HYDRAULICS BRANCH
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Hyd-56

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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MEMORANDUM TO CHIEF DESIGNING ENGINEER

HYD-56

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HYDRAULIC MODEL STUDIES OF THE WICKIUP OUTLET WORKS STILLING BASIN DESCHUTES PROJECT - OREGON

by

J. H. DOUMA, ASSISTANT ENGINEER

- - - -

Denver, Colorado,

June 30, 1939.

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MEMORANDUM TO CHIEF DESIGNING ENGINEER.
(J. H. Douma, Assistant Engineer)

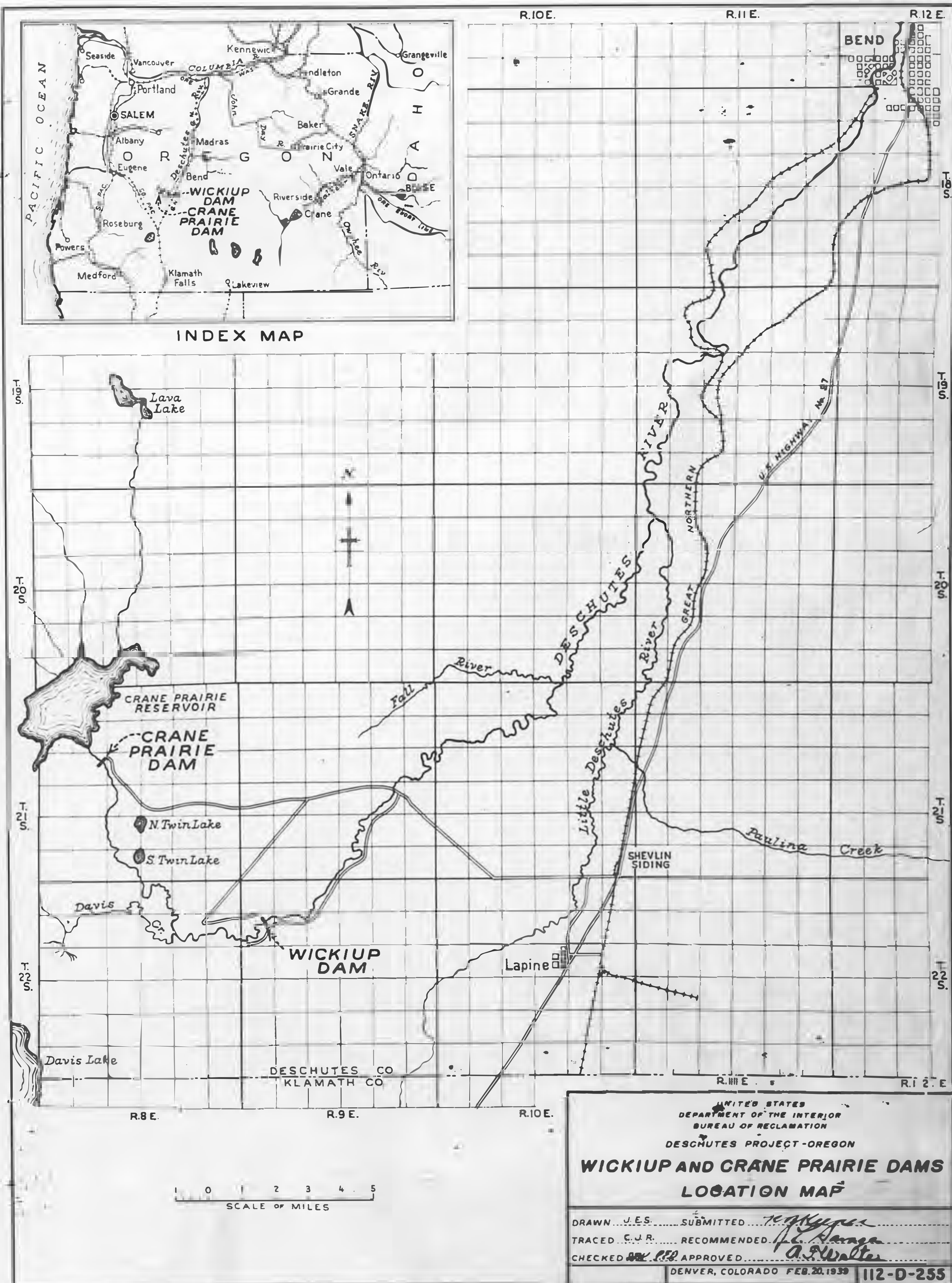
Subject: Model study of Wickiup Dam outlet works, Deschutes project, Oregon.

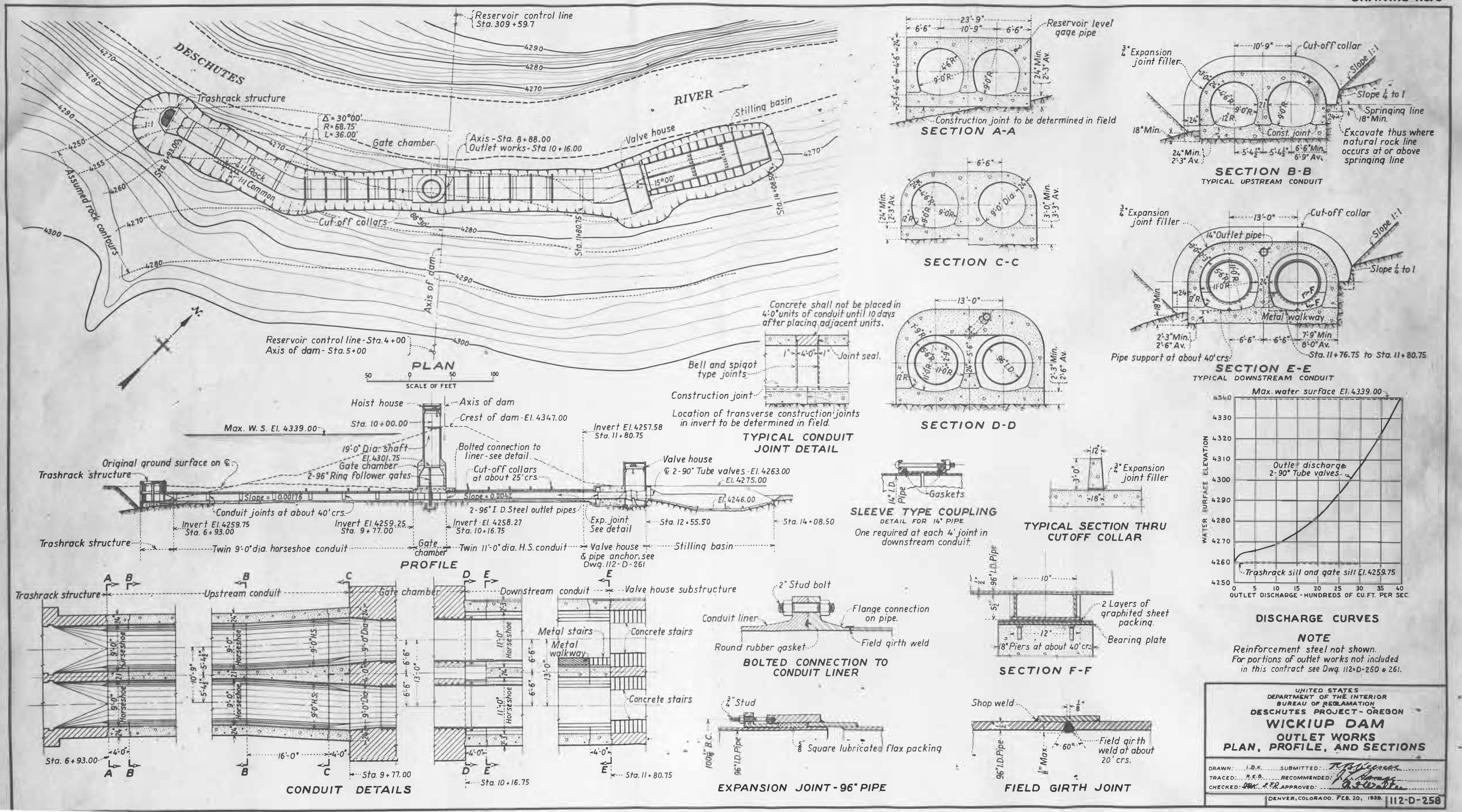
1. Introduction. Wickiup Dam will be an 87-foot high earth structure located on the Deschutes River about 35 miles southwest of Bend, Oregon, (figure 1). The outlet works, designed to discharge 3,950 second-feet at the normal full reservoir elevation 4339.00, will provide for emergency release of floodwater during flood periods. In addition to the emergency requirement, by valve control the outlet works will have frequent use in regulating the flow downstream from the dam.

The outlet works is located a short distance to the right of the river bed so the conduits will rest on an excavated foundation (figure 2). A short open channel excavated to elevation 4259.00 leads to the conduit entrances which are protected by a standard trashrack structure. A 284-foot length of twin, 9-foot 0-inch diameter, reinforced concrete, horseshoe conduit leads to a gate chamber located a short distance upstream from the axis of the dam. Two 96-inch ring-follower gates placed in a gate chamber provide closure of the conduits for inspection or repairs of the 90-inch tube valves, which are located at the ends of the two 96-inch I.D. steel pipes. Eleven-foot long discharge guide vanes extend from the valve exits to a chute which leads to a rectangular stilling basin. A dividing wall along the center line of the chute and stilling basin provides a separate stilling basin for each valve.

2. Necessity for model study. While several model studies have been conducted in the Bureau of Reclamation laboratory of outlet structures of the type in which the needle valve or tunnel discharged directly into the river channel downstream from the dam and one case where a hydraulic jump and stilling basin were employed, no studies have been previously made of the chute stilling-basin type of outlet works. The designs of several features of this type of structure were uncertain. The necessity of a center line dividing wall and the required height and length of such a wall were particularly in doubt. Other questions of design requiring investigation were: (1) Whether the jets would spread properly in the short chute section before reaching the stilling basin; (2) whether a solid end

FIGURE 1
~~DRAWING No. 1~~





Reservoir control line Sta. 309+59.7
DESCHUTES
RIVER
Trashrack structure
Δ = 30°00' R = 68.75' L = 36.00'
Gate chamber
Axis - Sta. 8+88.00
Outlet works - Sta. 10+16.00
Valve house
Stilling basin
Sta. 6+93.00
1:1 Rock
1:1 Common
Cut-off collars
Assumed rock contours
Axis of dam
Sta. 11+80.75
Sta. 14+08.50
Reservoir control line - Sta. 4+00
Axis of dam - Sta. 5+00
PLAN
SCALE OF FEET
Hoist house
Axis of dam
Sta. 10+00.00
Crest of dam - El. 4347.00
Max. W. S. El. 4339.00
19'-0" Dia. shaft
El. 4301.75
Gate chamber
2-96" Ring follower gates
Bolted connection to liner - see detail
Cut-off collars at about 25' crs.
Original ground surface on ℄
Trashrack structure
Conduit joints at about 40' crs.
Invert El. 4259.75 Sta. 6+93.00
Invert El. 4259.25 Sta. 9+77.00
Invert El. 4258.27 Sta. 10+16.75
2-96" I. D. Steel outlet pipes
Invert El. 4257.58 Sta. 11+80.75
Valve house
℄ 2-90" Tube valves - El. 4263.00
El. 4275.00
El. 4246.00
Exp. joint See detail
Sta. 12+55.50
Sta. 14+08.50
Twin 9'-0" dia. horseshoe conduit
Gate chamber
Twin 11'-0" dia. H.S. conduit
Valve house & pipe anchor, see Dwg. 112-D-261
Stilling basin
PROFILE
Trashrack structure
Upstream conduit
Gate chamber
Downstream conduit
Valve house substructure
Metal stairs
Metal walkway
Concrete stairs
Sta. 6+93.00
Sta. 9+77.00
Sta. 10+16.75
Sta. 11+80.75
CONDUIT DETAILS
SECTION A-A
Reservoir level gage pipe
Construction joint to be determined in field
SECTION B-B
TYPICAL UPSTREAM CONDUIT
Cut-off collar
Expansion joint filler
Slope 1:1
Slope 1/4 to 1
Springing line
Excavate thus where natural rock line occurs at or above springing line
SECTION C-C
SECTION D-D
SECTION E-E
TYPICAL DOWNSTREAM CONDUIT
14" Outlet pipe
Metal walkway
Pipe support at about 40' crs.
Sta. 11+76.75 to Sta. 11+80.75
Concrete shall not be placed in 4'-0" units of conduit until 10 days after placing adjacent units.
Bell and spigot type joints
Joint seal.
Construction joint
Location of transverse construction joints in invert to be determined in field.
TYPICAL CONDUIT JOINT DETAIL
SLEEVE TYPE COUPLING
DETAIL FOR 14" PIPE
Gaskets
One required at each 4' joint in downstream conduit.
TYPICAL SECTION THRU CUTOFF COLLAR
2" Stud bolt
Conduit liner
Flange connection on pipe.
Round rubber gasket
Field girth weld
BOLTED CONNECTION TO CONDUIT LINER
2 Layers of graphited sheet packing.
8" Piers at about 40' crs.
Bearing plate
SECTION F-F
3/4" Stud
Square lubricated flax packing
EXPANSION JOINT - 96" PIPE
Shop weld
Field girth weld at about 20' crs.
FIELD GIRTH JOINT
Max. water surface El. 4339.00
WATER SURFACE ELEVATION
Outlet discharge 2-90" Tube valves
Trashrack sill and gate sill El. 4259.75
OUTLET DISCHARGE - HUNDREDS OF CU. FT. PER SEC.
DISCHARGE CURVES
NOTE
Reinforcement steel not shown.
For portions of outlet works not included in this contract see Dwg. 112-D-260 & 261.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
DESCHUTES PROJECT - OREGON
WICKIUP DAM
OUTLET WORKS
PLAN, PROFILE, AND SECTIONS
DRAWN:
TRACED:
CHECKED:
SUBMITTED:
RECOMMENDED:
APPROVED:
DENVER, COLORADO. FEB. 20, 1939.
112-D-258

sill is needed at the end of the level floor of the stilling basin when a sloped concrete apron is provided at the end of the basin; (3) whether when both valves operate at maximum capacity the additional tailwater in excess of the stilling-basin design tailwater for one valve operating at maximum capacity will result in a submerged, ineffective hydraulic jump; (4) whether destructive currents would form downstream from the stilling basin for one-valve operation. Finally, since the left bank of the channel downstream from the stilling basin is to be of fill material, a particularly efficient stilling basin is required.

A chart (appendix I, figure 17), constructed in the hydraulic laboratory from experimental results of the model studies of five stilling basins, in which the relations between variables in the design of rectangular stilling basins are given, was used by the outlet-works designing section in the initial design of the Wickiup Dam outlet-works stilling basin. It was desired to check the validity of the design chart by a model study of the stilling basin in which the most efficient dimensions would be determined. Furthermore, such a study would insure the incorporation of the most efficient stilling basin in the final design of the proposed structure.

3. The model. Space and pump capacity in the laboratory limited the length scale to 1:20. The corresponding velocity scale is 1:4.47 and discharge scale is 1:1789. The maximum prototype flood of 3,950 second-feet for reservoir elevation 4339.00 and both valves 100 percent open is represented by 2.207 second-feet in the model.

To facilitate construction of the model two short cuts were taken. First, the structure up to the valves was eliminated from the study by making the model head correspond to the effective head at the valves; second, the valves were represented by short tubes. The jet from a short tube and that portion of the jet from a tube or needle valve beyond the vena contracta are approximately similar, so that by making the model short tubes of the same diameter as that of the valve jet vena contracta the proper mean jet velocity for any discharge will be given by the short tubes. Partial valve openings may be similarly represented by smaller diameter tubes.

Materials used required values of Manning's N for prototype and model of 0.014 and 0.010, respectively. Neglecting such minor effects as those due to viscosity and surface tension of the fluid, the relative roughness of prototype and model surfaces fixes the scale at which strict geometric and hydraulic similitude may be achieved simultaneously. Lack of space and pump capacity prohibited use of the desired scale of $(Nm/Np)^6$ or 1:7.52 necessitating sacrifice of either geometric or hydraulic similitude.

In the design of a chute and stilling basin by a model study hydraulic similitude normally is of most importance. When prototype and model roughness are unequal hydraulic similitude requires a friction correction, which is attained by either a greater length of chute or increase in slope.

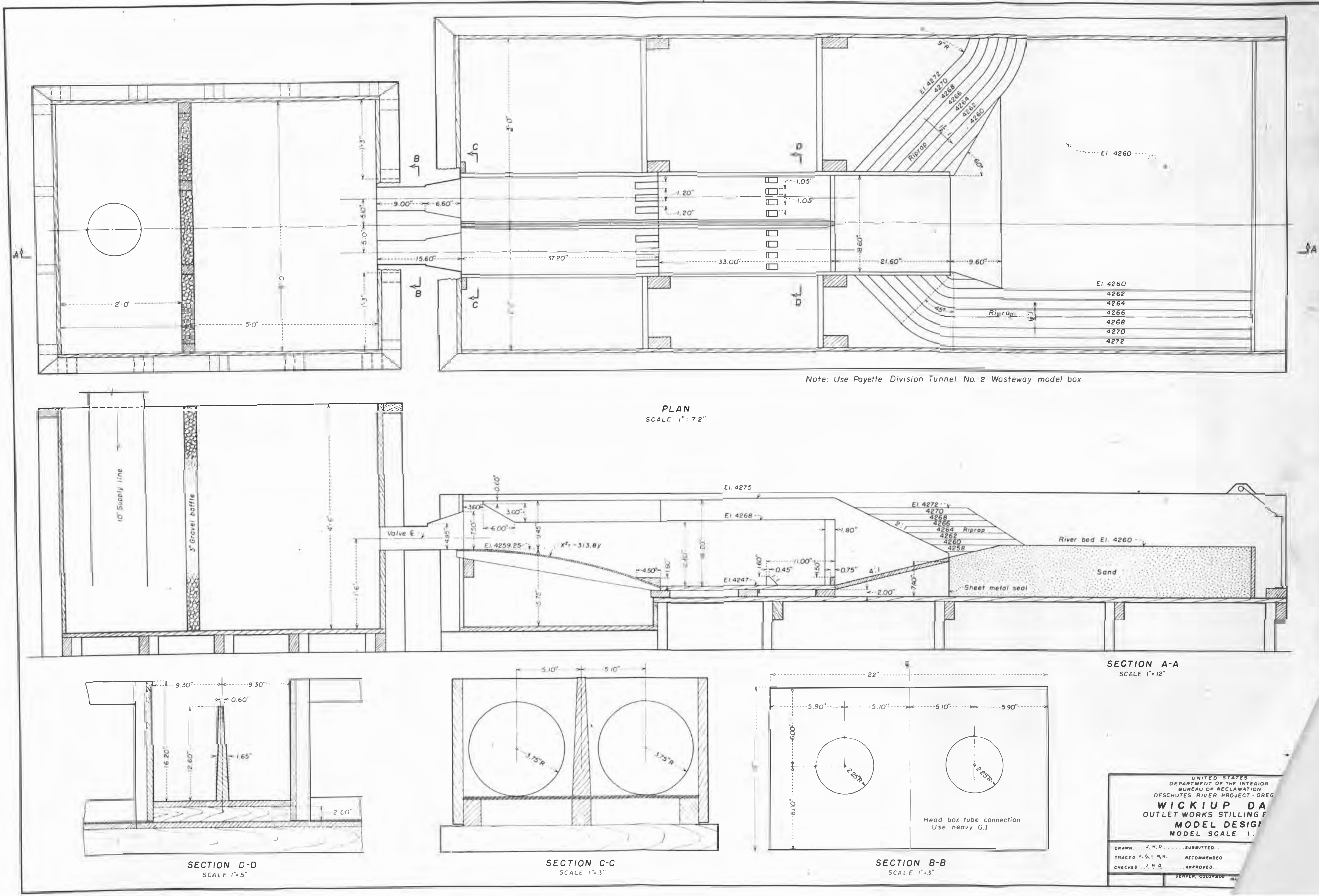
For the present study hydraulic similitude exists in regard to the jet velocity at the tube exits, since any difference in model and prototype losses up to this point is absorbed in the head on the model tubes. Probable dissimilarity of flow patterns within tube and valve jets **is** considered insignificant to the study.

The friction correction for the short chute will be slight warranting no correction for this model. Since the model velocities will then be slightly higher than those required for hydraulic similitude, the design will be on the safe side. The model was geometrically similar to the prototype, but lacked strict hydraulic similitude. Figure 3 shows the original model design.

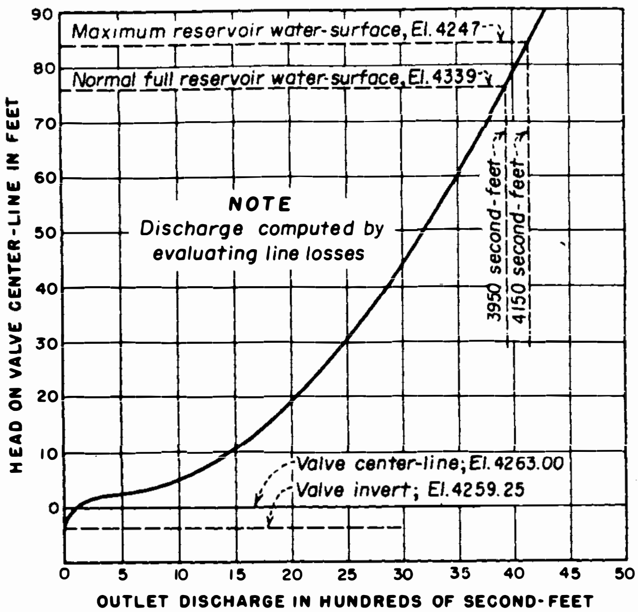
4. Relationship between model tube diameter and prototype valve opening. The discharge-reservoir elevation curve (figure 4a) for two 90-inch tube valves was determined by the designing section by properly evaluating all losses from the reservoir to the valve exits. The valve discharge coefficient based on the valve exit cross-sectional area (90-inch diameter for the Wickiup valves), as determined from tests on one 84-inch Boulder prototype needle valve and a 5-inch Boulder-Alcova model needle valve, is 0.78. Subsequent tests on a 5-inch model tube valve gave the same value. Tests also show the coefficient to be constant for a 100-percent valve opening and variable head for both types of valves.

The energy head available in front of the valves is given by $h_E = (0.78)^2 \, v_e^2 / 2g$, where v_e is the valve exit velocity. The head loss up to the valves for any discharge is the difference in energy head in front of the valves and the total available energy head given by the difference in valve center line and reservoir water-surface elevations. Computations for the total head loss up to the valves are given in table 1, and figure 4B shows the total head loss up to valves-discharge relationship, which allows the energy head in front of the valves to be computed for any discharge. The relationship is applicable to any valve opening, since valve opening is not a function of the loss up to the valves.

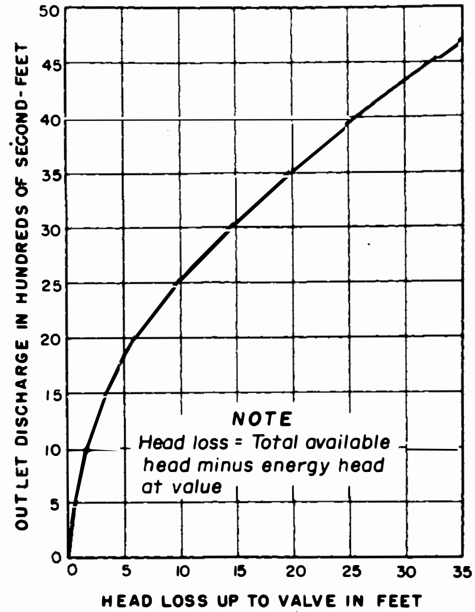
FIGURE 3



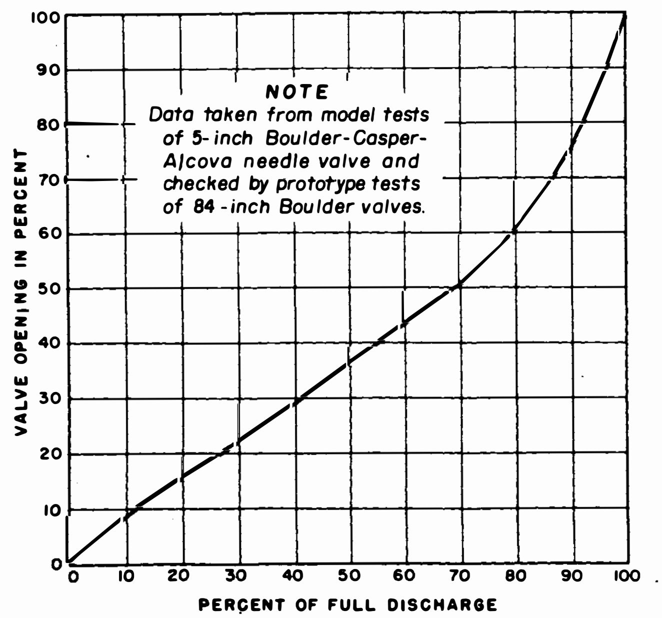
PLAN
SCALE 1" = 7.2"
Note: Use Payette Division Tunnel No. 2 Wasteway model box
El. 4260
El. 4272
4270
4268
4266
4264
4262
4260
Riprap
9.00"
6.60"
15.60"
37.20"
33.00"
21.60"
9.60"
1.20"
1.05"
18.60"
2'-0"
5'-0"
SECTION A-A
SCALE 1" = 12"
10" Supply line
3" Gravel baffle
Valve ℄
El. 4275
El. 4268
El. 4259.25
$x^2 = -313.8y$
El. 4247
River bed El. 4260
Sand
Sheet metal seal
4:1
2:1
SECTION D-D
SCALE 1" = 5"
9.30"
0.60"
1.65"
16.20"
12.60"
2.00"
SECTION C-C
SCALE 1" = 3"
5.10"
3.75"R
SECTION B-B
SCALE 1" = 3"
22"
5.90"
5.10"
6.00"
2.25"R
Head box tube connection
Use heavy G.I.
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
DESCHUTES RIVER PROJECT - OREG
WICKIUP DA
OUTLET WORKS STILLING
MODEL DESIG
MODEL SCALE 1:
DRAWN J. H. D.
TRACED F. G. - N. H.
CHECKED J. H. D.
SUBMITTED
RECOMMENDED
APPROVED
DENVER, COLORADO



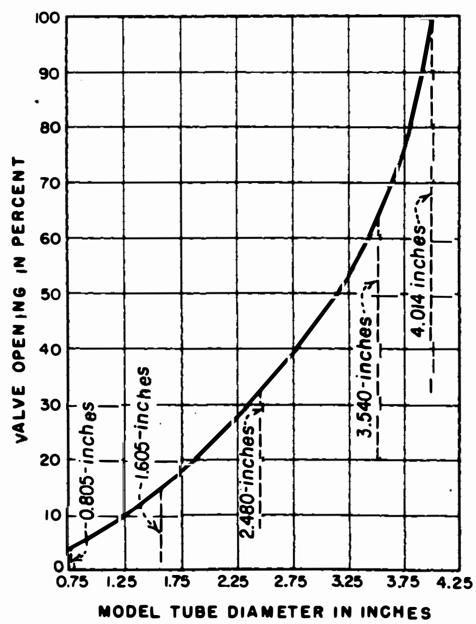
A - OUTLET DISCHARGE CURVE FOR TWO 90-INCH VALVES 100 PERCENT OPEN



B - TOTAL HEAD LOSS UP TO VALVE DISCHARGE RELATIONSHIP



C - VALVE OPENING - DISCHARGE RELATIONSHIP



D - VALVE OPENING - MODEL TUBE DIAMETER RELATIONSHIP

DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

WORKING CURVES TO DETERMINE THE RELATIONSHIP BETWEEN MODEL TUBE DIAMETER AND PROTOTYPE VALVE OPENINGS

TABLE 1

Computations for total loss up to valves

Reservoir water-surface elevation	Total head, H, in feet, above valve center line	Proto. Q, in c.f.s., for two valves 100% open	Velocity v_e, in f.p.s., at valve exits	Energy head, h_E, in feet, available in front of valves	Total head loss, h_f, in ft., up to valves
4347	84	4,150	47.0	56.4	27.6
4339	76	3,950	44.7	51.0	25.0
4330	67	3,700	41.9	44.8	22.2
4320	57	3,410	38.6	38.0	19.0
4310	47	3,110	35.2	31.7	15.3
4300	37	2,750	31.2	24.8	12.2
4290	27	2,370	26.8	18.3	8.7
4280	17	1,900	21.5	11.8	5.2
4270	7	1,200	13.6	4.7	2.3

The mean jet velocity at the vena contracta is given by $v_{vc} = C\sqrt{2gh_E}$, where the discharge coefficient C has been found to be equal to 0.98, and h_E is the energy head in front of the valves. The required model tube diameter to correspond to the valve jet vena contracta diameters for several discharges at normal maximum reservoir water-surface elevation 4339.00 is determined in table 2. The 4.014-inch tube diameter represents 100 percent valve opening, and all smaller diameters represent partial valve openings.

TABLE 2

Computations for model tube diameter - Prototype valve opening relationship. Constant reservoir elevation 4339.00 - 2 valve operation

Prototype discharge in c.f.s.	h_f up to valves in ft.	h_E at valves in ft.	Vel. of jets, v_{vc}, in f.p.s.	Proto vena contracta area in sq. ft.	Dia. of model tube in inches	% of full discharge	% of valve opening
3,950	25.0	51.0	56.1	70.37	4.014	100	100
3,500	19.8	56.2	58.9	59.40	3.69	88.6	73.0
3,000	14.3	61.7	61.5	48.76	3.34	75.9	56.0
2,500	9.7	66.3	64.0	39.05	2.99	63.3	45.6
2,000	5.9	70.1	65.8	30.40	2.64	50.6	36.7
1,500	3.4	73.6	67.4	22.25	2.26	38.0	27.6
1,000	1.8	74.2	67.7	14.77	1.84	25.3	18.6
500	0.7	75.3	68.2	7.33	1.296	12.7	10.4
200	0.2	75.8	68.4	2.92	0.818	5.06	4.5

The model tube diameter can be related to the percent valve opening by use of the percent valve opening-percent full discharge relationship (figure 4C), which was obtained from tests on the 5-inch model needle and tube valves and later checked by prototype tests on the 84-inch Boulder needle valve. The prototype valve opening-model tube diameter relationship is shown in figure 4D. Prototype values for the four model tube diameters tested are shown in table 3.

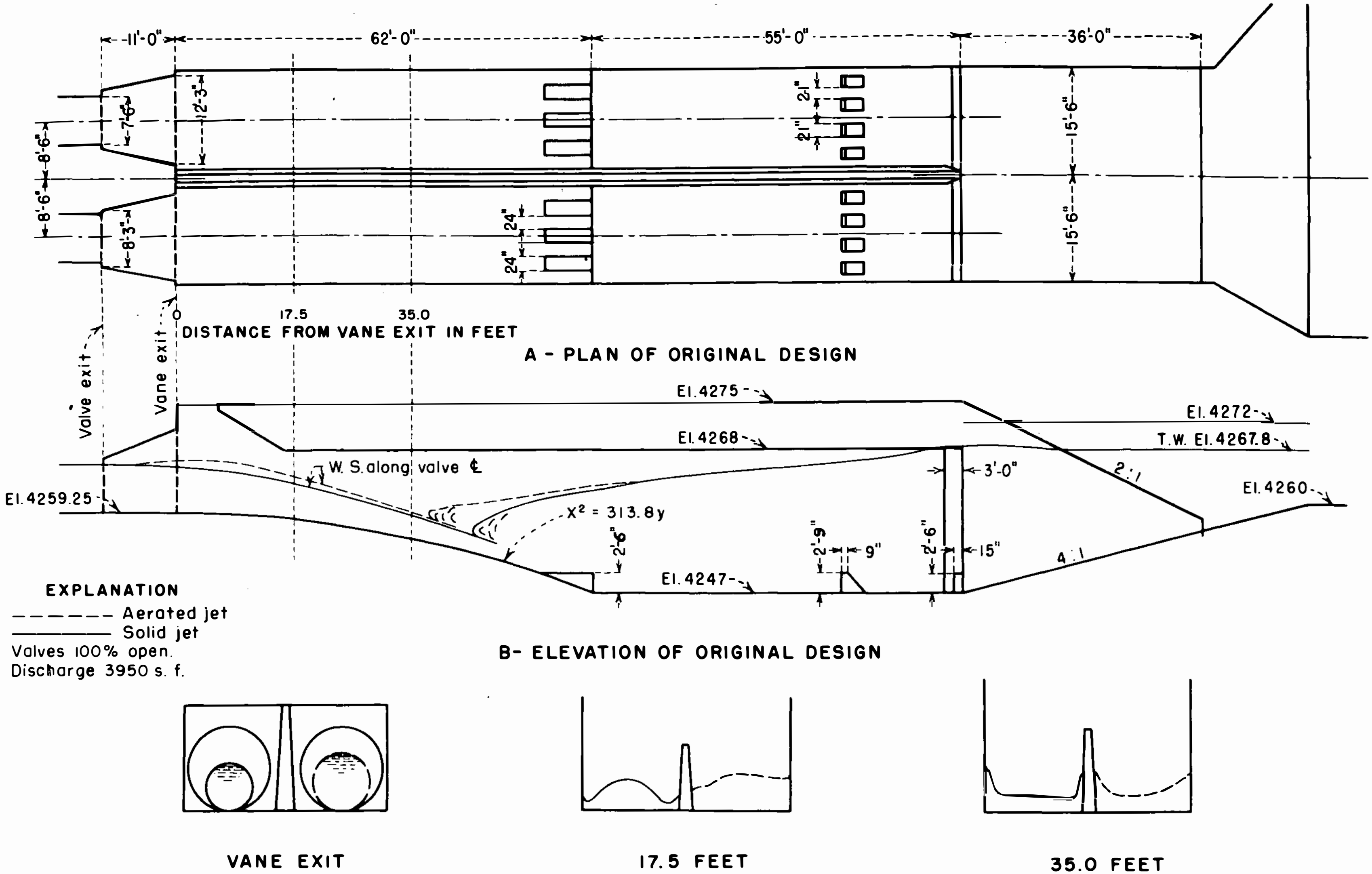
TABLE 3

Prototype quantities for model tubes tested - Reservoir elevation 4339.

Model tube diameter in inches	% of valve opening	% of full discharge	Prototype discharge in c.f.s.		Proto jet vel., v_{vc}, in f.p.s.
			2 valves	1 valve	
4.014	100	100	3,950	1,975	56.1
3.540	64.8	83.4	3,295	1,647	60.2
2.480	32.6	44.9	1,774	887	66.3
1.605	14.9	19.3	762	381	67.8

5. Original stilling-basin design. The original design, as presented by the designing section to the hydraulic laboratory for testing, is shown in figure 5. The stilling basin dimensions for this design were determined by the previously developed chart presented in appendix I, figure 17.

6. Influence of jet aeration on hydraulic-jump formation. The first tests of the model were made with square entrances to the tubes. This entrance condition was so unfavorable to smooth flow that the jets expanded considerably immediately beyond the tube exits. With the high degree of turbulence, expansion of the jets and an existing mean jet velocity in the model of 13.2 feet per second conditions were favorable for air entrainment, and from the appearance of the jets there undoubtedly was some air entrapped in the flow. It is expected that considerable air will be entrained by the prototype jets. The expanded model jet gives an indication of the behavior of the prototype jets and the effect on flow in the chute and hydraulic jump formation. Figure 5C shows better depth distribution for the aerated jet than for a solid jet. The solid jet was obtained by using a smooth bellmouth entrance to the tubes. Due to the lower mean velocity of the aerated jet, the jump is located farther upstream (figure 5B). Except for slight difference in friction loss, theoretically, the momenta of the aerated and solid jets are equal, which is demonstrated experimentally by the agreement of the hydraulic-jump forma-

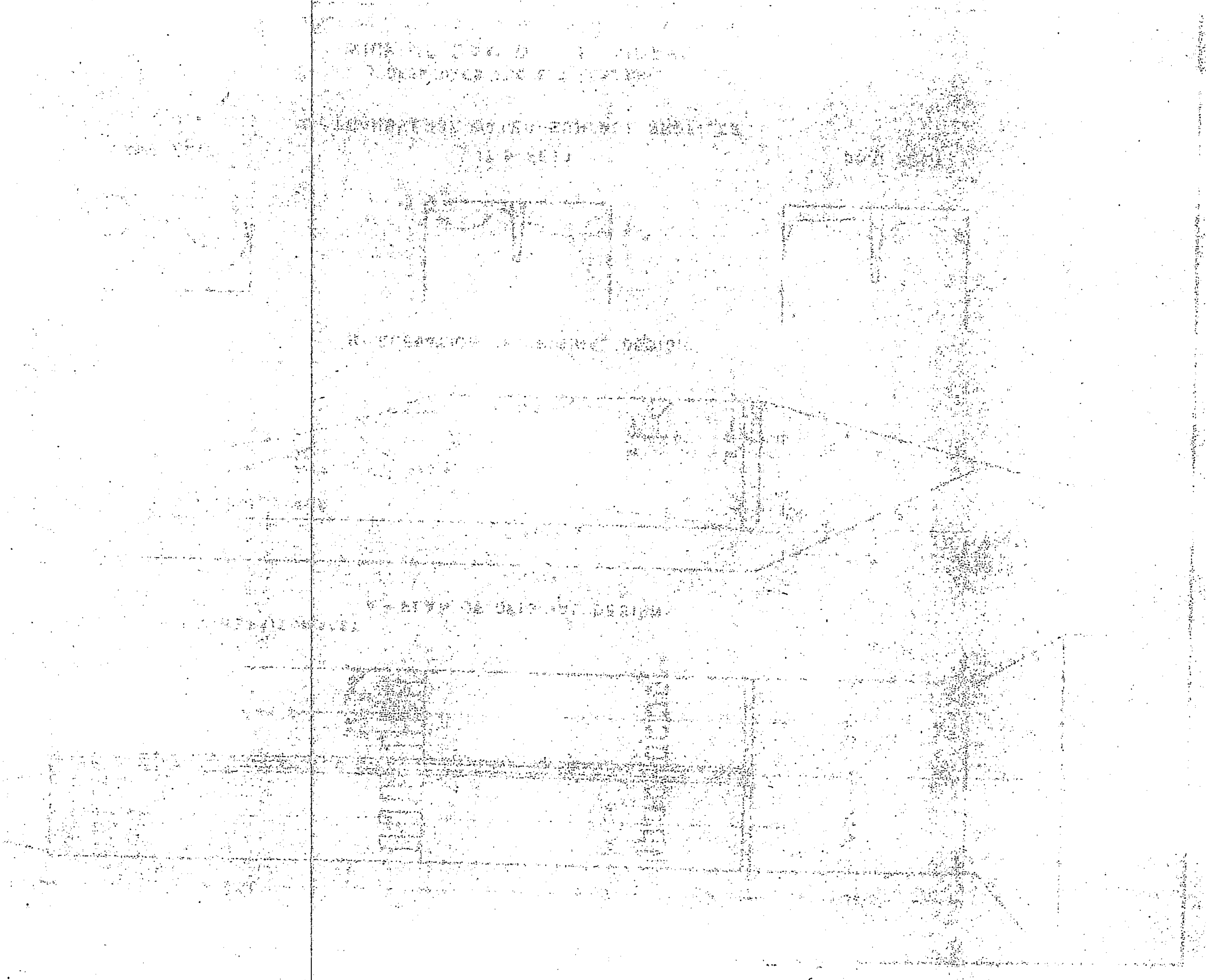


DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

INFLUENCE OF JET AERATION ON HYDRAULIC JUMP FORMATION

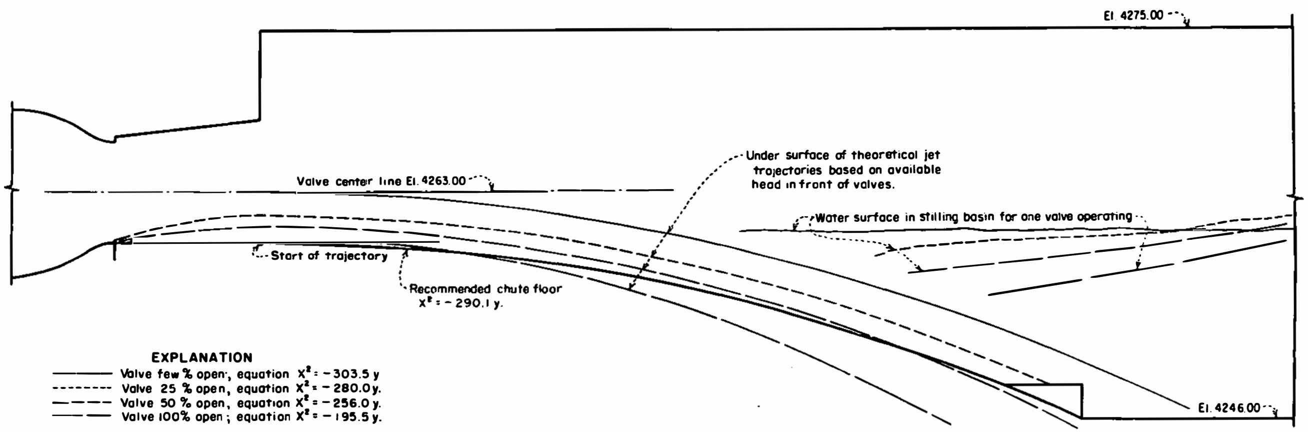
FIGURE 5



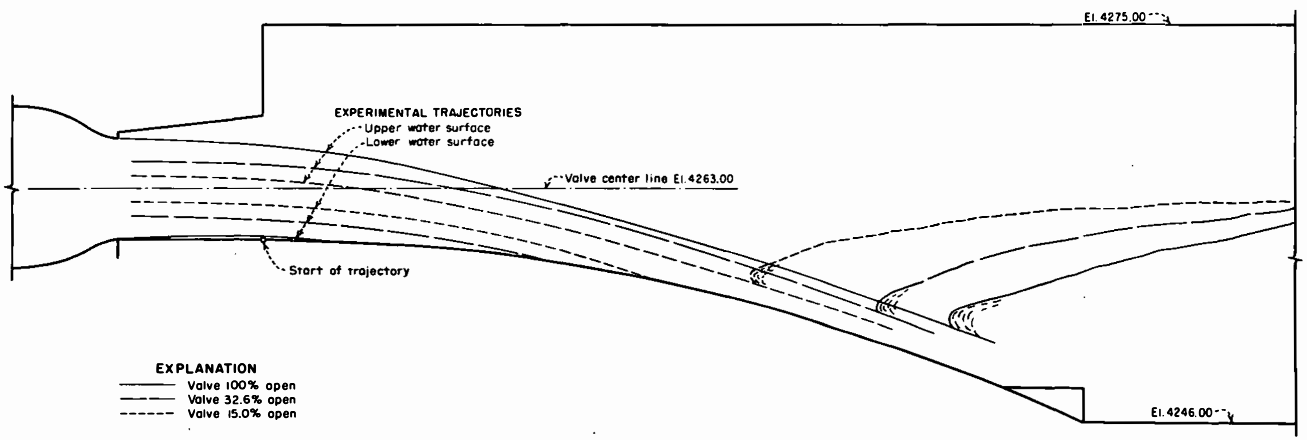
tions for the two cases. It is apparent that air entrainment has but small effect on the hydraulic jump formation and that on the safe side. Except for possible increased splashing, air entrainment in the flow of the Wickiup structure will improve the flow conditions. Plate 1A shows the aerated jet on the right and the solid jet on the left.

7. Chute floor. It is impossible to establish a rigid rule for the proper design of the chute floor trajectory; a long trajectory is more effective in spreading the jets than a short trajectory, but the short one is more economical. It is desirable that the highest velocity jet for a very small valve opening and maximum reservoir elevation strike the chute floor before reaching the chute blocks. This requires a longer floor than given by the maximum jet trajectory, since the origin of the floor trajectory is lower. However, in almost all cases there will be at least several feet depth of water in the basin for small valve openings, so that the jets strike the pool before reaching the chute blocks which enables the chute floor to be shortened. The under surface of the theoretical trajectories based on mean velocities is shown in figure 6A and the experimental trajectories in figure 6B for several valve openings. The point at which the jet strikes the floor moves upstream as valve opening increases in accordance with the decrease in head at the valves. Since particles near the surface of the jets have smaller velocities than the mean jet velocity, the experimental jets strike the floor upstream from the theoretical jets which allows further reduction in chute length. For best economy and good distribution of the jets the trajectory of the chute floor should be about equal to or slightly smaller than the trajectory for the maximum velocity jet. The maximum jet trajectory for this case is $x^2 = -303.5\ y$, and the recommended floor trajectory is $x^2 = -290.1\ y$.

8. Chute wall alinement. Spreading of the jets with parallel chute walls was not entirely satisfactory. A high fin existed at each wall and at the dividing wall, as shown in figure 7C. Although there is sufficient freeboard to prevent any damage by overtopping, smoother chute flow was desired. The only other feasible alternative to the parallel walls was considered to be walls flared from the valve exit to the end of the chute. The flared walls result in a uniform depth distribution and elimination of the fins in the chute (figure 7C), and the jump is located farther upstream (figures 10A and 10C and plates 1B and 1C). An important disadvantage of the flared walls is that excessive negative pressures, resulting in cavitation, near the valve exits will exist for operation near 100 percent valve opening. Further, since flaring the walls increases the cost, parallel walls were considered satisfactory for this design.



A - THEORETICAL VALVE JET TRAJECTORIES



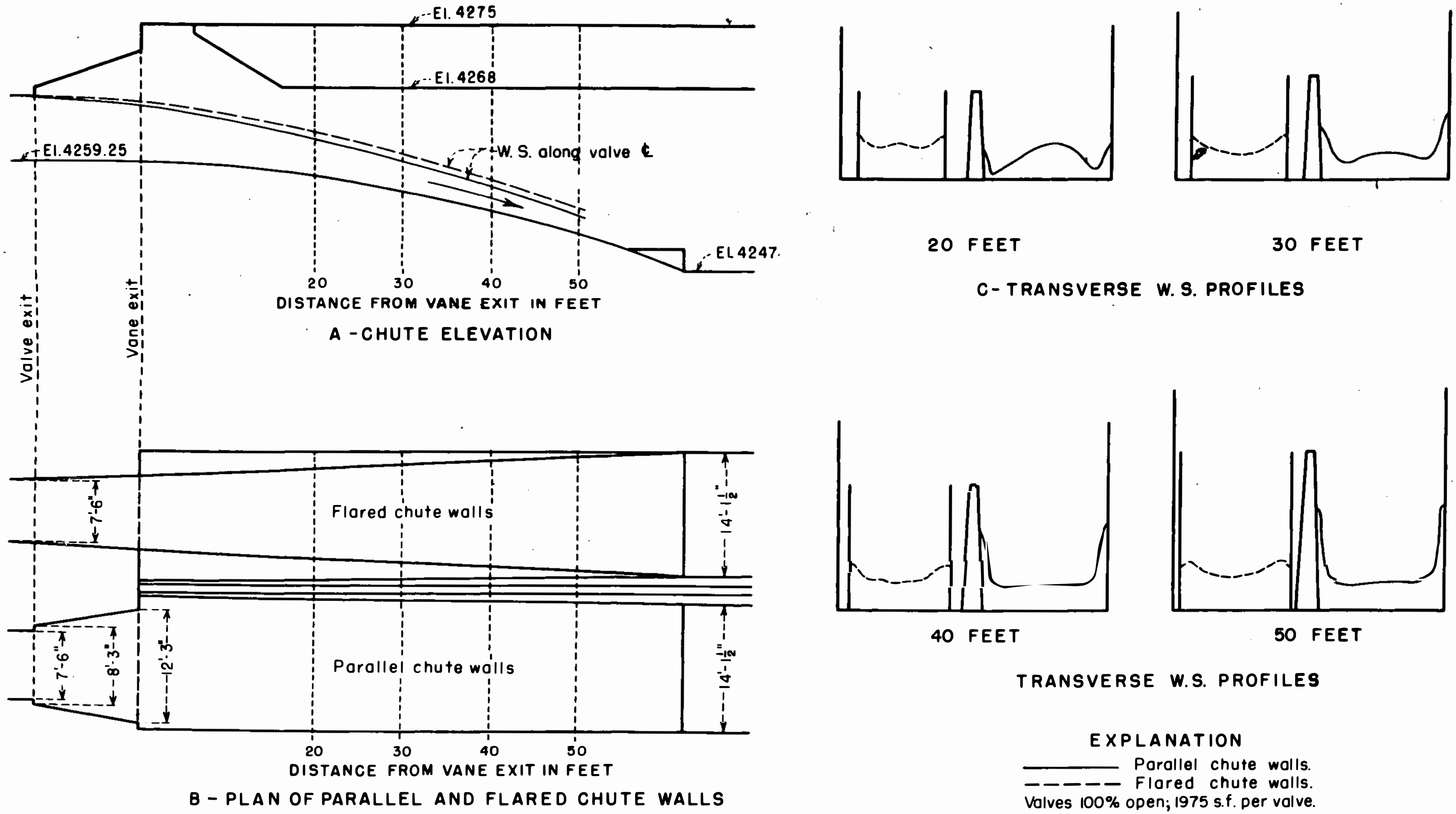
B - EXPERIMENTAL VALVE JET TRAJECTORIES

DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

VALVE JET TRAJECTORIES

FIGURE 6

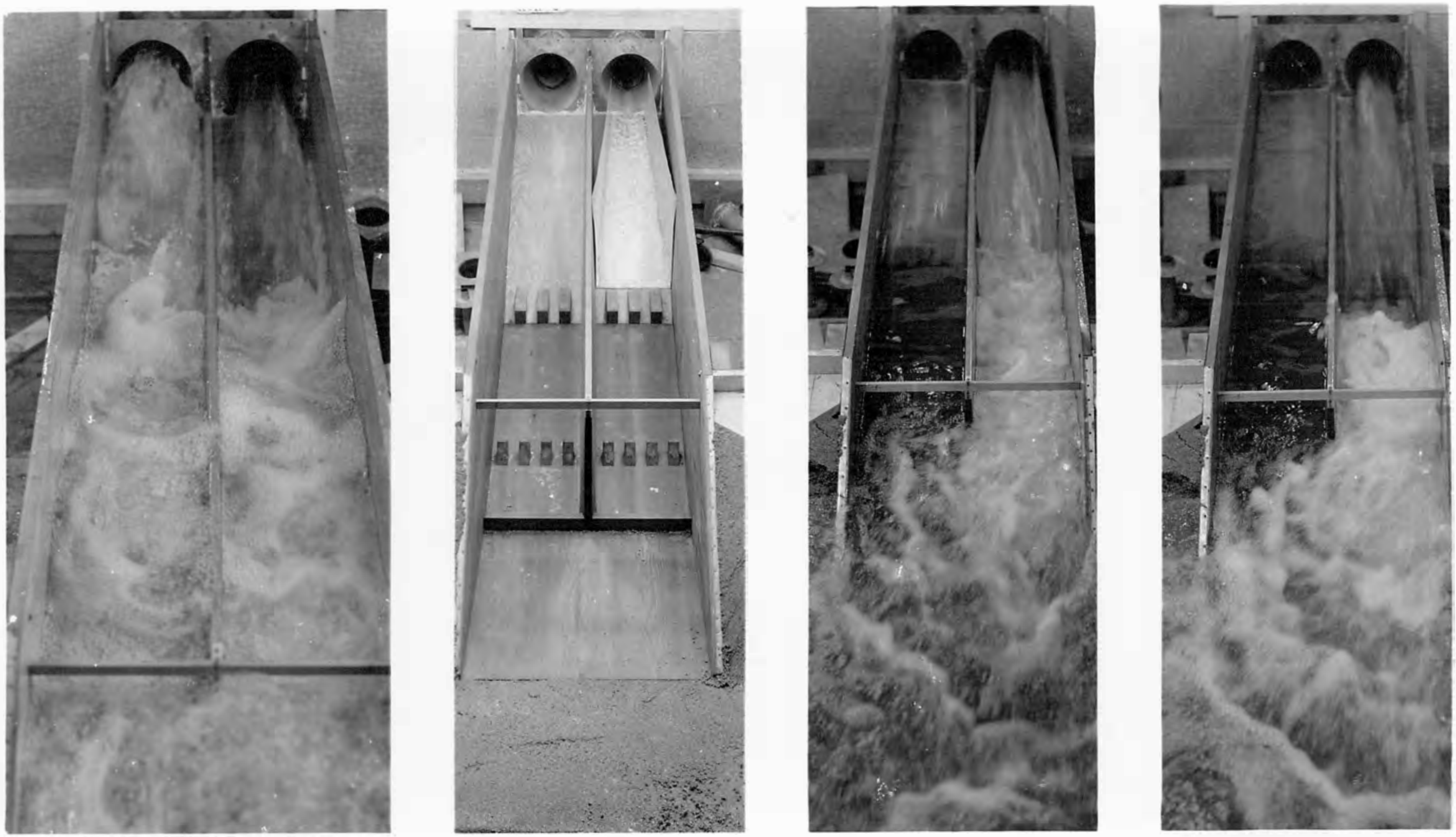


DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

COMPARISON OF PARALLEL AND FLARED CHUTE WALLS

FIGURE 7



A. 1975 SECOND-FEET PER VALVE; RIGHT JET AERATED; LEFT JET SOLID.

B. ORIGINAL DESIGN; FLARED CHUTE WALLS.

C. 1975 SECOND-FEET; FLARED CHUTE WALLS.

D. 1975 SECOND-FEET; FLARED CHUTE WALLS; FLOOR EL. 4247.

PLATE 1

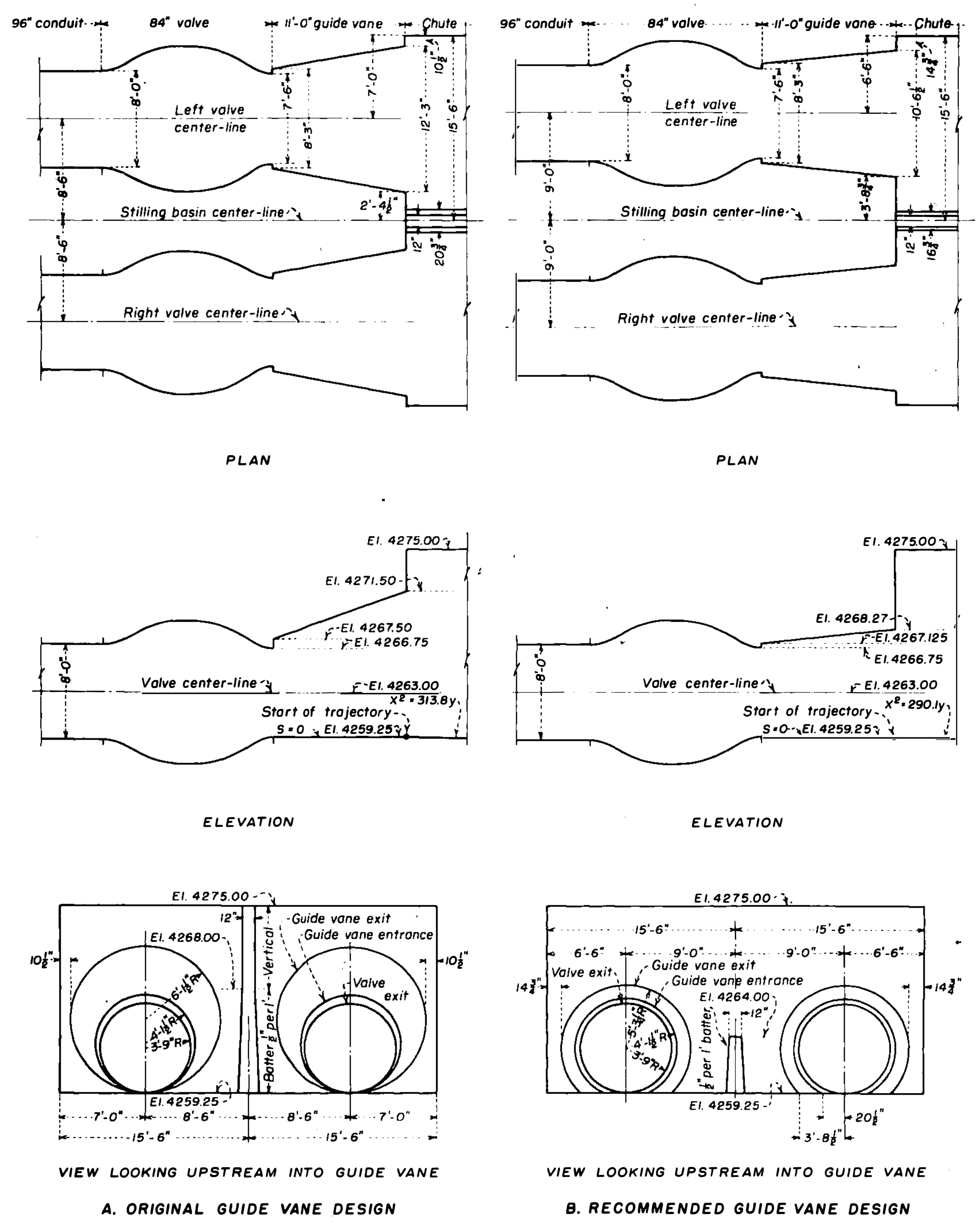
9. <u>Discharge guide vane.</u> The original discharge guide vanes (figure 8A and plates 2A and 2C) seemed excessively large, so to reduce cost their dimensions were reduced to those shown in figure 8B, corresponding closely to the Boulder designs which have recently proven satisfactory under field tests. If the vanes are too small, the jets will be disturbed due to improper aeration. There was some argument in favor of eliminating the vanes, but they were considered necessary to facilitate removal of the valves for repairs.

The distance from center line to center line of valves was increased from 18 feet to 19 feet, and the recommended vanes (plates 2B and 2D) were tested for the new spacing. In plate 2D, the right jet is solid and the left jet is aerated. Comparative operation of the original and recommended vanes and valve spacing (figure 9) indicates essentially no difference in chute flow or jump formation, but the recommended design is the most economical.

10. <u>Width of chute and stilling basin.</u> Referring to figure 8B, the separate chute for each valve is not symmetrical about the valve center line. The result is slightly higher fins at the side walls than at the dividing wall and slightly unsymmetrical conditions within the jump. These conditions were not considered severe and the chute width was not increased to obtain symmetry. The basin width could have been increased from 31 feet to 36 which, according to appendix I, figure 17, would allow the basin floor to be raised 1.5 feet. In some cases, the broader and shallower basin may be the most economical. It is recommended that symmetry be adhered to in future designs, so that the basin width will be twice the valve spacing. Due to the relatively small valve spacing, the chute width will probably in no case be excessive for proper spreading of the jets.

11. <u>Stilling basin floor elevation.</u> Referring to figure 10A and plate 1D, it is seen that the original floor elevation 4247 is too high for satisfactory jump formation in the basin with one valve operating at maximum discharge. Satisfactory conditions (figure 10B and plate 3A) are obtained by lowering the floor one foot to elevation 4246. A close check of the design chart shows that the floor should be at elevation 4246 rather than 4247, as first determined. The additional 3.4 feet of tailwater for both valves operating at maximum discharge was not excessive resulting in no submerged jump for this condition.

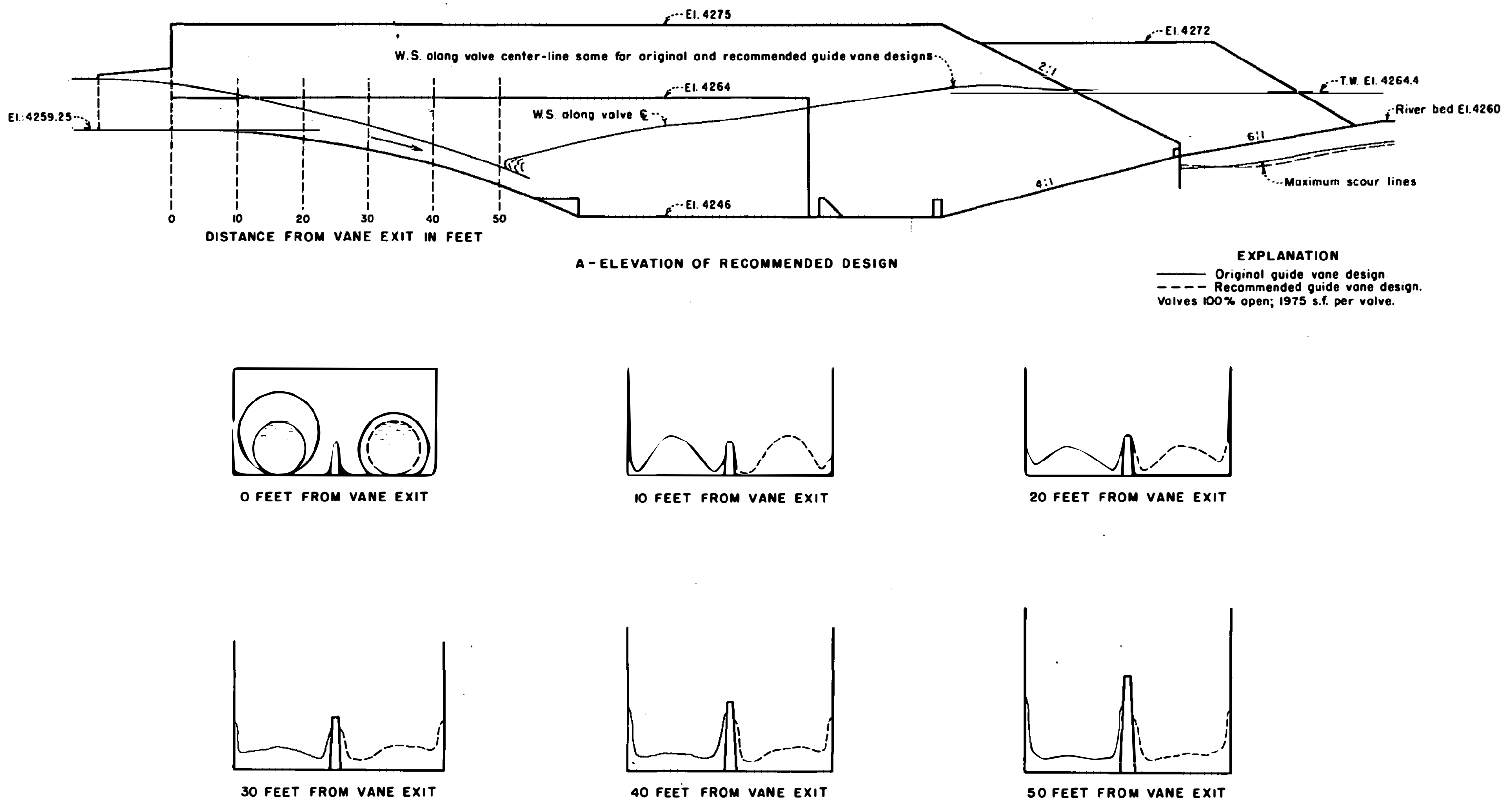
12. <u>Length of stilling basin.</u> The length of stilling basin required so that the jump is completely within the basin as given by the design chart is 65.4 feet. In the original design



DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

ORIGINAL AND RECOMMENDED GUIDE VANE DESIGNS



A-ELEVATION OF RECOMMENDED DESIGN

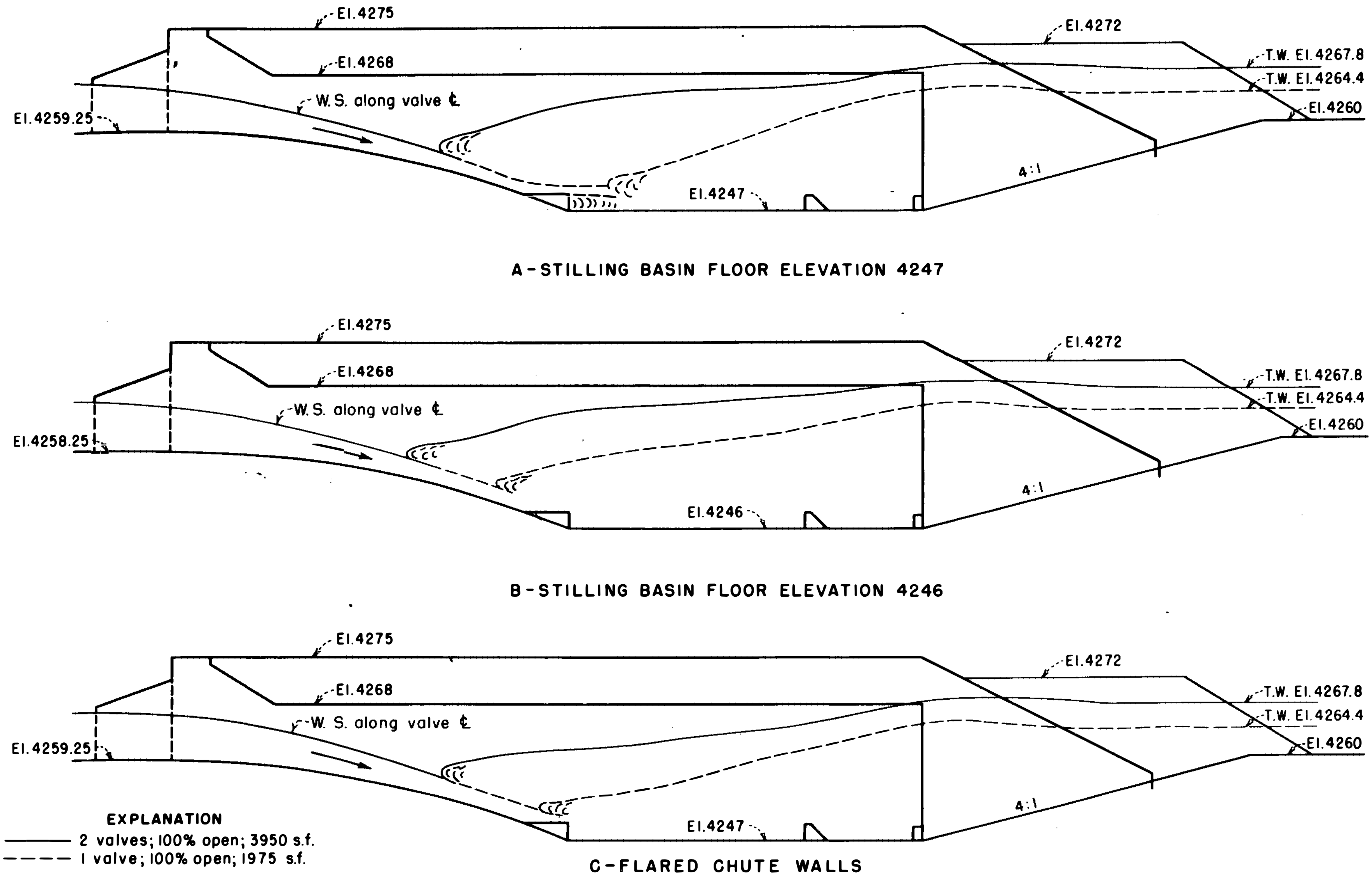
B-TRANSVERSE WATER SURFACE PROFILES IN CHUTE

DESCHUTES PROJECT-OREGON

WICKIUP DAM OUTLET WORKS

COMPARATIVE OPERATION OF ORIGINAL AND RECOMMENDED GUIDE VANE DESIGNS

FIGURE 9



A-STILLING BASIN FLOOR ELEVATION 4247

B-STILLING BASIN FLOOR ELEVATION 4246

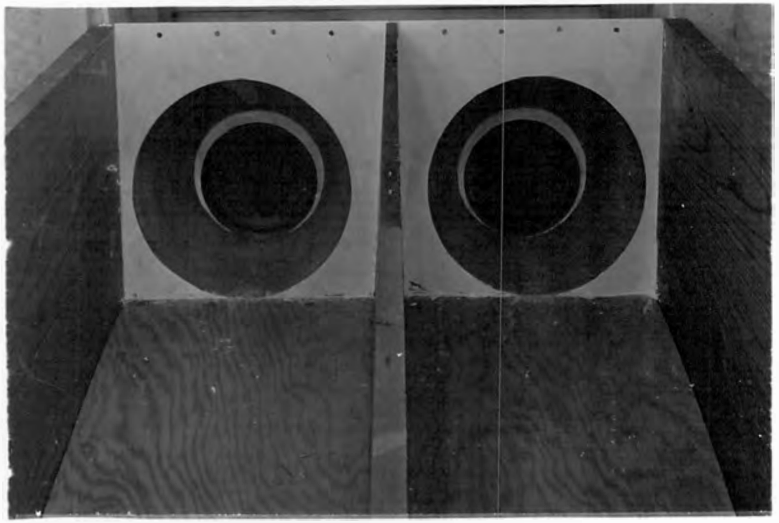
C-FLARED CHUTE WALLS

DESCHUTES PROJECT - OREGON

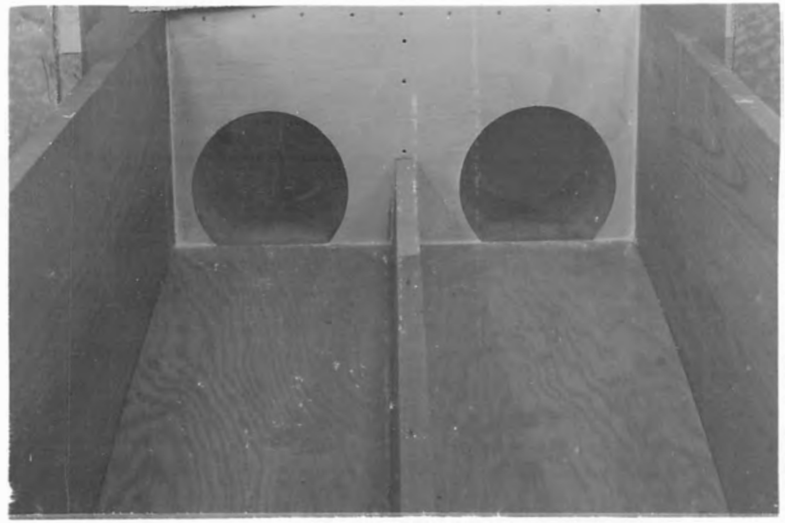
WICKIUP DAM OUTLET WORKS

DETERMINATION OF STILLING BASIN FLOOR ELEVATION

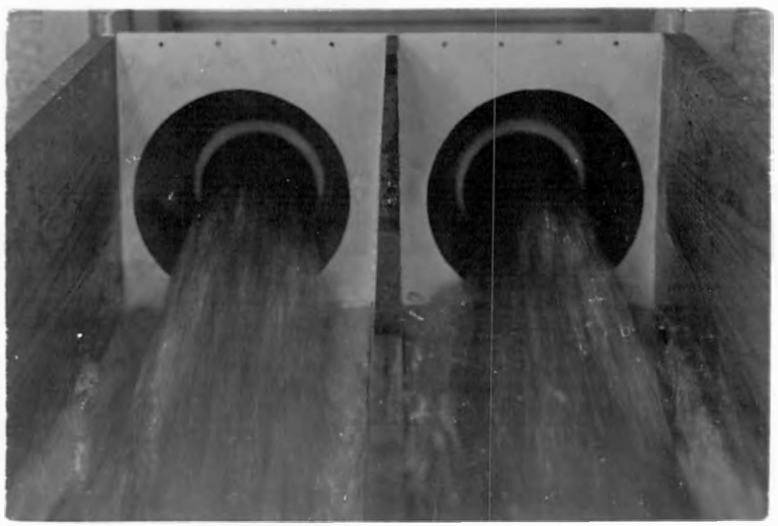
FIGURE 10



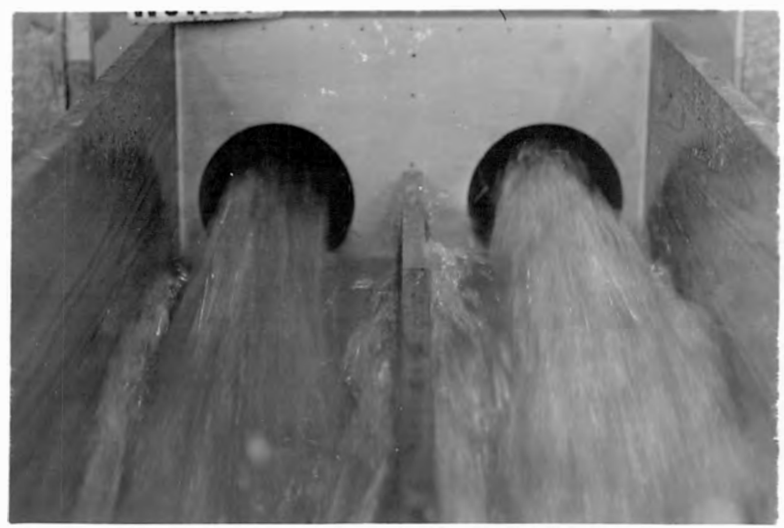
A. ORIGINAL DISCHARGE GUIDE VANE.



B. RECOMMENDED DISCHARGE GUIDE VANE.



C. ORIGINAL DISCHARGE GUIDE VANE;
1975 SECOND-FEET PER VALVE.



D. RECOMMENDED DISCHARGE GUIDE VANE;
1975 SECOND-FEET PER VALVE; LEFT JET AERATED.

A. 1975 SECOND-FEET;
FLOOR EL. 4246.

B. STILLING BASIN WITH NO DIVIDING WALL.

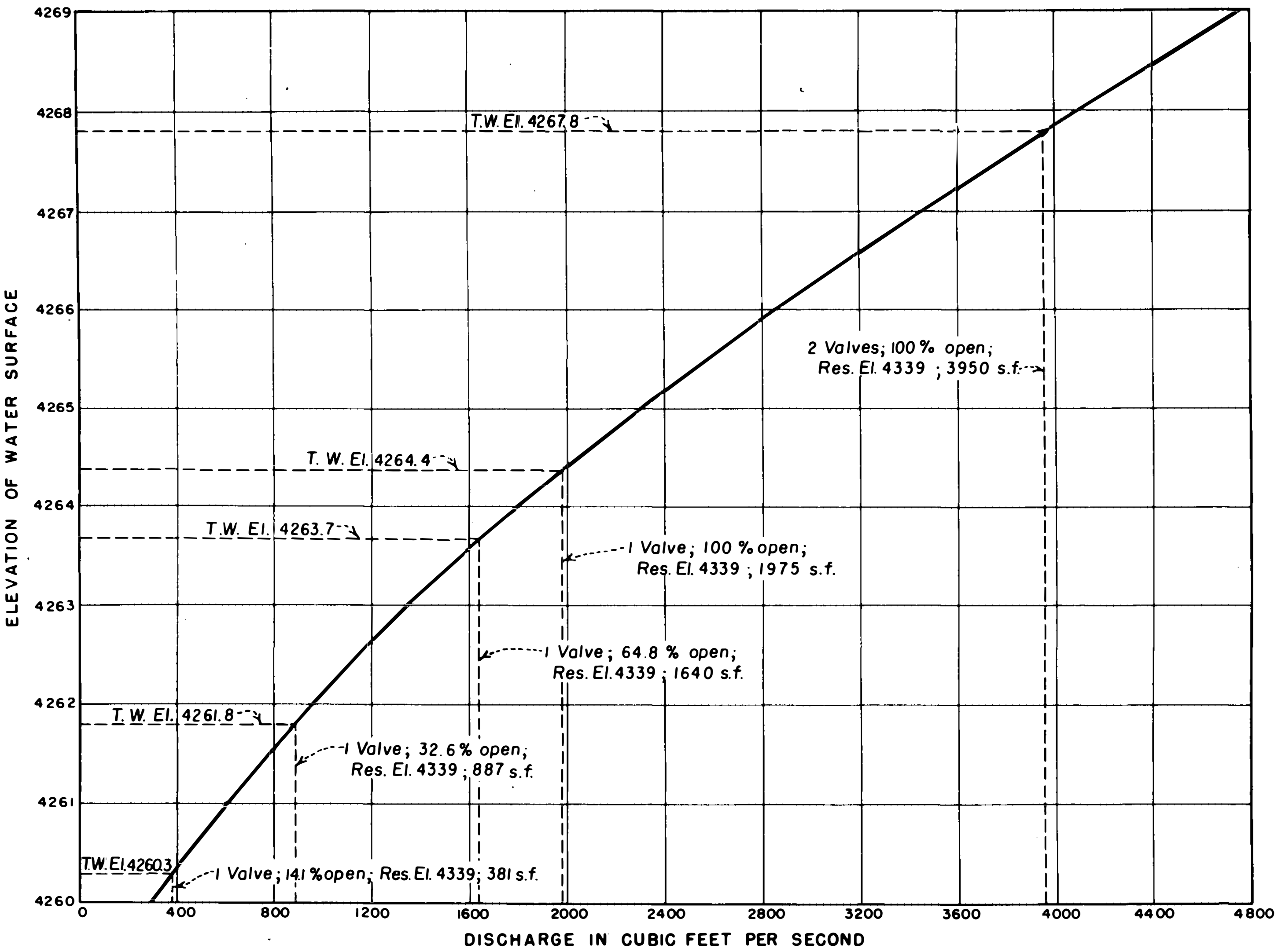
C. NO DIVIDING WALL;
1975 SECOND-FEET.

the concrete transition was considered to function as part of the basin so that the length of level floor was reduced to 55 feet. Referring to figure 10, the crest of the jump is located in the concrete transition about 10 feet beyond the end of the level floor basin. This condition proved entirely satisfactory and checks the length of jump as given by the design chart.

13. Critical operating condition. To eliminate unnecessary testing, one set of tests was made to determine the most severe operating condition, and all subsequent comparative tests were based on this condition. The proper tailwater for any condition tested was determined by figure 11. Observation of flows less than 100 percent valve opening and maximum reservoir elevation indicated that operation under these conditions was less severe than for full valve opening and head, and single valve operation was more severe than both valves operating. Comparative scour and jump water surfaces are shown in figure 12A for right, left, and both valves operating. The jump was identical for both conditions of single valve operation, but due to the unsymmetrical shape of channel downstream from the basin more severe scour resulted from the right valve operation, which condition was, therefore, used for further comparative tests.

14. Length and height of dividing wall. Plate 3B shows the basin without a center line dividing wall. The unsatisfactory condition existing in the basin for single valve operation leads to the requirement of the dividing wall (plate 3C). Satisfactory conditions without a dividing wall exist for symmetrical valve operation (plate 4A), but it is unlikely that this condition will always prevail.

In determining the proper length of wall tests were first made of a wall 30 feet shorter and 4 feet lower than the original wall. This wall was too short, allowing considerable water to flow around the end of the wall which disrupted the jump on the operating side of the basin (plate 4B). A wall 20 feet shorter and 4 feet lower than the original was satisfactory from the standpoint of the jump formation (plate 4C and figure 12B), and the scour was only slightly more severe than for the original wall. The water surface in the half of the basin not operating was one foot lower than the wall height allowing for some wave action. No harm will result should a small amount of water spill over the wall during one valve operation and from submergence of part of the wall for both valves operating under maximum conditions (plate 4D). A general rule for design is to make the wall extend over two-third the length of the basin with top elevation equal to the tailwater elevation for the maximum discharge of a single valve.

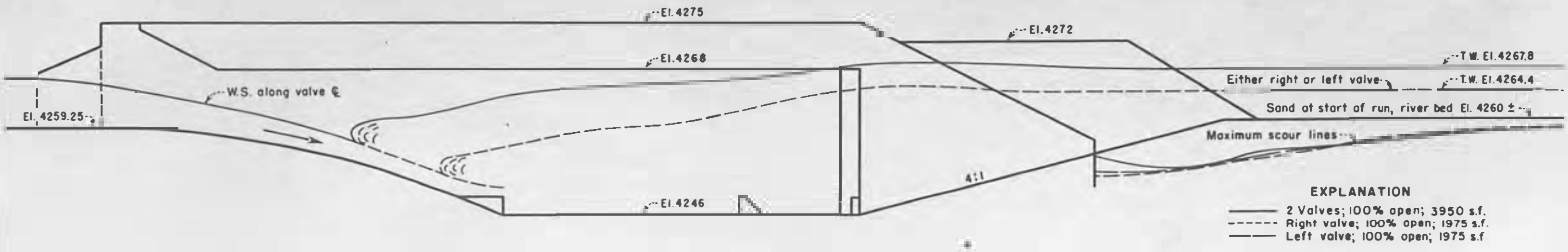


DESCHUTES PROJECT - OREGON

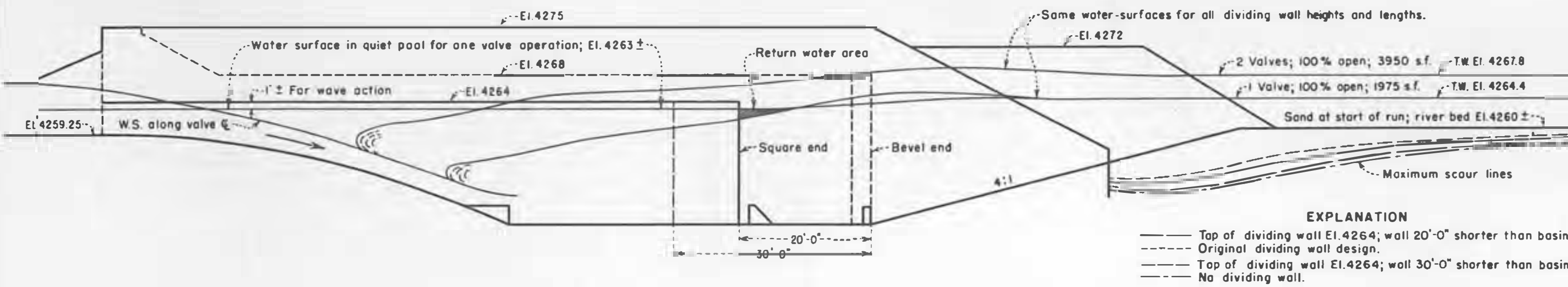
WICKIUP DAM OUTLET WORKS

ESTIMATED STAGE - DISCHARGE RELATIONSHIP FOR CRITICAL SECTION IN DESCHUTES RIVER BELOW WICKIUP DAM

FIGURE 11



A - DETERMINATION OF CRITICAL OPERATING CONDITIONS
ORIGINAL DESIGN EXCEPT FLOOR ELEVATION 4246



B - DETERMINATION OF LENGTH AND HEIGHT OF DIVIDING WALL
ORIGINAL BLOCKS AND SILL DESIGN - FLOOR ELEVATION

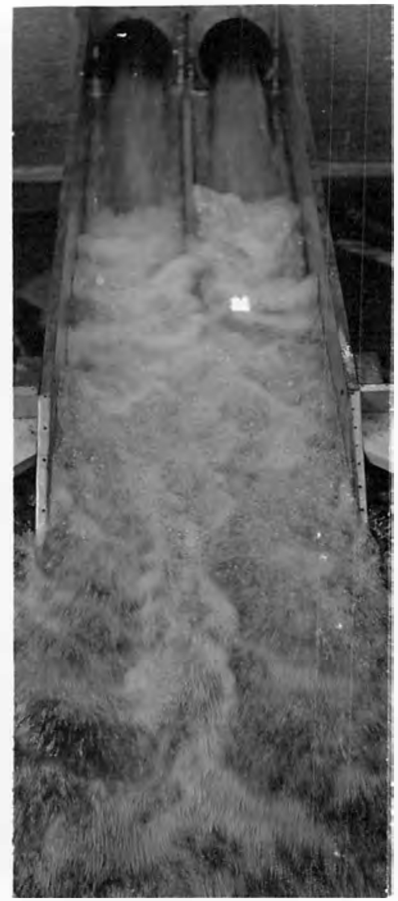
DESCHUTES PROJECT - OREGON
WICKIUP DAM OUTLET WORKS
STILLING BASIN STUDIES

FIGURE 12

A. NO DIVIDING WALL;
1975 SECOND-FEET PER VALVE.

B. 30 FEET SHORTER AND 4
FEET LOWER DIVIDING
WALL; 1975 SECOND-FEET.

C. 20 FEET SHORTER AND 4
FEET LOWER DIVIDING
WALL; 1975 SECOND-FEET.



D. 20 FEET SHORTER AND 4 FEET
LOWER DIVIDING WALL; 1975
SECOND-FEET PER VALVE.

PLATE 4

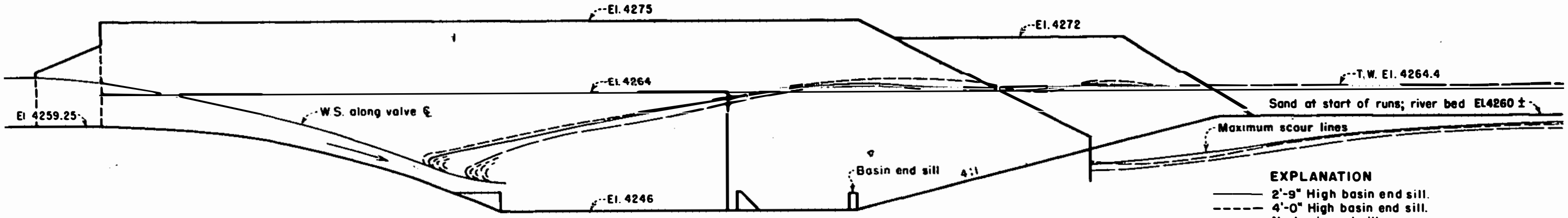
15. <u>Basin end sill.</u> With the 4:1 concrete slope at the end of the basin there was some question regarding the requirement of a basin end sill. For no end sill, the jump is located farther downstream and scour is more severe (figure 13A). When the sill becomes too high, as the 4-foot high sill tested, the water surface over the sill becomes rough and scouring increases. The 2-foot 9-inch high sill is more satisfactory than the 4-foot high sill or no sill.

16. <u>Concrete-slope end sill.</u> Although there is very little influence on the jump, a 12-inch high sill at the end of the 4:1 concrete slope is effective in reducing the scour (figure 13B).

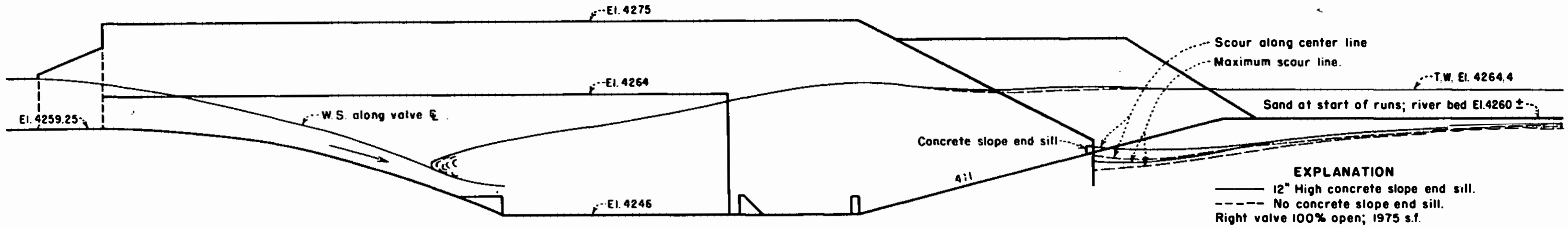
17. <u>Basin floor blocks.</u> For no basin floor blocks the jump is located too far downstream and the scour is more severe than when these blocks are present (figure 13C). The best jump formation and scour conditions are given for blocks placed about one-third the basin length from the end of the basin (figure 14C). When the blocks are located farther upstream they receive excessive impact resulting in a rougher jump and deeper scour, and when located farther downstream the jump moves downstream resulting in deeper scour. Likewise, when the blocks are too large or too small the jump becomes rough or moves downstream resulting in deeper scour (figure 15A). Best conditions were obtained by blocks 2 feet 6 inches high placed 18 feet 4 inches from the end of the basin.

18. <u>Chute blocks.</u> That chute blocks are effective as energy dissipators is shown by comparing the jump and scour with and without the use of these blocks (figure 14A). For no blocks the jump is located farther downstream and is rougher, and the scour is deeper. Two feet 6 inches proved to be the best block height (figure 15B).

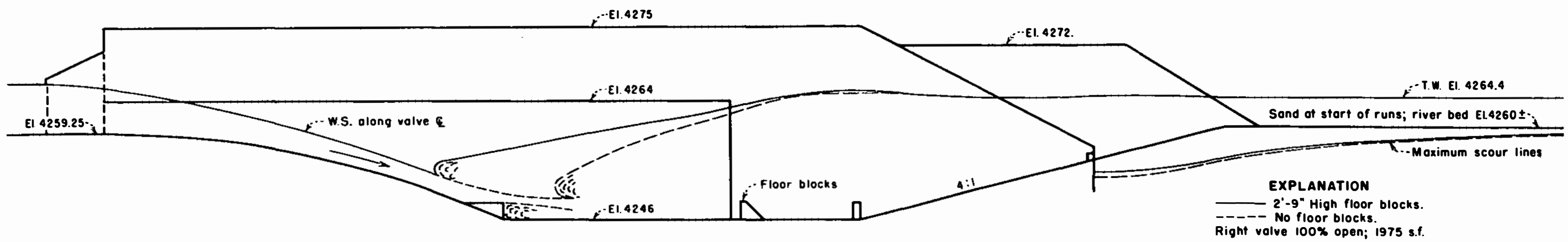
19. <u>Combined effect of blocks and sills.</u> The effectiveness of blocks and sills in maintaining the jump within the basin and reducing scour is determined by comparative tests with blocks and sills and with no blocks or sills (figure 14B). With no blocks or sills, one valve discharging 1,975 second-feet and tailwater elevation 4264.4 the jump is swept out of the basin. Due to insufficient depth in the river channel, standing waves instead of a jump are formed resulting in severe scour. By raising the tailwater 3 feet to elevation 4267.4 a jump is formed in the basin at the same position as for the case using blocks and sills with tailwater elevation 4264.4. Without the use of blocks and sills it would then be necessary to lower the basin floor 3 feet to obtain a satisfactory jump. Scour conditions, however, would not be as



A-EFFECT OF BASIN END SILL



B-EFFECT OF CONCRETE SLOPE END SILL



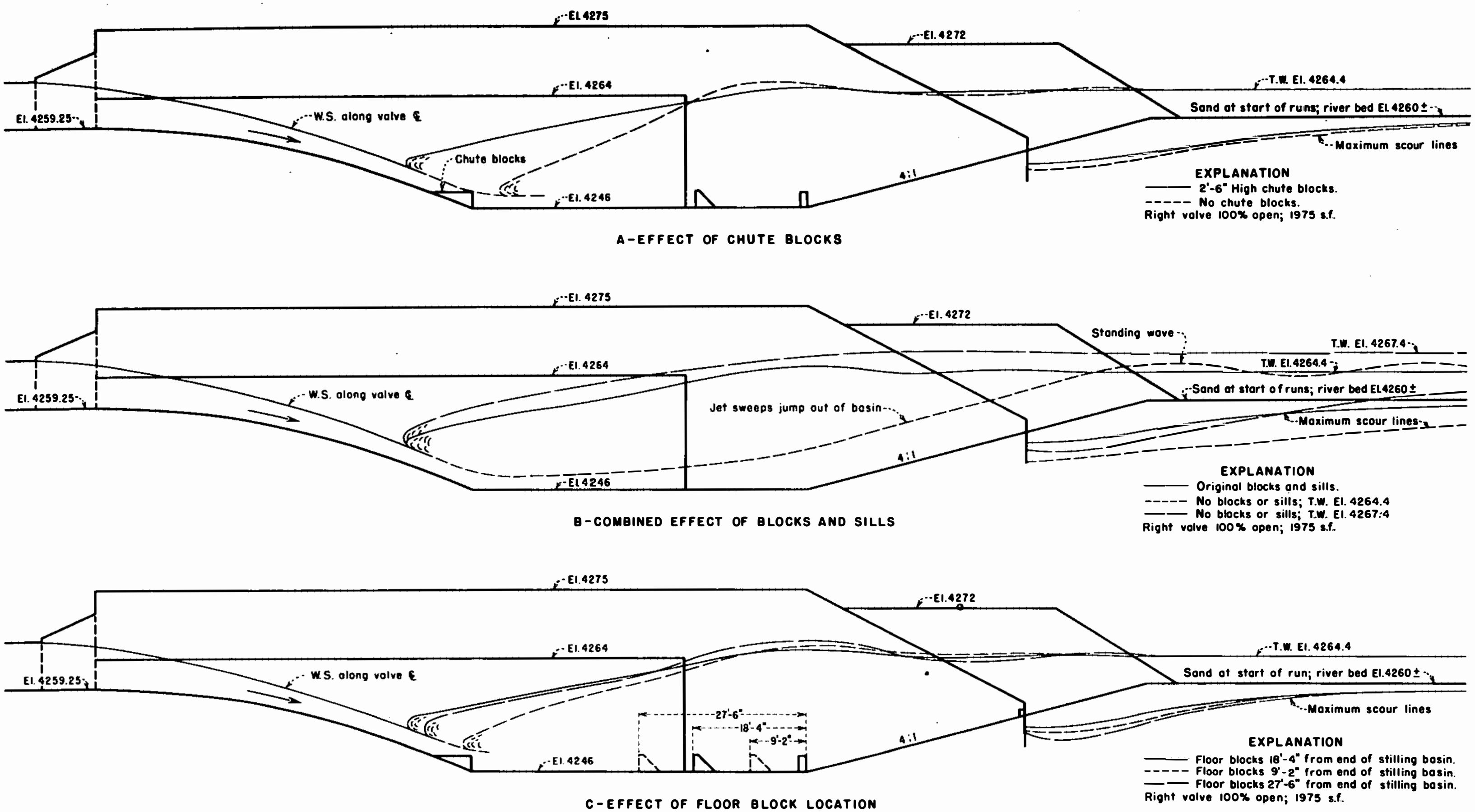
C-EFFECT OF BASIN FLOOR BLOCKS

DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

STILLING BASIN STUDIES

FIGURE 13

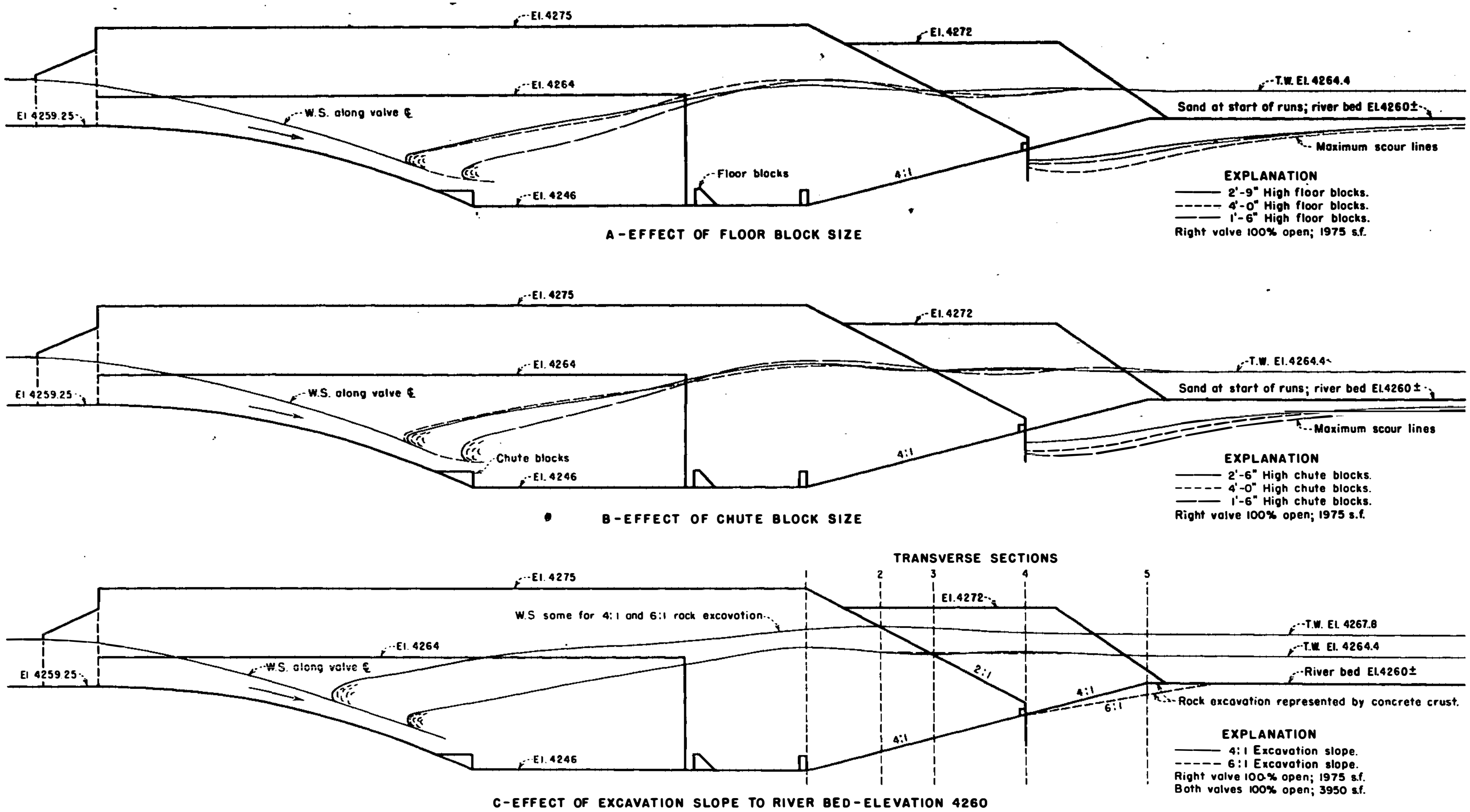


DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

STILLING BASIN STUDIES

FIGURE 14



DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

STILLING BASIN STUDIES

FIGURE 15

favorable as for the case using blocks and sills. The advantages of reduced cost and improved stilling-basin performance fully justifies the use of blocks and sills.

20. Slope from basin-floor elevation 4246 to river-bed elevation 4260. The length of channel whose bottom slopes from elevation 4246 to elevation 4260 is an outlet transition. The purpose of an outlet transition is to uniformly reduce the velocity from a high value to a lower value. A proper design would then require decreasing mean velocities from sections 1 to 5 (figure 15C). Table 4 shows the computations for mean velocity at these sections for one and two valves operating at maximum velocity and for 4:1 and 6:1 slope rock excavation at the end of the concrete slope. For the 4:1 slope the mean velocity at section 5 for the maximum discharge is greater than at section 4, and section 5 would then become a control. To eliminate the unfavorable flow conditions accompanying a control the 6:1 slope rock excavation is recommended. If the river bed was of sand and gravel, the 4:1 slope would soon scour sufficiently eliminating any control.

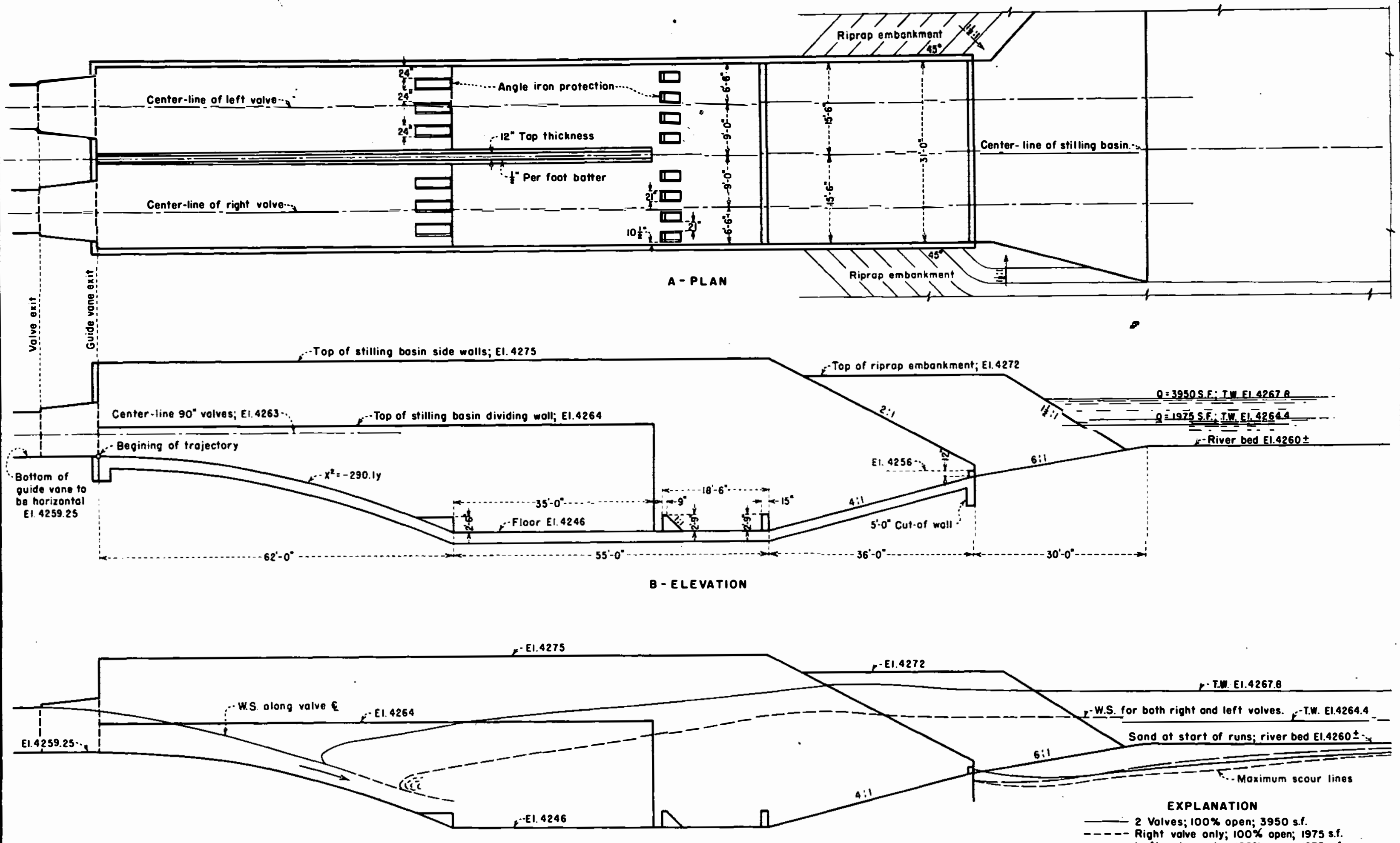
TABLE 4

Mean velocities at sections 1 to 5 (figure 15C)

	2 valves;Q=3,950 s.f.; T.W.El.4267.8					1 valve;Q=1,975; T.W.El.4264.4				
Section	1	2	4	5 S=4:1	5 S=6:1	1	3	4	5 S=4:1	5 S=6:
W.S.El.	4268.5	4269.1	4269.0	4267.8	4267.8	4265.6	4264.5	4265.0	4264.4	4264.4
Bot. El.	4248.5	4249.1	4256.0	4260.0	4258.3	4248.5	4251.3	4256.0	4260.0	4258.3
Depth	20.0	20.0	13.0	7.8	9.5	17.1	13.2	9.0	4.4	6.1
Bot. width	31.0	31.0	31.0	62.4	55.6	14.3	22.0	31.0	62.4	55.6
W.S. width	31.0	31.0	66.0	87.6	86.4	14.9	36.0	55.8	80.2	79.0
Mean width	31.0	31.0	48.5	75.0	71.0	14.6	29.0	43.4	71.3	67.3
Water area	620	620	631	585	675	250	283	291	314	405
Mean vel.	6.36	6.36	6.25	6.75	5.85	7.89	6.98	6.78	6.29	4.87

21. Recommended stilling-basin design. Dimensions in plan and elevation of the recommended stilling-basin design are shown on figures 16A and 16B and plate 5A. The scour and hydraulic jump for one- and two-valve operation are shown in figure 16C and plates 5B to 7D, inclusive.

22. Conclusions. Questions regarding the uncertain features of the design previously outlined were answered satisfactorily by the model study. The following conclusions should serve as useful guides for future model studies and prototype designs:



C - HYDRAULIC JUMP AND SCOUR

DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

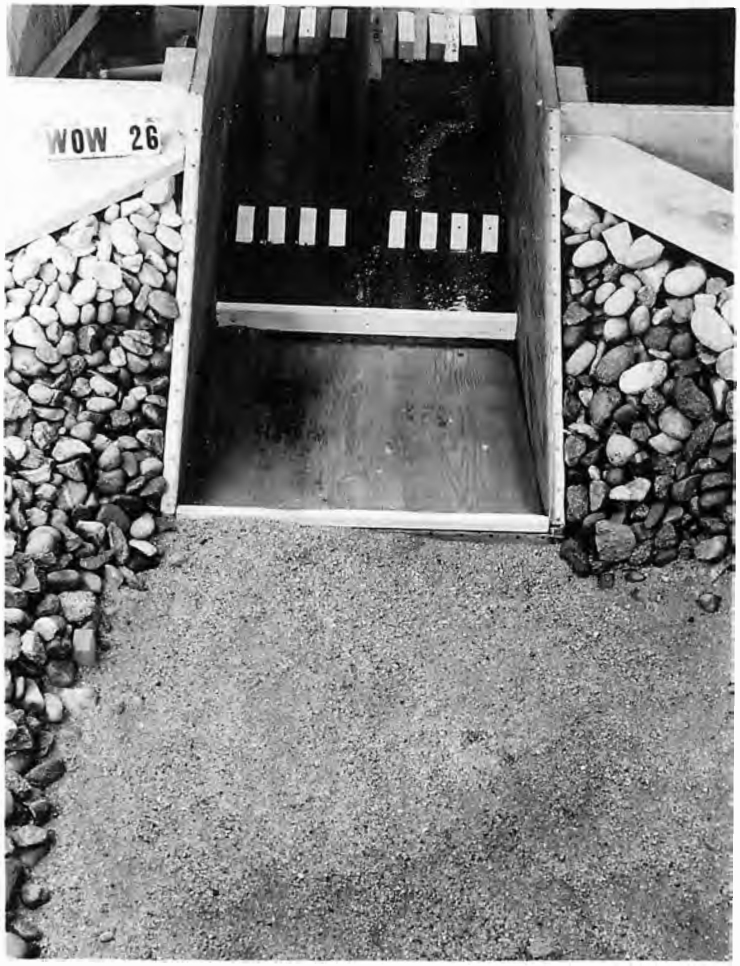
RECOMMENDED STILLING BASIN DESIGN

FIGURE 18

A. RECOMMENDED DESIGN.

B. RECOMMENDED DESIGN; RIGHT VALVE 1975 SECOND-FEET.

C. RECOMMENDED DESIGN; RIGHT VALVE 1975 SECOND-FEET.



A. RECOMMENDED DESIGN; SCOUR FOR RIGHT VALVE;1975 SECOND-FEET.

B. RECOMMENDED DESIGN; LEFT VALVE 1975 SECOND-FEET.

C. RECOMMENDED DESIGN; LEFT VALVE 1975 SECOND-FEET.

A. RECOMMENDED DESIGN; SCOUR FOR LEFT VALVE; 1975 SECOND-FEET.

B. RECOMMENDED DESIGN; 1975 SECOND-FEET PER VALVE.

C. RECOMMENDED DESIGN; SCOUR FOR BOTH VALVES DISCHARGING 1975 SECOND-FEET.

D. RECOMMENDED DESIGN; EACH VALVE DISCHARGING 1975 SECOND-FEET.

a. Needle or tube valve flow can be satisfactorily duplicated by short tubes in the model study.

b. Entrainment of air by the prototype valve jets has little effect on the hydraulic-jump formation, and the effect will be on the safe side.

c. The chute-floor trajectory should be approximately similar to the trajectory of the maximum velocity valve jet.

d. Chute walls should be parallel to the direction of the valve jets.

e. The discharge guide vane should have an angle of divergence of not less than about 9 degrees and need not be longer than about 10 feet.

f. The width of stilling basin should be twice the valve spacing insuring satisfactory spreading of valve jets.

g. A center-line dividing wall is required for satisfactory single-valve operation. In length, the wall should extend to one-third the length of the basin from the end of the basin. (The basin is defined as the level floor section of the outlet structure). The top of the wall should be at the same elevation as the tailwater for maximum single-valve operation.

h. The length of basin may be reduced somewhat when a concrete transition exists at the end of the basin. The transition is then considered to function in conjunction with the basin.

i. Proper size chute blocks, basin blocks, basin end sill and concrete slope end sill are required for economy and efficient hydraulic operation of the stilling basin.

j. The stilling-basin dimensions may be reliably determined by figure 17, appendix I.

k. Under no conditions of operation do destructive currents form in the unsymmetrical channel downstream from the stilling basin.

APPENDIX I

APPENDIX I

HYDRAULIC DESIGN OF RECTANGULAR STILLING BASINS

1. Introduction. Hydraulic experiments in the past three years at the Bureau of Reclamation hydraulic laboratory have shown the rectangular stilling basin incorporating chute blocks, basin blocks, and an end sill to be superior to other types for use with the usual spillway channel. On the basis of the experimental data obtained from the adopted stilling basins for the Boca, Deer Creek, Vallecito, and All-American canal wash overchute spillway structures, a chart (figure 17) was constructed in which the the several variables are given in the design of rectangular stilling basins.

By studying the experimental data of the mentioned models a general rule for each of the variables was determined to agree with the experimental measurements. The agreement was so good over the complete range of available data that it is believed these rules are without serious error universally applicable to the design of stilling basins of the type herein considered.

The discharge per foot of width at the pool entrance from which the chart was constructed varied from 41.7 to 240 second-feet, and the velocity at the pool entrance varied from 34 to 75 feet per second. Action of the hydraulic jump for the higher discharge and velocity indicated that the rules could be safely extended to at least a discharge of 450 second-feet per foot of width at the pool entrance and a pool-entrance velocity of 100 feet per second. These values have, therefore, been taken as the upper limits of the chart.

2. Rules for the design of a rectangular stilling basin.

1. The width, w, of the basin is determined to result in the most economical structure.

2. The discharge, q, per foot of width at the pool entrance is equal to the design maximum flood discharge divided by the width at the pool entrance.

3. The theoretical velocity, v_1, at the pool entrance is computed from the available energy head and properly evaluated losses. (For spillway chutes use King's formula for flow in steep chutes.)

4. The theoretical depth, d_1, at the pool entrance is equal to q/v_1.

5. The theoretical jump, d_2, depth is computed by the momentum formula.

6. The experimental jump, $d2'$, depth is equal to 85 percent of d_2.

7. The required stilling-basin floor elevation is equal to the maximum discharge tailwater elevation minus d'_2.

8. The required stilling-basin length, L, is equal to $3d_2$.

9. The height, h_1, of chute blocks is equal to d_1 or 1/9 d_2, whichever is largest.

10. The height, h_2, of basin blocks is equal to 1/4 d_2 for values of d_2 from 0 to 8 feet, follows a straight line variation of 1/4 d_2 to 1/8 d_2 from 8 to 24 feet and is equal to 1/8 d_2 for values of d_2 above 24 feet.

11. The height, h_3, of solid end sill is equal to 1/8 d_2.

12. The distance, a, from the end of the stilling basin to the vertical upstream faces of the basin blocks is equal to 1/3 L.

13. The maximum width of blocks and spaces between them are equal to h_1, and the minimum width is limited to about 18 inches.

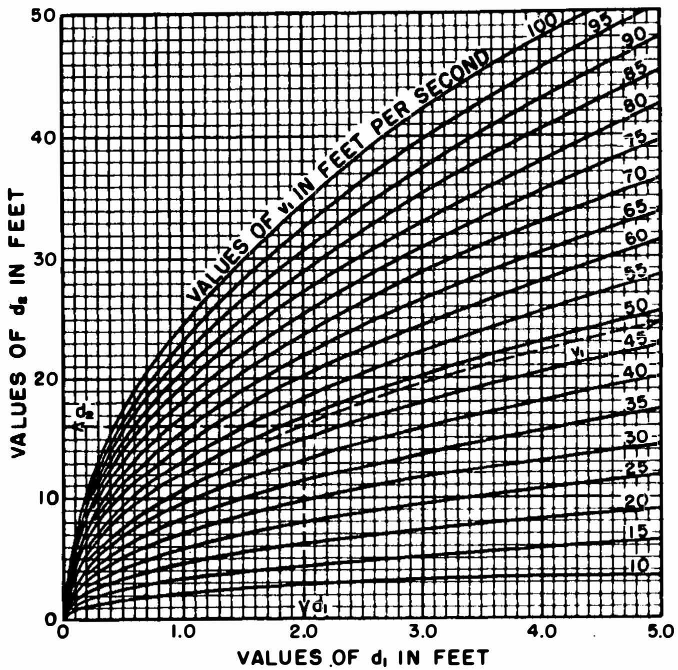
14. The top dimensions of the floor blocks and end sill parallel to the basin center line are equal to 1/4 h_2 and 1/4 h_3, respectively, with a minimum value of about 8 inches.

15. Chute and basin blocks should be staggered with no blocks against the side walls and one more basin block than chute blocks.

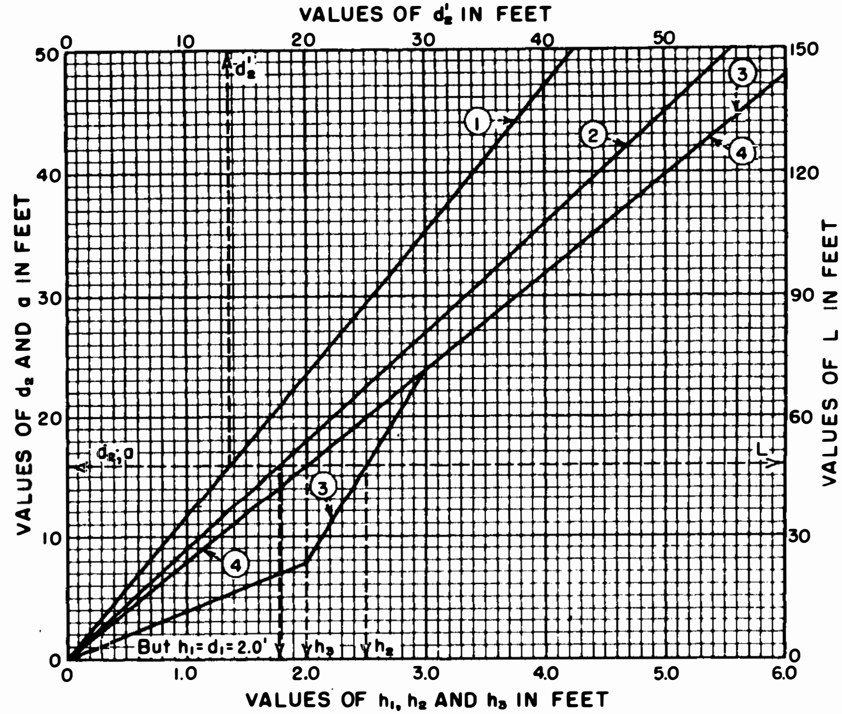
16. The back slope of the basin blocks and end sill may be such as to be the most economical, usually 1:1, and for economical reasons the end sill may be rectangular in cross section when less than 3 feet high.

17. The slope of the transition bottom at the end of the basin may vary from horizontal to 6:1 when of earth, rock excavation, or riprap and up to 3:1 when of concrete.

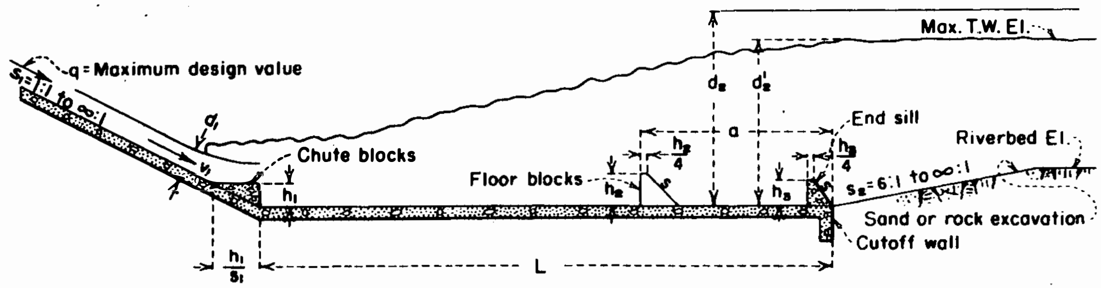
18. The chute slope entering the basin may vary from horizontal to 1:1.



A. SOLUTION OF MOMENTUM FORMULA



B. STILLING BASIN DIMENSIONS



C. ELEVATION ALONG STILLING BASIN CENTERLINE

MOMENTUM FORMULA

$$d_2 = -\frac{d_1}{2} + \sqrt{\frac{d_1^2}{4} + \frac{2v_1^2 d_1}{g}}$$

1. For values of d_2'
2. For values of h_1 when larger than 1.0 d_1
3. For values of h_2
4. For values of h_3

EXAMPLE

q = 96.0 sec.-ft. per ft. width	d_2 = 16.0 ft.	h_1 = 2.0 ft.	$h_2/4$ = 6 in.	a = 16 ft.
v_1 = 48.0 ft. per sec.	d_2' = 13.6 ft.	h_2 = 2.5 ft.	$h_3/4$ = 6 in.	s, s_1 and s_2 are
d_1 = 2.00 ft.	Floor el. = max. T.W. el. − 13.6 ft.	h_3 = 2.0 ft.	L = 48 ft.	all variable.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
DENVER OFFICE

RELATIONS BETWEEN VARIABLES
IN STILLING BASIN DESIGN
FOR RECTANGULAR SPILLWAY CHANNELS
BASED ON HYDRAULIC MODEL EXPERIMENTS

DRAWN J.H.D.	SUBMITTED Jacob E. Warnock
TRACED O.E.W.-C.I.L.	RECOMMENDED
CHECKED J.H.D.	APPROVED
DENVER, COLORADO MARCH 28, 1939	X-D-2619

FIGURE 17

3. <u>Comparison of design chart and experimental data.</u> The good agreement between values given by the design chart and those determined experimentally is shown by the comparisons of table 5. In almost every case, the chart gives slightly conservative values. The dimensions of the Wickiup stilling basin originally determined from the design chart were checked by extensive tests, and no changes were necessary except by use of a concrete transition at the end of the basin the length of basin could be reduced about 10 feet. While it is believed that the use of dimensions given by the chart will result in a good design, slight variation in dimensions, one way or the other, will have little or no effect on the performance of the basin. For example, there would be little difference between a 90- and 95-foot length basin or 4-foot and 4-foot 6-inch high blocks or sills for a given set of conditions.

TABLE 5

Stilling-basin dimensions given by design chart compared with experimental data.

Model variable	Boca Exp.	Boca Chart	Deer Creek Exp.	Deer Creek Chart	Vallecito Exp.	Vallecito Chart	Wash Overchute Exp.	Wash Overchute Chart	Wickiup Exp.	Wickiup Chart
q	106.7	-	160	-	240	-	41.7	-	140	-
v_1	73.2	-	75.1	-	76.4	-	34.0	-	61.6	-
d_1	1.46	-	2.13	-	3.14	-	1.23	-	2.27	-
d_2	-	21.3	-	26.0	-	32.5	-	8.9	-	21.8
d_2'	18.4	18.3	22.0	22.1	*30.0	27.6	7.7	7.6	18.4	18.5
L	58.7	63.9	75.0	78.0	92.6	97.5	25.0	26.7	55.0	**65.4
a	20.0	21.3	25.0	26.0	27.0	32.5	9.0	8.9	18.5	21.8
h_1	2.0	2.4	3.0	2.9	4.0	3.6	2.0	1.2	2.5	2.5
h_2	3.0	2.7	3.0	3.25	*5.0	4.1	2.0	2.1	2.75	2.8
h_3	3.0	2.8	3.0	3.25	*5.0	4.1	1.0	1.1	2.75	2.9

*Conservative.
**Concrete transition allowed reduction of basin length.

4. <u>The influence of entrained air.</u> The above rules and figure 17 are applicable to the case of entrained air provided the proper v_1, and d_1 values are used for the water-air mixture at the pool entrance. The influence of entrained air is to increase q and d_1 and reduce all other variables.

APPENDIX II

APPENDIX II

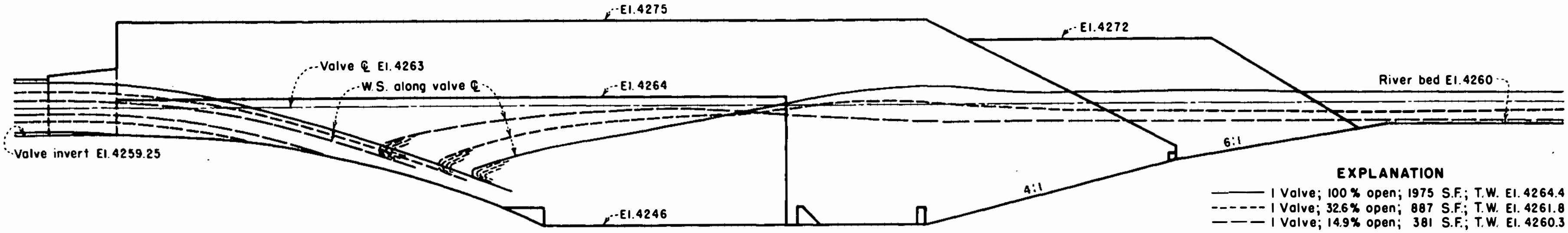
DESIGN OF OUTLET-WORKS STILLING BASINS

1. Introduction. Energy dissipation below outlet works through earth-fill dams frequently leads to the problem of scour prevention. If the canyon downstream from the outlet works is not of sound rock, or if damage would result from anticipated scour; it is necessary to provide a stilling basin to control the action of the high velocity valve jets. The types of stilling basins may be classed as free jet, chute, hump, and impact basins. The designs will be developed for the usual case of two outlet conduits.

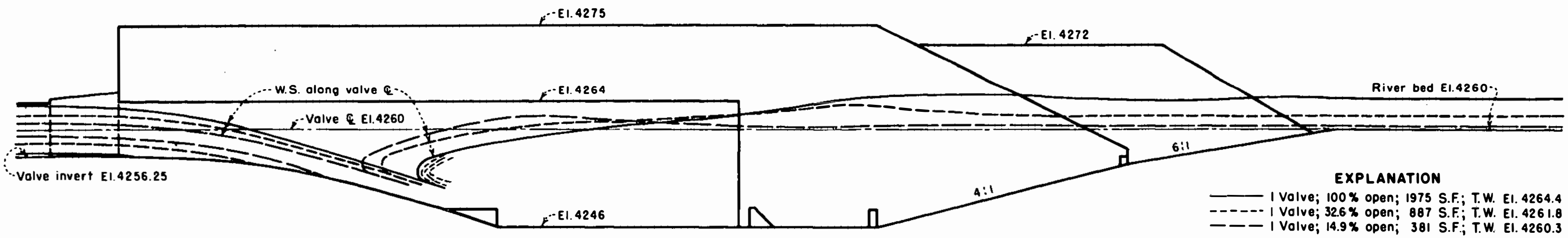
2. Application of types of outlet-works stilling basins. By a series of experiments the limits of application of each type of outlet-works stilling basin has been fairly well established. The use of each is determined by the relative location of the outlet gates or valves with respect to the maximum tailwater elevation and by the character of the downstream river channel.

Where the outlet invert is above the maximum tailwater and the channel below comparatively stable, a pool into which the jets will plunge is sufficient. According to a few preliminary tests (plates 8 and 9), when the valve invert is the same or lower than the tailwater elevation, the jets remain on the pool surface, developing severe reverse currents on the sides of the basin. By raising the valve invert to at least the maximum tailwater elevation the jets attain sufficient downward direction to cause their submergence by the pool. The reverse currents at the sides of the basin and immediately in front of the discharge guide vane and splashing in the basin are then reduced.

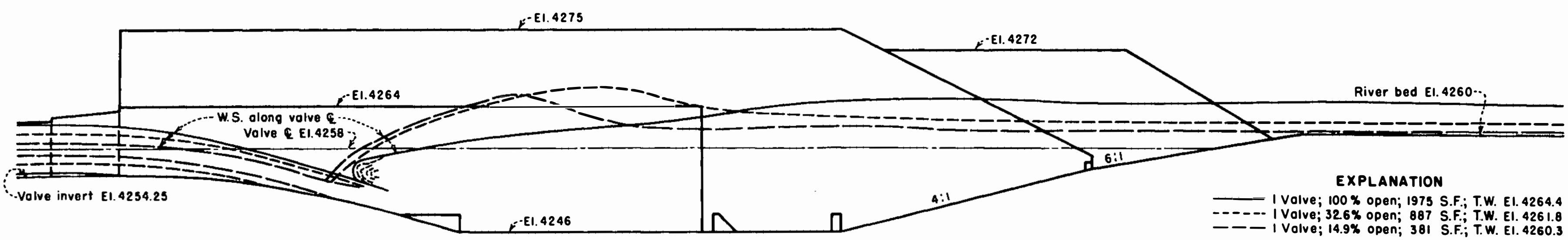
If the channel is narrow and erodible, where scouring might be dangerous to the structure, a chute basin should be used for all conditions with the outlets above the tailwater. The chute basin should also be used for all cases between valve invert at maximum tailwater elevation and valve center line at the river-bed elevation. Tests (plates 10 and 11) to determine the lower limit of valve elevation for satisfactory flow conditions indicated that when the valve center line is lower than the river-bed elevation the hydraulic jump will move up to the outlet valves causing undesirable flow conditions. Furthermore, the hydraulic jump is satisfactory for all valve openings and valve center line at or above the river-bed elevation (figures 18A and 18B); but when the valve center line is lower than the river bed the formation of the hydraulic jump is not satisfactory for all valve openings (figure 18C), and the hump basin should then be used to maintain the jump downstream from the outlet valves.



A - VALVE CENTERLINE ELEVATION 4263



B - VALVE CENTERLINE ELEVATION 4260



C - VALVE CENTERLINE ELEVATION 4258

DESCHUTES PROJECT - OREGON

WICKIUP DAM OUTLET WORKS

VALVE CENTERLINE - TAILWATER RELATIONSHIP FOR CHUTE STILLING BASIN

FIGURE 18

A. 1975 SECOND-FEET; VALVE CENTERLINE EL. 4260; TAILWATER EL. 4264.4.

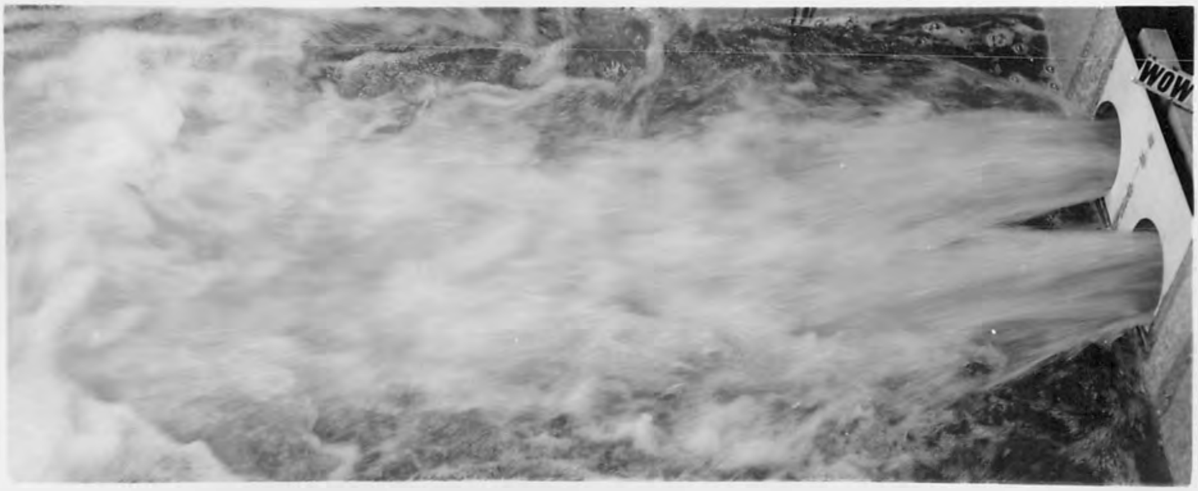
B. 1975 SECOND-FEET; VALVE CENTERLINE EL. 4263; TAILWATER EL. 4264.4.

C. 1975 SECOND-FEET; VALVE CENTERLINE EL. 4268; TAILWATER EL. 4264.4.

FREE JET POOL.

A. 3950 SECOND-FEET; VALVE CENTERLINE EL. 4260; TAILWATER EL. 4264.4.

B. 3950 SECOND-FEET; VALVE CENTERLINE EL. 4263; TAILWATER EL. 4264.4.

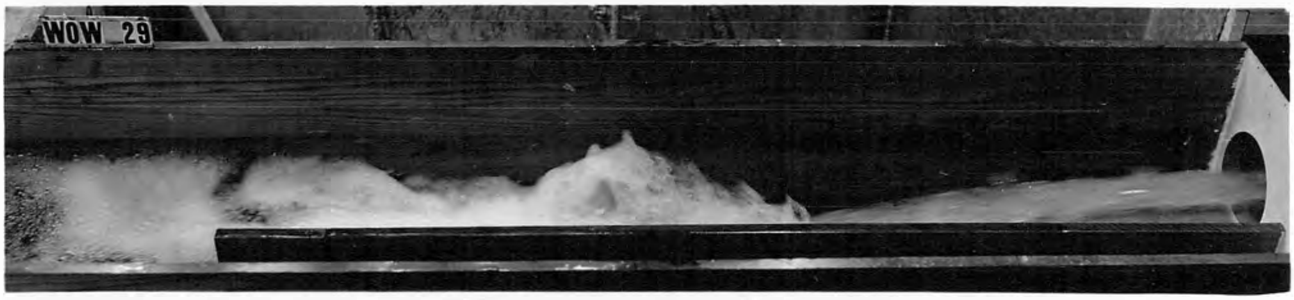


C. 3950 SECOND-FEET; VALVE CENTERLINE EL. 4268; TAILWATER EL. 4264.4.

FREE JET POOL.

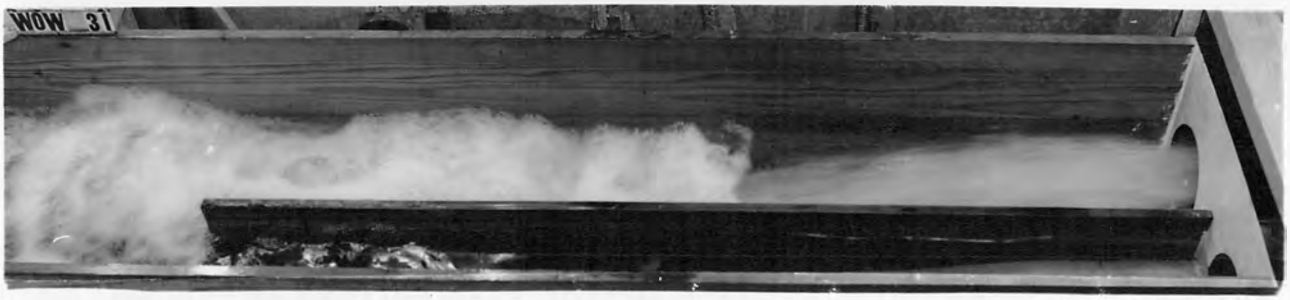
A. ONE VALVE 14.9% OPEN; CENTERLINE EL. 4258; DISCHARGE 381 S.F.;T.W. EL. 4260.3.

B. ONE VALVE 14.9% OPEN; CENTERLINE EL. 4260; DISCHARGE 381 S.F.; T.W. EL. 4260.3



C. ONE VALVE 14.9% OPEN; CENTERLINE EL. 4263; DISCHARGE 381 S.F.; T.W. EL. 4260.3

D. ONE VALVE 32.6% OPEN; CENTERLINE EL. 4263; DISCHARGE 887 S.F.; T.W. EL. 4261.8.

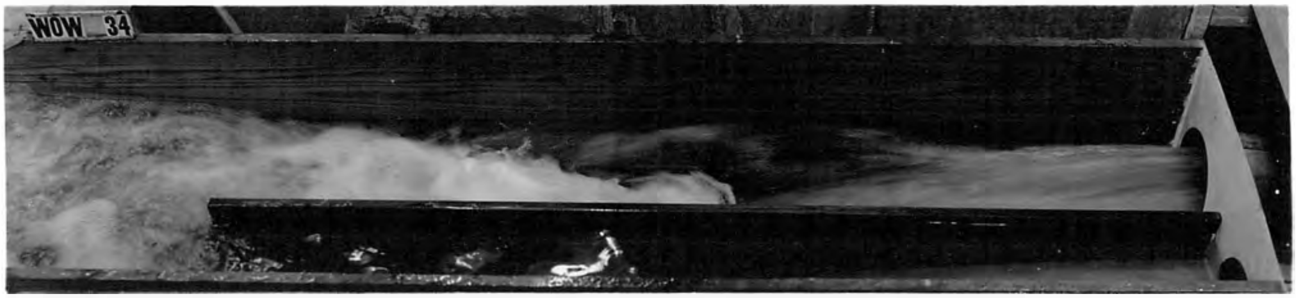


E. ONE VALVE 32.6% OPEN; CENTERLINE EL. 4260; DISCHARGE 887 S.F.; T.W. EL. 4261.8.

CHUTE STILLING BASIN

A. ONE VALVE 32.6% OPEN; CENTERLINE EL. 4258; DISCHARGE 887 S.F.; T.W. EL. 4261.8.

B. ONE VALVE 100% OPEN; CENTERLINE EL. 4263; DISCHARGE 1975 S.F.; T.W. EL. 4264.4.



C. ONE VALVE 100% OPEN; CENTERLINE EL. 4260; DISCHARGE 1975 S.F.; T.W. EL. 4264.4.

D. ONE VALVE 100% OPEN; CENTERLINE EL. 4258; DISCHARGE 1975 S.F.; T.W. EL. 4264.4.

CHUTE STILLING BASIN

In certain cases when the head is relatively small it may be desirable and economical to use slide gates in place of valves. With the gates the free jet, chute, and hump basins can be used for the conditions described above; in addition, an impact type of basin may be used for the condition defined for the hump basin. This type of basin is essentially a rectangular stilling basin placed against the outlet gates with a level floor at the same elevation as the gate sills. A jump will form at the gates or will be completely submerged depending on the tailwater elevation. Due to the low head and the small disturbance of the gate jets, submergence of the jets is considered permissible.

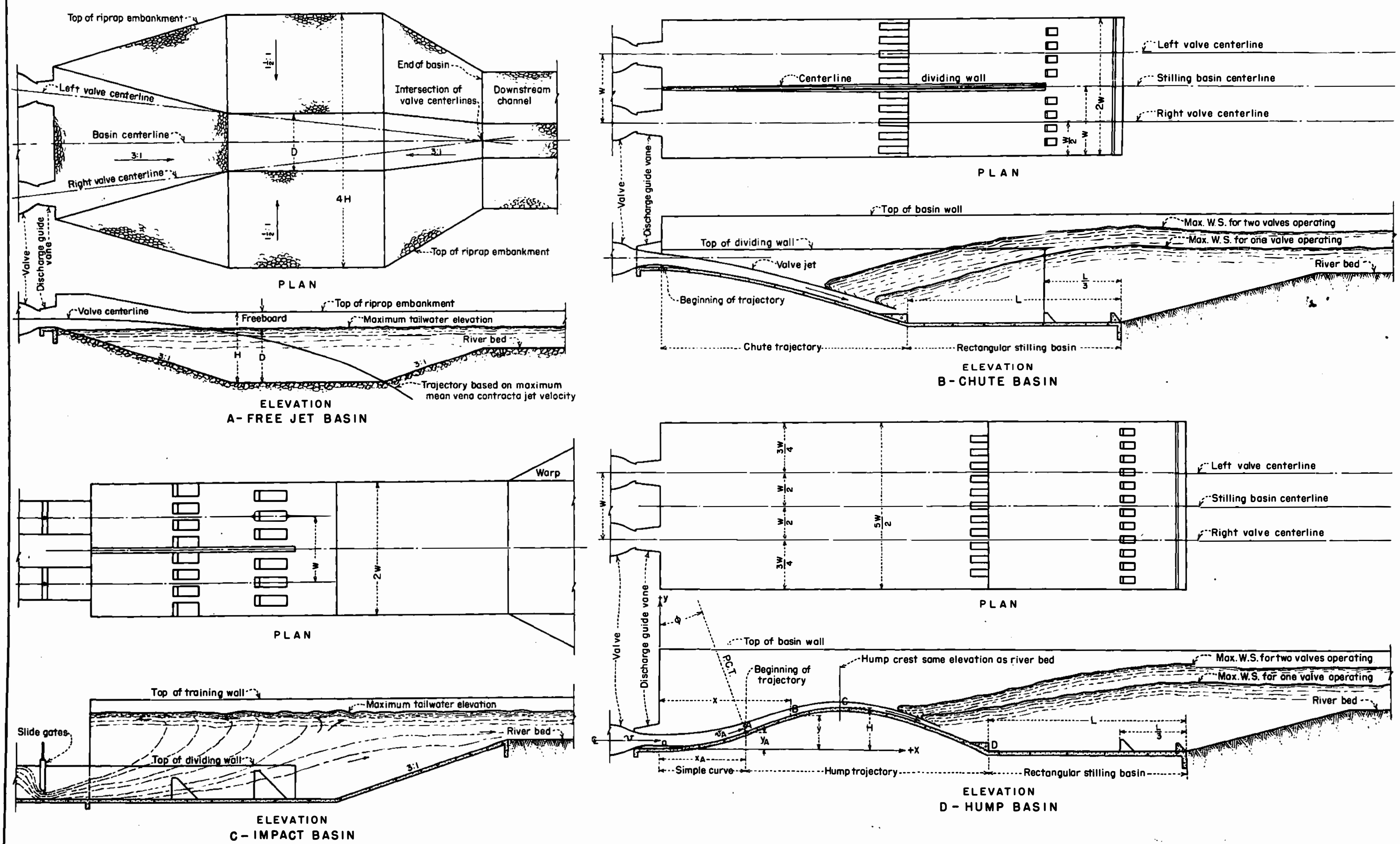
3. Design of free jet basin. The construction features of this type of basin depends on several conditions. When the walls and bottom of the river channel are of sound rock the jets may be allowed to discharge freely into the canyon without taking any measures for scour prevention. In some cases, the channel may consist of erodible gravel and rock, but scouring will not endanger any part of the structure. A natural basin will then be excavated by the scouring action of the jets; the small gravel will be carried downstream and the large material left to cover the basin as riprapping. When scouring of the channel will be dangerous to the structure shaping and riprapping of an already wide channel as part of the construction program is required. As previously stated, when the channel is very narrow and erodible a free jet basin is not feasible, and a chute basin is required where channel scour would be dangerous.

The proper design of a riprapped, free jet basin was determined by the Deer Creek Dam outlet works model study. The important features in design of such a basin are shown in figure 19A, in which dimensions outlined are minimum values for good performance of the basin. Since least cost is given by the dimensions most nearly fitting the river channel, dimensions greater than those shown in figure 19A may be used, and good basin performance can be expected provided the basin is symmetrical with respect to the valves. In some cases an unsymmetrical basin becomes feasible by placing heavy riprapping on the wider side to provide protection against the severe currents resulting from the unsymmetrical conditions.

Rules for designing the riprapped free jet basin:

(a) The depth of pool for maximum tailwater should be about one-fifth the difference in maximum reservoir and pool water-surface elevations. This depth may be reduced somewhat when the basin bottom is of good rock.

(b) The width at the maximum water line should be four times the depth of pool.



DESIGN OF OUTLET WORKS STILLING BASINS

FIGURE 19

(c) The level basin bottom should extend to the point where the maximum jet trajectory reaches the basin bottom elevation.

(d) The downward slope from the valves to the basin bottom may be 3:1 or greater.

(e) The upward slope from the basin bottom to the river-bed elevation may be 3:1 or smaller.

(f) Basin side slopes should be $1\frac{1}{2}$:1.

(g) For best basin performance with single-valve operation the alinement of valves should be such that their center lines intersect at the end of the basin.

4. Design of chute basin. The chute basin consists of a rectangular chute and stilling basin. The following rules outline the procedure of design (figure 19B):

(a) A dividing wall along the spillway center line is required for satisfactory jump formation for one-valve operation. The top of the wall should be at the maximum tailwater elevation for one valve operating, and the wall should extend over the full length of the chute and two-thirds the length of the stilling basin.

(b) Each half of the basin should be symmetrical with respect to the valve center line, so the basin width should be twice the valve spacing.

(c) Chute and basin walls should be parallel to the direction of the jets.

(d) The chute floor trajectory should be approximately similar to the trajectory for the maximum velocity jet.

(e) The stilling basin may be designed by the application of the rules and figure 17 of appendix I. Since each half of the basin functions separately, the maximum tailwater elevation for one valve operation should be used in determining the proper basin floor elevation.

5. Design of hump basin. This type of basin consists of a rectangular stilling basin and hump chute with a simple curve at the upstream end of the chute and a parabola, designed to fit the maximum jet trajectory at the downstream end. The cost decreases as the radius of simple curve decreases, but the jet will not be deflected upwards smoothly if the radius is made excessively small. The radius and mean jet velocity can be related by a consideration

of the jet acceleration introduced by the curve toward the center of curvature. The expression for acceleration in terms of velocity and radius is $a = \frac{v^2}{R}$. It can be specified that the allowable acceleration toward the center of curvature should be some proportion of the acceleration of gravity; $a = kg$.

The maximum value of k for satisfactory operation must be determined by model tests. A preliminary test for $k = 1.0$ proved satisfactory, and indications were that k could be increased to a value between 1.5 and 2.0. Due to urgency of other work and limited laboratory space, further testing was delayed. For the present $k = 1.5$ can be safely used.

A complete investigation of the value of k can be obtained by testing one curve designed for $k = 1.0$ and a velocity well below the maximum attainable in the model. Then by increasing the head, thus velocity, the value of k increases for the designed curve, and the maximum value of k for satisfactory operation can be determined. The radius of simple curve can then be determined by

$$R = \frac{v^2}{kg} \quad \text{(1)}$$

Referring to figure 19D, the equation of the hump trajectory will now be determined. Consider point O, the beginning of the simple curve, as origin of the coordinate system, point A as point of tangency of simple curve and trajectory, point C as highest point of trajectory, and point D as end of trajectory. The coordinates of the simple curve OA are determined by

$$y = R - \sqrt{R^2 - x^2} \quad \text{(2)}$$

The equation of the trajectory must be found in terms of x and y. Known conditions at point A are:

$$x_A = R \sin \phi \quad \text{(3)}$$

$$y_A = R\,(1 - \cos \phi) \quad \text{(4)}$$

$$\text{Velocity in X-direction, } \frac{dx_A}{dt} = v_A \cos \phi \quad \text{(5)}$$

$$\text{Velocity in Y-direction, } \frac{dy_A}{dt} = v_A \sin \phi \quad \text{(6)}$$

At any point, C, on the trajectory:

$$\text{Acceleration in X-direction, } \frac{d^2x}{dt^2} = 0 \quad \text{(7)}$$

Acceleration in Y-direction, $\frac{d^2y}{dt^2} = -g$ .... (8)

Integrating (7) and (8) for velocities in X- and Y- directions,

$$\frac{dx}{dt} = C; \text{ when } t = o, C = v_A \cos \phi$$

$$\frac{dy}{dt} = -gt + C; \text{ when } t = o, C = v_A \sin \phi$$

The second integration of (7) and (8) gives the X and Y coordinates:

$$x = tv_A \cos \phi + C; \text{ when } t = o, C = R \sin \phi$$

$$x = tv_A \cos \phi + R \sin \phi \quad \text{.................................. (9)}$$

$$y = tv_A \sin \phi - 1/2\ gt^2 + C; \text{ when } t = o, C = R(1-\cos \phi)$$

$$y = tv_A \sin \phi + R\ (1-\cos \phi) - 1/2\ gt^2 \quad \text{.................. (10)}$$

The equation of the trajectory, obtained by eliminating t and solving (9) and (10), is

$$y = \tan \phi\ (x-R \sin \phi) - \frac{g}{2v_A^2} \left(\frac{x-R \sin \phi}{\cos \phi}\right)^2 + R(1-\cos \phi) \quad \text{.. (11)}$$

An expression must be determined for the unknown angle ϕ of (11). The first derivative of (11) gives the slope of the tangent to the trajectory at any point, which is equal to zero when y = + H. Therefore, at point C

$$\frac{dy}{dx} = \tan \phi - \frac{g}{v_A^2} \left(\frac{x - R \sin \phi}{\cos^2 \phi}\right) = 0$$

from which

$$x_C = \frac{v_A^2}{g} \sin \phi \cos \phi + R \sin \phi \quad \text{.......................... (12)}$$

and by placing (12) in (11),

$$y_C = H = \frac{v_A^2}{2g} \sin^2 \phi + R\ (1 - \cos \phi) \quad \text{.................. (13)}$$

In equation (13), all values are known except v_A and ϕ. By writing Bernoulli's equation neglecting friction loss, between points O and B, v_A can be found in terms of the known mean jet velocity, v, at O.

$$\frac{v_A^2}{2g} = \frac{v^2}{2g} - R\ (1 - \cos \phi)$$

from which

$$v_A = \sqrt{v^2 - 2gR\,(1-\cos \phi)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

Placing (14) in (13)

$$H = \frac{v^2}{2g} \sin^2 \phi - R\,(1-\cos \phi) \sin^2 \phi + R\,(1-\cos \phi) \quad \ldots\ldots \quad (15)$$

Replacing $\sin^2 \phi$ by $(1-\cos^2 \phi)$ and recalling that $v^2 = kgR$, (15) reduces to

$$\cos^3 \phi + (1/2k - 1) \cos^2 \phi + \left(\frac{H}{R} - 1/2k\right) = 0 \quad \ldots\ldots\ldots \quad (16)$$

The roots of (16) may be determined by Newton's method of solution, and the proper value of $\cos \phi$ determined for any specific design. Let $x = \cos \phi$, then if x_1 is an approximate value of a root,

$$x_1 - \frac{f\,(x)}{f'(x)} = x_2 \text{ is a second approximation.}$$

Finally, the trajectory equation can be written in the form,

$$y = Ax^2 + Bx + C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

By introducing (14) and (1) in (11), the coefficients of (17) are:

$$A = \frac{-1}{2R \cos^2 \phi\,(k-2 + 2 \cos \phi)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

$$B = \tan \phi \left[1 + \frac{1}{\cos \phi\,(k - 2 + 2 \cos \phi)}\right] \quad \ldots\ldots\ldots\ldots \quad (19)$$

$$C = R \left[1 - \cos \phi - \sin \phi \tan \phi - \frac{\tan^2 \phi}{2(k - 2 + 2 \cos \phi)}\right]. \quad (20)$$

The hump dimensions may be determined by the above equations provided the hump crest elevation is known. The crest elevation must be determined to satisfy three conditions: (a) To properly spread the jets from the tunnels for all combinations of discharge; (b) to force the jump to form downstream from the valves for all combinations of discharge; (c) to form a quiet stable hydraulic jump in the stilling basin.

The extent of jet spreading will depend on the height, H, of the hump. When H is small the jets will not spread effectively, and the center-line dividing wall will then be required. When H is large the jets will spread so that they are of fairly uniform depth for all combinations of discharge over the hump crest, and the dividing wall will not be required. Sufficient tests to establish the proper height of hump required for good jet spreading have not as yet been conducted, but a preliminary test indicated a height of 14 feet satisfactory for the Wickiup basin, provided the basin width be made $2\frac{1}{2}$ times the valve spacing. Until more definite information is available regarding the spreading of jets by a hump, it is advisable to use the center-line dividing wall.

In order to force the jump downstream from the valves for a small valve opening the hump crest elevation must be at least at the river-bed elevation; otherwise, the tailwater would flood the valves. As the basin floor elevation will, in almost all cases, be lower than the river-bed elevation, the jump for larger discharges will form on the downstream side of the hump for the hump crest elevation equal to river-bed elevation.

A quiet stable hydraulic jump will form downstream from the hump crest for all combinations of discharge, provided the depth of jet entering the pool is relatively uniform.

Since the proper design of a hump basin has not been definitely established by model tests, no set of design rules will be given. The discussion merely outlines the features of the design which may be useful in attempting future designs without the aid of a model study. A complete investigation by model study of the hump basin in the future should prove useful in developing definite rules for designing the hump chute. The rectangular stilling basin can again be designed according to appendix I.

6. Design of impact basin. Figure 19C shows an impact type of basin with so much submergence that no jump is formed. This type of basin can also be used for no submergence, in which case a hydraulic jump forms against the gates. For the latter case, the basin should be designed the same as outlined for the chute basin with the chute section omitted. When the jump becomes submerged the basin remains essentially the same except that the dividing wall top elevation should be the same as the top of the outlet conduits, and an arrangement of larger blocks should be used as shown in figure 19C.

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