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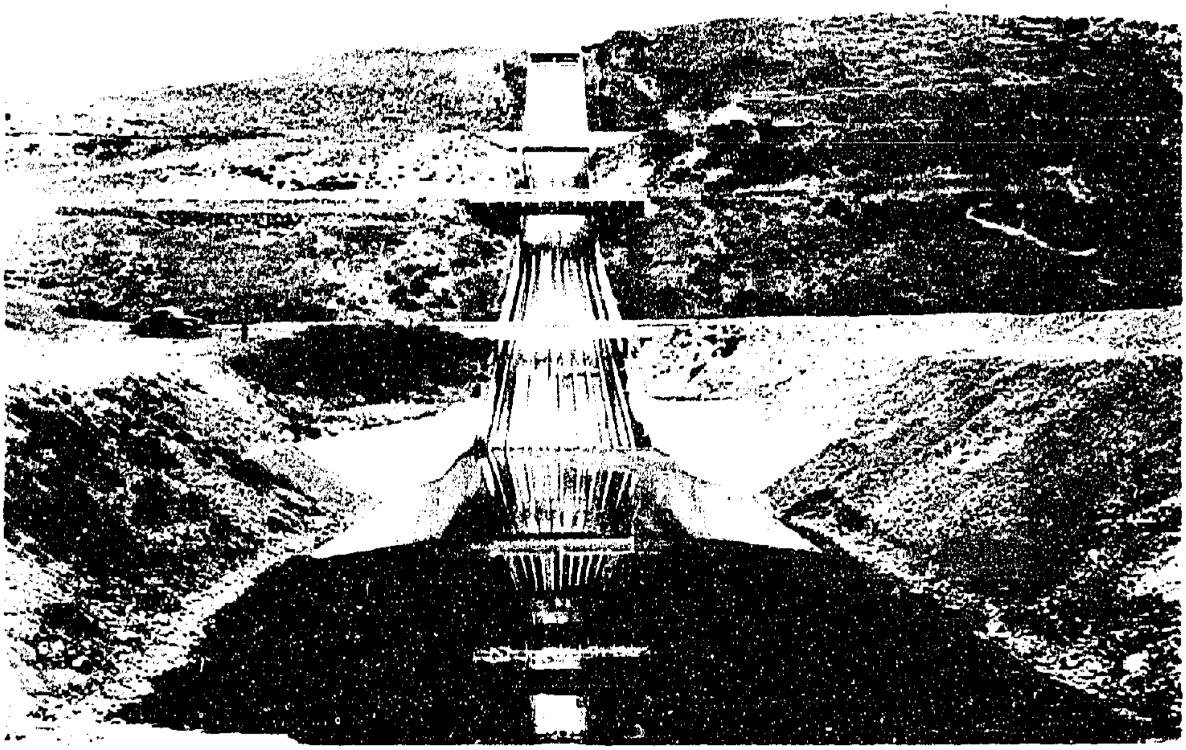
HYDRAULIC LABORATORY REPORT NO. 108

DEVELOPMENTS IN THE DESIGN OF LOW-HEAD SIPHONS AND DIVERING CHUTES FROM MODEL TESTS OF WASTEWAY NO. 2 ROSA DIVISION, YAKIMA PROJECT—WASHINGTON

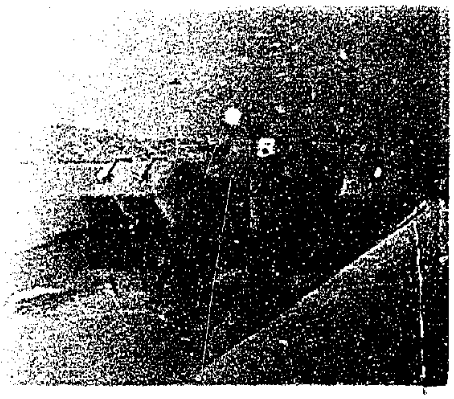
by
T. G. Owen

Denver, Colorado

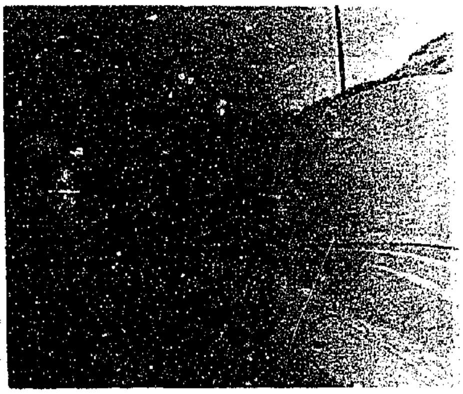
March 27, 1942



WASTEWAY CHUTE - LOOKING UPSTREAM



AUTOMATIC SIPHON HOODS
AT WASTEWAY ENTRANCE



A[illegible]TIC SIPHON OUTLETS
BELOW WASTEWAY GATES

PROTOTYPE STRUCTURE - ROZA WASTEWAY NO. 2

PREFACE

The model of Wasteway No. 2, described herein, was designed and tested in the hydraulic laboratory of the Bureau of Reclamation in Denver, Colorado, under the supervision of T. G. Owen, Assistant Engineer, and under the direction of J. E. Warnock, engineer in charge of the laboratory. All laboratories are under the supervision of Arthur Ruettgers, Senior Engineer, and R. F. Blanks, Senior Engineer.

The structures described herein were designed by W. E. Schneider, Associate Engineer, and K. K. Young, Assistant Engineer, under the direction of A. B. Reeves, Senior Engineer, and under the supervision of H. R. McBirney, Senior Engineer, and E. R. Crocker, Senior Engineer. All design work is under the general supervision of J. L. Savage, Chief Designing Engineer, and all engineering activities of the Bureau of Reclamation are directed by S. O. Harper, Chief Engineer. The activities of the Bureau of Reclamation are directed by John C. Page, Commissioner, in Washington, D.C.

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Denver, Colorado, March 27, 1942.

MEMORANDUM TO CHIEF DESIGNING ENGINEER
(T. G. Owen, Assistant Engineer,
through J. E. Warnock)

Subject: Developments in the design of low-head siphons and diverging chutes resulting from model tests of Wastoway No. 2 - Roza Division, Yakima Project - Washington.

CHAPTER I - INTRODUCTION

1. Purpose of investigation. Wastoway No. 2 is an emergency provision of the Yakima Ridge canal system, designed to return a maximum of 2,100 second-feet of water to the Yakima River. The location of the wasteway is shown in figure 1. The gate structure of the wasteway, located about 700 feet downstream from the junction of the wasteway with the Yakima Ridge canal, accommodates two 10-foot radial gates, figure 2. On each side of the gate structure are two siphons which empty into the spillway downstream from the radial gates, figure 3. Below the gate structure is a chute 22 feet wide which drops about 160 feet in 372 feet and terminates in a stilling pool 44 feet wide. Beyond the stilling pool is an unlined effluent canal which conducts the waste water to the Yakima River about 4,450 feet downstream.

It is planned at some future date to enlarge the canal immediately upstream of the gate structure into a forebay from which a maximum of 950 second-feet of water will be taken to supply the proposed power plant. When the power plant is operating, the siphons will function as emergency spillways to prevent overtopping of the lined portion of the canal and forebay if the turbine gates should be suddenly closed due to load failure. A load failure at the plant capacity of 950 second-feet will create a bore 1.2 feet high, a head on the siphon crests of 0.88 foot, and a total siphon operating head of 8.43 feet. It is also possible that the siphons may be required to act as water-leveling devices to accommodate fluctuations of the demand on the power plant. Under these conditions of operation it was imperative that the siphons prime quickly at a low head on the crest. The stilling pool, at the foot of the chute, was designed to operate for a normal discharge of 950 second-feet and to handle a maximum of 2,100 second-feet, a condition of rare occurrence and short duration.

The combination of the radial gates and siphons using the same chute presented such an unusual problem that it was considered advisable to check the design of gate structure, siphons, chute, and stilling pool by use of models.

The discussion that follows falls naturally under two headings: the gate structure, chute, and pool investigation; and the siphon investigation. The former will be treated under chapter II, the latter in chapters III, IV, and V.

2. Laboratory apparatus. The model tests were made in the hydraulic laboratory in the basement of the Customhouse, Denver, Colorado. The floor plan of the laboratory is approximately 50 by 103 feet, and the maximum available head room is 16 feet. The water system is of the recirculating type. Head is maintained by centrifugal pumps, and return to the pumps is effected by channels under the floor.

The details of the original model (scale 1:24) are shown in figure 4. The water supply was taken from a 6-inch centrifugal pump to the head box of the model where it was quieted and given a uniform velocity of approach to the canal by passing through a 4-inch gravel baffle. The length of canal approaching the gate structure was equivalent to 150 feet, prototype. The length of the effluent canal beyond the transition at the end of the pool was equivalent to 200 feet, prototype. The approach canal, chute, and stilling pool were made of cypress to resist soaking, swelling, and warping. The warped walls of the transition, upstream from the gate structure and downstream from the stilling pool, were made of a mixture of molding plaster and cement. The effluent canal was formed in packed sand. The siphons were made of laminated redwood, and the outer walls of the two outer siphons were made of 0.10-inch pyralin (a transparent, colorless plastic). The covers of the rectangular conduits leading from the siphons to the ports in the walls of the spillway were also made of 0.10-inch pyralin. Later in the testing program, it was found necessary to build a 1:8 scale model of one siphon. The construction was similar to that used in the 1:24 scale model. The invert and the crown were made of laminated redwood, each layer being about two inches thick with the grain running perpendicular to the grain in the adjacent layers. The crest length in the prototype was 6 feet; so the model crest length in the 1:8 model was 9 inches. This required a block of wood 9 inches thick with height and length equivalent to the over-all dimension of the model. From this block was cut both the invert and the crown of the siphon. The two pieces were then shaped until both fitted perfectly a negative template made of sheet metal. The surfaces of the crown and the invert were sanded until a smooth surface was obtained. Both blocks were then soaked for 24 hours in a bath of hot linseed oil. After the bath, both were checked against the template, and any swelling or warping was corrected. The blocks were allowed to dry thoroughly and then painted with several coats of aluminum paint. All the models were provided with two transparent sides, with the exception of the original and the first revision, both of which had but one transparent wall. These walls were made of 1/4-inch pyralin to facilitate visual observation and photographic recording. When the painted blocks were thoroughly dry, the transparent walls were screwed to them and an airtight seal effected by using a pipe joint compound between the sides and the wooden blocks. The model of the siphon was then installed. Since only one of the four siphons was tested, the forebay was so proportioned that the approach velocity for the one would be the same as in the case where all four were operating.

Heads on the siphons and gates, and tailwater elevations in the stilling pool, were measured by single-tube manometer gages. Discharges were measured by a 4-inch Venturi meter for the 1:24 model and by either a 4- or 6-inch meter for the 1:8 model. A point gage equipped with a neon glow lamp and needle point facilitated accurate water surface measurements in the chute.

3. Model scales. Where the force of gravitation is the most important consideration, for similarity the Froude number should be the same in model and prototype, or

$$\frac{V_p^2}{L_p g} = \frac{V_m^2}{L_m g}$$

where V, L, and g refer to velocity, length, and acceleration due to gravity, respectively, and the subscripts p and m refer to prototype and model. Since the acceleration due to gravity is the same in both model and prototype, it is obvious that $L_m \cdot N = L_p$ and $V_m^2 \cdot N = V_p^2$, where N is the scale ratio. The former condition establishes geometric similarity. For the latter equality to be true, $n_m \cdot N^{1/6} = n_p$, where n is the roughness factor in Manning's formula. This relation would determine the scale ratio; that is, if the roughness factor in the prototype were 0.014 and the roughness factor of the model is 0.010, then the scale ratio should be 7.55. Such a scale ratio would require a fall of over 21 feet in the model and a discharge of 13.4 second-feet, both of which exceeded the laboratory facilities. However, it has been shown that air will be entrained in the water of the prototype where velocities are above 16 feet per second and that entrained air increases the resistance to flow, resulting in lower velocities and consequently lower total energy. Velocities as high as 65 feet per second are expected at the junction of the chute with the stilling pool in Wasteway No. 2. The amount of resistance offered by the air in that velocity range cannot be accurately predicted, but in similar instances its effect, combined with the frictional resistance of the floor and the walls and expressed in terms of a total roughness coefficient, has been shown to be equivalent to a value of n of about 0.019. Assuming this to be true in the case of the prototype of Wasteway No. 2, the value of roughness for the material in the model chute agrees rather well for a scale ratio compatible with laboratory facilities. Under these conditions a model scale of 1:24 was acceptable for the wasteway. A discussion of the model scale ratio for the siphons, including the mathematical investigation of minimum model size, will be treated subsequently.

4. Summary and conclusions of wasteway studies. Model tests showed that entrance conditions in the original design were satisfactory, both at the gate and siphon structures. Flow through the chute past the siphon exits caused no objectionable disturbance. Although a high fin was formed in the chute when the siphons alone were discharging, the resulting waves in the chute did not endanger the freeboard nor cause undue disturbance in the operation of the pool. Model tests indicated that the vertical curve located at the start of the steep chute and designed according to the trajectory theory operated satisfactorily.

Both the parabolic wall design of the diverging chute (design 4) and the adopted design using diverging guide vanes were effective in spreading the high-velocity jet. The design using the diverging guide vanes gave a more even distribution of water across the section and had the further advantage of having lower specific energy of water entering the pool. Its main disadvantage was the construction cost as compared to the design using parabolic walls; but after considering the cost of the whole project, it was adopted because it allowed shorter bridge spans and therefore less costly construction of the three structures crossing the wasteway.

From the model experiments a pool design was developed which is 30 feet shorter, 4 feet narrower, with the pool floor 4.6 feet higher than the original design, resulting in a considerable saving in excavation and concrete. Twenty-five feet of rock paving downstream from the warped wall transition was demonstrated by the model to be adequate.

5. Summary and conclusions of siphon studies. An outline of the design of any but the low-head type of siphon is beyond the scope of this discussion. Generally, the conditions at the site of the proposed siphon will impose such restrictions as maximum available head, maximum width of crest, maximum radius of crest, total discharge, and required priming head. The designer must determine the details of the siphon which will most efficiently meet the conditions at the minimum cost. The following outline is proposed:

(a) Estimate the approximate number of siphons required and the approximate discharge per siphon.

(b) Determine the crest radius and the depth of throat, keeping in mind that for minimum loss the R/D ratio should be about 2.5 and that the crest radius determines the maximum allowable discharge except when the head is very small.

(c) Assign a width to the crest. Usual practice is to make the width equal to twice the depth at the throat. If the siphon is required to prime quickly, it may be expedient to increase the aspect ratio - the ratio of crest length to throat depth - to some value greater than 2.0.

However, no decrease in bend loss due to increased aspect ratio may be expected below an aspect ratio of 3.0.

(d) Customary practice makes the inlet area twice that of the throat. Experience has shown that the exact shape has little effect as long as the inlet has reasonably good lines. The lip of the hood should be well submerged below the forebay elevation at which siphonic action should cease. It should not be placed at the elevation required for breaking the vacuum. A pipe or air vent for breaking the action of the siphon must be provided. This procedure results in eliminating vibration when siphonic action is breaking and also minimizes the formation of vortices. The amount of air and, consequently, the size of pipe required depends upon the shape, size, and priming characteristics of the siphon. A model cannot be relied upon to accurately predict the air required by the prototype for the same reasons that the model cannot be used to accurately determine the priming characteristics. The prototype will require at least as much air as indicated by the model. There is little available data on how large the area of the air vent should be in comparison to the throat area. In installations on record, the ratio of the air-vent area to the throat area varies from 1/4.3 to 1/288. The latter value, however, was insufficient to break siphonic action. The value used for the siphons of Wasteway No. 2 was 1/54.2. However, it is believed that the air vent area is a little too small for safety and that it should be increased to about twice that value, or from a 6- to a 9-inch pipe, giving an air vent to throat ratio of 1/24.85.

(e) The radius of the lower bend may next be determined. As demonstrated by these tests, it does not have to be small for good priming qualities if a satisfactory priming device is used. For siphons with particularly low heads a large radius is a decided advantage. The larger radius is advantageous up to an R/D ratio of 2.5 to 3.0.

(f) The outlet tube, when it follows a right-angle bend, should diverge, the amount of divergence being a balance between increased discharge and increased cost. In the Wasteway No. 2 siphons, the divergence was 8 degrees and 30 minutes. The exits connecting the siphons with the chute were four feet high, so this dimension was allowed to control the amount of divergence, making the depth at the outlet 1.85 times the throat depth.

(g) The velocities at the entrance, throat, and exit may now be computed and all losses - entrance, upper bend, lower bend, diverging tube, and friction - expressed in terms of the velocity head at the throat. The sum of these losses plus the velocity head at the exit is equated to the total operating head. From this expression the mean velocity at the throat section can be found. This should be compared with the maximum permissible mean throat velocity found from the equation

$$V_t = \frac{r_1 \sqrt{2\ gh}}{r_2 - r_1} \log_e \frac{r_2}{r_1}$$

where

V_t = average throat velocity,

r_1 = radius of crest,

r_2 = radius of crown,

h = maximum allowable vacuum at the crest in feet of water.

If the mean velocity at the throat section exceeds that given by the above equation, the radius of the crest must be increased. The discharge can be computed by multiplying the mean throat velocity by the throat area. If this computed discharge is smaller than required, either the losses must be decreased or the cross-sectional area increased.

(h) The priming characteristics of the siphon are functions of the shape, size, and design features. If the head on the crest at which priming occurs is of no particular consequence, priming devices need not be considered, for with good design, priming may be accomplished at a head on the crest of d/3 without them. Where quick priming at a small head on the crest is imperative, many expedients may be utilized. A water seal at the lower bend is beneficial, but the depth of seal should be small, allowing the priming jet to penetrate the sealing pool and release the entrained air downstream from the low point of the lower bend crown. The lower leg may be either vertical or overhanging. A spur to cause the priming jet to spring free from the invert and cross the lower leg to seal against the lower bend crown will expedite priming at a low head. The spur, when located as in the siphons of Wasteway No. 2, should be designed so that the jet at the minimum priming head will strike slightly above the point where a vertical plane is tangent to the lower bend crown. A simple priming device consisting of a transverse slot in the crown of the lower bend connected to the diverging tube by a pipe may be used to great advantage to further decrease the minimum priming head and the time to prime, at the same time making no sacrifice of efficiency by decreasing the radius of the lower bend. The upstream edge of the slot should be located at that point on the curve of the lower bend where it will most effectively catch the air bubbles as they rise from the sealing pool.

As a result of the investigation, it may be concluded that laws pertaining to pipe flow are applicable to siphon design when the structure flows full. Friction losses in siphons may be computed as in other conduits. The bend loss is governed by the same laws as the bend loss in other conduits and is a function of the R/D ratio, the angle of deviation, and the square of the velocity. Where the bend losses can be estimated with a fair degree of accuracy, the discharge can be computed. This value can then be compared with the discharge as computed by the method of free vortex flow. If the former exceeds the latter, then the permissible vacuum at the throat has been exceeded and the design must be revised.

The coefficient of discharge is a confusing and misleading quantity when used in connection with siphons. The expression for efficiency as outlined in this discussion is probably the best indicator of siphon performance. It does not, however, consider the priming qualities.

High priming efficiency does not depend upon a sharp curvature of the lower bend. For best results, the priming jet should strike the crown of the lower bend at an acute angle, and as near the sealing pool as possible. This may be accomplished by properly designing the spur and using an aeration tube to maintain equal pressures above and below the jet, insuring a normal trajectory. Good priming qualities are not necessarily incompatible with high siphonic efficiency. The priming devices presented in this discussion are simple to construct and efficient in operation.

CHAPTER II - ENTRANCE, CHUTE AND STILLING POOL INVESTIGATIONS

6. Experimental procedure. As it is planned that the radial gates and siphons will not operate simultaneously, the flow through each was studied separately. Flow through the gate structure was investigated both with the gates maintaining the normal canal water surface elevation and for the condition of free flow without the use of gates. All observations on flow at the entrance to the gate structure were visual, as were those of the flow conditions when only the siphons were discharging.

Since economic considerations dictated a stilling pool twice the width of the wasteway control section, the principal chute studies concerned the method of diverging the high-velocity water as it passed through the inclined chute to the stilling pool. The criterion of good design was taken as the flow distribution at the bottom of the chute. This distribution was determined by cross-sectional water surface profiles which consisted of eleven readings at each of the several stations throughout the diverging chute for the first four designs and sixty-seven readings at each cross section for the adopted design. To facilitate these numerous observations, a point gage was constructed using an insulated needle point connected to a neon glow lamp which indicated contact of the point with the water surface. Thus the amount of divergence was measured.

The stilling pool designed for 950 second-feet is required to operate satisfactorily for 2,100 second-feet, a condition of operation that is expected rarely and for a duration of not more than 2 to 4 hours. The pool action was studied both visually and by point gage traverses. Flow conditions downstream from the pool were investigated by using dye in the water and also by noting the position and extent of scour.

7. Entrance conditions. The entrance conditions were satisfactory except for an unstable vortex in front of each gate. An attempt to eliminate these vortices was made by extending and rounding the noses of the walls between the radial gates and the siphons. The improvement was only slight and did not justify the expenditure. For a discharge of 2,100 second-feet under the radial gates, the water surface was above the siphon exits and there was little disturbance. When the siphons were operating, a high fin formed in the center of the wasteway channel but caused no serious splash. The fin induced waves which, though reflected back and forth down the chute, did not encroach on the freeboard or noticeably affect the pool operation.

8. Diverging chute design 1 (original). Four of the five designs of the diverging chute tested in the model are shown in figure 5, together with the corresponding water surface profiles. Design 1 was unsatisfactory, as may be seen from examination of the water surface profiles at stations 11+00 and 11+50, figure 5 and photographs figure 6. The jet was concentrated to the right of the center of the chute and resulted in a turbulent pool with high effluent velocities in the center.

9. Diverging chute design 2. To improve the divergence in the original chute, a 1,200-foot radius curve was fitted to the walls with the point of intersection of the tangents at station 10+50, the station of the start of straight-line divergence in the original design. The water surface profiles showed but slight improvement over design 1.

10. Diverging chute design 3. Since it was believed possible to accomplish satisfactory spreading of the wasteway flow by properly diverging the chute walls, an equation for their alinement was developed considering the down-chute velocity and the transverse component of the acceleration of gravity as prime factors influencing the divergence. Friction forces were neglected. The relation between the divergence and the down-chute distance was derived by obtaining expressions for the transverse component of gravity, the down-chute and transverse distances that a particle moves in time, t, and making proper substitutions. An expression for the transverse component was obtained by resolving the acceleration of gravity, for unit mass, into its down-chute and normal-to-floor components, then resolving the latter into components normal and parallel to the transverse water surface slope which was assumed constant between the center line and walls of the chute. The expression obtained from figures 7A and B is:

$$g_y = g \cos \alpha \sin \phi \quad \text{.......} (1)$$

To obtain an expression for the transverse distance, y, in figure 7C, traversed by a water particle in time, t, it was assumed that the transverse velocity was due solely to the component of gravity given by equation (1), that the velocity at the origin or point of divergence was zero, and that it increased as the flow moved downstream. With these assumptions, y may be expressed as the distance traveled by a freely falling body with acceleration, g_y, or

$$y = \frac{1}{2} g_y t^2 \quad \ldots\ldots\ldots\ldots\ldots (2)$$

In obtaining an expression for the down-chute distance traveled on the inclined floor, x, in figure 7C, it was assumed that the velocity through the diverging section was constant and equal to the average velocity in the section. With this assumption,

$$x = vt \quad \ldots\ldots\ldots\ldots\ldots (3)$$

An alinement equation $y = \frac{g \cos \alpha \sin \phi}{2 v^2} x^2$, a parabola of the form $y = kx^2$, results when the expressions for t and g_y in equations (1) and (3) are placed in equation (2).

An assumed transverse water surface slope of 0.10, and an average prototype velocity of 69.2 feet per second at station 10+50, based on the model tests from design 2, were used to determine the first equation. By inspection, it was seen that the diverging section supplied by this equation was too short. The maximum instead of the average velocity at station 10+50 was then used to obtain a new alinement equation, $y = 0.00024 x^2$, for design 3. The divergence, or maximum value of y, fixed at 11 feet by the pool and chute widths, limited the length of the diverging section in this design to 214.09 feet. Although the model tests indicated improvement over the two previous designs, a concentration of flow existed near the center of the chute at its junction with the stilling pool. No doubt the assumptions used in developing or evaluating the equation were incorrect. Had correct assumptions been made, the flow would have spread more evenly and the measured transverse water surface slopes in table I would have been more constant than those obtained for this design.

TABLE I

MEAN WATER SURFACE SLOPES DETERMINED FROM MODEL

Wall Design	Design No. 1 (Original)	Design No. 2	Design No. 3	Design No. 4
Station	Origin at Sta. 10+50.00	Origin at Sta. 9+96.78	Origin at Sta. 9+59.51	Origin at Sta. 8+58.34
9+00.00	-	-	-	+0.005
9+59.51	-	-	-	+0.007
9+96.78	-	-	-0.011	-0.006
10+50.00	-	-0.032	-0.017	-0.010
11+00.00	-0.043	-0.042	-0.030	-0.010
11+50.00	-0.042	-0.040	-0.027	-0.016
11+71.78	-	-	-0.027	-0.017

Note: The plus sign indicates a slope upward and outward from the center line; the negative sign indicates that the slope is downward and outward from the center line.

11. Diverging chute design 4. As it was desired to accomplish further improvement in flow distribution entering the stilling pool, a fourth design was developed, design 4, figure 5. The mean velocity in the diverging section of the model chute and the transverse water surface slope of 0.011, measured at station 9+96.78 on design 3, were used to establish a new equation for the wall alinement. The length of section required to accomplish the eleven feet of divergence was prohibitive, indicating the k value of 0.000011 to be too small, and signifying the equation to be empirical. A value of 0.00011 was then chosen for k as a trial, making the alinement equation $y = 0.00011x^2$, which gave a reasonable length of diverging section. Design 4, based on this equation, showed marked improvement in divergence with satisfactory entrance conditions at the stilling pool. This design was being considered as a final design when a new type was proposed by the design section. Although a great deal of data pertaining to the spreading of flow in an inclined chute was taken from this model, the experimental results indicated no justification for the assumptions made in developing the equation for the wall alinement. Moreover, the model was small and the data too meager to establish general laws pertaining to the divergence of flow in inclined chutes.

12. Diverging chute design 5 (adopted design). Except for the incorporation of vanes in the floor for spreading the wasteway flow, the diverging section, including the wall alinement, was identical to that of design 1, figure 5. A comparison of flow conditions in the stilling pool, figures 8, 9, and 10, and water surface profiles at station 11+50, figure 11, disclosed this type to be hydraulically superior to all previous designs. However, construction of the vanes was believed costly, and it was only after comparative cost estimates of this design and design 4, including the two flumes and the bridge spanning it, disclosed design 4 to be more costly because of the necessity for longer spans for the three structures, that the **vaned chute** was adopted for the prototype.

13. Stilling pool studies. After the studies on the diverging chute had been satisfactorily completed, attention was directed to the performance of the stilling pool. Studies of the pool embraced the original two revisions and the adopted design. The original pool design and the first revision, design 2, figure 12, were tested, using only design 4 of the diverging chute; the second revision, design 3, figure 12, was tested with both design 4 and the adopted design of the diverging chute.

Both visual and mathematical examinations of the original pool indicated that the floor should be raised and shortened. Accordingly, the floor was raised 7.68 feet and shortened 33 feet, figure 12B. Tests demonstrated that the change was too drastic. In design 3, the floor was lowered 3.08 feet and lengthened 3 feet. Chute blocks were used when this design was tested with diverging chute design 4, but the blocks were omitted when testing with the adopted chute design. The comparative data for the pool designs tested are compiled in table II.

TABLE II
COMPARATIVE DATA - MODEL POOL STUDIES

Item	Original Design	Design 2	Design 3	Adopted Design
Station at start of pool	11+73.78	11+59.46	11+63.61	11+63.61
Width of pool, W	44.00	44.00	40.00	40.00
Actual discharge per foot from model experiments, q	46.175	46.175	50.7925	52.485
Average depth entering pool, from model, d_1	0.823	0.836	0.917	1.170
Average velocity entering pool, from model, V_1	56.10	55.25	55.40	44.87
Tailwater elevation for 2,100 second-feet	1027.42	1027.42	1027.42	1027.42
Pool Floor elevation	1010.32	1016.80	1014.92	1014.92
Actual conjugate depth, d_2'	17.10	10.62	12.50	12.50
Theoretical d_2 from momentum	12.287	12.187	12.779	12.532
Actual length of pool, L'	75.00	42.00	45.00	45.00
Length of pool, L = 3.5 d_2	43.00	42.65	44.73	43.86
Average velocity in effluent channel, V_2	4.887	4.887	4.887	5.050

The water surface profiles through the adopted pool design and pool design 3 for both design 4 and the adopted design of the diverging chute are shown in figure 12C. It is evident from the profiles that the adopted pool design is superior. The reasons for this superiority were not self-evident; so a chart was prepared comparing the variation of the hydraulic elements for the two designs, figure 13. The wetted perimeter is the same for both designs at station 10+26, while at station 11+50.00 the wetted perimeter for the adopted chute design is roughly twice that for chute design 4. This increase in wetted perimeter results in an increase of friction loss and a decrease in specific energy. From model tests at station 11+50.00, the specific energy content for chute design 4 is 1.425 times that for the adopted design. It is to be expected, then, that the pool operation with the adopted design will be improved over that with design 4. Those two diverging wall designs used with pool design 3 are compared in figures 8, 9, and 10. In comparing the flow conditions shown in these figures, it should be remembered that the 950 second-foot discharge is the amount normally expected, and that the 2,100 second-foot discharge will occur rarely and for a period of not more than 2 to 4 hours. From these facts, it is concluded that either of the two pool designs would have been safe.

Downstream from the stilling pool it was found that the warped wall transition from rectangular to trapezoidal section was satisfactory. The model demonstrated that a 25-foot width of riprap adjacent to the transition section gave sufficient protection to the structure.

CHAPTER III - THEORETICAL CONSIDERATIONS OF SIPHONIC FLOW

When preliminary tests on the original 1:24 model indicated that the siphons were incapable of discharging the required quantity at the available head, an investigation was made of the conditions of similitude between model and prototype. The losses in the siphon were considered analogous to similar losses in a bent pipe or conduit, and other features of siphonic flow were examined, including vortex flow, the diverging tube, priming characteristics, the coefficient of discharge, and the efficiency of a siphon. The discussion of the theory involved in the flow of water through siphons makes use of more or less singular nomenclature. Figure 14 shows the terminology which will be used.

14. Vortex flow. It is generally agreed that flow over the crest of a siphon approximates free vortex flow. It has been assumed that the streamlines in the throat of a siphon are concentric circles, the boundaries being the crown and crest of the upper bend of the siphon, and that the velocities are entirely tangential.[1,2] For this type of flow the

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[1,2] These and all following notes in this memorandum refer to numbers listed in the Bibliography, in the order of their appearance.

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following relations may be written:

$$vr = v_1 r_1 = v_2 r_2 = \text{constant} \quad \text{.......... (1)}$$

$$q = v_1 r_1 \log_e \frac{r_2}{r_1} \quad \text{.......... (2)}$$

$$v_1 = \sqrt{2\,gh} \quad \text{.......... (3)}$$

where

r = the radius at any point,
v = the velocity at radius, r,
q = the maximum allowable discharge per foot of crest width,
v_1 = the maximum permissible velocity at the crest ($r = r_1$) based on h,
h = the maximum permissible vacuum at the crest, in feet of water,
r_1 = the radius of the crest,

r_2 = the radius of the crown at the throat section,
g = acceleration due to gravity.

Usually the value for h is taken as 75 percent of the barometric pressure at the site of the siphon, which produces a safe working pressure at which there will be no separation due to removal of entrained air from the water which would cause a break in flow continuity in the downstream water leg.

The theory of vortex flow over the siphon crest was used in the theoretical investigation of the siphons of Wastewny No. 2. The required discharge per foot of crest length for each siphon was 39.58 second-feet. From equation (3) the maximum permissible velocity at the crest was determined for $h = 24$ feet and used in equation (2) with $r_1 = 4$ inches and $r_2 = 3$ feet 4 inches to find q, the maximum allowable discharge per foot of crest length. The value of q was 30.16 second-feet, or 224 second-feet less than the required total of 950 second-feet for all four siphons. From these computations, it was obvious that even if the maximum allowable negative pressure at the crest could be developed, the discharge would still be only 76 percent of the desired capacity, and therefore, the design would have to be revised.

15. Conditions of similitude. In studies of hydraulic structures by the use of models it is important to ascertain the relation between the prototype and model data. When the force of gravitation is the most important factor, the Froude number for both model and prototype must be the same. The Reynolds number should be the same in both model and prototype where viscosity is the most important item. In cases where the surface tension or capillary forces become the most important consideration, both model and prototype must have the same Weber number. Where elasticity is a primary factor, the Cauchy number should be the same in model and prototype. In a siphon flowing full, the last two considerations may be neglected. The two factors that must be considered are the Froude and Reynolds numbers. Experiments have shown that in short siphons the Reynolds number is not extremely important, although for dynamic similarity $\frac{vd}{\nu}$ (the expression for Reynolds number for pipe) should be the same for model and prototype. Gibson[3] has shown that for coefficient of discharge and pressure-distribution measurement the model will give close agreement with the prototype if the value of vd for the model is greater than 1.8. This value of vd limits the size of the model. As Gibson points out, in the few instances where results of both model and prototype tests are available, agreement of coefficients is close where the model is large enough that the value of vd is greater than 1.8. Other investigators,[4,5,6,7] have confirmed the fact that when flowing full, the model closely represents the prototype when the scale is properly chosen. A second consideration in the choice of the model scale should be the pressure. The negative pressure in feet of water in the model, when multiplied by the scale ratio, must not exceed the allowable negative pressure in the prototype. A simple computation will indicate the minimum model

scale.

Another factor to be considered in scale models is that of friction. In order that the model represent the prototype as closely as possible, the coefficient of roughness in the model should be proportional to the coefficient of roughness in the prototype. It can be shown that the coefficient of roughness in the model multiplied by the scale ratio to the 1/6 power equals the coefficient of roughness for the prototype. Although friction is a minor loss in short siphons, it is quite possible, as Williamson[8] suggests, that the loss in bends, exclusive of friction, may be a function of the coefficient of roughness. This point should be the subject of further investigation.

Flow under the condition existing when the siphon is priming involves a consideration of two fluids of different kinematic viscosities. Furthermore, the effect of surface tension during priming becomes important. For dynamic similarity it is required that the kinematic viscosity be reduced in the proportion of the scale ratio to the 3/2 power, while the surface tension of the model should equal that in the prototype divided by the scale ratio squared. It is evident, then, that similarity of the model to the prototype is impossible, using the same fluids in each. However, experience has shown that the head required to prime, as indicated by the model, is always greater than the actual head required to prime the prototype. Some writers[1,6] say that the priming characteristics of a siphon can be predicted by studying three models to widely different scales. Then by extrapolation of the curves plotted from the data obtained from the three models, the priming head and time to prime for the prototype can be closely approximated. It is interesting to compare the heads to prime as extrapolated from the data given by Veronese.[8] The results of extrapolation by four different methods are given in the following table.

Siphon	Extrapolation Method	Extrapolation Head, cm.	Actual Head, cm.	Error Percent
Camuzzoni	A	9.1	13.0	-42.9
	B	8.9	13.0	-46.1
	C	16.42	13.0	+20.8
	D	9.04	13.0	-43.8
Carron	A	18.8	18.3	+ 2.7
	B	14.2	18.3	-28.9
	C	35.56	18.3	+48.5
	D	14.28	18.3	-28.2
S. Caterina	A	42.0	40.0	+ 4.8
	B	38.0	40.0	- 5.3
	C	48.57	40.0	+17.6
	D	47.47	40.0	+15.7

Extrapolation methods A and B were both graphical, but by different engineers. The curves were plotted with the scale ratios as the abcissa, and the model head to prime multiplied by the scale ratio as the ordinate. Method C is an algebratic solution accomplished by putting a curve of the form $y = ax^3 + bx^2 + cs + d$ through the three known points and further defining one end so that $dy/dx = 0$ when $x = 1$. Method D is similar to method C except that the equation was of the form $y = ax^k + b$ but with no limiting end condition. The error is the amount that the particular extrapolated head either exceeded (plus) or fell short of (minus) the actual head, and is expressed in percent of the extrapolated head. Examination of the table reveals that the graphical methods are as good as any method tried. It is apparent, furthermore, that the accuracy in predicting the prototype priming head, even by extrapolation from the results of models to three different scales, cannot be relied upon to be very close. Extrapolation from results of three models appears to be the closest approximation possible that has yet been developed, and, although not accurate, it is better than nothing.

Compiled in table III are the values of the minimum scale ratio as determined by the various methods. After consideration of all factors, a model scale of 1:8 was chosen.

TABLE III

MINIMUM SCALE RATIO FOR SIPHON DETERMINED BY VARIOUS METHODS

Conditions governing size of model	$vd > 1.8$ where d = depth of barrel at throat section	$vd > 1.8$ where d = diameter of pipe of area equal to throat area	$vd > 1.8$ where d = 4 times the hydraulic radius	$d \cdot \sqrt{h} > 0.28$ where d = the throat depth; h = average working head	$n_m \cdot N^{1/6} = n_p$; n_m = model roughness = 0.010; n_p = prototype roughness = 0.014; N = scale ratio
Minimum model scale ratio	1:7.85	1:10.72	1:9.51	1:8.89	1:7.54

16. Losses. With the total available operating head fixed by the conditions at the site of a low-head siphon, an investigation of the losses will reveal whether or not the permissible vacuum at the throat will be exceeded. The losses in the siphon occur at entrance, upper bend, lower bend, diverging tube, and due to friction.

Except in cases where the approach velocity to the siphon is high, the velocity head of approach may be considered a refinement and therefore negligible. The total operating head on siphons with various types of outlets is a subject of much controversy among hydraulic engineers, and a discussion of this point will be considered subsequently. For the present, the total operating head will be assumed to be the difference between the forebay and tailwater elevations, and this must equal the sum of the losses plus the velocity head at the exit section.

17. Entrance loss. Where the entrance is bellmouthed and has a large area compared to that of the throat section, the loss may safely be assumed as 0.5 the velocity head at the entrance section. Gibson[3] has shown that the exact shape of the entrance has little effect on the coefficient of discharge as long as it has reasonably good lines.

18. Bend losses. Although there has been much work done on losses in pipe bends, the available data of various investigators are not very consistent, and it is still a difficult task to estimate the loss due to bends in a siphon. The loss due to bends is usually expressed as a coefficient times the velocity head. In experiments on bend losses in pipes, Beij has divided the loss into three parts; (1) the loss due to friction in a straight pipe of length equal to that of the bend plus the upstream and downstream tangents, (2) the excess loss within the bend, which he calls the deflection coefficient, and (3) the excess loss in the downstream tangent, which he calls the tangent coefficient. His work was done entirely on 90-degree bends, using a pipe diameter of 10.23 cm. (approximately 4.03 inches) with various bend radii, and with uniform velocity distribution approaching the bend. By plotting the bend coefficient, which is the sum of the deflection and tangent coefficients, against the ratios of the radius of the bend to the pipe diameter (R/D), he has shown that the minimum loss due to the bend occurs when the ratio of R/D is between 2.5 and 3.5. Attempts have been made to predict the R/D ratios for minimum loss by means of the so-called "rebound polygon" method.[10] The results of this method of analysis would indicate that there should be minimum values of loss occurring at ratios of R/D of 1.2, 6.1, 16.9, and so forth. However, it is suggested that after three rebounds other factors would become prominent enough to modify the flow to such an extent that the results would be unpredictable. This method of analysis, however, does not agree with experimental results.

Yarnell measured losses in 6-inch bends with an R/D ratio of 1.375 but having various angles of deflection. The losses due to the bends, exclusive of friction, expressed as a coefficient of the velocity head were found to be 0.11 for a 45-degree bend, 0.15 for a 90-degree bend, 0.19 for 180-degree bend of continuous curvature, 0.31 for 180-degree bend of reverse curvature, and 0.40 for 270-degree bend of two reverses. Tests on the 180-degree bend with reverse curvature and uniform velocity of approach indicated that about 51 percent of the loss occurred in the bend itself; the remainder occurred in the downstream tangent. In other words, the loss in the 180-degree reverse curve bend developed in the bend itself, expressed as a coefficient of the velocity head, is about 0.158. The tests indicated further that with a nonuniform velocity distribution in the approach tangent, the velocity being highest on the inside of the bend, the loss was 1 to 4 times that found when using a uniform velocity of approach. When the velocity of approach was highest on the outer side of the approach tangent, it was found that some bends showed a slightly higher loss while others indicated a somewhat lower loss.

A recent paper by Williamson[8] gives the losses in 4- by 4-inch square teakwood bends of various angles of deflection and various ratios of R/D. The bends tested were all of continuous curvature, and the values given are those of extra loss to the bends alone. As stated above, the losses determined by Yarnell were all for bends of circular cross section and an R/D ratio of 1.375. Interpolations between values of the bend losses for all the R/D ratios of 1.5 and 1.06 given by Williamson were required so that the direct comparison, given in the following table, could be made.

Angle of Bend, Degrees	Loss in Bend of Circular Cross Section	Loss in Bend of Square Cross Section
45	$0.11 \frac{v^2}{2g}$	$0.08 \frac{v^2}{2g}$
90	$0.15 \frac{v^2}{2g}$	$0.16 \frac{v^2}{2g}$
180 (continuous)	$0.19 \frac{v^2}{2g}$	$0.32 \frac{v^2}{2g}$

Inspection of the values reveals that agreement is very close except for the 180-degree bend. In the past, it has been assumed, without proof, that losses in bends of rectangular cross section would approximate those in bends of circular sections. The above comparison would strengthen the assumption.

Madison and Parker[12] have published the results of their experiments on losses in bends of rectangular section using air as the fluid. The results of their experiments indicate that the R/D ratio for minimum loss is in the vicinity of 2.5 to 3. This is approximately the same value as was found for bends of circular cross section. In the experiments on bends of rectangular section there arises a term which Madison and Parker call the aspect ratio, and they define it as the ratio of the width along the axis of the bend to the depth in the plane of the bend. In a siphon this would correspond to the ratio of the length of the crest to the depth of the throat section. The results of these experiments show that in the range of R/D ratios of 1.0 to 3.0 the loss is practically independent of the aspect ratio for bends with aspect ratios from 1 to almost 3. For higher aspect ratios the loss due to the bend decreases until, for an aspect ratio of 4, the loss is 88 percent of that for a bend of aspect ratio of unity (square in cross section). For bends of lower aspect ratios the loss increases rapidly until, for an aspect ratio of 0.25, the loss is about 217 percent of that of a bend of aspect ratio of unity. In the range of R/D ratios from 0.0 to 0.5 the loss in a bend with an aspect ratio of 0.25 is 130 percent of that when the aspect ratio is unity. The loss decreases rapidly as the aspect ratio is increased to unity and more slowly as the aspect ratio is increased beyond unity. The value of the loss when the aspect ratio is 4 becomes 74 percent of that of a bend of aspect ratio of unity.

The results of the experiments also indicate that the loss in an elbow is practically proportional to the angle of turn up to 90 degrees. For a 45-degree bend the loss was found to be 52 percent of that for a 90-degree bend; and for a 180-degree bend the loss was found to be 165 percent of that for a 90-degree bend. These findings are more or less qualitatively consistent with the results of tests by Yarnell.

If it can be assumed that the results of these experiments which use air as the fluid can be applied directly to the instances where water is used as the fluid, some interesting observations result. It has been found that the ratio of R/D, giving minimum loss, lies between 2.5 and 3.5. By increasing the aspect ratio, holding the R/D ratio at the optimum, the loss due to the bend may be further decreased. The usual value of the aspect ratio at the throat section of a siphon is about 2. In cases where a value of R/D of 2.5 cannot be obtained, it may be possible to increase the aspect ratio until the loss is comparable with that of a bend of R/D of 2.5 and aspect ratio of, say, 2. Furthermore, logic would point to the conclusion that a siphon of large aspect ratio at the crest section would prime more quickly than another siphon of equal throat area but smaller aspect ratio, because, for the same value of the priming head, the area of the priming jet would be larger and the volume of air per foot of crest length to be exhausted would be less in the siphon of the larger aspect ratio. In a number of installations the aspect ratio has been decreased between the throat section and the lower bend of the siphon. In the light of the experiments performed using air, this procedure has resulted in increased loss at the lower bend, a fact confirmed from tests performed by Gibson, Aspey, and Tattersall.[3]

Adequate information on losses in bends of rectangular cross sections is very scant. What little there is available at the present time is not consistent. To design a siphon spillway without the use of hydraulic models, the engineer must be able to determine the losses rather accurately or serious difficulty will result. If, for instance, the assumed bend losses are too high, the permissible vacuum at the throat may be exceeded, resulting in cavitation at the crest or even a break in the water leg, causing the siphon to pulsate. On the other hand, if the assumed bend losses are too low the capacity of the siphon will be lower than that for which it is designed. Until such time as adequate data on bend losses are available, the designer must resort to model tests.

19. The diverging tube. An ingenious device for increasing the discharge and efficiency of a low-head siphon is the diverging outlet tube. When the diverging tube runs full, part of the kinetic energy is thereby converted to pressure energy, which causes a decrease in the pressure at the throat section and consequently an increase in the throat velocity, with a corresponding increase in the efficiency. A different, and possibly a simpler, concept of this same phenomenon would be to consider the outlet section of the siphon as an orifice discharging water under a head measured from the forebay level to the center of the outlet. The whole siphon might then be considered as a distorted mouth to the orifice. In comparing the discharges of two orifices operating under the same head, the orifice having the larger area will have the larger discharge. Furthermore, the orifice having a constriction in its mouth (which is analogous to a siphon with a diverging tube) would obviously have a lower coefficient than an orifice having no constriction. When the action of a siphon with a diverging tube is considered in this light, the reason for the increase in discharge is obvious. Furthermore, the reason for computing the discharge coefficient based on the outlet area is also obvious.

The diverging tube increases the capacity of the siphon without increasing the cross-sectional area of the throat section or of the lower leg which, in some designs, results in decreased cost and shorter priming time. By increasing the outlet area, the effluent velocity is decreased which, under certain conditions, such as in the case of Wasteway No. 2, may be an advantage. The diverging tube decreases the pressure at the throat section, thus necessitating a stronger crown.

The optimum angle of divergence in a tube following a right-angle bend was found by Gibson[3] to be 8 degrees 30 minutes. His experiments[13] indicate that the loss in a diverging tube, including friction, is:

$$h_d = \frac{0.17\,(v_1 - v_2)^2}{2g}$$

where

h_d = loss due to diverging tube,

v_1 = the initial velocity in the diverging tube,

v_2 = the final velocity in the diverging tube.

20. Friction loss. The loss due to friction can be computed conveniently by the Manning formula:

$$h_f = S \times L$$

$$S = \frac{(nv)^2}{2.208\ r^{4/3}}$$

where

h_f = head loss due to friction in the reach considered,

S = mean slope of hydraulic gradient in the reach,

L = the length of reach considered,

n = Coefficient of roughness,

v = the mean velocity in the reach,

r = the mean hydraulic radius in the reach.

The total loss due to friction is the sum of the individual losses in each reach. The friction loss should be computed only to the start of the diverging tube, since the loss in the diverging tube includes friction.

21. Total loss through siphon. The kinetic energy at the outlet is computed by the formula, $\frac{v^2}{2g}$, where v is the velocity at the exit section. If all the losses and the kinetic energy at outlet are now expressed in terms of a coefficient times the velocity head at the throat section and their sum is set equal to the available total head, the velocity at the throat section can be computed. Having the mean velocity at the throat section and the discharge per foot of crest length, then the radius of the crest depth at throat, and so forth, can be found.

22. Criteria of siphon design. In the last analysis, the best siphon design is the one which can satisfy the conditions of design at the lowest cost. While such a criterion is paramount when considering various siphon designs for a particular installation, it is impractical for comparing the operation of different siphons due not only to the different conditions of design but also to varying costs in various locali-

ties and during different periods of construction. It has therefore been necessary to find some other basis for comparing siphon performance. Unfortunately, no single criterion can be established which included minimum priming head, priming time, discharge, area, and operating head.

23. The coefficient of discharge. In computing the coefficient of discharge, the general form of the equation is:

$$C = \frac{Q}{A\sqrt{2gH}}$$

where

C = the coefficient of discharge,

Q = the total discharge in second-feet,

A = the area in square feet,

H = the operating head in feet.

Thus the expression should give a relation between the actual discharge and the theoretical discharge. There are two points, however, that are subjects of much controversy, the area and the head. Naylor[14] proposes that the outlet area is the only one upon which the computation should be based. If this practice is adhered to, the coefficient will never become unity or greater. For example, in the test on the Wasteway No. 2 siphon, a coefficient of 0.596 was obtained when the coefficients were based on the outlet area; but when based on the area of the throat, the coefficient became 1.093. In a paper on the coefficient discharge of siphons, Scimeni[4] bases the discharge coefficient on the throat area. In the same paper he also discusses several siphons, the most notable of which was a type reported by A. Weirich in "Selbstattige Sauguberfalle" (Deutsche Bauzeitung 1917, p. 225). This siphon had an overhanging crest, a diverging lower leg, and discharged vertically into a pool. Weirich did not mention the method employed in computing the coefficient of discharge, but gives values ranging from 0.956 to 0.984. Scimeni expressed his surprise at such a high coefficient. Apparently a coefficient of this size or larger could be obtained only if the throat area was used instead of the outlet area. This example has been cited to illustrate the confusion which results from having no universally standard method of computation. It seems most unfortunate that this condition should exist when its remedy appears to be so simple.

The second term in the expression for the coefficient of discharge of the siphon which, because of its indefiniteness, helps to complicate the already confusing term is the total operating head. In cases where the exit is sealed by the tailwater, determination of the operating head is simple. The head is the difference between the forebay and the level of the tailwater. When the siphon discharges horizontally and freely into the air, the exit section being vertical and flowing full, the head is measured to the center line of the jets. In almost all other cases the point to which to measure the head is a matter of opinion and thereby becomes an indefinite value.

Stevens[15] proposed that the coefficient be expressed by a relation which does not include the head and which involves the area of the outlet. Thus, he develops the expression:

$$C = \frac{Q}{A\sqrt{2gH}}$$

where

C = coefficient of discharge based on outlet area,

Q = discharge of siphon in second-feet,

A = area of outlet in square feet,

H = total operating head

$$H = h_f + h_1$$

where

h_f = head required to produce flow

$$= \frac{v^2}{2g} = \frac{Q^2}{2gA^2}$$

h_1 = total losses in the siphon from entrance to exit

$$= (a + b + c + \ldots\ldots) \frac{v^2}{2g} = K \frac{v^2}{2g} = K \frac{Q^2}{2\,gA^2} = B \frac{Q^2}{2g}$$

a, b, c, etc. = coefficients of losses due to entrance, bends, friction, etc.

$$K = a + b + c + \ldots\ldots\ldots\ldots$$

and

$$B = \frac{K}{A^2} = \text{sum of loss coefficient divided by } A^2.$$

Then

$$H = \frac{Q^2}{2\,gA^2} + \frac{B\,Q^2}{2g} = \frac{Q^2}{2g}\left(\frac{1}{A^2} + B\right)$$

and

$$C = \frac{Q}{A\sqrt{2g\left(\frac{Q^2}{2g}\left[\frac{1}{A^2} + B\right]\right)}} = \frac{1}{\sqrt{1 + BA^2}}$$

This expression was proposed by Stevens for computation of the coefficient of discharge. It will be remembered that B is the sum of the loss coefficients divided by A^2, or $B = \frac{K}{A^2}$. Thus the expression for the coefficient becomes:

$$C = \frac{1}{\sqrt{1 + \frac{K}{A^2} + A^2}} = \frac{1}{\sqrt{1 + K}}$$

This is in the form which Scimeni proposed. It is interesting also to note that a similar expression is given by Schoklitsch.[16] It appears to be an ideal expression, since it involves neither the indefinite head nor any area, throat or outlet. In those cases where the values of the integral parts of K can be determined either by velocity traverses or pressure measurements at the several necessary points throughout the siphon, the above expression can be used to determine the coefficient of discharge. Also, in designing the siphon this expression may be used, since the value K can be determined from the assumed losses. However, in most siphon installations the pressure or velocity measurements needed at numerous points are impossible to obtain, and therefore, the total operating head must be known in order to compute the coefficient of discharge. Fortunately, many siphon installations have sealed exits and in those cases the operating head is definite. The outlet area, as previously pointed out, is the only one used in computing the coefficient. It will be shown in the following chapter that the coefficient is an unreliable criterion of the effectiveness of the siphon.

24. Efficiency. The efficiency of any machine is the ratio of the output energy to the input energy. When applied to a siphon, this is equivalent to the ratio of the velocity head at the outlet to the total operating head on the siphon. The efficiency would be

$$\eta = \frac{h_o}{H}$$

but

$$h_o = \frac{V_o^2}{2g}$$

and

$$H = \frac{V^2}{2g}$$

then

$$\eta = \frac{V_o^2}{V^2}$$

$$C = \frac{Q}{A_o \sqrt{2gH}} = \frac{A_o V_o}{A_o \sqrt{2gH}}$$

$$C^2 = \frac{V_o^2}{2gH} = \frac{V_o^2}{2g\,\frac{V^2}{2g}} = \frac{V_o^2}{V^2}$$

$$\eta = C^2$$

where

η = efficiency of siphon,

h_o = velocity head at outlet,

H = total operating head,

V_o = velocity at outlet,

V = theoretical velocity corresponding to total operating head,

Q = actual discharge of siphon,

A_o = area of outlet,

C = coefficient of discharge.

If the coefficient of discharge is not considered satisfactory as a criterion of performance, then the efficiency as expressed by $\eta = C^2$ would be subject to the same criticism. Stevens[15] and Le Conte[17] both discuss this approach. Stevens[15] discusses another expression for efficiency which he defines as the ratio of actual flow to maximum attainable flow; the latter would occur when a subatmospheric pressure of one atmosphere is developed at the throat section. The efficiency in that case would be

$$\eta = \frac{Q}{A_t \sqrt{2\,ga}} = \frac{A_t\,V_t}{A_t\,V_a}$$

where

Q = actual discharge,

A_t = area at the throat section,

V_t = actual mean throat velocity,

V_a = theoretical mean throat velocity corresponding to a head of one atmosphere,

a = head equivalent to one atmosphere.

Naylor[14] developed a similar expression which he defines as "The ratio of the discharge to the discharge of a 'perfect' siphon of the same throat area. By a 'perfect' siphon is meant the purely theoretical conception of a siphon with a perfect vacuum across the throat." Thus, the expression:

$$\eta = \frac{Q}{A\sqrt{2\,ga}}$$

where

η = the efficiency of the siphon,

Q = the actual discharge,

A = the area of the throat section,

a = vacuum head in feet of water equivalent to one atmosphere.

When

a = 34 feet, the expression becomes

$$\eta = \frac{Q}{47 A_t}$$

This expression eliminates the indefinite head and definitely fixes the area as that of the throat section. Because it would be impossible to obtain an average negative pressure of one atmosphere across the throat section, the efficiency can never reach 100 percent. Naylor further points out that "the 'coefficient of discharge' diverts attention from the true desiderata of a siphon. It suggests that the discharge is proportional to the square root of the head available in any particular design, whereas it depends rather upon the vacuum attainable at the throat section." The truth of the foregoing statement may be demonstrated.

The total operating head must equal the sum of the losses plus the velocity head at the outlet. Thus, in a low-head siphon with a diverging tube:

$$H = a\frac{V_t^2}{2g} + b\frac{V_t^2}{2g} + c\frac{V_t^2}{2g} + d\frac{V_t^2}{2g} + e\frac{(V_t - V_o)^2}{2g} + \frac{V_o^2}{2g}$$

or

$$2gH = (a + b + c + d + e) V_t^2 - 2e V_t V_o + (1 + e) V_o^2$$

where

H = the total operating head,

V_t = the average throat velocity,

V_o = the average outlet velocity,

a, b, c, d, and e = the coefficients of loss for entrance, upper bend, friction, lower bend, and diverging tube, respectively.

By taking the first derivative of the head, H, with respect to the outlet velocity, V_o, and equating this to zero, a relation between the outlet velocity and throat velocity is obtained:

$$\frac{dH}{d\,V_o} = -2e\,V_t + 2(1 + e)V_o = 0$$

or

$$V_o = \frac{e}{1 + e}\,V_t$$

Therefore, the minimum head to develop the maximum allowable negative pressure at the crest, which, in turn, will limit the allowable average throat velocity and the maximum allowable discharge, is obtained by substituting the value of V_o in the original equation so that:

$$H = \left(a + b + c + d + \frac{e}{1 + e}\right)\frac{V_t^2}{2g}$$

Since $q = v_1 r_1 \log_e \frac{r_2}{r_1}$; $v_1 = \sqrt{2\,gh}$; and $q = (r_2 - r_1)V_t$, it may be seen that:

$$V_t = \sqrt{2\,gh}\,\frac{r_1}{r_2 - r_1}\log_e \frac{r_2}{r_1}$$

which, when substituted in the preceding equation, yields

$$H = \left(a + b + c + d + \frac{e}{1 + e}\right)(h)\left(\frac{r_1}{r_2 - r_1}\log_e \frac{r_2}{r_1}\right)^2$$

where

H = the total operating head,

h = maximum permissible vacuum at the crest in feet of water,

r_1 = the radius of the crest,

r_2 = the radius of the crown.

If, at the upper bend, we let $R/D = 2.5$, that is $r_2 = 1.5\,r_1$, and take $h = 24$ feet,

$$H = 15.78\left(a + b + c + d + \frac{e}{1 + e}\right)$$

Now, if $a = 0.10$, $b = 0.16$, $c = 0.10$, $d = 0.16$, and $e = 0.17$, the value for the minimum head becomes $H = 10.57$ feet. This means that for this particular design for heads in excess of 10.57 feet, the discharge cannot be safely increased by merely increasing the operating head, but the radii of the crest and crown must also be increased if the allowable vacuum at the crest is not to be exceeded.

It appears that equation $\eta = \frac{Q}{A\sqrt{2\,ga}}$, while it does not include the priming characteristics, would be a satisfactory criterion for comparing siphon performances, although in an actual design the construction cost may be of much importance. The efficiency may be increased by increasing the radii of the bends, by providing a long diverging tube, and by other means which, when carried to extreme, would involve a considerable increase in cost.

25. Priming characteristics. In installations in which siphons are to be used as water-level regulators, the interest is particularly in two factors; the head on the crest at which the siphon will prime, and the time required for the siphon to prime at this head. Both of these quantities are dependent upon the size and shape of the siphon and upon the rate of rise of the forebay level. Many investigators have attempted, in model tests, to determine the head required to prime when the forebay level was rising at a constant rate. They define the head required to prime for a specific rate of forebay rise as that head on the crest at the instant when all air is evacuated from the siphon. To establish this quantity, three variables, the time, the forebay level, and the quantity of discharge must be considered. Model data obtained by this procedure is subject to inaccuracies unless elaborate apparatus is used. Moreover, model data on priming characteristics cannot be scaled to the prototype. Therefore, the only value of such data is for comparison of priming qualities of models of the same scale. A more accurate and a simpler expedient is to determine the minimum head required to prime with a constant level of the forebay. This eliminates one variable, the rate of forebay rise, and is analogous to the situation in which the forebay area is large, with

the consequent slow rise in the forebay level resulting in the siphon priming, for all practical considerations, at a constant head on the crest.

Some experimenters have expressed the head required to prime in terms of depth at the throat section. Thus

$$h' = \frac{d}{k}$$

where

h' = head on crest required for priming,

d = depth of throat section,

k = priming constant.

If the throat depth were 3 feet and the head to prime were 0.5 foot,

$$k = \frac{d}{h'} = \frac{3}{0.5} = 6, \text{ or } h' = \frac{d}{6}$$

This expression suggests that the head required to prime is a function of the depth at the throat section, whereas the head to prime actually depends upon the shape of the siphon and the method employed to effect priming. Considering the rate of priming, a better criterion than the time alone would be the mean rate at which the air is evacuated. This latter value would take into account not only the time but also the volume of air to be exhausted.

26. Priming devices. In siphon installation where quick priming at a low head is one of the foremost considerations, various devices have been employed to decrease the head and the priming time. In one type, the effective crest was lengthened by zigzag metal strips embedded in the concrete of the crest. One investigator[18] claims the priming time was reduced 23 percent by use of the best type of zigzag crest or teeth as compared with that of the crest using no teeth. He fails to state the effect of the zigzag crest on the coefficient of discharge or the efficiency of the siphon. Obviously, during priming, with the same head on the crest, such a device would increase the discharge as compared with a straight, smooth crest, and therefore decrease the time to prime. However, when flowing full the loss over such a sharp and irregular crest would be higher

than the loss when a smooth crest was employed.

Another device is the priming weir. It is similar to the type with the castellated or zigzag crest in that it also has a crest of increased length which discharges more water per unit head than the ordinary siphon during priming. The weir is at the elevation of the crest; is connected to the crown of the lower leg; and is supplied with water by a channel which communicates with the forebay. Usually this priming device is used in siphons where the lower leg is not vertical but slopes downstream. The jet from the priming weir crosses the lower leg, sealing the air in the crown. The air in the crown is gradually evacuated and priming is produced. In the Bear River siphons,[19] a priming weir was used, and tests on the prototype structure indicated that when using this device the head required to prime was reduced to about half that when a priming weir was not used. Neither the priming weir nor the device using a castellated crest have met with much approval. It is felt that the advantage due to the lower priming head is more than offset by the reduction in the efficiency.

On many of the earlier installations requiring a low priming head, a small auxiliary siphon is used. The purpose of the auxiliary siphon is to reduce both the head and the time required to prime. This was accomplished in one of two ways. In the first, the auxiliary siphon discharged an unbroken jet obliquely across the lower leg of the main siphon, thus producing an airtight seal. The air trapped above the seal was gradually evacuated by the sheet of water flowing over the crest of the main siphon, and priming was effected. In the second case the auxiliary siphon primed and then acted as an ejector, drawing air from the main siphon until priming was completed. The disadvantages of the auxiliary siphons again outweigh the advantages. They are not only difficult but expensive to construct. Usually they act as an obstruction to flow in the main siphon, and because they are necessarily small, there is also the danger that they may become fouled with trash.

Although not a priming device in a strict sense, the sealing basin plays an important part in the priming of the siphon. On this point almost all authorities agree. After the forebay level has risen and covered the air vent, if the siphon is equipped with a sealing basin the interior of the siphon is then sealed completely. No air can enter. Air bubbles are then carried down by the jet into the sealing basin, where they are released to rise downstream from the lower bend and are thus exhausted to the atmosphere. Some designers consider that for best priming qualities, the radius of the lower bend must be sharp, even to the point of becoming a knife edge. The disadvantages of a sealing pool are that if the rate of rise of the forebay level is rapid, the air trapped in the interior of the siphon may be compressed. Furthermore, the sealing pool decreases the efficiency of the siphon somewhat. The advantages are the great reduction in the head and priming time.

Probably the most common method of producing priming in a siphon is

to induce the jet to leave the invert and cross the lower leg to impinge
at an acute angle on the lower leg crown, thereby producing a seal. The
methods of bringing this about vary. In some cases the lower leg is sud-
denly bent downward; in others, there may be a double bend to produce the
desired result. A small spur or step may be employed. The step or joggle
may be either with or without a sealing pool. If both the step and the
sealing pool are employed, it is advantageous to locate the step so that
the jet will strike the crown close to the outlet lip.

CHAPTER IV

EXPERIMENTAL INVESTIGATION OF SIPHONS

27. Experimental procedure. To obtain the various criteria of siphon
performance - coefficient of discharge, efficiency, and the head-discharge
relation - it was necessary to calibrate the model for a wide range of
total operating heads. The discharge was measured by venturi meters. In
test 1-2 (figure 15b), where the exit was not sealed by the tailwater, the
total head was measured from the forebay water level to the [illegible] of the
lower bend. In test 2-1, figure 15b, the head was measured from the fore-
bay water level to the elevation of the center of curvature of the lower
bend crown, except when the diverging tube was made to flow full by in-
creasing the tailwater. The tailwater elevation, to produce this condition,
corresponded very closely with the elevation of the crown at the exit sec-
tion. Thus, when the diverging tube was flowing full, the head was mea-
sured from the forebay level to the exit crown elevation. All the per-
formance characteristics of the siphon models, with the exception of the
priming qualities, were determined from these measurements.

Many investigators have determined the minimum head required for
priming, using a rising forebay water level, and define it as the head at
which the siphon primes, when the rate of rise is a given value. When
thus defined, the head required to prime is a function of the rate of rise
of the forebay water level for any given siphon. To duplicate in the
model a given prototype constant rate of rise, two factors must be varied:
(1) the head on the siphon crest must be increased at a constant rate; and
(2) the discharge must be increased at a varying rate in order to maintain
this constant rate of rise in the forebay water level. To follow this pro-
cedure with any degree of accuracy is difficult. If it is not accurately
done, the result is meaningless. It has already been pointed out that
even with three models at different scales, the prototype priming head can-
not be predicted too accurately. For these reasons it was decided to em-
ploy a simpler method of determining the minimum priming head. This pro-
cedure required the variation of only one quantity, the discharge. In the
model tests on the siphons of Spillway No. 2, a condition of flow was
established so that the siphon model would not prime in any length of time.
By increasing the head on the crest by small increments, the minimum head
required to prime was determined. This procedure was not only simpler,

but also resulted in much greater accuracy than could have been obtained by employing a rising water level. Furthermore, this procedure probably duplicates prototype conditions more closely than the others, since the rate of rise of the forebay water level is usually slow enough to be considered constant, except in the case where the forebay free water surface area is relatively small.

In determining the time to prime at the minimum priming head, the siphon was vented to the atmosphere to prevent priming during the time flow equilibrium was being established in the model. When the head on the crest was accurately set and equilibrium of flow existed, the air vents to the siphon were closed. The time required to prime was recorded as the elapsed time from the instant the air supply was cut off until the air was completely exhausted from the siphon.

In Wasteway No. 2 a bore causing an 0.88-foot head on the siphon crests will be formed if the turbines in the power plant are suddenly shut off. It was desired to determine the time required for priming under this practically instantaneous head, and this was accomplished in the model by raising the water in the forebay from normal elevation to the bore height level as quickly as possible and maintaining the 0.88-foot head during the priming action. The time required to prime under this condition was recorded as the elapsed time from the instant the water in the forebay began to rise until the siphon was completely primed.

The minimum discharge for continuous operation was considered a sensitive indicator relative to the priming characteristics and was therefore obtained in most cases. The heads on the crest of the siphon corresponding to various discharges through it were also determined.

25. <u>Original model (Test 1-1).</u> In the original design (figure 15D), the lip of the siphon was placed at the normal forebay water elevation so that the siphon would break its prime when the water was lowered to that level. A hump was placed in the exit tube to establish a water seal at the lower bend. Tests proved that this sealing pool was ineffective in facilitating priming. The flow followed the invert from the crest through the lower bend and removed the water in the sealing pool, thus rendering it useless. When a head on the crest equivalent to 1.33 feet prototype was attained, the jet sprang free from the crest and, crossing the lower leg, impinged on the opposite wall, forming a curtain seal. Priming quickly ensued.

When the siphon model was flowing full, the actual was far below the designed capacity. The designed discharge was 950 second-feet for four siphons, or 237.5 second-feet for each, at a head on the crest of 0.88 feet. At this head the discharge, as determined from the model, was only 153.5 second-feet, or 64.6 percent of the designed value.

The efficiency, computed by the equation

$$\eta = \frac{Q}{A\sqrt{2\,ga}}$$

was only 16.13 percent. At the designed head, the model showed a coefficient of discharge of 0.365 as compared to 0.65 which was used in the design. It was apparent that the hump in the exit tube was the source of much loss and, since it was ineffective in producing a sealing pool, should be eliminated.

A large eddy zone downstream and immediately below the crest of the original model indicated a definite loss due to sharpness of the upper bend. The water could not follow the inner radius and tended to crowd against the outer radius forming the eddy zone. The profile of the water passage in test 2-1 (figure 16D) was designed to follow the flow path and to eliminate the eddy zone indicated visually in the original.

The original model had a transparent face only on the front, which was a handicap in photographing the flow pattern. When the model was rebuilt for test 2, both faces were made transparent so that light could be reflected through the flow.

29. Removal of hump in original design (Test 1-2). When the hump was removed, the exit tube became diverging, as shown dotted in figure 15D. This change eliminated the double bend. The priming qualities were not affected by the change, but the discharge characteristics were improved considerably. With the outlet free, the discharge was 187.0 second-feet, an increase of 21.8 percent over the original model. The coefficient of discharge and efficiency were increased proportionately. When tailwater sufficient to submerge the exit was obtained by a control in the effluent channel, the discharge was increased to 205.8 second-feet, or an increase of 34.1 percent. This value was still considerably below the required discharge. A new model was then designed in which attention was given to reducing losses and thereby increasing the discharge.

30. Effect of increase of crest and lower bend radii (Test 2-1). Tests 1-1 and 1-2 showed that the entrance conditions could be improved; that the crest and lower bend radii should be increased; and that a diverging tube was a decided advantage in increasing the discharge when the exit was submerged. These features were incorporated in the model (figure 16D). The shape of the crest is a close approximation to the curved path described by the lower nappe as it sprang free from the crest of the original model, flowing under a 1.33-foot head. A 1-inch offset was introduced below the crest to cause the jet to spring free from the invert at that point, to facilitate priming, and provisions were made for aeration of the lower nappe at the offset by a vent to the atmosphere. The

lower leg was made in an S-shape to improve the priming characteristics and increase the efficiency. Tests showed that with the outlet free, the discharge, with a head on the crest of 0.88 foot, was increased to 270.4 second-feet, an increase of 44.6 percent over test 1-2. When the outlet was submerged, the discharge at the same head was 371.1 second-feet, or 80.3 percent greater than in test 1-2 with the outlet submerged. The diverging tube did not flow full (figure 17A) when the outlet was not submerged, even with a discharge of 317 second-feet and a head on the crest of 4.10 feet, the maximum possible head in the model. Figure 17B shows the diverging tube flowing full as the result of submerging the exit. For this condition, the maximum capacity of the model supply pump was reached before the maximum head on the crest could be obtained. Dye was introduced to show the stream lines. The priming characteristics for this model, when the outlet was free, were inferior to the original. The minimum head required to prime was 2.37 feet, with the nappe unaerated, giving a priming efficiency of d/1.27. With the nappe aerated and the outlet free, the minimum priming head was 1.53 feet, giving a priming efficiency of d/1.96.

The nappe, clinging to the invert, can be seen in figure 18A. Figure 18B shows the aerated nappe springing free at the offset, crossing the lower leg and forming a seal at the opposite side. When a seal at the lower bend was effected by controlling the tailwater and with nappe aerated, the minimum priming head was reduced to 0.45 feet, less than three-tenths of the value found with nappe aerated and the outlet free. With the nappe aerated and the outlet unsubmerged, the jet sprang free from the invert at the offset, crossed the lower leg, and impinged on the opposite side, thereby sealing the upper part of the siphon from the lower (figure 18B). The sheet of water flowing past the crown of the lower bend and dropping to the invert was broken and allowed air from the diverging tube to pass through it, maintaining a pressure of practically atmospheric intensity in the region below the nappe. The upper surface of the nappe gradually evacuated air from the space above it, and since the pressure below the nappe remained practically atmospheric, a difference in pressure between the upper and lower parts of the siphon, thus divided by the jet, was gradually created. When this difference in pressure reached a certain value, the nappe began fluttering, the intensity increasing until suddenly the seal between the upper and lower parts of the siphon was broken and the pressures equalized. With an increase of head on the crest, the nappe thickness increased, the duration of the fluttering motion became longer until at a head of 1.53 feet the thickness of the nappe was sufficient to maintain the pressure difference, and after a short period of nappe flutter, the siphon primed. With no sealing pool at the lower bend, the minimum head required to prime becomes that head which will produce a jet of sufficient thickness and velocity to maintain a seal without breaking. With sufficient tailwater, the sealing pool maintains the pressure difference, and the minimum head necessary for priming is that which produces a jet of size and velocity sufficient to penetrate the sealing pool to a point where the entrained air will rise downstream from the lowest part of the crown of the lower bend. The minimum priming head in the second case [illegible] than in the first, where no seal at the lower bend was provided. [illegible] sealing pool proved a definite advantage in priming and was incorporated in the subsequent test. A further increase in the radii of the crest and lower bend, and a decrease in the depth at the throat section was also indicated.

31. <u>Reduction of throat depth and further increase of crest and lower bend radii (Test 3-1).</u> The depth at the throat section was reduced from 3 feet to 2 feet 2 inches, making the ratio of the radius of the center line to the depth at the throat section R/D = 2.345, as compared to an R/D = 0.61 for the original model and an R/D = 0.83 for test 2-1. At a point 60 degrees down from the crest a transverse slot vented to the atmosphere, semicircular in section and with a 2-inch diameter, was included instead of the offset in test 2-1 to facilitate aeration of the nappe. The angle of divergence of the exit tube was made 8 degrees 30 minutes, which Gibson considered the optimum following a right-angle bend. Since the depth of the barrel at the start of the diverging tube had been decreased to 2 feet 2 inches, and because the depth at exit was fixed at 4 feet by the size of the effluent conduit, the length of the diverging tube was necessarily greater than previously. A seal at the lower bend was effected by locating the low point of the crown of the lower bend at the same elevation as that of the invert at the outlet section (figure 19D).

In test 3-1, the diverging tube always flowed full at the designed head of 0.88 foot, and the discharge at this head was 331.1 second-feet, a decrease of 10.8 percent as compared with test 2-1 with the outlet submerged. Because the throat area of this model was decreased 27.8 percent as compared with test 2-1, the decrease in discharge was expected.

The seal at the lower bend presented a new problem. As the water level in the forebay rose above the lip of the hood, air trapped in the siphon was compressed, with the result that the water level inside the siphon was less than the forebay water level. With this condition, the time of priming was increased. A compression relief tube (figure 19D) was installed connecting the upper part of the siphon with the diverging tube at a point such that its lower end would be sealed when the head on the crest was 0.88 foot. With the compression relief tube open, the minimum head to prime was 0.96 foot; the minimum head was 0.68 foot. Figure 20A is a view of test 3-1 flowing at the minimum discharge for continuous operation.

32. <u>Effect of step in crown of exit (Test 3-2).</u> A study of the sealing pool showed that many of the air bubbles which had passed the lowest point of the crown of the lower bend were carried back into the lower air zone of the siphon by water currents created by the jet entering the sealing pool. In an attempt to prevent this action and thereby decrease the time of priming, a step two inches deep was cut in the crown of the diverg-

ing tube (figure 19D). The step was not effective in improving the priming qualities.

33. Addition of spur above aeration slot (Test 3-3). It appeared that if the jet could be made to cross the lower leg and impinge upon the opposite side that it would cling to that side as it dropped into the sealing pool and the priming characteristics would be improved. To accomplish this end, a spur was installed above the aeration slot (figure 19E). This spur deflected the jet excessively so that it impinged too high on the opposite side.

34. Increase of spur radius (Test 3-4). A revised spur with a longer radius (figure 19E) deflected the jet the right amount. By reference to the summary of performance characteristics on figure 19, it will be seen that the effect of the spur used in test 3-3 was to decrease the discharge by only 8.3 second-feet, or 2.5 percent, while at the same time, the minimum head required to prime was decreased by 0.12 foot, or 17.7 percent. The time required to prime at this minimum head, as indicated by the model, was 10,350 seconds or almost 3 hours. Although it was known that the priming qualities in prototype would be better than indicated by the model, a further improvement was desired. During tests on the longer radius spur, it was observed that priming would start with a very low head on the crest and several large bubbles were noted to be in motion in the center of the crown (figure 20B). After a negative model pressure of about 0.02 foot of water was developed, the priming action would cease. That is, when the test was first started, a few air bubbles would escape beyond the low point of the crown of the lower bend, but after a few minutes, the depth of the seal was increased due to the negative pressure inside. Although the sealing pool was charged with bubbles, few, if any, could escape past the crown of the lower bend because of the increased depth of seal. It was not until a head of 0.56 foot on the crest was reached that priming action continued. A study of the priming phenomenon led to the development of a new priming device.

35. Guide vane in lower bend (Test 3-5). A guide vane spaced two inches from the crown of the lower bend was installed in the model (figure 19F). The purpose of the vane was to give the air-laden priming jet a horizontal direction so that the air released in the sealing pool would rise downstream from the lower bend. The guide vane was very successful in this respect. Figures 21A and B show the siphon during priming when the head on the crest was 0.51 foot and with air escaping from the end of the priming guide vane during flow at the minimum head to prime. There is a complete absence of air bubbles in the left side of the sealing pool. The absence of air is even more striking when compared with figure 20A or figures 22A and B in which the guide vane was not used. The minimum head required to prime was reduced to 0.15 foot, giving a priming efficiency of d/14.45. At this head the siphon primed in 690 seconds with the compression relief tube closed. At a head on the crest of 0.88 foot, the siphon

primed in 130 seconds with the compression relief tube open and 138 seconds when closed.

The discharge of the siphon was decreased by 28.6 second-feet or 8.9 percent, due to the interference of the priming vane. There were, however, much more serious objections. It was felt that trash might fill the small space between the vane and the crown, or that ice might bend or break it.

36. Trashrack in guide vane entrance (Test 3-6). To overcome the objection that trash might plug the space between the guide vane and the crown, another vane was designed incorporating a trashrack (figure 19G). Furthermore, the passage between the crown and the vane was diverged slightly. With this device the siphon primed at the same head as it did with the original vane, but it required a much longer time. The discharge characteristics were worse than in the former case. For these reasons, the priming vane was not considered to be entirely satisfactory, and another approach to the problem was tried.

37. Transverse priming slot with air-escape tube (Test 3-7). A transverse priming slot cut in the crown of the lower bend was connected by a 6- by 8-inch air-escape tube to the downstream end of the diverging outlet tube (figure 19I). The minimum head required to prime was 0.16 foot, the same as when the guide vanes were used, but the priming time at this head was considerably reduced. The time to prime at a head of 0.88 foot was reduced to 78 seconds. The discharge characteristics were superior to those when the guide vane was used. When the siphon was running full, it was noticed that there was a circulation of water back from the diverging tube to the priming slot. A test was made in which the air-escape tube was choked such as to allow air flow but impede water flow back through the tube. The effect of closing the air-escape tube in this manner was to increase the discharge 2.1 percent. Compared with test 3-4, the effect of the priming slot on the discharge with the air-escape tube open was to decrease it by only 1.2 percent.

38. Enlargement of priming slot and air-escape tube (Test 3-8). The original priming slot appeared to be inadequate, so it was widened, the corners of the entrance rounded, and another air-escape tube added (figure 19J). Experiments indicated that the minimum priming head remained unchanged, but the time required for priming was reduced by 58.7 percent, or to 166 seconds, as compared with 402 seconds required for the original priming slot. The time to prime at a head of 0.88 foot was reduced by 29.5 percent, or to 55 seconds, as compared with 78 seconds for the original priming slot. By rounding the edges of the priming slot, the discharge was increased only 1.4 second-feet, or 0.44 percent. When the air-escape tubes were choked to prevent return water flow, the discharge was increased by 2.5 percent, compared with the original priming slot operating under the same conditions. The model showed further that

check valves in the air-escape tubes to prevent this return flow might justify the expense of installation, since by using them the discharge could be increased by 4.2 percent, or the efficiency increased by 2.35 percent.

When the priming slot was used, the compression relief tube was omitted. The spur, however, was considered quite essential, since it caused the jet to strike the side of the lower leg opposite the crest, where it tended to cling to the crown of the lower bend, thereby giving the released air bubbles a downstream direction as they passed through the sealing pool. When the jet does not first strike the wall opposite the crest before entering the sealing pool, as with the spur, a large portion of the entrained air returns to the air zone below the under nappe and hinders priming. The action of the jet with and without the spur is illustrated in figure 19D. By using the spur, the area in the vicinity of the priming slot is more densely charged with air.

39. Pressure equalizer (Test 3-8). The priming of a siphon consists essentually of evacuation of the air in the structure and replacing it with a flow of water, which may be accomplished by some outside agency such as an air pump, providing the entrance and exit are closed by water seals. In large structures, under automatic operation this is not economical or completely practical; so the jet of water flowing over the crest must be made to perform that function.

The pressure equalizer (figure 19D) was introduced to increase the effectiveness of the jet. The offset in test 2-1 and the 2-inch semi-circular transverse aeration slot in test 3-1 were introduced to disrupt the continuity of the viscous force which caused the thin sheet of water to cling to the invert and not break free to impinge on the opposite wall to form a seal. As the flow passed the offset or slot, an eddy was formed which bridged the gap and allowed the water to continue to cling. In the first attempts to remedy that condition the offset or slot was vented to the atmosphere to relieve the subatmospheric pressure in the eddy. As the tests progressed, it became apparent that with such aeration the reduction in pressure in the upper air zone deflected the jet upward, causing it to impinge at an adverse angle and rebound. This tended to defeat the purpose of the jet deflection. Since the air above the jet had to be evacuated to prime the siphon and air was being taken in from the atmosphere to relieve the low pressure under the nappe at the aeration slot, the idea was advanced to take the air needed in the aeration slot from the upper zone, from where it had to be removed anyway. The pressure equalizer shown in figure 19D was installed to perform this dual function. It equalized the pressure in the two air zones, stabilizing the jet and allowing it to impinge at the optimum angle. Instead of the lower nappe removing the air drawn in through the aeration slot, it, in effect, assisted the upper nappe in evacuating the air in the siphon. When the aeration tube is not used and the slot is vented to the atmosphere, there is a considerable rebound, with the result that the center of gravity of the air-charged area in the sealing pool lies farther from the priming slot. The effect of this is to increase the priming time. Figure 22A shows the normal jet with the pressures balanced by the pressure equalizing tube, and 22-B, the condition with a difference in pressure between the upper and lower parts of the siphon when the pressure equalizer is not used.

40. Longitudinal slots in lower bend crown (Test 3-9). A series of longitudinal slots in the crown of the lower bend were considered as a possible means of improving the priming characteristics of the siphon by an action similar to that of the priming guide vane. Such a device is shown in figure 19H. The results were disappointing.

41. Fillet in aeration slot (Test 3-10). The aeration slot used in previous designs to expedite priming was filled with modeling clay to permit evaluation of the loss due to the eddy in the slot when the siphon was flowing full (figure 19E). The model indicated that the fillet increased the efficiency by approximately one percent. Subsequently the same measurement was made in test 4-1, with comparable results (figure 23D). This fillet resulted in a slight increase in efficiency but showed a definite tendency for the jet to cling to the siphon invert at low heads. Moreover, aeration would be more difficult with the fillet.

42. Sharp lower bend radius (Test 4-1). Some authorities believe that the radius of the lower bend must be small to obtain good priming characteristics and that priming efficiency is gained at the expense of the siphonic efficiency. A new model was constructed, essentially similar to the model in test 3-1 except the crown of the lower bend had a radius of 8 inches instead of 48 inches (figure 23D). The minimum head required to prime was 0.14 foot, or a decrease of only 0.01 foot. Figures 24A and B show the process of priming. The priming and discharge characteristics are given in the table and curves, figure 23. The time to prime at the minimum priming head was 163 seconds, which compares favorably with [illegible] seconds, the time required to prime in test 3-8 when using the enlarged priming slot. The time to prime with a head of 0.88 foot was [illegible] seconds as compared with 55 seconds in test 3-8. Experimental error could account for some of this difference, but it would appear that the priming qualities in test 3-8 were superior at the 0.88-foot head. On the other hand, the value of the minimum discharge for continuous operation in test 4-1 is smaller than the value found in test 3-8, [illegible] second-feet for the former as compared with 21.7 second-feet for the latter.

The discharge characteristics in test 4-1 were inferior to those in test 3-8, 255.1 second-feet as compared with 320.4 second-feet when the air-escape tubes were open, or a decrease of 65.3 second-feet. Expressed in another way, the effect of increasing the radius of the lower bend was to increase the discharge by 25.6 percent, and, by using an appropriat priming device, there was no adverse effect on the priming qualities of the siphon.

CHAPTER V - ANALYSIS AND INTERPRETATION OF RESULTS OF SIPHON STUDIES

43. Effect of increasing crest radius. The discharge of the siphon was increased by lengthening the crest radius. Curves 3, 5, and 6 in figures 15C, 16C, and 19C give the relation between head and discharge for three models tested under similar conditions. The diverging tube, the crest length, and the outlet area were constant in all three tests. The throat area for curves 3 and 5 was the same, but the throat area for curve 6 was considerably reduced because of the material increase of efficiency due to lengthening of the crest radius and the desirability of reducing the size of the structure. The crest radii were 4, 11.84, and 48 inches, respectively. By comparison, curve 5 indicates a much higher discharge for the same head than either of the other two curves. The 11.84-inch crest radius gives the best results. However, the area of the throat section for curves 3 and 5 was 18 square feet, while the throat area of curve 6 was reduced to 13 square feet. In comparing the effect of the crest radius, the comparison should be on the basis of throat area. At a head on the crest of 2.0 feet, the discharge per square foot of throat area with a 4-inch crest radius was 12.1 second-feet; with an 11.84-inch radius, 21.9 second-feet; and with a 48-inch radius, 27.8 second-feet. By increasing the crest radius from 4 to 11.84 inches, an increase in discharge of 81.0 percent was obtained; and by increasing the radius from 4 to 48 inches, an increase in discharge of 129.6 percent was obtained. This increase in discharge was due to decreasing the losses. Increasing the crest radius was not alone responsible for the increased discharge, for, in all cases where the crest radius was enlarged, so also was the radius of the lower bend.

The head-discharge curves, in almost all cases, have a point at which a sudden change of slope occurs. It is at this point that the siphon ceases to draw air. The head at which this occurs varies with the particular design. The siphons having the best head-discharge curves also have the best efficiency curves. Efficiency, as defined in this discussion, may also be expressed as the square root of the ratio of the actual vacuum to a perfect vacuum at the throat section. As the discharge characteristics of a siphon are improved, so also will the efficiency or the vacuum at the throat be increased. The increased vacuum at the throat results in a greater entrance velocity, accompanied by a greater draw-down curve, with the ultimate result that the head on the crest at which the siphon ceases to draw air will be higher.

A comparison of the coefficient of discharge, curves 3, 5, and 6, on figures 15A, 16A, and 19A, indicate that by increasing the crest radius from 4 to 11.84 inches, the discharge characteristics were greatly improved; but when the crest radius was increased to 48 inches, the discharge characteristics were worse. Such is not the case, however, since no consideration is made of the area of the barrel from the throat section to the beginning of the diverging tube. If, on the other hand, the area of the throat section is used in computing the coefficient, a value greater than unity may result. This illustrates the inherent difficulties in using the coefficient of discharge as a measure of the effectiveness of the siphon.

For another example, consider curves 4 and 5 on figure 16A. Although the discharge was lower in the case of curve 4 than in curve 5, the coefficient of discharge is larger. The outlet area in the case of curve 4 was the same as the throat area, while in curve 5 the outlet area was 33 percent greater. The head for curve 4 was measured to approximately the center of curvature of the lower bend, since that was considered the point where atmospheric pressure was attained. The head used in computing curve 5 was measured to the surface of the tailwater, which was approximately the elevation of the crown at the exit section. Because both the area and the head were smaller, the coefficient shown by curve 4 is larger than in curve 5. This serves to illustrate another inconsistency of the coefficient as a measure of the effectiveness of a siphon.

The effect upon the efficiency of increasing the radius of the crest is shown by curves 3, 5, and 6 in figures 15B, 16B, and 19B. For a head of two feet, curve 3 shows an efficiency of 25.8 percent for the four-inch crest radius and curve 5 an efficiency of 46.7 percent for the 11.84-inch radius, or an increase of 20.9 percent. By increasing the crest radius to 48 inches, the efficiency as indicated by curve 6 was increased to 58.6 percent, more than double the value given by curve 3. This clearly illustrates the advantage gained by enlarging the radii of the bends.

44. <u>Effect of the diverging tube.</u> The use of a diverging tube increases the siphon discharge. Curves 4 and 5, figure 16C, illustrate this point. With a head of 0.88 foot on the crest, the discharge, when the action of the diverging tube was not utilized, was 270.4 second-feet. With sufficient tailwater to cause the diverging tube to flow full, the discharge was 371.1 second-feet, an increase of 100.7 second-feet or 37.2 percent. The diverging tube is an advantageous feature so long as the pressure at the crest does not too closely approach the vapor pressure of water.

The coefficient of discharge, as shown in the table on figure 16, is decreased when the diverging tube is in action. The coefficient without the diverging tube is 0.[illegible]1; but operating with it, the coefficient is decreased to 0.668. As previously explained, the head and the outlet area in the computation of the coefficient are the cause of this inconsistency.

Without the divergent tube action, the head was measured to the point where atmospheric pressure first occurred in the lower leg, approximately the center of curvature of the lower bend. The outlet area was taken as that of the lower leg at the same point. This area was the same as that of the throat. But in the case where the diverging tube was made to flow full, the head was measured to the crown of the outlet section and the area was that of the outlet section. Although the discharge in the second case was 100.7 second-feet larger than in the first, the increased outlet area and total head were sufficient to decrease the coefficient.

The efficiency in the same case was increased from 31.90 to 44.20 percent by employing the diverging tube. Thus the efficiency is a much better indicator of effect of the diverging tube upon the performance of the siphon than is the coefficient of discharge. The difference in efficiency gives an indication as to the amount by which the negative pressure at the throat is changed.

45. <u>Effect of priming devices upon efficiency.</u> One of the principal purposes of the Roza Wasteway siphon investigation was to determine the relation between good priming qualities and siphonic efficiency. After an efficient siphon design was obtained at a reasonable cost, figures 15B, 16B, and 19B, attention was concentrated upon the priming characteristics. Many previous investigators have concluded that high siphonic efficiency is incompatible with good priming qualities and that for high priming efficiency the radius of the lower bend should be very small, with a water seal in the lower bend. Curves 8 to 15, inclusive, figure 19B, illustrate the effect on efficiency of progressively improving the priming characteristics. Curve 15 shows that the efficiency of the model in test 3-8 is about as high as that of any model tested. Furthermore, the priming characteristics of that model were as good as any of the various models tested which included test 4-1 having a sharp curvature at the lower bend. Curve 18 represents the efficiency of a model with a sharp lower bend, and, when compared with curve 15, the conclusion is that the radius of the lower bend does not have to be sharp to develop good priming characteristics. Furthermore, good priming characteristics are not necessarily incompatible with high siphonic efficiency. Results of the investigation confirm the fact that for good priming characteristics a water seal at the lower bend is essential.

46. <u>Siphon inlet section.</u> The entrance conditions in test 3-1, figure 19D, were satisfactory for all heads except those that allowed air to enter the siphon. Under the latter conditions, the model vibrated. To alleviate this condition it was recommended that the lip of the hood of the siphon be extended below normal forebay level and a pipe for breaking siphonic action be incorporated in the prototype design.

- - -

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FIGURE 1

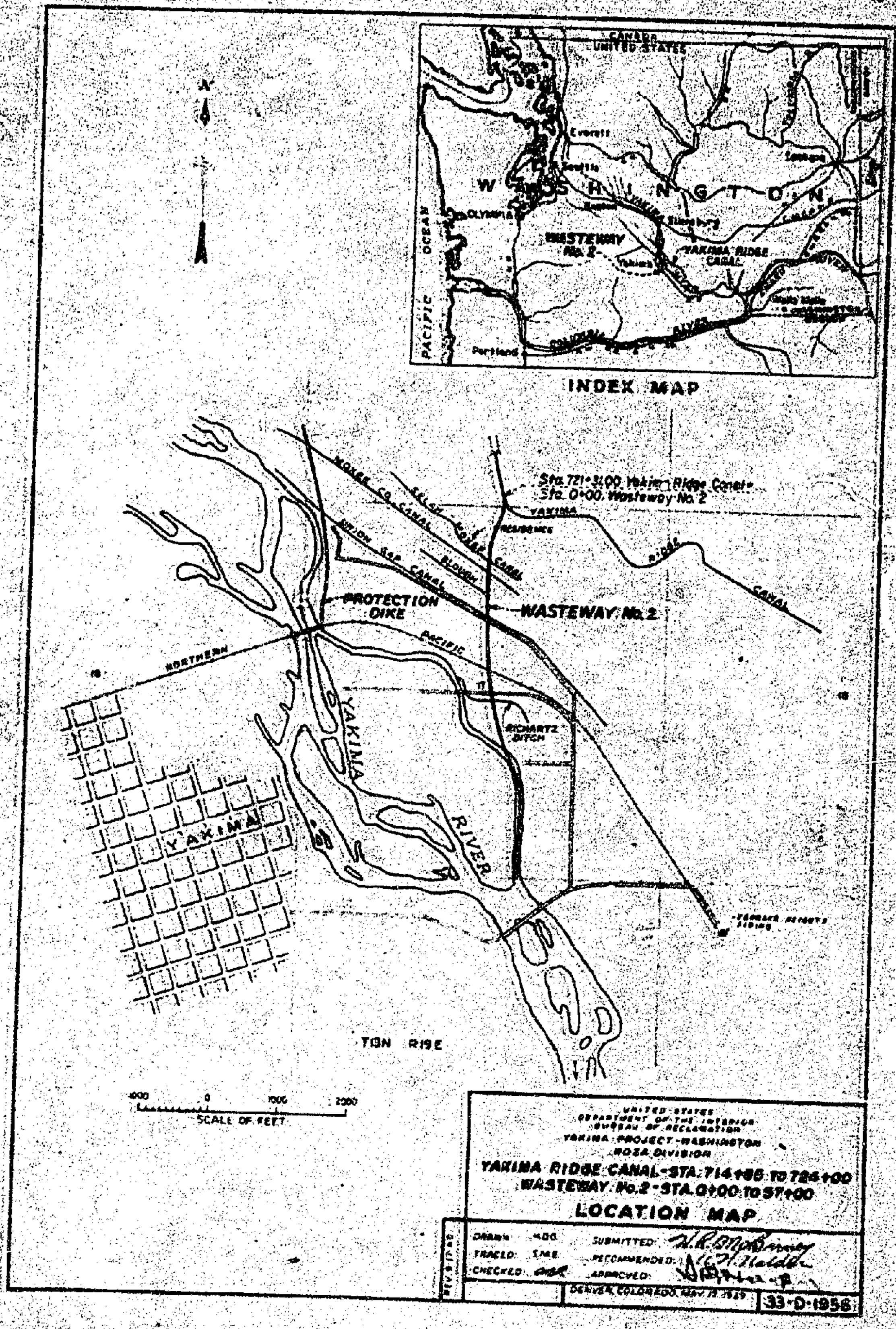
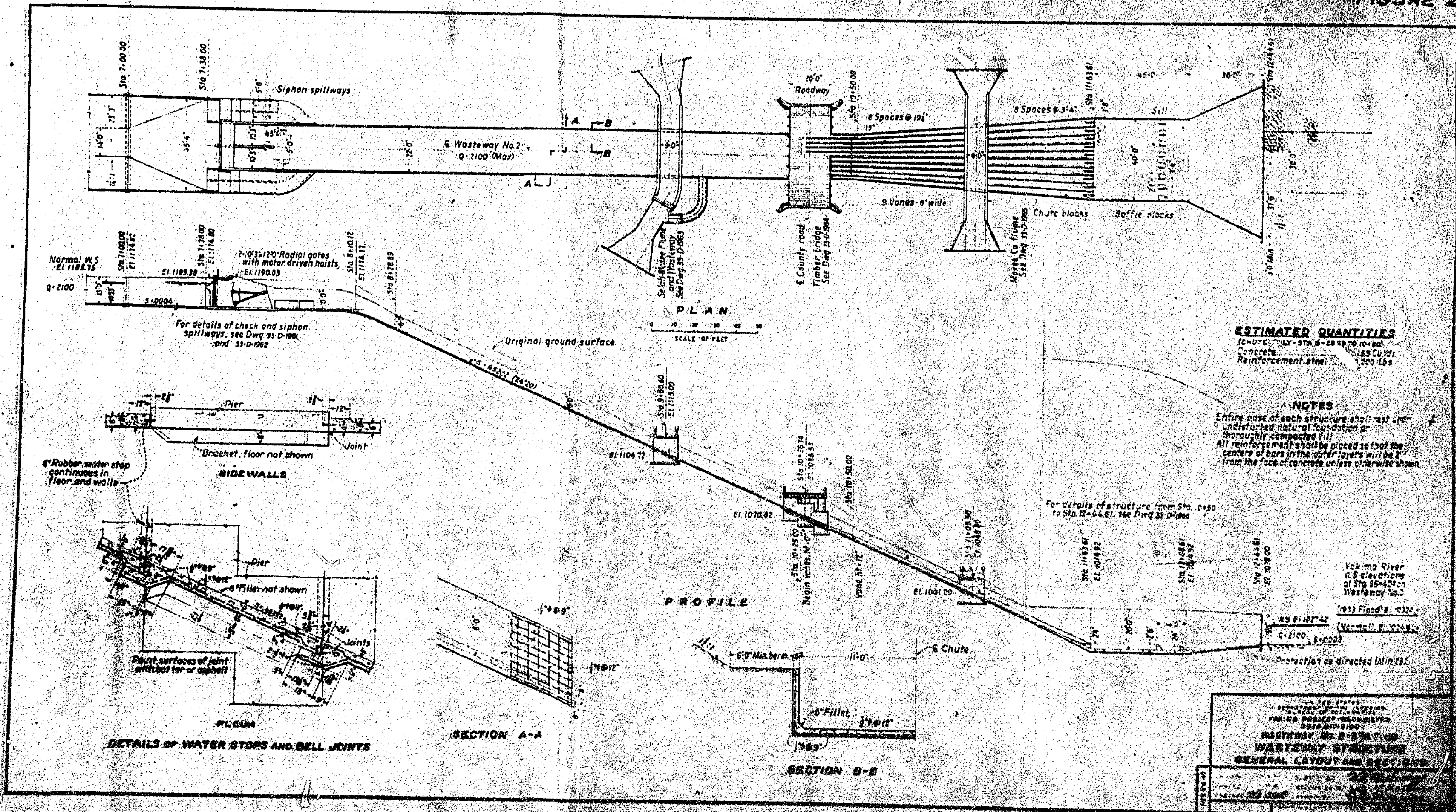
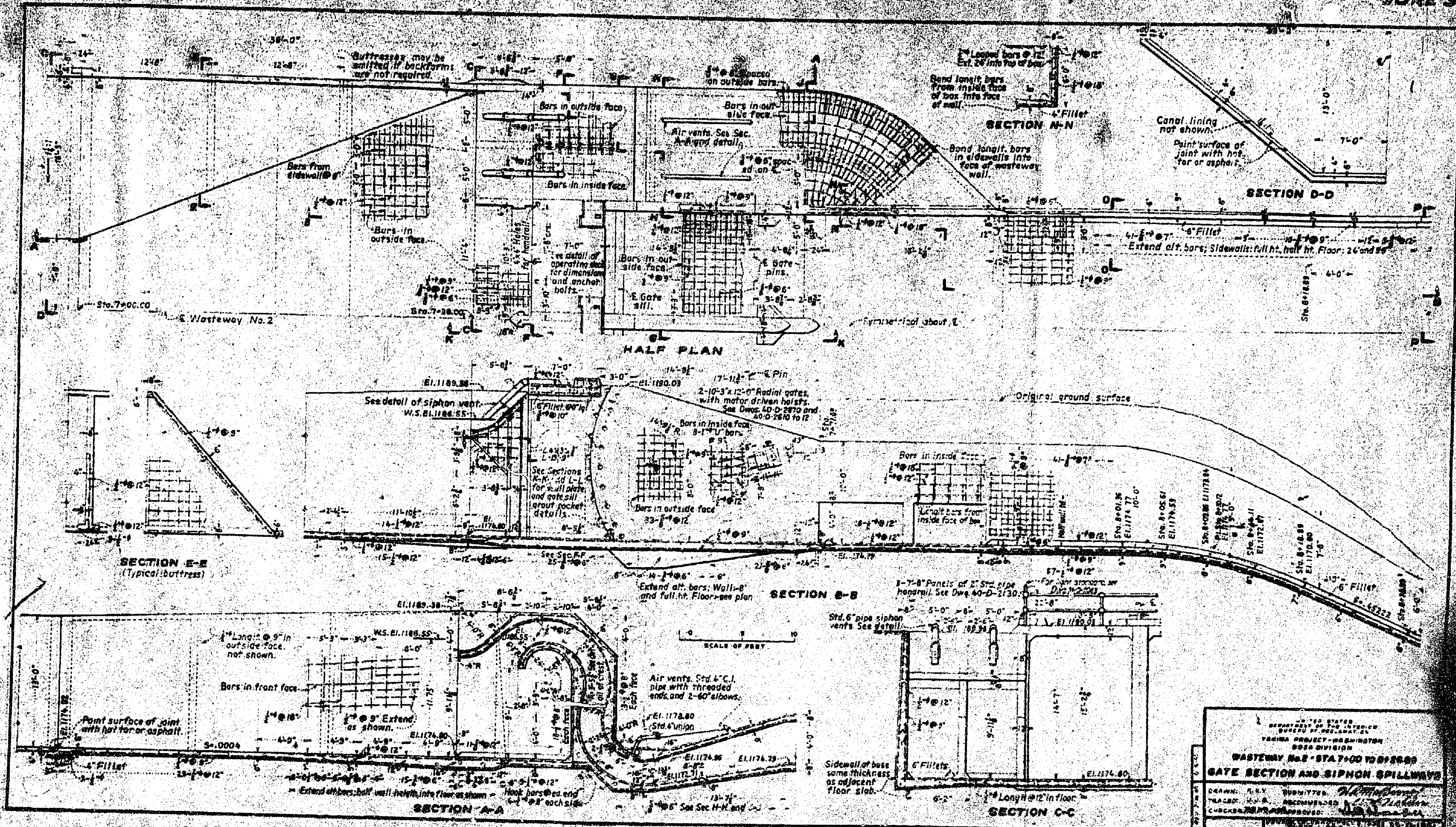

INDEX MAP
CANADA
UNITED STATES
Everett
Seattle
Spokane
W A S H I N G T O N
OLYMPIA
Ellensburg
WASTEWAY No. 2
Yakima
YAKIMA RIDGE CANAL
PACIFIC OCEAN
COLUMBIA RIVER
Portland
Sta. 721+31.00 Yakima Ridge Canal = Sta. 0+00 Wasteway No. 2
YAKIMA
RIDGE
CANAL
PROTECTION DIKE
WASTEWAY No. 2
NORTHERN
PACIFIC
RICHARTZ DITCH
YAKIMA RIVER
YAKIMA
T13N R19E
SCALE OF FEET
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
YAKIMA PROJECT-WASHINGTON
ROZA DIVISION
YAKIMA RIDGE CANAL-STA. 714+88 TO 724+00
WASTEWAY No. 2-STA. 0+00 TO 57+00
LOCATION MAP
DRAWN
TRACED
CHECKED
SUBMITTED
RECOMMENDED
APPROVED
DENVER, COLORADO, MAY 19, 1949
33-D-1958

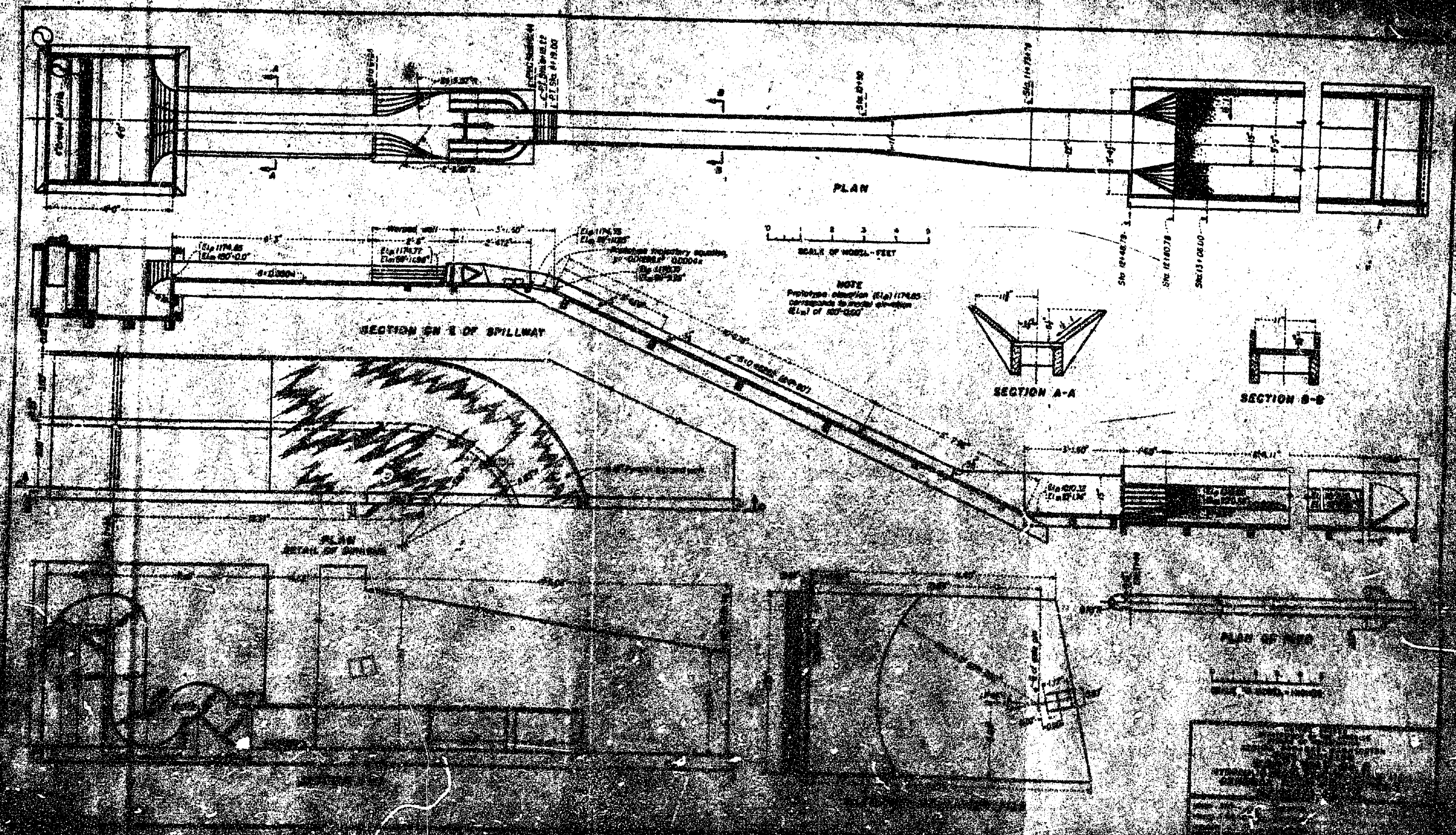
FIGURE 2



Siphon spillways
Wasteway No. 2
Q = 2100 (Max)
Roadway
8 Spaces @ 3'-4"
9 Vanes - 6" wide
Chute blocks
Baffle blocks
Sill
County road
Timber bridge
PLAN
SCALE OF FEET
Normal W.S. El. 1182.75
2-10'3"x12'0" Radial gates with motor driven hoists
For details of check and siphon spillways, see Dwg. 33-D-1961 and 33-D-1962
Original ground surface
PROFILE
ESTIMATED QUANTITIES
Concrete
Reinforcement steel
NOTES
Entire base of each structure shall rest upon undisturbed natural foundation or thoroughly compacted fill.
All reinforcement shall be placed so that the centers of bars in the outer layers will be 2" from the face of concrete unless otherwise shown.
Pier
Bracket, floor not shown
Joint
6" Rubber water stop continuous in floor and walls
SIDEWALLS
6" Filler not shown
Joints
Paint surfaces of joint with hot tar or asphalt
DETAILS OF WATER STOPS AND BELL JOINTS
SECTION A-A
6'-0" Min. berm
Chute
6" Fillet
SECTION B-B
Yakima River
Protection as directed
WASTEWAY STRUCTURE
GENERAL LAYOUT AND SECTIONS

FIGURE 3


HALF PLAN
SECTION N-N
SECTION D-D
SECTION E-E
(Typical buttress)
SECTION B-B
SECTION A-A
SECTION C-C
Buttresses may be omitted if backforms are not required.
Wasteway No.2
Symmetrical about ℄
Original ground surface
Canal lining not shown.
Paint surface of joint with hot tar or asphalt.
SCALE OF FEET
WASTEWAY No.2 - STA.7+00 TO 8+26.80
GATE SECTION AND SIPHON SPILLWAYS


PLAN
SECTION ON ℄ OF SPILLWAY
SECTION A-A
SECTION B-B
NOTE
PLAN

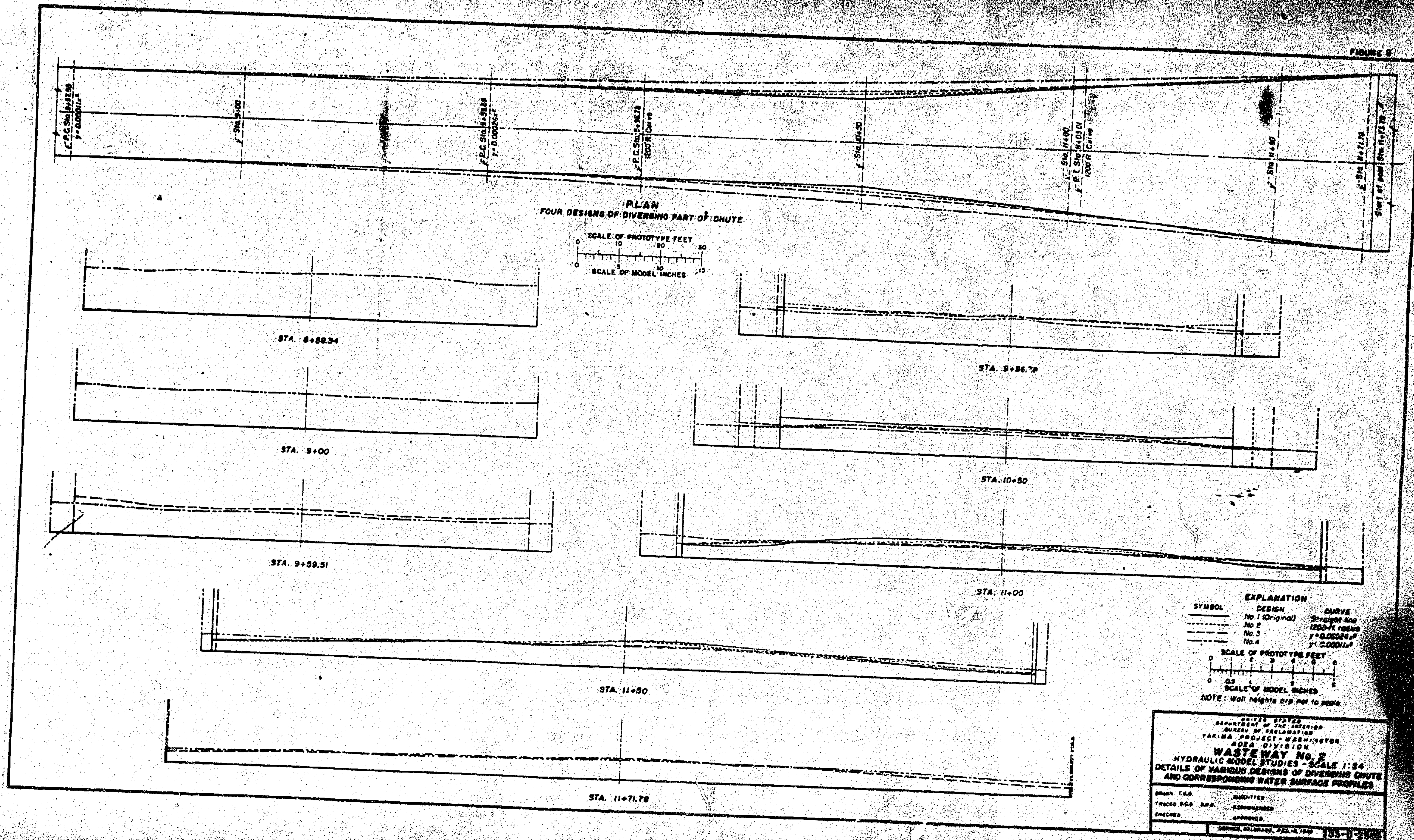
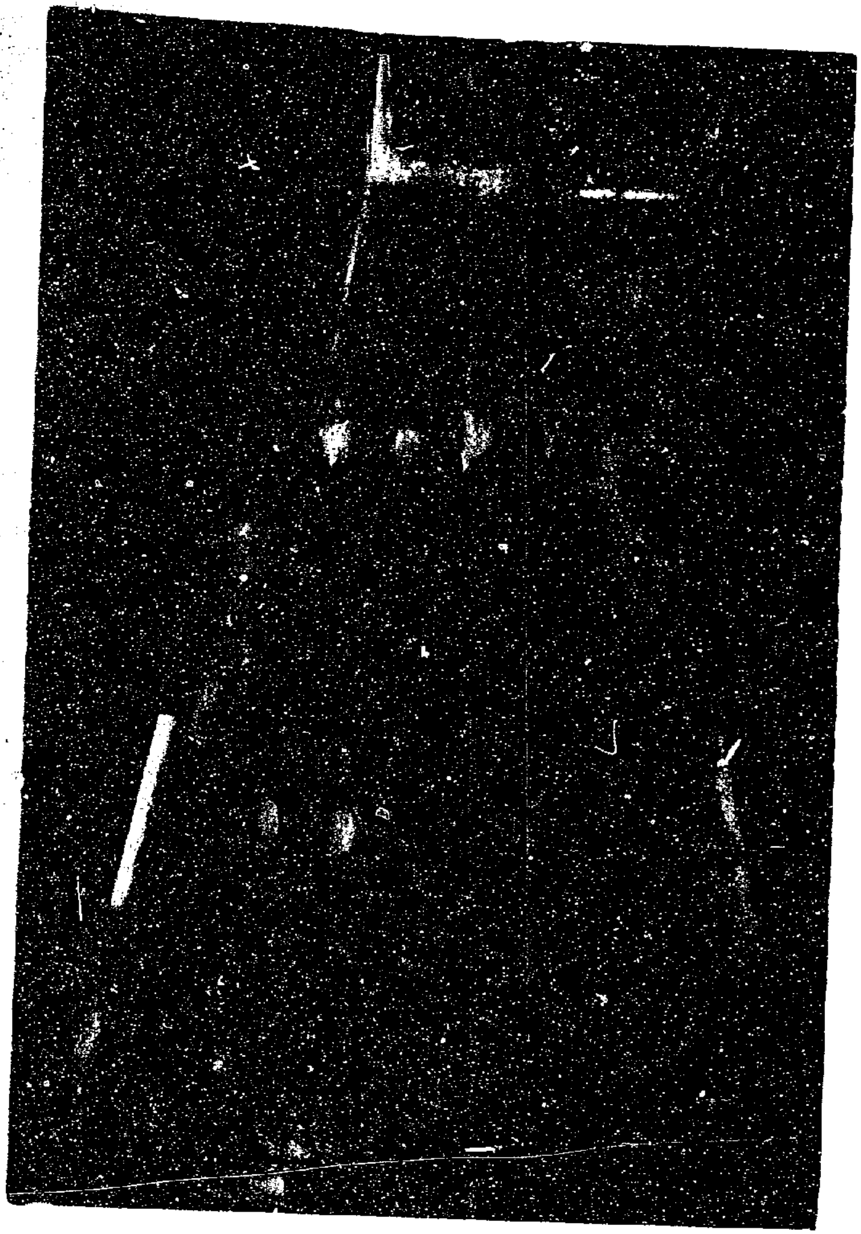
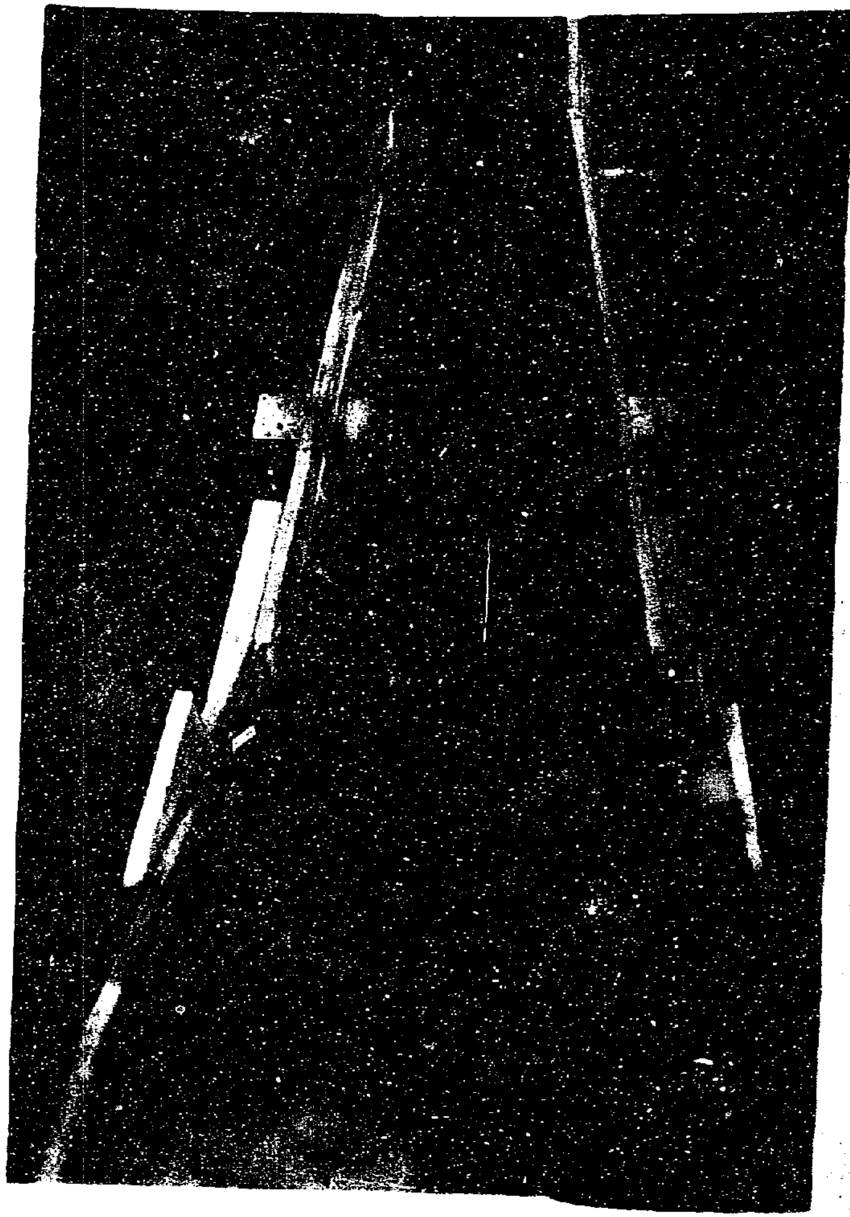


FIGURE 5
PLAN
FOUR DESIGNS OF DIVERGING PART OF CHUTE
SCALE OF PROTOTYPE FEET
SCALE OF MODEL INCHES
STA. 8+88.34
STA. 9+00
STA. 9+59.51
STA. 9+96.79
STA. 10+50
STA. 11+00
STA. 11+50
STA. 11+71.79
EXPLANATION
SYMBOL
DESIGN
CURVE
No. 1 (Original)
No. 2
No. 3
No. 4
1200-ft. radius
NOTE: Wall heights are not to scale
WASTEWAY No. 2
HYDRAULIC MODEL STUDIES - SCALE 1:24
DETAILS OF VARIOUS DESIGNS OF DIVERGING CHUTE
AND CORRESPONDING WATER SURFACE PROFILES

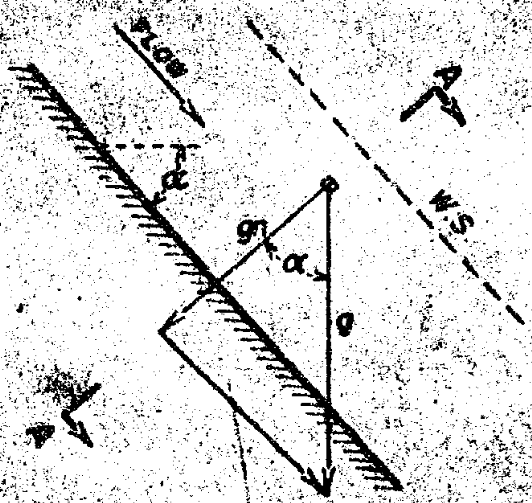


A. NO DISCHARGE

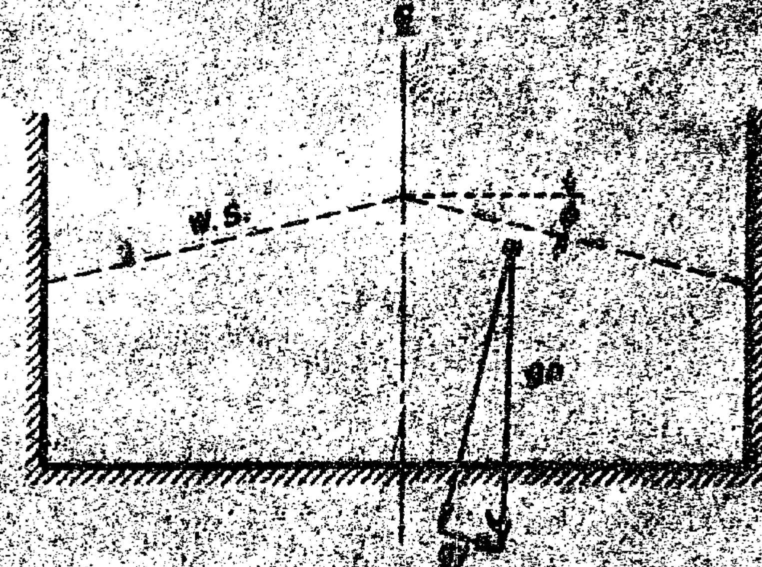


B. DISCHARGE, 2100 SECOND-FEET

DIVERGING SECTION OF ORIGINAL WASTEWAY CHUTE (DESIGN 1)

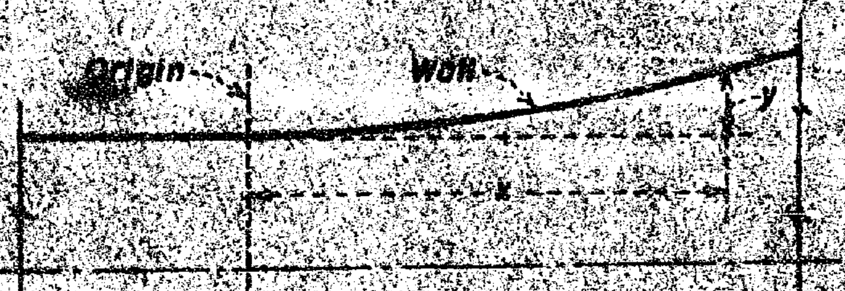


(A)



(B)

SECTION A-A



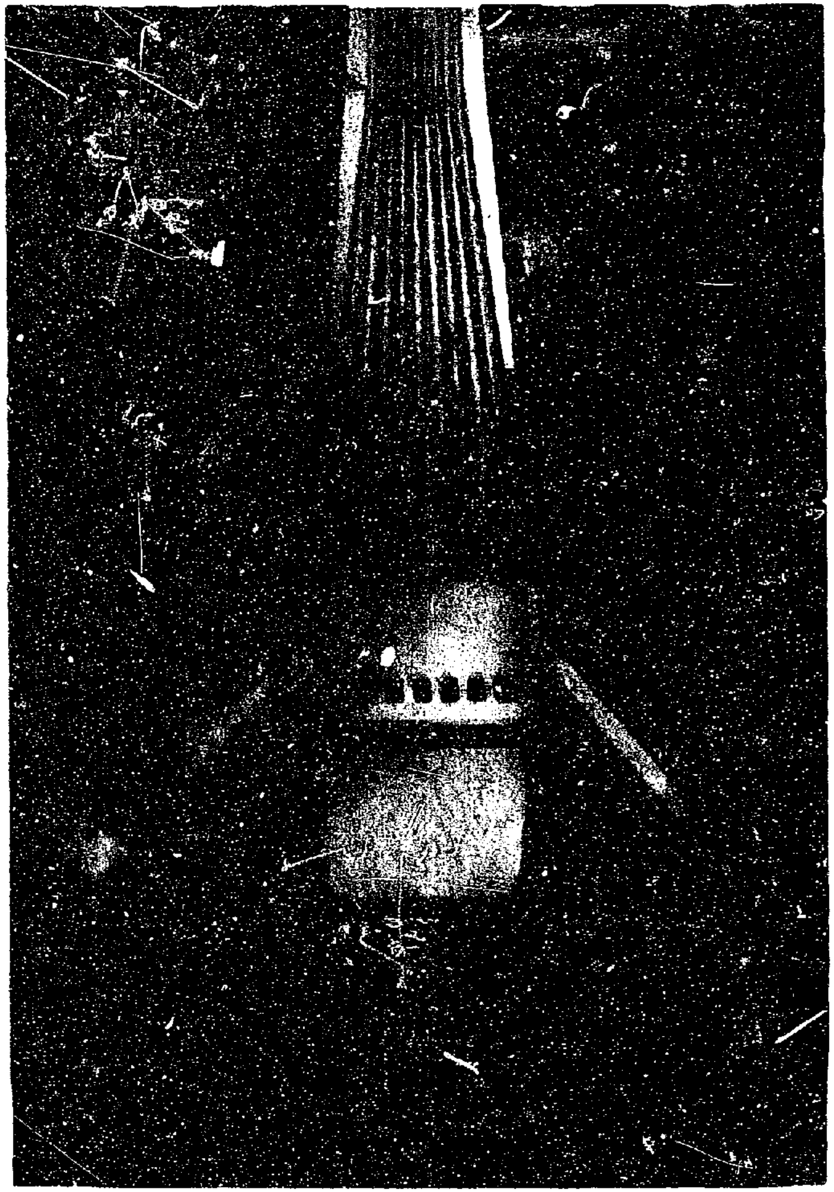
(C)

EXPLANATION

α = Angle between chute floor and horizontal.
φ = Transverse water surface slope.
g = Acceleration of gravity.
gn = Acceleration component normal to floor.
gy = Acceleration in y direction. (Transverse component.)
x = Down-chute distance along inclined floor.
y = Transverse distance, or divergence.

ROZA WASTEWAY No. 2
HYDRAULIC MODEL STUDIES - SCALE 1:24
DEVELOPMENT OF WALL ALINEMENT EQUATION - DIVERGING CHUTE

W.B. 2-13-42

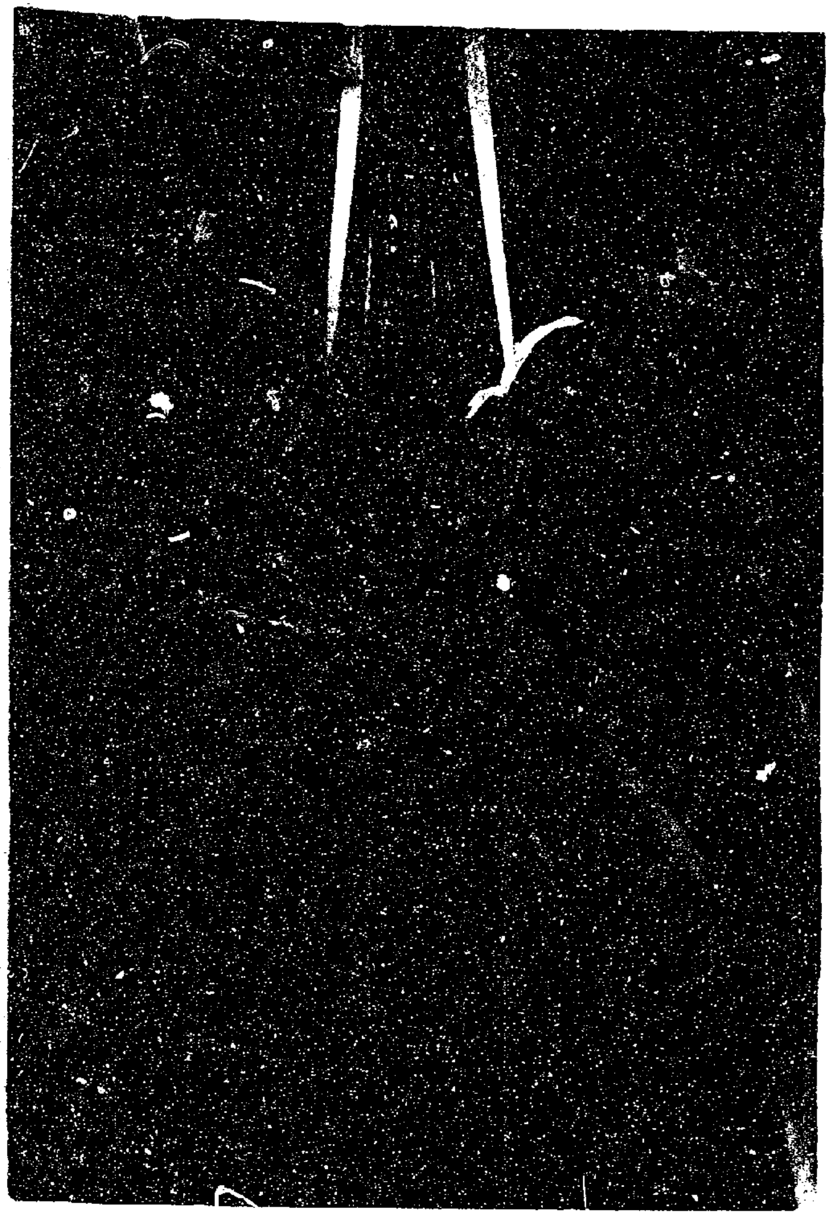


A. DIVERGING CHUTE WITH SPREADING VANES
ADOPTED POOL AND WALL DESIGN.

B. DIVERGING CHUTE WITH PARABOLIC WALL
DESIGN 4 AND POOL DESIGN 3.

WASTEWAY CHUTE AND STILLING POOL - NO DISCHARGE

FIGURE 9



A. DIVERGING CHUTE WITH SPREADING VANES.
ADOPTED POOL AND WALL DESIGN.

B. DIVERGING CHUTE WITH PARABOLIC WALL
DESIGN 4 AND POOL DESIGN 3.

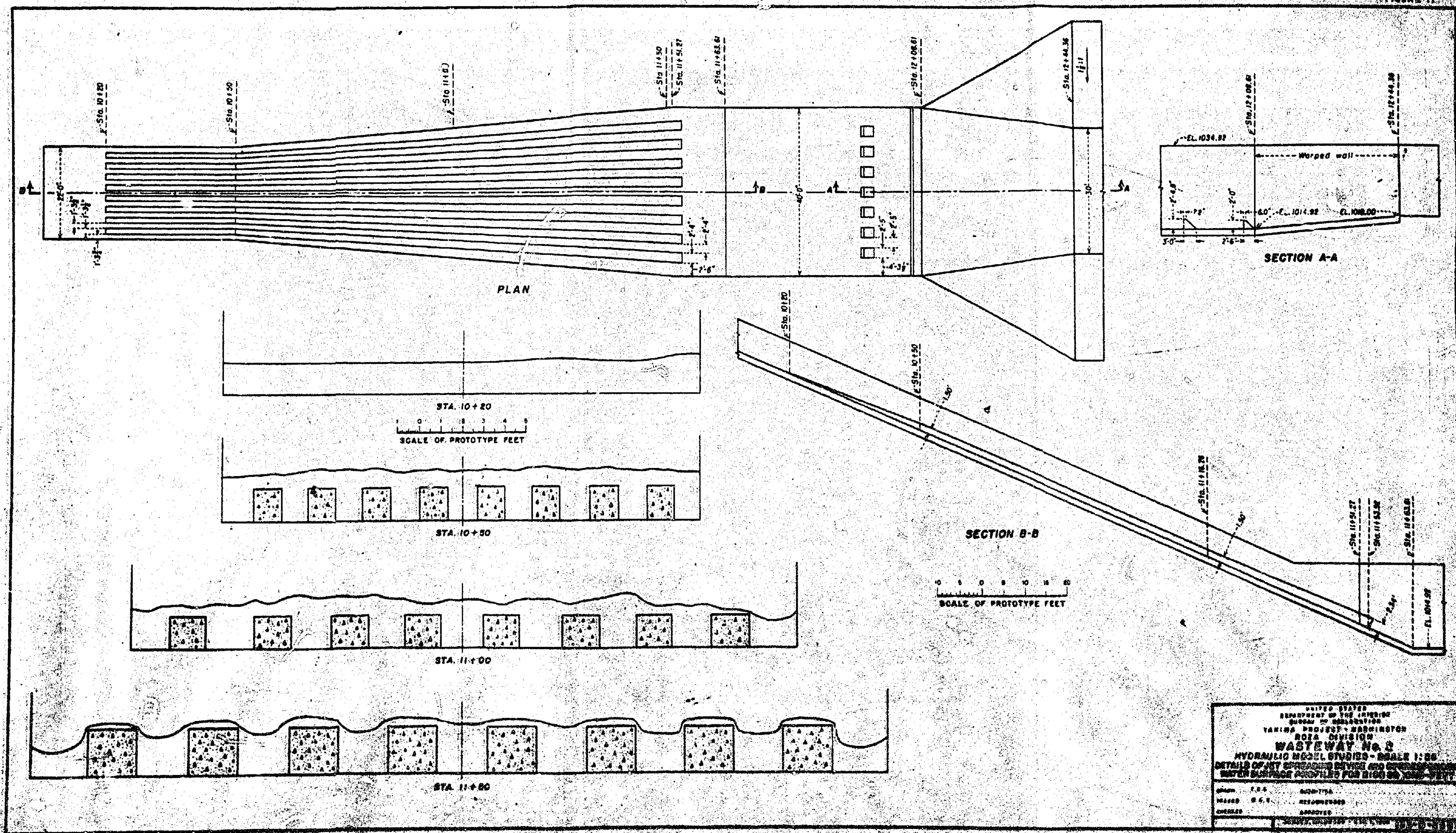
WASTEWAY CHUTE AND STILLING POOL - DISCHARGE 950 SECOND-FEET

A. DIVERGING CHUTE WITH SPREADING VANES.
ADOPTED [illegible] AND WALL DESIGN.

B. DIVERGING CHUTE WITH PARABOLIC WALL
DESIGN 4 AND POOL DESIGN 3.

WASTEWAY CHUTE AND STILLING POOL - DISCHARGE 2100 SECOND-FEET

FIGURE 11


PLAN
SECTION A-A
SECTION B-B
STA. 10+20
STA. 10+50
STA. 11+00
STA. 11+80
SCALE OF PROTOTYPE FEET
Warped wall
EL. 1034.92
EL. 1014.92
EL. 1018.00
Sta. 10+20
Sta. 10+50
Sta. 11+00
Sta. 11+50
Sta. 11+51.27
Sta. 11+63.61
Sta. 12+08.61
Sta. 12+44.36
Sta. 11+16.78
40'-0"
30'-0"
ROZA DIVISION
WASTEWAY No. 2
HYDRAULIC MODEL STUDIES - SCALE 1:20

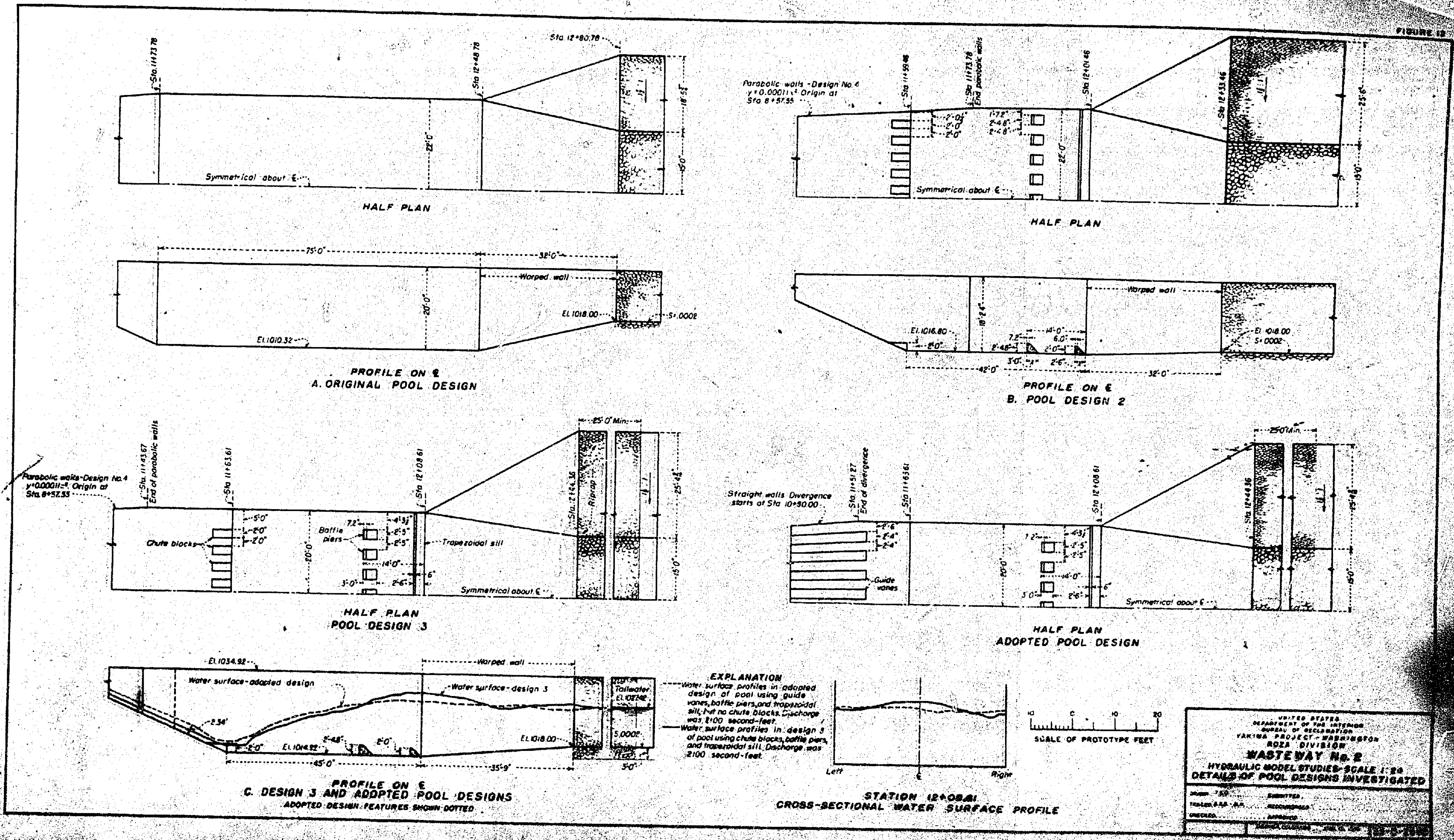
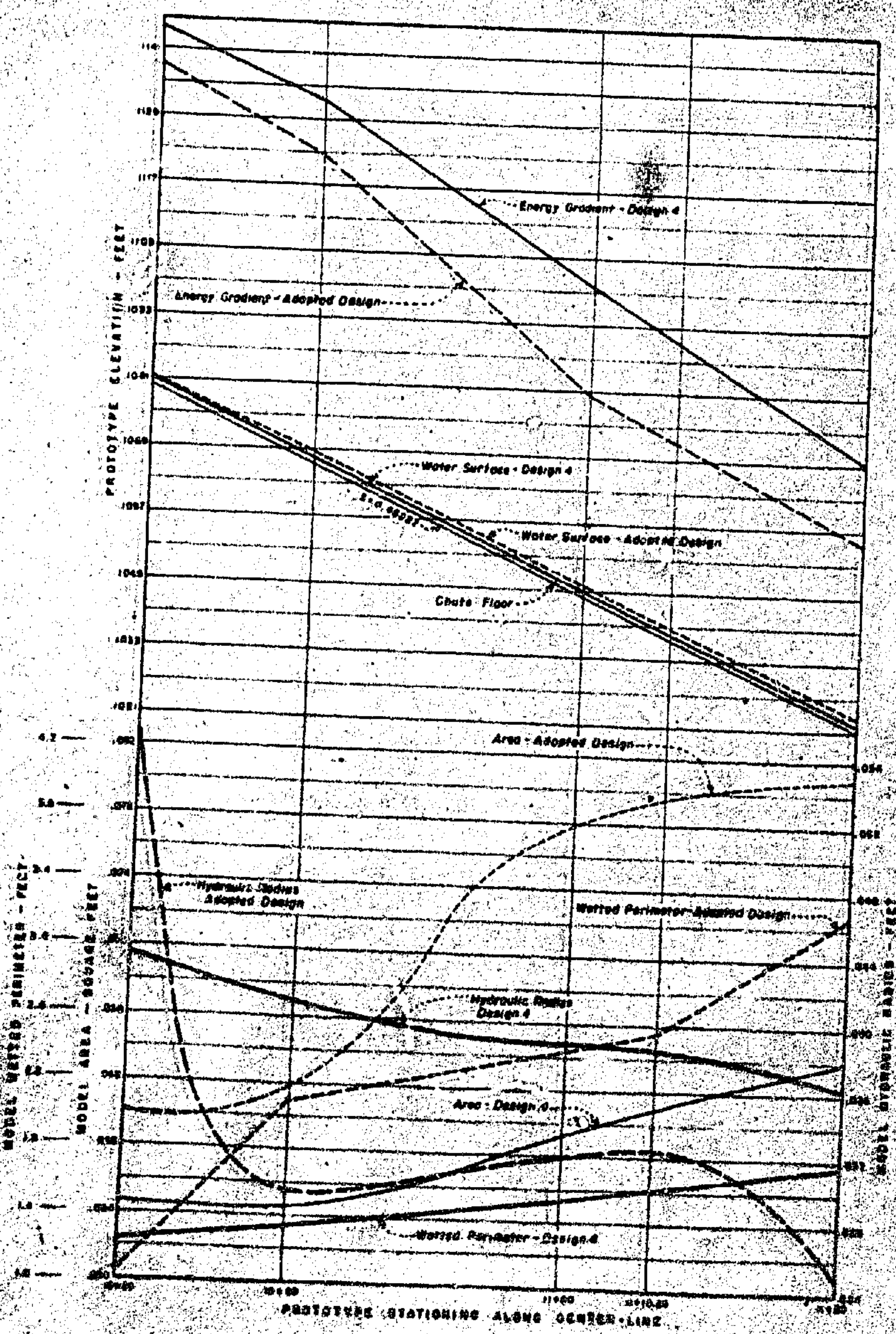


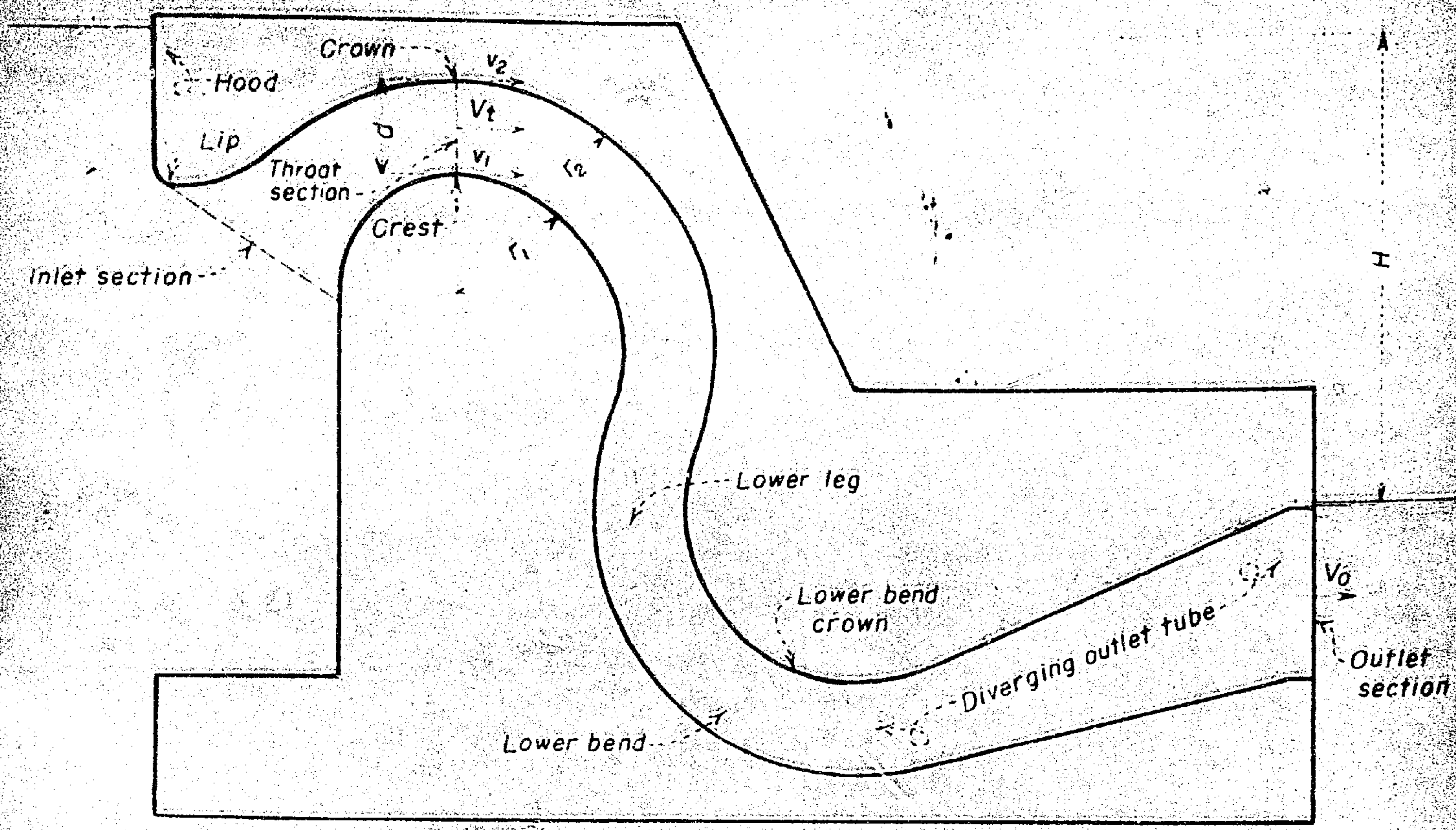
FIGURE 12
HALF PLAN
PROFILE ON ℄
A. ORIGINAL POOL DESIGN
Symmetrical about ℄
Warped wall
El. 1018.00
El. 1010.32
S=.0002
HALF PLAN
PROFILE ON ℄
B. POOL DESIGN 2
Parabolic walls - Design No. 4 y=0.00011x² Origin at Sta. 8+57.55
HALF PLAN
POOL DESIGN 3
Chute blocks
Baffle piers
Trapezoidal sill
Riprap
HALF PLAN
ADOPTED POOL DESIGN
Straight walls Divergence starts at Sta. 10+50.00
Guide vanes
PROFILE ON ℄
C. DESIGN 3 AND ADOPTED POOL DESIGNS
ADOPTED DESIGN FEATURES SHOWN DOTTED
El. 1034.92
Water surface-adopted design
Water surface-design 3
Tailwater El. 1032.46
EXPLANATION
Water surface profiles in adopted design of pool using guide vanes, baffle piers, and trapezoidal sill, but no chute blocks. Discharge was 2100 second-feet.
Water surface profiles in design 3 of pool using chute blocks, baffle piers, and trapezoidal sill. Discharge was 2100 second-feet.
Left
Right
STATION 12+08.61
CROSS-SECTIONAL WATER SURFACE PROFILE
SCALE OF PROTOTYPE FEET
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
YAKIMA PROJECT - WASHINGTON
ROZA DIVISION
WASTEWAY No. 2
HYDRAULIC MODEL STUDIES-SCALE 1:24
DETAILS OF POOL DESIGNS INVESTIGATED

FIGURE 19



UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
YAKIMA PROJECT - WASHINGTON
ROZA DIVISION
WASTEWAY NO. 2
HYDRAULIC MODEL STUDIES - SCALE 1:20
COMPARISON OF HYDRAULIC ELEMENTS AS DETERMINED FROM MODEL EXPERIMENTS FOR DESIGN 4 AND THE ADOPTED DESIGN OF DIVERGING PART OF CHUTE

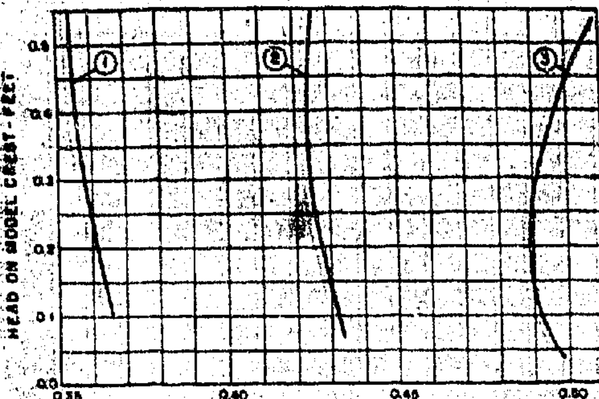
FIGURE 14



SIPHON NOMENCLATURE
WASTEWAY No. 2 MODEL STUDIES

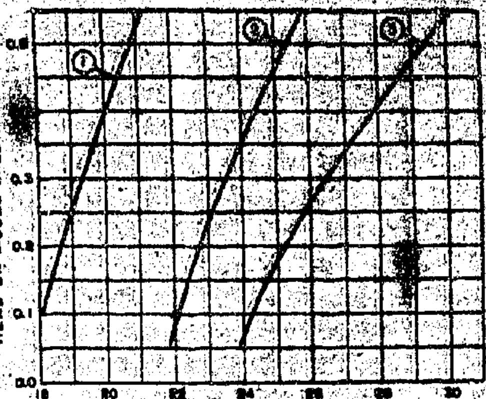
J.W.B. 2-19-42

33-D-2590



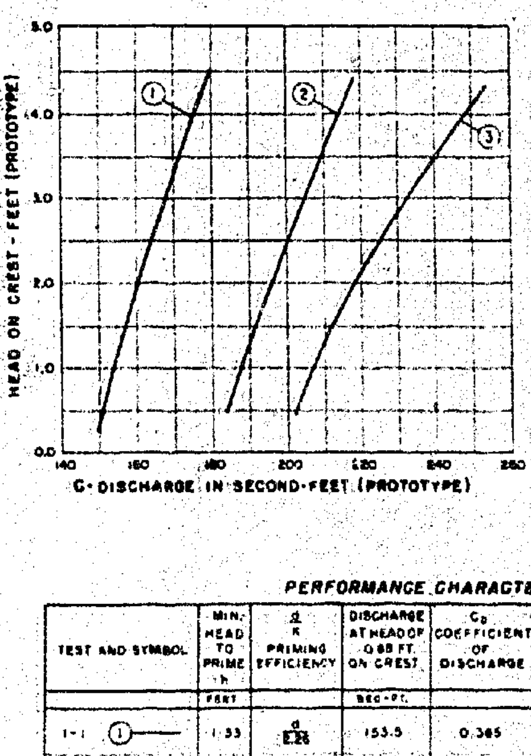
A - COEFFICIENT OF DISCHARGE "C_D" IN $Q_M = C_D A_0 \sqrt{2gH}$

A_0 = OUTLET AREA; H = TOTAL HEAD; Q_M = MODEL DISCHARGE

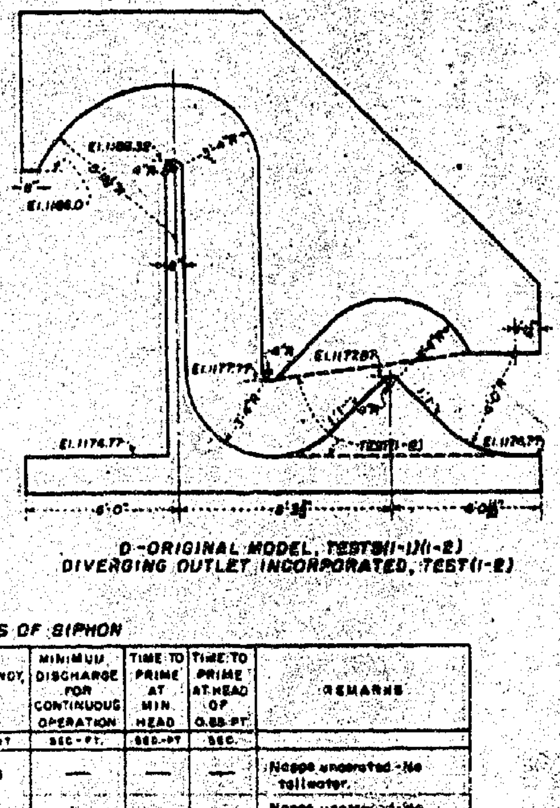


B - PERCENT EFFICIENCY "η" IN $Q_P = \eta A \sqrt{2gG}$

G = ONE ATMOSPHERE (34 FEET); Q_P = PROTOTYPE DISCHARGE; A = THROAT AREA



C - DISCHARGE IN SECOND-FEET (PROTOTYPE)



D - ORIGINAL MODEL, TESTS (1-1)(1-2)
DIVERGING OUTLET INCORPORATED, TEST (1-2)

PERFORMANCE CHARACTERISTICS OF SIPHON

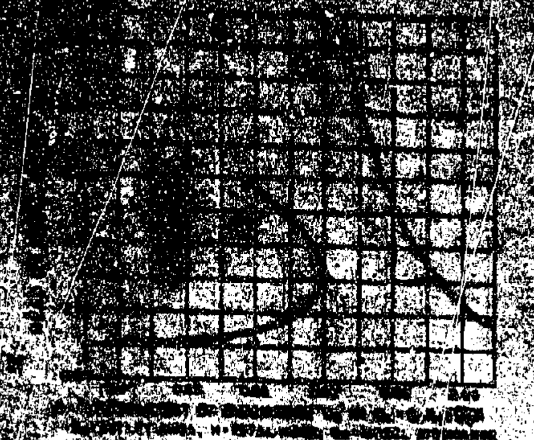
TEST AND SYMBOL	MIN. HEAD TO PRIME h	d/h PRIMING EFFICIENCY	DISCHARGE AT HEAD OF 0.85 FT. ON CREST	C_D COEFFICIENT OF DISCHARGE	η EFFICIENCY	MINIMUM DISCHARGE FOR CONTINUOUS OPERATION	TIME TO PRIME AT MIN. HEAD	TIME TO PRIME AT HEAD OF 0.85 FT.	REMARKS
	FEET		SEC.-FT.		PERCENT	SEC.-FT.	SEC.-FT.	SEC.	
1-1 (1)	1.33	d/2.26	153.5	0.365	16.13	—	—	—	Nappe unaerated - No tailwater.
1-2 (2)	1.33	d/2.26	157.0	0.432	22.08	—	—	—	Nappe unaerated - No tailwater
1-2 (3)	1.33	d/2.26	205.8	0.491	24.33	—	—	—	Nappe unaerated - Sufficient T.W. to fill Divergent Tube.

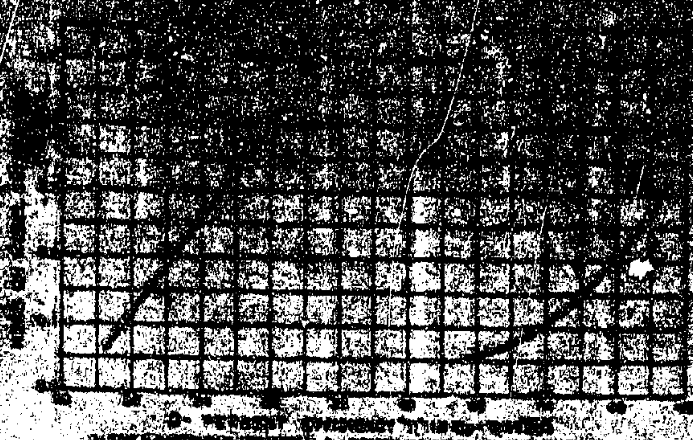
YAKIMA PROJECT - WASHINGTON
ROZA DIVISION

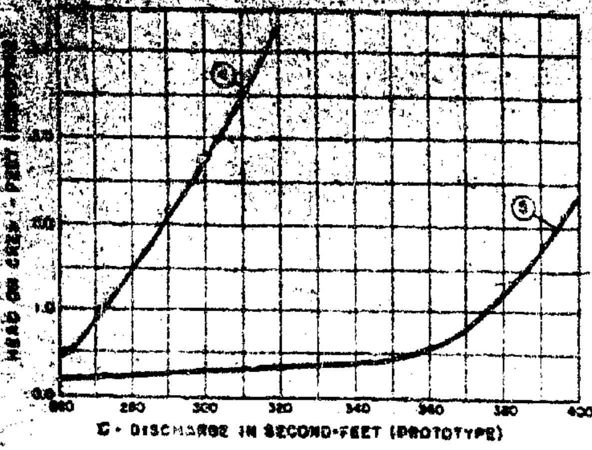
WASTEWAY No. 2 SIPHONS

HYDRAULIC MODEL STUDIES - SCALE 1:8
DISCHARGE AND PRIMING CHARACTERISTICS

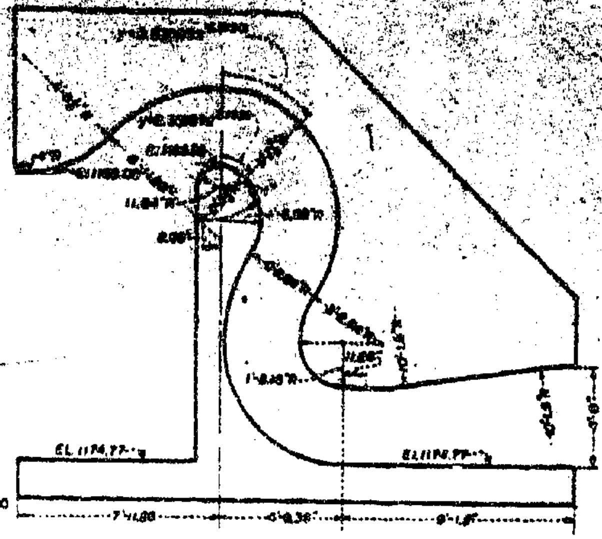
ORIGINAL MODEL, TESTS (1-1) AND (1-2)







C - DISCHARGE IN SECOND-FEET (PROTOTYPE)



D-MODEL WITH INCREASED CREST AND LOWER BEND RADII TEST (2-1)

PERFORMANCE CHARACTERISTICS OF SIPHON

TEST AND SYMBOL	MIN HEAD TO PRIME h	d/h PRIMING EFFICIENCY	DISCHARGE AT HEAD OF 0.88 FT ON CREST	Cd COEFFICIENT OF DISCHARGE	η EFFICIENCY	MINIMUM DISCHARGE FOR CONTINUOUS OPERATION	TIME TO PRIME AT MIN HEAD	TIME TO PRIME AT HEAD OF 0.88 FT.	REMARKS
	FEET		SEC.-FT.		PERCENT	SEC.-FT.	SEC.-FT.	SEC	
2-1	2.37	d/1.87	—	—	—	—	—	—	Nappe unaerated - No tailwater
2-1 (4) ——	1.53	d/1.96	270.4	0.691	31.90	—	—	—	Nappe aerated - No tailwater
2-1 (5) ——	0.45	d/0.67	371.1	0.865	44.20	—	—	66	Nappe aerated - Sufficient T.W. to fill Divergent Tube

YAKIMA PROJECT - WASHINGTON
ROZA DIVISION

WASTEWAY No. 2 SIPHONS

HYDRAULIC MODEL STUDIES - SCALE 1:8
DISCHARGE AND PRIMING CHARACTERISTICS

MODEL WITH INCREASED CREST AND LOWER BEND RADII
TEST (2-1)

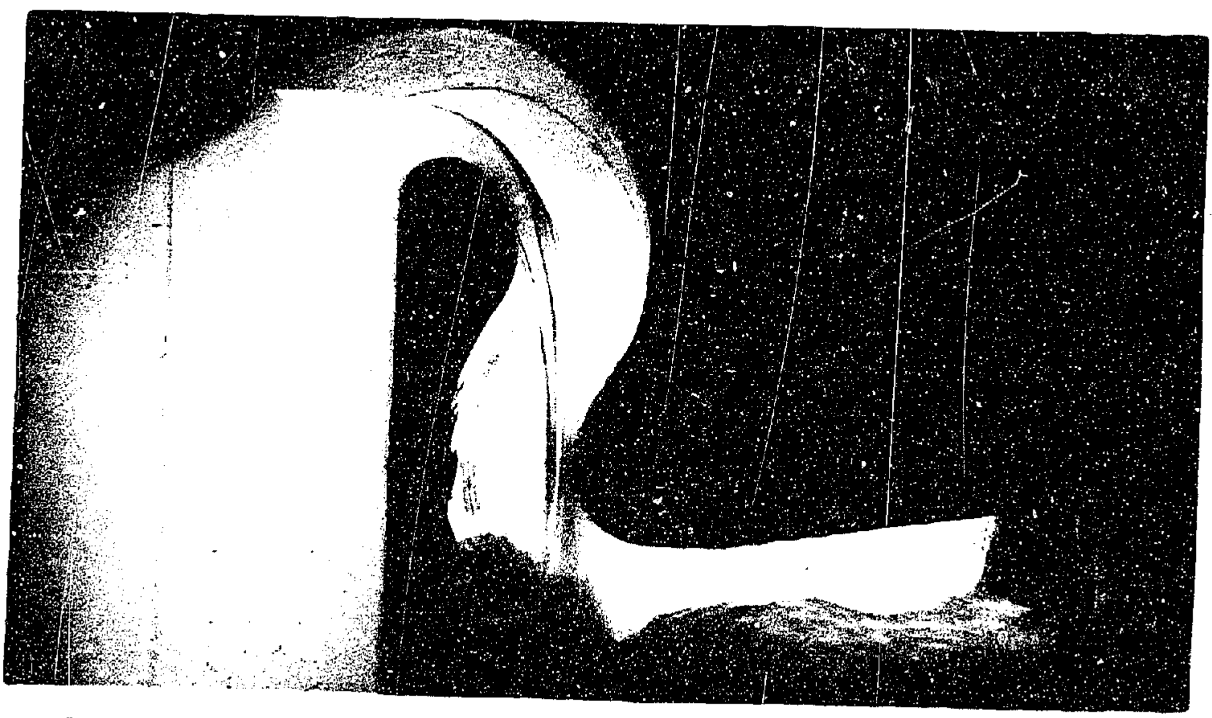
A. DISCHARGE 317 SECOND-FEET WITH HEAD OF 4.10 FEET(PROTOTYPE), NO TAILWATER.

B. DISCHARGE 404 SECOND-FEET WITH HEAD OF 2.50 FEET(PROTOTYPE)
TAILWATER TO SEAL EXIT.

EFFECT OF TAILWATER ON SIPHON PERFORMANCE.

MODEL WITH INCREASED CREST AND LOWER BEND RADII - SCALE 1:8

A. DISCHARGE 44 SECOND-FEET WITH HEAD OF 1.53 FEET(PROTOTYPE). UNAERATED NAPPE CLINGING TO INVERT, INCREASING TIME AND HEAD TO PRIME.



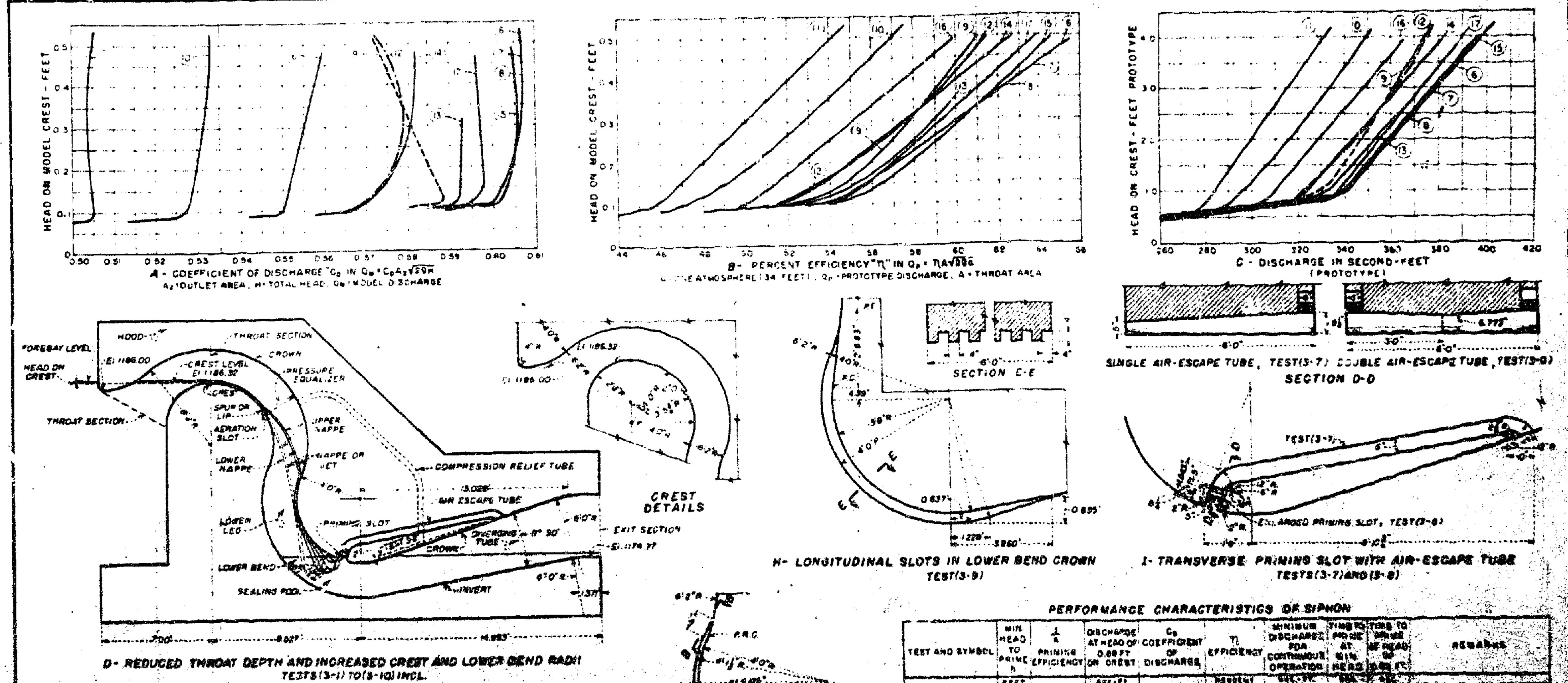
B. DISCHARGE 44 SECOND-FEET WITH HEAD OF 1.53 FEET(PROTOTYPE). AERATED AT OFFSET, NAPPE SPRINGS FREE, SEALS UPPER AIR ZONE, INDUCING PRIMING.

EFFECT OF NAPPE AERATION ON PRIMING.

MODEL WITH INCREASED CREST AND LOWER BEND RADII - SCALE 1:8

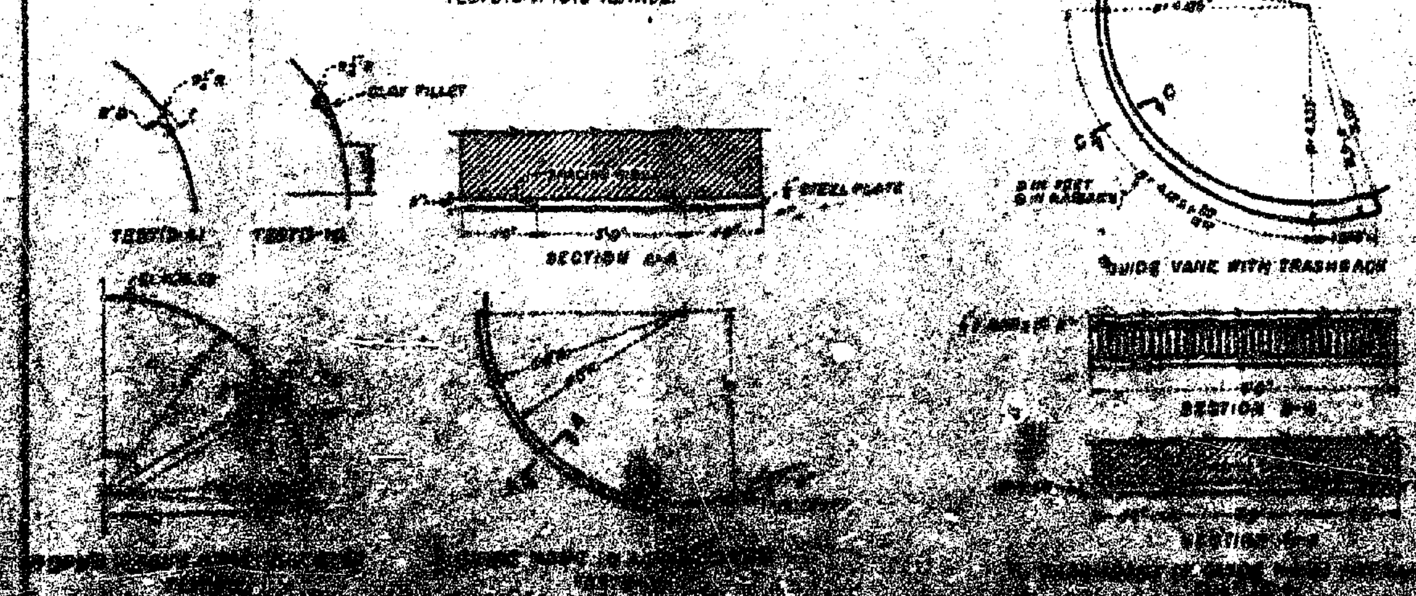
[redacted]

FIGURE 15

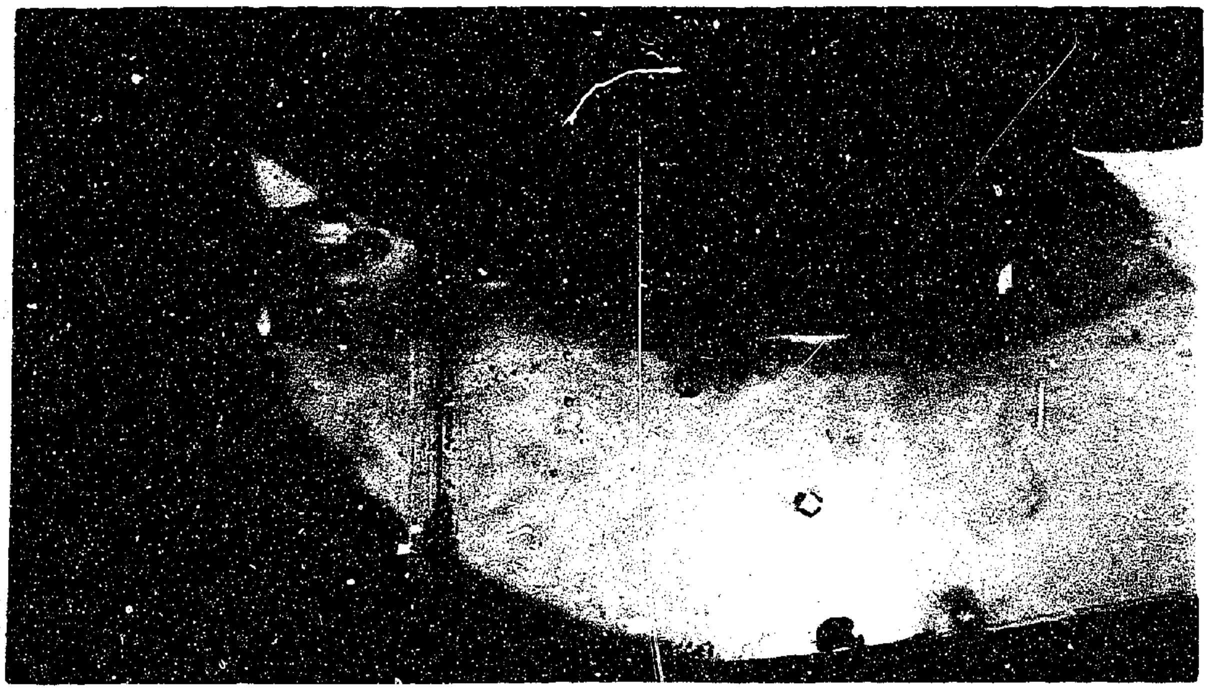


PERFORMANCE CHARACTERISTICS OF SIPHON

TEST AND SYMBOL		MIN. HEAD TO PRIME h	$\frac{1}{h}$ PRIMING EFFICIENCY	DISCHARGE AT HEAD OF 0.88 FT ON CREST	C_D COEFFICIENT OF DISCHARGE	η EFFICIENCY	MINIMUM DISCHARGE FOR CONTINUOUS OPERATION	TIME TO PRIME AT MIN. HEAD	TIME TO PRIME AT HEAD OF [illegible] FT	REMARKS
		FEET		SEC-FT		PERCENT	SEC-FT	[illegible]	[illegible]	
3-1	(6)	0.94	[illegible]	—	—	—	—	[illegible]	—	[illegible]
3-1	(7)	0.49	[illegible]	331.1	[illegible]	[illegible]	—	[illegible]	—	[illegible]
3-4	(8)	[illegible]	[illegible]	331.1	[illegible]	[illegible]	—	[illegible]	—	[illegible]
3-4	(9)	0.56	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]
3-5		—	—	—	—	—	—	—	[illegible]	[illegible]
3-5	(10)	0.16	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3-6	(11)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]
3-7	(12)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3-7	(13)	—	—	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	(14)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	(15)	—	—	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	(16)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	(17)	—	—	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]



A. DISCHARGE 22 SECOND-FEET(PROTOTYPE). FLOW CONDITIONS FOR MINIMUM HEAD TO PRIME.



B. CROWN OF LOWER BEND - BUBBLES MOVING SLOWLY OUT TO INDUCE PRIMING.

MODEL WITH SEALING POOL, REDUCED THROAT DEPTH AND FURTHER INCREASED CREST AND LOWER BEND RADII - SCALE 1:8

A. SIPHON DURING PRIMING, HEAD OF 0.51 FOOT(PROTOTYPE).
NOTE ABSENCE OF AIR IN SEALING POOL.

B. AIR ESCAPING FROM END OF VANE PAST CROWN OF LOWER BEND.
AT MINIMUM PRIMING HEAD OF 0.15 FOOT.

ACTION OF PRIMING GUIDE VANE IN LOWER BEND.

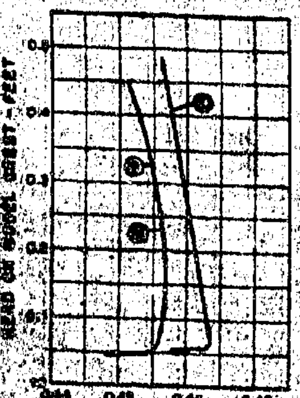
MODEL WITH GUIDE VANE IN LOWER BEND - SCALE 1:8

A. PRESSURES IN UPPER AND LOWER ZONES EQUALIZED. NAPPE IN NORMAL POSITION.

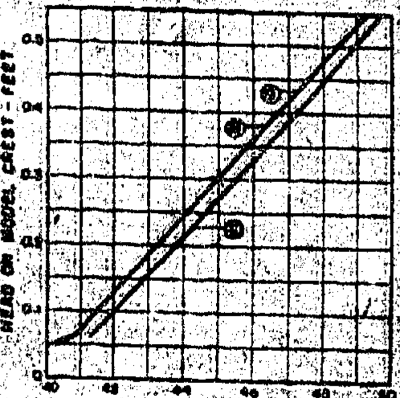
B. AIR ZONE PRESSURES NOT EQUALIZED, NAPPE DEFLECTED UPWARD.

EFFECT OF PRESSURE EQUALIZER.

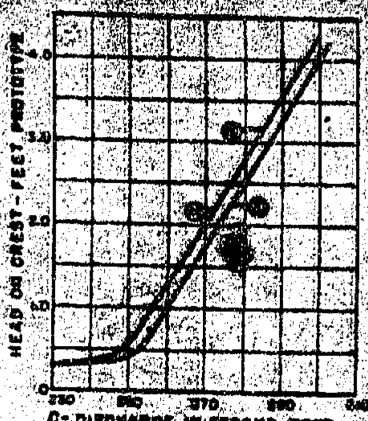
MODEL WITH LONGITUDINAL SLOTS IN LOWER BEND CROWN - SCALE 1:8



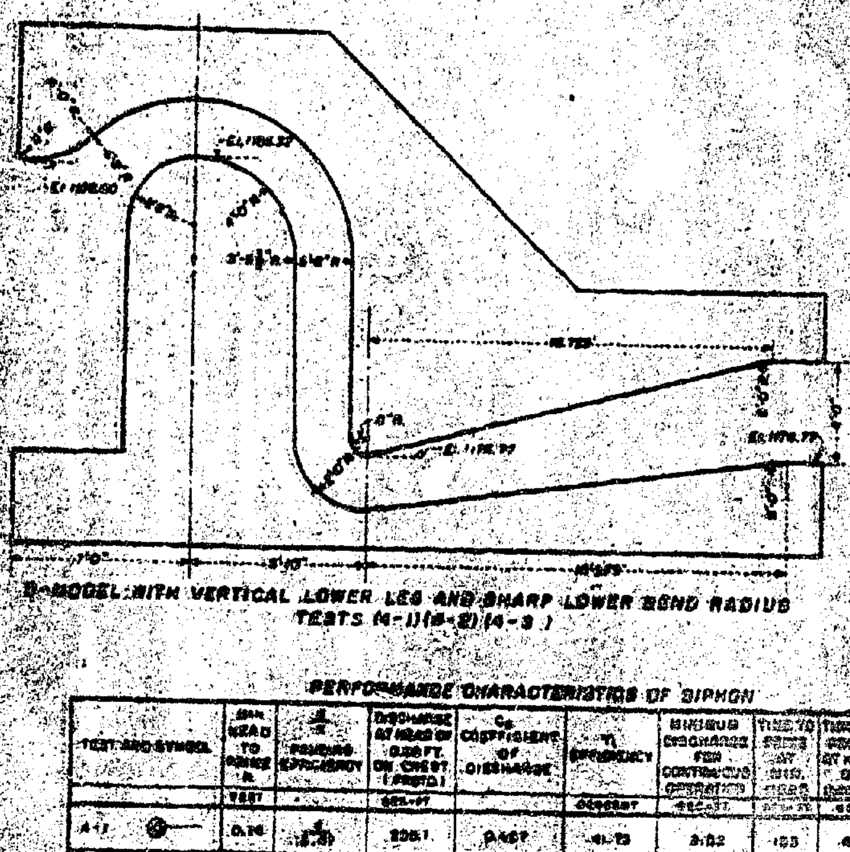
A - COEFFICIENT OF DISCHARGE
C_Q IN $Q_M = C_Q A_0 \sqrt{2gH}$
A_0 = OUTLET AREA, H = TOTAL HEAD; Q_M = MODEL DISCHARGE



B - PERCENT EFFICIENCY "η" IN $Q_P = η A \sqrt{2gH}$
H = ONE ATMOSPHERE (34 FEET) Q_P = PROTOTYPE DISCHARGE
A = THROAT AREA

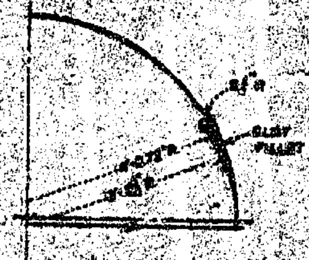


C - DISCHARGE IN SECOND-FEET
(PROTOTYPE)



D - MODEL WITH VERTICAL LOWER LEG AND SHARP LOWER BEND RADIUS
TESTS (4-1)(4-2)(4-3)

AERATION SLOT FILLED
TEST (4-2)



AERATION SLOT FILLED
TEST (4-3)

PERFORMANCE CHARACTERISTICS OF SIPHON

TEST AND SYMBOL	MIN. HEAD TO PRIME H.	PRIMING EFFICIENCY	DISCHARGE AT HEAD OF 0.50 FT. ON CREST (PROTO.)	C_Q COEFFICIENT OF DISCHARGE	η EFFICIENCY	MINIMUM DISCHARGE FOR CONTINUOUS OPERATION	TIME TO PRIME AT MIN. HEAD	TIME TO BREAK AT HEAD OF 0.50 FT.	REMARKS
	FEET		SEC-FT		PERCENT	SEC-FT.	SECONDS	SECS.	
4-1	0.16	4/(5.8)	206.1	0.457	41.73	3.02	155	46	
4-2	—	—	295.1	0.457	41.73	—	—	—	
4-3	—	—	306.3	0.461	42.30	—	—	—	

YAKIMA PROJECT - WASHINGTON
ROZA DIVISION
WASTEWAY No. 2 SIPHONS
HYDRAULIC MODEL STUDIES - SCALE 1:16
DISCHARGE AND PRIMING CHARACTERISTICS
MODEL WITH VERTICAL LOWER LEG AND SHARP LOWER BEND RADIUS, TESTS (4-1) TO (4-3), INCLUSIVE