UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

HYDRAULIC MODEL STUDIES OF THE SIPHON AND FEEDER-CANAL TRANSITION FOR GRAND COULEE PUMPING PLANT--COLUMBIA BASIN PROJECT

Hydraulic Laboratory Report No. Hyd. 224

RESEARCH AND GEOLOGY DIVISION

BRANCH OF DESIGN AND CONSTRUCTION
DENVER, COLORADO

MARCH 11, 1949

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Laboratory Report No. 224
Hydraulic Laboratory
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Subject: Hydraulic model studies of the siphon and feeder-canal transition for Grand Coulee Pumping Plant--Columbia Basin Project.

PURPOSE OF STUDIES

The hydraulic model investigations described herein concern the development of an appropriate hydraulic structure for the outlet ends of the Grand Coulee Pumping Plant discharge lines where they empty into the feeder canal to the irrigation storage reservoir in the Grand Coulee.

CONCLUSIONS

The proposed straight 140-foot-long transition connecting the pump outlet structure to the feeder canal was too short to give smooth flow.

A transition 193 feet long and curved in plan to fit existing excavation was developed and found satisfactory.

The circular siphon outlet was the simplest to construct and had the lowest overall loss for a wider operating range than either the branching siphon or the floating radial gate.

The priming characteristics of the original circular siphon outlet were inadequate because at least six pumps would have to be operating at maximum capacity to provide enough tailwater to prime the siphons when the storage reservoir level is such that there will be no backwater effect on the flow in the canal.

The energy loss through the original circular siphon outlet was higher than necessary at low tailwater elevations.

A circular siphon outlet, capable of priming with a tailwater elevation in the feeder-canal transition corresponding to that for two pumps operating and with free flow at the end of the feeder canal, was developed. This siphon outlet design had a low energy loss for the full range of tailwater elevations.

The hydraulic losses, using the circular siphon outlet, will be no greater than the losses which would result from discharging the 12-foot-diameter pump lines directly into the bottom of the feeder-canal transition.

There will be no cavitation or separation in the water column in the siphon bend under normal operating conditions.

The 30-inch siphon vent systems will have sufficient capacity to prevent backflow in the pump lines for all operating conditions.

RECOMMENDATIONS

1. Use the longer and curved feeder-canal transition to connect the pump line outlet structure to the canal.

2. Use the circular siphon bend on the discharge ends of the pump lines.

3. Take special care during construction of the pump lines to obtain smooth continuous passages in the siphon bends so that irregularities will not exist to produce local discontinuities where cavitation and pitting might occur.

4. Provide a time delay for reclosing the siphon vents, once they have been opened, to allow the water column on the pump side of the siphon to reach a sufficiently low elevation that the vacuum produced by closing the vents too rapidly would not collapse the lines.

5. Install sufficient instrumentation in the prototype structure and make adequate field tests to determine the operating characteristics of the structure.

INTRODUCTION

Description of Prototype

The Grand Coulee Pumping Plant will be located on the west bank of Lake Roosevelt adjacent to the left, or west, abutment of Grand Coulee Dam, Figure 1. It will include 12 pumps, each having a maximum capacity of approximately 1,650 second-feet. Power for the pumps will be furnished by generators at Grand Coulee Dam, and it is planned to operate the pumps in pairs since two units will require the capacity of one generator. The water pumped by these units will discharge into individual 12-foot-diameter conduits to be raised 300 feet above Lake Roosevelt before being released into a feeder canal where it will flow 1.75 miles to the irrigation storage reservoir in the Grand Coulee. The maximum water surface in the storage reservoir will be at elevation 1570. The invert at the upstream end of the feeder canal will be at elevation 1548.65.

An arrangement was proposed in which the discharge ends of the pump lines would be submerged in the entrance structure to the feeder canal since this would insure the minimum pumping head for all pump combinations and storage reservoir elevations. A siphon bend or check gate was proposed for the exit of each discharge line to prevent return flow in the conduits when the pumps were not running. The minimum pumping head for a siphon can be realized only if the discharge line operates with no break in the water column and there is no accumulation of air in the crown of the siphon bend. Backflow in the design containing siphons was to be prevented by air valves which would open automatically to vent the crowns of the siphons when the pumps stopped. Backflow in the design using gates was to be prevented by the gates automatically lowering when flow in the normal direction ceased.

A transition structure was provided between the discharge ends of the 12 pump lines and the feeder canal to transfer the water smoothly f.om the wide outlet structure to the narrower feeder canal.

Scope of Model Tests

The model tests made to accomplish the hydraulic design of the pump line outlet structure and feeder-canal transition were concerned with four separate investigations which included the selection of the type of pump discharge outlets, the design of the transition from the pump line outlet structure to the feeder canal, the priming characteristics and energy losses of the selected siphon outlet, and the flow conditions in the siphon bend.

The three designs of pump line outlets studied on a 1:24-scale model to compare the head losses were:

a. A siphon with a flattened section at the high point which separated into two conduits before terminating in the canal transition (Figure 2-A).

b. A floating radial gate with an internal air chamber of sufficient size to cause the gate to float when the pumps were operating and water was flowing in the normal direction, and which would lower rapidly into the closed position to prevent loss of water from the storage reservoir when the pumps were stopped (Figure 2-B).

c. A siphon with a simple circular cross-section, easy to construct, and requiring a relatively narrow transition to the feeder canal (Figure 2-C).

The development of a design for the transition between the pump discharge outlets and the feeder canal was accomplished through investigations on a 1:24 model of the outlets and transition. The criterion was to obtain acceptable hydraulic flow conditions in the transition for any combination of pumps operating, from a minimum of 2 to a maximum of 10 pumps.

Improvements in the priming characteristics and the determination of energy losses for the selected siphon outlet design were accomplished through studies conducted on a 1 to 18 scale model containing the siphon bend, siphon outlet, and feeder-canal transition. It was essential that the outlet have a low energy loss and that the siphon flow full to obtain the minimum possible pumping head. Included in these studies were tests to verify the ability of the siphon vents to prevent backflow in the lines when the pumps were stopped.

It will be possible to develop a vacuum of 25.5 feet of water (6.5 feet of water absolute pressure at the damsite) in the crown of the prototype siphon under certain normal operating conditions. A 1 to 18 scale model was constructed with a transparent section in order to observe the flow conditions and determine whether cavitation or separation of the water column would occur at these conditions. The model was operated at prototype pressures and velocities for these studies.

INVESTIGATION FOR SELECTION OF PUMP DISCHARGE OUTLET DESIGN

Description of Model

Three types of controls for the outlets of the discharge lines were proposed by the Design Section for study in the hydraulic model (Figure 2).

The siphon, designated as Design 1 (Figure 2-A) was represented by a 1 to 24 scale model constructed from laminated plastic while those designated as Designs 2 and 3 (Figures 2-B and C) were represented by models of the same scale constructed of sheet metal.

The method used in the construction of the plastic model was novel. Sheet-metal templets representing cross-sections of the conduit at selected stations were mounted on a wooden saddle and a plaster mortar was filled and screeded between them to form a male mold (Figure 3-A). A plaster female mold was cast from the male mold, and it in turn was used to cast a hollow core, or second male mold, which was used as a form upon which to fabricate the final model. The form was wrapped first with plastic-impregnated glass cloth and then with a canvas dipped in a plastic solution. The plastic was cured under infra-red lamps and the hollow core broken and removed, leaving a hardened shell approximately

1/8-inch thick (Figure 3-B). This type of construction proved very satisfactory as it was accurate, lightweight, easy to install, and retained its shape despite its complexity.

The three models were connected to a supply manifold with their discharge flowing into a common tailbay having a gate for regulating the depth of the tailwater. They were arranged in this manner to facilitate comparison of hydraulic losses.

Piezometers were installed at corresponding locations in the three designs to obtain the overall head loss from the entrance to the exit. The rate of flow in each case was 0.567 cfs, corresponding to 1,600 cfs for the prototype. The tailwater depth at the entrance to the feeder canal was varied to represent various numbers of pumps in operation and water surface elevations in the Grand Coulee storage reservoir. The depths used on the model corresponded to those shown in Figure 4 for free flow at the downstream end of the canal and a roughness factor of N = 0.014. This curve was used since more severe flow conditions were obtained with the low tailwater elevations.

Selection of Type of Outlet for Pump Discharge Lines

The results of the tests conducted on the three models are shown graphically in Figure 5 where the overall head loss from the entrance manifold to the tailwater is plotted versus tailwater depth. The following table contains values from Figure 5, giving comparative head losses for the different designs.

Table 1

HEAD LOSSES FOR THE THREE DESIGNS OF OUTLET CONTROLS

No of pumps operating at 1,600 cfs	Discharge in cfs (prototype)	Tailwater Depth in: ft at headwall	Tailwater Elev in ft	Overall loss in ft of water (prototype) Design 1	Design 2 36,000 lb	Design 2 62,000 lb	Design 3
4	6,400	12.0	1560.7	1.4	2.6		1.1
6	9,600	15.0	1563.6	1.4	1.5	3.1	1.1
8	12,800	17.3	1565.9	1.4	1.1	1.9	1.1
10	16,000	19.3	1567.9	1.4	0.9	1.2	1.1
12	19,200	21.2	1569.8	1.4	0.8	0.9	1.1

Tests on Design 2 were made with two different model gates representing prototype structures weighing 36,000 and 62,000 pounds, respectively. The heavier model gave a higher loss, requiring a greater depth of water on the pump side to cause it to float.

Design 3 was selected for further investigations because of its simplicity of construction and higher operating efficiency over a wide range of water surface elevations in the canal.

INVESTIGATION OF FEEDER-CANAL TRANSITION

Description of Model

A 1:24 model of the original design, Figure 6-A, including 12 discharge outlets, the feeder-canal transition (tailbay), and a short length of the feeder canal, was constructed to study the flow conditions in the transition for various combinations of pumps in operation. The siphon bends were attached to a common head supply box. They were constructed of metal and terminated in a sheet-metal-lined wooden box in which the boundary surfaces of the transition and canal section were constructed of concrete. A hinged gate was installed at the end of the model for regulating the depth of water in the canal. Wooden blocks inserted in the upstream ends of the individual model conduits permitted a study of any desired pump combination.

Flow Conditions in Feeder-canal Transitions

The change in cross-sectional area in the original design of the feeder-canal transition was too rapid, inducing a high acceleration that resulted in a turbulent water surface (Figure 7). Since the widths at the entrance and the exit of the transition were fixed by the pump outlets and the canal cross-section, the only means of making the change in cross-section more gradual was to lengthen the transition. Additional field data obtained at this time indicated that the entire transition would need to be curved in plan to fit the alinement of the excavation already completed. The revised design was made about 50 percent longer than the original and curved to fit the excavation (Figure 6-B).

The water surface on the inside of the curve was still rough, but there was improvement over that for the straight transition. An attempt was made to improve the flow further by lessening the rate of convergence as shown in Figure 8 (recommended design). A slight improvement was obtained. Flow conditions for this design are shown on Figure 9. Because of the improvement in the flow characteristics and appearance of the structure, this design was recommended. The priming characteristics of the siphon were not investigated in this model due to the small size.

INVESTIGATION OF SIPHON OUTLET

Description of Model

To investigate the priming characteristics of the siphons a 1:18 scale model of the pump outlet structure was constructed, using a single pump line and outlet and the recommended design of the feeder-canal transition (Figure 10-A). Piezometers were placed in the walls of the pipe 53.6 inches (80 feet 6 inches prototype) upstream from the siphon crest and in the headwall of the feeder-canal transition (Stations 1 and 2, Figure 10-A). The siphon bend and a section of pipe immediately downstream were made of transparent plastic so the nature of the flow in this section of the structure could be observed. A window was placed immediately upstream from the low point in the crown of the outlet to permit observing the start of the priming action.

Priming Characteristics and Hydraulic Losses for Various Exit Designs

Model tests on the original circular siphon (Design 3, Figure 2-C) showed that a tailwater elevation of 1563.4 would be required in the full-sized feeder-canal transition to prime the siphons. This condition would not exist unless six pumps were operating at maximum discharge or there was a backwater effect from the storage reservoir. Failure of the siphons to prime would not permit operation at the minimum pumping head, because the water must then be elevated to the crest of the siphon at elevation 1571 instead of to the water surface elevation in the feeder canal. Therefore, changes in design would be necessary in order to make the siphons prime and obtain good efficiency when less than six pumps were operating.

The tests on Design 3 showed that a relatively low loss in energy occurred between Stations 1 and 2 when the tailwater elevation was sufficient to submerge the outlet opening. The loss increased rapidly as the tailwater decreased (Figure 10-G).

A series of designs was tested to obtain a siphon outlet which would prime at the lowest possible tailwater and have a minimum loss of energy. The width of the model siphon exit was maintained to represent 12 feet 4-1/2 inches to conform to the dimensions of the feeder-canal transition.

In Design 4 the discharge line at the upstream end of the siphon exit transition was lowered the equivalent of 6 feet. The elevation and height of the exit were the same as in Design 3 (shown by dotted lines on Figure 10-B). The siphon primed at a lower tailwater elevation (Figure 10-F), but there was an appreciable increase in energy loss (Figure 10-G), so further changes were made.

In Design 5 the slope of the downleg of the siphon was made 21°. The exit opening was lowered the equivalent of 6 feet 10 inches, and the divergence of the transition decreased to 7° (Figure 10-C). The exit height was made 16 feet 4 inches (prototype). The tailwater depth for priming was less than for either of the previous designs, and the energy loss at low tailwater was less than for Design 4. However, the tailwater depth required for priming was still greater than desired.

In Design 6 the floor at the exit was lowered to elevation 1539.29. The upward slope of the roof was made 1° and the slope of the floor was made 6° to produce a 7° divergent passage with an exit height of 16 feet 6 inches (prototype)(Figure 10-D). A further decrease in the overall loss was obtained at the lower tailwater elevations, and less tailwater was needed to start the priming (Figures 10-G and F). In fact, the tailwater elevation required to prime was slightly less than the water surface elevation in the feeder-canal transition when there was no backwater effect from the storage reservoir and only two pumps were operating.

Design 6 required that the floor of the feeder-canal transition be lowered in the vicinity immediately downstream from the pump line outlets. As this would necessitate additional excavation, it was desirable to determine a shape of the lowered section which would require the minimum excavation. The lowered portion of the feeder-canal floor was extended horizontally downstream from the headwall at the same elevation as the bottom of the siphon exit and was connected to the main floor of the transition by a 3:1 slope. Horizontal extensions of 8, 16, and 24 feet were tested. The 8-foot extension gave acceptable characteristics as to priming, and there was no apparent difference between the energy losses for the three extensions. Since it was structurally undesirable to make the extension shorter than 8 feet, this length was adopted for Design 6 and all subsequent designs.

As the performance of Design 6 was satisfactory and it was urgent that the final design be obtained so that rock excavation for the prototype structure could be completed on schedule, Design 6 was selected by the Canals Division for detailed structural studies. This design, incorporating revisions dictated by structural features, was later returned to the Hydraulic Laboratory for final testing and was designated Design 8 (final design). In the meantime, the test program was continued to determine whether additional performance improvements could be obtained for the higher tailwater elevations.

In Design 7 the slope of the transition floor was increased to 8° to form a 9° divergent passage with an exit height of 17 feet 8 inches (prototype). The energy loss was less than for Design 6, but there was a slight increase in the tailwater elevation required for priming the siphon (Figures 10-G and F).

Since the tests to this point indicated that further reductions in energy loss could be obtained by increasing the divergence of the siphon outlet, it was desirable to continue the tests. However, due to more urgent work and the necessity of making a final check of the revised version of Design 6 submitted to the laboratory by the Canals Division, it was not possible to complete the investigation until a later date.

In Design 9 (Design 8 being the revised version of Design 6 which is discussed subsequently), the siphon outlet floor was sloped downward at an angle of 11° making a 12° divergent passage with an exit height of 18 feet 10 inches (prototype). This increase in exit area resulted in the lowest energy loss of any design tested, while the priming characteristics remained the same as Design 6 (Figures 10-G and F).

Design 8 (Design 6 modified to meet structural conditions) differed from Design 6 in that the roof at the exit was lowered to elevation 1555.32, the slope of the outlet floor was increased to 9° and the flow passage was extended 7 feet downstream (Figure 10-E). Tests showed that Design 8 required less tailwater for priming than any other design, although not much less than for Designs 6 and 9. The energy loss was increased slightly over that of Design 6, possibly because of the increased length of the passage. Because of its good priming characteristics and acceptable energy losses, this design was retained as the final design.

Computations indicate that the losses incurred through the use of the circular siphon, with the final outlet design (Design 8), are no greater than the losses which would result from discharging the pump lines directly into the bottom of the feeder-canal transition.

Effectiveness of Siphon Vents for Preventing Backflow

The action of the siphon vents in breaking the siphonic action to prevent backflow when power to the pumps is interrupted was studied on the 1:18 model of the pump outlet structure (Figure 10-A and E). A circular plastic pipe with an inside diameter equivalent to 30 inches and a length equivalent to 52 inches was placed at the crown of the siphon. This vent, which was machined flat on the top, was opened and closed by sliding a metal plate coated with grease across the opening. Tests were made by establishing flow in the normal direction, stopping the supply pump, and then sliding the straight-edged plate across the vent to open it sufficiently to break the siphon. Time delays for opening the vent varying from nearly zero up to the time required for complete reversal of flow, and tailwater elevations varying from a minimum of 1555.5 to the maximum of 1571.0 were used. The studies indicated that the 30-inch vent systems would be capable of breaking the siphonic action under all conditions and would thus prevent backflow in the prototype lines whenever the pumps are stopped.

It is considered advisable to delay reclosing a vent, once it has been opened, to allow the column of water on the pump-side of the siphon to reach a sufficiently low elevation that the vacuum produced by closing a vent too rapidly will not collapse the line.

Computations indicate that it is possible for the pressure in the top of the siphon bend to reach approximately -30 feet of water gage should there be reverse flow and the relief valve fails to open.

INVESTIGATION OF SIPHON BEND

Description of Model

A 36°, 9', 8-inch-diameter bend, with a radius of 24 inches on the centerline, was formed from transparent plastic sheet and made geometrically similar to the design chosen for the high points of the Grand Coulee pump lines (Design 3, Figure 2-C). This model was mounted on the roof of the laboratory (Figure 11-A) to obtain the subatmospheric pressures which will be prevalent in the prototype. The model was supplied with water from a pump on the main floor (Figure 11-B). The rate of flow was regulated by a gate valve on the discharge side of the pump. The flow from the outlet of the siphon bend was returned to the sump approximately 30 feet below by a welded steel pipe. A valve on the lower end of the return line regulated the pressure in the plastic siphon bend. A pitot tube was inserted in the supply line to determine the amount of water flowing through the model. The pressure in the siphon bend was measured with a U-tube mercury manometer. Two piezometers were provided, one in the crown and the other in the invert of the line at the high point.

Pressure and Flow Conditions in Siphon Bend

The testing consisted of establishing various rates of flow through the plastic bend, varying the pressure within the bend and observing the type of flow in the transparent section. Observations were made for eight different velocities with pressures corresponding to those shown in the following table.

Table 2

SUMMARY OF VELOCITIES AND PRESSURES IN MODEL SIPHON BEND

Test No	Velocity ft per sec (model)	Q cfs (model)	Gage pressure at crown (in of hg)	Absolute pressure at crown ft of water
1	13.5	4.71	-20.5	4.8
2	11.1	3.87	-22.0	3.1
3	8.5	2.96	-23.0	1.9
4	5.8	2.02	-22.8	2.2
5	18.0	6.27	-15.4	10.5
6	17.1	5.96	-10.3	16.3
7	11.6	4.05	-22.2	2.8
8	15.4	5.38	-17.5	8.2

Air entrainment in the model was excessive during initial operation because the pump sump was too shallow and did not allow sufficient separation of the air from the water before recirculation. The model operation was improved by increasing the depth of the sump box and adding more baffles.

When one pair of the prototype pumps is operating with a total discharge of 3,200 second-feet, and there is free flow from the end of the feeder canal, the elevation of the water surface at the headwall of the feeder-canal transition will be about 1558.0. Considering atmospheric pressure to be 32.0 feet of water at the altitude of Grand Coulee Dam, a pressure of approximately -25.5 feet gage or 6.5 feet of water absolute may be expected at the top of the siphon bend (elevation 1583.5) if friction, bend, expansion, and exit losses and the force to change the direction of the flow are considered.

The magnitude of the absolute pressure at the high point of the siphon bend was considered to be of primary importance, and the testing was conducted with this factor in mind. During the testing, when water was flowing, it was noted that a lower absolute pressure existed at the crest than at the crown; for instance, in Test 8, Table 2, the pressure at the crest was -18.0 inches of mercury compared to -17.5 inches at the crown. As this condition was not expected on the full-size structure, the reason for its presence on the model was investigated and found to result from using prototype velocities in the more abruptly curved model bend.

The dynamic force effective on water flowing around a curve increases the pressure on the outside of the curve and reduces the pressure on the inside. Calculations of the pressure difference between the crown and the crest of the Grand Coulee Siphon based on an average velocity of 14.15 feet per second (prototype flow of 1,600 second-feet) and a bend with a radius to centerline of 36 feet was made using the assumptions that the velocity has a constant value throughout the cross-section, and that it varies inversely with the radius of curvature, similar to flow in a free vortex. The first assumption gave a pressure difference of 2.2 feet and the second, 1.64 feet. For actual flow conditions the pressure difference will be between these two values.

Two tests were made to check the calculated pressure difference between the crown and the invert. The model siphon was operated at pressures above atmospheric to facilitate this measurement, and the velocity was reduced as near the scale value of 3.33 feet per second as the pump controls would permit. The observed value of the pressure difference in each test was adjusted to correspond to a velocity of 3.33 feet per second (the equivalent of 14.15 feet per second prototype). Multiplying this difference by the scale ratio gave the prototype value of 1.74 feet of water for both tests. The absolute pressure at the crest of the siphon will be approximately 12 - 1.7 or 10.3 feet greater than at the crown.

The maximum velocity used in the model was 18 feet per second which was higher than that expected on the prototype. The model was operated with gage pressures at the crown ranging from -23 to -10 inches of mercury (2 to 26 feet of water absolute).

Particularly detailed observations were made in Test 8 since the pressure at the crown of the siphon and the mean velocity in the bend corresponded closely to those expected in the prototype. No irregularities of flow were noted except that small bubles of entrained air caused a slight cloudiness of the water. The bubbles, however, moved as part of the flowing stream and showed no tendency to accumulate in the crown of the bend.

No separation of the water column was evident at any pressure greater than 3.1 feet of water absolute. At this pressure separation was first indicated by the formation of a cavity or vapor pocket at the point where the supply pipe joined the transparent section. This pressure is 3.4 feet of water lower than the minimum pressure which will occur in the crown of the siphon bend under normal operating conditions.

The discontinuity at the joint in the model caused more disturbance in the flow than would be possible in the prototype if the concrete surfaces are smooth and continuous. Separation should not occur in the prototype if such surfaces are obtained.

When the pressure at the crown of the siphon was reduced to 3 feet of water, absolute, the cavity enlarged but did not form and collapse in typical cavitation manner or cause pulsation. When the pressure was reduced as much as possible in the model, the flow through the siphon bend resembled the flow over a broad-crested weir.

Water naturally has some air in solution which may collect in excessive amounts at points of low pressure if conditions for its removal by entrainment are not favorable. Such an accumulation in a siphon bend will increase the pumping head. The model data for both the scale and prototype conditions indicated that air would not accumulate in the prototype siphon. Other information indicates that air will accumulate and should be removed by external means if a minimum pumping head is to be realized. This information is included in Appendix I of this report.

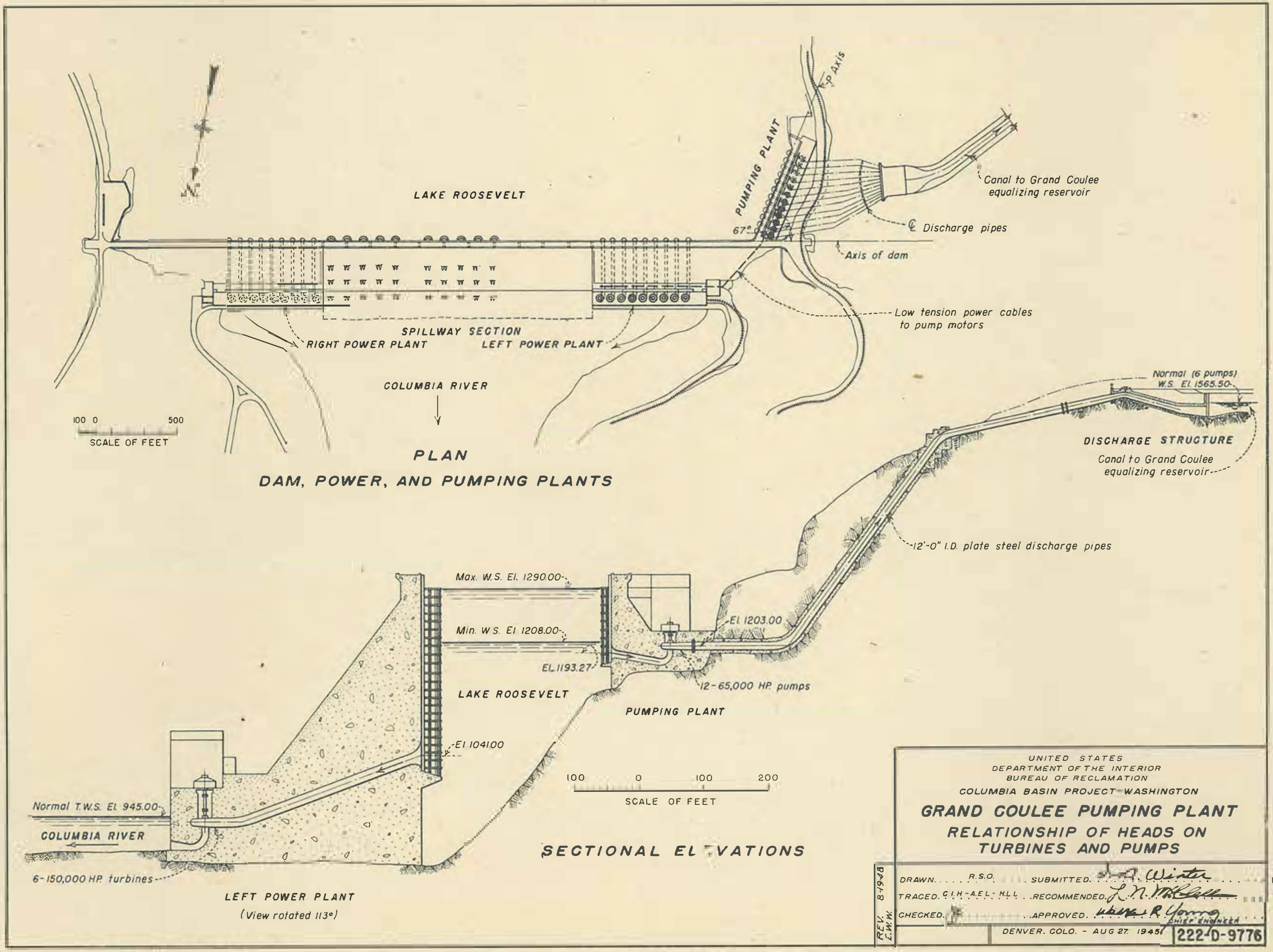
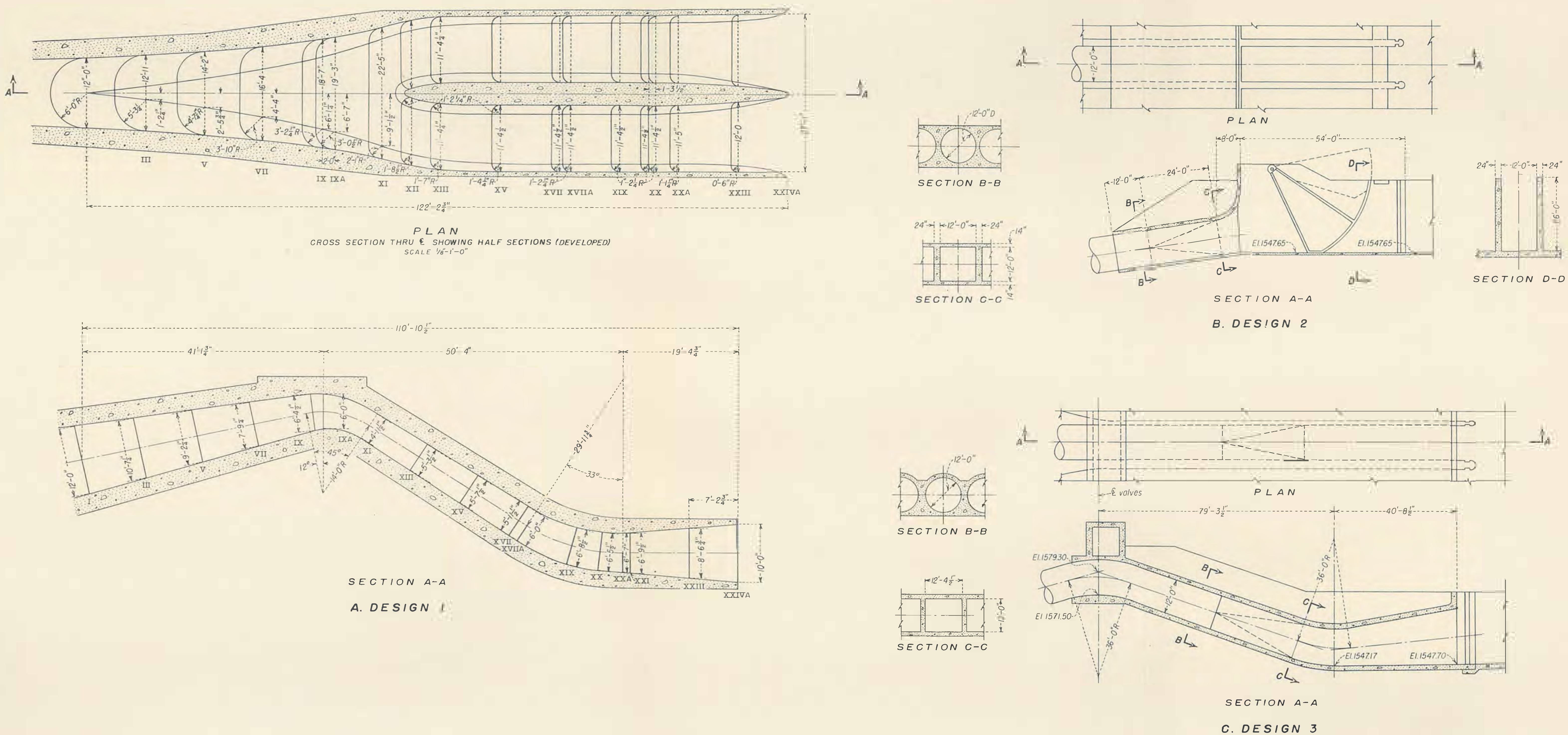
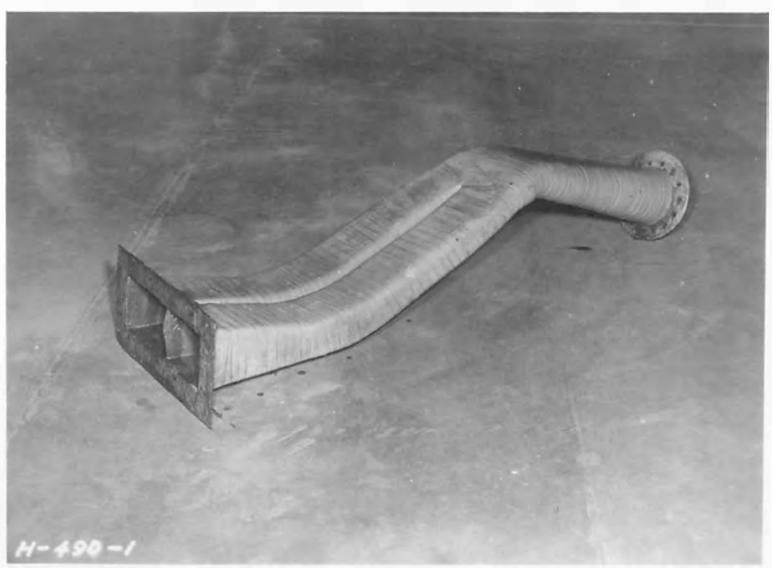

LAKE ROOSEVELT
N
PUMPING PLANT
P. Axis
67°
Canal to Grand Coulee equalizing reservoir
℄ Discharge pipes
Axis of dam
Low tension power cables to pump motors
SPILLWAY SECTION
RIGHT POWER PLANT
LEFT POWER PLANT
COLUMBIA RIVER
100 0 500
SCALE OF FEET
PLAN
DAM, POWER, AND PUMPING PLANTS
Normal (6 pumps) W.S. El. 1565.50
DISCHARGE STRUCTURE
Canal to Grand Coulee equalizing reservoir
12'-0" I.D. plate steel discharge pipes
Max. W.S. El. 1290.00
Min. W.S. El 1208.00
El. 1203.00
El. 1193.27
LAKE ROOSEVELT
12-65,000 HP. pumps
PUMPING PLANT
El 1041.00
100 0 100 200
SCALE OF FEET
Normal T.W.S. El 945.00
COLUMBIA RIVER
6-150,000 HP. turbines
LEFT POWER PLANT
(View rotated 113°)
SECTIONAL ELEVATIONS
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLUMBIA BASIN PROJECT–WASHINGTON
GRAND COULEE PUMPING PLANT
RELATIONSHIP OF HEADS ON
TURBINES AND PUMPS
DRAWN. R.S.O. SUBMITTED.
TRACED. G.I.H.-A.E.L.-H.L.L. RECOMMENDED.
CHECKED. APPROVED. CHIEF ENGINEER
REV. L.W.W. 8-1948
DENVER, COLO. – AUG 27, 1945
222-D-9776

FIGURE 1



PROPOSED DESIGNS
FOR
OUTLETS OF GRAND COULEE
PUMPING PLANT DISCHARGE PIPES
MAY 14, 1946

A. Pattern for model.

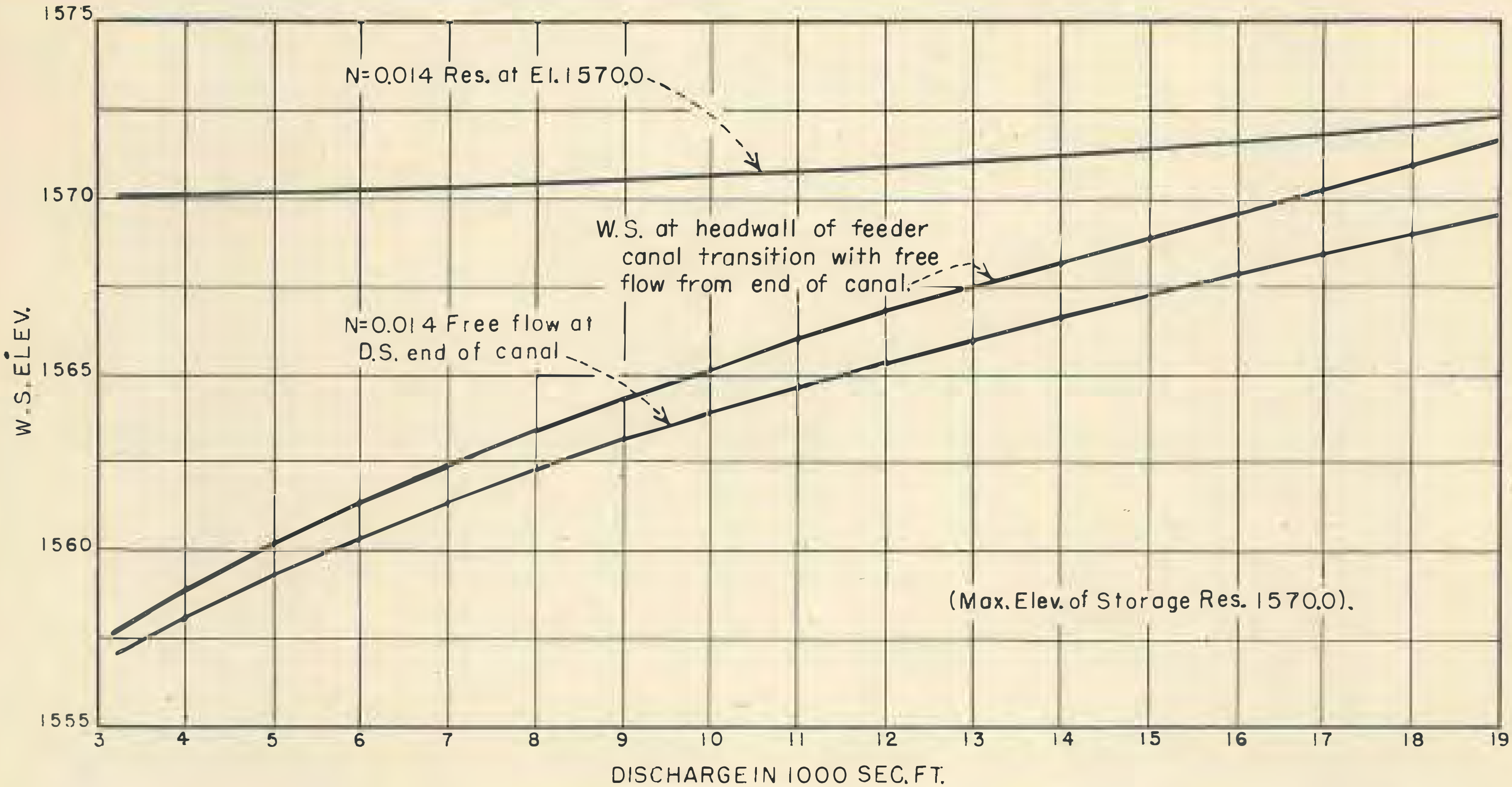


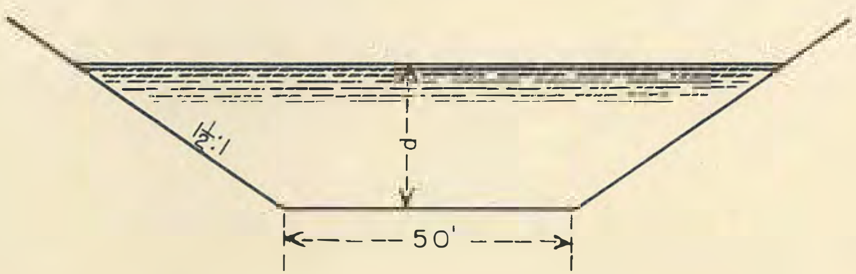
B. Completed model.

Plastic model of Grand Coulee Pumping Plant siphon outlet.

Design No. 1, Branching type.

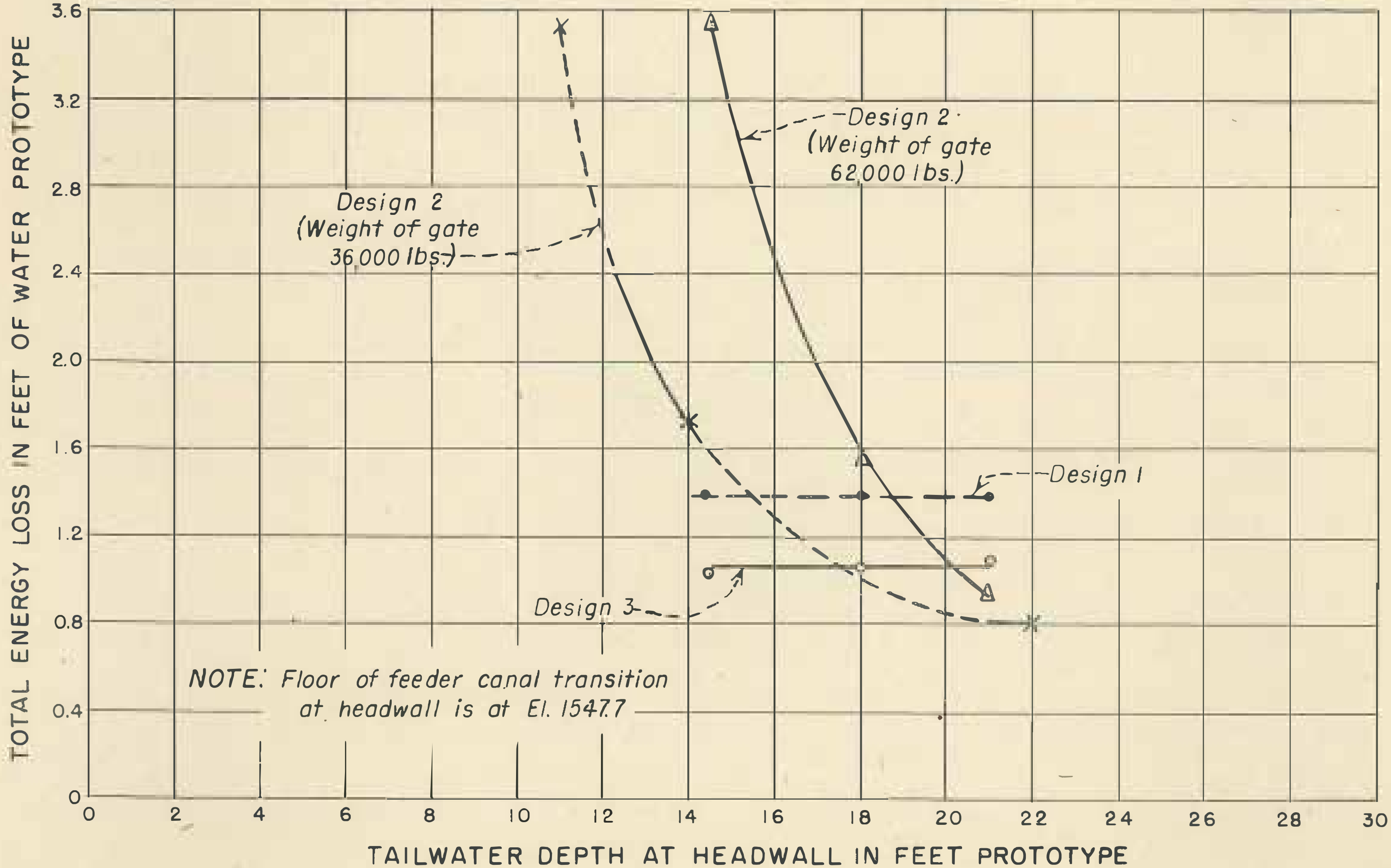
Scale 1 to 24.





COLUMBIA BASIN PROJECT
GRAND COULEE PUMPING PLANT
FEEDER CANAL WATER SURFACE STA. 0+00
GRADE ELEV.=1548.65

FIGURE 4



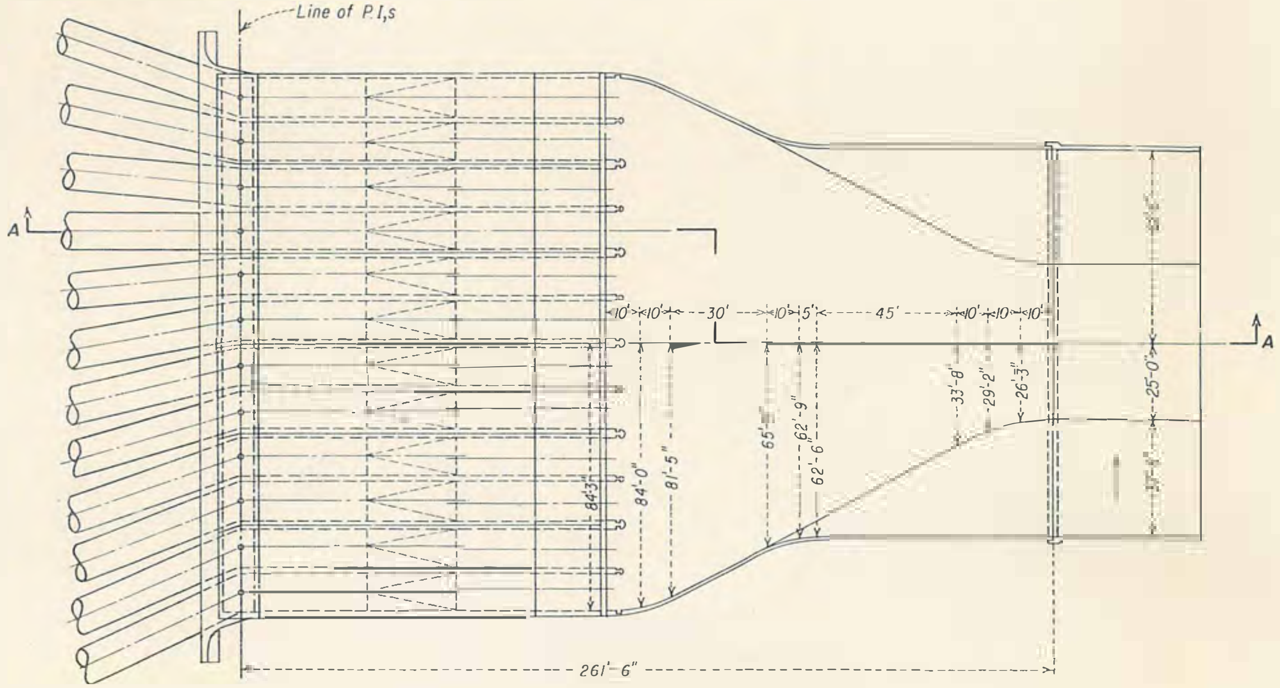
COLUMBIA BASIN PROJECT

GRAND COULEE PUMPING PLANT

LOSSES IN PROPOSED OUTLET DESIGNS

F.L. 7-25-46

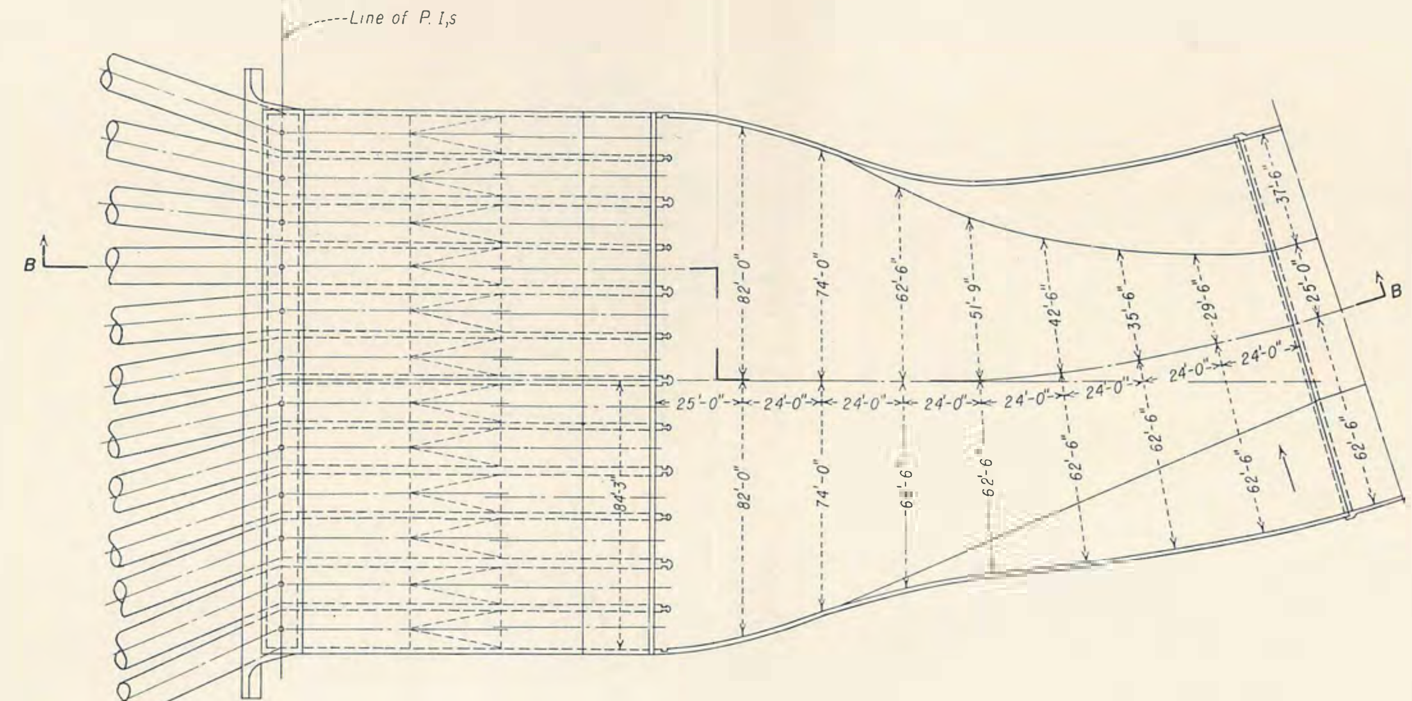
FIGURE 5



PLAN

SCALE 1" = 30'

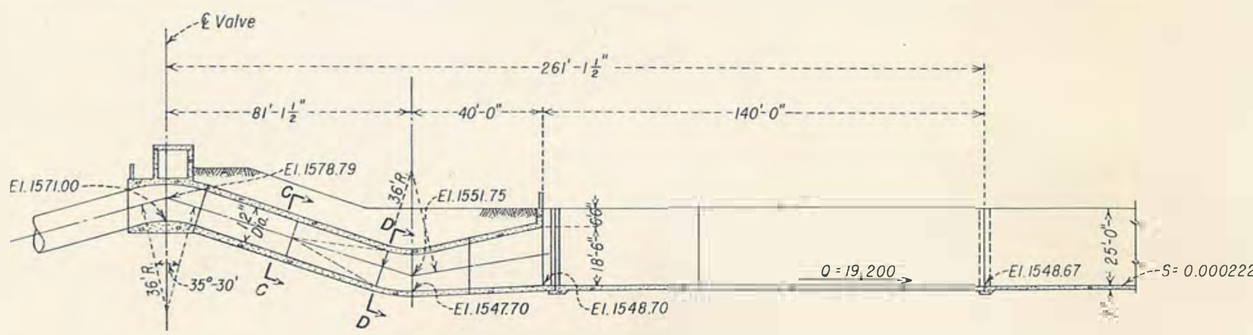
A. ORIGINAL DESIGN



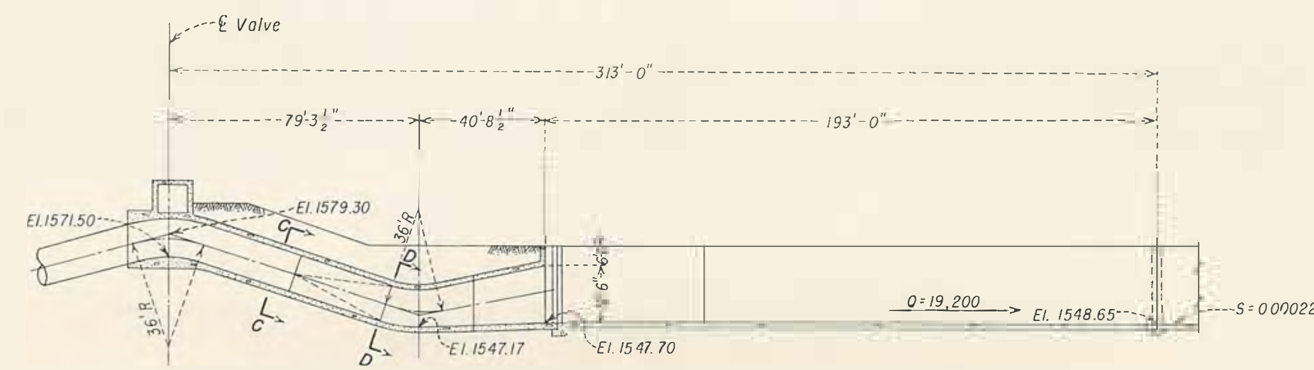
PLAN

SCALE 1" = 30'

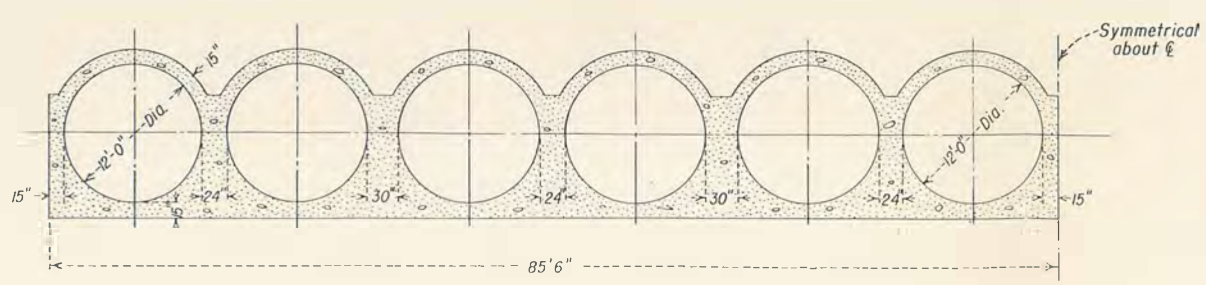
B. REVISED DESIGN I



SECTION A-A TUNNEL P-9

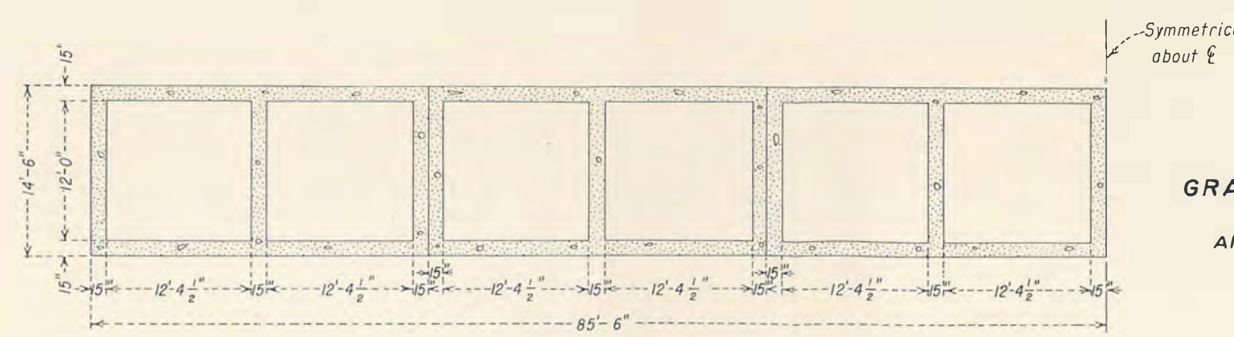


SECTION B-B TUNNEL P-9



SECTION C-C

SCALE ⅛" = 1'-0"



SECTION D-D

SCALE ⅛" = 1'-0"

COLUMBIA BASIN PROJECT

GRAND COULEE PUMPING PLANT

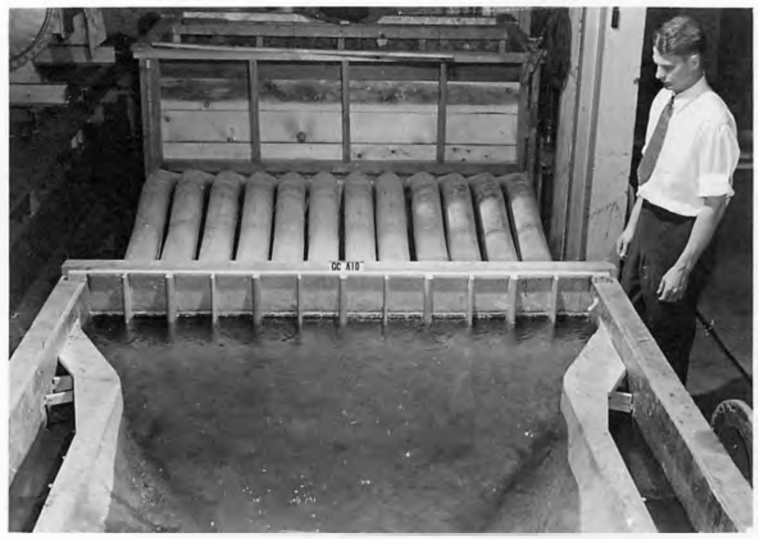
PUMP DISCHARGE OUTLETS
AND FEEDER CANAL TRANSITION

MAY 9, 1946

A. Model arrangement showing discharge pipe exists and transition to canal.

B. Four center units discharging 1,600 cfs. each.

C. Six center units discharging 1,600 cfs. each.

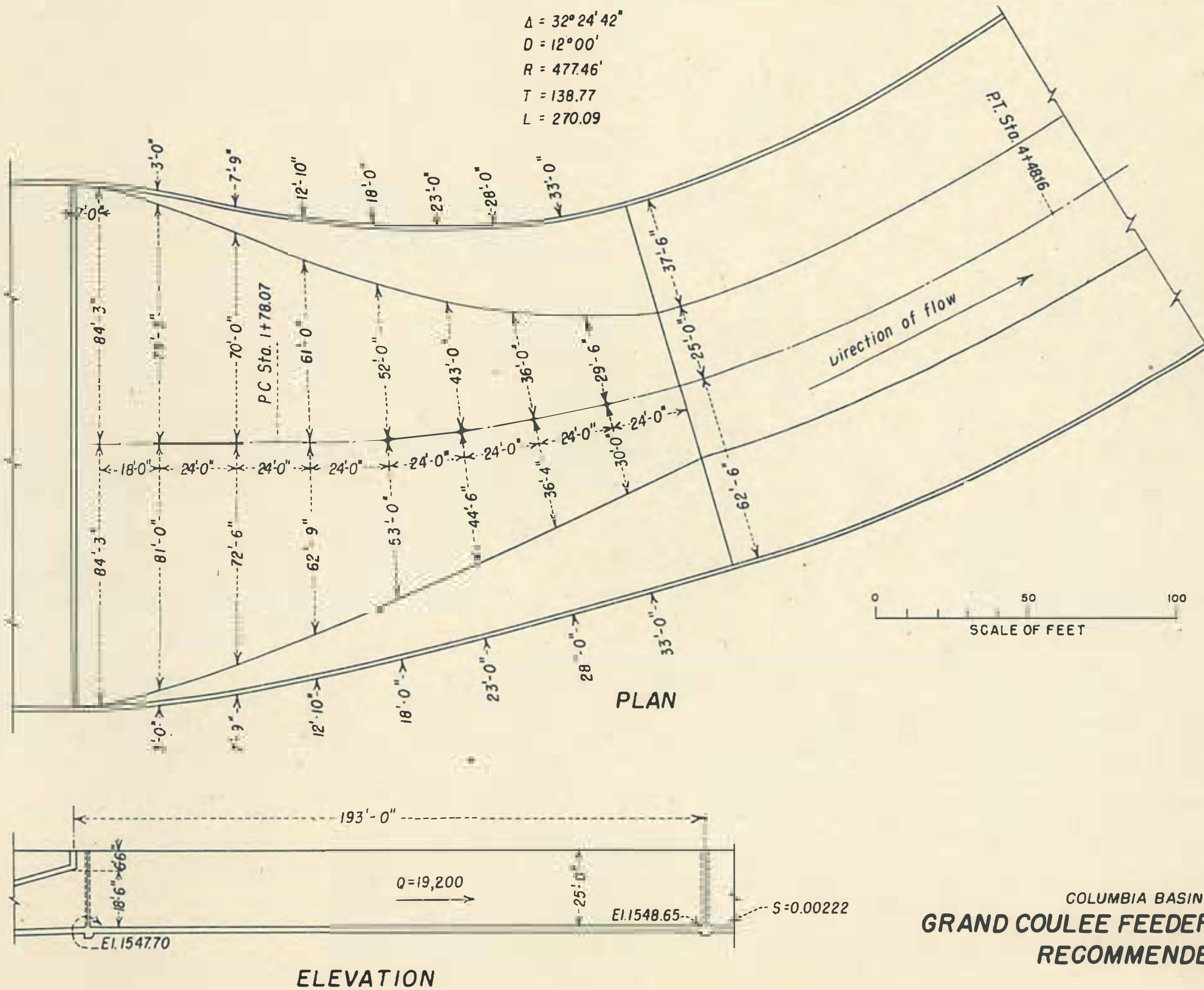


D. Ten center units discharging 1,600 cfs. each

Flow conditions in model of original design of Grand Coulee Feeder canal transition.

Scale 1 to 24.

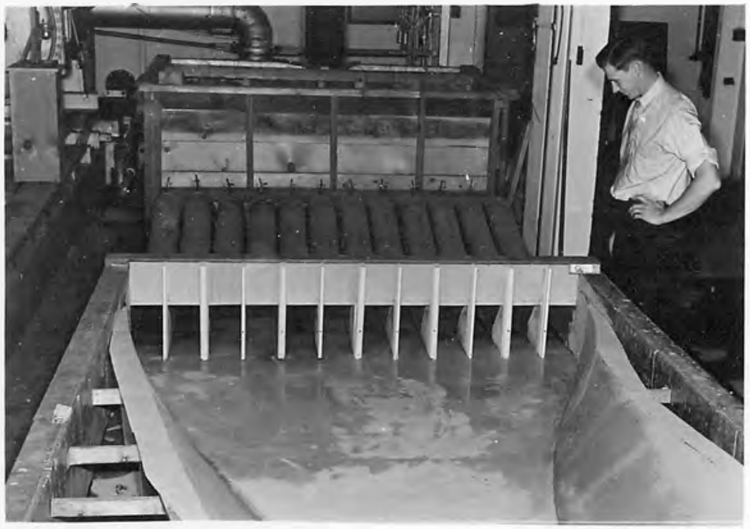
Figure 7



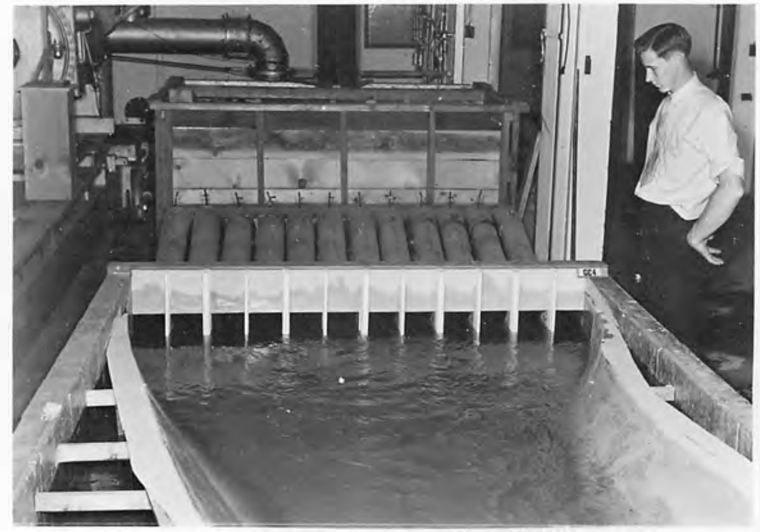
COLUMBIA BASIN PROJECT

GRAND COULEE FEEDER CANAL TRANSITION
RECOMMENDED DESIGN

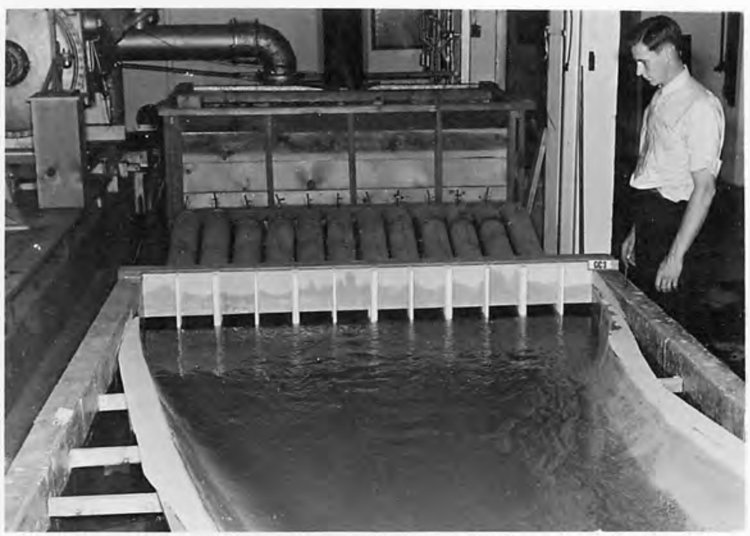
FIGURE 8



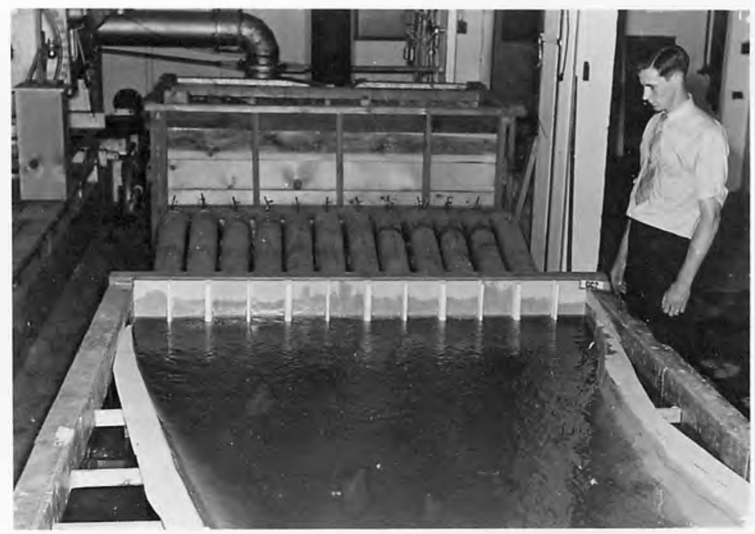
A. Model arrangement showing discharge pipe exists and transition to canal.



B. Four center units discharging 1,600 cfs. each.



C. Six center units discharging 1,600 cfs. each.



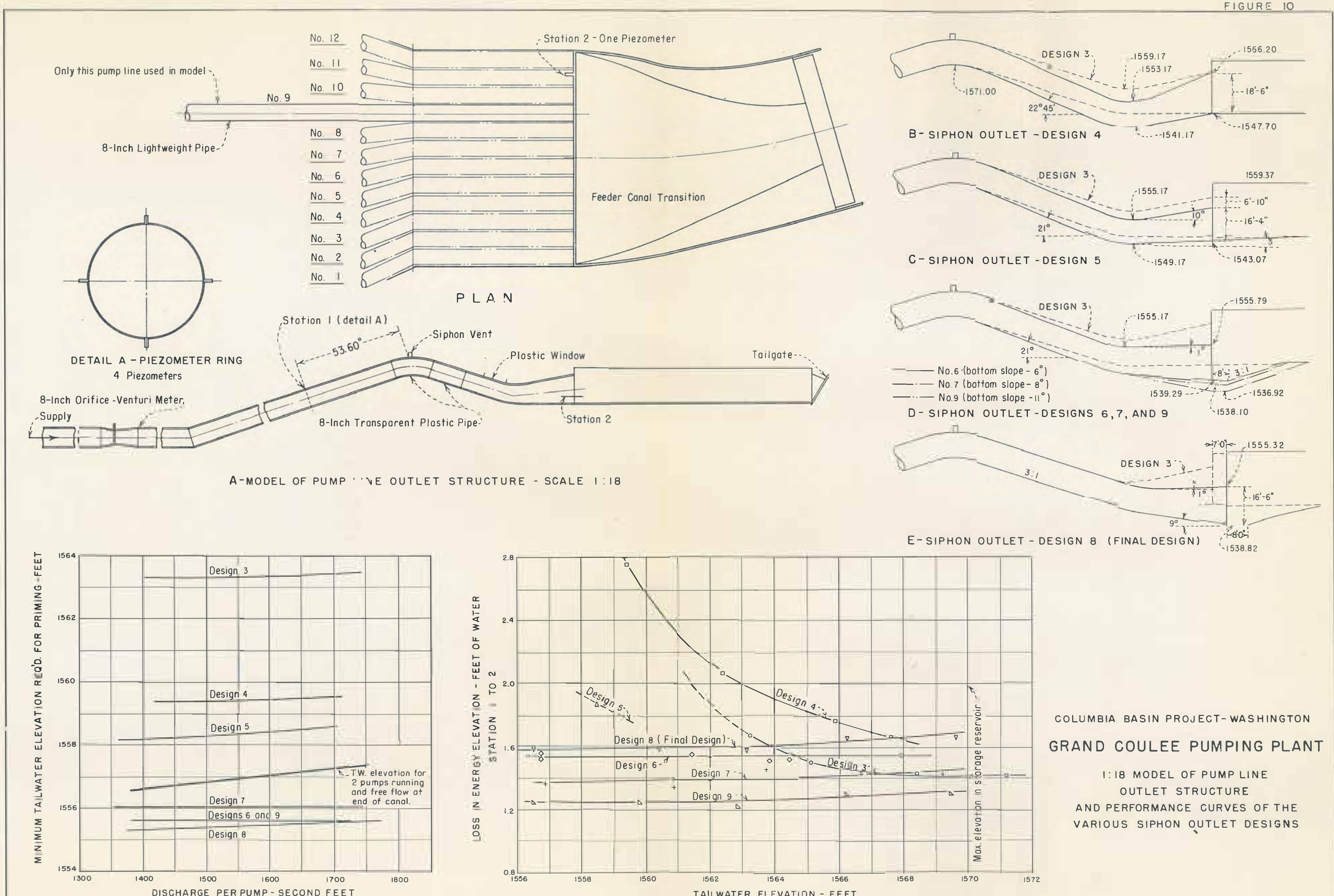
D. Ten center units discharging 1,600 cfs. each.

Flow conditions in Revised Design of Grand Coulee feeder canal transition.

Scale 1 to 24.

Figure 9

FIGURE 10



A-MODEL OF PUMP LINE OUTLET STRUCTURE - SCALE 1:18

B- SIPHON OUTLET - DESIGN 4

C- SIPHON OUTLET - DESIGN 5

D- SIPHON OUTLET - DESIGNS 6, 7, AND 9

E- SIPHON OUTLET - DESIGN 8 (FINAL DESIGN)

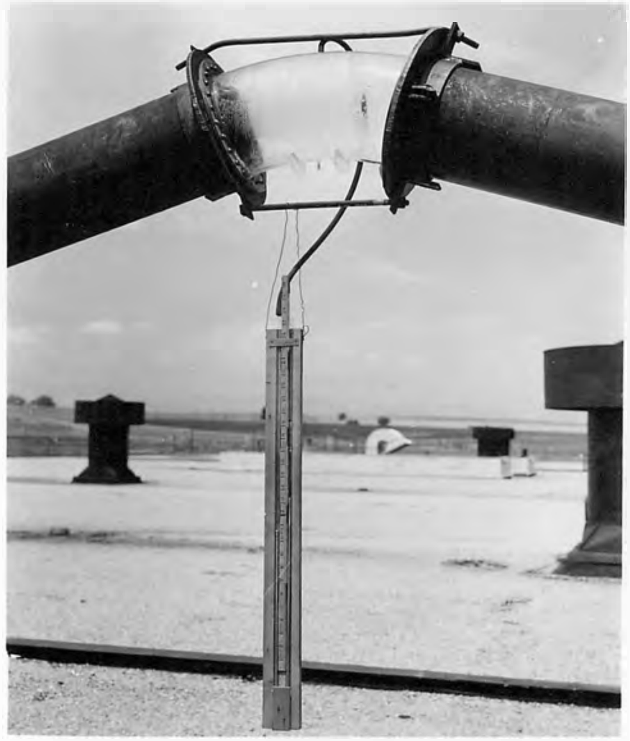
F-TAILWATER ELEVATION REQUIRED FOR PRIMING THE VARIOUS SIPHON OUTLET DESIGNS

G-LOSS IN ENERGY ELEVATION BETWEEN STATION 1 AND 2, COMPARED TO TAILWATER ELEVATION IN THE FEEDER CANAL TRANSITION. DISCHARGE = 1600 SECOND-FEET PER PUMP

COLUMBIA BASIN PROJECT- WASHINGTON

GRAND COULEE PUMPING PLANT

1:18 MODEL OF PUMP LINE OUTLET STRUCTURE AND PERFORMANCE CURVES OF THE VARIOUS SIPHON OUTLET DESIGNS



A. Transparent model of siphon bend.

B. Circulating pump and water supply piping.

Model of Grand Coulee Pumping Plant discharge line siphon bend.

Scale 1 to 18.

Appendix

ACCUMULATION OF AIR IN SIPHON BEND
GRAND COULEE PUMPING PLANT

Denver, Colorado

April 2, 1948

To: L. K. Maires and W. G. Weber

From: John Parmakian

Subject: Rate of Air Accumulation at the Siphon Outlets at Grand Coulee, Granby, and Tracy Pumping Plants.

1. Introduction

The purpose of the following study was to determine the rate at which air can accumulate at the crests of the siphon outlets at Grand Coulee, Granby, and Tracy Pumping Plants. A search of the available engineering literature on this subject has indicated that except for a few isolated installations very little factual data exists. Recently tests were conducted by the Hydraulic Laboratory[1/] on a siphon which was made out of 8 inch diameter pipe. These tests indicated that when the velocity of water in the pipe was in excess of about 4 feet per second the siphon cleared itself of any air which tended to accumulate at the siphon crest. Since the velocity of water in the discharge lines in the pumping plants which are under study will nearly always be in excess of 4 feet per second it can be erroneously concluded that in view of the test data on the siphon model, air cannot accumulate at the siphon crests in the actual pumping plants.

In the following paragraphs a discussion of an analytical method of computation will be given for determining the rate at which air may be separated from the water at the crest of the siphon outlets. A discussion will also be given for the conditions which must be present in the pipe line in order for the siphon to clear itself of any air which may be separated from the water.

2. Air Separation at Pump Impeller

When a pipe line is supplied by a centrifugal pump there is initially a physical distrubance in the flow of water at the pump impeller which causes air to be extracted from the water near the pump. This type of disturbance usually causes many small bubbles of air of various sizes to form. Due to the buoyancy of air in water these air bubbles will rise vertically in the pipe as the column of water with the air bubbles moves toward the siphon. During the time that it takes the water column to reach the siphon, part of the air bubbles will be redissolved in the water and part of the air bubbles will rise to the top of the pipe to form a series of larger bubbles. These larger bubbles will then move with

1/ The report on these tests has not yet been published. The data pertaining to these tests was obtained from J. W. Ball of the Hydraulic Laboratory.

the water column toward the siphon. If the siphon is not a self clearing one, the air bubbles will accumulate at the siphon crest. Unfortunately, the rate at which air is removed from the water at the pump impeller is unknown as far as the writer has been able to determine so that the rate of accumulation of air at the siphon crest cannot be accurately estimated.

3. Air Separation at the Siphon Outlet Due to a Reduction in the Pressure

It appears to be an established fact that the amount of air which can be dissolved in water is expressed with sufficient accuracy by Henry's Law for gases.[1] Briefly, according to this Law, the amount of air which can be dissolved in the water depends upon the partial pressure of the air which is in contact with the water surface. Thus as the air pressure increases the amount of dissolved air also increases. In the case of a pump line installation, water is drawn from a canal or reservoir in which the surface air pressure is essentially atmospheric pressure. When the water column in the pipe reaches the siphon, the water and air pressure in the pipe will drop below atmospheric pressure. Inasmuch as the amount of dissolved air is dependent upon the pressure inside the pipe there will be an immediate elimination of air at the siphon which will result in the formation of minute air bubbles. This phenomena has been observed in transparent pipe models where the air bubbles are discernible only as a milky hue in the water. The velocity of ascent of these small bubbles is about 2 inches per second.[2]

Since the water which passes through the siphon is exposed to the sub-atmospheric pressure for a short time, only that portion of the water column near the top of the pipe will evacuate air into the siphon crest. For the most part, after the water column passes the crest of the siphon, the remainder of the minute air bubbles which have not yet reached the top surface will be carried down by the vertical component of the water velocity and will be redissolved in the water as the pressure in the pipe returns to atmospheric pressure.

A determination of the rate of air separation at the siphon crest due to the reduction in pressure has been made on the physical basis which is described above. The results of these computations are shown in the tabulation on the next page. Note that when there is more than one pump on a discharge line these computations show that an increase in the flow in the discharge line reduces the length of time that the water column is under

1/ See "Chemical Engineers' Handbook", Second Edition, Page 1122.

2/ See "Water Power", by Joseph P. Frizell, Page 477.

MAXIMUM RATE OF AIR SEPARATION IN CUBIC FEET PER

SECOND MEASURED AT ATMOSPHERIC PRESSURE DUE

TO REDUCTION IN PRESSURE AT THE SIPHON

No. of Pumps Operating	Grand Coulee Pump. Plant 1/ (water temp. = 59° F)	Granby Pump. Plant 2/ (water temp. = 45°F)	Tracy Pump. Plant 3/ (water temp. = 65°F)
1	0.65	0.31	0.46 4/
2	1.30	0.24	0.82 4/
3	1.95	0.16	0.78 4/
4	2.40		0.47
5	2.65		0.31
6	2.94		0.21
7	3.15		
8	3.20		
9	3.24		
10	3.30		
11	3.30		
12	3.24		

1/ Data on the minimum canal watersurface elevations in the Feeder Canal at Grand Coulee Pumping Plant was furnished by L. K. Maires. This Pumping Plant has 12 discharge lines with one pump on each discharge line.

2/ The minimum canal water surface elevation in the canal at Granby Pumping Plant is controlled by the water surface elevation in Shadow Mountain Reservoir. This Pumping Plant has 3 pumps and one discharge line.

3/ Data on the minimum canal water surface elevation in Delta Mendota Canal was furnished by H. K. Brickey. This Pumping Plant has two pumps on each of three discharge lines.

4/ This value applies for 1 pump operating on each of the discharge lines sub-atmospheric pressure and in spite of the increased flow of water there is actually a reduction in the rate of air separation.

4. Maximum Rate of Air Separation at the Siphon Outlets Due to the Combined Effects

In order to obtain an estimate of the maximum rate at which air tends to separate at the siphon crest due to the reduction in pressure and also due to the action of the pump impeller, the maximum values given in the above tabulation will be arbitrarily increased by 50 percent.1/ Then the estimated maximum rate of air which will tend to separate at the siphon is as follows:

For Grand Coulee Pumping Plant - - - 4.95 cubic feet per second
For Granby Pumping Plant - - - - - - 0.47 cubic feet per second
For Tracy Pumping Plant - - - - - - 1.23 cubic feet per second

5. Rate of Air Removal in a Pipe Line

A published account2/ on the removal of air from pipe lines by flowing water indicates that for a pipe line of a given slope the air removal capacity of flowing water depends on the value of $\frac{V^2}{g D}$ where:

V is the velocity of water in feet per second,
g is the acceleration of gravity in feet per second per second,
D is the diameter of the pipe in feet.

The minimum water velocity for complete air removal has also been determined from other tests3/ as $V = 5.5 \quad D$. Inasmuch as the air removal capacity which is defined by the two relations above also appears to check the results of the tests which were conducted by the Hydraulic Laboratory, these relations will be used in this study. From the data which is given above the minimum velocity of water which is required for a siphon to clear itself of all air which may be separated from the water is then as follows:

8" diameter pipe (Laboratory Test Model)	= 4.5 ft/sec
12' diameter pipe (Grand Coulee Pumping Plant)	= 19.1 ft/sec
11' diameter pipe (Granby Pumping Plant)	= 18.2 ft/sec
15' diameter pipe (Tracy Pumping Plant)	= 21.3 ft/sec

1/ Such an approximation for accounting for the effect of the pump impeller was suggested, in an article, "Important Factors in the Design and Operation of Siphons", by J. W. MacMeeken, published in Byron-Jackson News Letter, July 15, 1931.

2/ See "Removal of Air from Pipe Lines by Flowing Water", by A. A. Kalinske and Percy H. Bliss, published in Civil Engineering, October, 1943.

3/ See article by J. W. MacMeeken given in footnote 1/

The air clearing capacity of each of the 4 pipe sizes may then be expressed as a percentage of complete clearing capacity as follows:

8" dia. pipe for the experimental pipe (V_{min} = 4.5 ft/sec) = 100%
12' dia. pipe for Grand Coulee Pump. Plant (V_{min} = 9.46 ft/sec) = 24.5%
11' dia. pipe for Granby Pumping Plant (V_{min} = 2.15 ft/sec) = 1.4%
15' dia. pipe for Tracy Pumping Plant (V_{min} = 4.34 ft/sec) = 4.2%

From a study of the values given in this tabulation it is apparent that siphons in small diameter pipes can carry off larger proportions of air than siphons in large diameter pipes. It can also be seen that the effect of air removal due to the flow of water in the pipe at The Granby and Tracy Pumping Plants is negligible. However, at the Grand Coulee Pumping Plant the effect of air removal is appreciable and must be taken into account.

6. Maximum Rate of Air Accumulation at the Siphon Outlets

After including the effect of the air removal capacity of the water the maximum rate of air accumulation at the siphon crests is as follows:1/

At Grand Coulee Pumping Plant - - - - - 3.8 cubic feet per second
At Granby Pumping Plant - - - - - - - - - 0.5 cubic feet per second
At Tracy Pumping Plant - - - - - - - - - 1.2 cubic feet per second

7. Comments

It is believed that the results given in the above tabulation are of the proper order of magnitude. In view of the fact that the results were obtained by deduction alone no pretense of extreme accuracy is implied. If the apparatus for removing the accumulated air is not used, an air pocket will form at the siphon crests at each of the three pumping plants. The volume of this air pocket will increase until a water velocity of about 18 feet per second is attained past the air pocket. Thereafter this higher velocity will prevent a further enlargement in the volume of the air pocket. For the case of Grand Coulee Pumping Plant the head loss due to the presence of such an air pocket will be about 0.5 foot. Such a head loss would require an additional power input of about 100 horsepower at each pump motor. Hence it is apparent that the use of a suction pump or similar device for evacuating the air will be very profitable.

1/ Measured at atmospheric pressure.

8. Personnel

These computations were checked by Leo Krisl. Assistance was also obtained from J. L. Gilliland of the Chemistry Laboratory.[1]

(Sgd.) John Parmakian

1/ See Memorandum to John Parmakian by J. L. Gilliland, dated March 22, 1948, subject, "Solubility of air in water - Grand Coulee Pumping Plant, Columbia Basin Project."

Denver, Colorado
March 22, 1948

To: John Parmakian

From: J. L. Gilliland

Subject: Solubility of air in water - Coulee Pumping Plant, Columbia Basin Project.

1. In accordance with your request, the following calculations have been made to show the amount of gas dissolved in the water at the intake and at the top of the siphon of the Coulee Pumping Plant under equilibrium conditions.

2. In making these calculations, certain assumptions were necessary, the first of these being that the amount of dissolved air at the intake equals the amount dissolved at the reservoir surface at equilibrium. All solubility calculations are based on Henry's Law

$$P = HX$$

where

P = partial pressure of gas in gas phase

H = Henry's law constant

X = mol fraction of dissolved gas

The following values of Henry's Law Constant were used (pressure in mm Hg - temp 15° C):

$O_2 = 2.766 \times 10^7$

$N_2 = 5.606 \times 10^7$

3. The amount of air in solution at the intake is as follows:

Basis: 1000 cu ft H_2O = 3460 mols.

Vapor pressure H_2O @ 15° C = 12.8 mm

Air = 79% N_2, 21% O_2

For N_2 from Henry's Law

$$(760 - 12.8).79 = 5.606 \times 10^7 \times \frac{X}{3460}$$

X = .03642 mols. N_2

For O_2

$$(760 - 12.8).21 = 2.766 \times 10^7 \times \frac{X}{3460}$$

$$X = .01963 \text{ mols. } O_2$$

Total dissolved gas = .03642 + .01963 = .05605 mols.

Since 1 mol. occupies 359 cu ft at 0° C, 760 mm, the volume of dissolved gas at 15° C is:

$$.05605 \times 359 \times \frac{288}{273} = 21.2 \text{ cu ft}$$

4. Because of the differing solubility of the two gases, they will go into solution at different rates, and be expelled at different rates. Therefore, in order to determine the volume of gas expelled at the top of the siphon, it is necessary to set up a series of equations for simultaneous solution.

Basis - 1000 cu ft H_2O = 3460 mols.

- 15° C

Let X = partial pressure of O_2 in gas phase

Y = partial pressure of N_2 in gas phase

a = mols of O_2 in gas phase

b = mols of N_2 in gas phase

Assume the total pressure at the top of the siphon to be 310 mm absolute (20 ft. vacuum). This pressure is the sum of the partial pressures of O_2, N_2, and water vapor (13 mm):

Therefore:

$$X + Y + 13 = 310$$

or

$$X = 297 - Y \quad \text{-----------------} \quad (1)$$

From the gas laws

$$PV = NRT \qquad \text{or} \qquad \frac{V}{RT} = \frac{N}{P}$$

At a constant temperature, each gas occupies the total volume at its partial pressure, or $\frac{N_{O_2}}{P_{O_2}} = \frac{N_{N_2}}{P_{N_2}}$

or $\frac{a}{X} = \frac{b}{Y}$

and $\frac{a}{297 - Y} = \frac{b}{Y}$

and $b = \frac{aY}{297 - Y}$ - - - - - - - - - - - - - - - - (2)

Now, using Henry's Law as in Paragraph 3:

For O_2

$297 - Y = 2.766 \times 10^7 \times \frac{.01963 - a}{3460}$ - - - - - - (3)

and for N_2

$Y = 5.606 \times 10^7 \times \frac{.03642 - b}{3460}$ - - - - - - - - - - - (4)

From equation (3)

$a = \frac{Y - 140}{7990}$ - (5)

From equations (4) and (2), then substituting

$\frac{Y - 140}{7990}$ for a

$887\ Y - Y^2 = 17.52 \times 10^4 - 1.62 \times 10^4\ ay$

$= 175{,}200 - 16200\ Y\left(\frac{Y - 140}{7990}\right)$

$Y^2 + 571\ Y - 166{,}800 = 0$

$Y = 213$ mm (part. press. N_2)

$\therefore X = 297 - 213 = 84$ mm (part press. O_2)

$\therefore a = \frac{73}{7990} = .00913$ mols O_2

$\therefore b = \frac{213 \times .00913}{84} = .0231$ mols N_2

Therefore the total mols stripped

$= .00913 + .0231 = .03223$

At 15° C and 747 mm pressure the stripped gas would occupy

$$\frac{760}{747} \times .03223 \times 359 \times \frac{288}{273} = 12.4 \text{ cu. ft.}$$

Or at 297 mm

$$.03223 \times \frac{760}{297} \times 359 \times \frac{288}{273} = 31.2 \text{ cu. ft.}$$

5. From these calculations it appears that if all the gas to equilibrium comes out of solution, 12.4 cu. ft. (measured at atmospheric conditions) will have to be removed per 1000 cu. ft. of H_2O.

(Sgd.) J. L. Gilliland

Denver, Colorado

July 18, 1948

Memorandum

To: W. G. Weber

From: D. J. Hebert and C. R. Daum

Subject: Rate of air accumulation resulting from unsaturation of the water in the outlet siphons--Grand Coulee Pumping Plant--Columbia Basin Project.

1. Reference is made to the following material:

a. Memorandum to L. K. Maires and W. G. Weber from John Parmakian, "Rate of air accumulation at the siphon outlet at Grand Coulee, Granby and Tracy Pumping Plants." April 2, 1948

b. Properties of Ordinary Water-Substance, by Dorsey, pp. 552-4

c. Summary--Grand Coulee Pump tests at California Institute of Technology, July, 1940

2. At your request the study reported herein was made to serve as a check against the rate of air accumulation estimated in reference (a) above. A review of this study and a conference attended by Messrs. Weber, Parmakian, Ball, Gilliland, Hebert, Daum and Krisl led to the conclusion that the recommendations in the Parmakian memorandum were based on a sound and reasonable approach but were vulnerable on one score. The assumption that an equilibrium condition would be obtained when the water in the siphon is subjected to a reduced pressure for a period of some 10 seconds does not recognize that the rate at which air comes out of solution is fairly slow.

3. Material contained in reference (b) allows a computation to be made for the condition of water in a vessel of volume "V" exposed to air with an area of contact "A". The formula is given as:

$$(C_t - C_0) = (C_\infty - C_0)\left(1 - e^{\frac{-\beta A t}{V}}\right)$$

where C = concentration of air at time t, zero, or infinity, as indicated by subscripts

β = exit coefficient, which for water at 10° C is 0.436 cm/min.

A = area of interface

V = volume of liquid

Although the conditions to which the equation applies are not duplicated in the Coulee Siphon, a computation was made using for "V" the volume of water contained in the conduit above the plane of atmospheric pressure and for "A" the wetted area of the same portion of the conduit. Using a time of 10 seconds as the period spent at reduced pressure, the air that would come out of solution ($C_{10} - C_0$) expressed as a ratio of the amount that would come out if allowed sufficient time ($C_\infty - C_0$) would be:

$$\frac{C_t - C_0}{C_\infty - C_0} = 0.0008, \text{ or approximately } 0.1 \text{ percent}$$

The value of 0.1 percent is extremely small and is subject to the limitation that the wetted area of the pipe was used in place of the area of a clearly defined air-water interface. The significance of the ratio which should be regarded as a minimum estimate only is that, during the first ten seconds following a pressure reduction only 0.1 percent of the air corresponding to equilibrium conditions is released.

4. The same equation was used to compute the air being stripped in a siphon which was described in Engineering News Record of September 16, 1920. Operation data indicated that air collected in the siphon at a minimum rate of 3 cubic feet per hour at the receiver pressure. Assuming the receiver pressure equal to that in siphon or 9.5 psi the rate would be 0.84 cubic feet per hour of air under atmospheric pressure. Based on a time interval of 116 seconds (estimated by Parmakian) spent at subatmospheric pressure the equation, using "A" and "V" as previously discussed, results in a value of 0.2 or 20 percent of equilibrium conditions. Since the entire flow can contribute air (air bubbles originating at the invert have ample time to reach the top) the possible air that can be stripped is the difference in concentration at atmospheric pressure and at a vacuum of 24.5 feet of water (the pressure at the top of the siphon). The possible quantity of air is 50.2 cubic feet per hour at standard conditions. Applying the ratio of 20 percent to the value of 50.2 results in a rate of accumulation of some 10 cubic feet per hour compared to a measured value of 0.8. If the pressure of the receiver were atmospheric instead of 9.5 psi as assumed, the measured accumulation would be 3.0 compared to the computed value of 10.0. The difference between computed and measured values is in part due to the fact that some of the air would be pumped on through siphon. The not too unfavorable comparison provides some assurance that the interpretation of the terms "A" and "V" leads to results which are of the proper order of magnitude.

5. The experiments, called "bubble-point studies", described in reference (c) involved the sudden reduction of the pressure on a water sample, saturated with air, by expanding it with a piston. As the air came out of solution the pressure increased until the concentration of air remaining in solution was in equilibrium at the partial pressure which prevailed. The conclusions reached by the experimenters are quoted below.

"(1) Approximately one hour is required at present for the establishment of equilibrium between liquid and gaseous phase.

(2) The time required for the dissolution of the air from the water is nearly independent of the quantity of air to be separated.

(3) Increasing the agitation of the sample reduces the time required for the process, but may cause local cavitation which results in what may be termed super-unsaturation of the aqueous solution."

Note: The samples were agitated by a propeller rotating in the fluid. The experiments prove that an appreciable time is required for air to be separated from an aqueous solution following a reduction in pressure, even though the water is agitated violently. In the experiments the initial pressure after expansion of the fluid was usually only a few inches of water above vapor pressure.

6. The test results of two experiments, Runs 9 and 29 of the Grand Coulee tests, were used to estimate rates of air separation that might be applied to the Coulee Siphons. The data taken during the tests include readings of time and pressure as indicated by the height of mercury in a manometer connected to the water sample. Since the data did not include the zero reading of the manometer corresponding to atmospheric pressure, absolute values of pressure could not be extracted from the available records. Pressure changes for the first recorded intervals in percent of the pressure changes for equilibrium conditions were computed from the manometer readings. Since the system was closed the volume changes at a given time relative to the total volume changes when allowed to reach equilibrium were approximately equal to the relative pressure changes. The relative volume changes for the first interval in Runs 9 and 29 were respectively: 24.7 percent in 2 minutes and 47.1 percent in 5 minutes. Assuming that initial rates to be the same as the average rates, the percentage changes in 10 seconds would be: 10/2 x 60 (24.7) or 2.0 percent for Run 9, and 10/5 x 60 (47.1) or 1.2 percent for Run 29.

7. A rather coarse experiment was performed in the hydraulic laboratory to demonstrate that the rate of separation of air from solution is relatively slow. The experiment consisted of lowering the pressure of a water sample to a vacuum of about 20 feet of water. The action, which you observed, proceeded very slowly and resembled boiling in that the bubbles of air formed at the bottom and sides of the container. The bubbles detached themselves and rose in the fluid after expanding somewhat from

the size when originally formed. Agitation of the sample by oscillation of a glass tube in the water accelerated the action but a 50-fold increase in the observed rate would still be slow.

8. The maximum ratio obtained in the preceding considerations was 2 percent of equilibrium conditions. It is recommended that this ratio be applied to the rate estimated in reference (a) for computing the rate of air accumulation in the Grand Coulee Siphon. The ratio to be applied to the rate estimated for other siphons in reference (a) can be obtained by multiplying the value of 2 percent by the ratio of the time spent at subatmospheric pressure to 10 seconds.

9. Since the results of two independent computations differ widely and since data on the problem of air separation is so limited it is strongly urged that the proposed field test program of the Grand Coulee Siphon be enlarged to include determinations of air accumulation and its possible effects.

10. The advice and assistance of J. L. Gilliland in connection with this study is herewith acknowledged.