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HYDRAULIC LABORATORY REPORT NO. 163

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HYDRAULIC MODEL STUDY OF A SIPHON ELBOW PROPOSED FOR THE GRAND COULEE PUMPING PLANT DISCHARGE LINE COLUMBIA BASIN PROJECT

By

F. TESSITOR, ASSOCIATE ENGINEER
and
D. J. HEBERT, ENGINEER

- - -

Denver, Colorado
March 1, 1945

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HYDRAULIC LABORATORY REPORT NO. 183

SUBJECT: HYDRAULIC MODEL STUDY OF A SIPHON ELBOW PROPOSED FOR THE GRAND COULEE PUMPING PLANT DISCHARGE LINE

COLUMBIA BASIN PROJECT

- - -

By F. TESSITOR, ASSOCIATE ENGINEER
and
D. J. HEBERT, ENGINEER

- - -

Under direction of
G. J. HORNSBY, ENGINEER
and
R. F. BLANKS, SENIOR ENGINEER

- - -

Denver, Colorado,
March 1, 1945

F O R E W O R D

The tests that are recorded in this report were made in the Hydraulic Machinery Laboratory by F. Tessitor and D. J. Hebert under the direction of G. J. Hornsby. They were begun in 1939, continued through 1940, and were concluded early in 1941. Urgency of other work prevented an earlier compilation of the report.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Branch of Design and Construction
Engineering and Geological Control
and Research Division
Denver, Colorado
March 1, 1945

Laboratory Report No. 155
Hydraulic Laboratory
Compiled by: F. Tessitor
D. J. Hebert
Reviewed by: G. J. Hornsby

Subject: Hydraulic model study of a siphon elbow proposed for the Grand Coulee pumping plant discharge lines - Columbia Basin project.

1. Introduction. The Grand Coulee pumping plant will be located at the left end of the dam adjacent to the upstream face and will be designed to lift water from the normal reservoir level at elevation 1288 up to a receiving canal with the maximum water surface at elevation 1585, or a normal lift of 297 feet. The head on the pumps will increase as the reservoir water surface elevation recedes, reaching a maximum of 367 feet at a reservoir elevation of approximately 1218. The pumps will be rated at 1,425 second-feet for a head of 330 feet and shall be capable of delivering 1,600 second-feet at the minimum head of 295 feet.

The pumping plant will comprise 12 pumps of the vertical type, each direct-connected to a 65,000-horsepower synchronous motor. The motors will receive their power from six of the turbo-generator units in the left powerhouse. The pumping units will be connected in pairs, each pair to be driven by one of the first six units in the power plant.

The pumps will take the water direct from the reservoir through individual, 14-foot-diameter suction tubes and discharge it through individual, 12-foot-diameter pipes, partly underground and partly on the surface, into the stilling basin of the receiving canal.

The arrangement of a typical pump discharge line, together with the proposed siphon elbow, is shown by the sectional sketch of a typical pumping unit in figure 1. Each line terminates in a siphon elbow that will discharge under water in the stilling pool of the receiving canal. In the absence of control valves in the discharge lines proper, it was

proposed that backflow, caused by shut-down of the pump, be controlled by admitting air at the top of the elbow to disrupt the siphon action and thus stop the flow. An electrically operated, solenoid air valve would provide the required air relief.

At the time the tests described in this report were undertaken, consideration was being given to the use of pumping units as turbines, to provide power for peak loads, by reversing the direction of flow. The siphon elbow would then be required to act as an efficient intake elbow, and the solenoid air valve would have to act as a valve to shut off the flow of water when required.

The effectiveness of the siphon elbow, with its automatic air valve, in the performance of functions required of it under the conditions which have been sketched, was investigated in the tests described in this report. Studies of the intake portion of the pumping plant have been described in an earlier report.+

+Hydraulic Laboratory Report No. HYD-64 (HM-3), "Hydraulic Model Studies of the Grand Coulee Pumping Plant Intake."

Studies with the model were handicapped to the extent that the model could not be made to exact prototype scale for the lower end of the discharge line, including the pump. Only the siphon elbow and a portion of the discharge line immediately above the elbow, as indicated in figure 1, were reproduced in the model. As each of the 12 discharge lines in the prototype will have a different slope and alinement because of variations in the topography, one model could supply only general information.

Throughout this report the data and observed phenomena will be discussed on the basis that the prototype pump will not be of the wicket-gate type because if it [illegible] alter entirely the conditions that were studied.

2. Summary. The following general points have been established by this study of the proposed siphon elbow:

(a) Steady-state hydraulic conditions indicated that the proposed siphon elbow expanded too rapidly at the discharge end for efficient operation as a discharge elbow.

(b) As an intake during reverse-flow conditions, the siphon elbow was quite efficient.

(c) The pressure fluctuation that occurred when pumping was initiated indicated the need for special consideration of stress reversals in the structural design of the siphon elbow.

(d) Most of the pressure fluctuation during the starting cyle of normal pumping was eliminated by delaying the closure of the air valve until the discharge line was full of water.

(e) The size of the air intake was a factor only as it affected the length of time required to reach atmospheric pressure. In every case the siphon action of the elbow was broken in a matter of seconds after air was admitted through the air valve.

(f) All the various sizes of the air intake, which had areas of 1.5, 2, 3, and 4 percent of the area of the discharge line, were effective in interrupting the siphon action. Other considerations, such as noise prevention, may indicate the use of the larger sizes.

(g) The need for further studies with a model, which would include all the discharge lines and the complete stilling pool, was indicated.

3. Purpose of tests. This investigation was undertaken for the purpose of determining the hydraulic characteristics of the proposed siphon elbow with both normal and reverse flow. Information was also desired as to the quantity of air required to break the reverse flow, as well as the best location of the air inlet for breaking the flow in either direction.

4. Testing arrangement and procedure. The model scale of 1 to 24 was determined to a large extent by the space and equipment available for conducting the test. The testing arrangement is shown schematically in figure 2. Water was circulated through the model from a sump by an 8-inch, vertical, centrifugal pump that was not intended to represent the prototype pump. This pump discharged through a 6-inch diameter pipe to a 4-way plug valve. One line from this valve, which was inclined to connect through the siphon elbow to an elevated tailwater box, represented a portion of the proposed discharge line and the stilling pool. Another line from the valve was connected to a weir box,

located under the tailwater box, where the discharge was measured. The remaining line from the valve was connected into the bottom of the tailwater box through a check valve, to supply water to the box for the reverse-flow periods. During normal operation this line was closed by the check valve. From the tailwater box the overflow could be emptied either into the weir box or directly into the sump by shifting the position of a diverter. During normal pumping operation, water from the pump was circulated through the discharge line and the siphon elbow into the tailwater box, then to the weir box for measurement, and finally back to the sump. For reverse operation, the 4-way valve was turned through 90 degrees without stopping the pump and the water was circulated direct to the tailwater box from whence it flowed back through the siphon elbow and discharge line to the 4-way valve, and finally to the weir box for measurement. During this latter operation, any excess flow was wasted over the adjustable gate at the end of the tailwater box and returned to the sump. The rate of siphon flow was controlled by a gate valve in the line leading to the weir box.

The determinations of the steady-state hydraulic characteristics of the model were made by the usual laboratory methods. Velocity traverses and pressure measurements were taken for several discharges, with normal flow and with reverse flow.

In order to determine the transient hydraulic conditions which prevailed during the periods when the air valve was opening or closing, it was necessary to develop special measuring devices that would give instantaneous values of the quantities being measured. The initial attempts to measure the rapidly changing pressures, by photographing the position of water manometers and a timing disk on motion picture film, were unsatisfactory because of inertia effects that could not be segregated from the actual, instantaneous pressure conditions. This indicated the need for a pressure-responsive element whose movement would be so small that its inertia could be neglected.

A study of the literature disclosed the work that is being done in the field of strain-gaging, by measuring with special bridge circuits the impedance changes in an eddy-current field introduced by very slight displacements of the impedance coils. A method for adapting this type

of gaging to measurements of pressure changes was worked out with the cooperation of the Hathaway Instrument Company of Denver, Colorado. A photograph of this electric gage, with its pressure unit, is shown in figure 5. The pressure unit contains a set of copper bellows that transfers changes of fluid pressure into slight mechanical movements of the order of 0.0001-inch, which are then converted to magnified electrical changes by suitable circuits. Used in conjunction with a recording oscillograph, as shown in figure 5, permanent records can be made of the phenomena picked up by the pressure unit. Since the output of the electric gage contained an alternating-current component of 60 cycles, no timing wave was necessary.

5. Steady state conditions. The hydraulic characteristics of the siphon elbow were determined for steady flow conditions by measurements of velocity distribution and pressure. These measurements were made before the air intake was installed in the top of the elbow, but a few check values made after installation of the intake verified the fact that it had no measurable effect on the velocity of pressure.

The velocity traverses were taken at three sections, as shown on figure 3. The procedure that was followed and the instrument that was used were the same as those described in the model studies of the pumping plant intake.[+] The data for both a normal flow and a reverse flow

[+] Loc. Cit.

of 0.571 second-feet are shown in the form of velocity contours in figure 3. The model discharge of 0.571 second-feet corresponds to a prototype discharge of 1,600 second-feet. The velocity patterns for normal flow show that whereas the water approached the elbow with a uniform velocity distribution and developed the usual pattern in the bend, the distribution at the end, or section C, was far from uniform. The velocity varied at the end section from practically zero to a maximum of 2.25 feet per second as compared to the average velocity of 1.51 feet per second based on the discharge and the cross-sectional area. Apparently the diffuser, which began immediately downstream from the bend proper, as shown in figure 1, expanded too rapidly to

accomplish efficiently its function of decelerating the water after it had passed the bend. Another factor contributing to rather poor performance of the diffuser was the fact that it followed so closely after the bend. Previous studies[+] of a diffuser in a similar situation showed

[+]Hydraulic Laboratory Report No. HYD-95 (HM-6), "Hydraulic Model Studies of Green Mountain Penstock - Colorado-Big Thompson Project, Colorado."

that the deceleration action was improved by inserting a short tangent length between the end of the bend and the beginning of the diffuser.

The velocity distribution at section C of the elbow, for reverse flow conditions, was much better when the siphon elbow was functioning as a transition entrance and bend, as shown in figure 3. At the other two sections, A and B, the distributions were the same for both normal and reverse flows.

Measurements of pressure at the critical sections are shown in figure 4, with a sketch showing the location of the various piezometers. All the piezometer connections were located in a vertical plane through the center line of the elbow except those for sections A and C which were ring piezometers for measuring average pressures. The lowest pressure for normal flow conditions occurred at piezometer No. 2 where the model pressure was negative 0.615 feet of water for the normal discharge of 0.571 second-feet. This model value corresponds to a negative pressure of 14.7 feet of water in the prototype. The maximum vacuum for negative flow conditions occurred at the same piezometer where, for approximately the same discharge, the measured pressure indicated a negative pressure of 16.5 feet of water in the prototype. These pressures were measured with the tailwater at its maximum elevation. Pressure measurements were also made with the tailwater at its minimum level, corresponding to elevation 1580.0, prototype, but the data are not shown because the only change was that all pressures decreased by an amount equal to the change in tailwater elevation. If then, the prototype is operated with the low tailwater and with a discharge of 1,600 second-feet, the maximum negative pressures for normal and reverse flows will be greater than the values shown for high tailwater by the difference

in tailwater level of 5 feet, or 19.7 and 21.5 feet, respectively. The higher negative pressures shown in figure 4 for a model discharge of 0.910 second-feet bear no significance, since this high discharge will never occur in the prototype. It was tested in the model only to amplify any effect that might escape notice at the lower or normal discharge.

Although no special test was made in this series of tests, a study of the velocity and pressure conditions indicated that a pier, located on the center line of the elbow from section 11 (figure 1) to the tailwater end of the siphon elbow, would improve flow conditions in much the same manner that it improves conditions in elbow draft tubes. In addition to its effect as a guide vane in prohibiting the formation of secondary flow, the pier would reduce the rate of increase in velocity that was apparently too high in the design tested. Furthermore, due to its expected beneficial effect on flow conditions, the pier would serve to strengthen the structure. The investigation of transient conditions, which will be discussed subsequently, showed that a condition of severe and rapid pressure fluctuations could occur in the end portion of the siphon elbow under certain pumping operations. In addition to pressure measurements the plastic model supplied visual evidence of this condition. The top of the diffuser could be seen to move in and out in a sort of breathing action when the pump was started with the air valve closed. The same action in the prototype would introduce stress reversals which would require special consideration in the structural design. A central pier would reduce the span by 50 percent and would virtually eliminate the structural problem.

A tabulation of energy losses for both normal and reverse flows is shown in figure 4. The energy head referred to the elevation of the tailwater was obtained by adding the pressure head and the velocity head, based on the average velocity for a given discharge and cross section. Since the energy level in the tailwater was represented by the water surface elevation, the energy heads listed in the last column of figure 4 represent the energy losses between the given section and the tailwater. It will be noted that whereas the loss from section A for normal flow

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amounted to over 50 percent of the velocity head, the loss to section A for reverse flow was only slightly more than 20 percent. The siphon elbow was much more efficient as an intake than as a discharge elbow.

6. Stilling pool studies. When this model study was outlined originally, it included a second, smaller model which would reproduce all 12 discharge lines and would be used to study hydraulic conditions in the stilling pool. These tests have not yet been made. The 1:24 model was used to make a few preliminary tests of stilling pool conditions. Side walls and a movable floor were installed in the manner shown in figure 6. The influence of the walls approximated conditions that would occur downstream from the central one of three adjacent discharge lines operating simultaneously. With the floor at elevation 1565, prototype, the stilling pool action was quite smooth for normal operation, even with low tailwater, as shown in figure 6 (3A and 3B). There will be times when the discharge lines will operate with the air valves open. One such occasion will be during the filling cycle following a shut-down, for the reasons discussed subsequently. With the air valve open, the stilling pool was much rougher, especially with low tailwater, as shown in figure 6 (3C). The effect of lowering the floor of the pool to elevation 1550, prototype, particularly when the air valve was open, is evident in figure 6 (1A, 1B, and 1C). The effect on stilling pool action of operating the discharge lines in various combinations can be determined only when the complete model is built.

7. Transient state conditions. Before the measurements of transient conditions were made with the electric gage and oscillograph, it was necessary to make several preliminary tests of the oscillograph to establish the proper method for interpreting the records.

The speed of response of the oscillograph unit was established by sudden application of a voltage direct to the element. The oscillogram obtained in this manner is shown in figure 7 (B), with a timing wave having a frequency of 50.6 cycles per second. The steepness of the trace indicates that the response of the element was fast enough that it can be neglected in interpreting the pressure records.

The frequency of the pressure cell was obtained by tapping the armature and allowing it to vibrate at the natural frequency. The record obtained is shown compared to the timing wave in figure 7 (A). From this record, the natural frequency of the cell was 150 cycles per second with the bellows full of air. It was apparent that the cell was heavily damped.

As the operation of the instrument was based on the modulation of a 60-cycle alternating current, this frequency was the limiting factor. The cell being heavily damped, it is estimated that the pressure records should be reliable for pressure fluctuations of as short a duration as one-thirtieth of a second, which is one-half the operating frequency of the 60-cycle current.

After the dynamic characteristics of the instrument were determined, it was calibrated for pressure in feet of water against deflection of the galvanometer element. Starting with zero pressure, the pressure was changed by increments of 0.2 feet of water by means of a differential water gage attached to one side of the pressure cell, and a short record was taken. The results, as shown in figure 7 (C), indicate a nearly linear calibration. A scale made up from this record was traced on the pressure records to aid in their interpretation.

Operation of the electric gage is based upon modulation of a 60-cycle current by the movement of an armature under the influence of differential pressures applied to it by means of bellows. That it was immaterial whether the cell was loaded by putting a pressure on one side or by putting an equivalent vacuum on the other side had been established previously. The magnitude of any pressure was indicated by the change in amplitude of the basic 60-cycle trace from its value with zero pressure; the scale for evaluating the pressure is shown on each record. There is a peculiarity in the trace that is explained as follows: The output of the power unit which feeds the oscillograph was not a pure 60-cycle wave but contained some distortions that give the peculiar double-exposure look to the records. When the output wave was examined with a cathode-ray oscilloscope, there was a toothed appearance at the peaks, which accounts for the double line in the records. This does not interfere

with the interpretation of the records so long as the same point of the wave is used to measure the changes in amplitude. No timing wave was necessary on the pressure records because the 60-cycle current reversals serve this purpose.

After completion of the tests it was found that many of the peculiarities of the oscillograms were due to the unfamiliarity of the experimenters with this type of equipment, as well as to certain limitations of the oscillograph that was used. Actually, the output from the gage was rectified current, which varied in magnitude with the pressure applied to the bellows of the pressure unit. If the galvanometer unit of the oscillograph had been sensitive enough, the pressure records would have appeared as single lines following the peaks of the records, such as those shown in figure 8. Because the galvanometer unit was not sensitive enough to react to the output of the electric gage, it was necessary to amplify the output. The amplifier used was an alternating-current type that responded only to changes in current, with the result that only secondary oscillations of 60-cycle frequency in the output current from the gage were amplified. The amplitude of these oscillations was proportional to the pressure as demonstrated by the calibration record in figure 7, but the records of transient pressure were difficult to read in those cases where determination of actual pressure was desired. With recent improvements in the gage and a more modern oscillograph, it is now possible to obtain records that are much easier to read, since they show only a single line whose abscissa is proportional to the pressure being measured.

Transient pressure conditions were studied for the following conditions:

1. Pump started with discharge line full of air and the exit sealed by tailwater, with air valve open and closed.

2. Pumping stopped with simultaneous opening of the air valve.

3. Reverse flow in the discharge line, air valve opened to break siphon and stop flow.

8. <u>Condition 1 - Pumping started with discharge line empty and the exit sealed by the tailwater.</u> Although this test was not originally

planned it became evident during operation of the model that whenever the pump was started with the discharge line empty and the end of the siphon submerged there was a serious pressure fluctuation which called for investigation. The action is sketched as follows: When the pump was started, the air in the line was compressed by the water as it started to fill the discharge line. As the pressure of the trapped air increased the water surface in the downstream leg of the siphon elbow was depressed against the pressure of the tailwater until some of the air escaped with an explosive action. The pressure was immediately relieved and the tailwater pressure forced the water into the downstream leg again and the cycle was repeated. The violence of the pressure fluctuation is shown in figure 8 (A) which is a record of the pressure at the top of the siphon elbow from the time the pump started until the air originally filling the discharge line was sensibly exhausted.

To relieve this pressure fluctuation, which would require special provision in the structural design for stress reversals, a time lag was introduced into the operation of the air valve. The air valve was left open until the air in the discharge line had been exhausted through the air orifice. Two sizes of orifices were tested. The improvement in pressure conditions is apparent in figure 8 (B). With No. 1 orifice, which had an area equal to four percent of that of the discharge line, the pressure increased until the flow of air out equaled the flow of water into the line. The maximum pressure reached with this orifice was less than tailwater pressure so there was no escape of air through the exit of the siphon elbow and the entire operation was smoothly accomplished. In the case of No. 3 orifice, whose area was only one-half that of No. 1, the pressure did build up high enough so that some of the air escaped into the tailwater and set up a fluctuation similar to the action with the air valve closed but much less severe. It would appear that for condition 1 the No. 3 orifice was too small or in other terms the resistance to flow through the air valve was too large.

The time for which the delay must be designed cannot be obtained from the pressure records because the model included only a portion of

the discharge line and did not attempt to assimilate the prototype pump. The time lag for the prototype can be computed from the known characteristics of the pump and the volume of the discharge line.

9. Condition 2 - Pumping stopped with simultaneous opening of the air valve. The condition wherein pumping may be stopped with simultaneous opening of the air valve may occur in the prototype in two ways; first, normal shut-down of pumping with the air valve opened manually if desired and second, power failure to the pumps with automatic operation of the air valve. The model was designed to assimilate the second condition. The air valve plunger was spring loaded to stay open and was held closed for normal operation by means of a solenoid interconnected to the power source of the pump motor. When the power supply to the motor was interrupted to assimilate power failure the solenoid was deenergized and the air valve opened under the force of the spring.

Pressures were measured at two piezometers, one just downstream from the inlet orifice of the air valve, and the other at the crown of the siphon elbow, as shown in figure 5 (A). The pressure at the first piezometer was less than atmospheric pressure by an amount which was a known function for each orifice, of the discharge of air. The second piezometer served to indicate the pressure in the siphon elbow.

The records of pressure drop across the orifice for the two orifices Nos. 1 and 3 are shown in figure 9 (A) and (B). The differential pressure reached its peak in a fraction of a second and then dropped to practically zero which indicates that the siphon flow had been broken and the water was practically motionless. Very shortly thereafter the water started to flow back through the pumps and the orifice differential increased as the reverse flow increased. Then as the head creating flow back through the pumps decreased as indicated by the drop in the free water surface in the discharge line, the reverse flow decreased and the orifice differential gradually returned to zero. Only the first part of the pressure record is valid for the reason explained previously that neither the pump nor the discharge line was representative in the model. The pressures during the latter part of the cycle which are not critical can be computed from the prototype characteristics. The smaller

the orifice, the greater the pressure drop to supply the discharge of air required to replace the water flowing out through the pump.

Both curves, figure 9 (A) and (B) were taken with low tailwater. Tests were made with a higher tailwater and the only difference from those shown was that the differential pressures were not as pronounced because of the higher back pressure at the exit of the siphon elbow.

The pressure changes at the crown of the siphon elbow during the same operation are shown for both orifices in figure 9 (C) and (D). Immediately after the air valve was opened the pressure, which was initially negative, increased to atmospheric pressure and even appeared to become slightly positive, then it became negative again in much the same manner as the orifice differential. With the small orifice the second peak was a little higher but otherwise there was not much difference due to the change in orifice size. As pointed out previously, the first portion of figures 9 (C) and (D) indicates the fluctuation in pressure for normal operation.

10. <u>Condition 3 - Reverse flow in the discharge line, air valve opened to stop flow by disrupting siphon action.</u> If the pumps are used as turbines, the only way available for stopping the flow will be that of opening the air valve and admitting air at a rate high enough to disrupt the siphon action.

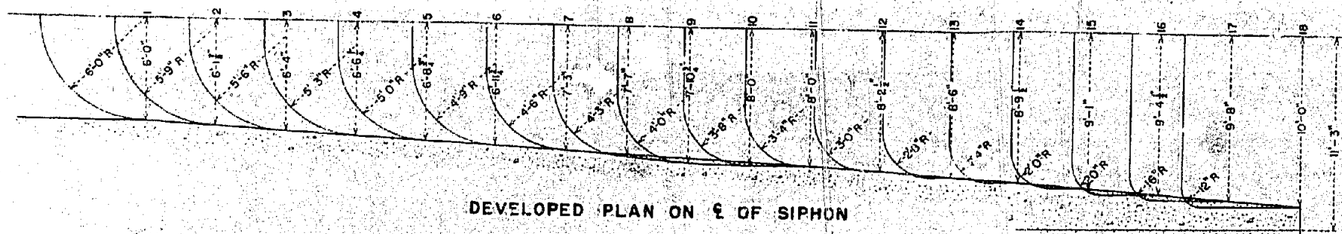
Since the characteristics of the pumps were not known it was necessary to test this condition with several discharges covering the possible range to ensure that the siphon action would be broken by opening the air valve. The variations in orifice differential are shown in figure 10 for the minimum and maximum discharges, each with two different inlet orifices. The tests were all made with high tailwater because with low tailwater the draw-down at the entrance tended to admit air which helped to break the siphon action.

The maximum value of the vacuum depended upon the discharge and the orifice size but the siphon action was definitely broken in all cases. Here again the time required for the pressure to become zero was not significant. As soon as the negative pressure began to decrease

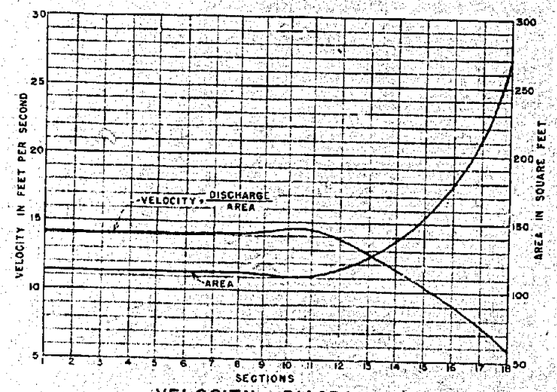
the siphon action was definitely broken and the balance of the record represents merely the emptying of the discharge line which can be computed for the prototype.

- - -

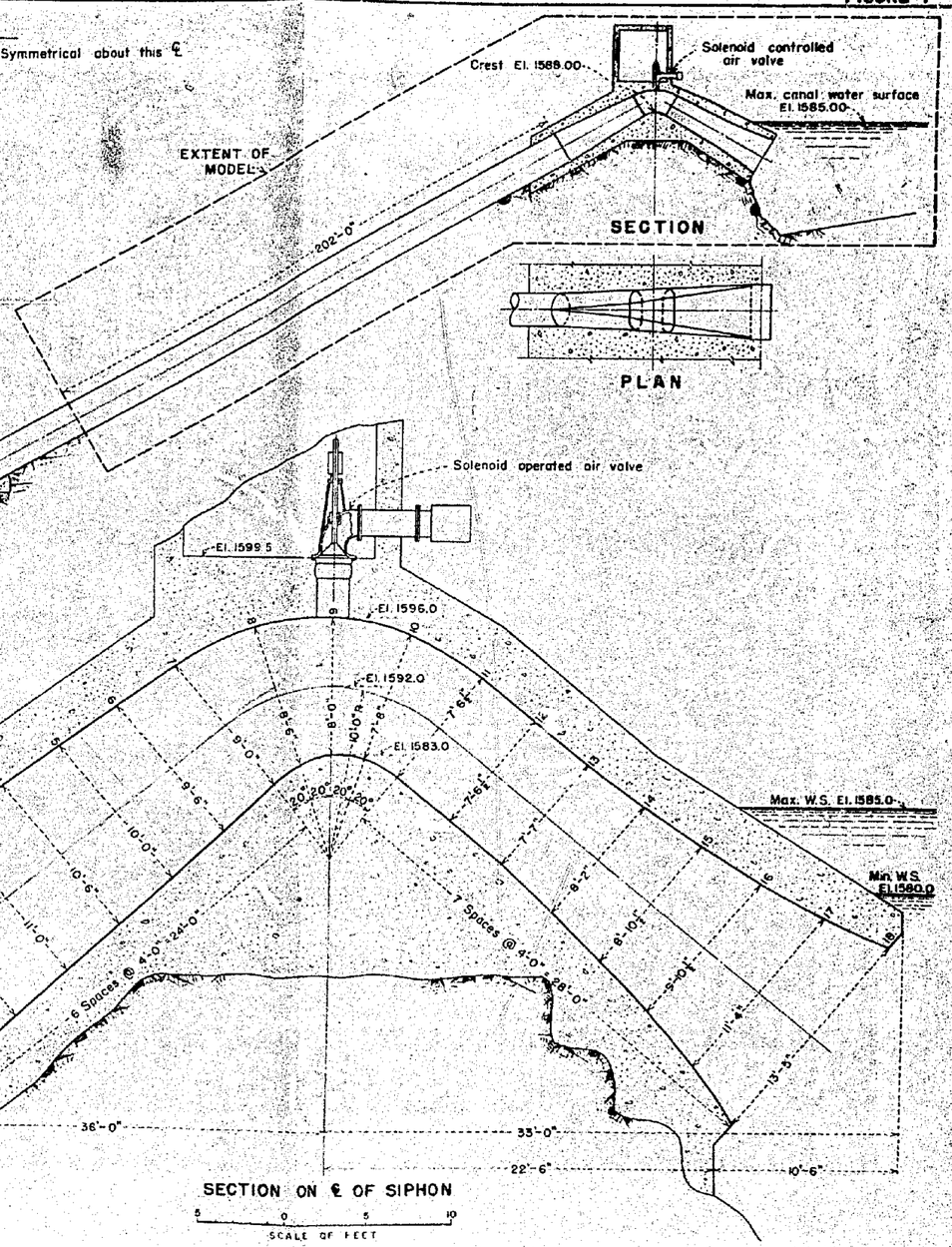
FIGURE 1



DEVELOPED PLAN ON ℄ OF SIPHON

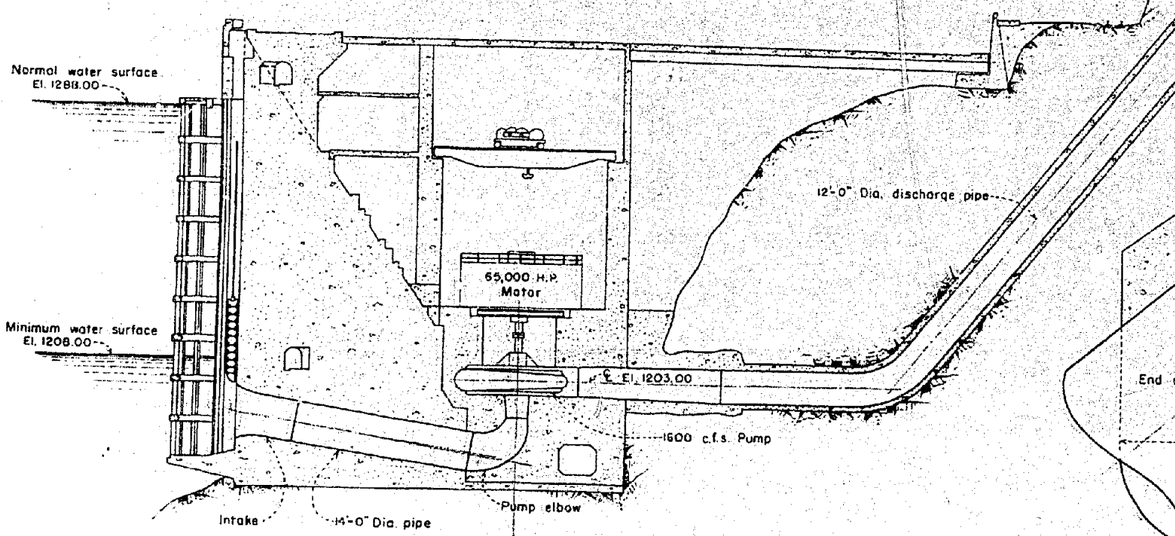


VELOCITY DIAGRAM
Q = 1600 CU. FT. PER SECOND



SECTION ON ℄ OF SIPHON

SCALE OF FEET



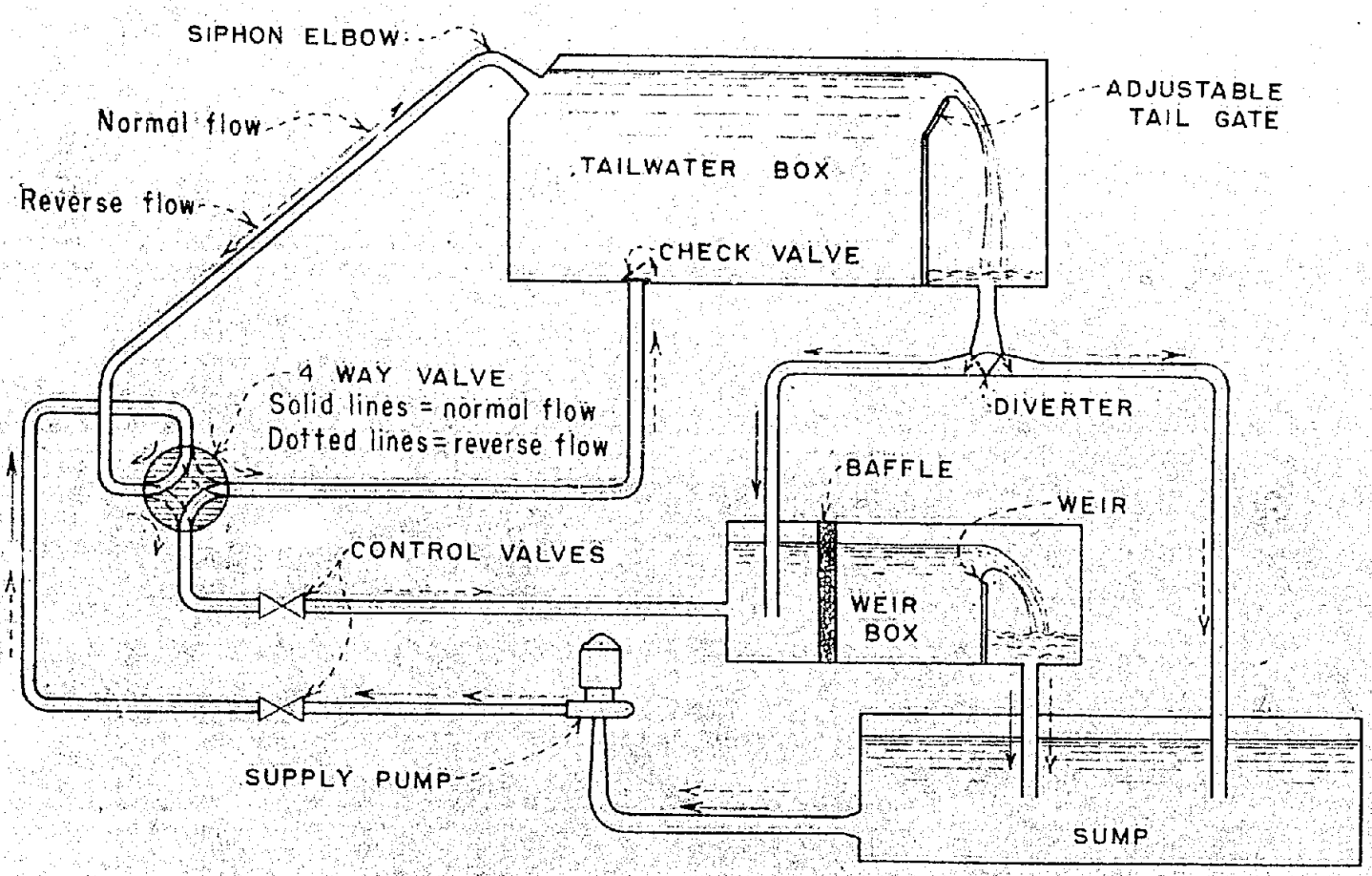
SECTION ON ℄ OF PUMP AND DISCHARGE PIPE

SCALE OF FEET

COLUMBIA BASIN PROJECT

GRAND COULEE PUMPING PLANT

TYPICAL DISCHARGE LINE AND SIPHON ELBOW USED FOR MODEL STUDIES



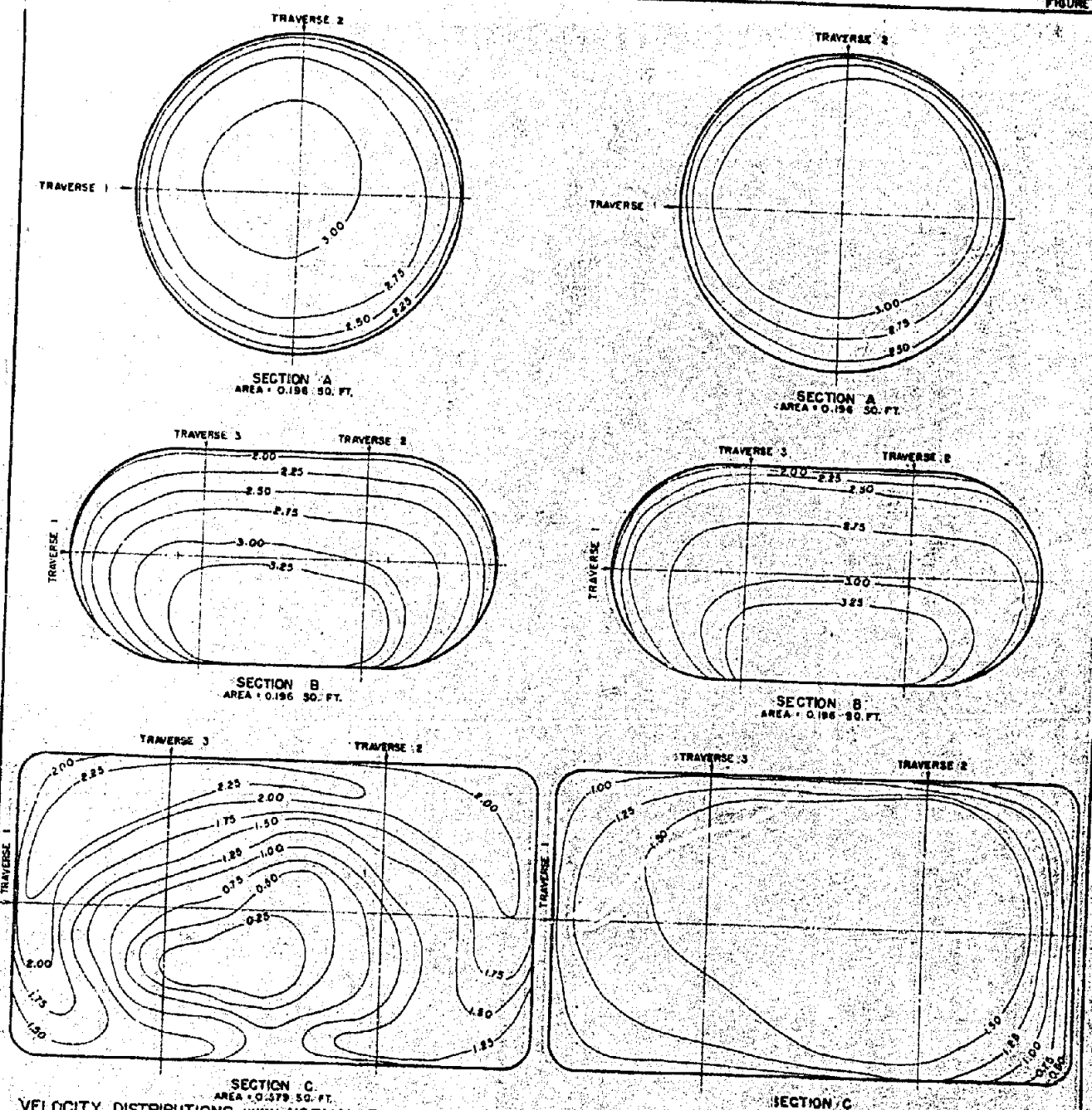
GRAND COULEE PUMPING PLANT

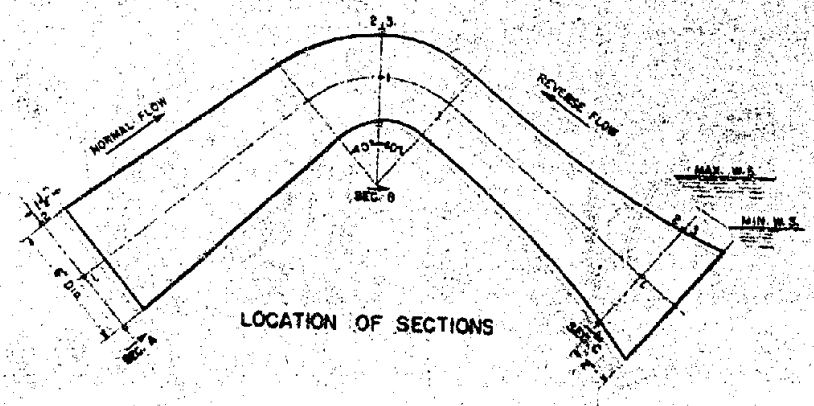
SIPHON ELBOW STUDY

SCHEMATIC ARRANGEMENT OF MODEL

FIGURE 2

FIGURE 3





LOCATION OF SECTIONS

NOTES
Model velocities shown
Model scale = 1:24

COLUMBIA BASIN PROJECT
GRAND COULEE PUMPING PLANT
VELOCITY DISTRIBUTION IN SIPHON ELBOW

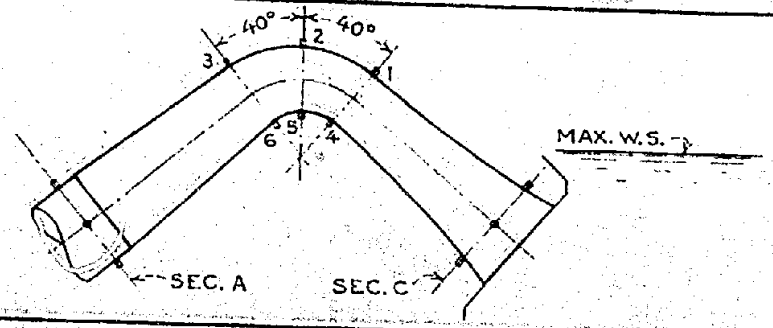
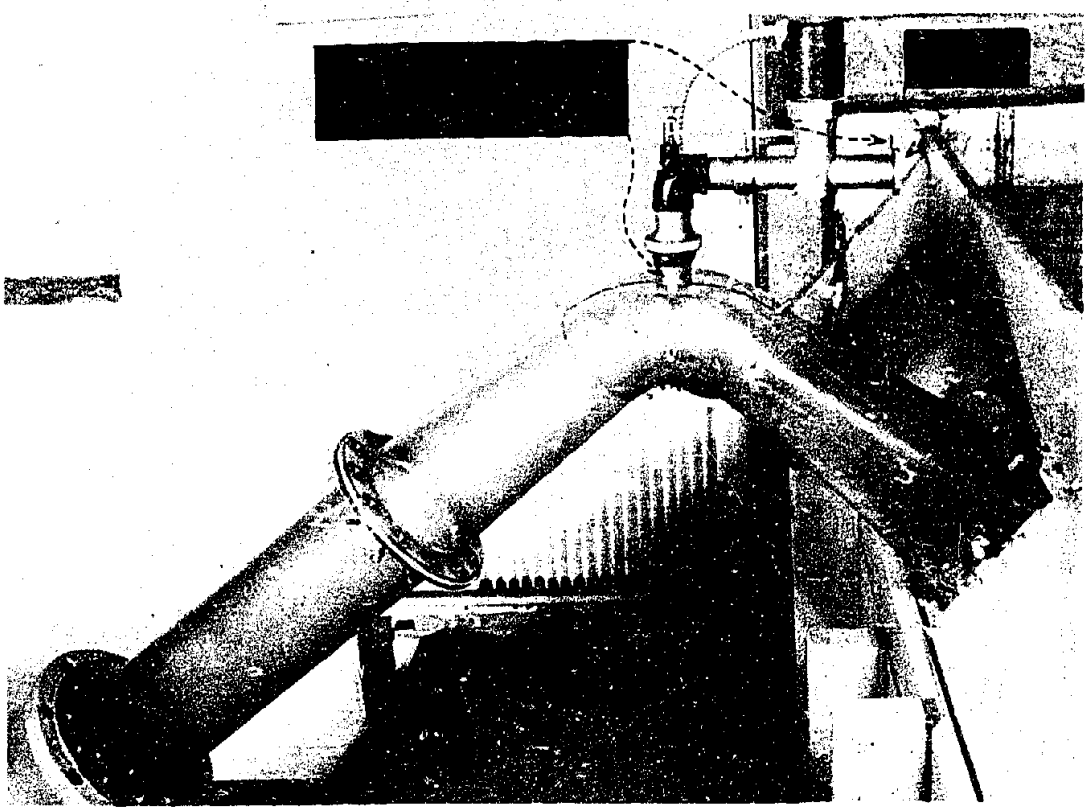


TABLE SHOWING MODEL PRESSURES AND LOSSES

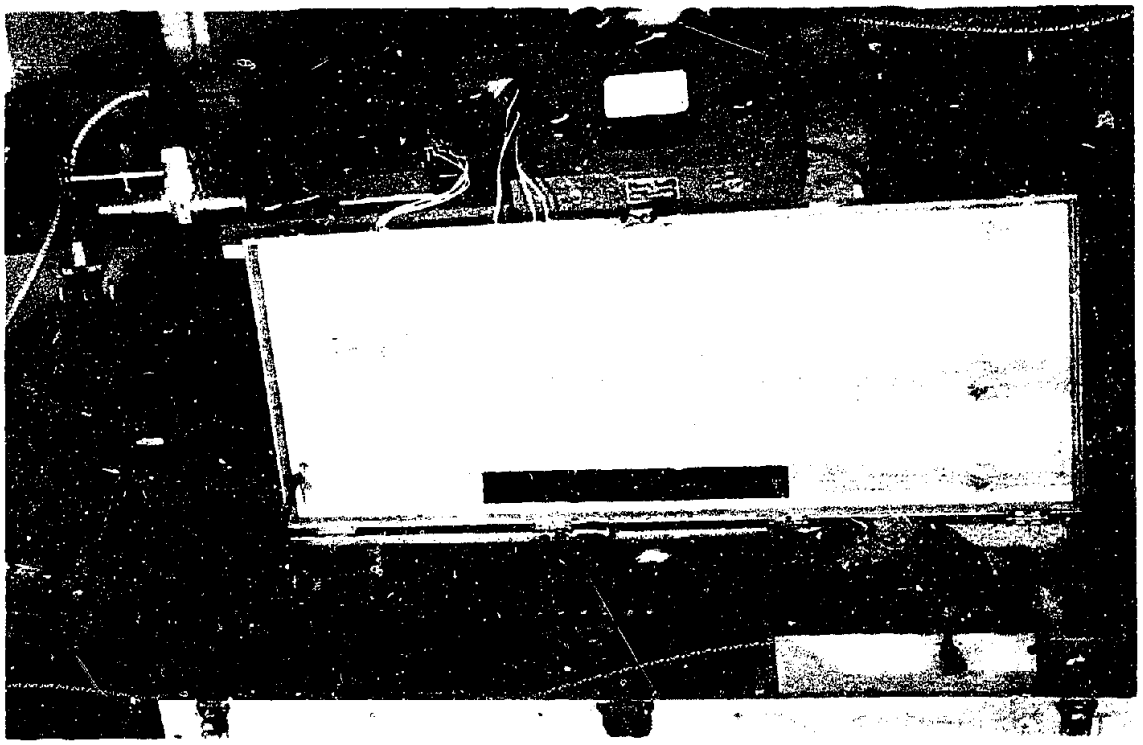
Piezometer No.	Zero reading in ft.	Pressure head in feet referred to piezometer for normal flow in s.f.			Pressure head in feet referred to T.W. elev. for normal flow in s.f.			Average velocity head in feet for normal flow in s.f.			Energy head referred to T.W. elev. for normal flow in s.f.		
		0.910	0.571	0.496	0.910	0.571	0.496	0.910	0.571	0.496	0.910	0.571	0.496
T.W.	7.820												
Sec. A	7.370	+0.292	+0.360	+0.422	-0.158	-0.055	-0.017	0.355	0.134	0.100	0.177	0.079	0.083
Sec. C	7.440	+0.336	+0.328	+0.360	-0.044	-0.017	-0.009	0.090	0.038	0.027	0.046	0.021	0.018
1	8.202	-0.412	-0.430	-0.400									
2	8.410	-0.565	-0.612	-0.596									
3	8.223	-0.463	-0.459	-0.420									
4	7.960	-0.490	-0.310	-0.205									
5	8.010	-0.935	-0.487	-0.284									
6	7.935	-0.453	-0.272	-0.168									
		For reverse flow in s.f.			For reverse flow in s.f.			For reverse flow in s.f.			For reverse flow in s.f.		
		0.896	0.565	0.395	0.896	0.565	0.395	0.896	0.565	0.395	0.896	0.565	0.395
T.W.	7.812												
Sec. A	7.370	+0.045	+0.276	+0.360	-0.397	-0.164	-0.082	0.325	0.129	0.063	-0.072	-0.035	-0.019
Sec. C	7.440	+0.260	+0.320	+0.326	-0.112	-0.052	-0.026	0.087	0.035	0.017	-0.025	-0.017	-0.009
1	8.202	-0.662	-0.504	-0.448									
2	8.410	-0.805	-0.688	-0.642									
3	8.223	-0.668	-0.523	-0.468									
4	7.960	-0.740	-0.390	-0.260									
5	8.010	-1.110	-0.555	-0.355									
6	7.935	-0.660	-0.350	-0.248									

FIGURE 4

FIGURE 5

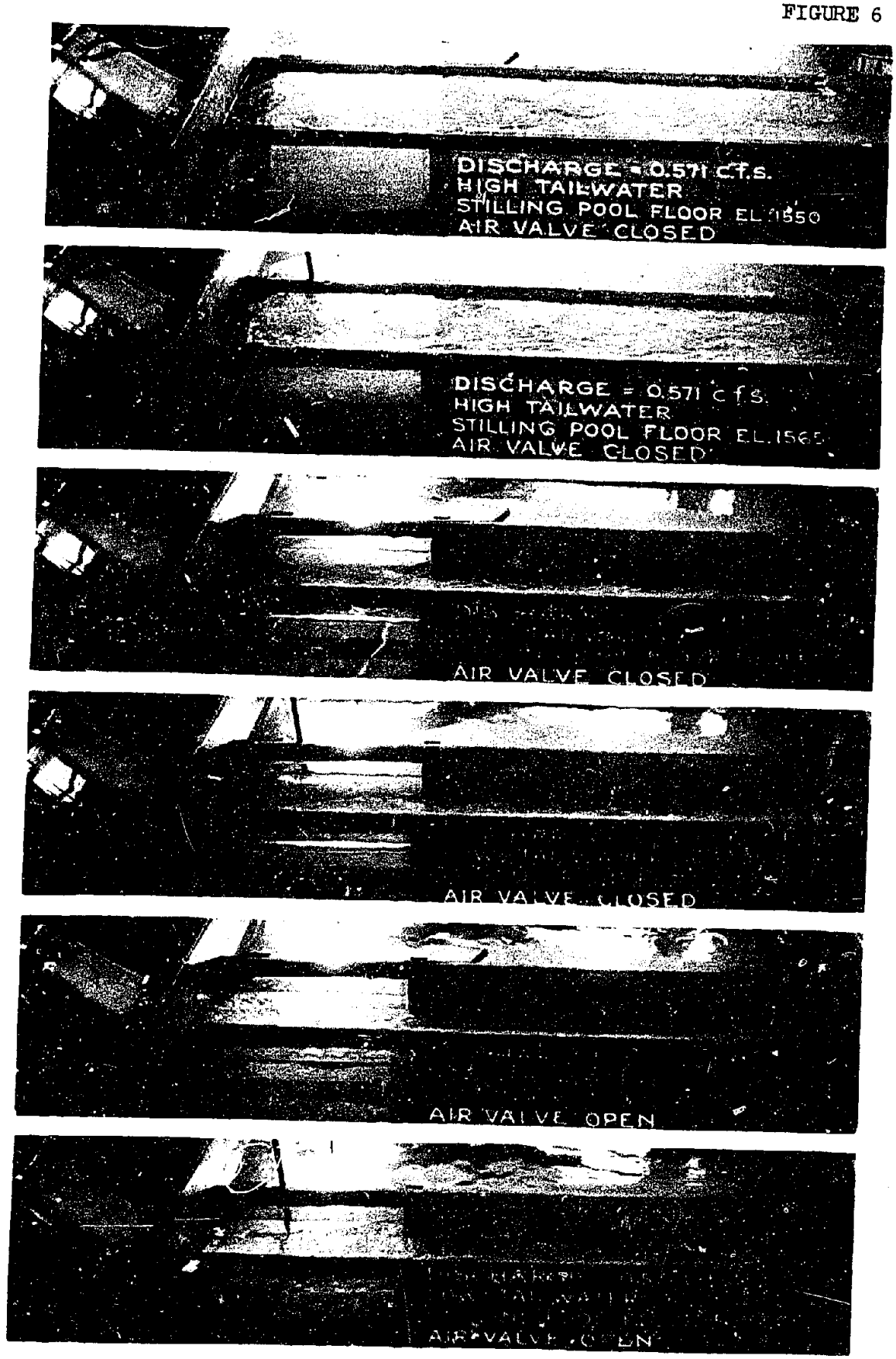


(A) Siphon elbow with electrically-operated solenoid air valve.



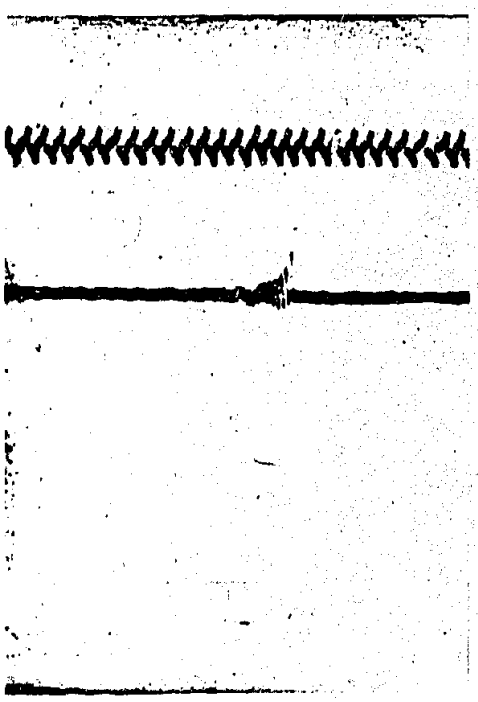
(B) Apparatus for measuring transient pressures

FIGURE 6

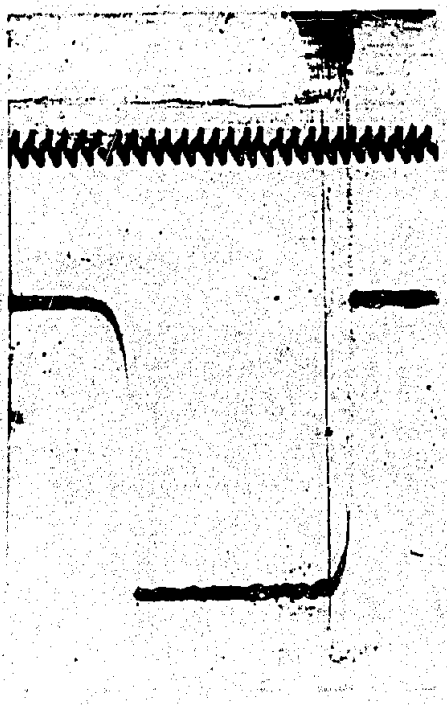


FLOW CONDITIONS IN STILLING POOL.

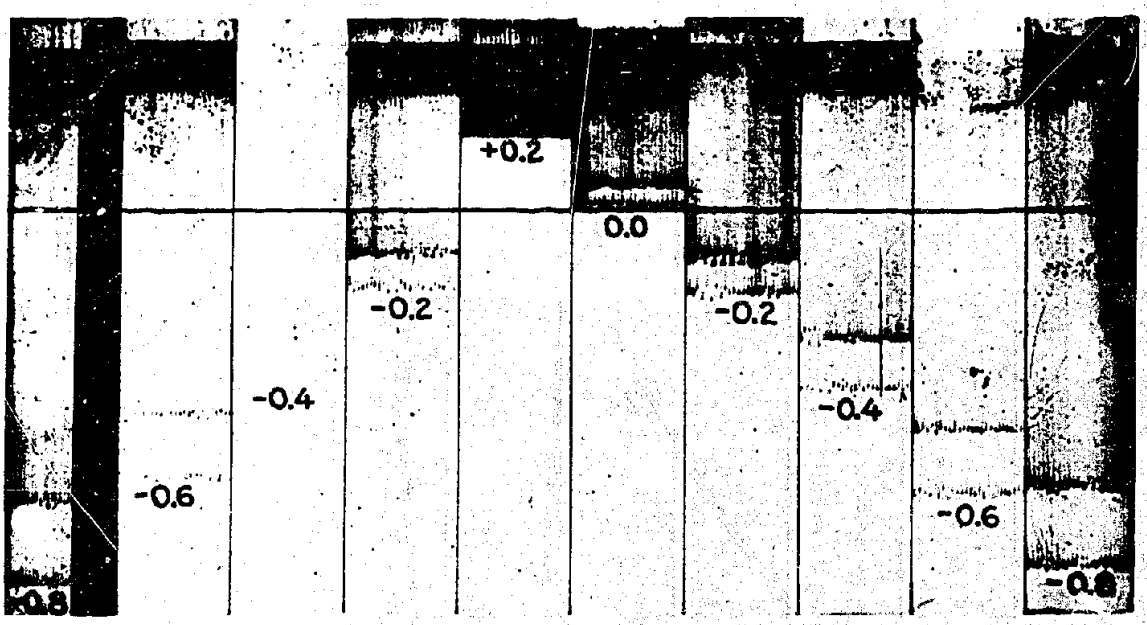
FIGURE 7



(A) Frequency of pressure cell



(B) Response of oscillograph un-

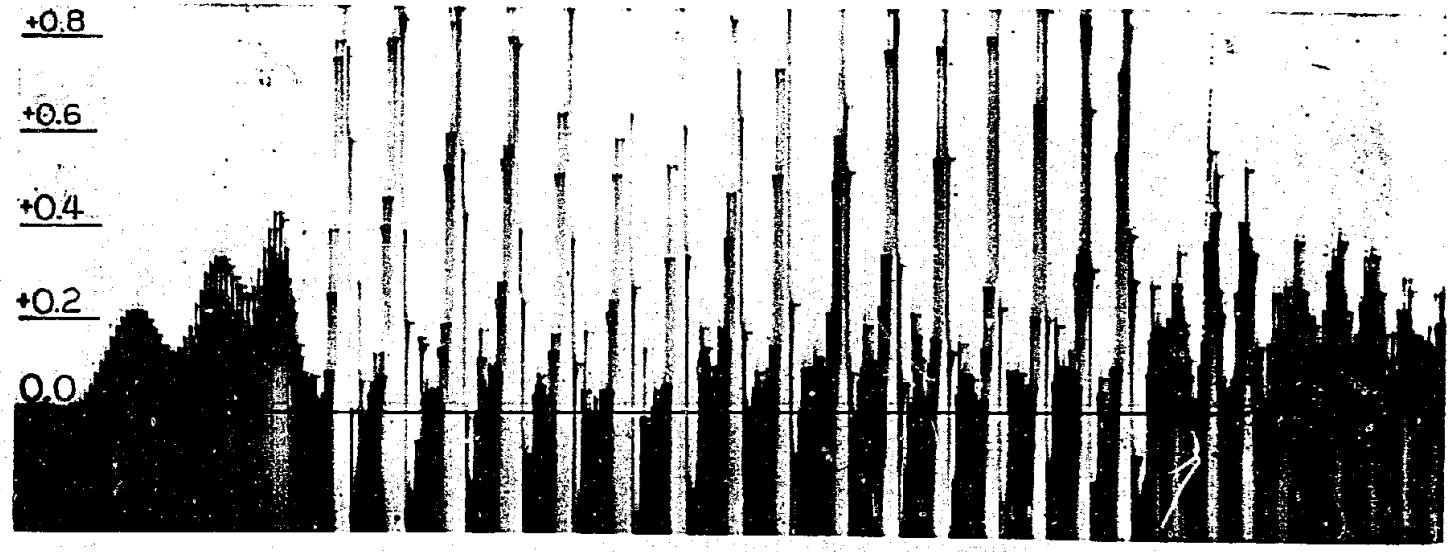


(C) Calibration of pressure cell in feet of water

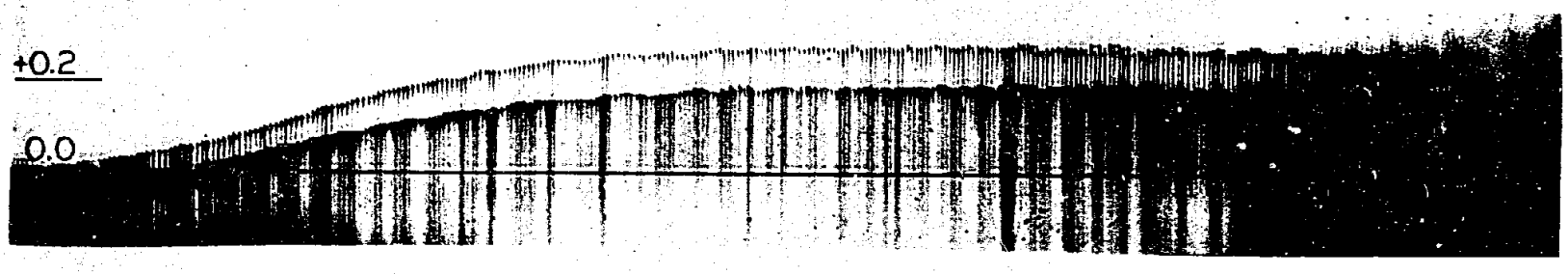
CONDITION 1

Pumping started with discharge line empty and exit sealed by tailwater.
Pressure at top of siphon elbow

(A) Air valve closed



(B) Air valve open - air inlet orifice No. 1



(C) Air valve open - air inlet orifice No. 3

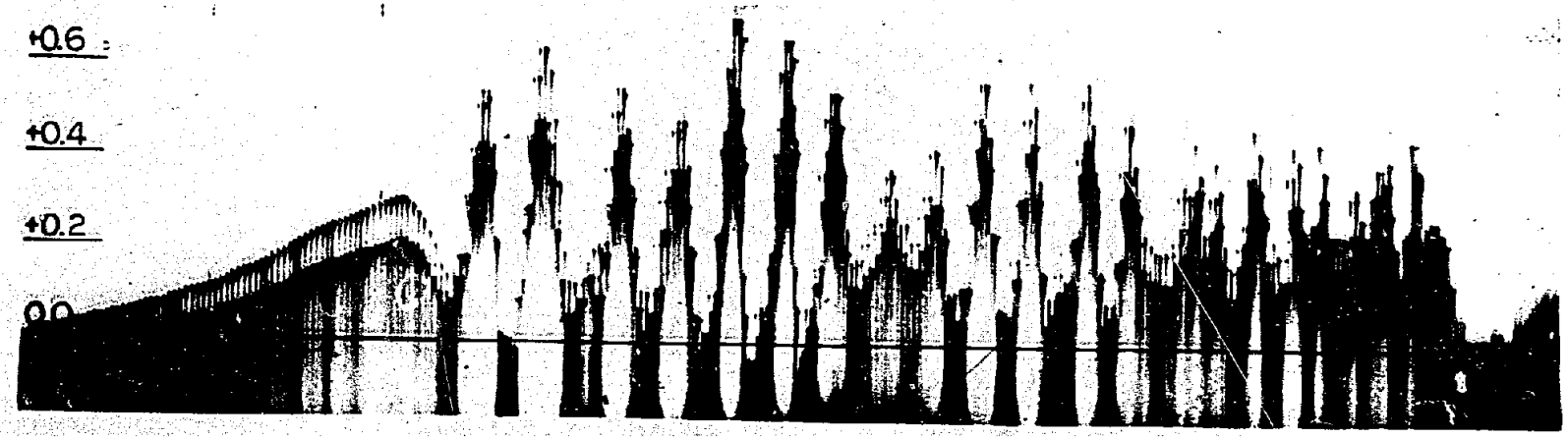
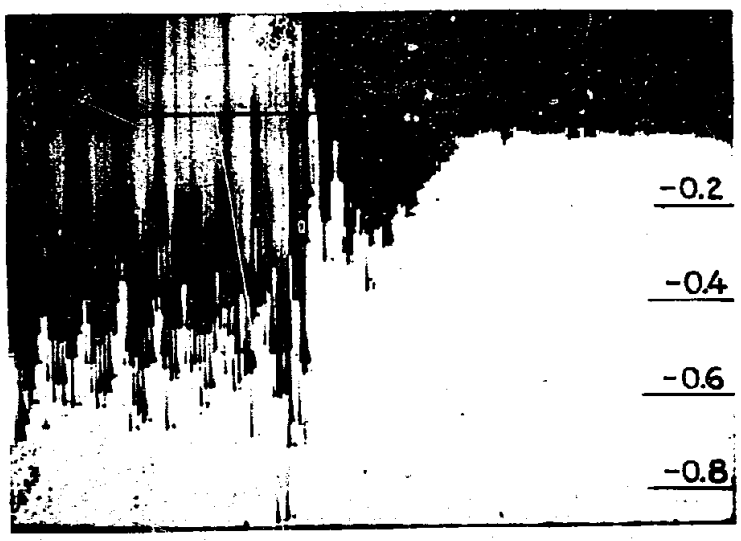
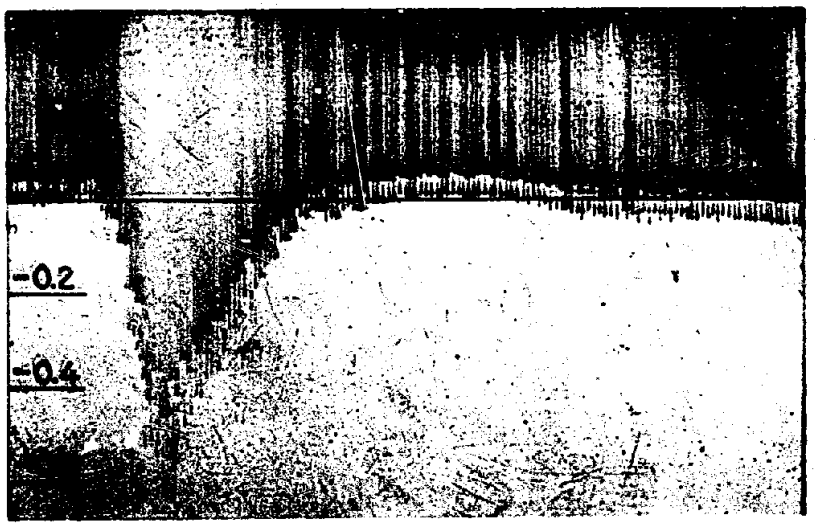


FIGURE 8

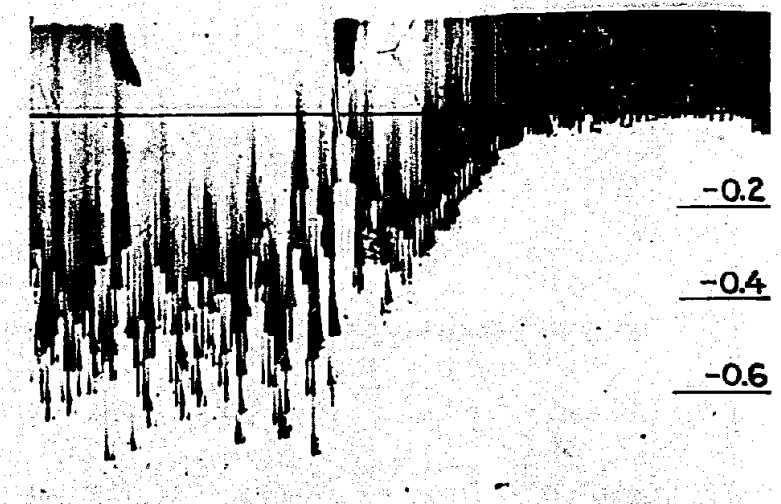
(A) Orifice differential - air inlet orifice No. 1



(C) Pressure at top of siphon elbow air inlet orifice No. 1



(B) Orifice differential - air inlet orifice No. 3



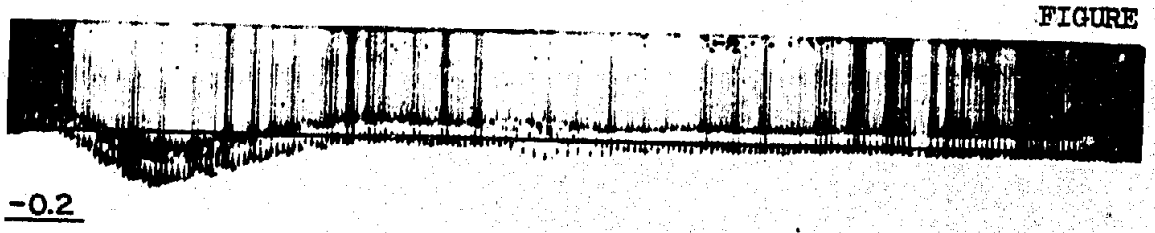
(D) Pressure at top of siphon elbow air inlet orifice No. 3

CONDITION 2

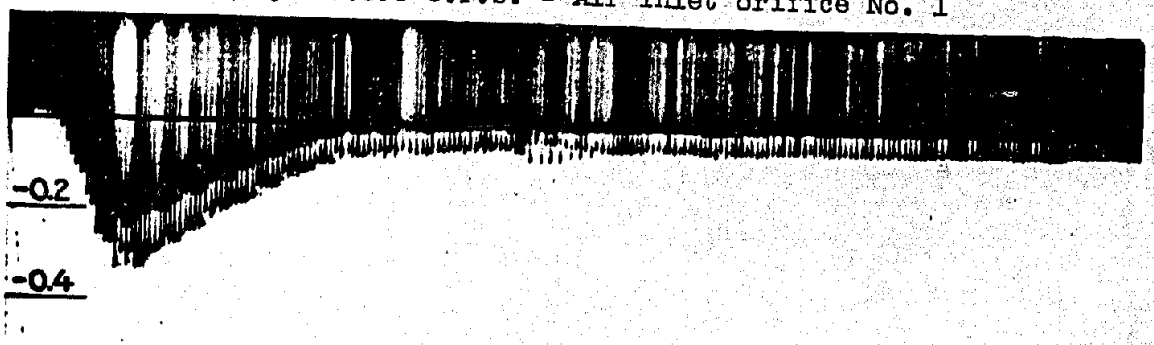
Pump stopped with simultaneous opening of air valve

FIGURE 9

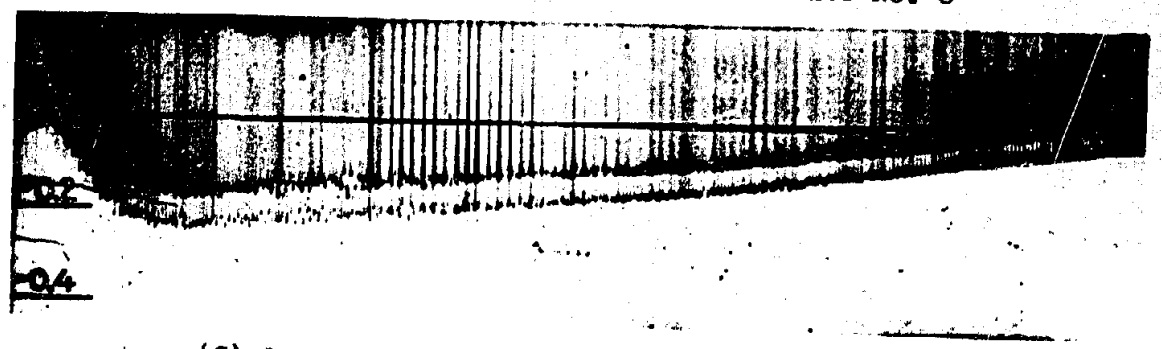
FIGURE 10



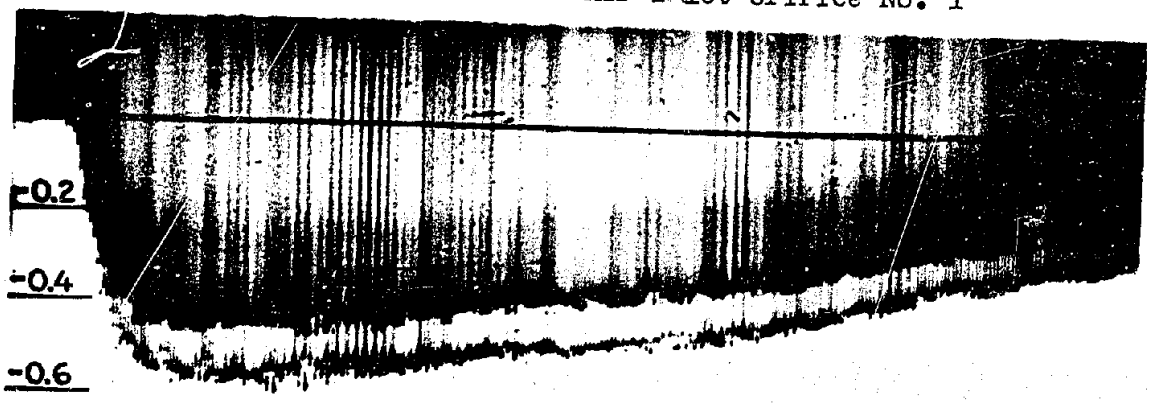
(A) Q = 0.393 c.f.s. - Air inlet orifice No. 1



(B) Q = 0.393 c.f.s. - Air inlet orifice No. 3



(C) Q = 0.689 c.f.s. - Air inlet orifice No. 1



(D) Q = 0.689 c.f.s. - Air inlet orifice No. 3

CONDITION 3

Reverse flow - air valve opened to break siphon orifice differential