A STUDY OF LOW-HEAD SIPHONS

by

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FOREWORD

The experiments described in this thesis were performed by the author in the laboratory of the U.S. Bureau of Reclamation, located in Denver, Colorado. The hydraulic laboratory is under the direction of J. E. Warnock, Research Engineer, and under the supervision of R. F. Blanks, Engineer, and Arthur Ruettgers, Senior Engineer. These studies were made under the general supervision of W. H. Mulder, Assistant Chief Designing Engineer and J. L. Savage, Chief Designing Engineer. All engineering work of the Bureau of Reclamation is supervised by S. O. Harper, Assistant Chief Engineer, and R. F. Walter, Chief Engineer. All activities of the Bureau are directed by John C. Page, Commissioner.

The author is indebted to the Bureau of Reclamation for permission to use these data for a graduate thesis, and also for furnishing the illustrative materials.

It should be clearly understood that the statements appearing herein are solely the opinions of the author, and as such do not necessarily represent the general opinion of the Bureau of Reclamation.

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CHAPTER I -- INTRODUCTION

Brief History. The word siphon, which comes from the Greek, is defined as a bent pipe or tube having two legs of unequal length, through which a liquid will flow from a higher to a lower level over an intermediate elevation. The actuating force is the atmospheric pressure. Although the siphonic principle has been known for hundreds of years, the application of the principle to hydraulic spillways has been comparatively recent. It is believed that the first siphon spillway was constructed by M. Hirsch at Mittersheim in Lorrain in 1860.[1] The first installation of a siphon spillway in the United States was on the New York State Barge Canal in 1900.[2] Until recently there has been much prejudice against siphon spillways, but they are now gaining wider recognition and favor among engineers. Siphon spillways are used in reservoirs or canals where a high discharge per foot of crest width accompanied by a comparatively small rise in the water-level is desirable. They also find a most useful application as automatic water-leveling devices.

Classification. Siphons have been classified in various ways. There are two general types of siphons: the true siphon in which the intermediate elevation is greater than the exit level; and the inverted siphon in which the intermediate elevation is less than the exit level. Siphons may further be classified as self-priming, and non-self-priming siphons. Both of these groups may be further

classified according to the operating head as high-, medium-, or low-head siphons. The authors say quite [illegible] the lower leg or the exit section must converge in order that the possible vacuum at the throat will not be exceeded, should be designated as the high-head class; that those siphons in which the area of cross-section of the lower leg is constant, be distinguished as the medium-head class; and that those siphons in which the lower leg is divergent be classified as low-head siphons. This appears to be the most logical method of classification the authors have seen, and will be adopted in this thesis. Each of these groups, classified according to head, could be sub-divided further according to the type of priming device used. In this discussion, however, there is no advantage to be gained by further classification.

This thesis will concern itself mainly with the self-priming siphon of the low-head type.

Statement of Problem. Due to the fact that there has been no prejudice against the use of siphons, much information is lacking which the hydraulic engineer needs for adequate design. The hydraulic problem of design is not simply one of a consideration of losses due to entrance, friction, bends, etc., but there is also the important consideration of priming. Furthermore, there are limitations concerning the negative pressure that can safely be developed within the siphon. The science of hydraulics has not yet advanced to the stage where solutions to these

siphons could be designed scientifically. The engineer must draw his information from the scant amount of data which had been compiled from tests on existing structures, or from model tests. The specific object of the investigation conducted by the author was to design, by means of hydraulic models, a siphon which would be efficient and also possess good priming characteristics.

<u>Scope of Paper</u>. The design of and theory involved in siphonic flow is herein presented together with the results of the author's experiments. The data gathered in this investigation were to be used primarily in designing a siphon whose total head was about 1[illegible] feet. This confined the investigation to siphons of the low-head type. The experiments were conducted in two parts. First, the efficiency of the siphon was improved as much as was deemed consistent with cost. Second, attention was then directed to the priming qualities of the siphon and they were improved as much as possible. Though no actual measurements of losses were carried out, computations were made which indicated the probable losses. The priming phenomenon was investigated and several priming devices were developed. It is hoped that the knowledge gained in these experiments will be of value to the designer in future work.

CHAPTER II -- DISCUSSION OF THEORY

Vortex Flow. The discussion of the theory involved in the flow of water through siphons makes the use of nomenclature peculiar, perhaps, to siphons. Figures S-B and S-C show the various parts of a siphon and bear the terminology which will be used throughout the discussion. Most authorities agree that flow over the crest of the siphon approaches free vortex flow.[1,3,4] Assuming free vortex flow, the maximum permissible velocity and consequently, the maximum permissible discharge can be shown to be a function of the permissible vacuum at the crest and the radii of the crest and crown. Thus, the velocity at the crest is:

$$v_1 = \sqrt{2g \times a}$$

where v_1 = the velocity at the crest in feet per second.

a = the permissible vacuum at the throat expressed in feet of water.

Usually the value for "a" is taken as 75 per cent of the barometric pressure at the site of the siphon. The reason for reducing the actual barometric reading to 75 per cent of its value is to have a safe working pressure at which neither air coming out of solution nor water vapor due to reduced pressure will cause a break in the water leg. It also takes care of variations in barometric pressure due to climatic conditions.

Since in free vortex flow the product of the velocity and the radius is constant, we have at any point:

$$v \times r = v_1 \times r_1$$

$$v = \sqrt{2g \times a} \frac{r_1}{r}$$

Taking unit width of crest, and integrating between the radius of the crest and the radius of the crown as limits, we have:

$$= \int_{r_1}^{r_2} v\,dr = \int_{r_1}^{r_2} \sqrt{2g \times a} \frac{r_1}{r}\,dr = \sqrt{2g \times a}\, r_1 \log_e \frac{r_2}{r_1}$$

where q = the discharge in second-feet per foot of crest width

v = velocity at any point

r = the radius at any point

r_1 = the radius of the crest

r_2 = the radius of the crown

Losses. Having thus established that the discharge of the siphon is a function of the radius of the crest, the depth of the throat section, and the allowable vacuum at the crest, the next problem is a consideration of the losses in the siphon. The available total operating head being fixed by the conditions at the site of the siphon, an investigation of the losses will reveal whether or not the permissible vacuum at the crest will be exceeded. The losses in the siphon may be enumerated as follows: the loss at entrance, the loss due to the upper bend, the loss at the lower bend, the loss due to friction, and the loss in the diverging tube. The total operating head must equal

the sum of these losses plus the velocity head at exit. The total operating head should include the velocity head of approach except in cases where the approach velocity is low enough to be negligible. The total head on siphons with different outlet conditions is a subject of much controversy among hydraulic engineers, and a discussion of this point will be taken up subsequently. For the present discussion, the total head will be assumed to be the difference between the forebay and tailwater elevations.

Entrance Loss. Where the entrance has a large area as compared to that of the throat and has a bell-mouth shape, the loss is safely taken as 0.5 times the velocity head at the entrance section. This loss is small and therefore unimportant as compared with the other losses. Professor Gibson 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.[4]

Bend Losses. Although there has been much work done on losses in pipe bends, it is still a difficult task to estimate the loss due to bends. The loss due to bends is usually expressed as a coefficient times the velocity head. In experiments on loss in pipe bends, H. Beij[5] has broken up the loss into three parts: first, the loss due to a straight pipe of length equal to that of the bend plus that of the upstream and downstream tangents; second, the excess loss due to the bend, which he calls the deflection coefficient; third, the excess loss in the downstream

tangent, which he calls the tangent coefficient. His work was done entirely on 30° bends and with a pipe diameter of [illegible] (approx. 4.3", with various radii of bend, and with uniform velocity distribution approaching the bend. By plotting the deflection coefficient against the ratios of radius to diameter (R/D) he has shown that 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.[6] 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, 15.0, etc. However, it is suggested that after three "rebounds" other factors would become prominent enough to modify the flow to such an extent that the result would be unpredictable. This method of analysis, however, does not agree with experimental results. Another good investigation on losses in pipe bends is that reported by D. L. Yarnell.[7] In this set of experiments, losses in bends of various angles of deflection were tested. The tests were made on 6-inch pipes. In all bends which had a constant circular cross-section, the R/D ratio was 1.375. The loss due to the bend, exclusive of friction, expressed as a coefficient of the velocity head was found to be: 0.19 for a 45° bend; 0.15 for a 90° bend; 0.1 for a 180° bend of continuous curvature; 0.31 for a 180° bend of reverse curvature; and 0.40 for a 270° bend of two reverses. Tests on the 180° bend

with reverse curvature and uniform velocity of approach indicated that about 51 per cent of the loss occurred in the bend itself; the remainder occurred in the downstream tangent. In other words, the loss in the 180° reverse curve bend due to the bend itself expressed as a coefficient of the velocity head is about 0.158. The tests indicated further that with a non-uniform velocity distribution in the approach tangent, the velocity being highest on the inside of the bend, the loss was 1 to 4 times greater than 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 J. Williamson[8] gives the losses in 4-inch by 4-inch square teakwood bends of various angles of deflection and various ratios of R/D. The bends tested are all of continuous curvature, and the values given are those of extra loss due 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. Interpolation between values of the bend losses for R/D ratios of 1.5 and 1.06 given by Williamson was required so that the direct comparison, given in the following table, could be made.

Angle of bend	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° bends. In the past it has been assumed without proof that the losses in bends of rectangular section would approximate those in bends of circular section. The above comparison should strengthen the assumption.

It should be kept in mind that the loss in bends of circular cross-section is compared only with the values found for bends of square cross-section. To the writer's knowledge no experimental work has been done on losses in bends of various rectangular cross-sections using water as the fluid. However, E. D. Madison and J. K. Parker have published the results of their experiments on losses in bends of rectangular section using air as the fluid.[3] 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 86 per cent 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 .25 the loss is about 217 per cent 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 0.33 is 130 per cent 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 per cent 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°. For a 45° bend the loss was found to be 55 per cent of that for a 90° bend, and for a 180° bend the loss was found to be 105 per cent of that for a 90° bend. These findings are more or less consistent with the results of tests by Yarnell, and at variance with the data

ves by Gibson.

If it can be assumed that the results of these experiments using air as the fluid can be applied directly to the installations where water is used as the fluid, the interesting observations result. It has been found that the ratio of R/D giving minimum loss lies between 2.6 and 3.5. By increasing the aspect ratio, holding the R/D ratio at the optimum, the loss due to the bend may further be 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 2.6 cannot be attained, the same effect can be obtained by increasing the 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 increased the loss at the lower bend. This assumption is confirmed by the tests performed by Gibson, Aspey, and Tattersall.[4]

Adequate information on losses in bends of rectangular cross-section is very meagre. 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 bend losses assumed 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 head losses assumed are too low, the capacity of the siphon will be lower than that for which it is designed. Until such a time when adequate data on head losses are available, the designer must resort to model tests.

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 the corresponding increase in the efficiency. A different and, possibly, a simpler concept of this same phenomenon would be to consider the outlet section of a 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. Naturally, then, 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.

Angle of Divergence and Loss. The optimum angle of divergence in a tube following a right angle bend is found by Professor Gibson[4] to be 8°-30'. His experiments[10] indicate that the loss in the diverging tube, including friction, is:

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

where v_1 = the initial velocity in the diverging tube

v_2 = the final velocity in the diverging tube

Thus can the loss due to the diverging tube be computed.

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

$$h_f = S \times L$$

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

where h_f = head loss due to friction in 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, of course, the sum of the

the individual losses in each reach. The friction loss should be figured only to the start of the diverging tube since the loss in the diverging tube includes friction.

The kinetic energy at the outlet is computed by the formula, $\frac{V_2^2}{2g}$, where V_2 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 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, etc., can be found.

Coefficient of Discharge. A discussion of the coefficient of discharge will, no doubt, be justified. The coefficient of discharge is a subject of much discussion. The equation for the coefficient is of the form:

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

where C = the coefficient of discharge

Q = the discharge

A = the area

H = the head

Thus, the expression should give a relation between the actual discharge and the theoretical discharge. However, there are two points that are the subjects of much controversy: first, the area; second, the head. This writer shares the opinion with A. E. Taylor 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. As an example, in the siphons of Wastoway No. 2, Roza Division, Yakima Project, Washington, the results of the tests on Revision No. 3, the general dimensions of which are shown in figure 8-C, indicated a coefficient of discharge of 0.596 when the computations were based, as they should be, on the outlet area; but when based on the area of the throat, the coefficient became 1.033. In a paper on the coefficient of discharge of siphons, L. Saimeni[11] bases the coefficient of discharge on the throat area. In the same paper this author also discusses several siphons most notable of which was a type reported by A. Meirich in "Selbstattige Saugueberfalle" (Deutsche Bauzeitung 1917, p. 225). This siphon has an overhanging crest, a diverging lower leg, and discharges vertically into a pool. A. Meirich does not mention the method employed in computing the coefficient of discharge but gives values ranging from 0.256 to 0.296. Professor Saimeni expressed his surprise at such a high coefficient. However, as previously pointed out, a coefficient of this size or larger could be obtained if the throat area were 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 is so simple.

The second term in the expression for the coefficient of discharge of a 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 level 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 centerline of the jet. In almost all other cases the point to which to measure the head is a matter of opinion, and thereby becomes an indefinite value.

In a paper by J. C. Stevens[12] it is 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 = the coefficient of discharge based on the outlet area

Q = the discharge of the siphon in second-feet

A = area of outlet in square feet

h = total operating head

$h = h_f + h_v$

where h_c = head required to produce flow

$= \frac{\quad}{\quad} = \frac{\quad}{\quad}$

= the total losses in the siphon from the entrance to the exit

$= a + b + c + \ldots \quad \frac{V^2}{2g} = \frac{V^2}{2g} = \frac{Q^2}{2gA^2} = \frac{BQ^2}{2g}$

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

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

and $B = \frac{\quad}{\quad}$ = the sum of the loss coefficients divided by A

Then:

$$\frac{\quad}{\quad} = \frac{\quad}{\quad} + \frac{B}{2g} = \frac{\quad}{2g}\left[\frac{1}{\quad} + B\right]$$

and

$$Q = \frac{\quad}{\sqrt{2g \quad \frac{\quad}{2g} \quad + B}} = \frac{\quad}{\sqrt{\quad + B}}$$

This expression as it now stands is 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 $B = \frac{\quad}{\quad}$. Thus, the expression for the coefficient becomes:

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

This is now in the form which Professor Kei[illegible] has proposed. It is interesting also to note that a similar expression is given by Schoeffitsch. It appears to be an

ideal expression since it involves neither the indefinite head, nor any area, [illegible] outlet. In those cases where the values of the [illegible] parts [illegible] be determined either by velocity traverses or pressure measurements at the several necessary points throughout the siphon, in those cases, then, the above expression can be used to determine the coefficient of discharge. Also, in designing [illegible] this expression may be used since the value [illegible] can be determined from the assumed losses. However, [illegible] siphon installations the pressure or velocity [illegible] to be added at the numerous points are impossible to obtain, and, therefore, the total operating head must be known in order to [illegible] the coefficient of discharge. Fortunately, many [illegible] installations have sealed crits, [illegible] the operating head is definite. The outlet area, as previously pointed out is the only one to use in computing the coefficient. It will be shown in a following chapter, however, that the coefficient is an unreliable criterion of the effectiveness of a siphon.

<u>Efficiency</u>. As usually conceived, 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 [illegible] outlet to the total operating head on the siphon, thus:

$$\eta = \frac{[illegible]}{[illegible]}$$

but

$$\frac{[illegible]}{[illegible]}$$

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

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

$$C = \frac{\quad}{Ao\sqrt{2gH}} = \frac{Ao\ Vo}{Ao\sqrt{2gH}}$$

$$= \frac{Vo^2}{2gH} = \frac{Vo^2}{2g\frac{V^2}{2g}} = \frac{Vo^2}{V^2}$$

$$\eta = C^2$$

where η = the efficiency of the siphon

ho = velocity head at outlet

H = the total operating head

Vo = the velocity at outlet

V = theoretical velocity corresponding to the total operating head

Q = the actual discharge of the siphon

Ao = the area of the outlet

C = the coefficient of discharge

Thus, Mr. Stevens[illegible] on the efficiency of siphons. This same expression for efficiency is given by Professor Le Conte.[illegible] In the same paper Stevens develops another expression for efficiency which he defines as the ratio of the actual flow to the maximum attainable flow. The maximum attainable flow occurs when a negative pressure of one atmosphere is developed at the throat section. The efficiency is then:

$$\eta = \frac{Q}{A_t\sqrt{2gH}} = \frac{\quad}{\quad} = \frac{V_a}{\quad}$$

where Q = the actual discharge

A_t = the area of the throat section

V_t = the actual mean throat velocity

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

a = the head equivalent to one atmosphere

Naylor[1] develops a similar expression for the efficiency of a siphon:

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

and when a = 34 feet, the expression becomes:

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

"This is a true efficiency and can never attain a value of 100%. It is a measure of the intensity of discharge over the crest. The only shortcoming is that, like the coefficient of discharge, it can take no account of priming level But it has the advantage of definiteness for this very reason. A further advantage is disappearance from consideration of the somewhat indefinite H. 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." These are Naylor's observations on the efficiency and coefficient of discharge of a siphon.

The writer is of the opinion that the only true efficiency of a siphon from an engineering standpoint is the

ratio of the discharge to the cost of a siphon. The efficiency, as usually conceived, can be increased by increasing the radii of the bends, by providing a long diverging tube, and by other methods which, when carried to extreme, involve the use of much reinforced concrete and therefore become very expensive. Thus, the ultimate criterion should be the cost. However, this would not afford a basis for comparison of the flow characteristics of various siphons. For comparison of various siphons, then, the most reasonable basis appears to be that of efficiency as proposed by Naylor, Stevens, and others. The priming characteristics must be considered separately.

Priming Characteristics. The priming characteristics of a siphon are the head required to prime and time required to prime. Most experimenters have determined these data employing a rising forebay elevation. Few experimenters use the same rate of rise, and since the head and time required to prime are functions of the rate of rise, the resulting data are useless for comparison between other siphons. When a constant elevation of the forebay is employed in the tests, there is only one minimum head required for priming a particular siphon, and therefore that value is a definite characteristic of that siphon. Furthermore, the time required to prime at the minimum head when the forebay elevation is constant is also definite, and is a function only of the size and shape of the siphon rather than dependent also upon the rate of rise of the

forces. Many writers express the head required to prime in terms of a coefficient times the depth of the siphon at the throat section. Thus, the head to prime a siphon having a depth at the throat of 3 feet, and requiring a ... head to prime of ... feet, would be expressed as ... The initial head required for priming, expressed in this form, is an effect called the "priming efficiency." This method of expressing the head required to prime is apt to attract attention to the depth of the siphon at the throat section and give the erroneous impression that the head to prime is a function of depth at the throat.

Priming Devices. In installations of siphons where quick priming at a low head is one of the foremost considerations, designers have resorted to employing various devices the purpose of which is to decrease the head to prime and the time to prime the siphon. In one type of these devices the effective crest is lengthened by zig-zag metal strips imbedded in the concrete of the crest. One investigator claims that by use of the best type of zig-zag crest or teeth, the time required to prime as compared with that of a crest using no teeth was reduced by 23 per cent. He fails to state how the coefficient of discharge or efficiency of the siphon was reduced by the use of such a device. Obviously, during priming, for 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

[illegible] a sharp and irregular crest would be higher than the loss when a smooth crest was employed.

Another priming device is the so-called priming weir. It is similar to the type with the castellated or zig-zag crest in that it also has a crest of increased length which discharges more water for unit head than the ordinary siphon during priming. In this type, a weir at the elevation of the crest and located in the crown of the lower leg is supplied with water by a channel which communicates with the forebay. Usually this type of 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 scaling the air in the crown. The air in the crown is gradually evacuated and priming is produced. In the Bear River siphons, 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 slightly greater than half that value when the priming weir was not used. Neither the priming weir nor the device using a castellated crest have met with much approval among designers. 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 or "baby" siphon was used. The purpose of the auxiliary siphon was to reduce both the head and the time required to prime. The "baby" siphon

[illegible] accomplished [illegible] of two ways. [illegible] first, the [illegible] jet obliquely across the lower leg of the air siphon, thus producing an air-tight seal. The air trapped above the seal was gradually evacuated by the sheet of water flowing over the crest of the main siphon and [illegible] was [illegible]. In the second case, the "baby" siphon primed and then acted as an ejector, [illegible] air from the main siphon until priming was [illegible]. The disadvantages of the "baby" or auxiliary [illegible] out-weigh the advantages. The "baby" siphons [illegible] only difficult but expensive to construct. Usually [illegible] construction to flow in the main siphon, and because the [illegible] small, there is also the [illegible] they may [illegible] with trash.

Although not a priming device in the strict sense, the [illegible] plays an important part in the priming of a siphon. [illegible] this point almost all authorities agree. After the [illegible] level has risen and covered the air-vent, if the siphon is equipped with [illegible], the interior of the siphon is then completely sealed. [illegible] enter the [illegible]. Air bubbles are then carried down by the jet into the [illegible] basin where they are released to rise down-stream from the lower [illegible] and are thus exhausted to the atmosphere. Most authorities believe that for best priming [illegible] the radius of the [illegible] must be sharp, even [illegible] point of [illegible]. It will later be [illegible] this [illegible]. 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 time required to prime.

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 crown, thereby producing a seal. The methods of bringing this about vary. In some cases the lower leg is suddenly bent downward; in others, there may be a double bend to produce the desired result. In still other instances, a small spur or step is employed. The step or joggle is used either with or without a sealing pool. Where both the step and sealing pool are employed it is advantageous to locate the step so that the jet will strike the crown close to the outlet lip.

Conditions of Similitude. In all studies of hydraulic structures by the use of models it is important to ascertain the relation to the prototype of data obtained from the model. When the force of gravitation is the most important factor, the Froude's 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 considerations,

both model and prototype must have the same Weber number. Where elasticity is the 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's and Reynolds' numbers. Experiments[4] 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 pipes) should be the same for model and prototype, Gibson[4] had shown that for coefficient of discharge and pressure distribution measurements the model will give close agreement with the prototype if the value of $\frac{vd}{\nu}$ for the model is greater than 1.8. This value of $\frac{vd}{\nu}$ limits the size of the model. As Gibson[4] 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 $\frac{vd}{\nu}$ is greater than 1.8. Other investigators, [illegible], 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 limiting model scale.

Another factor to be considered in some 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 one-sixth 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 conditions 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 raised to the three-halves power, while the surface tension in 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 with 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[9] say that the priming characteristics of a siphon can be predicted by building three models to widely different scales. Then, by cotangential plotting 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 head to prime as extrapolated by the writer from the data given by Veronese.[17] The results of extrapolation by four different methods are given in the following table.

Dimension	Extrapolation Method	Extrapolated Head-Cm.	Actual Head-Cm.	Error Per cent
Cavanagh	A	9.1	13.[illegible]	-42.9
	B	[illegible]	13.[illegible]	-46.1
	C	16.42	13.[illegible]	+20.[illegible]
	D	[illegible]	13.[illegible]	-[illegible]
Carron	A	[illegible]	[illegible]	+[illegible]
	B	14.2	18.3	-23.0
	C	38.[illegible]	[illegible]	+[illegible]
	D	14.28	[illegible]	-28.2
Caterina	A	42.0	4[illegible].0	+ 4.8
	B	38.0	4[illegible].0	- [illegible]
	C	4[illegible]	4[illegible]	+17.[illegible]
	D	47.[illegible]	4[illegible].0	+[illegible].7

Referring to the table, extrapolation methods "A" and "B" were both graphical but done by two different engineers. The curves were plotted with the scale ratios as abscissa, and the model head to prime multiplied by the scale ratio as ordinates. Method "C" is an algebraic solution accomplished by putting a curve of the form $y = ax + bx + cx + d$ through the three known points and further defining one end so that $dy/dx = 0$ when $x = 1$. Method "D" is similar to [illegible] except that the equation was of the form $y = ax + b$ but with no limiting end condition. The error is the amount that the predicted or extrapolated head either

exceeded (plus), or fell short of (minus) the actual head, and is expressed in per cent 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 pipe one, 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, is better than

CHAPTER III

EXPERIMENTAL PROCEDURE AND DESCRIPTION OF MODELS

Conditions of Design. The function of the siphons investigated by the writer is that of an automatic emergency spillway. There are to be four siphons in all, two on either side of a wasteway which is equipped with two non-automatic radial gates. They will be built at the same time as the wasteway structure. Later, it is planned, a power plant will be built and its forebay will include the siphons and wasteway gates. The siphons will then be used as emergency spillways and possibly as water-leveling devices. If, while the turbines are running at [illegible] second-feet capacity, they should be suddenly shut down, a bore [illegible] feet high would be started. This bore would impose a head on the siphon crests of [illegible] feet, and a total operating head on the siphons of [illegible] feet. It is required that under these conditions the siphons prime as quickly as possible, and when primed have a capacity of a little greater than [illegible] second-feet. Considering the possibility that the siphons might also be used as water-level regulating devices during fluctuations of demand on the generators, it is desirable that the siphons prime quickly and at a low head. Because the total available operating head is small, the siphons fall into the low-head type.

Laboratory Equipment. The [illegible] model was obtained from a [illegible] with a maximum capacity of 2-1/2 second-feet. The system was of the

recirculating type. By a suitable arrangement of pipes and valves two venturi meters were available for measuring the discharge through the model. One venturimeter was placed in the 6-inch line and had a capacity of two second-feet; the other was placed in the 4-inch line and had a capacity of one second-foot. A common gage board served both meters, but was equipped with a different scale for each meter. The system was so arranged that both meters could be operated simultaneously, and by reading the gage separately for each meter, their combined discharge could be obtained.

Water discharged from the pump passed first through the venturimeters and then to a tank which served as the forebay of the siphon. The tank was provided with two gravel-filled baffles to insure that the forebay water would be quiet and of uniform velocity distribution. Because only one of the total of four siphons was tested, it was necessary to proportion the width of the approach channel so that the approach velocity would be relatively the same for the single siphon as it would be when four were operating under the prototype conditions.

To measure the forebay water level a gage was installed which consisted of a single glass tube attached to a scale graduated in hundredths of a foot. Although a point or a hook gage would have given more accurate readings, it was felt that fluctuations in the forebay water level could be more easily and quickly followed with this type of gage. The gage communicated with a rather large

opening in the floor of the approach channel, and all connecting tubes were large enough to make the gage almost instantaneous in action. Further accuracy was obtained by using a sliding cross-hair so that thousandths of a foot could be readily estimated. It was felt that an accuracy in reading of plus or minus one one-thousandth of a foot could thus be obtained. The gage was referenced to the crest of the siphon model in such a manner as to compensate for capillary rise in the glass tube. A point gage was provided for measuring the tailwater elevation at the exit section of the model.

Construction of Model. All the models tested were made of laminated redwood. Each layer was about 2 inches thick, and the grain in each layer ran perpendicularly to the grain in adjacent layers. The crest length in prototype was 6 feet, so the model crest length was 9 inches since the scale chosen was 1:8. This required a block of wood 9 inches thick and equal in height and length to the over-all dimensions of the model. From this block was cut both the invert and crown of the siphon. The two pieces were then worked down until both perfectly fitted a negative template made of sheet metal. The surfaces of the crown and invert were sanded until as smooth a surface as possible was obtained. Both blocks were then soaked for 24 hours in a bath of hot linseed oil. After the bath, both blocks 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 revision number one to the original model, both of which had but one transparent wall. These walls were made of 1/4-inch pyrelin, which is one of the recently developed colorless plastics. The use of two transparent walls facilitated visual observation and photographic recordings. When the painted blocks were thoroughly dry, the transparent walls were screwed to them, and an air-tight seal effected by using a pipe-joint compound between the sides and the wooden blocks. The model of the siphon was then installed.

Data Procured. In Chapter II it was pointed out that certain data could be obtained from the model and applied directly to the prototype; while other data could only be considered to point out a trend. And, furthermore, in order that the model represent the prototype, certain conditions must be fulfilled. Thus, the model scale was restricted as to minimum size. The model siphons of Wasteway No. 2 were at first constructed as a part of the whole wasteway structure which included a section of the approach canal, the siphons and wasteway gates, a steep chute which dropped 150 feet (prototype) and terminated in a stilling pool, and a section of the effluent canal leading from the stilling pool. The model scale of the entire wasteway structure was 1:24. Then tests indicated that the siphons were discharging only 60 per cent of their designed

capacity, an investigation was made which revealed that the model scale was too small. The value of d/h for the 1:24 model was 0.166. A 1:8 scale was chosen, and this gave 0.333 for d/h which is well above the value of 0.20 given by Gibson.[4] The coefficient of discharge, then, and also the load-discharge relation and efficiency indicated by the model could safely be taken as representative of the prototype. Although it was known that the priming qualities found from the model would not be indicative of those of the prototype, model results could be compared with each other. It was felt safe to assume, also, that the design which showed the best priming qualities in the model would likewise perform best in prototype, and relatively better than the models.

Many investigators have determined the minimum head required for priming using a rising forebay water level, and define the minimum priming head as the head at which the siphon primed when the rate of rise was a given value. Then, thus defined it is obvious that 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 there are two factors which must be varied: the head on the siphon crest must be increased at a constant rate; and 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 procedure 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 of different scales the prototype priming head cannot be accurately predicted. For these reasons, then, it was decided to employ a simpler method of determining the minimum head required to prime and maintain a constant forebay water elevation during priming. This procedure required the variation of only one quantity, namely, the discharge. In the model tests on the sixteen of Eastaway No. 2, a condition of flow with a certain head on the crest was established such that the siphon model would not prime in any length of time, however long. Then, 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 the other method—that employing rising water level. Furthermore, this procedure probably duplicates the prototype condition more closely than the other, since the rate of rise of the forebay water level is usually slow enough to be considered practically constant except in the cases where the forebay free water surface area is relatively small.

In determining the time required to prime at the minimum head, the following method was followed. Flow was established at a head on the crest equal to the minimum priming head. Atmospheric pressure inside the siphon

was maintained by allowing air to enter. When the head on the crest was accurately set and equilibrium of flow existed, the air supply to the siphon was stopped. The time required to prime was recorded as the elapsed time from the instant the air supply was stopped until the siphon had completely exhausted all the air.

In the siphons of Fantessy No. 2, a bore causing an 0.03-foot head on the crest will be caused if the turbines of the power plant are suddenly shut off. It was desired to determine the time required for priming under this practically instantaneous head. This was done in the model by raising the water in the forebay from the normal elevation to the bore height level as quickly as possible and then maintaining the .03-foot head during priming. 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 determined for most of the models. It was defined as that minimum discharge which would keep the siphon in continuous operation without completely losing its prime and having to re-prime. This quantity, the minimum discharge for continuous operation, was recorded because it was believed to be a sensitive indicator relative to the priming characteristics.

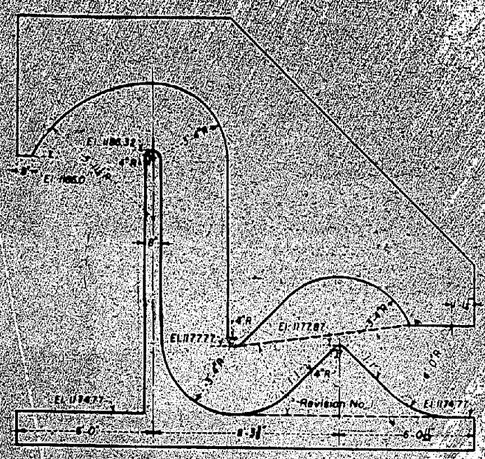
The head on the crest of the siphon corresponding to the discharge through it was determined for a wide range of

discharges. These data were used in computing the coefficient of discharge, the efficiency and the head-discharge relation. In the model called Revision No. 1, which is shown in figure 1-A, the total head was measured from the forebay water level to the P. C. of the lower bend in tests where the exit was not sealed by the tailwater. In Revision No. 2, figure 1-B, the head was measured from the forebay water level to the elevation of the center of curvature of the lower bend, except when the exit was covered by the tailwater. In all other tests, the total head was measured from the upstream water level to the crown at the exit section. For discharges above the value required to make the diverging tube run full, the tailwater elevation immediately downstream from the exit section was found to be very close to the elevation of the crown at the exit section. For uniformity in computation, then, the head was measured to the crown elevation at exit.

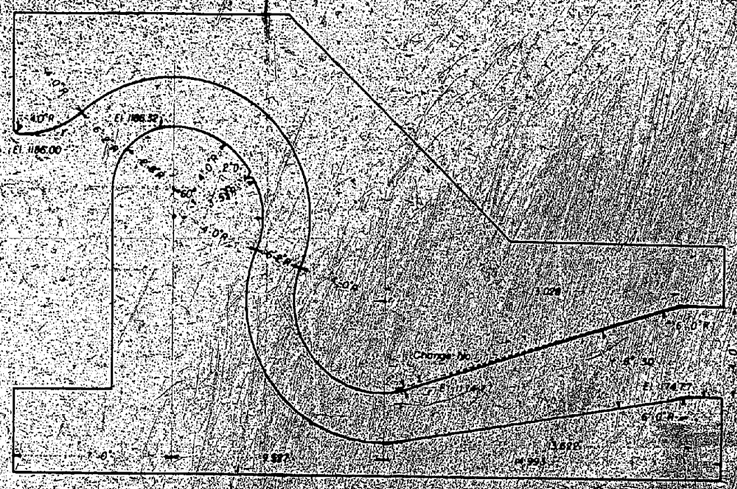
Original model. The line drawing in figure 1-A shows the profile of the original model. The lip of the siphon is placed at the normal forebay water elevation so that the siphon will break its prime when the water has been drawn down to that level. In the exit tube, a "hump" was designed for the purpose of establishing a water seal at the lower bend. Tests proved, however, that this sealing pool was ineffective in facilitating priming. The flow clung to the invert from the crest on down through the lower bend and swept out all the water in the sealing pool,

thus rendering it useless. When a head on the crest equivalent to 1.35 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.

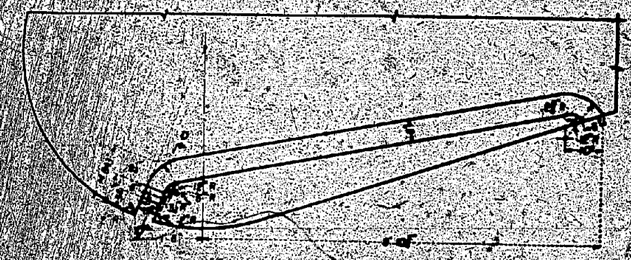
When the siphon model was running full, it demonstrated that its actual capacity was far below its designed capacity. The total designed discharge is 95 second-feet for four siphons, or 23.5 second-feet for one, when the head on the crest is 1.06 of a foot. When the model was operating under a head equivalent to the prototype value of 1.06 feet, the discharge was only 153.6 second-feet, or about 61.4 per cent of the designed value. (In this discussion, all data obtained from the model has been converted to equivalent prototype values. Thus, the head on the crest, model, times the scale ratio equals the head on the crest in prototype; the model discharge times the scale ratio to the five-halves power equals the prototype discharge; time in the model multiplied by the square root of the scale ratio equals time in the prototype; dimensionless quantities such as coefficient of discharge, efficiency, etc. are equally the same in both model and prototype.) The efficiency, computed as described in Chapter II, was 92.15 per cent. The model showed a coefficient of discharge, at the designed head, of 0.36 as compared to 0.71 which was used in designing the siphons. It was at once apparent that the "hump" in the exit tube was the



A - ORIGINAL MODEL
REVISION No. 1 IS SHOWN BY THE BROKEN LINE



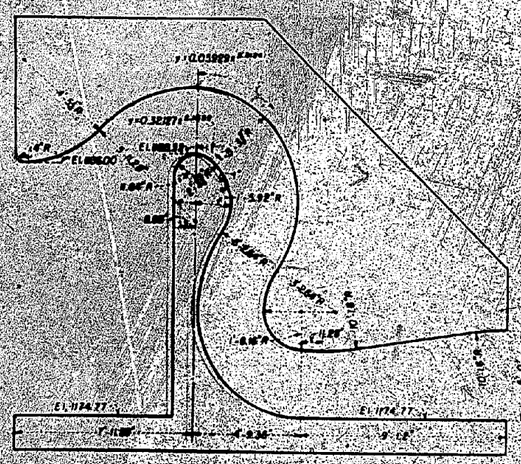
C - REVISION No. 3
CHANGE No. 1 IS SHOWN BY DOTTED LINE



K - CHANGE No. 6 TO REVISION No. 3
CHANGE No. 7 TO REVISION No. 3 IS SHOWN BY DOTTED LINE

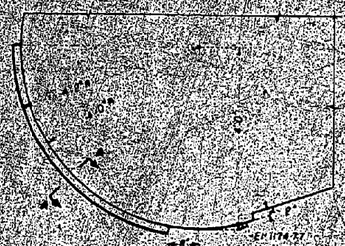
L - SECTION D-D CHANGE No. 6

M - SECTION D-D CHANGE No. 7

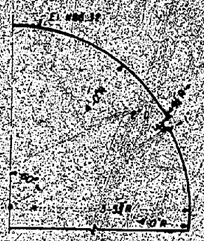


B - REVISION No. 2

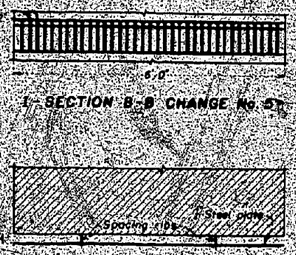
D - CHANGE No. 2 TO REVISION No. 3



F - CHANGE No. 4 TO REVISION No. 3

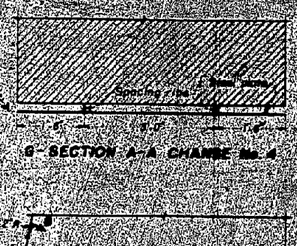


E - CHANGE No. 3 TO REVISION No. 3



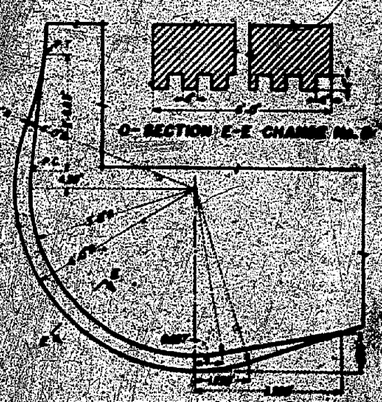
I - SECTION B-B CHANGE No. 5

J - SECTION C-C CHANGE No. 6

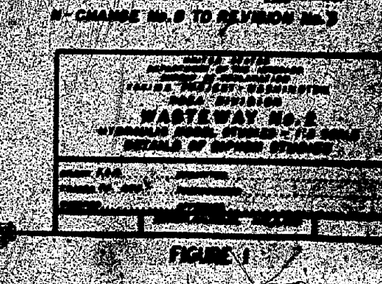


G - SECTION A-A CHANGE No. 4

H - CHANGE No. 5 TO REVISION No. 3



O - SECTION E-E CHANGE No. 8



N - CHANGE No. 8 TO REVISION No. 3

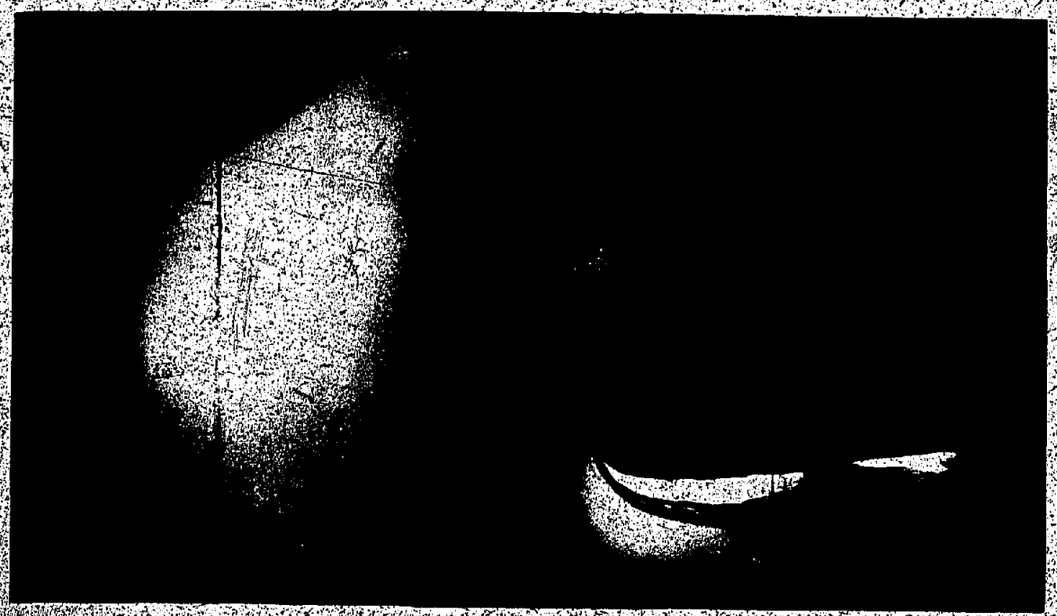
WASTEWAY No. 4

FIGURE 1

cause of much loss, and since it was ineffective in producing a sealing pool, it should be eliminated.

Revision No. 1. When the "hump" in the exit tube was removed, the exit tube became diverging as shown dotted in figure 1-A. This change eliminated what in effect was a double bend. The priming qualities were, of course, not affected by the change, but the discharge characteristics were improved considerably. With the outlet free, the discharge was 167.0 second-feet, an increase of 21.2 per cent over the original model. The coefficient of discharge and efficiency were increased proportionately. When tailwater sufficient to submerge the exit was effected by a control in the outlet channel, the discharge was increased to 305.5 second-feet, or an increase of 34.1 per cent. This value, however, 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.

Revision No. 2. Tests conducted on the original model 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 could be submerged. These features were incorporated in the design of revision No. 2, and are shown in figure 1-B. The shape of the crest from the exit down to the vertical plane is a close approximation to the curved path described by the lower nappe as

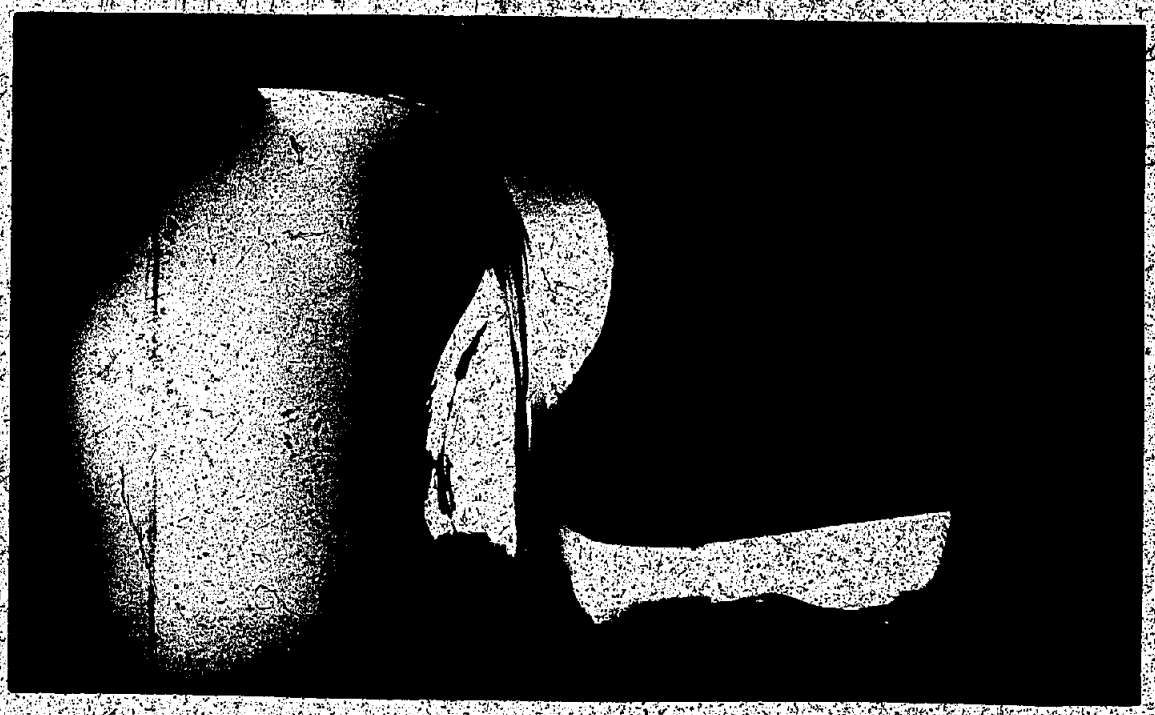


A. EXIT NOT SEALED BY TAILWATER, DIVERGENT TUBE WILL NOT RUN FULL
DISCHARGE IS 317 SECOND-FEET, HEAD, 4.10 FEET

B. EXIT SEALED BY TAILWATER, DIVERGENT TUBE RUNS FULL
DISCHARGE IS 204 SECOND-FEET, HEAD, 2.50 FEET

FIGURE 2 - FLOW CONDITIONS IN REVISION NO. 2

A. UNAERATED NAPPE CLINGS TO INVERT



B. AERATED NAPPE SPRINGS FREE AT STEP SEALS ON OPPOSITE SIDE SUBSEQUENTLY PRIMES

FIGURE 3 - PRIMING CONDITIONS IN REVISION NO. 2

to spring free from the crest of the original model flowing under a 1.[illegible] foot head. The 1-inch step was designed to cause the jet to spring free from the invert at that point, and provisions were made for aeration of the lower nappe at the step. The lower leg was made in an S-shape in an attempt to improve the priming characteristics. Tests showed that with the outlet free the discharge, with a head on the crest of [illegible] foot, was increased to 27[illegible].4 second-feet, an increase of 44.[illegible] per cent over Revision No. 1. When the outlet was submerged by the tailwater, the discharge at the same head was 371.1 second-feet, or 80.3 per cent greater than Revision No. 1 with the outlet submerged. In figure 2-A it can be seen that the diverging tube does not flow full when the outlet is not submerged, even with a discharge of [illegible]17 second-feet and a head on the crest of 4.10 feet, which was the highest permissible value without overtopping the model forebay. Figure 2-B shows the diverging tube flowing full as the result of a submerged exit. In this case the maximum capacity of the model supply pump was reached before a head on the crest of [illegible].10 feet could be obtained. Dye was introduced to show the streamlines. The priming characteristics for this model, when the outlet was free, were worse than in the original. When the nappe was unaerated, the minimum head required to prime was [illegible] feet, giving a priming efficiency of d/1.27. With the nappe aerated, the minimum priming head was 1.[illegible] feet, giving a priming efficiency of d/[illegible].

[illegible] the invert, [illegible]
from the [illegible] crown of the lower bend as a seal
at the [illegible] side. [illegible] at the lower bend was
effected by controlling the tailwater, the minimum priming
head was reduced to .45 foot, or to less than three-tenths
of the value found when the outlet was free. The reason
for this great difference is explained as follows: With
the apron aerated and the outlet unsubmerged, the nappe
was free from the invert at the crest, crossed the lower
[illegible] entered the [illegible] side, thereby sealing the
[illegible] of the siphon from the lower. The effect of
water flowing by the crown of the lower bend and dropping
to the invert was not unlike that allowed air from the
diverging tube to pass through it and maintain a pressure
of practically atmospheric into 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 nappe, was gradually built up. This difference in pressure reached a certain value, [illegible] was observed through the [illegible] wall of the [illegible], as mentioned [illegible] suddenly the seal between the upper and lower parts of the siphon was [illegible] the pressures were equalized. As the head on the crest was increased, the nappe

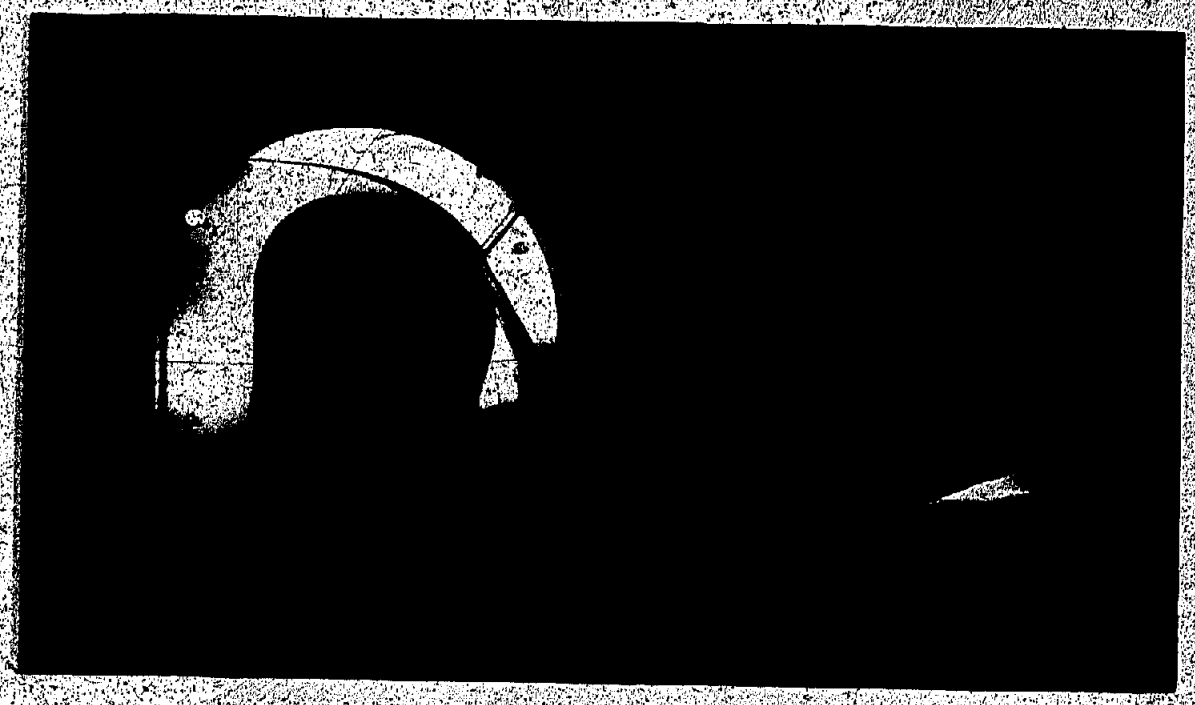
---

because this [illegible] thickness, the duration of the flattening [illegible] became longer until [illegible] the head on the crest of 1.5 feet was reached. With this value of head, the thickness of the [illegible] was sufficient to maintain the pressure difference, and after a short period of [illegible] flutter the siphon went on to prime completely. With no sealing pool at the lower bend, then, the minimum head required to prime is that head which will produce a jet of thickness and velocity such that it can maintain a seal without breaking. In the second case, the sealing pool maintains the pressure difference, and the minimum head necessary for priming becomes that head which will produce a jet of size and velocity sufficient to penetrate the sealing pool to such a point that the entrained air, which it releases, will rise downstream from the lowest part of the crown of the lower bend. It is obvious that in the second case, the [illegible] priming head would be less than in the first, where no seal at the lower bend was provided. Because a sealing pool proved such a definite advantage in priming, a third revision of design was made to incorporate this feature. It seemed advantageous to further increase the radii of the crest and lower bend, and also to decrease the depth at the throat section. The resulting [illegible] was called Revision No. 3.

Revision No. 3. In this model, the depth at the throat section was reduced to [illegible] feet, [illegible] inches as compared with [illegible] feet at the throat in all previous models. The ratio of the

radius of the center-line to the depth at the throat section, R/D, is 2.345. This closely approximates the value of R/D of 2.5 which has been found by various experimenters to give minimum bend loss. The value of R/D for Revision No. 3 is much larger than in the other models: for the original model, R/D was 0.61; for Revision No. 2, R/D was 0.85. At a point 60° down from the crest, a transverse slot, semi-circular in section and having a 2-inch diameter, was designed to facilitate aeration of the nappe. The angle of divergence of the exit tube was made 8°-30', which Gibson[6] found to be optimum when following a right angle bend. Since the depth of the barrel at the start of the diverging tube had been decreased to 8 feet, 6 inches, and because the depth at exit was governed by the size of the effluent conduit, which was 4 feet deep, the length of the diverging tube was necessarily greater than in previous models. 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. These features and the principle dimensions are shown in figure 1-C.

In Revision No. 3 the diverging tube always ran full at the designed head of 0.38 foot, and the discharge at this head was 352.1 second-feet. This is a decrease of 10.8 per cent as compared with Revision No. 2 with the outlet submerged. Because the throat area of Revision No. 3 was decreased 27.8 per cent as compared with Revision



A.- FLOW AT MINIMUM DISCHARGE FOR CONTINUOUS OPERATION, 22 SECOND-FEET

B. CLOSE-UP OF CROWN OF LOWER BEND VIEWED FROM DOWNSTREAM

FIGURE 4 - REVISION NO.3

[illegible] decrease in discharge was expected.

With a seal at the lower bend, a new problem arose. [illegible] the water level in the forebay rose above the lip of the [illegible], air thus trapped in the siphon was compressed with [illegible] result that the water level inside the siphon was less than the forebay water level outside. Obviously, with this condition existing, the time of priming of the siphon was [illegible]. To obviate this difficulty, a compression relief tube was installed connecting the upper part of the siphon with the diverging tube. The point where the compression relief tube entered the diverging tube was determined so that the water in the diverging tube would just seal the end of the compression relief tube when the head on the crest was [illegible] foot during priming. The compression relief tube can be seen in Figure [illegible]. In the same drawing [illegible] the aeration tube. With the compression relief tube open, the minimum head to prime was found to be [illegible] foot. When the compression relief tube was closed by a [illegible], the minimum head required for priming was found to be [illegible] foot. Figure [illegible] is a view of Revision No. [illegible] flowing at the minimum discharge for continuous operation. The aeration tube can be seen against the transparent wall. To the right is seen the compression relief tube.

Change No. 1 to Revision No. [illegible]. A study of the sealing [illegible] 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 leg of the siphon by water currents set

TABLE I

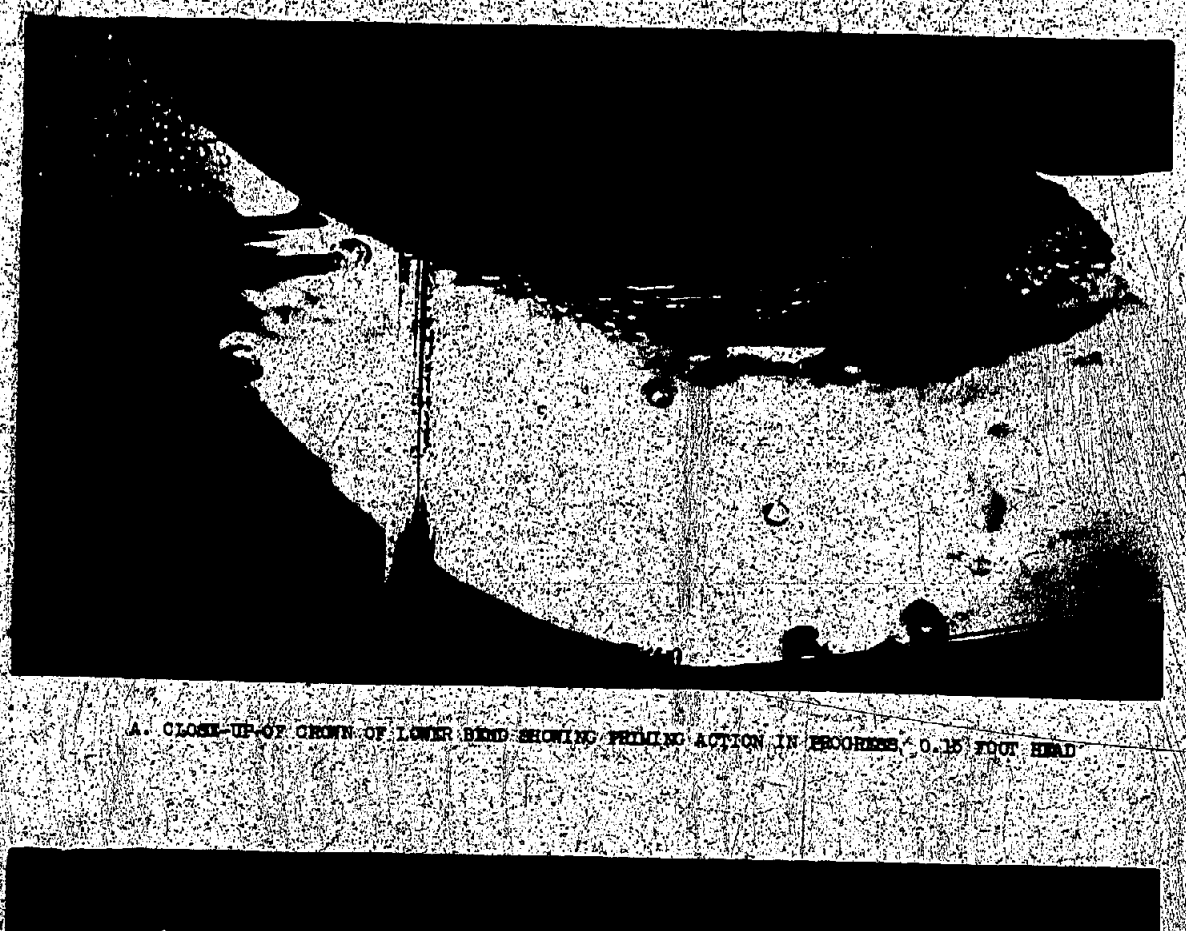
Siphon Design	Description	Minimum Head to Prime h Feet	Priming Efficiency	Discharge at Head of 0.88 Ft. Second-Feet	Coefficient of Discharge	Efficiency Percent	Minimum Discharge for Continuous Operation Second-Feet	Time to Prime at Minimum Head Seconds	Time to Prime at Head of 0.88 Ft. Seconds
Original	Nappe unaerated, outlet free	1.33	d/2.86	163.5	0.365	18.13	-	-	-
Revision No. 1	Nappe unaerated, outlet free	1.33	d/2.86	187.0	0.432	22.08			
	" " outlet submerged			205.8	0.491	24.33	-	-	-
Revision No. 2	Nappe unaerated, outlet free	2.57	d/1.27						
	Nappe aerated, outlet free	1.53	d/1.96	270.4	0.691	31.90			
	" " outlet submerged	0.45	d/6.67	371.1	0.668	44.20	-	-	66
Revision No. 3	Nappe aerated, C.R.T. open	0.96	d/2.86					294	
	Nappe aerated, C.R.T. closed	0.68	d/3.19	331.1	0.526	54.30	-	4313	-
Change No. 3 to Revision No. 3	Nappe aerated C.R.T. closed	0.56	d/3.87	322.8	0.584	53.20	23.53	10350	-
Change No. 4 to Revision No. 3	C.R.T. open	0.15	d/14.65	294.2	0.528	47.50	3.68	690	130
	C.R.T. closed								138
Change No. 5 to Revision No. 3		0.15	d/14.45	282.4	0.505	46.17	-	2786	-
Change No. 6 to Revision No. 3		0.15	d/14.45	319.0	0.568	51.90	21.7	402	78
Change No. 6 to Revision No. 3	Air-escape tube closed but not airtight	-	-	325.8	0.590	53.40	-	-	-
Change No. 7 to Revision No. 3		0.15	d/14.45	320.4	0.569	52.15	21.7	166	55
Change No. 7 to Revision No. 3	Air-escape tube closed but not airtight	-	-	334.0	0.597	54.50	-	-	-
Change No. 8 to Revision No. 3		0.51	d/4.25	307.6	0.550	50.30	23.5	2093	156
Change No. 9 to Revision No. 3		-	-	333.3	0.595	54.60	-	-	-
Revision No. 4		0.14	d/15.47	255.1	0.457	41.73	3.68	163	66
Change No. 1 to Revision No. 4		-	-	255.1	0.457	41.73	-	-	-
Change No. 2 to Revision No. 4		-	-	258.3	0.463	42.25	-	-	-

Note: Compression-relief tube is abbreviated as C.R.T.

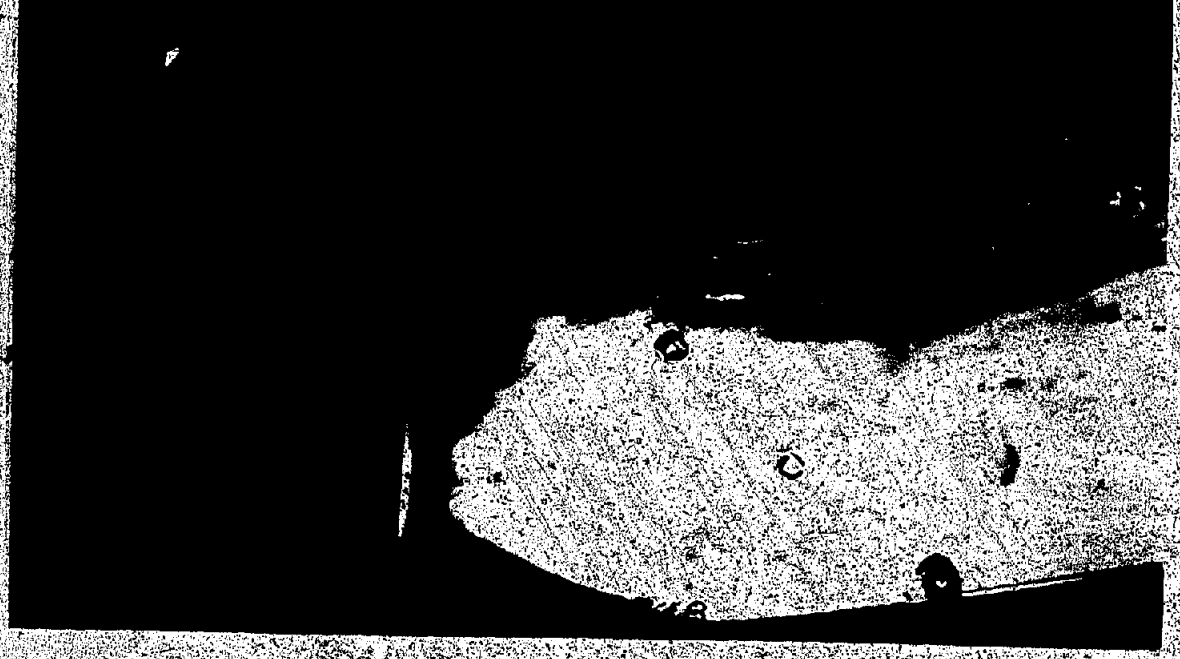
up by the jet entering the sealing pool. In an attempt to prevent this action and thereby decrease the time of priming a step 2 inches deep was cut in the crown of the diverging tube. This change is shown dotted in figure 1-C. The step was not effective in improving the priming qualities.

Change No. 2 to Revision No. 3. It was thought 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 flowed into the sealing pool, and the priming characteristics would be, thereby, improved. To accomplish this end, a lip or spur was installed at a point 60° down from the crest, as shown in figure 1-D. This spur deflected the jet too much, so that it impinged too high on the opposite side.

Change No. 3 to Revision No. 4. Change No. 3 to Revision No. 3 is a modification of Change No. 2. This spur is shown in figure 1-E. It proved to be satisfactory in deflecting the jet the right amount. Table I gives a comparison between most of the changes and revisions made in these experiments. It will be seen that the effect of the spur used in Change No. 3 was to decrease the discharge by only 8.3 second-feet, or 2.5 per cent; while at the same time the minimum head required to prime was decreased by 0.12 foot, or 27.9 per cent. The time required to prime at this minimum head as indicated by the model was 13,360 seconds, or almost 3 hours. Although it was known that the priming qualities in prototype would be better than

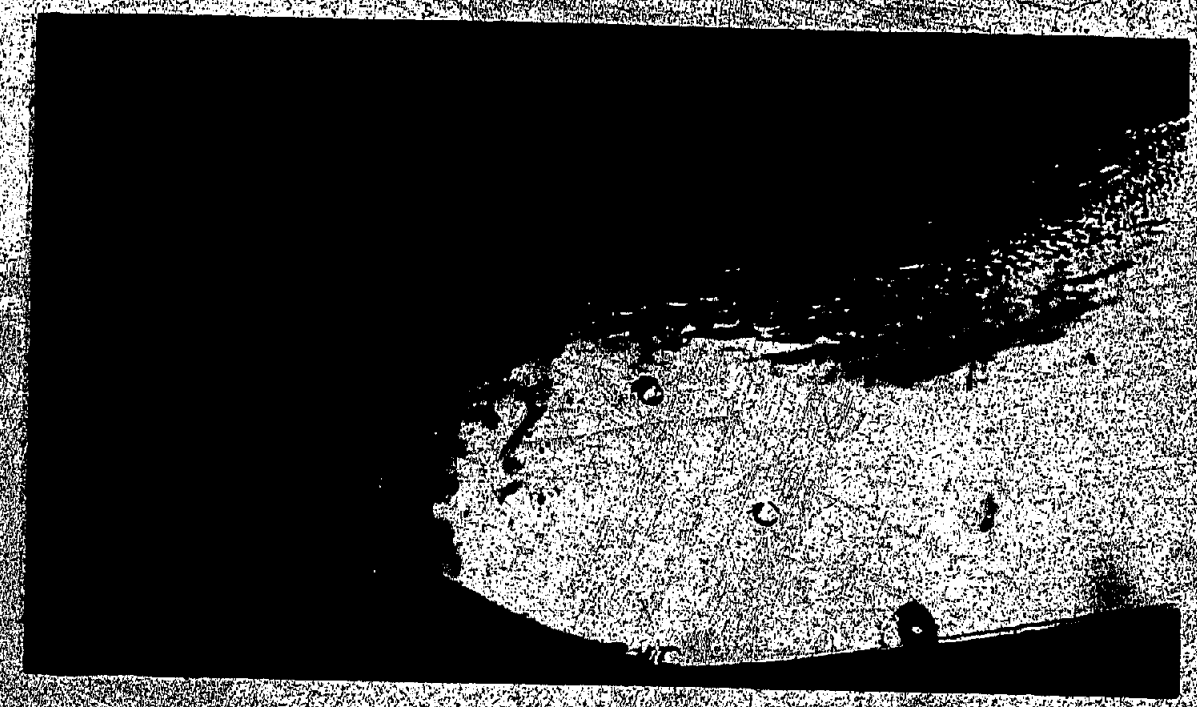


A. CLOSE-UP OF CROWN OF LOWER BEND SHOWING PRIMING ACTION IN PROGRESS, 0.15 FOOT HEAD



B. CLOSE-UP OF CROWN OF LOWER BEND SHOWING PRIMING ACTION HAS CEASED, 0.35 FOOT HEAD

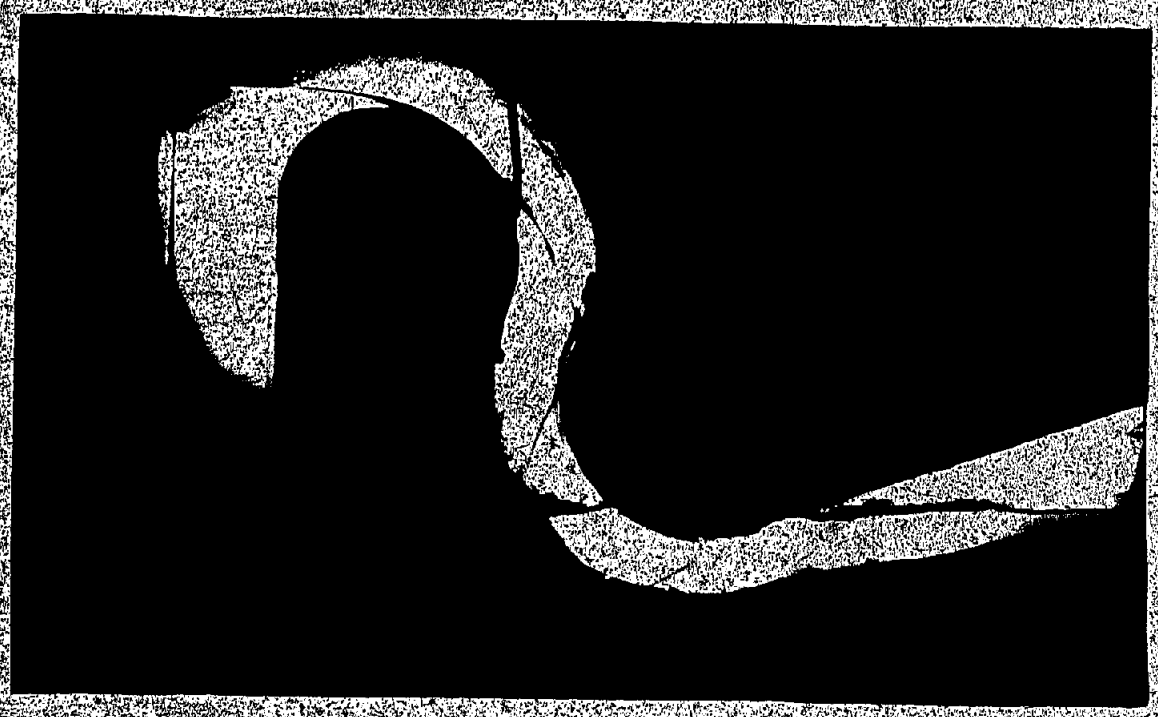
FIGURE 5 - PRIMING PHENOMENON, CHANGE NO. 5 TO REVISION NO. 3



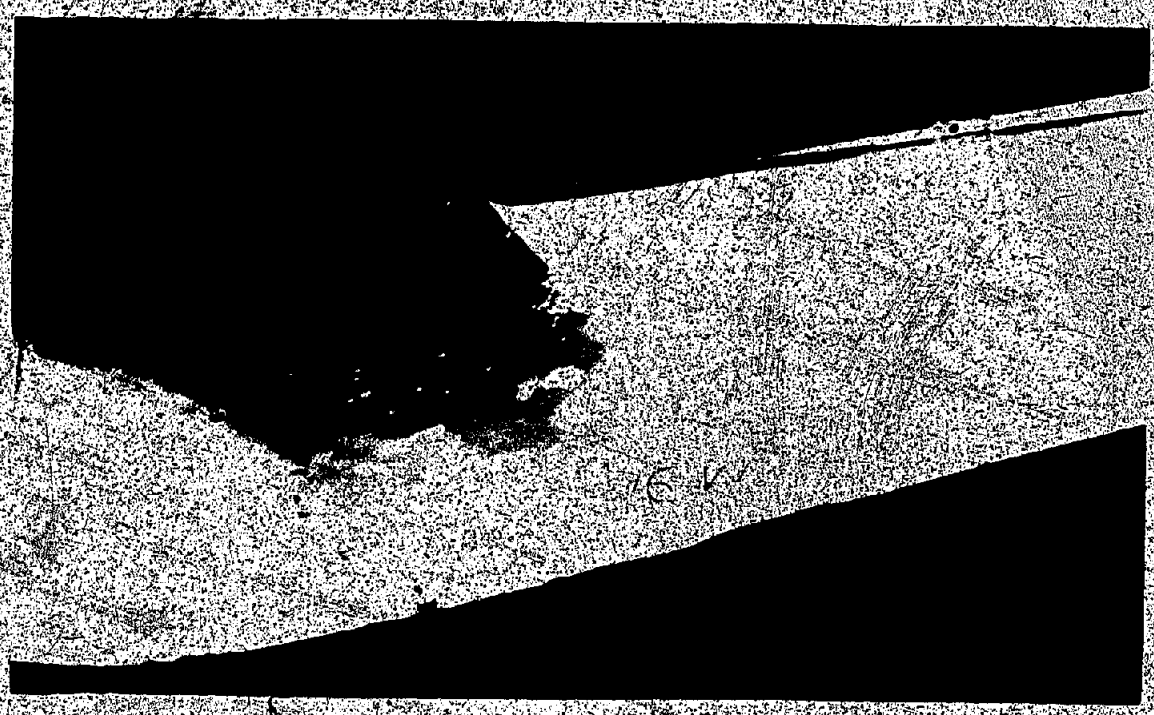
A. CLOSE-UP OF CROWN OF LOWER HEAD SHOWING PONDED ACTION AT MINIMUM HEAD TO PRIME, 0.56-FOOT HEAD.

B. CLOSE-UP OF LOWER HEAD FROM UPSTREAM SHOWING REGION CHARGED WITH AIR, 0.51 FOOT HEAD.

FIGURE 6.- PRIMING CONDITIONS, CHANGE NO. 3 TO REVISION NO. 3.



A. SIPHON DURING PRIMING - NOTE ABSENCE OF AIR IN SEALING FOOT (0.5) FOOT HEAD.

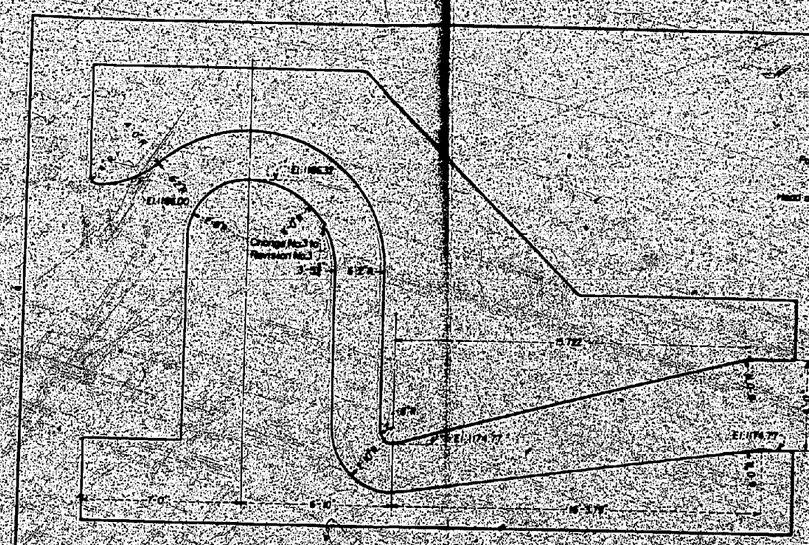


B. CLOSE-UP OF CROWN OF LOWER BEND DURING PRIMING AT MINIMUM HEAD - NOTE AIR ESCAPING FROM END OF PRIMING GUIDE VANE. 0.15 FOOT HEAD.

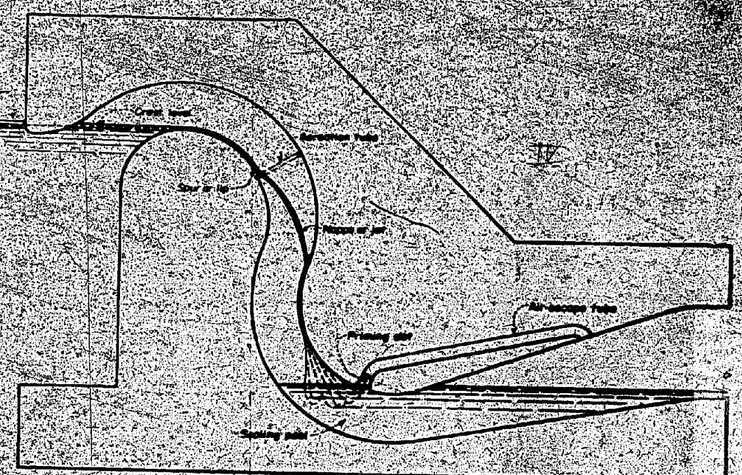
FIGURE 7 - PRIMING CONDITIONS, CHANGE NO. 4 TO REVISION NO. 3

indicated by the model, a further improvement was desired. During the tests conducted on Change No. 3, it was observed that priming would start with a very low head on the crest. After a negative model pressure of about 1.2 feet 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 lowest point of 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. This phenomenon is shown in the accompanying photographs. Figure 6-A is a close-up of the crown of the lower bend, viewed from a position somewhat downstream from the lowest point of the crown. Figure 6-B is a view of the priming action taking place with a head on the crest of 0.45 foot. One large bubble in particular can be seen to be in motion in about the center of the crown. It can be seen in figure 6-B that priming action has ceased, though the head is 0.35 foot. A view from upstream showing the lower crown charged with bubbles, none of which are escaping, can be seen in figure 6-H. Figure 6-A shows priming action continued at a head of 0.60 foot. A study of the priming phenomena led to the development of a new priming device.

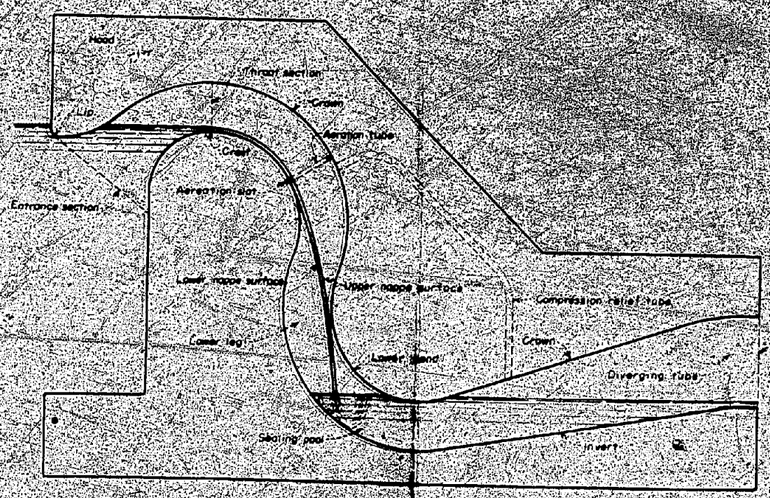
Change No. 4 to Revision No. 3. The priming device



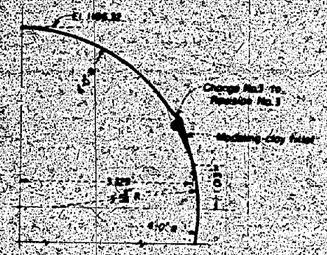
A - REVISION No. 4



C - REVISION No. 3 INCORPORATING LIP, PRIMING SLOT AND AIR-ESCAPE TUBE



B - REVISION No. 3 INCORPORATING AERATION SLOT, AERATION TUBE AND COMPRESSION-RELIEF TUBE



D - CHANGE No. 3 TO REVISION No. 3

E - CHANGE No. 2 TO REVISION No. 4

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
YAKIMA PROJECT - WASHINGTON
BOISE DIVISION

WASTEWAY No. 2

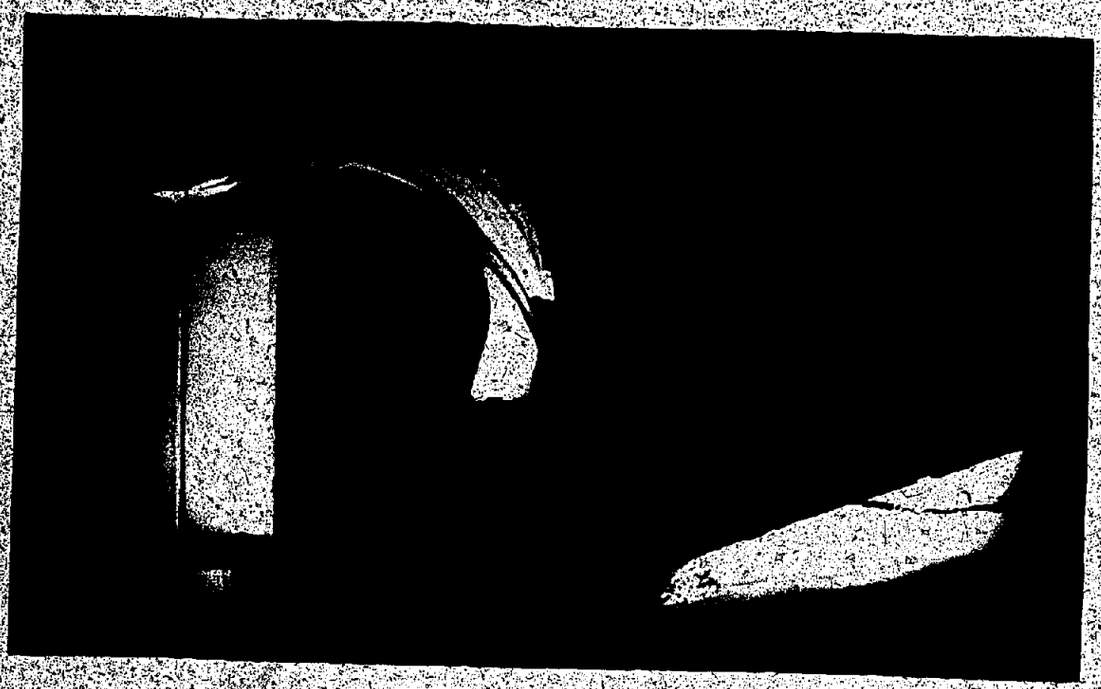
HYDRAULIC MODEL STUDIES - 1:8 SCALE
STUDY OF PRIMING DEVICES

FIGURE 8

developed as a result of tests on Change No. 3 is simply a guide vane or membrane spaced 2 inches out from the crown of the lower bend. It is shown in elevation in figure 1-F, and in section in figure 1-G. The purpose of the membrane was to give the air-laden priming jet a horizontal direction so that the air is released in the sealing pool would rise downstream from the lower bend. This priming guide vane was greatly successful in this respect. Figure 7-A shows the siphon during priming when the head on the crown was 0.81 foot. 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 figure 7-A is compared with figure 4-A or figures 12-A and 12-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 6/14.85. At this head the siphon primed in 600 seconds with the compression relief tube closed. At a head on the crown of 0.25 foot, the siphon primed in 130 seconds with the compression relief tube open, and in 188 seconds with it closed. Figure 7-B shows air escaping from the end of the priming guide vane during flow at the minimum head to prime.

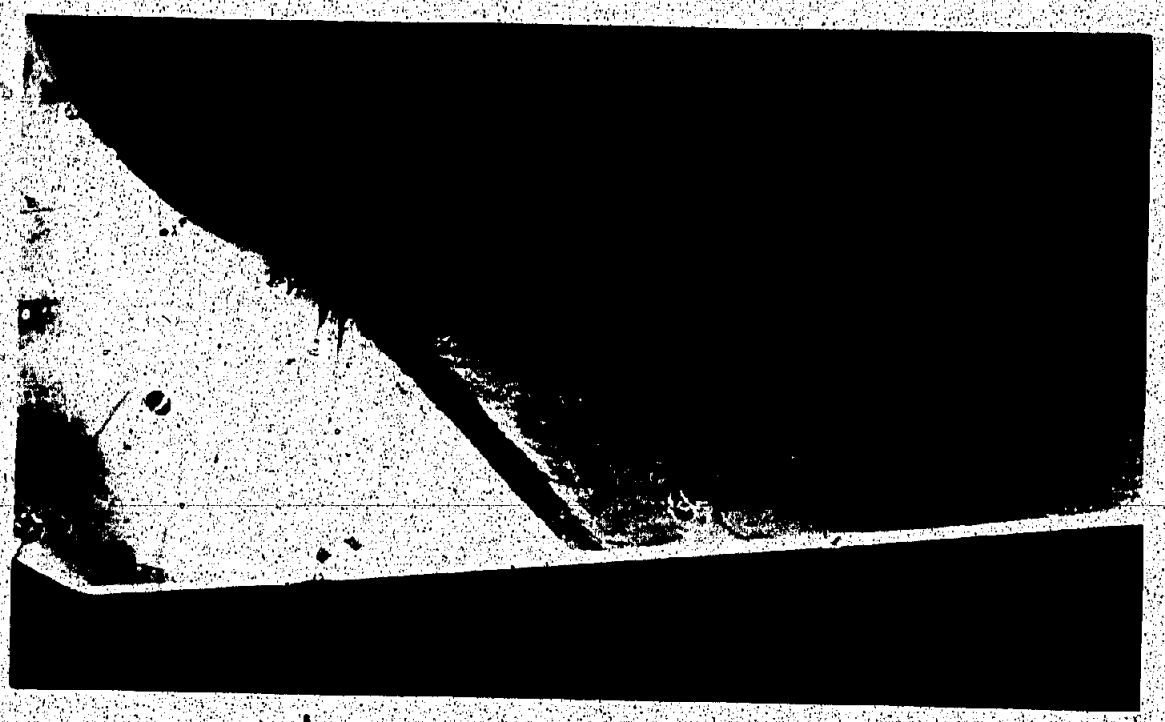
The discharge of the siphon was decreased by 20.8 second-feet, or 8.9 per cent, due to the interference of the priming vane. There were, however, much more serious objections. It was felt that trash might fill the small space between the membrane and the crown, or that ice might bend or break it.

A. NO FLOW - NOTE PRIMING SLOT IN CROWN OF LOWER BEND AND POINT WHERE AIR-ESCAPE TUBE ENTERS CROWN OF DIVERGING TUBE AT THE RIGHT

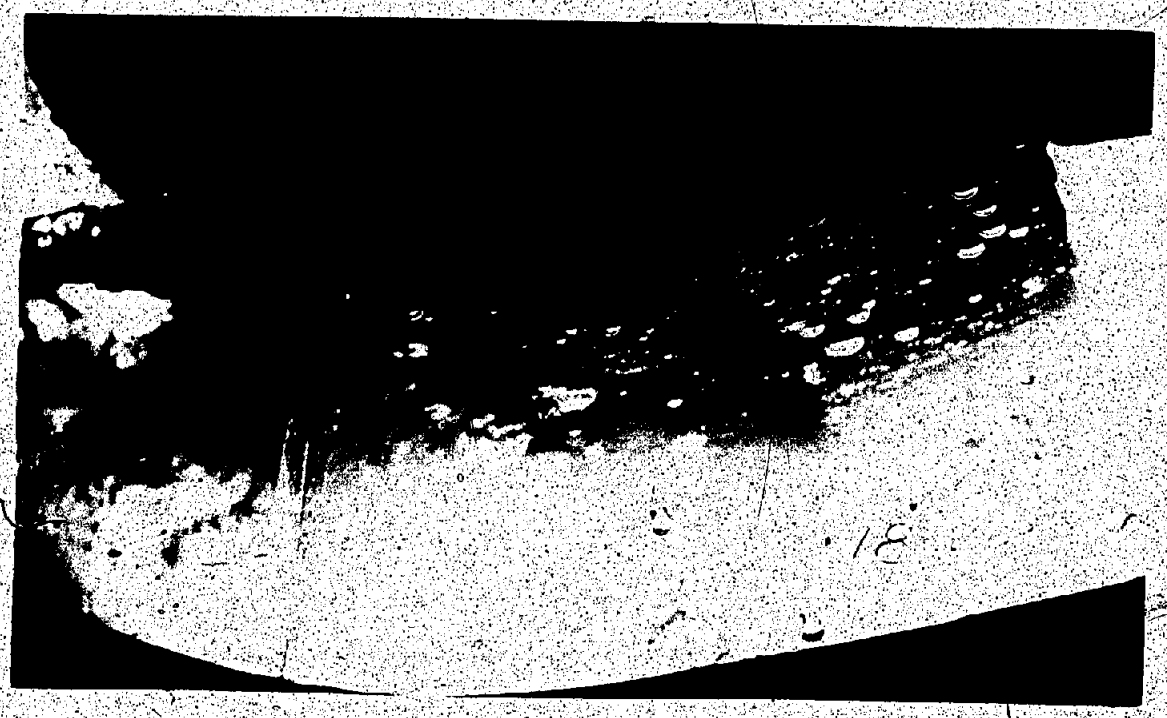


B. FLOW AT MINIMUM DISCHARGE FOR CONTINUOUS OPERATION, 22 SECOND-FEET

FIGURE 9 - CHANGE NO. 6 TO REVISION NO. 3



A. VIEW OF CROWN OF LOWER BEND SHOWING PRIMING SLOT



B. VIEW OF CROWN OF LOWER BEND DURING PRIMING SHOWING AIR BUBBLES ENTERING PRIMING SLOT, 0.35' FOOT HEAD

FIGURE 10 - THE ORIGINAL PRIMING SLOT

Change No. B to Revision No. 2. To overcome the objection raised that trash might plug up the space between the guide vane and the crown, another embrane was designed which incorporated a trash rack as shown in figure 1-I. Furthermore, it was divergent in shape as shown in figure 1-K. With this device, the siphon primed at the same head as it did with the former priming 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 proble was tried.

Change No. C to Revision No. 2. A transverse slot was cut in the crown of the lower bend. This has been called the priming slot. A 6-inch by 6-inch tube, called the air-escape tube, connects one end of the priming slot with the diverging tube. This device is shown in figure 1-K, and in section in figure 1-L. In figure 8-C is shown the priming slot in reference to the whole siphon. The minimum head required to prime was 0.15 foot, the same as in the cases when the guide vanes were used, but the time to prime at this head was considerably reduced. The time to prime at a head of 0.28 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 closed, though not

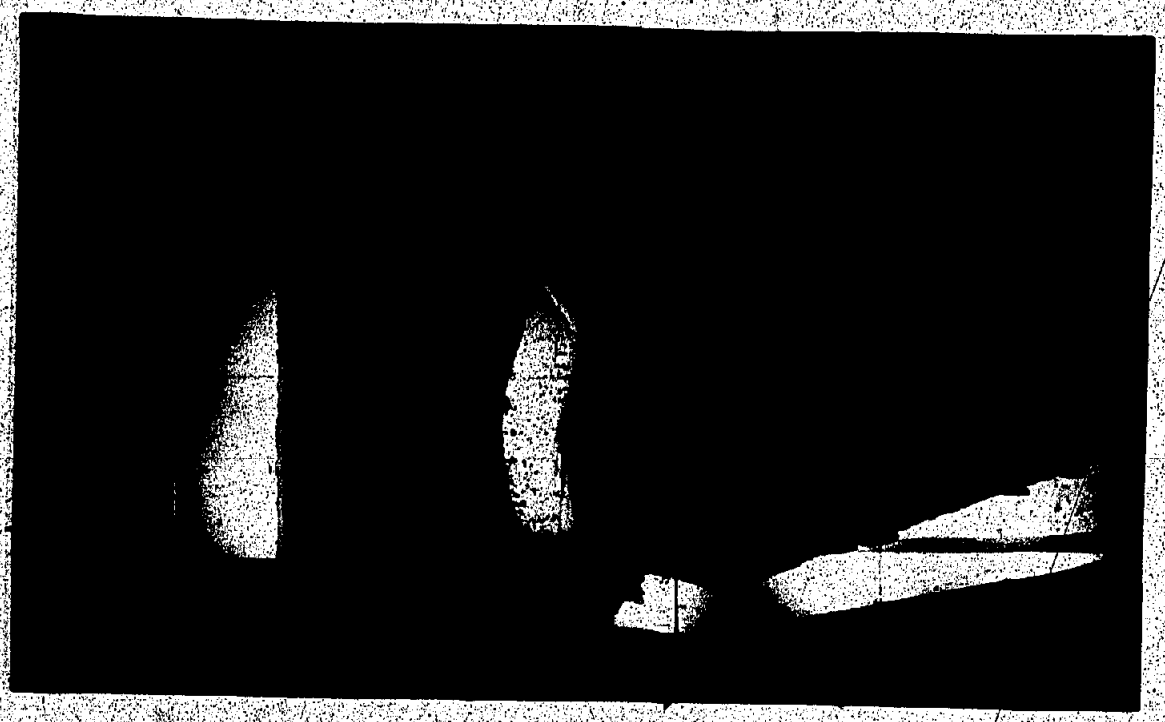
A. CLOSE-UP FROM SIDE SHOWING JET ENTERING POOL AFTER STRIKING OPPOSITE SIDE OF LOWER LEG. 0.15 FOOT HEAD

B. CLOSE-UP FROM SIDE SHOWING JET ENTERING POOL AFTER NOT STRIKING OPPOSITE SIDE OF LOWER LEG

FIGURE 11 - REVISION NO. 4 SHOWING JET ACTION

air tight. The effect of closing the air-escape tube was to increase the discharge 2.1 per cent. Compared with Change No. 3, the effect on the discharge of the priming slot with the air-escape tube open was to decrease it by only 1.2 per cent. In figure 9-A, a part of the priming slot can be seen, and also the point where the air-escape tube enters the diverging tube. Figure 9-B shows the siphon during flow at the minimum discharge for continuous operation. Figure 10-A shows the priming slot in the crown of the lower bend. In figure 10-B the priming slot can be seen in action.

Change No. 7 to Revision No. 2. The original priming slot appeared to be somewhat inadequate, so it was widened, the corners of the entrance were rounded and another air-escape tube added. The resulting priming device is shown dotted in figure 1-K and in section in figure 1-M. Experiments indicated that the minimum priming head remained unchanged, but the time required for priming at that head was reduced by 56.7 per cent, 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 28.5 per cent, 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 per cent. This change might easily be attributed to experimental error, except for the fact that since counter circulation through the single



A. VIEW OF NORMAL JET WHEN PRESSURES ABOVE AND BELOW ARE EQUALIZED

B. JET IS DEFLECTED UPWARD WHEN PRESSURES ABOVE AND BELOW ARE UNEQUAL

FIGURE 12 - NORMAL AND DEFLECTED JETS

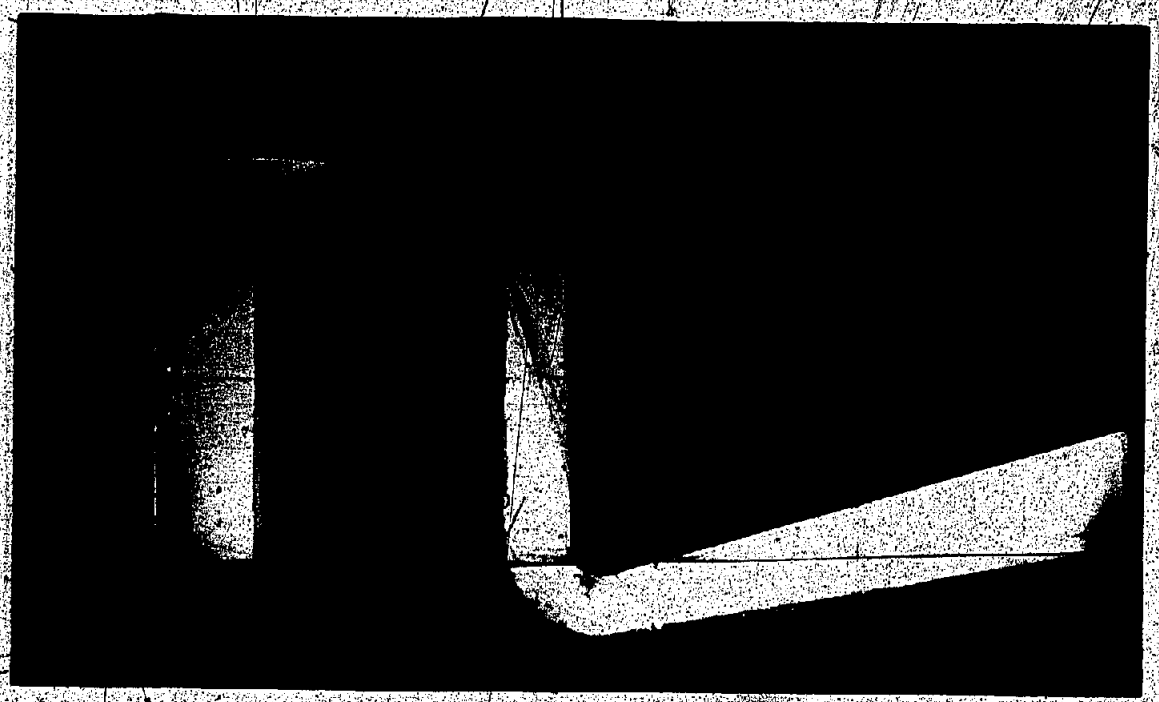
air-escape tube of the original priming slot device reduced the discharge, then, certainly, the decrease due to the air-escape tubes would be even more pronounced. Experiments bore out this assumption. When the air-escape tubes were closed to prevent counter circulation, the discharge was increased by 2.5 per cent 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 counter circulation right justify the expense of installation since by using them the discharge could be increased by 4.2 per cent, or the efficiency could be increased by 2.35 per cent.

When the priming slot was used, the compression relief tube was omitted. The spur, however, is quite essential. Figure 11-A shows the action of the jet on entering the sealing pool after striking the side of the lower leg opposite the crest. The jet tends to cling to the crown of the lower bend, thereby giving the released air bubbles a downstream direction. Figure 11-B illustrates the action of the jet when it has not first struck the wall opposite the crest before entering the sealing pool. When the photograph was taken, it was not possible to make the whole jet fall directly to the sealing pool without first striking the opposite wall of the lower leg. The part of the jet nearest the camera, however, illustrates the point. The action of the jet with and without the spur is illustrated in figures 8-C and 8-B respectively. By using the spur, the

area in the vicinity of the priming slot is more densely charged with air bubbles than when the spur is not used.

Another essential feature in connection with priming is the aeration tube. If the aeration tube is not used, the upper part of the jet evacuates air from the upper part of the siphon. The air entrained in the nappe is released in the scaling pool and that part of the air which does not escape through the priming slot returns to that part of the lower leg lying beneath the nappe. With this action taking place, a difference in pressure is soon built up between the parts of the siphon above and below the nappe. The result of this pressure difference is to deflect the nappe upward. When this occurs, there is a considerable rebound with the result that the center of gravity of area in the scaling pool charged with air bubbles lies further away from the priming slot. The effect of this action is to increase the priming time. Figure 18-A shows the normal jet result from equalizing the pressures by the aeration tube. Figure 18-B illustrates the condition resulting from a difference in pressure between the upper and lower parts of the siphon, which exists when an aeration tube is not used.

Change No. 8 to Revision No. 3. It was suggested that a series to longitudinal slots in the crown of the lower bend might improve the priming characteristics of the siphon by an action similar to that of the priming guide vane. Such a device is shown in elevation in figure 1-F,



A. FLOW AT MINIMUM HEAD REQUIRED TO PRIME, 0.14 FOOT HEAD

B. CLOSE-UP OF LOWER BEND DURING FLOW AT MINIMUM HEAD REQUIRED TO PRIME, 0.14 FOOT.

FIGURE 13 - REVISION NO.4

and in section in figure 1-C. The results, shown in Table I, were disappointing.

Change No. 2 to Revision No. 3. It was thought that if the area just below the spur were filled, the eddy loss due to the spur would be diminished. Figure 8-D gives the dimensions of the fillet tested. The model indicated that the fillet increased the efficiency by a little more than one per cent. However, when the same fillet was tried on Revision No. 4 it showed no improvement. A similar fillet, shown in figure 8-E, was tried on Revision No. 4 (called Change No. 2 to Revision No. 4). This fillet showed only a very slight increase in the efficiency, but a very definite tendency to make the jet cling to it when priming at a low head. Aeration would be made more difficult with such a fillet. For these reasons, then, the idea was abandoned.

Revision No. 4. Most authorities have stated that for good priming qualities the radius of the lower bend must be small, and that priming efficiency is gained at the expense of the siphonic efficiency. For these reasons it was decided to construct a new model, essentially similar to Revision No. 3 in every respect except that the radius of the lower bend would be much smaller. Accordingly, Revision No. 4 was built and the crown of the lower bend had a radius of 8 inches as compared with the 48-inch radius of the corresponding bend in Revision No. 3. Figure 8-A gives the general dimensions of Revision No. 4.

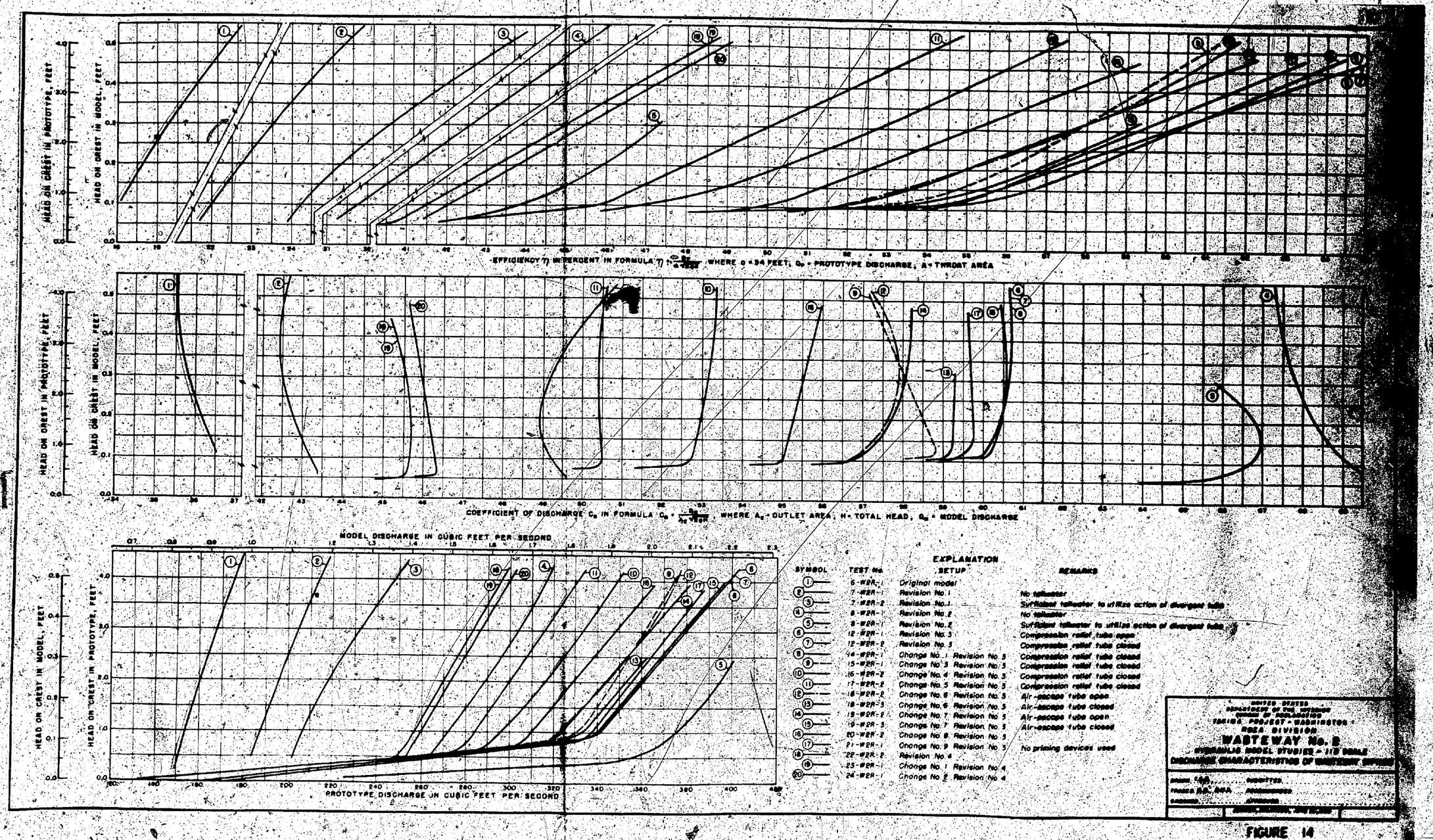

HEAD ON CREST IN PROTOTYPE, FEET
HEAD ON CREST IN MODEL, FEET
EFFICIENCY η IN PERCENT IN FORMULA η = Q_p / A√2gH, WHERE g = 34 FEET, Q_p = PROTOTYPE DISCHARGE, A = THROAT AREA
COEFFICIENT OF DISCHARGE C_D IN FORMULA C_D = Q_m / A_c√2gH, WHERE A_c = OUTLET AREA, H = TOTAL HEAD, Q_m = MODEL DISCHARGE
MODEL DISCHARGE IN CUBIC FEET PER SECOND
PROTOTYPE DISCHARGE IN CUBIC FEET PER SECOND
EXPLANATION
SYMBOL TEST No. SETUP REMARKS
1 6-W2R-1 Original model
2 7-W2R-1 Revision No. 1 No tailwater
3 7-W2R-2 Revision No. 1 Sufficient tailwater to utilize action of divergent tube
4 8-W2R-1 Revision No. 2 No tailwater
5 8-W2R-1 Revision No. 2 Sufficient tailwater to utilize action of divergent tube
6 12-W2R-1 Revision No. 3 Compression relief tube open
7 12-W2R-2 Revision No. 3 Compression relief tube closed
8 14-W2R-1 Change No. 1 Revision No. 3 Compression relief tube closed
9 15-W2R-1 Change No. 3 Revision No. 3 Compression relief tube closed
10 16-W2R-2 Change No. 4 Revision No. 3 Compression relief tube closed
11 17-W2R-2 Change No. 5 Revision No. 3 Compression relief tube closed
12 18-W2R-2 Change No. 6 Revision No. 3 Air-escape tube open
13 18-W2R-3 Change No. 6 Revision No. 3 Air-escape tube closed
14 19-W2R-2 Change No. 7 Revision No. 3 Air-escape tube open
15 19-W2R-3 Change No. 7 Revision No. 3 Air-escape tube closed
16 20-W2R-2 Change No. 8 Revision No. 3
17 21-W2R-1 Change No. 9 Revision No. 3 No priming devices used
18 22-W2R-2 Revision No. 4
19 23-W2R-1 Change No. 1 Revision No. 4
20 24-W2R-1 Change No. 2 Revision No. 4
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
TAKIMA PROJECT - WASHINGTON
ROZA DIVISION
WASTEWAY No. 2
HYDRAULIC MODEL STUDIES - 1/10 SCALE
DISCHARGE CHARACTERISTICS OF WASTEWAY SYSTEM

FIGURE 14

The minimum head required to prime was 0.14 foot, or a decrease of only [illegible] foot which might easily have been experimental error. Figures 13-A, and 13-B show Revision No. [illegible] during the process of priming. The priming and discharge characteristics are given in Table I. The time to prime at the minimum priming head was 163 seconds which compares favorably with the priming time of 1[illegible] seconds for Revision No. 3 when using the larger priming slot. The time required for Revision No. 4 to prime when the head on the crest was 0.88 foot was [illegible] seconds, which is considerably greater than the [illegible] seconds required for Revision No. 3 using the large priming slot. Experimental error could account for some of this difference, but it would appear that the priming qualities of Revision No. 3 using the larger priming slot is somewhat superior at a head on the crest of 0.[illegible] foot. On the other hand, the value of the minimum discharge for continuous operation for Revision No. 4 is very much smaller than the value found for Revision No. 3 [illegible] second-feet for the former as compared with 21.7 second-feet for the latter. Considering all the priming characteristics together, then, the model tests would seem to indicate that the priming qualities of Revision No. 4 and Change No. 3 to Revision No. 4 are about equal.

The discharge characteristics for Revision No. 4 were greatly inferior to those found for Revision No. 3 using the large priming slot. The discharge of the former was [illegible] second-feet; while the discharge for the latter was

320.4 second-feet when the air-escape tubes were open. The difference in discharge is 65.3 second-feet. Expressed in another way, the effect of the larger radius of the lower bend was to increase the discharge by 25.6 percent, and by using an appropriate priming device, there was no adverse effect on the priming qualities of the siphon.

CHAPTER IV

DISCUSSION OF TESTS RESULTS

Effect of Increasing Crest Radius. By increasing the radius of the crest, the discharge of the siphon was increased. In figure 14 the efficiency, coefficient of discharge, the head-discharge relation curves are shown. Referring to the head-discharge graph, the curves numbered "3," "5," and "6" give the relation between head and discharge for three models tested under the same conditions. That is, the effect of the diverging tube was present in all three, and all three had the same crest length, and the same outlet area. The radii of the crests of the models from which data were obtained for curves 3, 5, and 6 were respectively 6 inches, 11.04 inches and 48 inches. In comparing these curves, it would appear that, since curve 5 indicates a much higher discharge for the same head than either of the other two, the 11.04-inch crest radius gives the best results. The area of the throat section for the models represented by curves 3 and 6 is 18 square feet for each, but the throat area of the model whose curve is number 6 is only 13 square feet. In comparing the effect of the radius of the crest, the discharge per square foot of throat area should be used. Thus, at a head on the crest of 2.0 feet, the discharge per square foot of throat area for the siphon with a 6 inch crest radius was 12.1 second-feet; for the siphon with an 11.04 inch crest radius it was

21.9 second-feet; and for the siphon with a 48 inch crest radius, the discharge per square foot of throat area was 27.8 second-feet. In other words, by increasing the crest radius from 4 inches to 11.84 inches, an increase in discharge of 80.3 per cent was obtained; and by increasing the radius from 4 inches to 48 inches, an increase in discharge of 129.8 per cent 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.

In studying the curves representing the head-discharge relation for the various siphons it will be noticed that, in almost all cases, for any particular curve there is a point at which a sudden change of slope occurs. It was at this point that the siphon ceased to draw in air together with the water. The head on the crest at which the siphon ceases to draw in air varies with the particular siphon. The reason for this is explained as follows: It will also be noticed that, in general, the siphons having the best head-discharge curves also have the best efficiency curves, and, further, the curve for one particular siphon occurs in the same relative position with respect to the other curves on both the head-discharge, and the efficiency charts. 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. In

general, then, as the discharge characteristics of a siphon are progressively increased, 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 drag-down curve, with the ultimate result that the load on the crest of which the siphon ceases to draw in air will be higher.

A comparison of curves 3, 5, and 6 on the coefficient of discharge chart shown in figure 14 would seem to indicate that by increasing the crest radius from 4 inches (curve 3) to 11.06 inches (curve 6) that the discharge characteristics were greatly improved; but when the crest radius was increased to 20 inches (curve 5) the discharge characteristics were no worse. This is not the case, however, since in the coefficient of discharge, no consideration is made of the size of the barrel from the throat section to the beginning of the diverging tube. It is, on the other hand, the area of the throat section is used in computing the coefficient, a value greater than unity may result. The foregoing serves to illustrate the inherent difficulties encountered when using the coefficient of discharge. For another example, consider curves 4 and 5 on the coefficient chart. Although the discharge was lower in the case of curve 4 than in the case of 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 32 per cent greater than in the case of

curve 4. The head for curve 4 was measured to about the elevation of the center of curvature of the lower bend, since, as can be seen in figure 2-A, that was about 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. It is apparent that the coefficient of discharge is an unreliable criterion, and should not be used in siphon studies.

The effect of increasing the radius of the crest upon the efficiency is shown by curves 5, 6, and 8 in figure 14. Comparing the efficiency curves for a head of 2 feet, curve number 5 shows an efficiency of 25.8 per cent for the siphon whose crest radius was 4 inches. Curve number 8 represents the siphon whose crest radius was 11.94 inches, and indicates an efficiency of 46.7 per cent, which represents an increase 80.9 per cent. By increasing the crest radius to 48 inches, the efficiency, as indicated by curve 6, was increased to 58.6 per cent which is more than double the value given by curve 5. This clearly illustrates the advantage gained by enlarging the radii of the bends.

Effect of the Diverging Tube. The effect of the diverging tube upon the discharge of a siphon is to increase

the discharge. Revision No. 2 illustrates this point clearly. With the same head on the crest, the discharge in the case where the action of the diverging was not utilized was 270.4 second-feet; but when the diverging tube was made to run full, the discharge was 371.1 second-feet. This represents an increase in discharge of 100.7 second-feet, or 37.2 per cent. The diverging tube has a very desirable effect upon the discharge. However, its use is restricted to low-head siphons where an increase in the negative pressure at the throat section can safely be allowed.

The coefficient of discharge, as shown in Table I, is decreased by operating Revision No. 2, so as to take advantage of the diverging tube. The coefficient at a head on the crest of 0.83 feet and without utilizing the action of the diverging tube is 0.801; but operating with it the coefficient is decreased to 0.608. As it was previously pointed out, the head and the outlet area, which both enter into the computation of the coefficient, are the cause of small inconsistencies. In the case of Revision No. 2, operating without the divergent tube action, the head was measured to the point where atmospheric pressure first occurred in the lower leg, which was at about the elevation of the center of curvature of the lower bend. The outlet area was taken as the area of the lower leg at the point to which the head was measured. This area was the same as that of the throat. But in the case where the diverging tube was made to run 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 case, the increased outlet area and total head were great enough to show a decrease in the coefficient.

The efficiency was increased, in the case of Revision No. 2, from 31.90 per cent to 44.20 per cent by employing the diverging tube. The efficiency gives a much better indication of effect of the diverging tube upon the performance of the siphon. The difference in efficiencies gives an indication as to the amount by which the negative pressure at the throat is changed.

Discussion of Losses. A study of the losses through the siphon models was not the purpose of the investigation, and, therefore, no pressure measurements nor velocity traverses were made. However, by making certain assumptions, an approximate value of the bend losses, which are usually the most important ones, can be obtained. The total head on a siphon is equal to the sum of the losses throughout the siphon plus the loss of kinetic energy at the exit. The total head in the examples which follow was taken as the velocity head of approach plus the difference between the forebay water elevation and the tailwater elevation. This total head, H, equals the loss at entrance, plus the loss in the upper bend, plus the loss due to friction, plus the loss at the lower bend, plus the loss in the diverging tube plus the kinetic energy at exit. Gibson[4] has shown that

the exact shape of the fillet has little effect upon the loss as long as it has "reasonably good lines." Naylor[9], in the design of the Lagrar Dam siphons, assumes the loss of entrance to be $0.5\frac{v^2}{2g}$, where v is the velocity at the throat section. Gibson[10] gives $0.17\frac{(V_1-V_2)^2}{2g}$ as the value of loss in the diverging tube. This value also includes friction in that part of the siphon. In computing the loss due to friction, the author has used Manning's formula and taken the value of the coefficient of roughness to be 0.012. For the model called Change No. 3 to Revision No. 3 a discharge of 1.80 second-feet was chosen. The model head at the throat was 0.115 feet. The velocity of approach was 1.630 feet per second, giving a velocity head of 0.037 feet (model). The total model head was, then, 1.80 feet. The computed friction loss was $0.19\frac{V^2}{2g}$, where V is the throat velocity. The kinetic energy at exit was found to be 0.358 feet. Expressed as a coefficient of the velocity head at the throat section, the sum of the losses at the bends plus the loss due to the spur was 0.838. It was assumed that the difference between the total head for Revision No. 3 and the total head for Change No. 3 to Revision No. 3 when the two were both discharging 1.80 second-feet (model) was the loss in head due to the spur alone. This head loss, expressed as a coefficient of the velocity head at the throat, was found to be 0.66. Thus, the loss due to the bends alone was $.173\frac{V^2}{2g}$. From data on bend losses given by Yarnell[7], it was found that in a 180°

reverse bend about 51 per cent of the total loss due to the bend occurred in the bend itself, the rest being developed in the downstream tangent. Yarnell found the total loss in the 180° reverse bend to be $0.51\frac{V^2}{2g}$. The value, then, of the loss developed in the bend alone is $0.158\frac{V^2}{2g}$. This cannot be compared directly with the loss of $0.178\frac{V^2}{2g}$ found for Revision No. 3 because the value of R/D which Yarnell used was 1.378; while the value of R/D for Revision No. 3 was 2.346. Also, the bend in the siphon was a little more than 180°, and, furthermore, the velocity distribution approaching the bend was not uniform in the siphon, but it was uniform in the approach to the bend tested by Yarnell. Allowing for these differences, it would seem that the value for the bend loss found for the siphon reasonably agrees with that found by Yarnell.

In a manner similar to that outlined above, the sum of the bend losses was determined for Revision No. 1 for the submerged exit condition. For Revision No. 1, in which the R/D ratio was 0.61, the sum of the bend losses was $2.25\frac{V^2}{2g}$. In experiments on losses in duct bends, Beij has determined the total loss due to bends of various R/D values. From these data he has plotted a curve of the bend loss as a function of the R/D ratio. The lowest value of R/D used was 0.97. Since the curve through this point is very steep, the extrapolation below the value of 0.97 would be of very questionable value. It does, however, indicate that bend losses in this region increase very rapidly as the

R/D ratio is diminished, and it gives assurance that the value of loss computed for Revision No. 1 is, at least, reasonable.

No attempt has been made to compute the bend loss for Revision No. 2 because at the crest bend, the radius is not constant. In the case of Revision No. 4 it was assumed that all losses, except those due to the lower bend, were the same as in Change No. 3 to Revision No. 3. It was further assumed that in Change No. 3 to Revision No. 3, the loss due to either bend was half the sum of the losses due to each. In the light of Yarnell's[7] experiments, this is a safe assumption. Allowing these assumptions, then, for a flow of 1.80 second-feet through both siphons, the difference between the head required for Revision No. 4 and that required for Change No. 3 to Revision No. 3 is a direct measure of the difference between the lower bend loss of Revision No. 4 and that of Change No. 3 to Revision No. 3. The value of the difference in loss was found to be $0.43\frac{V^2}{2g}$, and the total loss for the lower bend of Revision No. 4 was $0.5\frac{V^2}{2g}$. The R/D for this bend was 0.908. The author extrapolated data given by Williamson[8] for losses in bends of rectangular cross-section and found the loss for a corresponding R/D was $0.426\frac{V^2}{2g}$. The two values do not agree very closely, the loss for the lower bend of Revision No. 4 being about 31.6 per cent higher than the loss found by extrapolating the data given by Williamson. Beij has plotted values of bend losses, found by various investigators, as

functions of R/D ratios. In the range of R/D equal to 1.0 or less, his curves show a variation of about 37 per cent between extreme points. Thus, again, although no actual measurements of losses were made, the computed value is reasonable and within the range found by other experimenters.

Effect of Priming Devices upon Efficiency. One of the principal purposes of the investigation was to determine the relation between good priming qualities and siphonic efficiency. Efficiency curves numbers 1 to 7 inclusive, figure 14, show how the efficiency was progressively increased. After a design was obtained of a siphon which gave a high efficiency, yet still compatible with good, attention was concentrated upon priming characteristics. All previous investigators without a single exception, as far as the author knows, have concluded that: High siphonic efficiency is incompatible with good priming qualities; for high priming efficiency, the radius of the lower bend should be very small; a water seal at the lower bend should be provided. Curves 8 to 16 inclusive shown in figure 14 illustrate the effect on efficiency of progressively improving the priming characteristics. Curve number 16 shows that the efficiency of Change No. 7 to Revision No. 3 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 one, Revision No. 4, having a sharp curvature at the lower bend.

On the efficiency chart in figure 14, curve No. 18 represents the efficiency of Revision No. 4. This curve should be compared with number 16 in the same figure. The obvious conclusion is that, contrary to current opinion, the radius of the lower bend does not have to be sharp to develop good priming characteristics, and, furthermore, good priming characteristics are not necessarily incompatible with high siphonic efficiency. Results of the author's investigation confirm the fact that for good priming characteristics a water seal at the lower bend is essential.

Summary Conclusions. As a result of the investigation, it was concluded that laws pertaining to pipe flow may be applied to siphon design when the structure flows full. Friction losses in siphons may be computed exactly as in other conduits. The bend loss in siphons is governed by the same laws as the bend loss in other conduits, and it is at least a function of the R/D ratio, the angle of deviation, and the square of the velocity.

In designing a siphon without the aid of hydraulic models, the discharge can be computed if the bend losses can be estimated within a fair degree of accuracy. This value should 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.

In the case of low-head siphons, the diverging tube may be advantageously employed to increase the efficiency and the discharge.

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 indication of the performance of a siphon. It does not, however, take account of the priming qualities, which must be considered separately.

A sealing pool is very effective when a high priming

efficiency is desired. The depth of seal should be small.

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. By properly designing the spur, this end may be accomplished, and an aeration tube will maintain equal pressures above and below the jet, insuring a normal trajectory.

High priming efficiency does not necessarily depend upon a sharp curvature of the lower bend. And, also, 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.

Additional Study Needed. Because bend losses form an important part of the total loss through a siphon, further investigation of the losses occurring in bends of rectangular section should be conducted. The relation of loss to the R/D ratio should be determined. Also, the relation of loss to aspect ratio should be established. It is possible that the value of the coefficient of roughness is a factor which affects the bend loss as well as do the R/D ratio, the aspect ratio, and the velocity.

There is an urgent need for information concerning the amount of air that will be entrained, or carried off, by a jet of water. With this information available, the designer could predict the priming characteristics of a siphon. The reader will recognize that these data would

also be useful in a number of other applications.

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It should be clearly understood that the statements appearing herein are solely the opinions of the author, and as such do not necessarily represent the general opinion of the Bureau of Reclamation.

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