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HYDRODYNAMICS LABORATORY

DEPARTMENT OF CIVIL AND SANITARY ENGINEERING

TECHNICAL REPORT NO. 33

MODEL STUDY OF A FLOOD-CONTROL PUMPING STATION AT THE CHARLES RIVER DAM

BY

D.R.F. HARLEMAN, R.S. BROUGHTON, C.J. HUVAL and H.W. PARTENSCKY

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PREPARED UNDER CONTRACT
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METROPOLITAN DISTRICT COMMISSION
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Department of Civil and Sanitary Engineering

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FOREWORD

The investigations reported here describe the approach flow conditions found in a model of a flood-control pumping station proposed for a site immediately downstream of the Charles River Dam. The project was conducted under a contract with the Metropolitan District Commission of the Commonwealth of Massachusetts, with Dr. Arthur T. Ippen, Professor of Hydraulics, acting as administrative supervisor for the Division of Sponsored Research of M.I.T. Liaison was provided by Elson T. Killam Associates, Millburn, N. J., and Charles A. Maguire and Associates, Boston, Massachusetts, who are consulting engineers on the overall flood-control project for the sponsor.

The experimental investigations described herein were carried out by Messrs. C. J. Huval and R. S. Broughton, Research Assistants, and Dr.-Ing. H. W. Partenscky, Research Associate in the Hydrodynamics Laboratory. The entire project was under the technical direction of Dr. D. R. F. Harleman, Associate Professor of Hydraulics.

ABSTRACT

This report describes the design, construction and testing of a Froudian model of a proposed 8400-cfs capacity pumping station. Site restrictions require that the flow approach the high specific-speed pumps asymmetrically from an existing ship lock through the Charles River Dam (Boston, Massachusetts).

The model included a portion of the Charles River Basin, the existing navigation lock and the pump forebay at the exit of the lock. A single recirculating pump and a suction manifold was used in the model to withdraw water from the forebay through six intakes simulating the prototype pumping station. Flow patterns were obtained by photographs of floating confetti and subsurface streamers. Water surface measurements were made with a point gage read through a surveyor's level. The majority of tests were run with the maximum design discharge and the minimum basin pumping elevation. This provided the most severe forebay conditions of high velocity and low intake submergence.

Tests were made to investigate: (1) the improvement of flow conditions at the entrance to the lock; (2) the performance of a single intake in uniform approach flow; and (3) the performance of several forebay and pumping station arrangements. The tests showed that: (1) an 18 ft diameter semi-cylindrical pier was needed at the lock entrance to reduce flow contraction and entrance loss; (2) the intake performed very well when the approach flow was uniform; and (3) the most satisfactory forebay arrangement, within the design restrictions imposed by the site, was with equal lengths of intake chambers. The center line of the pumps and the straight portion of the intake chamber walls were deflected 20° toward the approach flow. The straight portion of the intake chamber walls were 51 ft in length and thence curved upstream in a circular arc. The circular arc terminated six ft from the lock line and the chord of the arc forced an angle of 40° with the line of the lock. Vertical struts placed behind the intakes retarded circulation in the intake chambers and improved the flow into the intakes.

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LIST OF SYMBOLS

c = wave celerity ft/sec

D = diameter, ft

g = acceleration due to gravity, ft/sec^2

h = mean water depth where waves are occurring

L_r = length ratio

L_R = resonant length

Q_m = model discharge, cfs

Q_p = prototype discharge, cfs

Q_r = discharge ratio

S_p = prototype intake submergence, ft

T = wave period, secs

T_r = time ratio

V_m = model velocity, ft/sec

V_p = prototype velocity, ft/sec

V_r = velocity ratio

λ = wave length, ft

I INTRODUCTION

A. General Statement of the Problem

The model study is concerned with a pumping station to provide flood protection for those low lying areas of metropolitan Boston and Cambridge which are located upstream of the Charles River Dam. Recent intense rainfalls (1954, 1955) have shown the existing gravity discharge facilities at the dam to be inadequate to provide the necessary degree of basin-elevation control. Under the design storm tide the harbor water elevation is higher than the normal basin level for approximately 6 hours of the tide cycle. During this time no gravity discharge from the basin is possible. On the other hand, the basin is unable to provide sufficient storage for the run-offs from intense rainfall which occur during these periods.

Charles A. Maguire and Associates, and Elson T. Killam Associates have made extensive studies of the overall flood problem. Their Report on Charles River Basin Control (1) shows that the Basin should be regulated between elevation 106.5 ft and 110.5 ft with an average elevation of 108.0 ft (M.D.C. Base). To provide this degree of regulation a station of six high specific speed pumps each with a maximum design discharge of 1400 cfs is required. Of the several possible station sites in the vicinity of the dam which were investigated by the consulting engineers, a site on the Boston side immediately downstream of the dam was selected. As can be seen on the location map in Fig. 1, this site requires that the water flow from the basin through the existing ship lock into a forebay. The maintainance of an adequate channel for the normal gravity sluice discharges in the region north of the ship lock precludes the construction of a forebay symmetrical with respect to the lock. The forebay is therefore located on the southeast side of the lock which would have to be extended in the downstream direction. Provision for boats to be locked from the harbor to the basin when the pumps are not operating prevents any obstructions from being placed in the lock chamber extension.

The resulting asymmetry of the forebay with respect to the approach flow through the lock, together with the relatively high approach velocities made it desireable to investigate the arrangement of the pump intakes by means of a model. Therefore, a model which included the forebay, the ship lock, and a portion of the Charles River Basin, as outlined in Fig. 1, was constructed in the M.I.T. Hydrodynamics Laboratory. The water was withdrawn from the forebay through suction pipes simulating a prototype design, but the pumps themselves were not modeled.

II REVIEW OF LITERATURE ON MODEL TESTING OF PUMP SUMPS

Investigators agree with Fraser (2) that "any wet pit pump is no better than its intake performance and as much study, and investigation must go into its design as into the pump itself". For sumps where the design conditions are complicated it is considered a wise and economically justified procedure to make an hydraulic model study to arrive at a satisfactory design. Pump sump model tests have been largely qualitative, with observations made of flow directions, and tendencies for vortices to form in particular areas. Much of the literature on pump intake and sump testing is concerned with layouts where the pumps and intakes are vertical. Since the intakes are inclined and the pumps horizontal in the design considered for the model tests described in this report, many of the conclusions from the literature can only be inferred and not applied directly.

Among the investigators reporting, it is generally felt that two aspects of the flow approaching pump intakes are important.

1) The flow should be uniform across the approach channel so that a good velocity distribution in the suction pipe can be provided.

2) There should be no entrainment of air into the pump through a vortex.

A. Similarity Considerations in Forebay Models

It is generally agreed that the basic pattern of flow distribution in a given forebay is obtained by operating the model in accordance with Froude (i.e. gravational) similarity.

Previous reports are contradictory in regard to the method of interpreting tests on Froudian models involving the presence of air-entraining vortices. Strict similarity would require Reynolds (i.e. viscous) number equality in addition to the gravitational requirements for free surface flows. This has been shown to be impossible if the same fluid is used in model and prototype. Various compromises aimed at increasing the model Reynolds number have been suggested. Most of these involve testing the Froudian model at a velocity higher than that given by the condition $V_r = \sqrt{L_r}$. Denny (3) suggests testing the model at the same velocity as the prototype if the "critical submergence" is to be predicted. The difficulties in testing a model on this bases are evident — especially if the scale ratio is small. The Froude number of the model approach flow could be deceptively high and give rise to an undulating or near critical flow which would not exist in the prototype. For example, the Froude number for the flow in the lock chamber approaching the forebay (under design conditions) is 0.3. If the model were operated at the prototype velocity the Froude number would be 1.8. The model flow would thus be supercritical whereas the prototype is subcritical and flow conditions would have no similarity.

As the scale ratio gets small undoubtedly surface tension will begin to cause a discrepancy between the actual prototype air-entrainment and that predicted from the model. Although these considerations bring considerable doubt into the scaling of air-entraining vortex formations from model to prototype the general experiences have been that:

1) it is always possible, at velocities based on Froude similarity, to observe the persistant surface swirls which indicate the start of air-entraining vortices, and

2) if these swirls can be prevented in the model one is reasonably sure of avoiding air-entraining vortex troubles in the full scale suction pit.

There is undoubtedly considerable interrelation between the degree of non-uniformity of approach flow and the development of air-entraining vortices.

Denny's experiments (3) showed that air-entraining vortices formed more readily when small swirls already existed in the intake chamber due to non-symmetrical inflow.

B. Intake Considerations

The major flow patterns both in the forebay and the intake chambers can be reproduced by withdrawing the fluid through intakes whose relationships with their chambers are the same on model and prototype whether or not there is an impeller in the pipe. This is borne out both by Iversen's (4) and Denny's (3) studies which indicate that only "suction nozzles" and not scaled down pumps need be used in sump study models.

The spacing between the pump intake and the walls of the intake chamber is an important consideration in the design of a pump sump. Stepanoff (5) gives spacings for optimum efficiency for vertical pumps as: floor to suction bell D/2; side walls to suction bell D/2; rear wall to suction bell D/4; where D is the maximum suction bell diameter. Iversen's data (4) show the reduction in pump efficiency to be negligible if the rear wall is brought against the suction bell and the side walls brought to within D/4 of the bell edge. Both Iversen's (4) and Denny's (3) experiments indicate that the closer the walls the lower the submergence required to prevent air-entrainment. However, it can be inferred that with pumps having horizontal or inclined intakes, it would probably be advantageous to bring the rear wall close to the rear edge of the pipe. A side wall clearance of D/4 is likely to be adequate for peak performance, and give extra insurance against the development of air-entraining vortices.

III THE MODEL

The general layout of the model, shown in Fig. 2, includes the pump intakes, the pumping station forebay, the existing ship lock, and a portion of the Charles River Basin.

The model was built to an undistorted scale of 1:36 on the basis of Froude similarity. Accordingly, its operation was governed by the following scale ratios:

Length ratio	L_r	=	$1/36$
Velocity ratio	V_r	=	$L_r^{1/2} = 1/6$
Discharge ratio	Q_r	=	$L_r^{5/2} = 1/7776$
Time ratio	T_r	=	$L_r^{1/2} = 1/6$

Pertinent data from the Charles River Basin Control Report (1), as well as other information provided by the consulting engineers were the basis of the design, construction and testing of the model.

A. Construction

Fig. 2 shows the model equipment in plan and cross-section views. With six pumps operating at the maximum design discharge the corresponding model discharge was 6 x 1400 x 1/7776 = 1.08 cfs. As shown in Fig. 2 this discharge was provided for by a single pump. The water was drawn through a manifold from 6 intakes, similar to the suction pipes of the prototype pumps. A comparison of the intake shape used in the model and the shape given in the preliminary design (drawing 311 PRE 22) is shown in Fig. 3. The small differences, due to construction simplicity, were considered allowable since the prototype design was a preliminary one. The elevation of the intake lip was made to correspond to that of the prototype, which is important, for submergence considerations. A photograph of a model intake is enclosed as Fig. 8.

The water in the model was continuously recirculated, and the discharge in each intake was metered through 2 1/4-inch diameter orifices located 15 diameters downstream of the point where the long radius rubber hose bend joins the 4 inch diameter steel suction pipe. The total discharge was metered through a 4 1/2-inch diameter orifice placed in the 6-inch discharge pipe 19 diameters below the elbow. The summation of the intake discharges was compared with the total discharge as a precaution against discharge setting discrepancies and as a check on the discharge equations.

The air-water manometers for all orifice meters were mounted on the same board with a 4.5 ft useable reading length. The manometers could be readily evacuated through a manifold to remove any air which gathered in the lines from the piezometer taps. The two-story arrangement of equipment minimized the laboratory space, and placed the model pump and orifice meters under a positive pressure for most operating conditions thus reducing the possibility of air leaks.

Gravel baffles and a flow spreading flange at the end of the discharge pipe were used in the Charles River Basin tank to provide a uniform velocity distribution upstream of the lock entrance. The basin bottom was contoured over the width of the tank for a distance of 150 ft (prototype) upstream of the lock entrance.

In order to allow ready alteration of the forebay arrangement, a plywood enclosure in which the forebay walls were placed, was employed. The dimensions of this enclosure were based on the given maximum allowable downstream location of the pumping station. The model platform was made level within $\pm$ 1/32 inch, and the mean level platform corresponded to a prototype elevation of 82.6 ft. Sills corresponding to those existing in the prototype lock chamber were placed in the model lock chamber. Figure 1-A shows a plan and profile of the lock chamber.

B. Instrumentation and Measuring Procedure

1. Water Surface Elevation Measurements

The water level in the Charles River Basin tank was measured by means of a point gage fixed 100 ft upstream of the lock entrance and 96 ft north of the south basin wall. A bench mark was established outside of the model with its elevation based on the mean model bottom which corresponded to prototype elevation 82.6 ft. The basin tank point gage was referred to this datum. The level of the water in the basin tank during any one test could usually be adjusted within ± 0.02 ft prototype.

Water surface profiles throughout the model were measured by a point gage mounted on an aluminum bar which was supported by the model walls. To eliminate errors due to deflection of the bar and variation in elevation of the model walls, the point gage readings were taken through a surveyor's level set up on the laboratory floor. The accuracy of reading the point gage in this manner was about ±0.03 prototype ft.

2. Flow Pathline Data

Flow pathlines were obtained by taking time exposure photographs of confetti floating on the water surface. In order to be able to compare the flow patterns of different tests, all photographs were taken with an exposure time of 8 seconds. The water was colored with potassium permanganate to improve the contrast between the water and the confetti. Local flow directions were found at various water depths by supporting threads as well as thin brass flags on wires and observing their direction and action. Photographs were taken of the threads in order to compare the flow directions in front of the intakes for different tests.

3. Unsteady Flow Phenomena

With some forebay arrangements waves and surges of varying heights occurred in the model. These waves frustrated attempts to get satisfactory flow pathlines with time exposures. Some 16 mm movie films were taken of these phenomena in order to give a graphic impression of the relative wave heights and flow directions. In order to determine the wave heights and periods at various locations a two-wire resistance wave gage coupled with a one channel type 140 Sanborn recorder was utilized.

IV PRESENTATION AND DISCUSSION OF RESULTS

In order to evaluate and improve flow conditions in the pump forebay three categories of tests were made. (A) Improvements to the flow at the entrance to the lock. (B) A single intake, placed such that the approach flow was uniform, was investigated as a control test on the intake performance. (C) Several asymmetrical forebay arrangements of the six intakes were investigated. Model results will be presented in terms of prototype dimensions.

Since the most severe suction conditions are likely to occur when the pumps have their greatest discharge and least submergence, the majority of test runs were made with the maximum design discharge of 1400 cfs per intake and the minimum Charles River Basin elevation of 106.5 ft. A table(from Ref. 1) of the expected range of pump operating heads and discharges is included in the appendix.

A. Lock Entrance Test and Alterations

There is an abrupt change in cross-section from the Charles River Basin to the lock. With the design discharge passing through the lock, and its entrance as currently exists in the prototype, there was a large zone of separation with associated head loss. Regardless of what alterations were made to the forebay the design flow would still have to pass through the lock and lock-entrance alterations could affect flow conditions in the forebay. Thus, it was decided that before tests were made in the forebay, the flow conditions in the lock should be improved by altering the shape of the pier at the north corner of the lock entrance. While it might have been equally good hydraulicly to remove the existing pier and round off the entrance corner, it would be better from a construction viewpoint to enlarge and streamline the entrance pier.

Tests with a discharge of 8400 cfs and a basin elevation of 106.5 ft were made for four different entrance shapes,

a) Pier 1, a 6-ft diameter semi-cylindrical pier — as exists in the prototype

b) Pier 2, an 18-ft diameter semi-cylindrical pier

c) Pier 3, a well streamlined pier of 36-ft base width

d) Square-edged entrance (to compare the extreme case with the other tests)

A drawing showing the relative shape and size of these piers is included as Fig. 5. The results of the tests for the different entrance conditions are shown in Figs. 6 and 7.

The time-exposure photographs of confetti on the water surface, Fig. 6, give a good indication of the relative degrees of separation. The profiles of water surfaces and energy gradients along the centerline of the lock projected into the Charles River Basin, which are given as Fig. 7, corroborate the photographic data and indicate the relative reductions in head loss to be expected from the various piers.

The anomaly of positive energy gradients which appear to exist just downstream of the lock entrance, as shown in Fig. 7, is due to the use of the average velocity head at each section without correction for non-uniform velocity distribution. The positive energy gradients shown for a short distance serve to indicate the degree of non-uniformity in the velocity distribution across the lock. This is borne out by the test with the well streamlined pier. There was no separation of the flow from the pier, the velocity distribution is more uniform, and there is no region where the energy grade line has a positive slope. Because of the non-uniformity of the velocity distributions at the entrance and the convenience of using the average velocity at a section to compute the velocity head, it was decided to consider the loss in energy between section 0, located 100 ft upstream of the lock entrance, and section 1, located 216 ft downstream of the entrance as the entrance loss, $\Delta H_{ENT.}$, for comparison of pier shapes. The friction loss of a straight reach of this length is small compared to the actual entrance loss.

A comparison of the four entrance conditions is given in the following tabulation of head losses expressed in prototype values.

TABLE I Lock Entrance Losses

Pier	$\Delta H_{ENT.}$ ft	$\frac{\bar{V}_1^2}{2g}$ ft	$K_{ENT.} = \frac{\Delta H_{ENT.}}{\bar{V}_1^2/2g}$
None	1.06	1.17	0.91
1	0.62	1.13	0.55
2	0.27	1.06	0.26
3	0.26	1.06	0.25

These lock-entrance tests show that the replacement of the existing 6-ft diameter pier with an 18-ft diameter pier would result in an increased forebay depth of 0.35 ft for the same Charles River Basin elevation and in an improvement in flow distribution at the lock entrance. The well streamlined pier, while giving only a negligible additional saving in head, does give a more uniform flow distribution than the 18-ft diameter pier. The well streamlined pier gave no evidence of flow separation while there was definite separation with the 18-ft diameter pier.

Since a pier of 18-ft diameter could be reasonably constructed in the prototype, tests, in which forebay conditions were altered, were therefore continued with the 18-ft diameter pier at the lock entrance.

B. Tests of a Single Intake with Uniform Approach Flow

Tests, in a uniform approach flow, of a single intake of the same design as those in the six-intake station should give an upper limit against which to compare the performance of the asymmetric pumping station forebay. A single intake was therefore placed in the model lock channel as shown in Fig. 4. The lock channel was fitted with a false interior wall, 234 ft long, to make the approach chamber the same width as the basic pump chamber design of 27 ft. The intake pipe was located with the spacing between the channel floor and the pipe lip corresponding to that of the basic prototype setting of 14.0 ft. There was a gradual flow transition from lock width to intake chamber width which would tend to stabilize the flow and provide a uniform distribution of velocity in the chamber approaching the intake pipe.

The discharge through the intake was varied over a considerable range and various flow features in the approach chamber were observed. The elevation of the water surface over the intake was also varied to show the effect of changes in submergence. With a discharge Q_p of 1400 cfs and an elevation of 105.0 ft at the intake lip, the water surface was very quiet and no vortices tended to form.

Fig. 9 shows direction indicating streamers placed at 3, 9, 15, and 21 ft above the chamber bottom and 9 ft upstream of the intake lip. The streamers all pointed toward the intake with very little fluctuation, which indicates that the velocity direction was favorable over the whole channel. The discharge through the intake was varied from 1060 to 5200 cfs, which gave a velocity in the intake entrance $\overline{V}_p$ from 4.16 to 20.4 ft/sec, or $\overline{V}_m$ from 0.69 to 3.4 ft/sec. At constant values of discharge within the above range the submergence was gradually reduced from an S_p of 9 ft until air-entrainment began. The average water surface elevation was measured 40 ft upstream of the intake lip and the submergence was computed from this. A summary of these test results is given below in Table II.

TABLE II

Summary of Submergence Tests with Uniform Approach Flow

Average Velocity in Intake Entrance ft/sec		Discharge through Intake	Submergence at which air-entrainment began	Water Surface Elevation at which air-entrainment began
$\overline{V}_p$	$\overline{V}_m$	Q_p cfs	S_p ft	ft
20.4	3.4	5200	2.6	99.2
11.0	1.85	2800	1.7	98.3
5.5	0.92	1400	2.8	99.4
4.16	0.69	1060	1.5	98.1

No vortices developed around the intake. There was a surface roller at the upstream side of the intake due to this being a stagnation point in the flow. As the submergence became very low this roller became more unstable and fluctuated considerably. Occasionally it would fluctuate low enough to let a bubble of air under the intake lip. Continuous entrainment of air did not occur until the submergence was so low that the intake lip would be laid bare periodicly. Thus air-entrainment was not through vortices but due to the water surface being lowered intermittently to the elevation of the intake lip. At the minimum design pump chamber water surface elevation of 105.0 ft the velocity in the model intake was raised to 62 o/o of the maximum prototype intake velocity. This was done at a model Froude number 3.7 times greater than the prototype Froude number for intake chamber flow and no vortices or dimples developed. With a discharge of 5200 cfs some small swirls and dimples developed along the sides of the intake when the water surface elevation was lowered to 100.0 ft. At lower discharge rates the

the water level had to be brought slightly below elevation 100.0 ft before dimples were noticed around the intake. These swirls and dimples never developed into distinct air-entraining vortices.

The single-intake tests have complied with the suggestions from the literature that velocities in the model be raised to values greater than that based on Froude similarity. With the highest discharge used in these single-intake tests, 5200 cfs, the submergence had to be reduced to 2.6 ft before any air was entrained. Under this condition the intake chamber flow had a Froude number of 0.5. Whereas the maximum Froude number for the flow in the prototype intake chamber would be 0.085. When the model Froude number was 0.5 it is not surprising that the water surface in front of the intake fluctuated considerably before air-entrainment began.

The tests with a single intake indicate that this intake and chamber design should perform very well in the prototype if the flow can be made to enter the chamber in a uniform manner.

C. Forebay Tests

During the course of this study several different arrangements of intakes, dividing walls, and basic pump locations were tested. Each arrangement that represented an alteration of the forebay was given a variation symbol. Plan views of the major variations tested are shown in Figs. 10 and 11. The intakes were numbered 1 to 6 as can be seen in Figs. 14 through 22, with intake 6 adjacent to the south forebay wall. Accordingly, the intake chambers will be referred to by their intake number, and the walls between the intakes by the intake numbers on either side. Directions will be referred to as right or left hand looking toward the intake in the direction of flow.

Variation A

The first forebay arrangement tested was that given by the consulting engineers' drawing 311 PRE 22 and outlined in plan in Fig. 10. This represents the maximum downstream location of the pumping station and is denoted variation A in the model tests.

Fig. 12 shows the presence of a large eddy comparable in size to the dimensions of the forebay. This is caused by the separation of the flow at the forebay entrance and results in an intense cross-flow upstream of the intakes. This circulation pattern also results in eddies and air-entrainment in chambers 3 through 6. In chambers 1 and 2 the water surface was relatively quiet, but occasionally an air-entraining vortex would form.

A water surface profile taken 75 ft upstream of the pump support wall is given in Fig. 13. This profile shows the steep water surface slopes which accompanied the cross flow in front of the intakes. Stagnation points were observed in front of intakes 1 and 2 and at the south boundary of the forebay in front of intake 6.

The mean water surface elevation and the mean fluctuations of the surface were measured within the pump intake chambers 9 ft upstream of the lip of the intake and are given in Figs. 26, 27 and 28 along with the corresponding data for other variations. The relative intensity of the intake chamber disturbance is indicated by the relative height of the water surface fluctuations. Fig. 28 shows chambers 4 and 5 to have the highest degree of disturbance. Also, intakes 4 and 5 had the lowest submergence as can be seen from Figs. 26 and 27. Wave gage observations showed that these fluctuations had no distinct periodicity.

A sequence of tests was made with the flow through various intakes shut off, and the remaining intakes passing 1400 cfs each. The flow pattern in the forebay did not change appreciably from that which occurred under normal discharge. The circulation in the intake chambers was intense, but very similar to the situation with all intakes passing 1400 cfs, except when intake 2 was closed. With intake 2 closed small surges occurred regularly in chamber 2 and occasionally in chambers 1 and 3. In variation A the main flow turned very sharply in front of intake 2 and the location of this zone of high flow curvature was probably less stable when there was no discharge through intake No. 2.

An attempt was made to adjust the intake discharges such that the water surface 75 ft upstream of the pump support wall would be level. With the total discharge held constant at Q_p = 8400 cfs, a range of individual intake discharges from zero to 2300 cfs was tried; in no case was there a significant change from the profile shown in Fig. 13. It thus appears that the general circulation in the forebay, and not the distribution of discharges among the intakes, was responsible for the shape of the water surface profile.

The results of the tests of variation A indicated that the large forebay area was of no value in distributing the flow uniformly.

Variation B

Variation B was developed from the basic layout of variation A by extending the intake chamber walls to the line of the southeast lock wall. It was desired to investigate the effect of preventing the formation of the large scale eddy by simulating a manifold type withdrawal from the lock chamber extension.

Attempts to get pathline photographs which would indicate the flow pattern into the elongated intake chambers were frustrated by the development of standing waves in the chambers. Ripples at the ends of the walls also deflected the confetti somewhat. However, the photograph in Fig. 14 gives some idea of the zone of separation occurring downstream of the ends of the extended walls. The separation zones at the ends of walls 4-5 and 5-6 was quite unstable. These separation zones periodically changed in size and excited standing waves whose heights reached about 4.5 ft near intakes 4 and 5 at the design discharge. The wave heights were less in the other chambers. A more detailed discussion regarding the standing waves will be presented later, since they occurred in other variations.

Local circulation in the vicinity of the intakes was less in variation B than in variation A. However, air-entraining vortices persisted at intakes 2 and 3. Occasional dimples and vortices developed at the other intakes.

Variations C, D and E

As can be seen from Fig. 10, variations C and D were developed from variation A by extending walls 2-3 and 4-5, and wall 3-4 respectively to the line of the south lock wall. Variation E differs from variation C only by a reduction in the length of wall 4-5 of 41 ft. Flow pathline photographs for these variations are presented in Fig. 14. These photographs show that in all cases the forebay flow is dominated by large undesireable zones of circulation. The local circulation in the intakes was least in variation E, as was the separation zone at the end of wall 4-5. Air-entraining vortices occurred at most intakes in these variations. Standing waves occurred in the forebay in variations C, D and E. The waves were less pronounced in variation E probably due to the shortening of wall 4-5 and the consequent better alignment of the approach flow with this wall.

Standing Waves in Intake Chambers

As pointed out earlier, there was good reason to suspect that the standing waves in the intake chambers were excited by unstable separation zones at the ends of the chamber wall extensions. Accordingly, the flow through the intakes of the chambers having the most pronounced waves was shut off while the total discharge was kept constant. With zero net flow the waves in the chambers were as high as, or higher than before. This showed that the waves were not caused by surging of the flow through the intakes. A slightly streamlined piece of sheet metal was placed at the end of the wall extension to confine the zone of separation. When this was done the wave heights diminished almost to zero. These checks indicate that the standing waves were excited by the instability of the separation zone at the end of the wall extensions.

Undoubtedly the length of the chambers had an effect on the height of the standing waves. The highest and most regular waves occurred in the chambers whose lengths were close to the shortest resonant length for a standing wave, $L_R = \lambda/4 = \frac{CT}{4} \approx \frac{\sqrt{gh}\,T}{4}$. Where λ is the wave length, T is the measured period, and h is the average depth. The approximate 1/4 wave length, along with other pertinent data measured for the variations in which standing waves occurred, are summarized in terms of prototype dimensions in Table III below.

Comparison of the values of L_R with the forebay channel dimensions of variations B, C, D, E and G2 given in Table III, reveals the length of the channel in which the waves were highest to be very close to the resonant length for a standing wave of the period observed.

The standing waves in variations B, C and D had heights of the same order as the pump design head. This difficulty together with the cost of the long dividing walls indicates the desirability of moving the pumping station closer to the lock.

TABLE III Summary of Standing Wave Data

Forebay Variation	Total Q_p cfs	Basin Elev. ft.	Dominant Period T, secs.	Average Chamber Depth $h_{av.}$ ft	Chamber of Dominant Wave	Approx. 1/4 wave Length L_R ft	Mean* Length of Dominant Wave Chamber ft.	Max. Measured Wave Height ft.
B	8400	106.5	36	23	5 4	240	290 240	1.9 2.25
B	10800	107.1	42.6	23	5	296	290	8.85
C	8400	106.5	48	23	5 and 6	332	315	5.9
D	8400	106.5	50.4	23	4,5 and 6	348	290	2.0
E	8400	106.5	46.8	23	5 and 6	322	315	1.5
G2	8400	106.5	18	23	5	124	115	5.0

*Mean chamber length is measured from the pump support wall to the point where the center line of the chamber intersects the line of the south lock wall.

Variation F

Plan view details of variation F are given in Fig. 11. The following changes have been made from the forebay arrangement of variation A: 1) The lock extension has been shortened 70 ft. 2) The pumps have been moved upstream and the direction of their centerlines has been rotated 40° clockwise. The pump dividing walls are straight for a length of 66 ft with vertical semicylindrical ends. Intake 6 has been located sufficiently downstream of the lock exit to allow room for future construction at the exit of the Boston Marginal Conduit.

The pathline photographs in Fig. 15 show that the flow turned to the right near the forebay entrance; a large slowly rotating eddy developed in the projected lock; separation occurred along the curved south forebay wall upstream of pump chamber 6; and the main current flowed across in front of the ends of the pump-dividing walls resulting in considerable circulation in the intake chambers.

As can be seen from Fig. 15 the flow appears to approach intake 5 more uniformly than the others. However, an air-entraining vortex persisted in the right half of this chamber. Vortices tended to form in the other chambers but were swept away by the intense circulation before a continuous air tube developed. In a test in which the forebay level was raised such that the water surface elevation at intake 5 was brought from 105.9 ft to 115.6 ft (submergence increased from

9.3 to 19.0 ft) there was no significant decrease in the continuity of the air-entraining vortex. The data from water surface measurements in the intake chambers are presented along with data from other variations in Figs. 26, 27 and 28.

A flow pattern such as occurred in variation F would be unsatisfactory for pump operation. However, this flow pattern was improved considerably by curving and extending the pump chamber dividing walls toward the approach flow.

Variations G

The G variations were developed from variation F by extending the pump separating walls with differing lengths and degrees of curvature. The main changes of these walls are shown in Fig. 11 as variations G1, G2, G3, G4 and G5. Some other minor variations were also tried. With the walls extended to the line of the southeast lock wall the deflection of the mean curved wall chord from the line of the lock was placed at 74°, 59°, 44° and 39° in variations G1, G2, G3 and G4, respectively. In addition, for a deflection of the mean chord line of 44° the length of the walls was changed in variations G5, G6 and G8. To minimize the separation at the entrance of the intake chambers it was evident that wall extensions would have to point upstream at a small angle. The above range of chord angles and lengths were tested in order to arrive at the best flow guidance in a systematic fashion. It should be noted that the tangent to the tips of the curved walls makes a much smaller angle with the lock line than does the chord line.

Figs. 16 through 20 show surface flow patterns for the G variations. Flags and threads at various depths indicated that the subsurface flow directions were essentially the same as surface directions in the region of the lock extension and in the entrance of the intake chambers. It should be pointed out that the confetti flow patterns close to the intakes are somewhat deceptive. In this region the surface flow in the right half of the chambers was reversed while at depths of 3 ft or greater the water was moving toward the intake. Two adjacent layers of fluid flowing in opposite directions tend to generate vorticity. The back flowing surface layer is a case of a separation zone occurring at the top rather than along the walls of a flow channel. While this may be partly caused by the intake drawing off the subsurface water, it is largly due to the deceleration occurring between the lock and the pumps.

The pathline photographs in Figs. 15 through 19 show that extending the pump dividing walls has reduced the size of the dead water zone along the north forebay wall which occurred in variation F. In variations G1 and G2 the separation zones in the intake chambers are quite long. There are high velocity flows toward the intakes along the left walls of the chambers and a reverse flow in the right half of the chambers. In the photographs in Fig. 17 for variation G2 a circular pathline of diameter about equal to the chamber width can be seen filling the end of chamber 5. Eddies such as indicated by this pathline formed behind the end of wall 5-6 and periodicly swept in or out of chamber 5 exciting standing waves. The waves were highest in chamber 5 but were also quite evident in chambers 4 and 6. As can be seen from the data presented earlier in Table III the waves had a period very close to a resonant period for a channel the length of chamber 5. The waves in this chamber reached a height of 5 ft. Continuous standing waves did not occur in any of the other G variations.

In variation G3 the water enters the chambers more smoothly than before but there is still a zone of separated flow in the right third of the intake chambers. There was no tendency for surges or standing waves to form in the intakes but air-entraining vortices persisted in chamber 5 and formed occasionally in the other chambers.

Reducing the angle between lock and chamber wall chord by 5° developed variation G4 from G3. Further deflection of the walls in an upstream direction would constrict the entrance to the chamber unduly. As can be seen from the photographs in Fig. 19 the confetti entered the chambers more smoothly and the width of the circulation zones is less in variation G4 than in the other variations. There were no surging or standing wave tendencies but air-entraining vortices were persistant in chambers 3, 4 and 5 and formed occasionally in intakes 1 and 2.

Variation G5 had a wall chord deflection angle of 44° and the curved walls extended 2/3 of the distance from the end of the straight pump dividing walls to the line of the southeast lock wall. No tendencies for waves or surges to form were observed with this variation. The separation zones in the chambers are still large even though the flow turned a little more toward the chambers before reaching the tips of the walls than it had in the variations with the walls extended the maximum amount.

Variations G6 and G8 are developed from G5 by extending walls 3-4 and 2-3, and wall 4-5 respectively to the line of the southeast lock wall. The intakes on the upstream side of the further extended walls benefited at the expense of those on the downstream side. The flow was more uniform and quieter on the upstream side and more disturbed and separated on the downstream side of the walls which extended to the lock line. Vortices tended to form in all intakes except No. 6 but were intermittent and short lived in the more disturbed chambers. No standing waves or surges developed in either variation G6 or G8.

In all of the G variations the flow was more rapid along the left than the right side of the chambers and flow continued around the back of the intakes. Variation G4 had the most uniform flow into the chambers of the G variations. In addition to the uniform approach criterion it was important to do something locally to prevent the development of air-entraining vortices. The flow of water around the back of the intakes appeared to be a major factor in the development of air-entraining vortices on the right side of the intake chambers. Accordingly, struts 2 1/2 ft wide were made to fit behind the intakes.

With these struts, as shown in Fig. 3, placed behind the intakes no air-entraining vortices were observed during further tests with variation G4. Swirls and dimples still tended to form occasionally though the subsurface flow in the intake chambers near the pipe entrance appeared more orderly when the struts were in place. Photographs of subsurface streamers in the intake chambers are presented in Figs. 23 and 24. The streamers on the right side of the chamber do not rotate as much when the struts are in place. Without struts the streamers in the right portion of the chambers were observed to rotate through 360° whereas, with the struts in place the streamers always pointed in the 2 quadrants toward the intake.

Water surface measurements taken 9 ft upstream of the ends of the intakes for variation G4 with and without struts behind the intakes are given in Figs. 25, 26, 27 and 28 along with data from other variations for comparison. Of interest is the consistently higher water surface elevation in G4 with struts in place compared with G4 without struts (see Fig. 25). Comparison of variations G4 with struts and F indicates a greater degree of uniformity in water level for intakes 1 through 4. Intakes 5 and 6 are both lower, with intake 6 the lowest. The water surface fluctuations indicate little difference between variations F, G4 with struts and G4 without struts. It is important to note that the average of water surface fluctuations at the lock exit for all tests was equal to 0.23 ft. This is only slightly lower than the observed fluctuations in the intake chambers.

A sequence of tests with the discharge from one or more intakes closed off was made with variation G4. In no case did any serious anomalies show up. No air-entraining vortices or surges were observed. Fluctuations in levels up to 0.4 ft occurred in the chambers which had no net discharge. In general the water surface was less disturbed with 5 or fewer intakes discharging.

While air-entraining vortices were retarded by the placing of struts behind the intakes in variation G4, the velocity distribution in the intake chambers was far from uniform. The flow was constricted in front of chambers 1 and 2 by the dead water region in the lock extension. The curved extension on walls 1-2 and 2-3 were comparatively short and of large curvature. The zone of reverse surface flow along the right wall extended in most intake chambers from the beginning of the intake chamber to the intake. The possibility of formation of standing waves, although occurring for only one variation in the G series, could probably be eliminated by having equal lengths of intake chambers. It was therefore decided to equalize and shorten the lengths of the intake chambers in the next variation.

Variation H2

A plan view of variation H2 is given in Fig. 29. The pump support wall was placed 68.2 ft - approximately the minimum distance required for auxiliary station equipment - southeast of and parallel to the line of the southeast lock wall. The center line of the pumps and the intake chamber walls are deflected 20° toward the approach flow and extend to the end of the intakes. From here the pump dividing walls curve upstream and terminate 6 ft from the line of the southeast lock wall. The mean chord line of the walls form an angle of 40° with the line of the lock. The lock chamber extension is 33 ft shorter than in variation G4. The center to center distance of the intakes along the pump support wall was kept at 30 ft. This reduces the spacing between the intakes and the pump separating walls by 0.85 ft on each side. The struts were kept behind the intakes in this variation. A range of extension wall curvature and lengths was tried, similar to the trials in the G series. Variation H2 provided the most uniform flow in the chambers. More chamber entrance disturbance resulted when the curved walls were extended to the line of the southeast lock wall.

As can be seen from the pathline photographs in Fig. 21, the dead water zone in the extended lock was reduced in size from that in variation G4, and the flow entered chambers 1 and 2 more uniformly than before. Figs. 23 and 24 are photographs of subsurface streamers placed 9 ft upstream of intakes 3 and 6. The photographs for intake 3 given in Fig.23 are representative of the flow directions at this section for intakes 1, 2, 3 and 4, while Fig. 24 presents the situation for chambers 5 and 6. A distinct improvement in uniformity of approach flow is evidenced by the changes from variation F through variation G4 with and without struts to variation H2. The separation zones were smaller in all chambers than with the previous variations tested but a small separation zone persisted in chambers 5 and 6.

Figs. 26, 27 and 28 show water surface elevation data in the intake chambers. Generally, water surface elevations for H2 are higher, although the difference is not large. The largest improvement is noted in intake 5. Intake 6 was not affected appreciably by the change from variation G4 to H2. Water surface fluctuations are of the same order of magnitude as variation G4.

Swirls and dimples formed in chambers 3, 4 and 5. The dimples in chamber 3 intermittantly developed into weak air-entraining vortices. When screens were placed across the ends of the curved walls to simulate the effect of trash racks, all vortices ceased and the water surface was quiet. The flow into the chambers in the prototype could receive some beneficial guidance from trash racks. The rack bars should be made longer than usual and aligned with the tangent to the tip of the mean camber line of the curved walls (i.e. an angle of 25° with the lock line).

Standing waves could not be produced in variation H even though the intake wall extensions were adjusted through a wide range of directions and shapes. It thus appears that an arrangement having all chambers the same length is preferable from the standpoint of standing waves. A sequence of tests with the discharge from one, two or three intakes shut off was performed. No surge or other anomalies developed. As the total discharge was decreased by stopping some intake flows, the circulation and the tendency for swirls to form in the intake chambers reduced.

In accordance with the above conditions, the pumping station should have equal intake chamber lengths. In an effort to reduce the weak air entraining vortices noted in intakes 3, 4 and 5, another variation with slightly longer chambers was tested.

Variation I

Fig. 30 shows a plan view of variation I. Since it was already established in variations G and H that flow conditions were better with a chord angle of 40°, this angle was chosen as the basic chord angle of variation I. Variation I is essentially the same as H2 but with longer straight portions of the intake chamber walls. The straight walls were increased from 36 ft in H2 to 51 ft for variation I. This had the effect of moving the intakes out of the curved region of the intake chambers. As in H2, struts were used behind the intakes.

Photographs of flow patterns are shown on Fig. 22. The zone of separation in chambers 4, 5 and 6 is larger in variation I than H2. There is a greater degree of circulation in all intakes, although the difference in intakes 1, 2 and 3 is slight. Photographs of subsurface current directions may be seen in Figs. 23 and 24. As in variation H2, the photograph of intake 3 (Fig. 23) is representative of the flow directions for intakes 1, 2, 3 and 4. The flow pattern for intakes 5 and 6 is indicated by the photograph of intake 6. The approach flow is less uniform for variation I than variation H2. In addition, the streamers were observed to be more erratic. The streamers on the right side of the chamber placed in intakes 5 and 6 were observed to rotate through angles of 180° at all depths.

Water surface data for this and other variations are summarized in Figs. 26, 27 and 28. Water surface elevations are higher for variation I than H2 in almost all the intakes. The fluctuations of water level are not significantly lower in variation I.

An attempt was made to improve the flow distribution in intake 6. The intake chamber was decreased in width by decreasing the radius of curvature of the right wall of intake 6. The zone of separation in intake 6 increased in size and severity with this slight modification. Hence decreasing the width of chamber 6 would cause the flow distribution to be less uniform and such a change would not be beneficial.

In general, the overall flow patterns observed in variation H2 were changed only slightly in variation I. The separation zones were larger than that observed in variation H2 and persisted at all depths. Consequently the approach flow was not as uniform as H2. The swirls and dimples observed in chambers 3, 4 and 5 in variation H2 were almost completely eliminated in variation I. In addition, the water surface elevation in the intake chambers were slightly higher. No standing waves were observed in variation I.

V EVALUATION OF RESULTS AND CONCLUSIONS

A. Flow Conditions at the Lock Entrance

The results of the lock entrance tests indicated that a vertical pier of 18-ft diameter on the Cambridge side of the lock entrance materially reduces the flow contraction and entrance loss for the design discharge. It is therefore recommended that a pier with this basic dimension be incorporated in the design.

B. Tests of a Single Intake with Uniform Approach Flow

These tests showed that the performance of the intake used in this study was satisfactory under all possible operating conditions when the approach flow was uniform. Air-entraining vortices were not formed even when the submergence was reduced to 30 per cent of the design submergence.

C. Forebay Performance

The flow pattern, as indicated by the photographs in Fig. 14, as well as the cost of the long forebay walls make the variations with the intakes in the maximum downstream position (variations A, B, C, D and E) undesirable. Standing waves of varying degrees of severity developed in all these plans with the exception of variation A. The water surface elevations in the intake chambers (see Fig. 27) are less uniform in variation A than for any other pumping station location tested. The largest degree of circulation in intake chambers 3 through 6 was observed in variation A, and occasional air-entraining vortices obtained in intakes 1 and 2. These considerations make variations A through E unacceptable.

The flow pattern, as shown in Fig. 15, for variation F is an improvement over variation A. However, a cross-flow in front of the intake chambers caused a large amount of circulation in all intake chambers except chamber 5 in which a continuous air-entraining vortex was observed. This flow pattern is considered unsatisfactory for pump operation.

Of the variations tested in the G series, variation G4, with struts behind the intakes, produced the best overall performance. No air-entraining vortices were observed. However, the velocity distribution in the intake chambers was not uniform and the flow was constricted at the entrance to intakes 1 and 2 by the slowly rotating eddy in the lock extension. The possibility of formation of standing waves, although occurring for only one variation in the G series, plus the above mentioned non-uniform velocity distribution made further testing desirable.

No standing waves were observed in variation H2. Thus, a plan with equal lengths of intake chambers is considered preferable. By comparison with previous arrangements tested, variation H2 resulted in the most uniform velocity distribution in the intake chambers. Water surface measurements as seen in Fig. 27 indicate increasing uniformity of water levels between intake chambers from variations A, F, G4 through H2. However, swirls and dimples observed in intakes 3, 4 and 5 occasionally developed into weak air-entraining vortices.

The overall flow pattern observed in variation H2 was changed only slightly in variation I. The swirls and dimples observed in chambers 3, 4 and 5 in variation H2 were almost completely eliminated in variation I. As can be seen in Fig. 27, the water surface elevations were slightly higher in variation I than H2. However, the separation zones in variation I were larger than observed in variation H2 and persisted at all depths. Consequently the approach flow in the intake chambers was not as uniform as variation H2.

It is concluded that variation I, because of the reduction of the possibility of air-entraining vortices, is the most satisfactory location within the restrictions imposed by the site immediately downstream of the Charles River Dam. It is recommended that struts be placed behind the intakes to retard circulation in the chambers. Trash racks with bars should also improve the flow distribution in the intake chambers.

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3) Denny, D.F., "An Experimental Study of Air-Entraining Vortices in Pump Sumps", Proc. of the Inst. of Mech. Eng., Vol. 170, No. 2, pp. 106-116, 1956.

4) Iversen, H. W., "Studies of Submergence Requirements of High-Specific Speed Pumps", Trans. ASME, Vol. 75, No. 4, p. 635, 1953.

5) Stepanoff, A. J., "Centrifugal and Axial Flow Pumps, Theory, Design and Application", John Wiley and Sons, Second Edition, p. 358, 1957.

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APPENDIX

Head Range and Pump Capacity
(from Table VII-2, reference 1)

	Basin Level ft	Discharge Level ft	Head Pool-to-Pool ft	Capacity per pump cfs.	Est'd Horse-power
Extreme Max. Head	106.5	115.6**	9.1	980	1690
Normal Max. Head (design tide)	106.5	113.0*	6.5	1200	1650
Normal Mean Head	108.0	112.5	4.5	1320	1620
Minimum Head	110.0	112.5	2.5	1400	1610

*Design Tide

**Highest Tide of Record

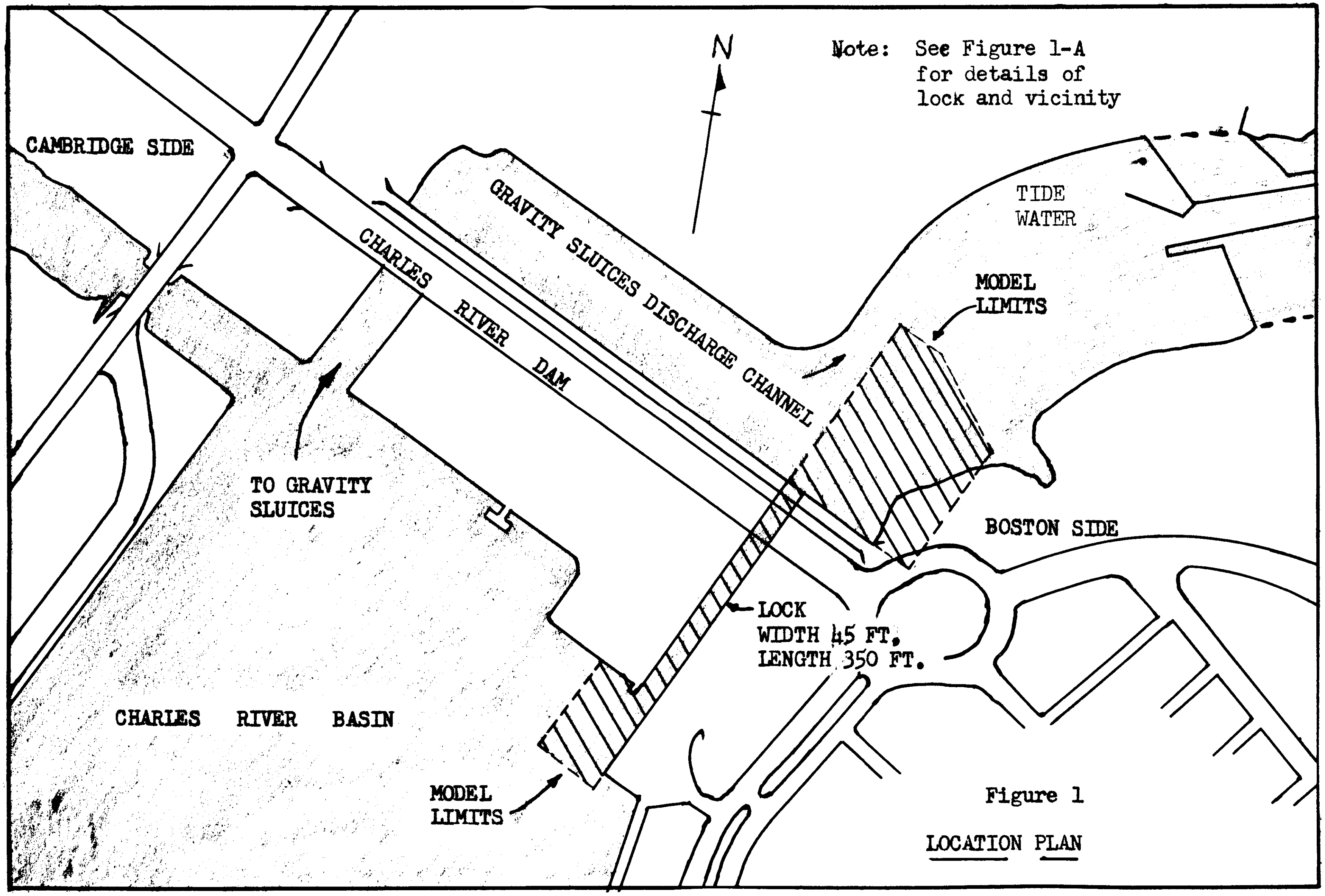


Figure 1

LOCATION PLAN

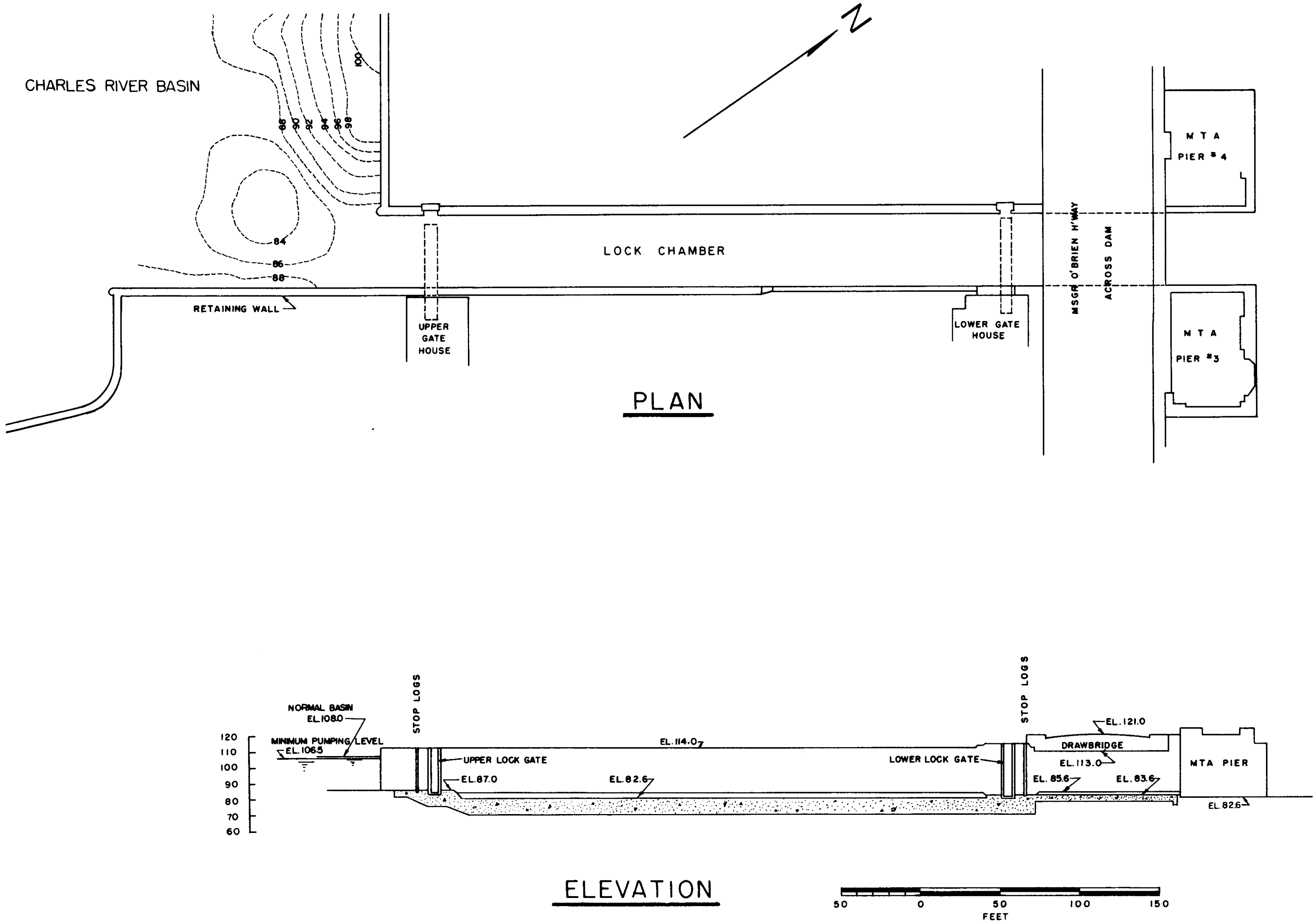
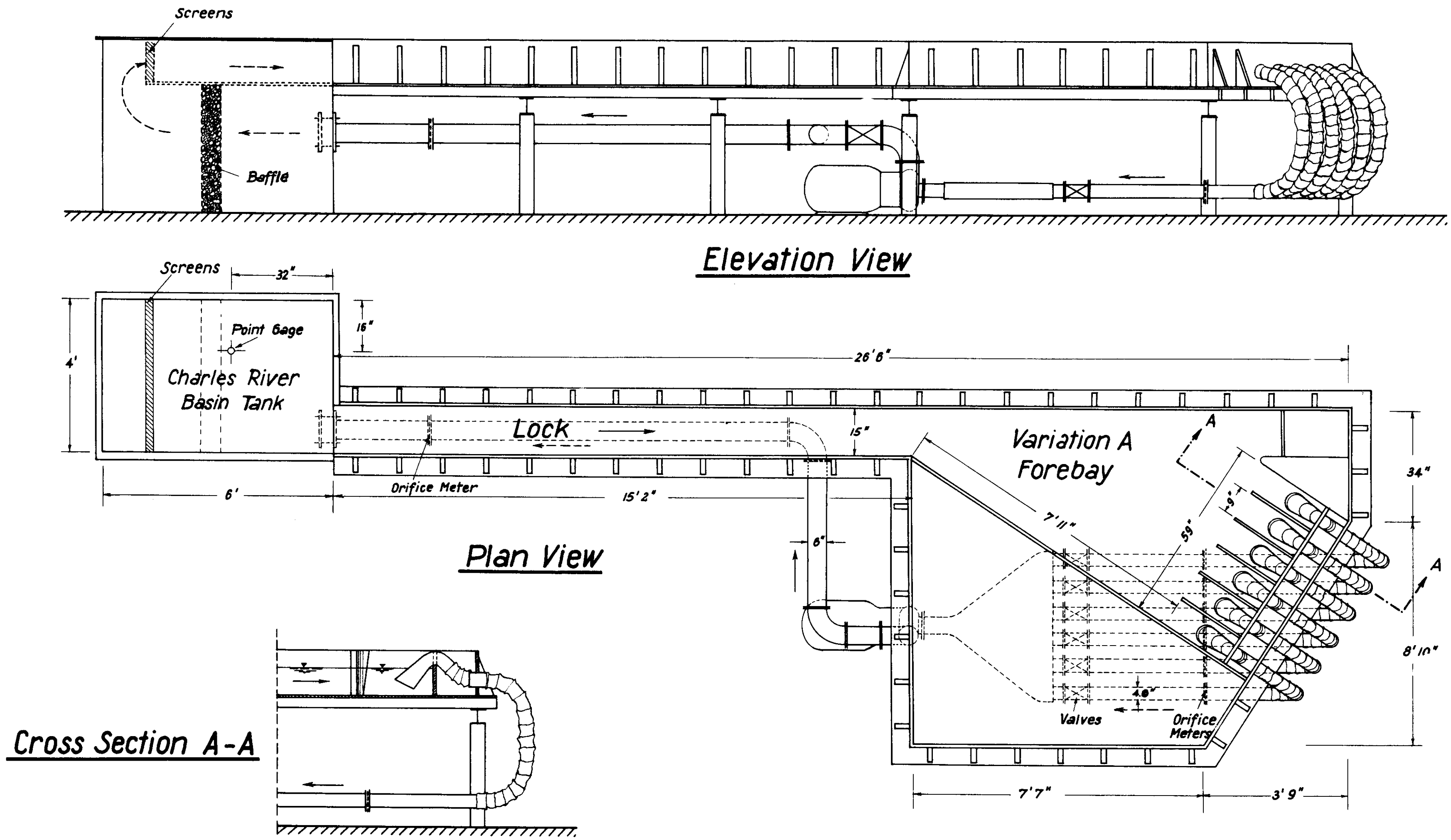


FIG. 1A LOCK AND VICINITY

Figure 2 :

General Layout and Equipment of the Model of the Charles River Flood-Control Pumping Station

Length Ratio 1:36



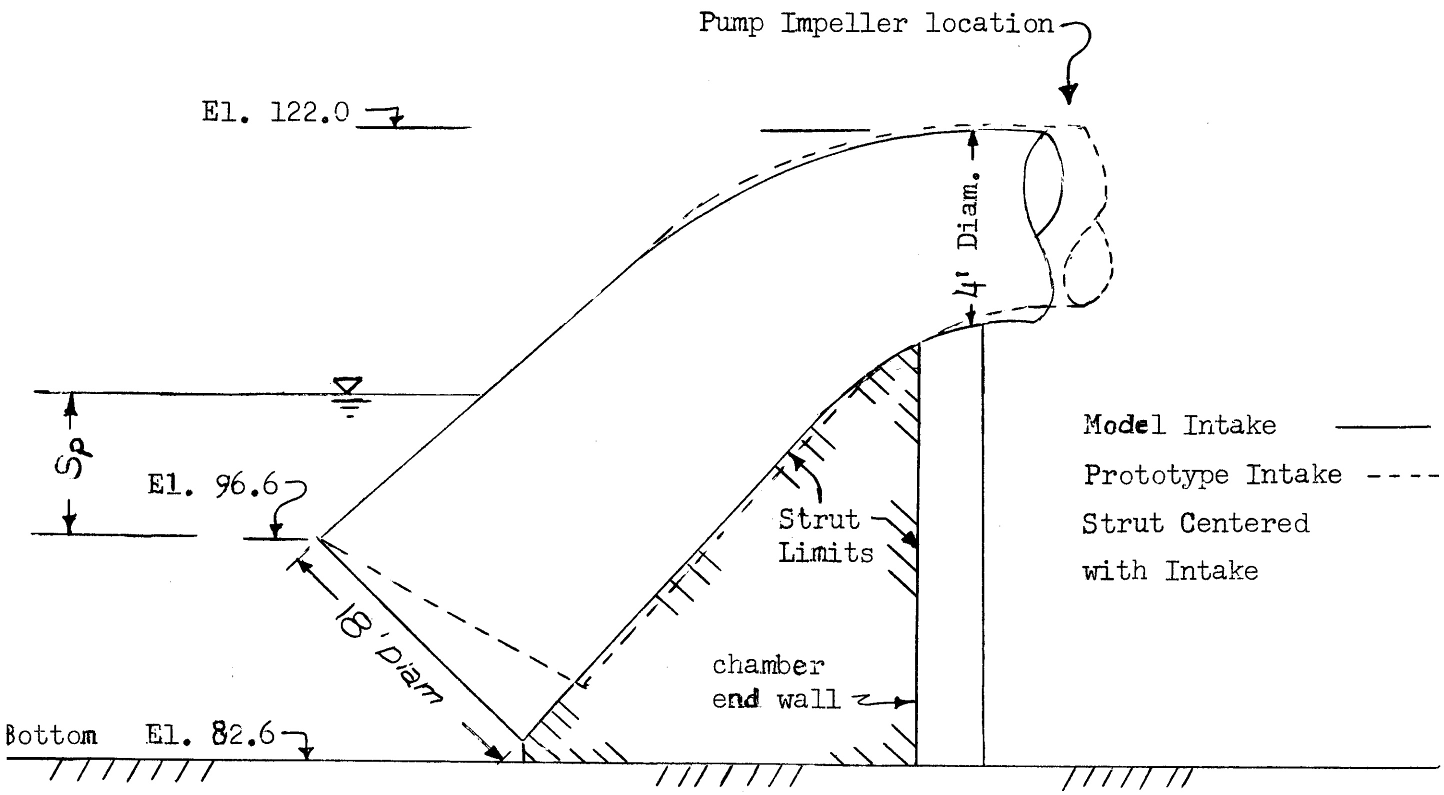


Fig. 3 Comparative Drawing of Model and Prototype Intakes. Dimensions in Prototype ft.

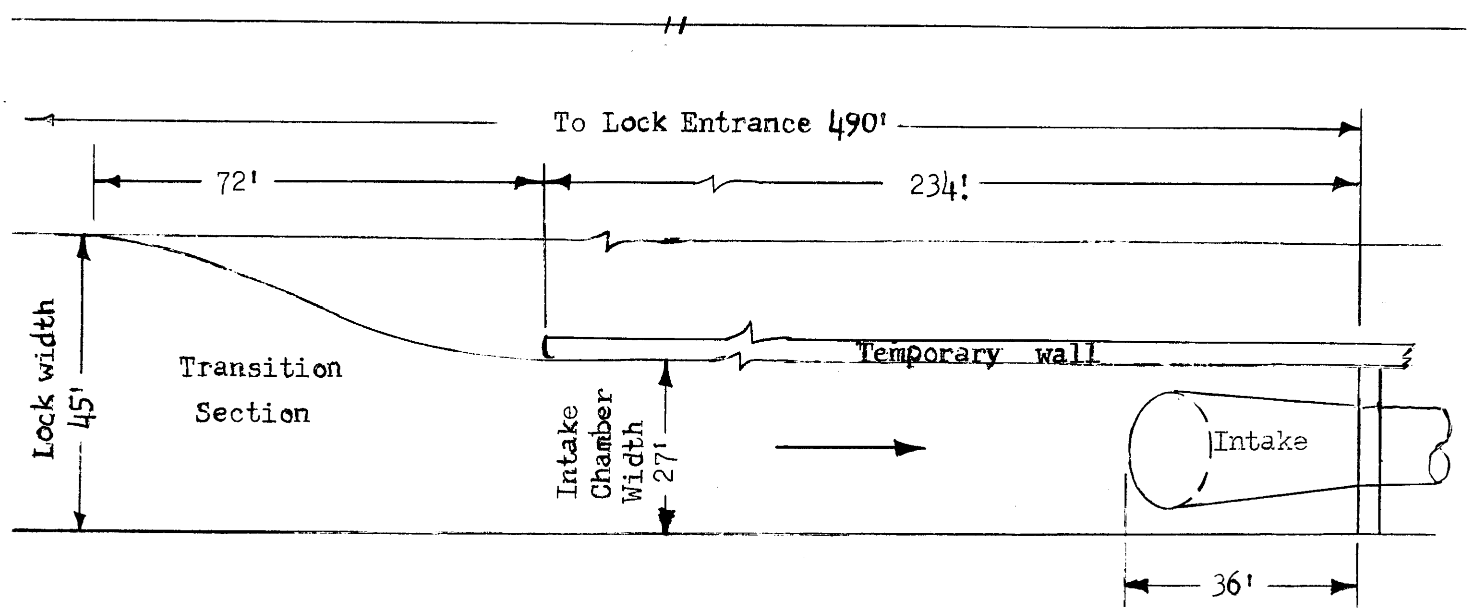


Fig. 4 Arrangement to Provide Uniform Approach Flow to a Single Intake in the Model Lock Chamber. Dimensions in Prototype ft.

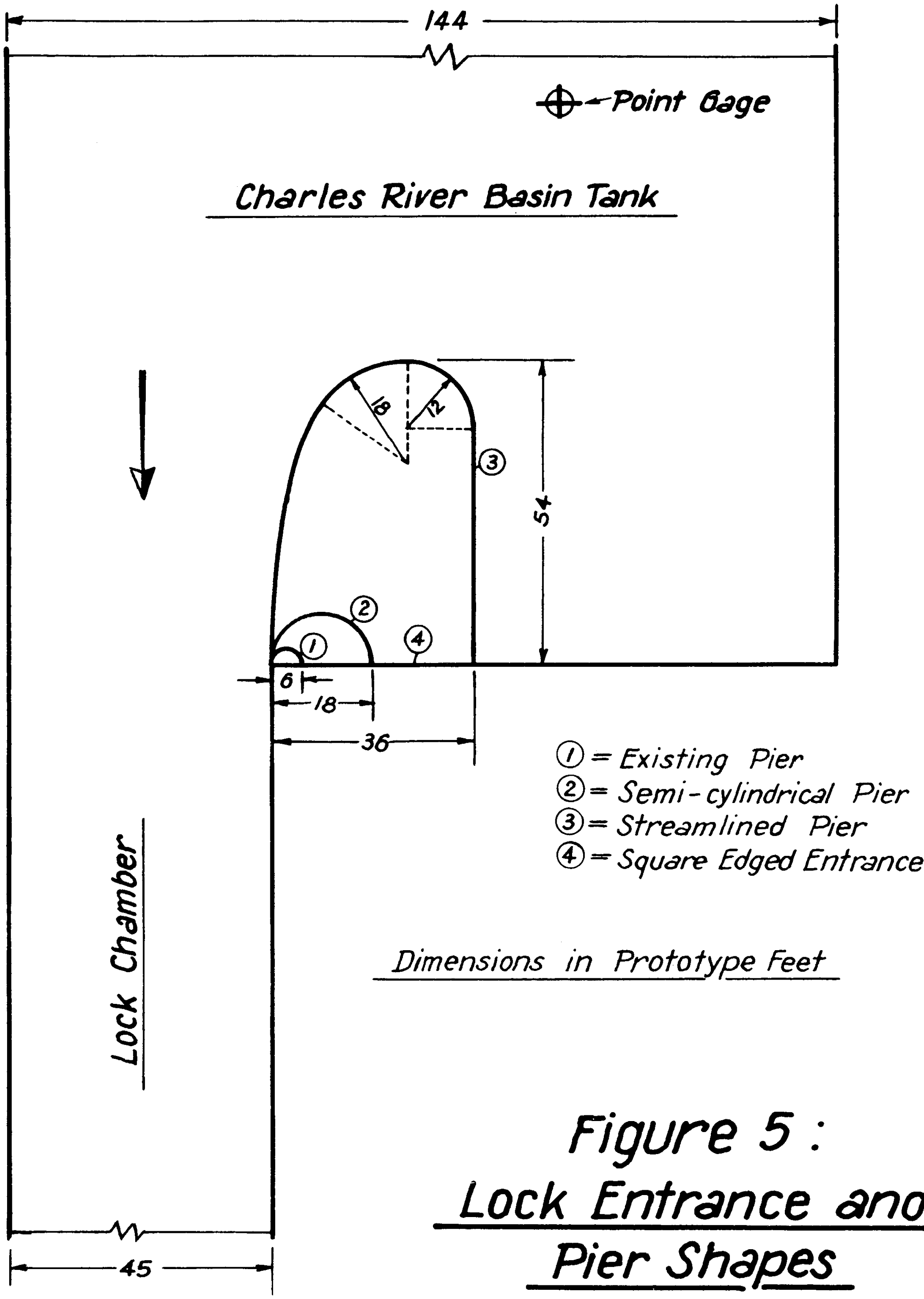


Figure 5 :
Lock Entrance and
Pier Shapes

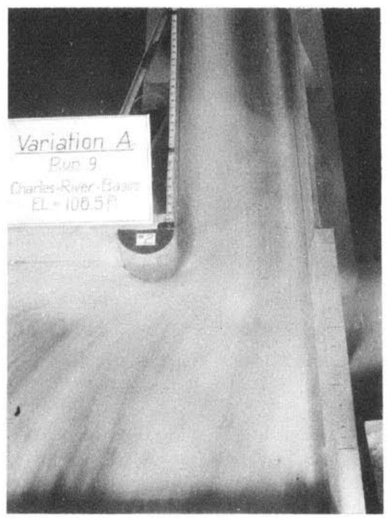
Figure 6 :

Flow Patterns at the Lock Entrance

Discharge 8400 cfs

— 1 —

6 ft. diameter semi-cylindrical pier

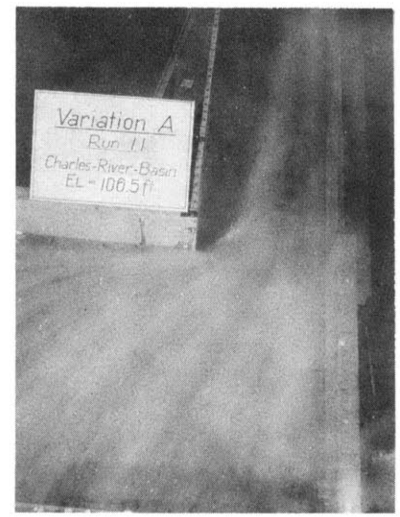


— 2 —

18 ft. diameter semi-cylindrical pier

— 3 —

well streamlined pier with 36 ft. base width



— 4 —

square edged entrance (no pier)

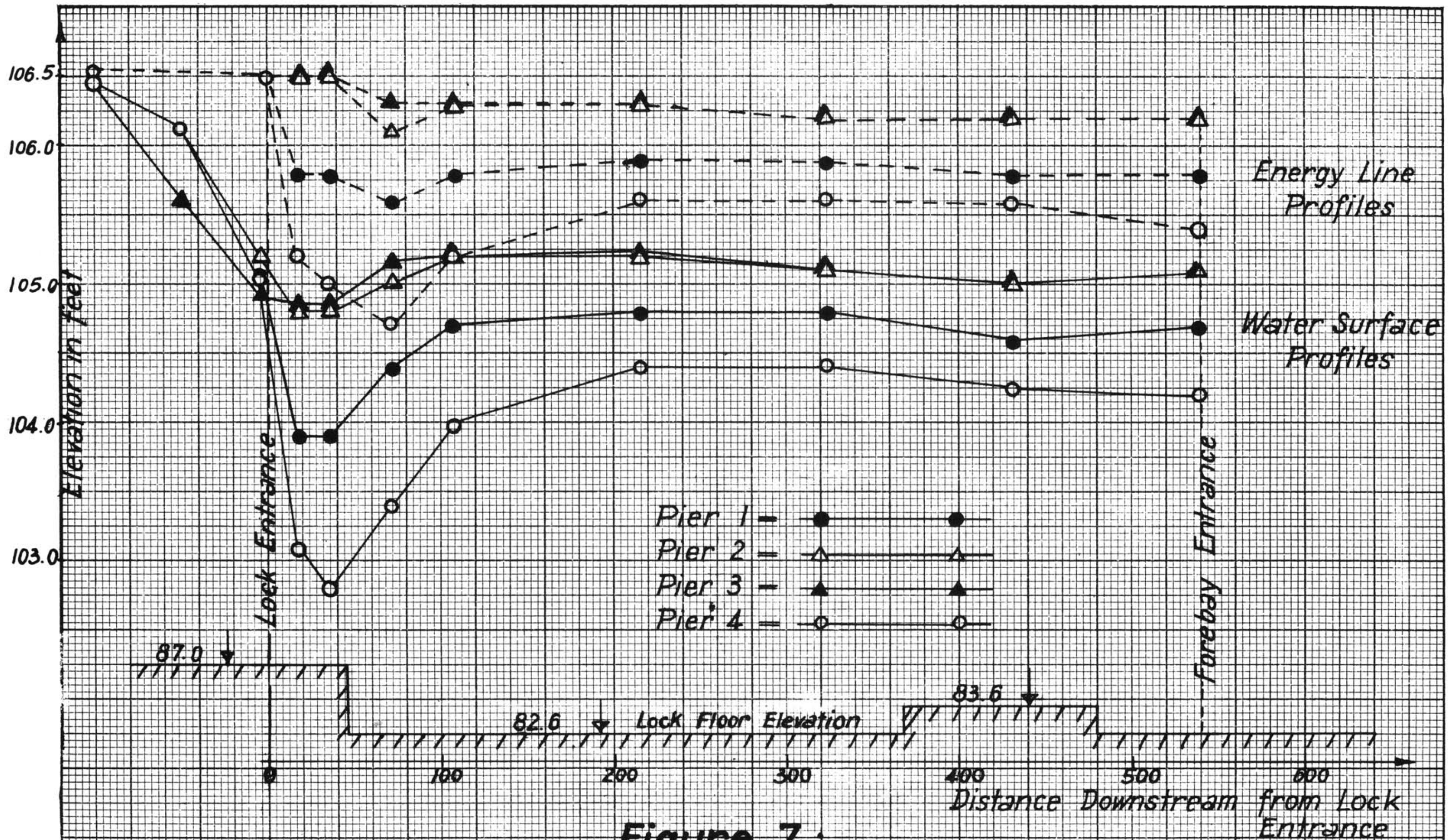


Figure 7.

Water Surface and Energy Profiles along the Lock Centerline

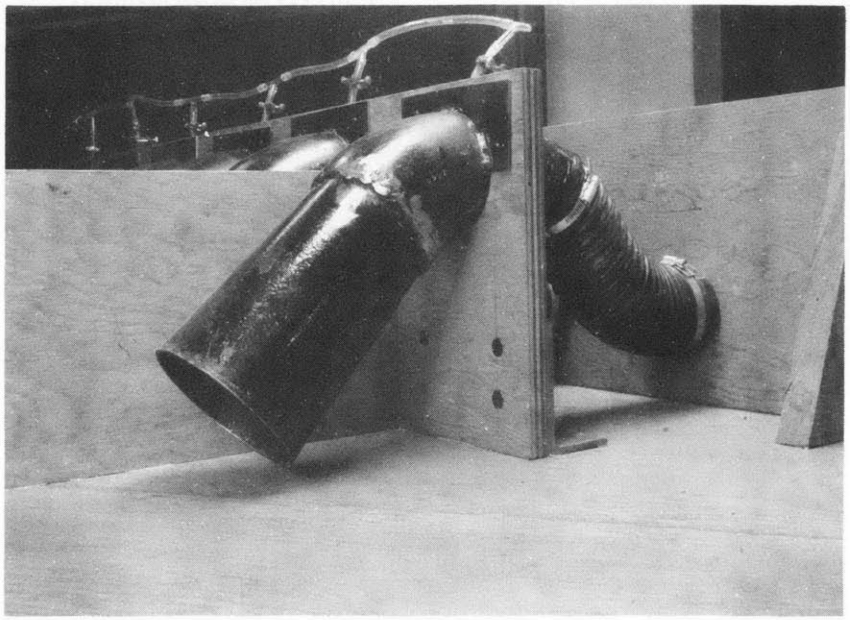


Figure 8
View of a Model Intake

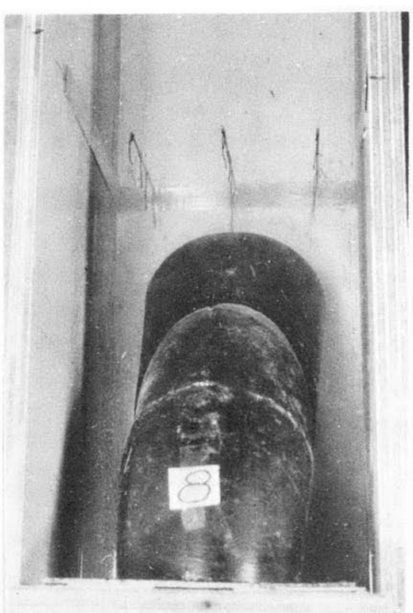
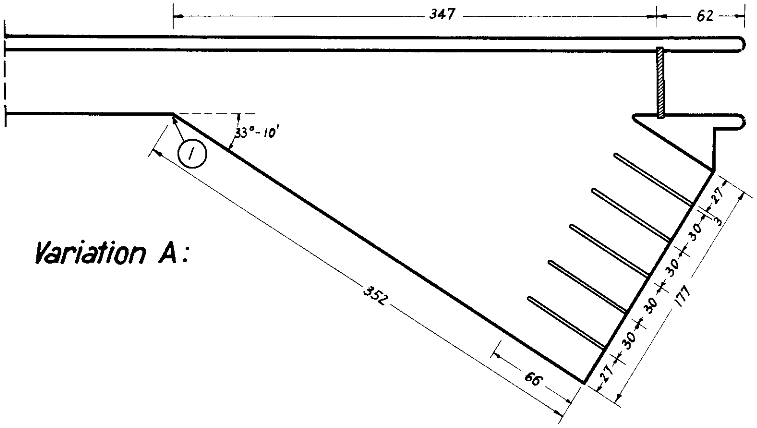
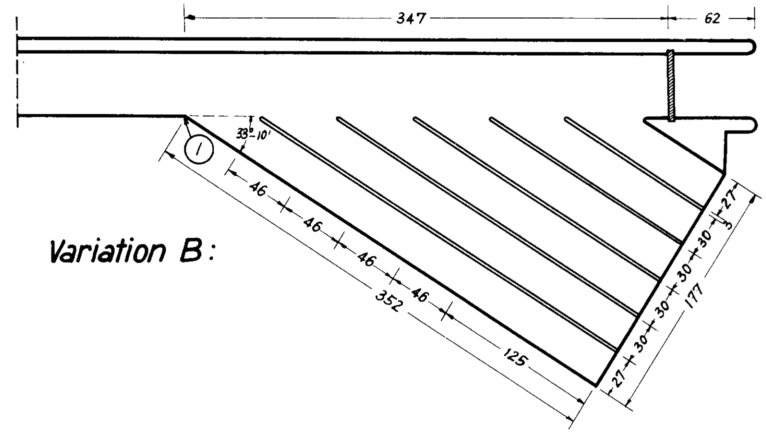
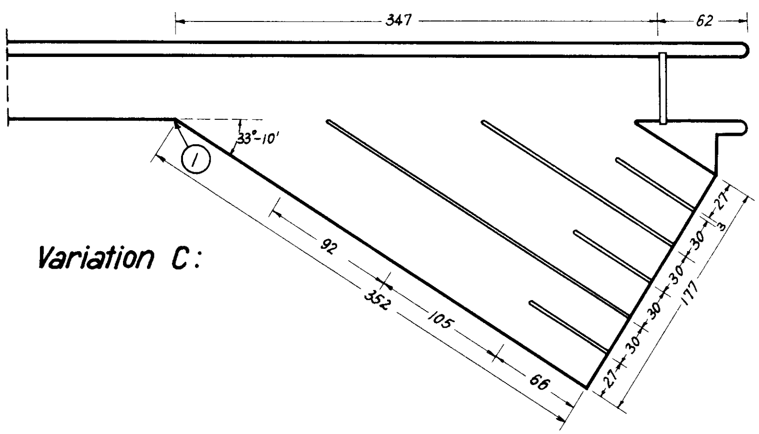
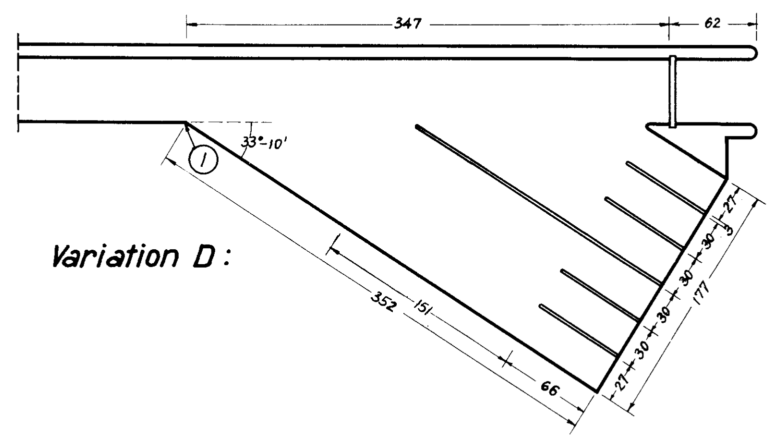


Figure 9
Single Intake with Uniform Approach Flow.
Flow Directions Indicated by Streamers Placed at 3, 9, 15 and 21 ft. Above the Chamber Bottom.
Qp = 1400 cfs. Water Surface Elev. 105.0 ft.









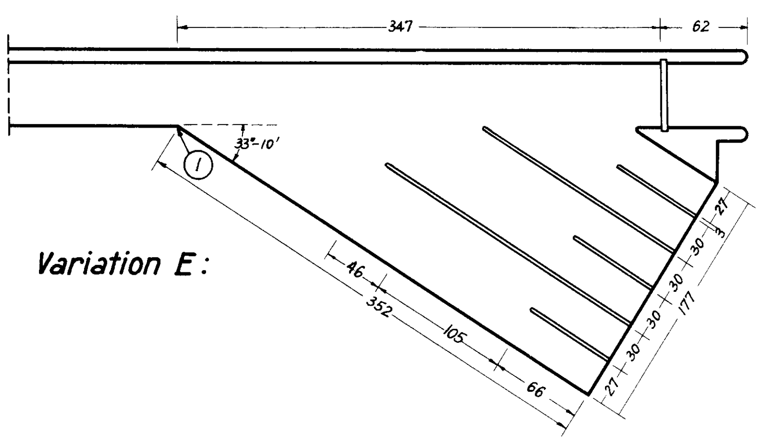


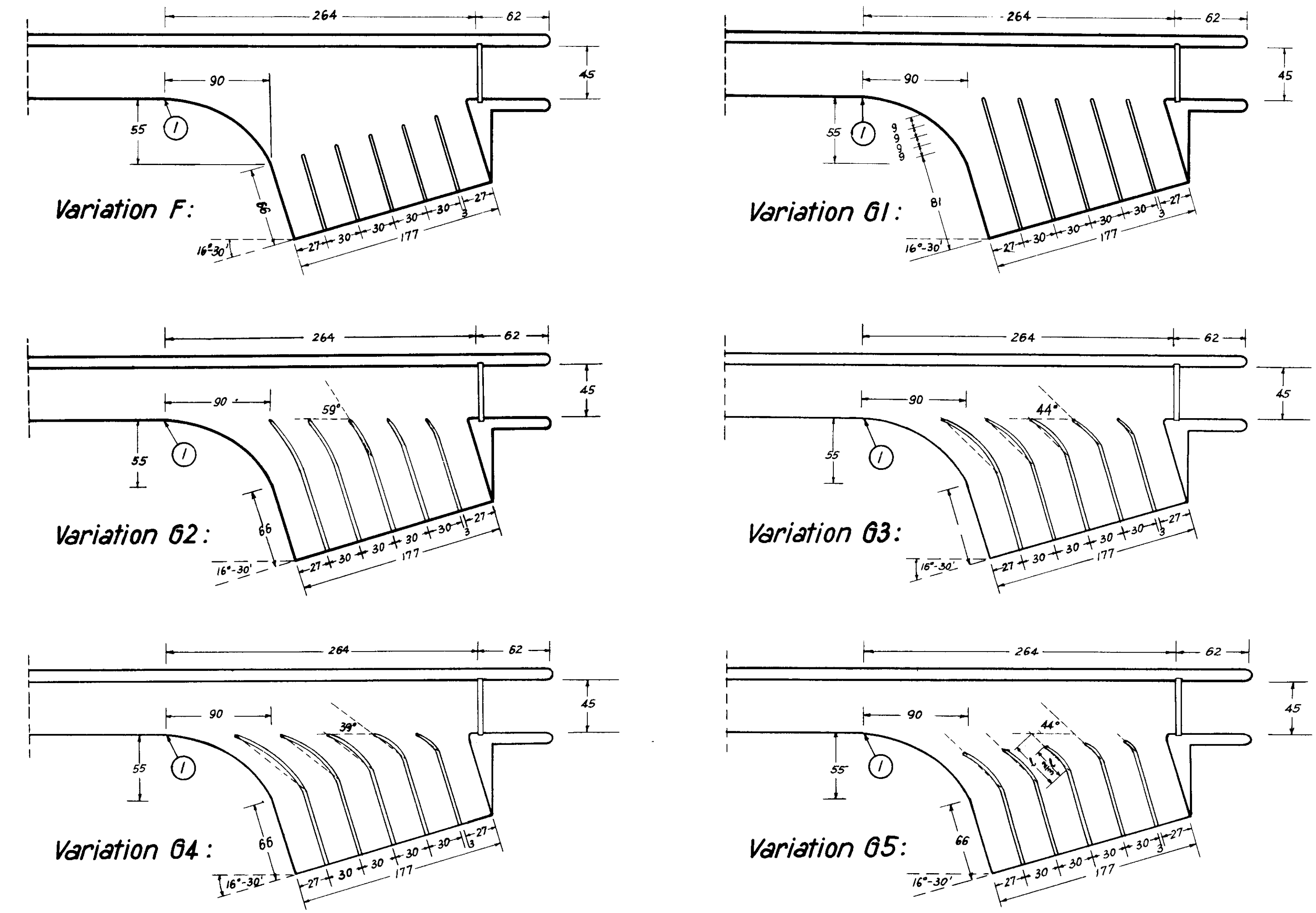
Figure 10 :

Plan Drawings of Forebay Variations A, B, C, D and E

Intakes in the Maximum Downstream Position

Dimensions in Prototype Feet

(1) = Northeast Corner M.T.A. Pier No. 3



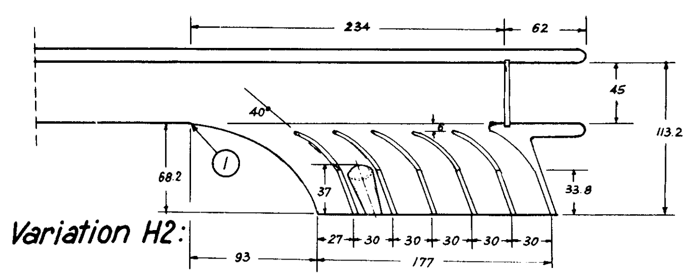


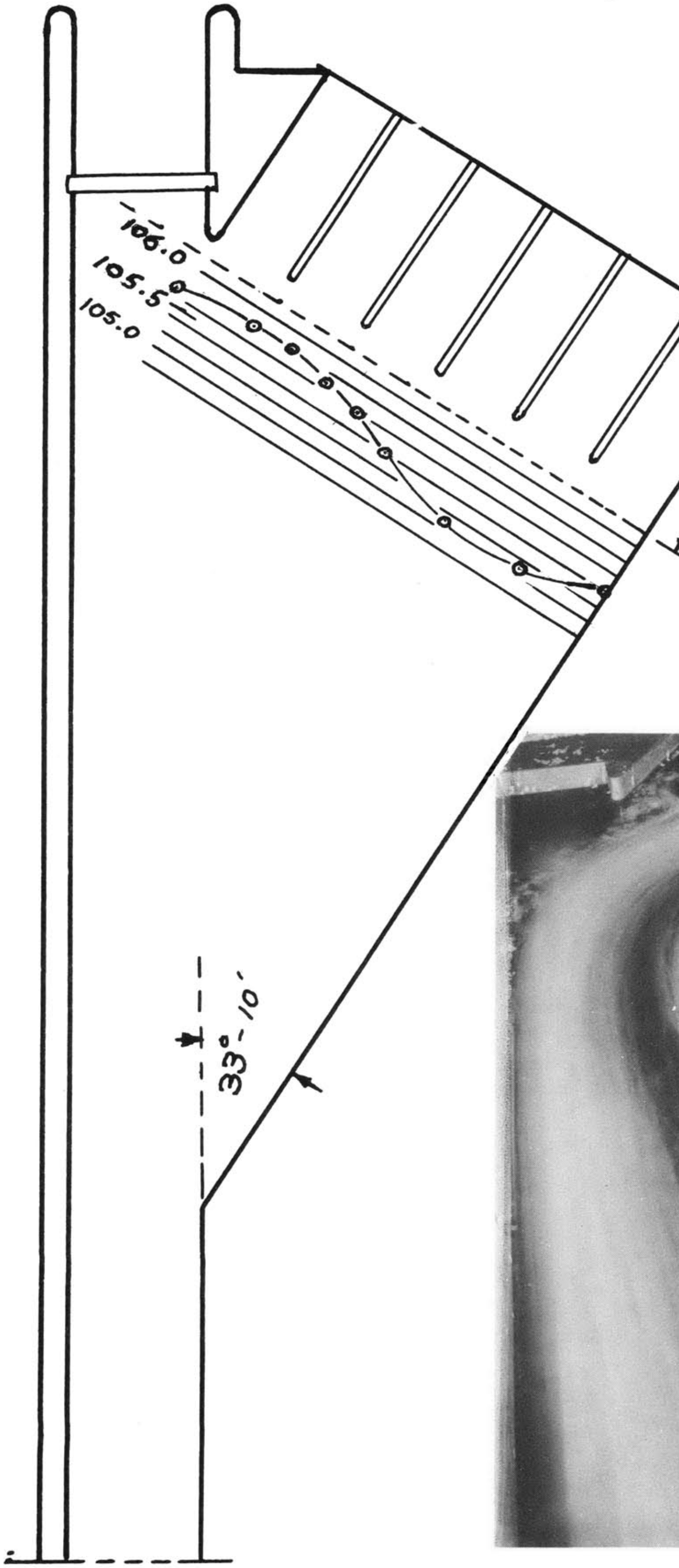
Figure II :

Plan Drawings of Forebay Variations F, G1, G2, G3, G4, G5 and H2

Dimensions in Prototype Feet

(1) = Northeast Corner M.T.A. Pier No. 3

Fig. 13: Variation A; Water Surface Profile 75 ft. Upstream of the Intake Support Wall. Charles River Basin El. 106.5 Each Intake Withdrawing 1400 cfs.



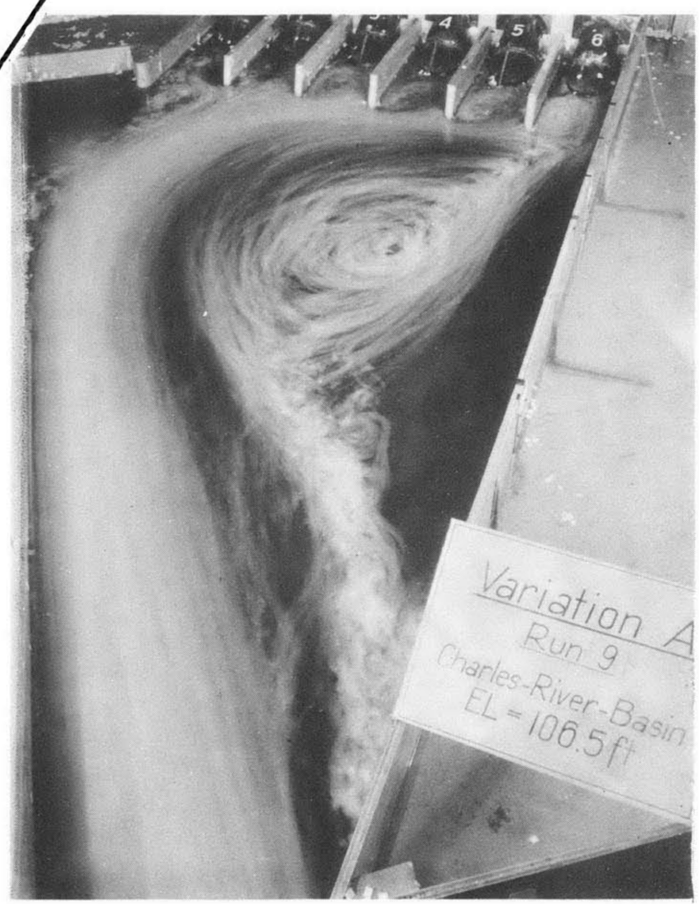
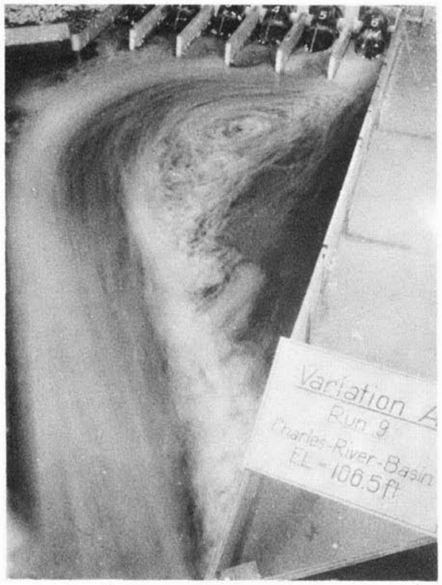
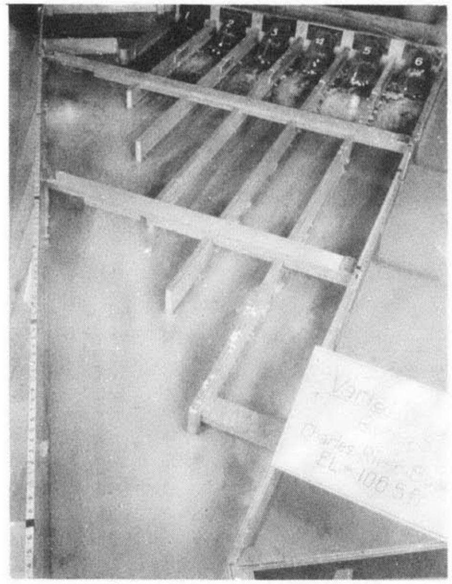


Fig. 12: Forebay Flow Pattern, Variation A. Each Intake Withdrawing 1400 cfs.

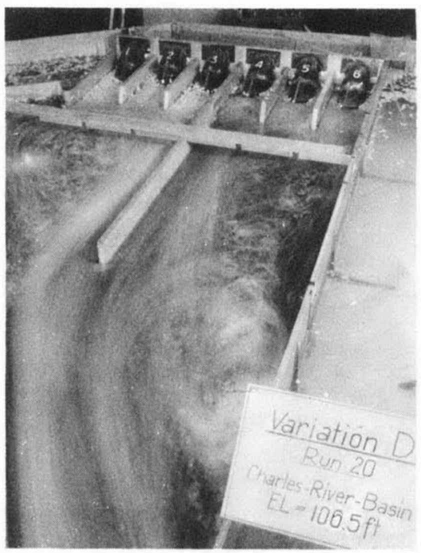


Variation A

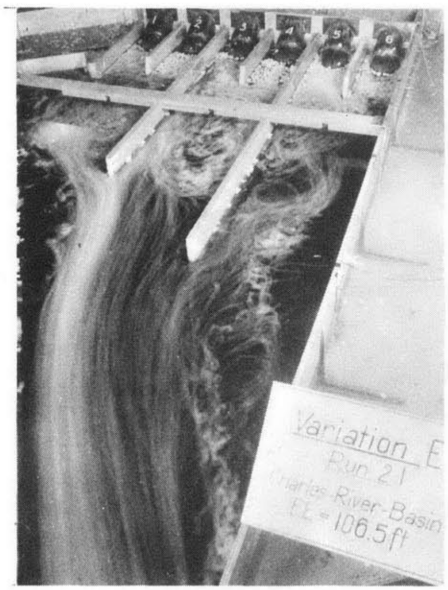


Variation B

Variation C



Variation D



Variation E

Figure 14.

Flow Patterns in the Forebay, Intakes in the Maximum Downstream Position, Each Intake Withdrawing 1400 cfs.

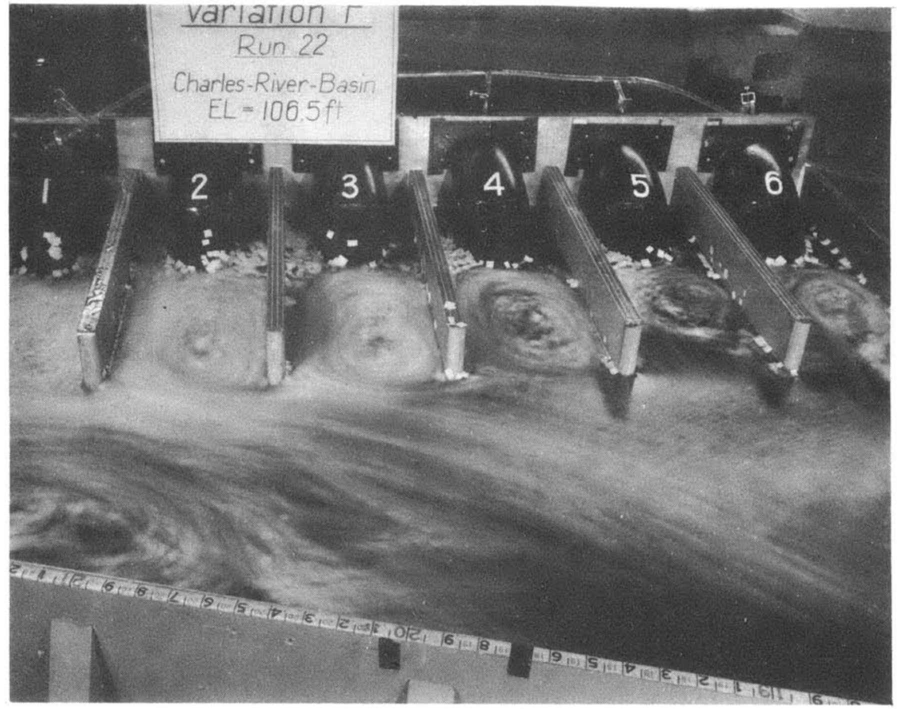


Figure 15: Flow Patterns in the Forebay, Variation F, Each Intake Withdrawing 1400 cfs.

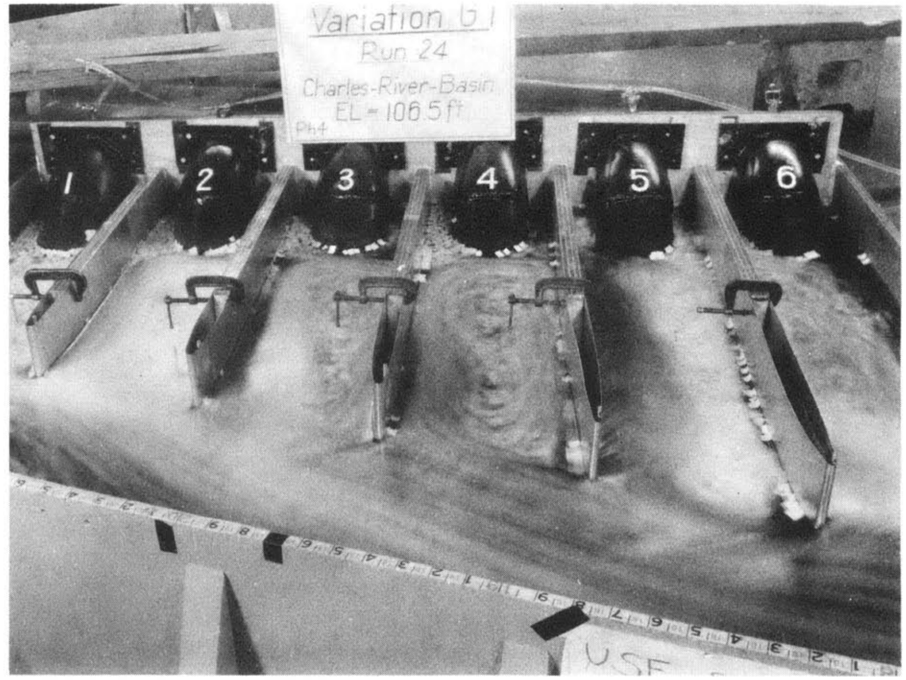
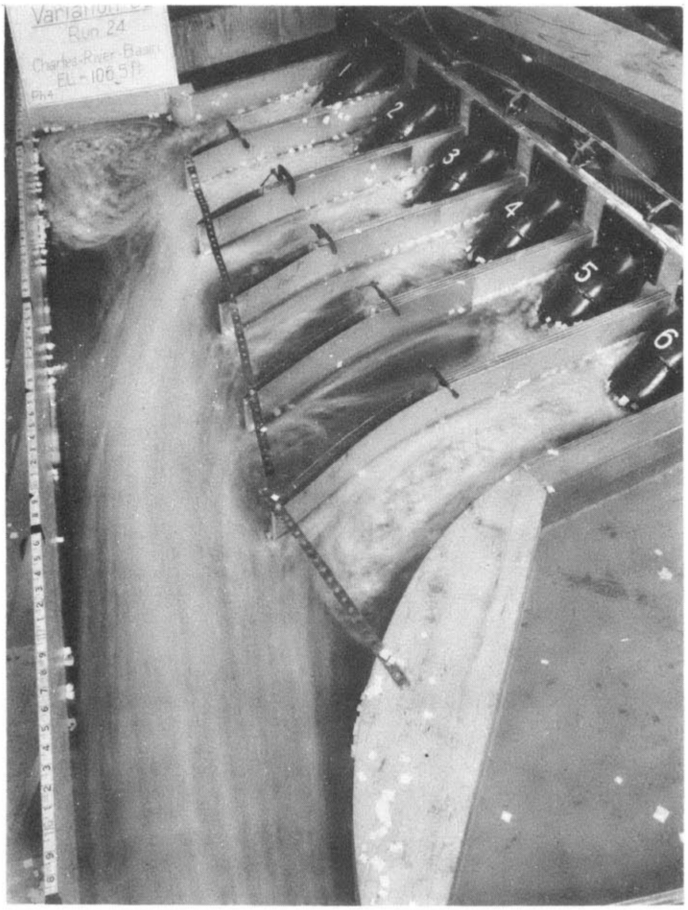


Figure 16: Flow Patterns in the Forebay, Variation GI, Each Intake Withdrawing 1400 cfs.



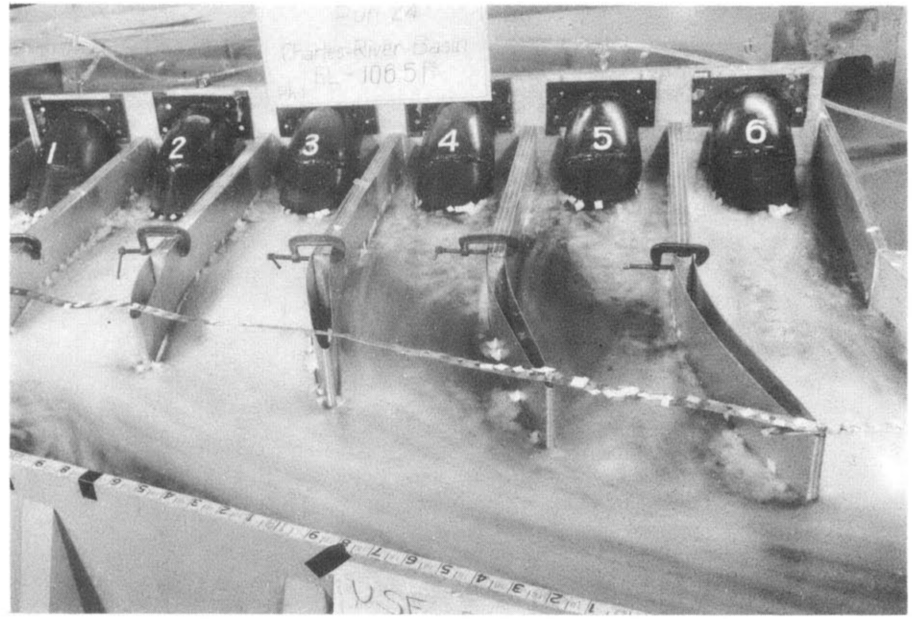
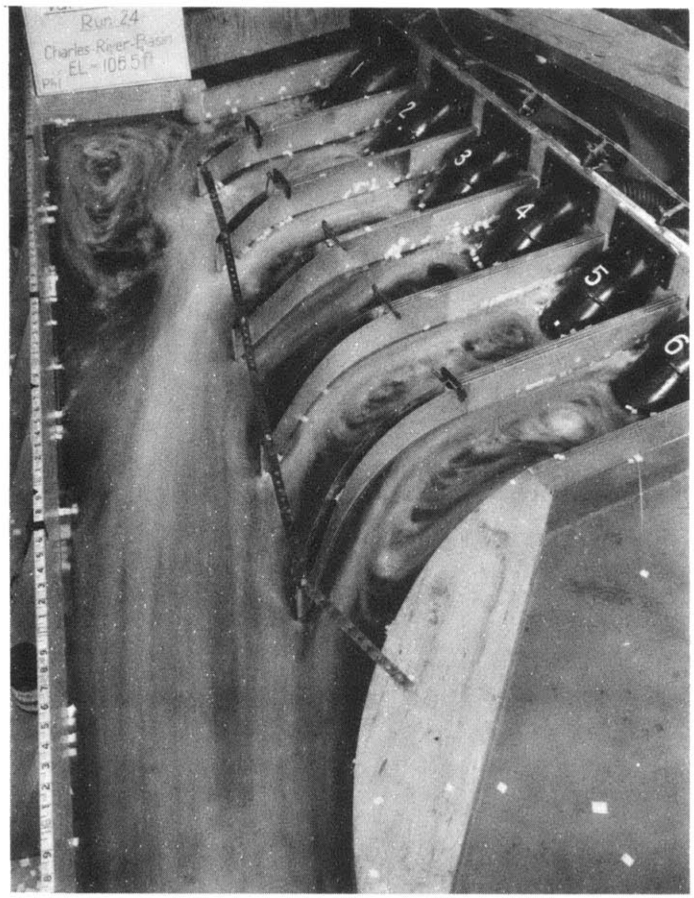


Figure 17: Flow Patterns in the Forebay, Variation G2, Each Intake Withdrawing 1400 cfs.



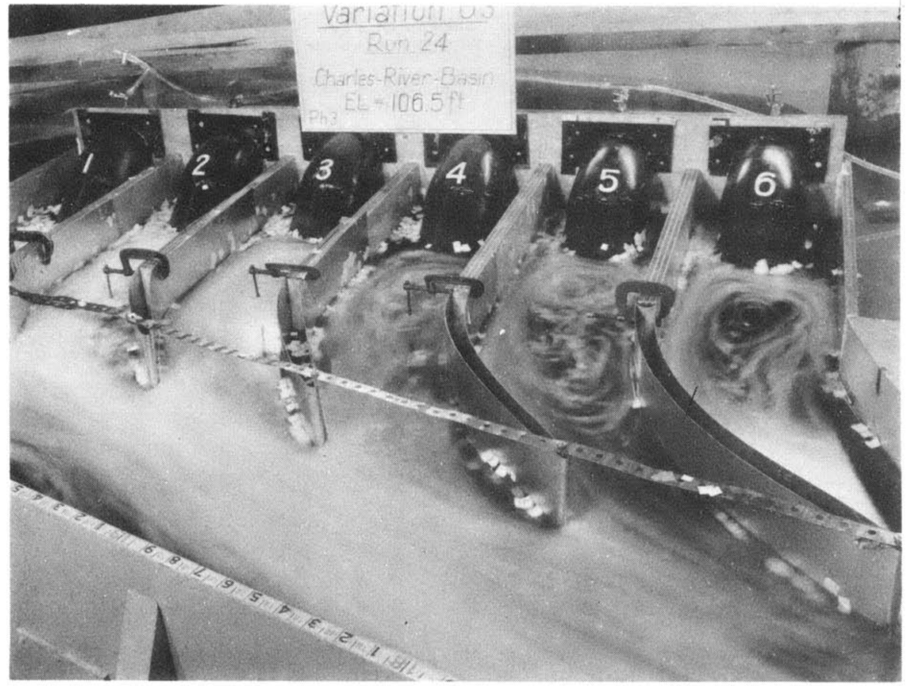
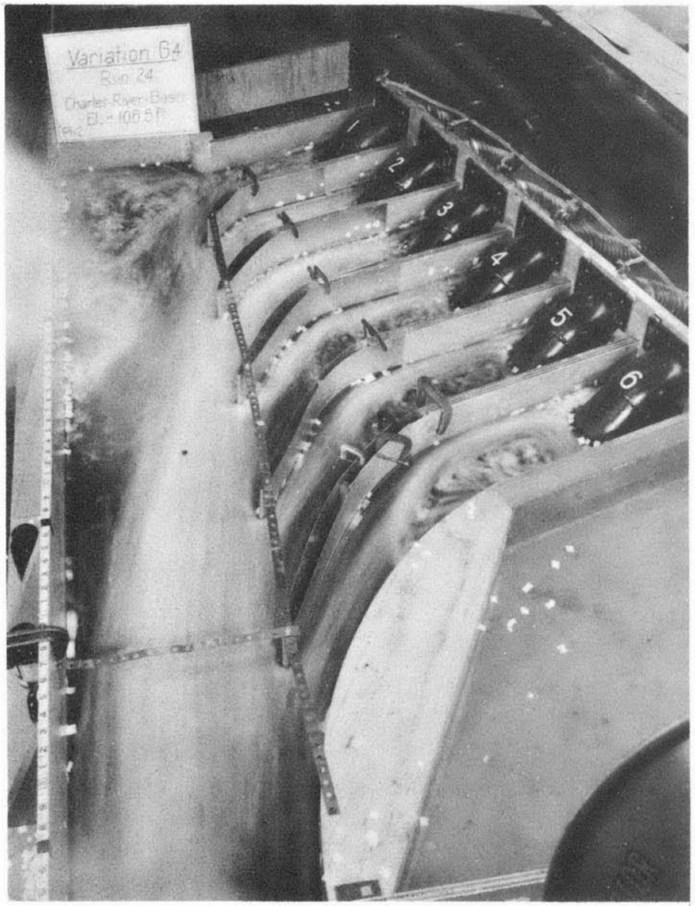


Figure 18: Flow Patterns in the Forebay, Variation G3, Each Intake Withdrawing 1400 cfs.



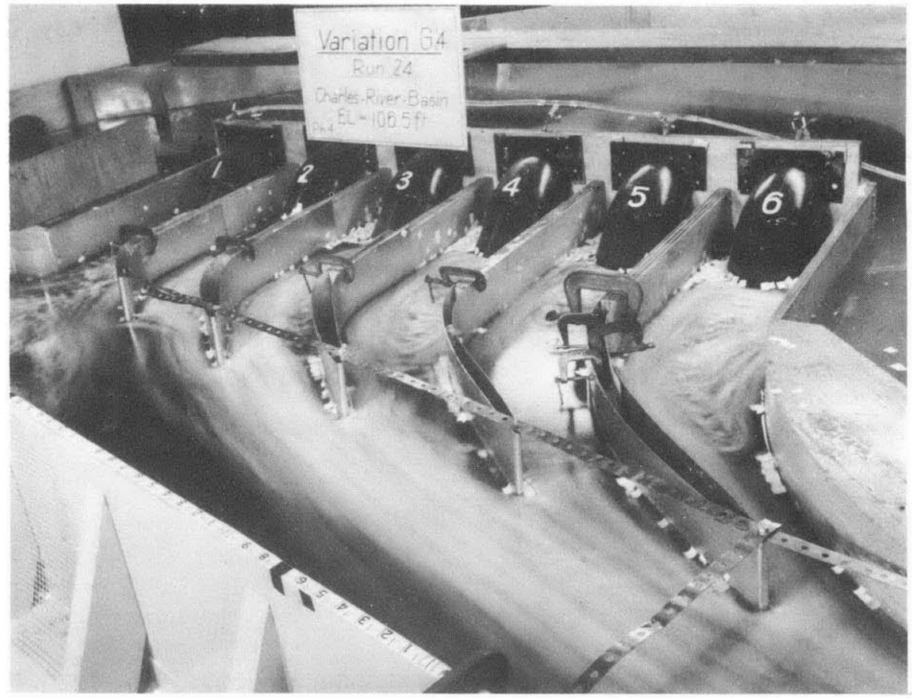


Figure 19: **Flow Patterns in the Forebay, Variation G4, Each Intake Withdrawing 1400 cfs.**

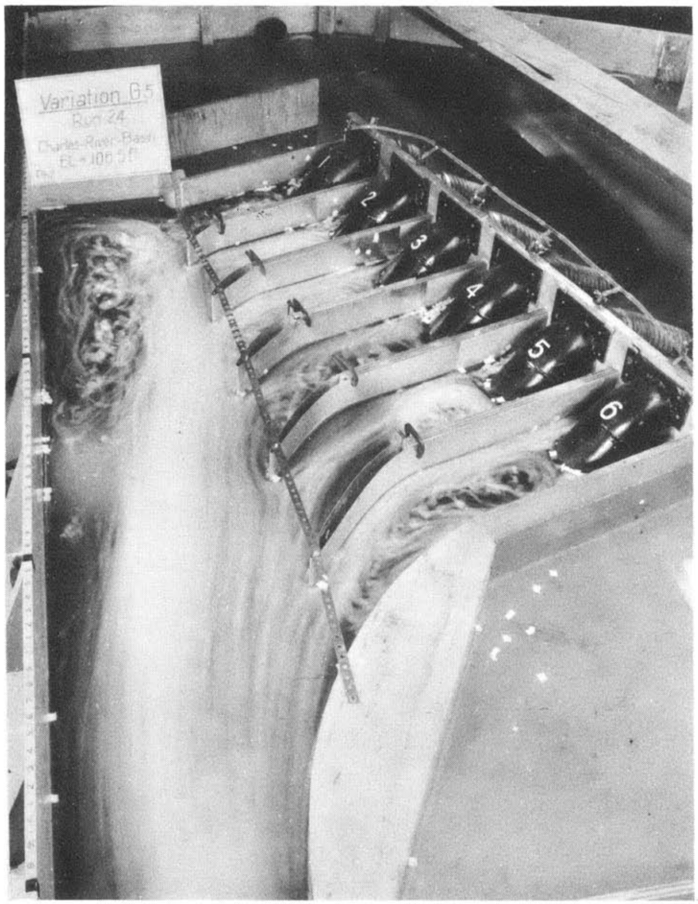


Figure 20: Flow Patterns in the Forebay, Variation G5, Each Intake Withdrawing 1400 cfs.

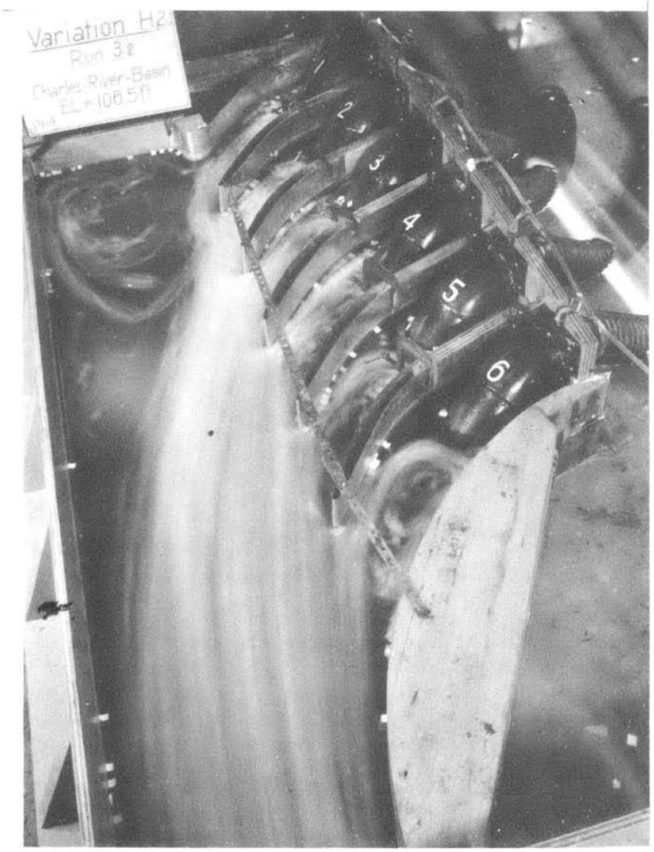
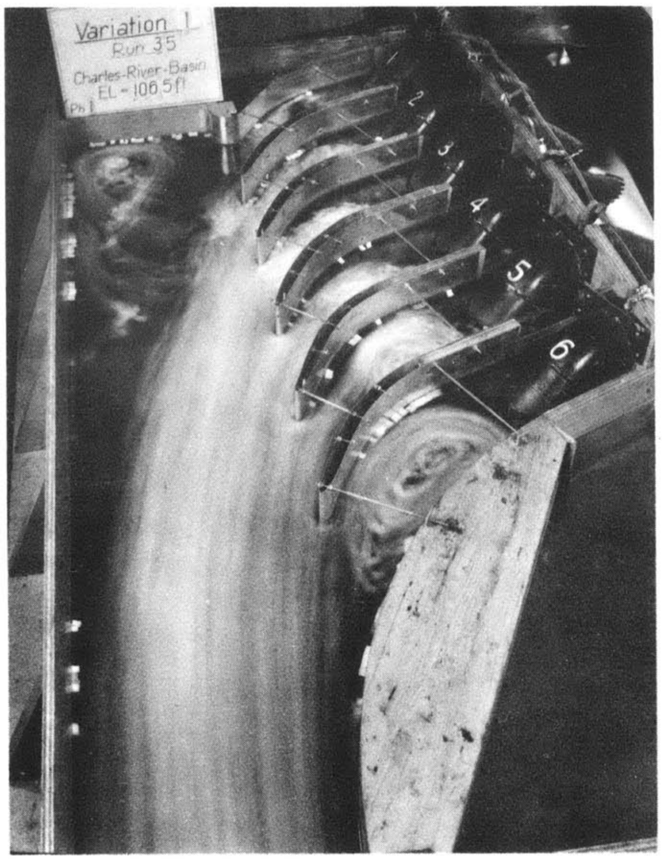


Figure 21: Flow Patterns in the Forebay, Variation H2, Each Intake Withdrawing 1400 cfs.



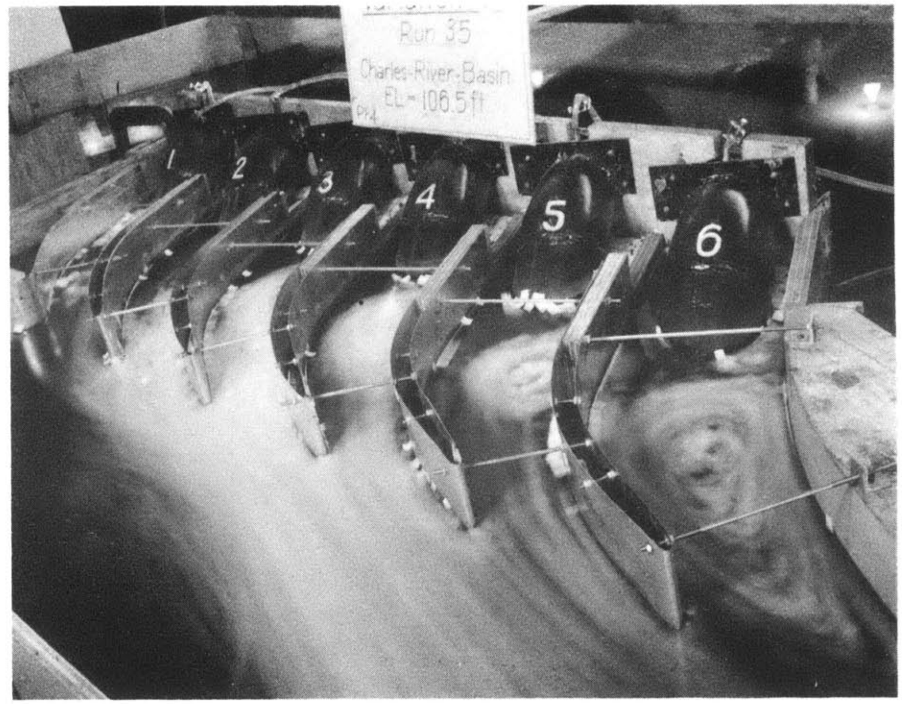
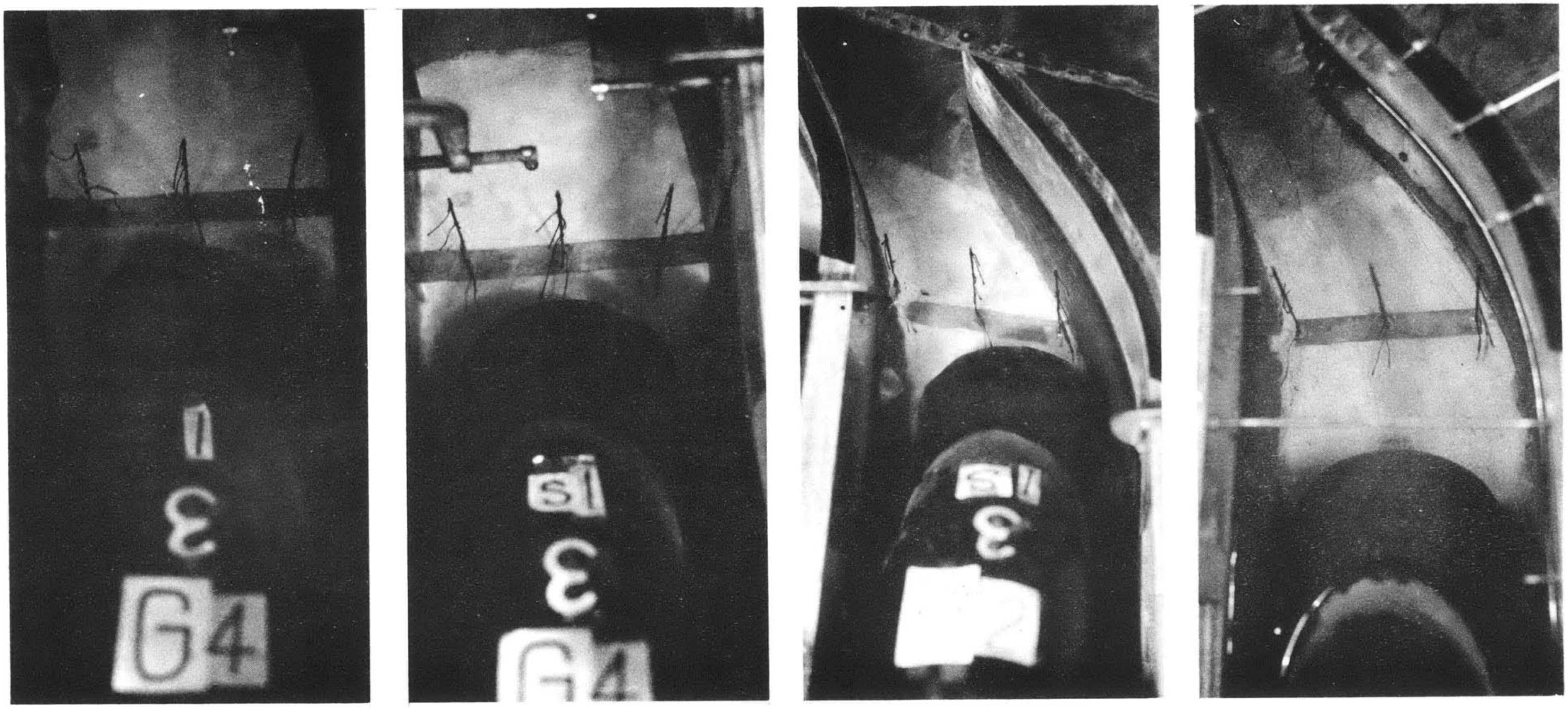


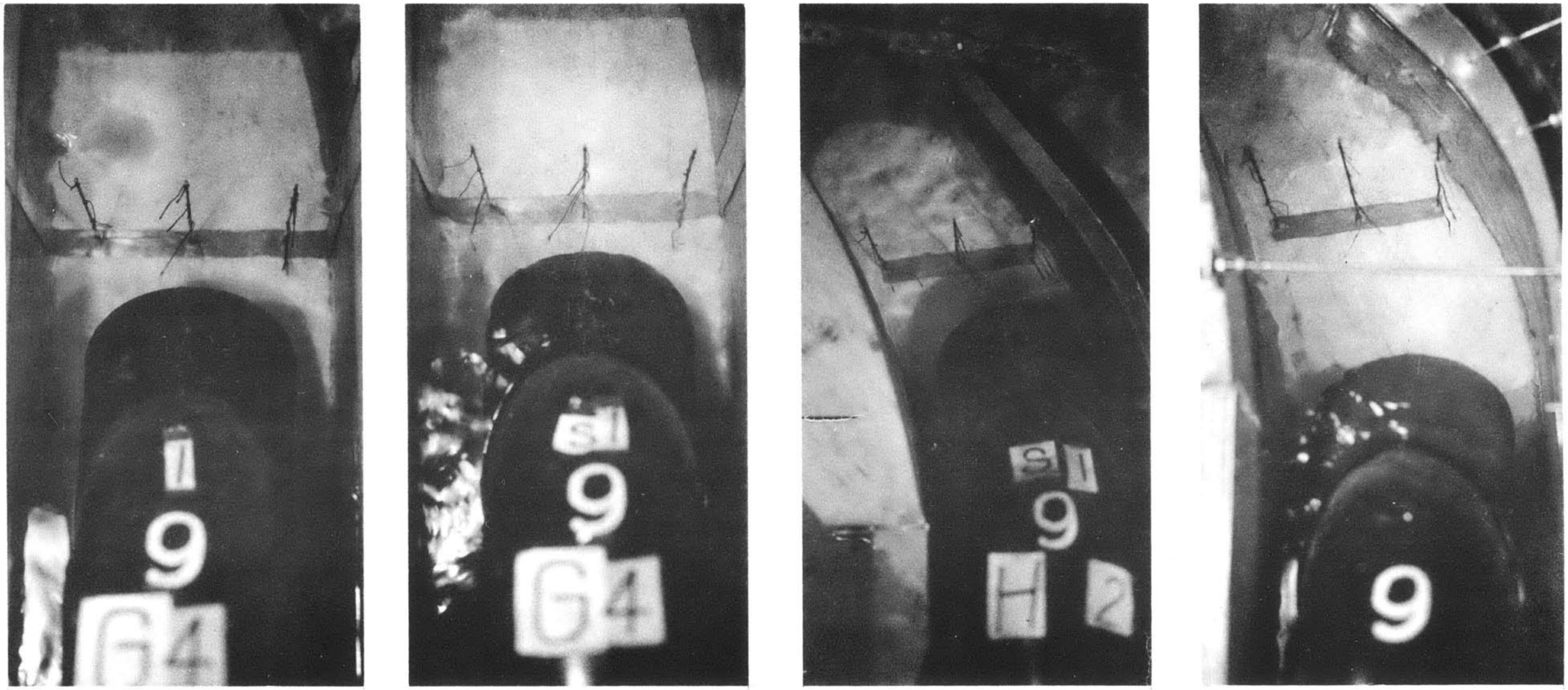
Figure 22 Flow Patterns in the Forebay, Variation I, Each Intake Withdrawing 1400 cfs.



Variation G4 without struts | Variation G4 with struts | Variation H2 | Variation I

Figure 23 Intake Chamber 3 Flow Directions Indicated by Streamers Placed 3, 9, 15 and 21 ft. above the Chamber Bottom.

Each Intake Discharging 1400 cfs. Charles River Basin Elevation 106.5 ft.



Variation G4 without struts

Variation G4 with struts

Variation H2

Variation I

Figure 24 Intake Chamber 6, Flow Directions Indicated by Streamers Placed at 3, 9, 15 and 21 ft. above the Chamber Bottom.

Each Intake Discharging 1400 cfs. Charles River Basin Elevation 106.5 ft.

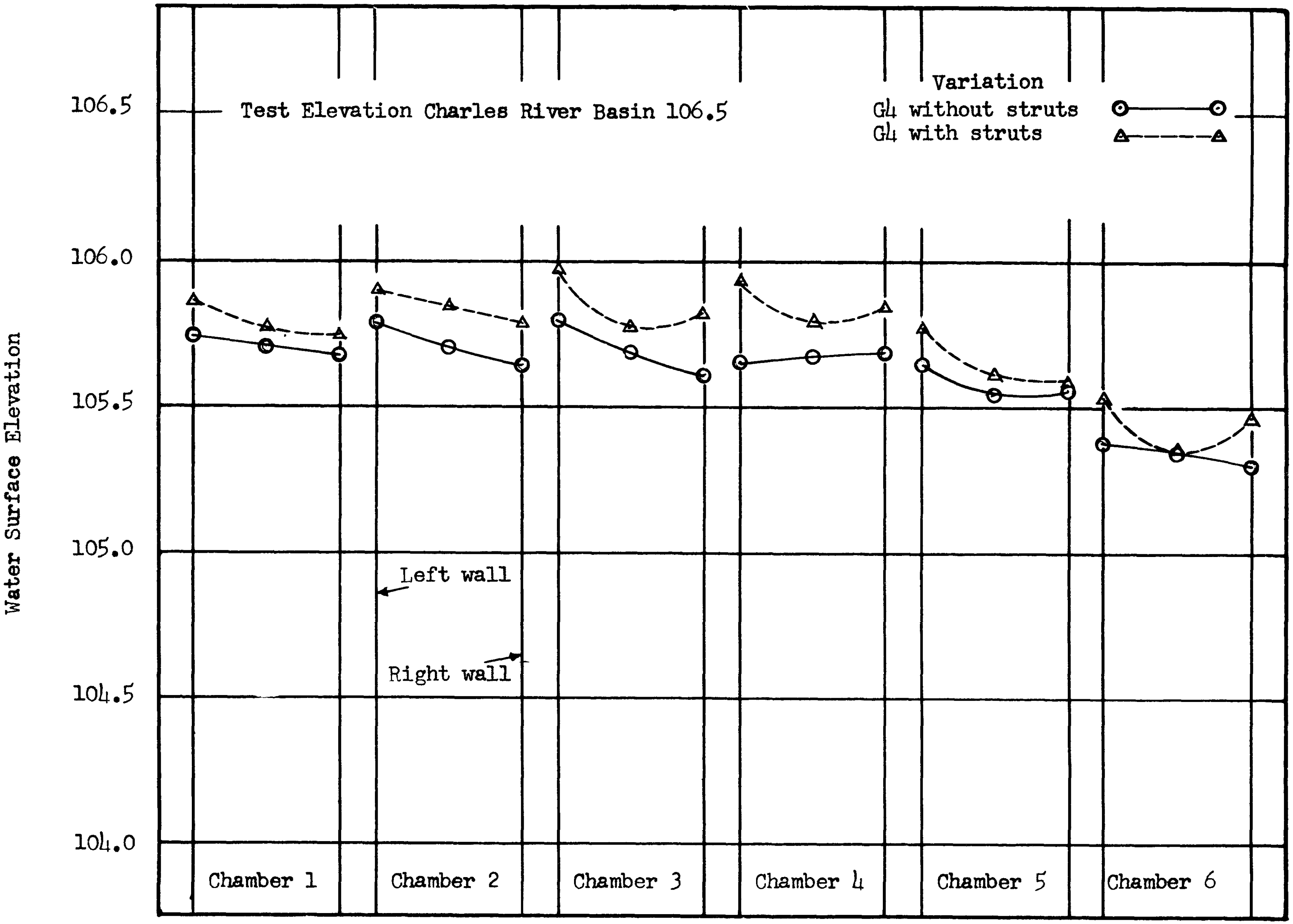


Figure 25. Water Surface Profiles 9 ft. Upstream of the Intake Lip.
Each Intake Withdrawing 1400 cfs.

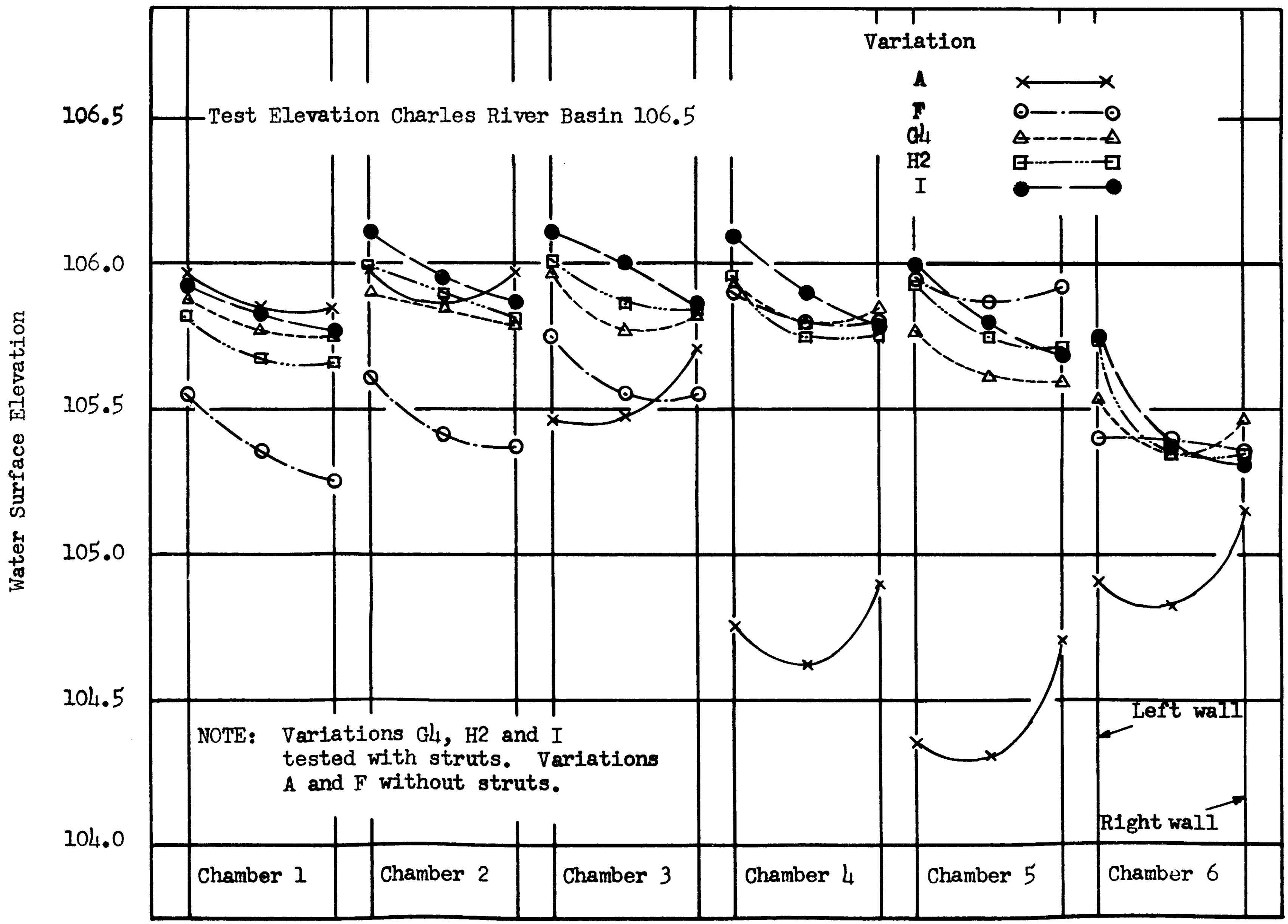


Figure 26. Water Surface Profiles 9 ft. Upstream of the Intake Lip. Each Intake Withdrawing 1400 cfs.

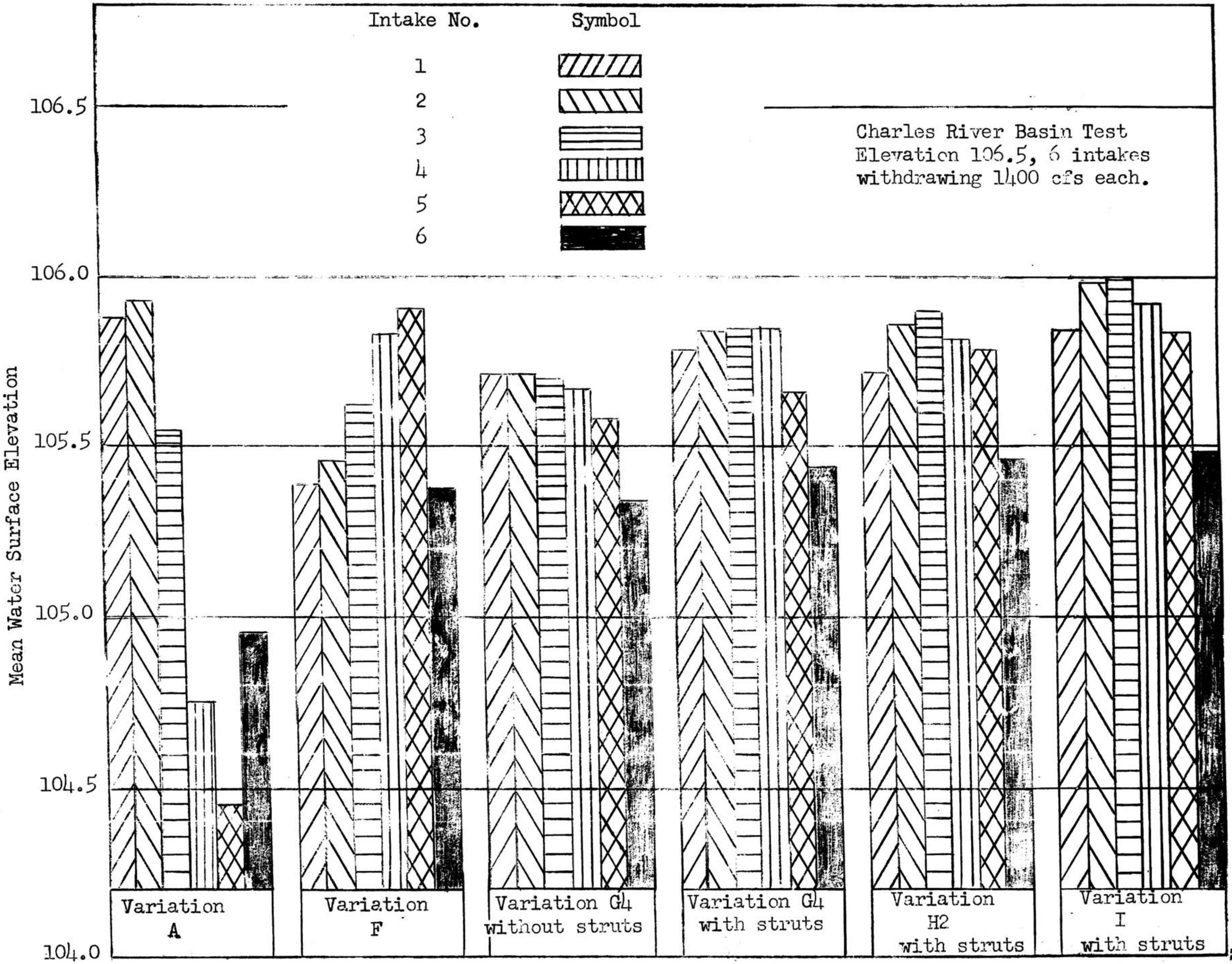


Fig. 27 Mean Chamber Water Surface Elevations 9 ft. Upstream from intake lip

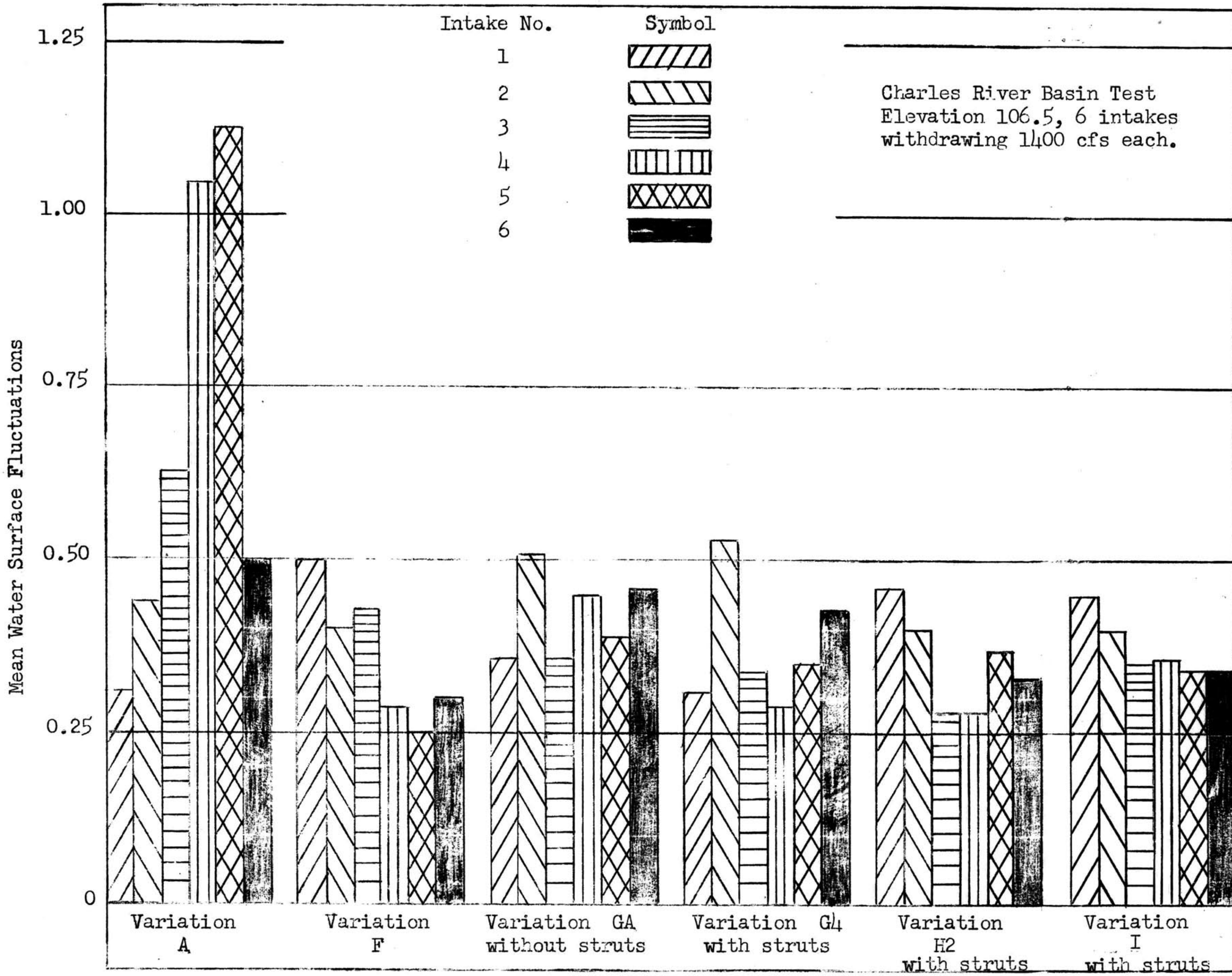


Fig. 28 Mean Water Surface Fluctuations in the Chambers 9 ft. Upstream of the Intake Lip

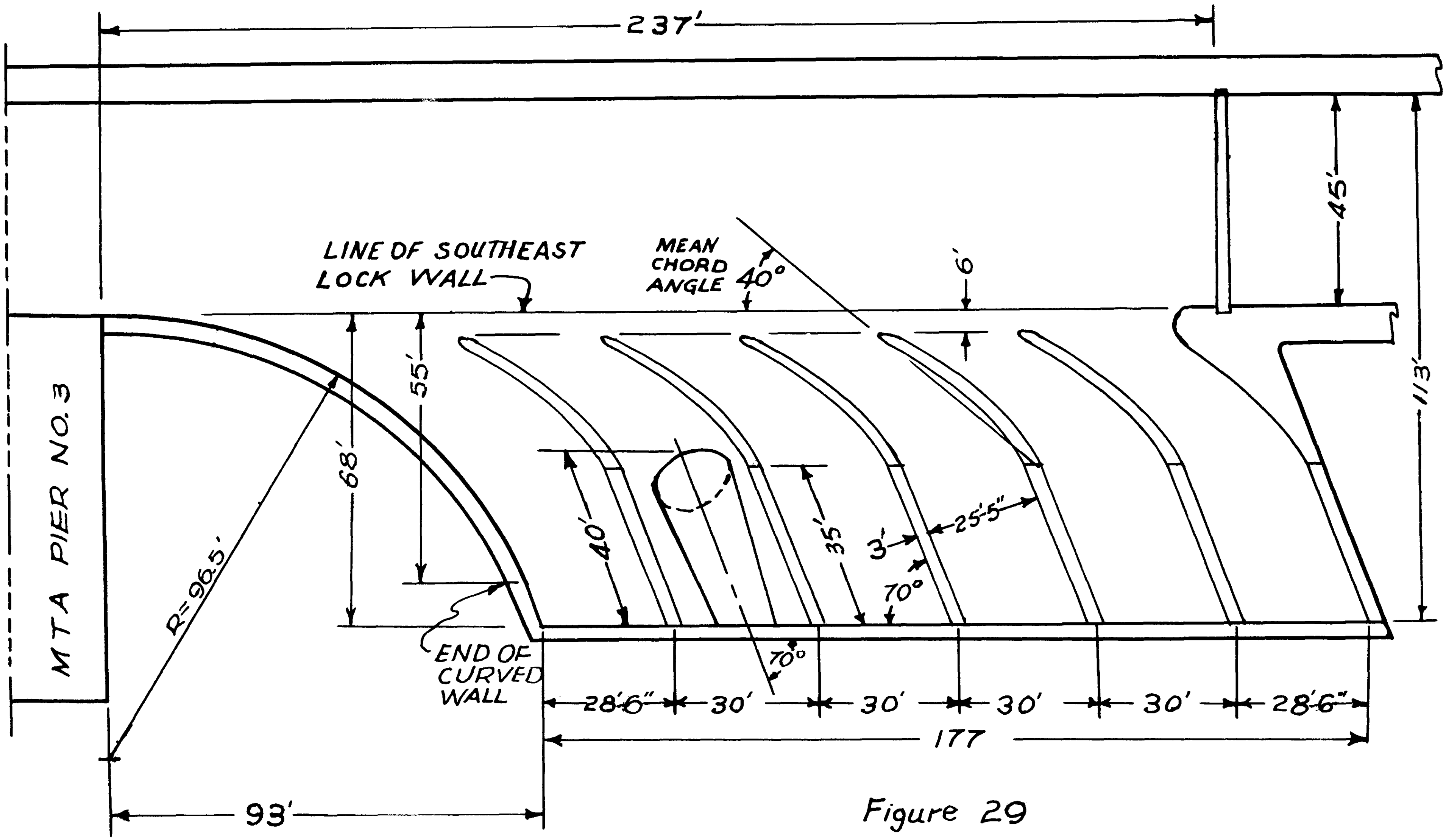


Figure 29

PLAN DRAWING OF
FOREBAY VARIATION H2

Dimensions in Prototype Units

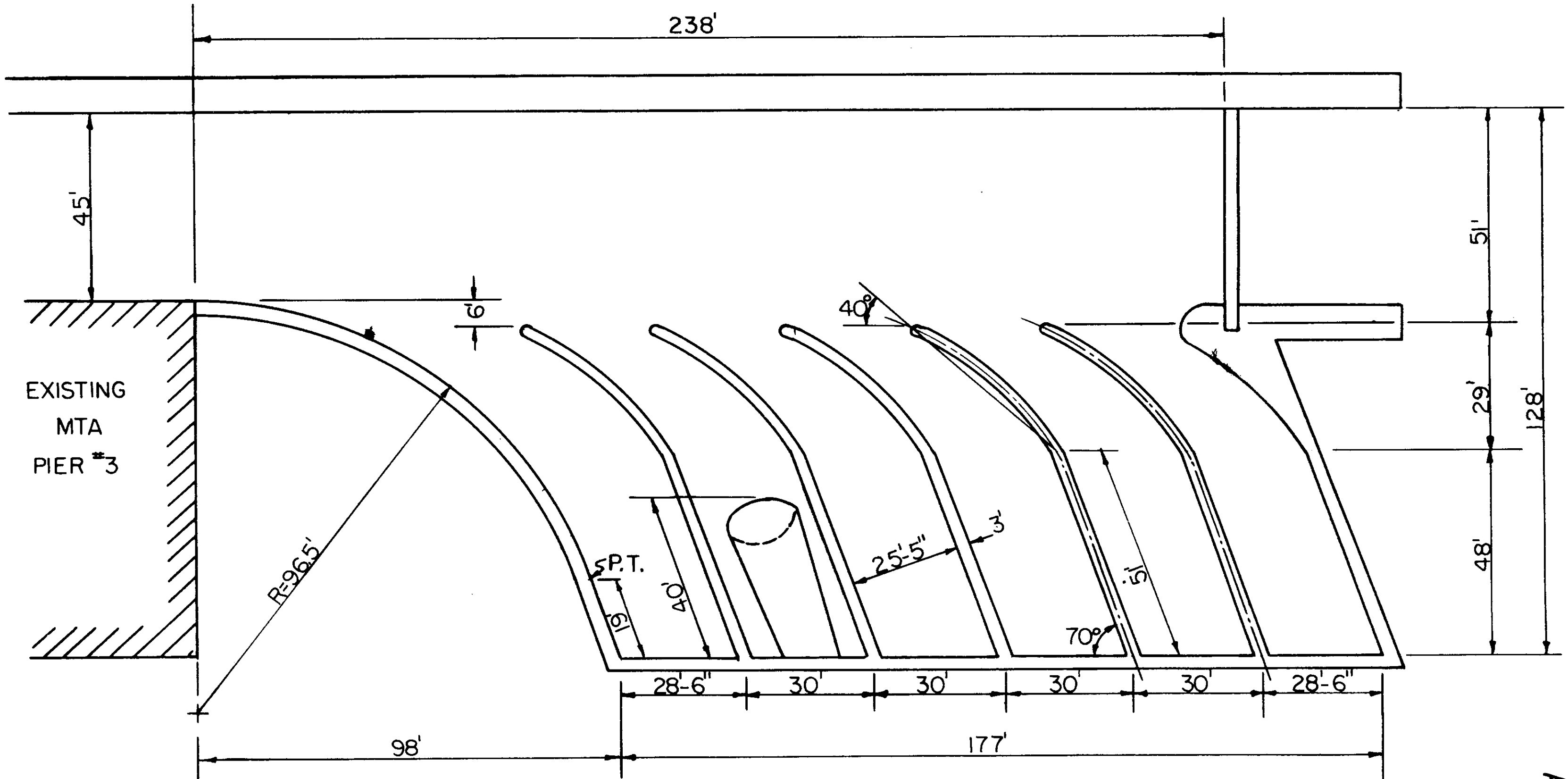
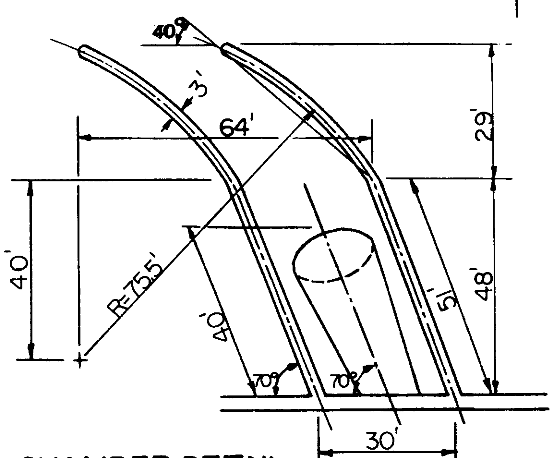


FIG. 30 PLAN DRAWING
OF FOREBAY
VARIATION I

DIMENSIONS IN PROTOTYPE UNITS



CHAMBER DETAIL

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Hydrodynamics Laboratory
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2	J.W. Daily, K.C. Deemer, A.L. Keller	The Unsteady Flow Water Tunnel at the Massachusetts Institute of Technology	Office of Naval Research	May, 1951
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5	A.T. Gifford, R.E. Nece, R.E. DuBois	Water Tests of Eight-Inch Check and Stop Valves	U.S. Atomic Energy Commission	Aug., 1953
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14	A.T. Ippen, C.E. Carver, Jr.	Oxygen Absorption and Turbulence Characteristics in Bubble Aeration	U.S. Public Health Service	Apr., 1955
15	A.T. Ippen, G. Kulin	Shoaling and Breaking of the Solitary Wave	Office of Naval Research	Apr., 1955
16	A.T. Ippen, G. Kulin, Mir A. Raza	Damping Characteristics of the Solitary Wave	Office of Naval Research	Apr., 1955
17	D.R. Harleman, R.S. Gooch, A.A. Vulgaropulos	Hydraulic Model Performance of Spillway and Outlet Works of Peligre Dam	Brown and Root, Inc.	Apr., 1955
18	A.T. Ippen, P.S. Eagleson	A Study of Sediment Sorting by Waves Shoaling on a Plane Beach	Beach Erosion Board	May, 1955
19	D.R. Harleman, W.C. Shapiro	Experimental and Analytical Studies of Wave Forces on Basic Components of Offshore Structures, Part I: Results for Vertical Cylinders	Humble Oil Company	May, 1955
20	A.T. Ippen, R.S. Tankin, F. Raichlen	Turbulence Measurements in Free Surface Flow with an Impact Tube-Pressure Transducer Combination	Office of Naval Research and the David Taylor Model Basin	July, 1955
21	J.W. Daily, V.E. Johnson	Turbulence and Boundary Layer Effects on the Inception of Cavitation from Gas Nuclei	Office of Naval Research	July, 1955
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26	P.S. Eagleson, R.G. Dean, L.A. Peralta	The Mechanics of the Motion of Discrete Spherical Bottom Sediment Particles Due to Shoaling Waves	Beach Erosion Board	Oct., 1957
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30	J.W. Daily, G. Bugliarello	The Effects of Fibers on Velocity Distribution, Turbulence and Flow Resistance of Dilute Suspensions	Technical Association of the Pulp and Paper Industry	Oct., 1958
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32	P.S. Eagleson	The Damping of Oscillatory Waves by Laminar Boundary Layers	Beach Erosion Board, U.S.Dept. of the Army, Corps of Engrs.	Apr., 1959
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34	J.W. Daily, J.D. Lin, R.S. Broughton	The Distribution of Mean Static Pressure in Turbulent Boundary Layers in Relation to Inception of Cavitation	Office of Naval Research	June, 1959
35	J.W. Daily, G. Bugliarello, W.W. Troutman	Measurement and Analysis of Turbulent Flow of Wood Pulp Fiber Suspensions	Tech.Assoc.of the Pulp and Paper Industry	Sept., 1959

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3	A.T. Ippen	The Influence of Viscosity on Centrifugal Pump Performance	Trans. A.S.M.E.	Nov., 1946
4	J.W. Daily	Cavitation Characteristics and Infinite Aspect Ratio Characteristics of Hydrofoil Section	Trans. A.S.M.E.	Apr., 1949
5	A.T. Ippen	Mechanics of Supercritical Flow, Symposium on High-Velocity Flow in Open Channels	Trans. A.S.C.E., Vol. 116	1951
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11	H.M. Paynter	Methods and Results from M.I.T. Studies in Unsteady Flow	Jr.,Bos.Soc.of Civil Engrs.	Apr., 1952
12	J.W. Daily, S.C. Stephan	Characteristics of the Solitary Wave	Trans. A.S.C.E., Vol. 118	1953
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31	A.T. Ippen, P.S. Eagleson	A Study of Sediment Sorting by Waves Shoaling on a Plane Beach	Beach Erosion Board Tech. Memorandum No. 63	Sept., 1955

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41	A.T. Ippen, J.W. Daily, G. Bugliarello	Pertinent Factors in Flow Research on Dilute Fiber Suspensions	TAPPI Mag. Vol.40, No.6	June, 1957
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3	G.H. Toebes, F.E. Perkins, P.S. Eagleson	Design of a Closed Jet, Open Circuit Water Tunnel for the Study of Wake Mechanics	David Taylor Model Basin	Apr., 1958
4	J.W. Daily, A. Tsuchiya	Flow of Nylon Fiber Suspensions. A Progress Report on a Phase of Work under TAPPI Project 147	Tech.Assoc.of the Pulp and Paper Industry	Feb., 1959
5	F.E. Perkins, P.S. Eagleson	The Development of a Total Head Tube for High Frequency Pressure Fluctuations in Water	David Taylor Model Basin	July, 1959
6	R.E. Nece, C.A. Givler	Measurement of Boundary Shear Stresses in an Open Channel Curve with a Surface Pitot Tube	ARS, U.S. Dept.of Agriculture	Aug., 1959

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