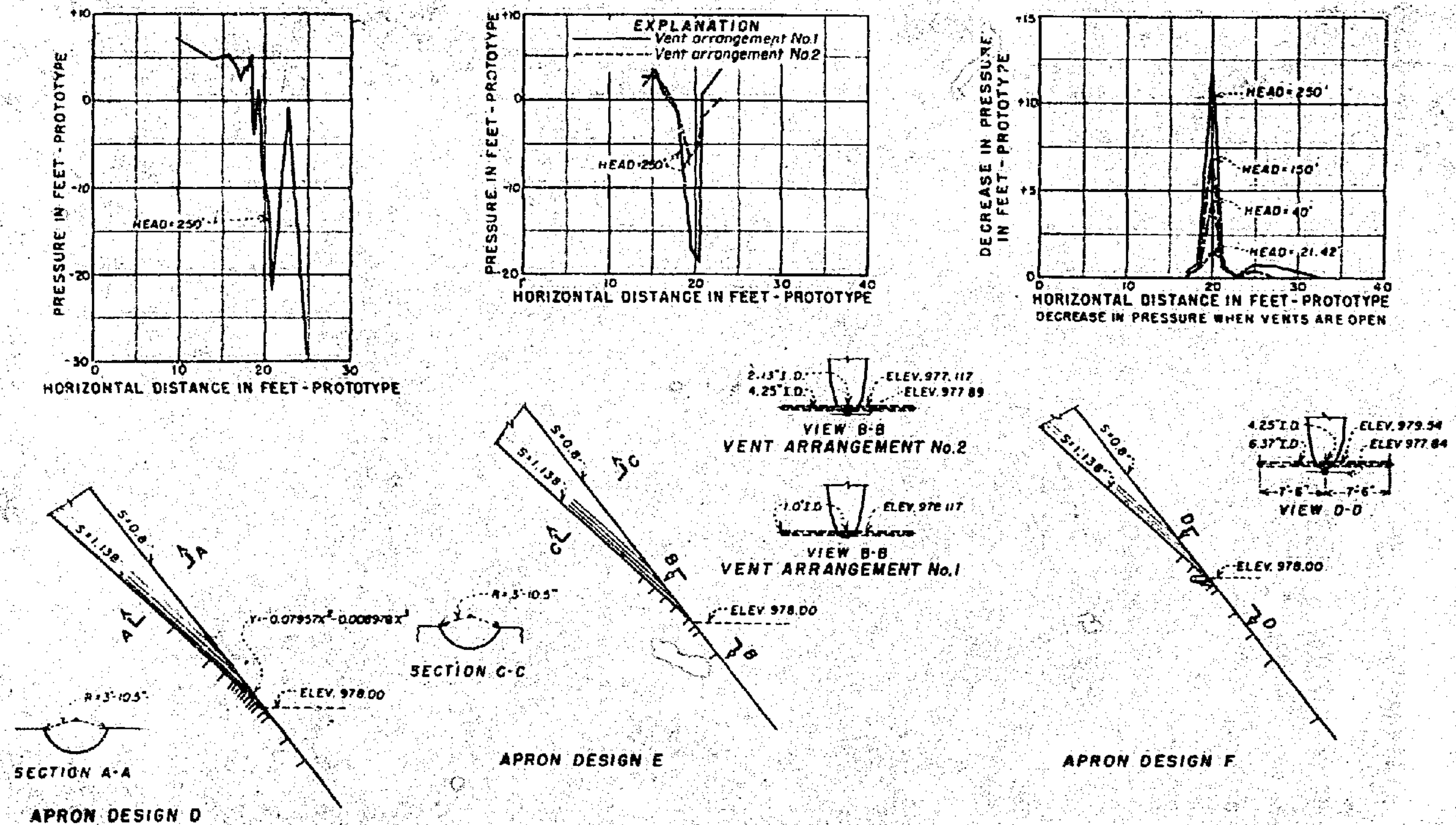
FIGURE 17



GRAND COULEE DAM

OUTLET STUDIES

APRON DESIGNS D, E, AND F
PRESSURES ON APRON

NOTE
The head indicated on the pressure diagrams is the distance of the water surface above the center line of the entrance and is not the total static head.

D.W.L. 3-9-1940

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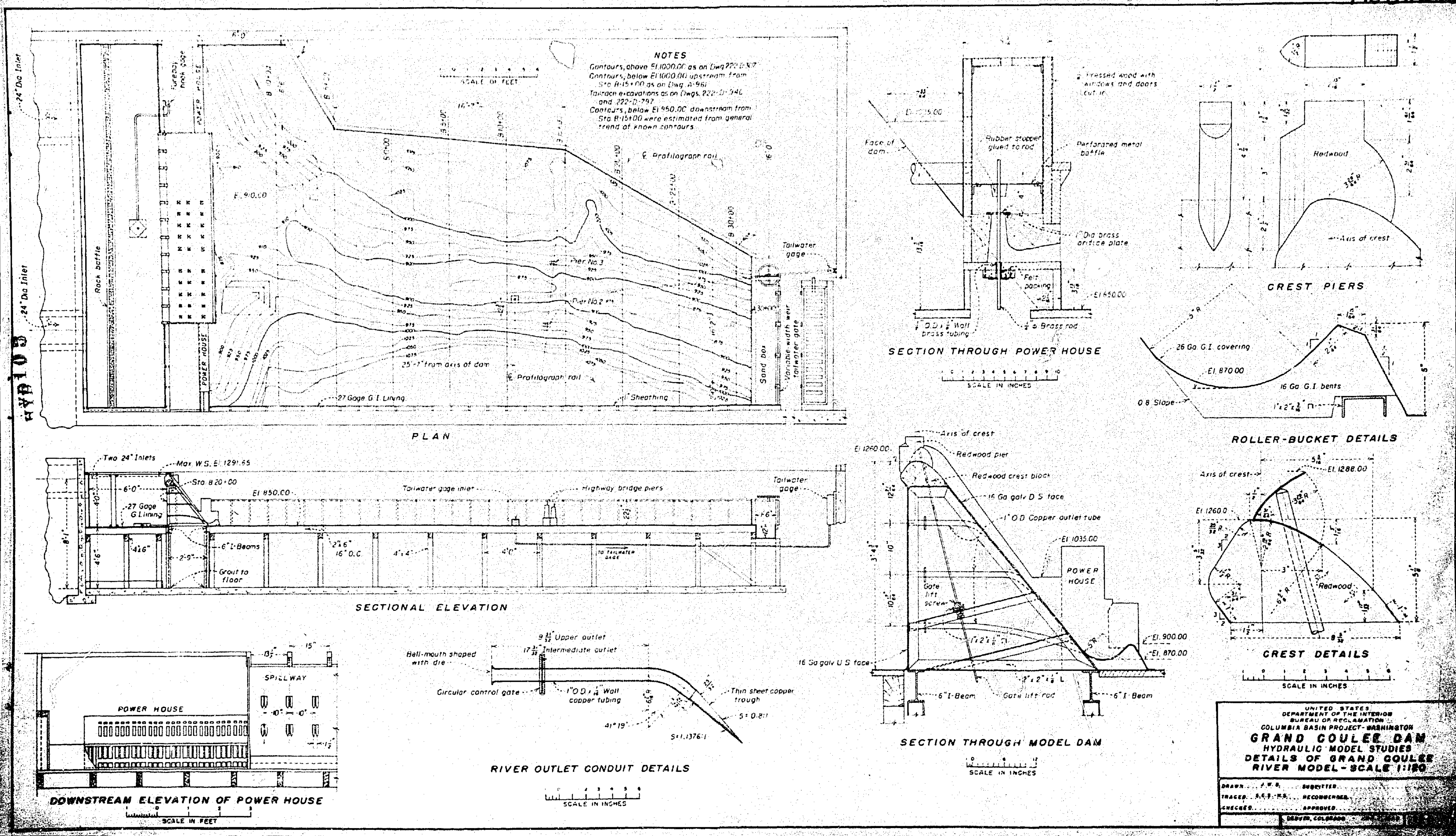

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NOTES
Contours, above El 1000.00 as on Dwg 222-D-307
Contours, below El 1000.00 upstream from Sta B-15+00 as on Dwg. A-961
Tailrace excavations as on Dwgs. 222-D-346 and 222-D-292
Contours, below El 950.00 downstream from Sta B-15+00 were estimated from general trend of known contours
SCALE OF FEET
24" Dia Inlet
Rock baffle
Point gage
Hook gage
POWER HOUSE
Pier No. 3
Pier No. 2
℄ Profilograph rail
25'-7" from axis of dam
27 Gage G.I. Lining
Sheathing
Tailwater gage
Sand box
Variable width weir tailwater gate
PLAN
Two 24" Inlets
Max. W.S. El. 1291.65
Sta. B 20+00
El. 850.00
Tailwater gage inlet
Highway bridge piers
27 Gage G.I. Lining
6" I-Beams
Grout to floor
16" O.C.
TO TAILWATER GAGE
SECTIONAL ELEVATION
POWER HOUSE
SPILLWAY
DOWNSTREAM ELEVATION OF POWER HOUSE
SCALE IN FEET
Upper outlet
Intermediate outlet
Bell-mouth shaped with die
Circular control gate
1" O.D. x 1/16" Wall copper tubing
Thin sheet copper trough
S = 0.8:1
S = 1.376:1
RIVER OUTLET CONDUIT DETAILS
SCALE IN INCHES
Face of dam
Pressed wood with windows and doors cut in
Rubber stopper glued to rod
Perforated metal baffle
1" Dia brass orifice plate
Felt packing
El. 850.00
O.D. x 1/16" Wall brass tubing
1/4" ø Brass rod
SECTION THROUGH POWER HOUSE
SCALE IN INCHES
Redwood
Axis of crest
CREST PIERS
26 Ga. G.I. covering
El. 870.00
16 Ga. G.I. bents
0.8 Slope
ROLLER-BUCKET DETAILS
Axis of crest
El. 1260.00
Redwood pier
Redwood crest block
16 Ga. galv. D.S. face
1" O.D. Copper outlet tube
El. 1035.00
POWER HOUSE
Gate lift screw
El. 900.00
El. 870.00
16 Ga. galv. U.S. face
6" I-Beam
Gate lift rod
SECTION THROUGH MODEL DAM
SCALE IN INCHES
El. 1288.00
Redwood
CREST DETAILS
SCALE IN INCHES
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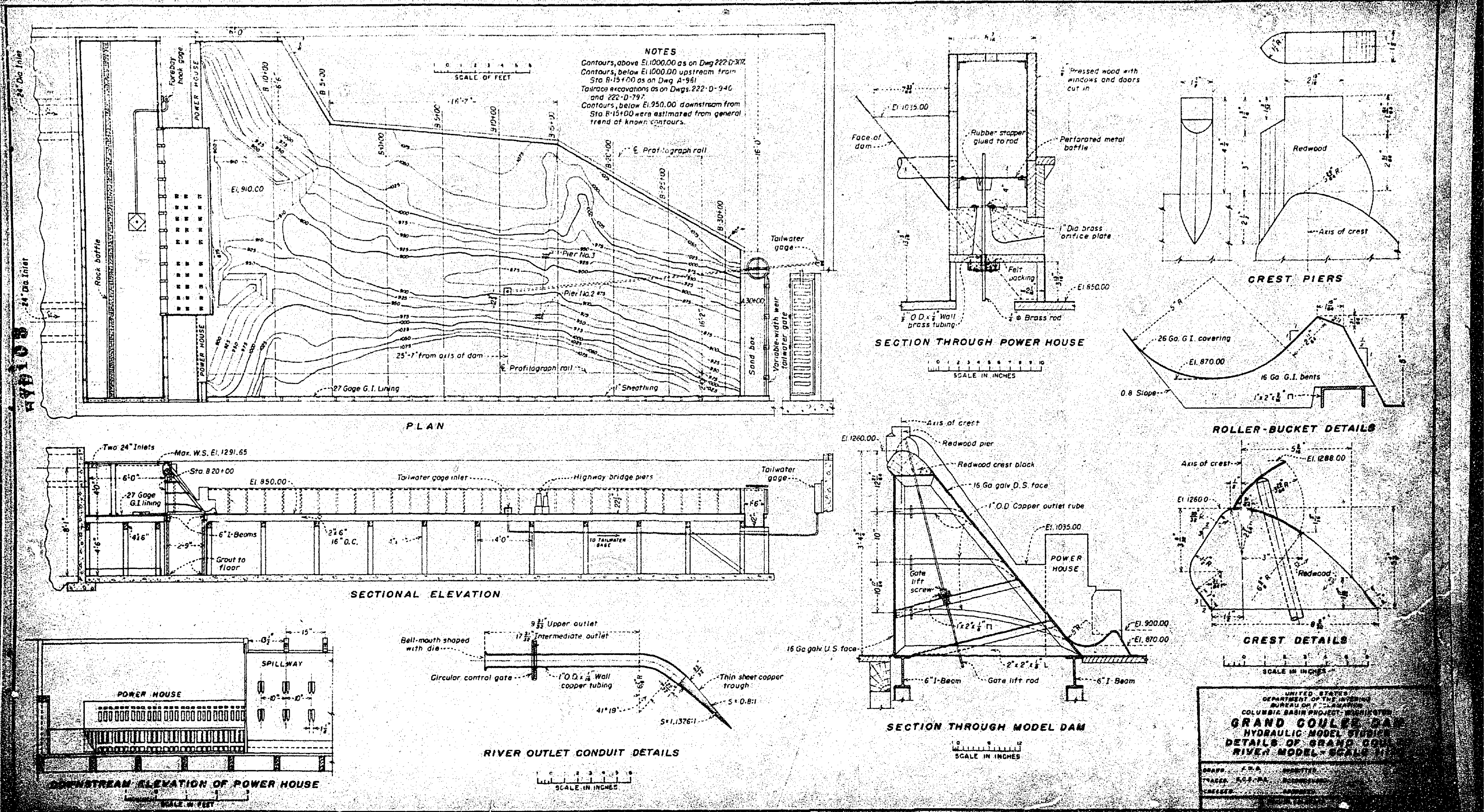
GRAND COULEE DAM
HYDRAULIC MODEL STUDIES
DETAILS OF GRAND COULEE RIVER MODEL - SCALE 1:120
DRAWN
TRACED
CHECKED
SUBMITTED
RECOMMENDED
APPROVED
DENVER, COLORADO


NOTES
Contours, above El. 1000.00 as on Dwg 222-D-3012
Contours, below El. 1000.00 upstream from Sta B-15+00 as on Dwg A-961
Tailrace excavations as on Dwgs. 222-D-940 and 222-D-797.
Contours, below El. 950.00 downstream from Sta B-15+00 were estimated from general trend of known contours.
SCALE OF FEET
24" Dia Inlet
Forebay hook gage
POWER HOUSE
Rock baffle
El. 910.00
Pier No. 3
Pier No. 2
℄ Profilograph rail
25'-7" from axis of dam
27 Gage G.I. Lining
1" Sheathing
Tailwater gage
Sand box
Variable-width weir tailwater gate
PLAN
Two 24" Inlets
Max. W.S. El. 1291.65
Sta. B 20+00
El. 850.00
Tailwater gage inlet
Highway bridge piers
27 Gage G.I. lining
6" I-Beams
Grout to floor
16" O.C.
TO TAILWATER GAGE
SECTIONAL ELEVATION
SPILLWAY
POWER HOUSE
DOWNSTREAM ELEVATION OF POWER HOUSE
SCALE IN FEET
Bell-mouth shaped with die
Upper outlet
Intermediate outlet
Circular control gate
1" O.D. x 1/16" Wall copper tubing
Thin sheet copper trough
S = 0.8:1
S = 1.376:1
41°19'
RIVER OUTLET CONDUIT DETAILS
SCALE IN INCHES
Pressed wood with windows and doors cut in
El. 1035.00
Face of dam
Rubber stopper glued to rod
Perforated metal baffle
1" Dia brass orifice plate
Felt packing
El. 850.00
O.D. x Wall brass tubing
Brass rod
SECTION THROUGH POWER HOUSE
SCALE IN INCHES
Redwood
Axis of crest
CREST PIERS
26 Ga. G.I. covering
El. 870.00
16 Ga. G.I. bents
0.8 Slope
ROLLER-BUCKET DETAILS
Axis of crest
El. 1260.00
Redwood pier
Redwood crest block
16 Ga galv. D.S. face
1" O.D. Copper outlet tube
El. 1035.00
POWER HOUSE
Gate lift screw
El. 900.00
El. 870.00
16 Ga galv. U.S. face
6" I-Beam
Gate lift rod
SECTION THROUGH MODEL DAM
SCALE IN INCHES
El. 1288.00
El. 1260.0
Redwood
CREST DETAILS
SCALE IN INCHES
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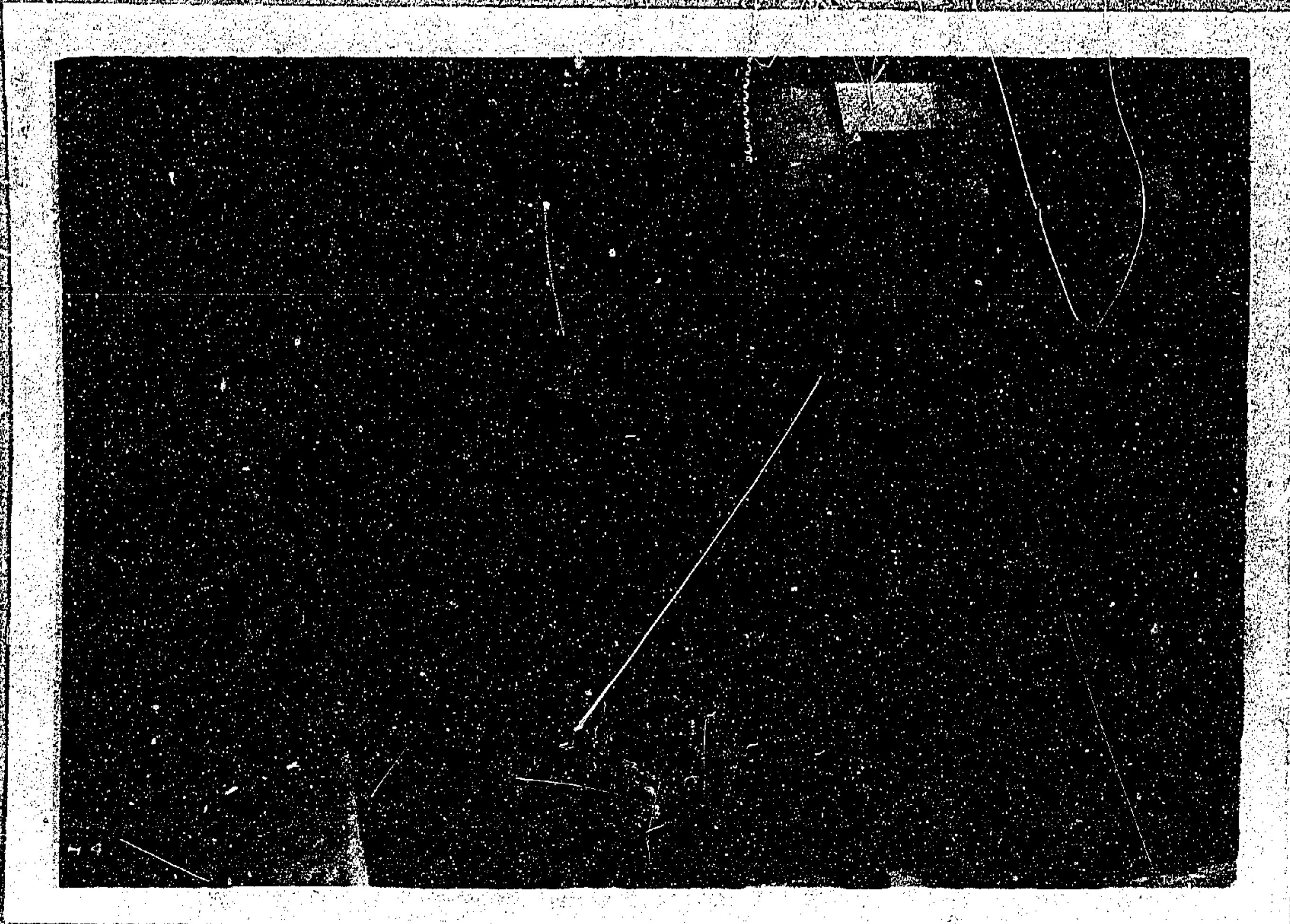
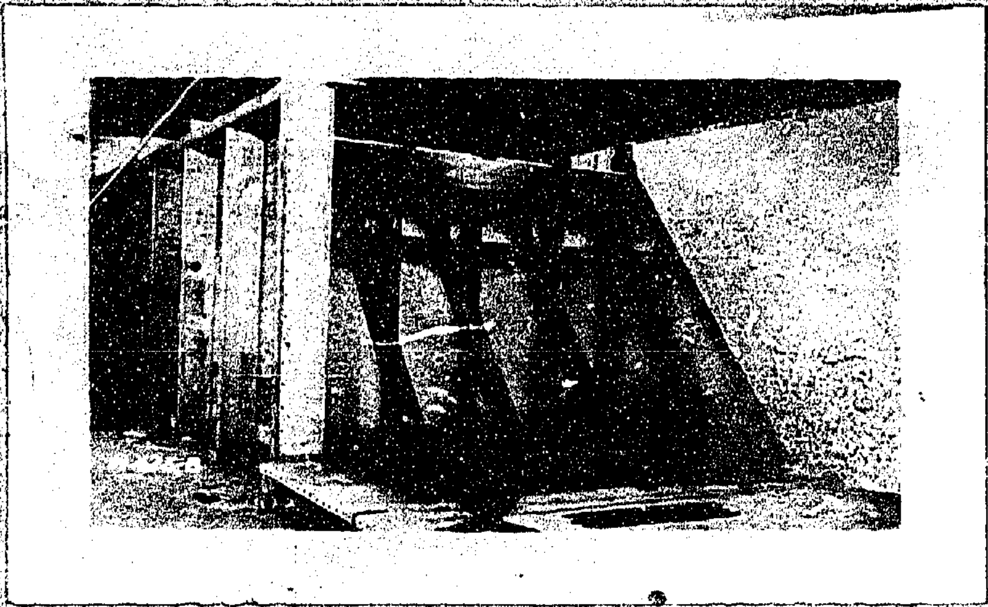
COLUMBIA BASIN PROJECT
GRAND COULEE DAM
HYDRAULIC MODEL STUDIES
DETAILS OF GRAND COULEE
RIVER MODEL



THE 1 : 120 GRAND COULEE RIVER MODEL.



Framework of 1:184 sectional model of Grand Coulee Dam.

Framework, river outlets, and drum gate operating mechanism
1:120 model of Grand Coulee Dam.

The original design river outlets, rectangular in section, were formed by two pieces of brass angles soldered together. The outlets were controlled by slide gates on the upstream face of the model base. Each gate controlled ten outlets and was operated by rack-and-pinion from underneath the model. Later designs in which the outlets were circular in cross-section were formed of copper tubing. These were provided with individual gates constructed of three pieces of brass plate shaped in the lathe and soldered together.

The power houses were constructed of redwood. The superstructures contained metal boxes connected by a valve-controlled pipe to the headtank. Orifices conveyed the water from this box to the draft tubes in the powerhouse substructure.

The features discussed to this point might be divided into three separate construction divisions: (1) the model setting consisting of headtank, baffle, tailwater tank, gage connections and tailwater regulator; (2) the model base consisting of the steel beam support, angle iron bents and covering, the stilling pool, the tailrace, lower training walls, river outlets, and powerhouses; (3) the superstructure consisting of the spillway crest, piers, gates, gate operating mechanism, and training walls.

Still another division might be that of architectural details such as bridges, windows, doors, handrails, elevator towers, valve houses, etc. While these features are not essential, they add materially to photographs and assist in visualizing the finished structure.

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