University of Minnesota
ST. ANTHONY FALLS HYDRAULIC LABORATORY

Project Report No. 148

HYDRAULIC MODEL TESTS FOR MAYFIELD POWER PLANT

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Conducted for

Department of Public Utilities
CITY OF TACOMA, WASHINGTON

and

HARZA ENGINEERING COMPANY
Chicago, Illinois

April 1974
Minneapolis, Minnesota

CONTENTS

HYDRAULIC MODEL TESTS FOR MAYFIELD POWER PLANT

I. INTRODUCTION

This report describes the results of the hydraulic model tests for the forebay structure of the Mayfield hydroelectric power plant conducted at the St. Anthony Falls Hydraulic Laboratory during the period May 1973 through March 1974.

There are three existing power generating units, each of which is fed by an 18-ft-diameter penstock. Provisions have been made for an additional unit to be installed in the near future. Water is taken from Mayfield Lake, conveyed through a 37-ft-diameter tunnel, and discharged into a forebay. There are four intake structures, one for each penstock, at the downstream end of the forebay. Presently, the operation is hampered at high loading conditions. It is generally believed that unstable hydraulic conditions in the forebay are the cause of the present poor operating conditions. Strong vortices at the intakes have been observed in the field. The flow in the forebay is rough and turbulent. There are large shock waves at the pier noses, causing the water surface to fluctuate and become higher at units 42 and 43 and lower at unit 44.

It is planned to add the fourth unit in the immediate future. Because an additional unit would mean an increased flow requirement, it is probable that the problems stated above would worsen. For this reason, a model study has been conducted to assess the problems for the expanded operation and find means of alleviating them.

A 1:36 scale model was constructed and tested. After calibration, the model satisfactorily reproduced the existing flow conditions. The model indicated an increase in flow distortion and in water surface instability for the planned expansion. Air-entraining vortices were observed for all flows tested without modification of the existing facilities. On the basis of the experiments with various alternatives, the following schemes are recommended to provide good flow conditions: (a) two 18-ft-wide submerged guide vanes to be installed near the tunnel portal to redistribute the flow and improve the water surface profile and (b) a V-shaped vortex suppressor to be installed at each intake bay to eliminate the air-entraining vortices.

A documentary motion picture showing the highlights of the model tests has been made as part of this test program.

II. THE MODEL AND CALIBRATION

The overall layout of the Mayfield power plant hydraulic system is shown in Fig. 1. The shaded area is the area included in the model. An overall view of the completed model is shown in Fig. 2. Since the major concern is with the flow characteristics in the forebay, particularly the air-entraining vortices and the water surface stability near the water intake structure, the forebay is the central feature. In addition to the forebay, the model includes the curved portion and 300 ft of the straight portion of the tunnel supplying the forebay. This is to allow a reasonable simulation of the flow regime entering the forebay. The upstream end of the tunnel is attached to a head tank with a smooth transition to avoid excessive flow separation. A screen has been installed in the head tank to dampen excessive turbulence. River water is supplied to the head tank through a 12-inch pipe by gravity. The flow rate is controlled by a valve and measured by an orifice meter attached to the supply pipe. Four penstocks immediately downstream of the forebay are modeled up to, but not including the spiral case distributor. A 6-inch discharge pipe fitted with a valve and an orifice meter is connected to the end of each penstock. Thus the rate of flow, but not the detailed flow pattern, through the turbine was simulated.

Lucite material was used extensively for the model to facilitate visual observations and photography. Exceptions are the lower half of the horseshoe-shaped tunnel, which is of molded concrete, and the bottom portion of the transition at the penstock intake, which is made of sheet metal.

The total discharge was controlled by the valve on the 12-inch supply pipe. The flow rate through individual penstocks and the water surface level in the forebay were controlled by the valves located at the downstream end of each penstock.

The hydraulic performance of the model was compared with field data obtained for the three existing units by comparing data on velocity distributions and water surface levels. Figure 3 shows the locations at which data from the prototype were available and comparison with the model possible. Data were taken and compared for cases in which the nominal water surface elevation measured at the portal was equal to 414.0, 416.0, 418.0, and 423.0. In all cases except at El. 414.0, the flow rate was 3500 cfs through each of the three existing units. With El. 414.0 the discharges were reduced because of rough operating conditions in the field. The field data were taken by Harza Engineering Company and made available to the Laboratory. Figure 4 is a typical comparison of the velocity distributions at a section near the tunnel portal. All the velocity data, model and prototype, are listed in Table 1. Agreement between model and prototype is good except at point 4. The model generally overpredicts the velocity near the water surface at point 4. The reason for this discrepancy has not been determined, although it is suggested that the flow separation at the prototype tunnel portal may be responsible. The expansion angle of the walls at the forebay is too large for a complete expansion to take place, and this causes flow separations, as is evidenced by the reverse current shown in Fig. 5. Since flow separation is a boundary layer phenomenon, it cannot be modeled correctly in a Froude model. The curved tunnel causes non-uniform flow distribution, which also complicates the problem.

To achieve better flow agreement with the prototype, a 1/4-in. mesh screen was placed at the tunnel portal to retard the flow at point 4. Figure 6 shows a comparison of the prototype data and model measurements at the portal after the screen was installed. A typical comparison of velocity profiles measured near the penstock intakes is shown in Fig. 7. Various velocity data with the screen in place are shown in Table 1. It is generally agreed that the model with a screen at the portal satisfactorily simulates the existing prototype condition.

Low and high water surface elevations measured with the portal screen in place are summarized in Table 2. A fine mesh screen was also installed in each model intake to simulate the prototype trashracks. The use of the portal screen provided satisfactory agreement between model and prototype. The difference was well within experimental accuracy. Water surface elevations measured at the penstock intakes are generally higher than those measured near the tunnel portal (model and prototype). This is due to partial conversion of kinetic energy to potential energy as the flow decelerates. Average water surface rises indicated by the model are compared with the field data in Fig. 8.

III. THE QUALITY OF FLOW OBSERVED IN THE MODEL

The flow entering the forebay from the tunnel was observed to separate from the side walls at the portal for all cases tested, including the existing three-unit operating condition and the planned four-unit operation. As a result, eddies are generated next to the side walls and the inflow is concentrated near the centerline of the forebay like a jet, as illustrated in Fig. 5. This imperfect expansion of the jet causes uneven velocity distribution in the penstock intake area. Relatively concentrated flow near units 42 and 43 is evidenced by the existence of large shock waves at the pier noses. This also causes an uneven water surface profile at the intake. Under the existing conditions, the water surface elevation is generally lower at unit 44 than at units 42 and 43.

Figure 9 shows the measured maximum and minimum water surface elevations for four units operating at $Q = 3500$ cfs each with nominal portal water surface elevation 418.0. The average water surface is highest at unit 43 and lowest at unit 41. The amplitude of the water surface fluctuations is 1 to 2 ft measured from average surface levels. Figure 10 is a photograph taken at an arbitrarily selected instant showing the existence of uneven water surfaces at the four intakes. Spatial as well as time variations of the water surface at intakes are greater for shallower flow (low portal water surface elevation). Measured velocity distributions and water surface elevations are summarized in Tables 3 and 4, respectively.

Intermittent appearance of vortices was observed at each bay for all flow depths tested. Frequently, these vortices grew to such intensities that they entrained air and carried air bubbles into the penstocks. An air-entraining vortex is visible in the photograph of Fig. 11.

The model test definitely revealed two major flow problems associated with the existing configuration: uneven and fluctuating water surfaces and air-entraining vortices at the intakes. These conditions would limit plant operations at lower lake levels.

IV. RESULTS OF FLOW IMPROVEMENT STUDY

Various alternatives were considered and tested in order to find practical methods of alleviating the problems described in the previous section. Since the water surface irregularity at the intakes is caused by the flow separation at the portal, and this reduces the effectiveness of the forebay as a diffuser, it is necessary to redirect the flow near the portal using guide vanes. A number of alternative configurations were tested using 12- or 18-ft-wide plates as guide vanes. It was found that either a single 18-ft plate or two 12-ft plates would largely accomplish the objective of distributing the flow more evenly to the four intakes. After detailed comparison it was determined that a set of two 12-ft guide vanes located as shown in Fig. 12 performed most satisfactorily. These full-height vanes extend from the bottom to the top of the forebay (El. 444.0). The vane located near the centerline guides the flow toward unit 41, and the other vane guides some flow to unit 44.

The set of full-height guide vanes described above was very effective in reducing the shock waves at the pier noses and equalizing and stabilizing the water surface levels at the intakes. Water surface elevation data taken with the 12-ft guide vanes installed are included in Table 4 for comparison with the data taken without guide vanes. Considerable improvement in the water surface profile should be noted. The elimination of flow separation near the tunnel portal and the improvement of the flow near the penstock intake structure were achieved at the expense of flow quality near the guide vanes, however. Large shock waves were merely shifted from the pier noses to the guide vanes. It appears that shock waves at the guide vanes would exert large vibratory and steady state forces on the structure. Although no attempt was made to measure the forces, a rough computation indicates a possible structural problem.

As a compromise between structural and flow considerations, a set of two 18-ft-wide submerged guide vanes as indicated in Fig. 13 was chosen as the final design configuration (top El. 410.0±). This configuration resulted in shock-free flow near the guide vanes without materially worsening the flow near the intakes. There were weak flow separations at the water surface near the tunnel portal, because the guide vanes did not extend to the water surface. Fortunately, these separation eddies are limited to a shallow zone near the water surface, and there was no flow separation deeper under the free surface. Figure 14 is a photograph showing eddies on the water surface made visible by the motions of confetti. The air-entraining vortices clearly visible near the intakes could not be eliminated by means of the guide vanes. A typical set of water surface data at the intakes taken with the submerged guide vanes in place is shown in Fig. 15. Considerable improvement is noted when this figure is compared with Fig. 9. Additional water surface data with submerged guide vanes are also included in Table 4 for comparison.

Average water surface rises from the tunnel portal to the penstock intakes without guide vanes and with submerged guide vanes, as predicted by the model, are shown in Fig. 16. Without guide vanes, the water surface rises considerably at intakes 42 and 43, but actually drops at intake 41. With the submerged guide vanes the water surface rises modestly at all intakes except when the lake level is above El. 423.0. At this high lake level, the water surface at intakes 41 and 42 may drop by less than 0.5 ft.

The Harza Engineering Company believed that a horizontal bracing plate was needed to prevent guide vane vibrations. Experiments were conducted to determine the effect of the bracing plate on the flow. It was found that the plate must be located deep enough to prevent critical flow over the bracing plate. The dimensions indicated in Fig. 13 satisfy this requirement.

Various types of vortex suppressors were tested. A submerged horizontal plate was found to be effective provided that it spanned the entire width of the intake bay. This is not very practical, because the plate would interfere with the gate structure. To avoid this interference, a shorter horizontal plate supplemented by two vertical wings (shown on right in Fig. 17) must be used. An alternate device which will be very effective in eliminating vortices and will not interfere with the gate structure is the V-shaped vortex suppressor shown in Figs. 17 and 18. Figure 19 shows the improved water surface flow pattern near the intakes with the V-shaped vortex suppressors in place. Comparison of this photograph with Fig. 14 indicates the effectiveness of the vortex suppressor.

The V-shaped vortex suppressor was tested for various flow conditions, including water surface elevations ranging from 414.0 to 423.0 and discharges through each unit varying from 2800 cfs to 4200 cfs with all four units operating. The vortex suppressor was found to be effective for all the flow conditions tested. No air-entraining vortices were observed at any time.

The effectiveness of the submerged guide vanes and the V-shaped vortex suppressor was also verified for partial flow conditions. Various combinations of three-unit and two-unit operation were tested. In general, velocities were lower and the flow less turbulent than when four units were operating. Thus the combination of the proposed guide vanes and the vortex suppressors appeared satisfactory for all possible operating conditions. The results of the partial flow tests are summarized in Table 5.

V. CONCLUSIONS

A 1:36 scale model including tunnel, forebay, intakes, and penstocks was constructed and tested. The model satisfactorily simulated the hydraulic performance under the existing prototype conditions. The model also revealed two major problems associated with the existing configuration. The first problem is the existence of large shock waves at the pier noses and the uneven and fluctuating water surface at the intakes believed to be caused by the flow separation near the tunnel portal. The second problem is the existence of air-entraining vortices in the intake bays.

Two 12-ft-wide full-height guide vanes placed near the tunnel portal would redistribute the flow more uniformly and alleviate the irregularities in the flow near the intake structure. However, this would merely transfer the shock waves from the pier noses to the guide vanes, posing a structural problem for the guide vanes. Therefore, as a final design, two 18-ft-wide submerged guide vanes are recommended. The submerged guide vanes are almost as effective as the full-height guide vanes in regulating the flow near the intake structures and have the advantage of creating no shock-wave irregularities near the guide vanes. Shock waves would cause structural design difficulties.

A horizontal submerged plate spanning the entire width of an intake bay will prevent the formation of air-entraining vortices. If a gap at each end of the plate is necessary to avoid interference with the gate structure, vertical wingwalls must be added to the horizontal plate. Equally effective in suppressing the vortices is a V-shaped vertical suppressor. The adoption of this V-shaped vortex suppressor is recommended, because it appears to be the most economical of the alternatives considered.

LIST OF TABLES

TABLE 1. Comparison of velocity distributions, model with and without portal screen and prototype. Q = 3500 cfs for units 42, 43, 44; Q = 0 for unit 41.

		0.2 Depth			0.6 Depth			0.8 Depth		
Nominal Elev.	Point	Model w/out Screen	Model with Screen	Prototype	Model w/out Screen	Model with Screen	Prototype	Model w/out Screen	Model with Screen	Prototype
414	2	11.06	11.78	11.46	11.28	11.74	11.90	11.28	11.60	11.46
	3	9.82	10.62	10.82	11.34	11.48	11.46	11.94	11.50	11.25
	4	7.48	6.54	5.64	10.54	8.82	8.43	11.12	9.96	9.74
	6	6.36	6.54	4.92	7.78	6.88	6.39	8.36	6.94	7.44
	7	5.54	5.30	4.60	7.37	5.82	7.42	8.00	6.16	8.39
	8	4.84	5.40	3.25	7.20	5.90	5.26	9.22	6.64	7.45
416	2	11.10	12.30	12.12	11.41	12.48	11.68	11.34	12.38	11.46
	3	10.30	11.76	11.03	11.11	12.30	11.68	11.34	12.30	11.68
	4	7.99	7.46	8.21	10.66	8.64	8.66	11.86	9.56	10.60
	6	6.00	6.45	4.60	7.12	7.05	6.20	7.96	7.40	8.70
	7	4.52	5.66	5.27	6.84	6.24	6.32	7.48	6.64	7.41
	8	4.85	5.60	5.41	6.56	6.42	5.90	8.50	7.48	7.40
418	2	11.78	12.10	11.25	11.92	11.82	11.03	12.02	11.62	11.03
	3	11.82	11.24	10.38	12.34	11.86	11.03	12.32	12.04	10.82
	4	10.60	7.48	7.36	11.54	8.80	8.66	11.48	10.39	9.96
	6	---	5.30	5.31	---	5.88	4.95	---	6.80	6.79
	7	---	5.20	5.39	---	5.60	5.32	---	6.08	6.61
	8	---	5.54	4.08	---	6.48	4.13	---	6.92	6.50
423	2	---	10.22	9.74	---	10.20	9.74	---	10.32	---
	3	---	9.40	9.52	---	10.28	9.52	---	10.40	---
	4	---	5.68	5.85	---	7.00	---	---	8.10	8.43
	6	---	4.60	---	---	5.28	---	---	5.92	---
	7	---	4.46	---	---	4.92	---	---	5.44	---
	8	---	4.72	3.55	---	4.74	5.07	---	5.22	6.05

TABLE 2. Comparison of water surface elevations, model with portal screen and prototype. Q = 3500 cfs for units 42, 43, 44; Q = 0 for unit 41.

Nominal Elev.	Point	Model With Screen High	Low	Avg.	Prototype Avg.
414	1	414.1	413.6	413.3	413.9
	3	414.4	414.1	414.2	413.9
	5	414.5	414.3	414.4	413.9
	10	414.8	414.0	414.4	414.7
	11	415.6	414.6	415.1	415.0
	12	414.1	413.6	413.9	414.1
416	1	416.0	415.4	415.7	415.8
	3	416.1	415.9	416.0	415.8
	5	416.3	415.9	416.1	415.8
	10	416.3	415.2	415.8	416.4
	11	417.4	416.5	417.0	417.0
	12	416.3	415.3	415.8	416.0
418	1	417.5	417.0	417.3	418.0
	3	417.5	417.1	417.3	418.0
	5	418.2	418.0	418.1	418.0
	10	418.6	417.2	417.9	418.4
	11	419.2	418.0	418.6	419.2
	12	417.6	416.8	417.2	418.2
423	1	422.9	422.3	422.6	422.6
	3	422.9	422.7	422.8	422.6
	5	423.1	422.9	423.0	422.6
	10	423.3	422.6	423.0	422.8
	11	423.7	422.9	423.3	423.4
	12	422.5	422.1	422.3	422.6

TABLE 3. Velocity distribution predicted by model with portal screen, four units operating without guide vanes, Q = 3500 cfs for each unit.

Nominal Elev.	Point	0.2 Depth	0.6 Depth	0.8 Depth
416	2	15.86	15.42	15.64
	3	15.82	16.64	16.26
	4	11.22	13.54	15.28
	6	6.80	7.32	7.50
	7	5.42	5.94	6.12
	8	5.82	6.46	6.28
	9	7.90	7.36	7.84
418	2	14.90	15.04	14.89
	3	14.82	14.90	14.97
	4	11.14	12.16	14.14
	6	6.18	6.78	7.16
	7	5.18	5.62	6.08
	8	5.52	6.40	6.74
	9	7.42	6.94	7.26
423	2	13.28	13.28	12.90
	3	12.56	13.34	13.52
	4	9.54	10.46	12.78
	6	4.96	5.54	5.94
	7	4.47	4.60	5.24
	8	4.98	5.24	5.90
	9	5.66	6.18	6.58

TABLE 4. Water surface elevations with four units in operation -- Q = 3500 cfs for each unit -- without guide vanes, with 12 ft guide vanes, and with 18 ft submerged guide vanes.

Nominal Elev.	Point	Without Guide Vanes High	Without Guide Vanes Low	Without Guide Vanes Avg.	With 12 ft Guide Vanes High	With 12 ft Guide Vanes Low	With 12 ft Guide Vanes Avg.	With 18 ft Submerged Guide Vanes High	With 18 ft Submerged Guide Vanes Low	With 18 ft Submerged Guide Vanes Avg.
416	1	417.0	415.6	416.3	416.1	414.7	415.4	415.7	414.8	415.3
	3	417.1	416.5	416.8	417.8	417.0	417.4	416.9	416.2	416.6
	5	415.8	414.5	415.2	415.1	414.3	414.7	416.4	415.4	415.9
	10	418.5	414.6	416.6	417.9	416.3	417.1	418.2	416.8	417.5
	11	419.7	417.7	418.7	417.6	416.4	417.0	418.3	416.7	417.5
	12	419.4	417.1	418.3	417.2	415.3	416.3	418.2	415.9	417.1
	13	416.6	414.0	415.3	417.1	415.0	416.1	417.5	415.3	416.4
418	1	418.4	417.7	418.1	417.7	417.3	417.5	417.4	415.4	416.4
	3	419.2	418.4	418.8	419.6	418.3	419.0	418.6	417.4	418.0
	5	418.9	417.7	418.3	418.7	417.1	417.9	417.7	416.3	417.0
	10	420.4	417.5	419.0	419.4	417.9	418.7	419.3	418.0	418.7
	11	421.6	419.4	420.5	419.6	418.4	419.0	419.1	417.9	418.5
	12	420.8	419.0	419.9	419.7	417.8	418.8	418.7	416.5	417.6
	13	419.2	416.8	418.0	419.5	417.9	418.7	419.0	416.7	417.9
423	1	423.4	422.7	423.1	423.6	422.4	423.0	423.3	422.6	423.0
	3	423.3	422.7	423.0	424.9	423.9	424.4	423.0	422.3	422.7
	5	423.4	422.4	422.9	424.1	423.2	423.7	423.3	422.3	422.8
	10	424.6	422.8	423.7	423.9	423.2	423.6	423.6	422.8	423.2
	11	425.9	424.2	425.1	424.2	423.3	423.8	423.9	423.1	423.5
	12	425.1	423.4	424.3	423.9	422.4	423.2	423.2	422.1	422.7
	13	423.6	421.5	422.6	424.4	422.9	423.7	423.2	422.0	422.6

TABLE 5. Water surface elevations for partial operating conditions with 12 ft surface piercing guide vanes. Nominal elev. = 418 ft.

Penstocks Running	Point	Model with Screen		
		High	Low	Avg.
41 and 42	13	418.2	417.7	418.0
	12	418.3	417.6	418.0
	11	418.4	418.2	418.3
	10	418.2	417.9	418.1
41 and 43	13	417.9	417.2	417.6
	12	417.8	417.0	417.4
	11	417.6	416.8	417.2
	10	418.0	417.7	417.9
41 and 44	13	417.7	417.3	417.5
	12	417.9	417.6	417.8
	11	418.2	417.7	418.0
	10	417.7	417.3	417.5
42 and 43	13	418.3	417.8	418.1
	12	418.0	417.3	417.7
	11	418.4	417.7	418.1
	10	418.5	417.7	418.1
43 and 44	13	417.9	417.5	417.7
	12	418.4	418.2	418.3
	11	418.7	417.4	418.1
	10	418.8	418.2	418.5

LIST OF FIGURES

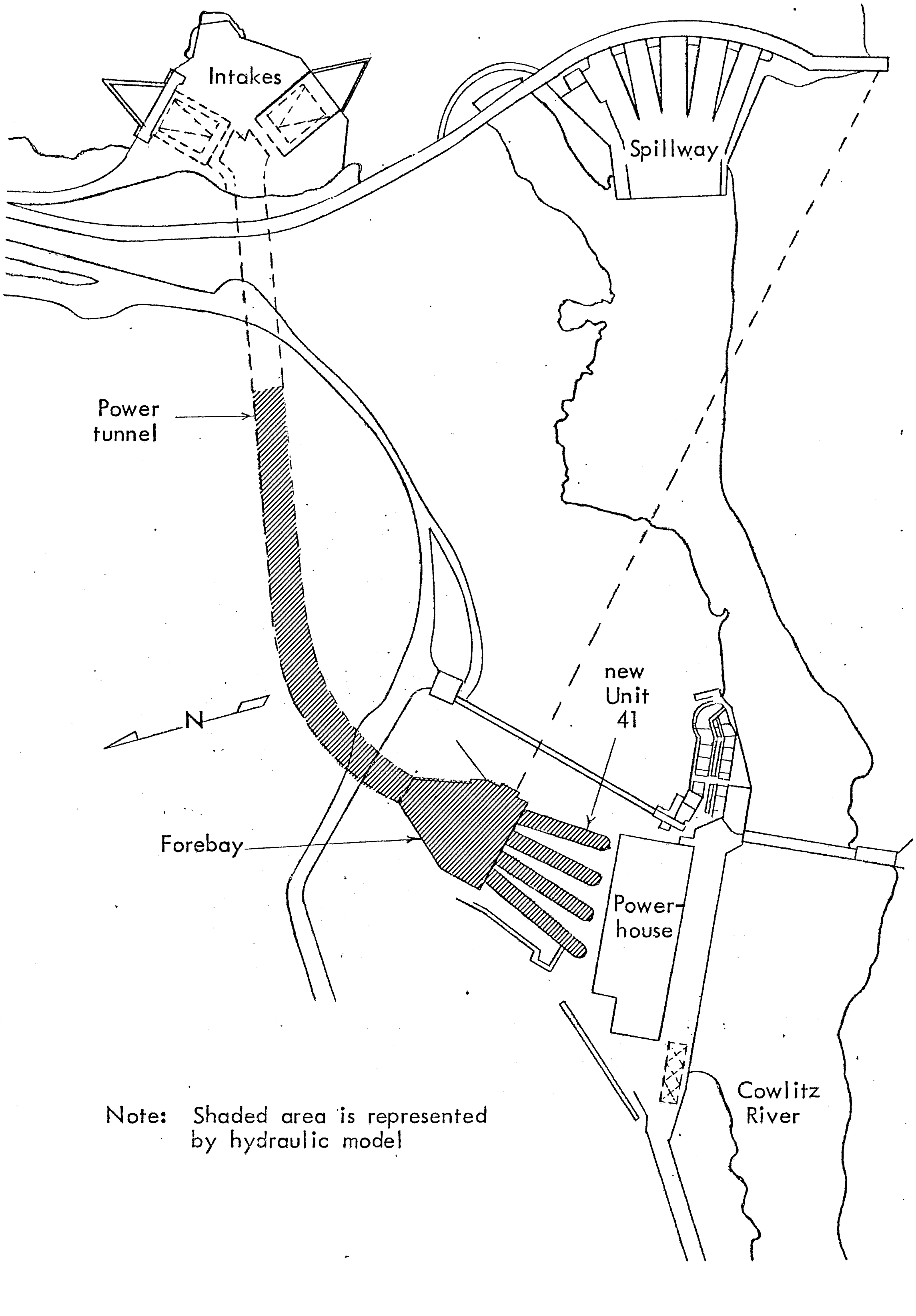


Fig. 1 - Overall layout of the Mayfield power plant hydraulic system

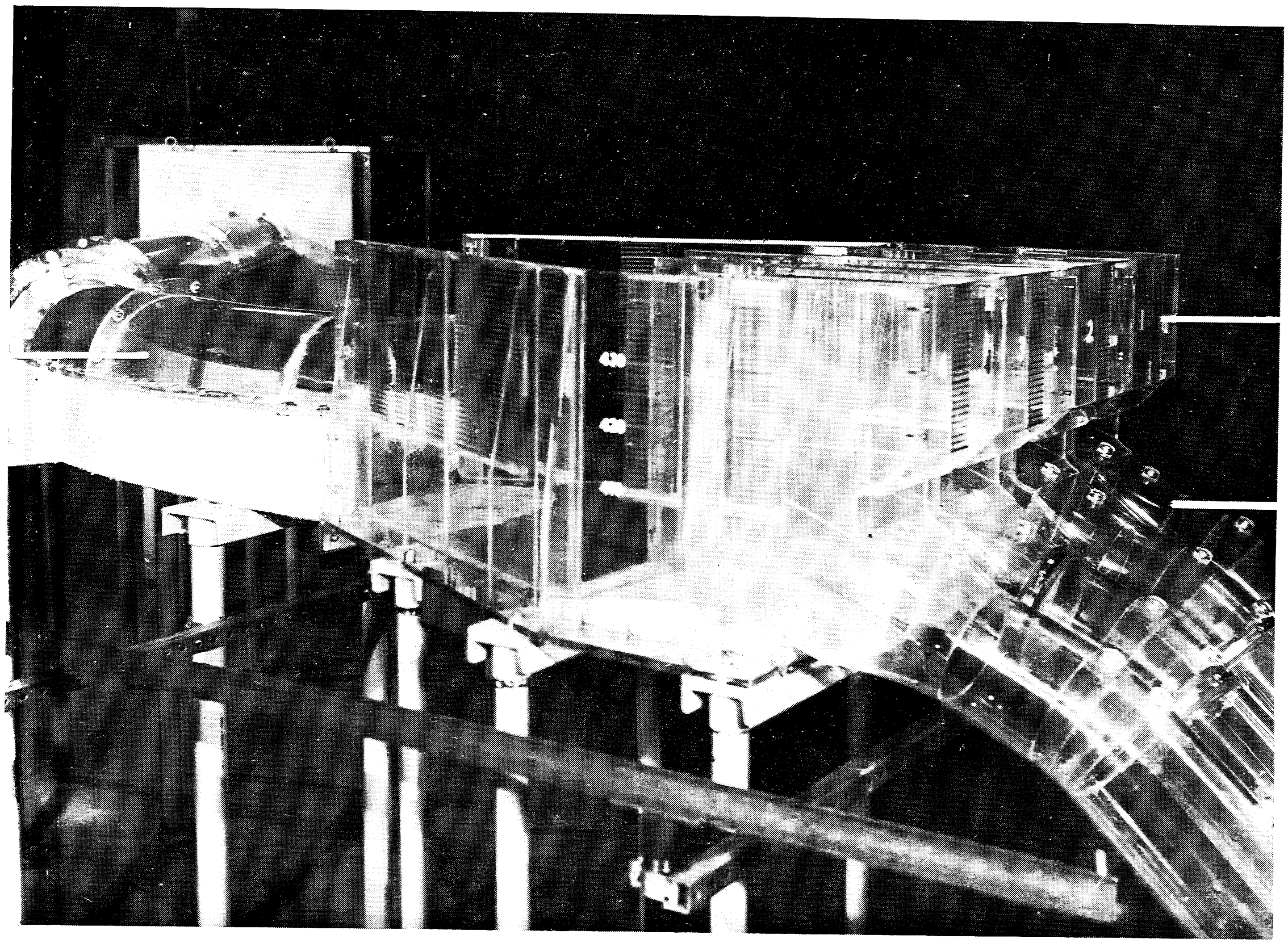


Fig. 2 - (Ser. No. 228-117) Overall view of the model

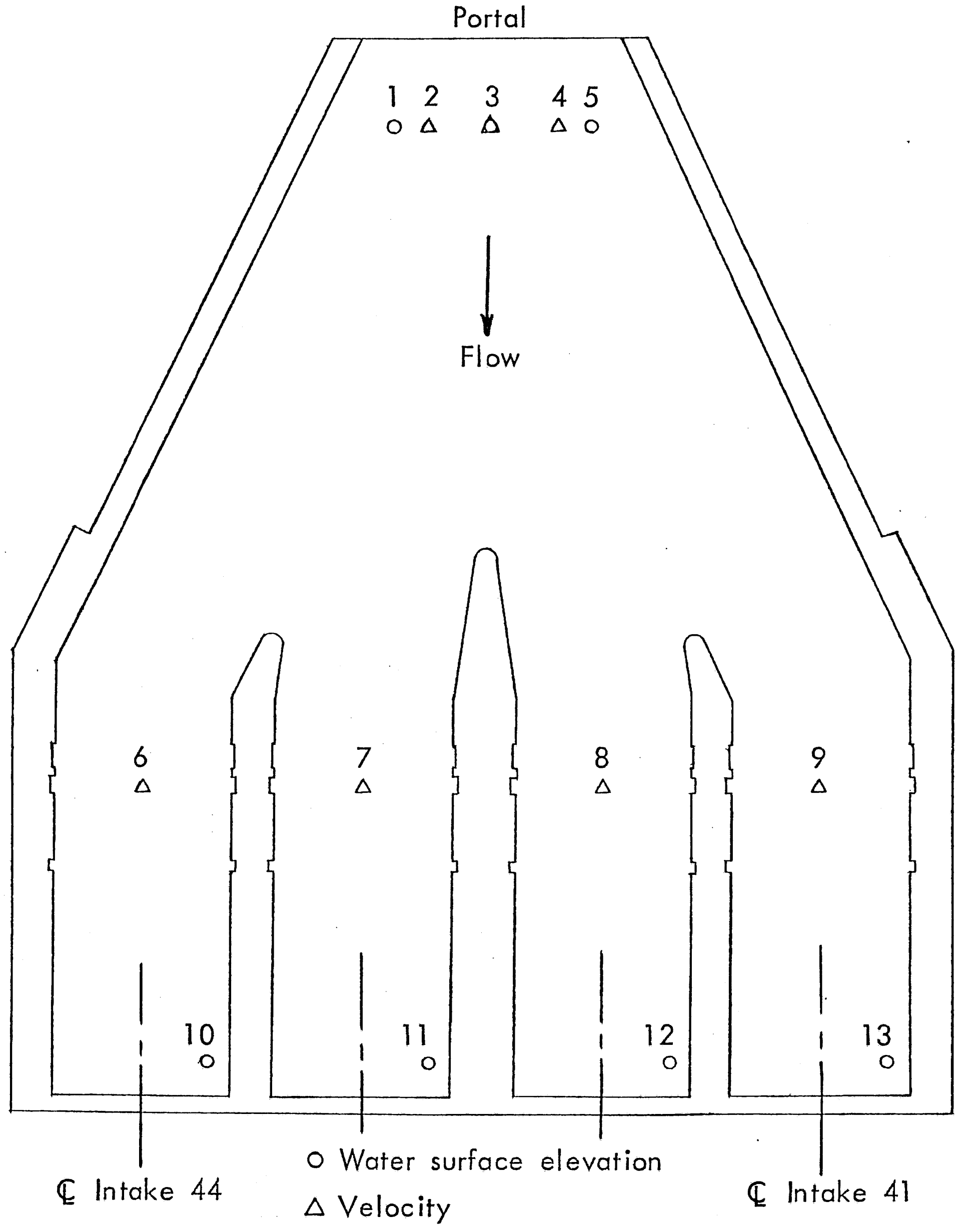
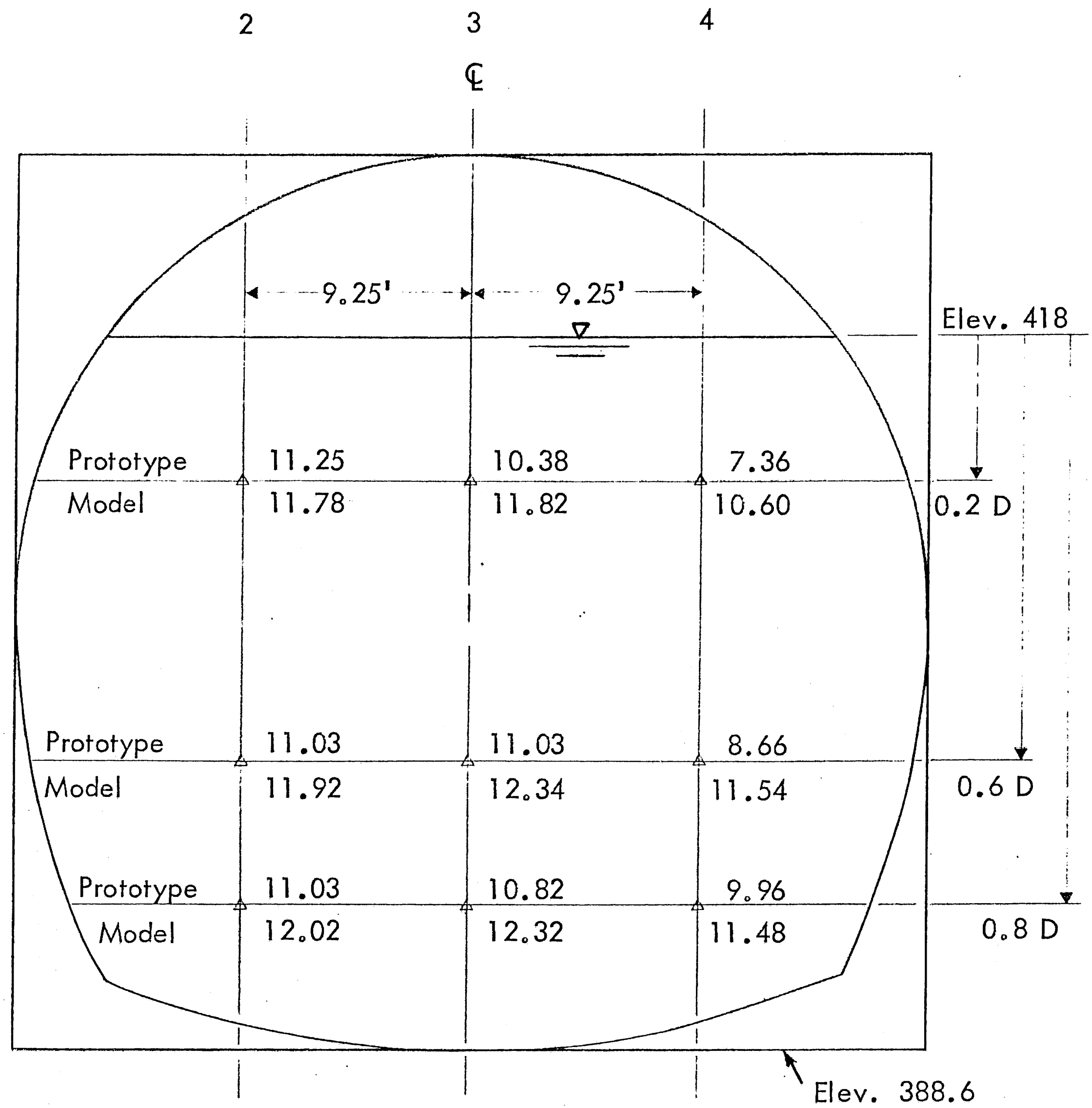


Fig. 3 - Plan view of forebay indicating locations at which field and model data were taken



Water Surface Elevation 418

Q = 3500 cfs for Units 42, 43, 44

Q = 0 for Unit 41

Velocities in feet per second

Fig. 4 - Comparison of velocity distributions near tunnel portal, model without portal screen and prototype, looking upstream

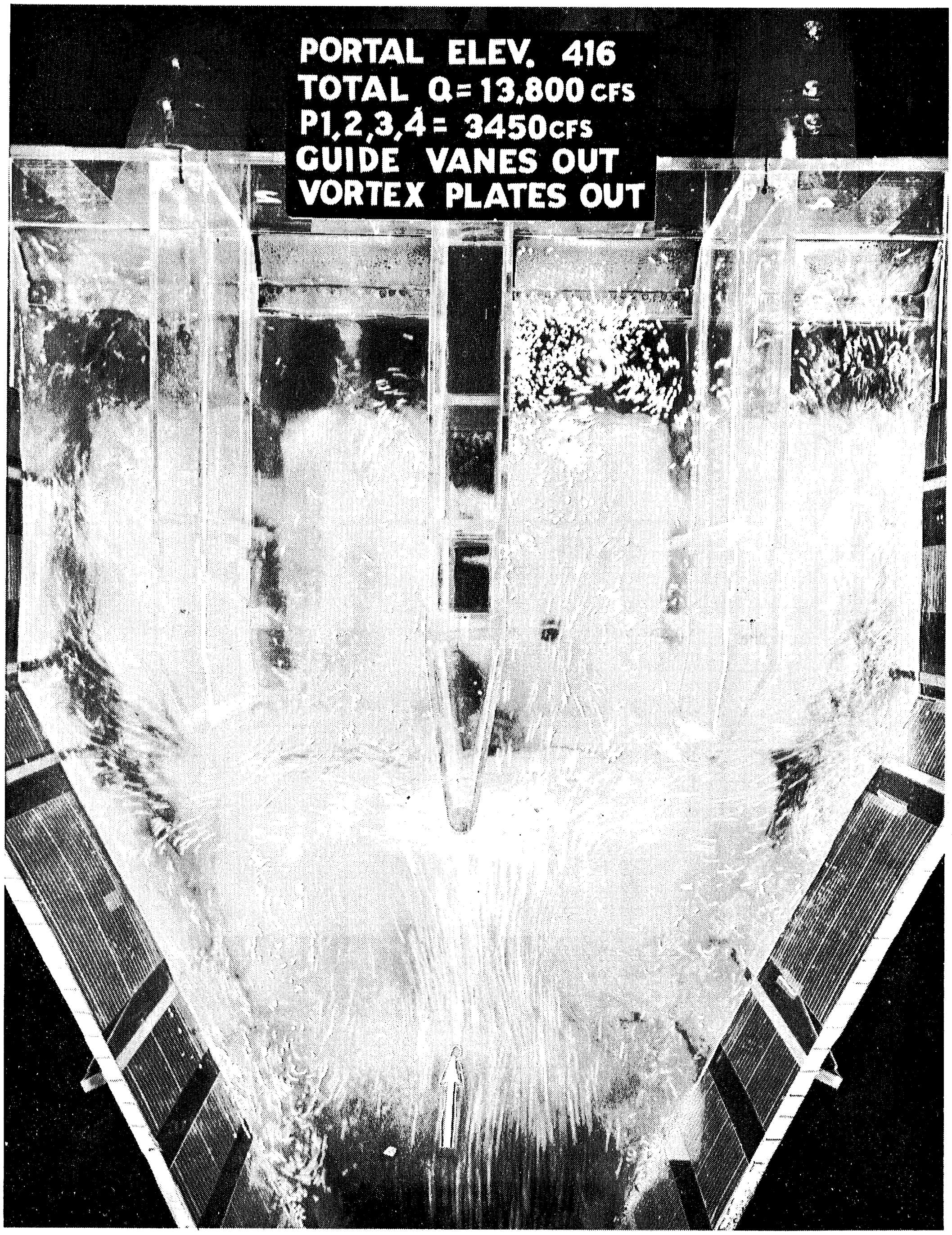
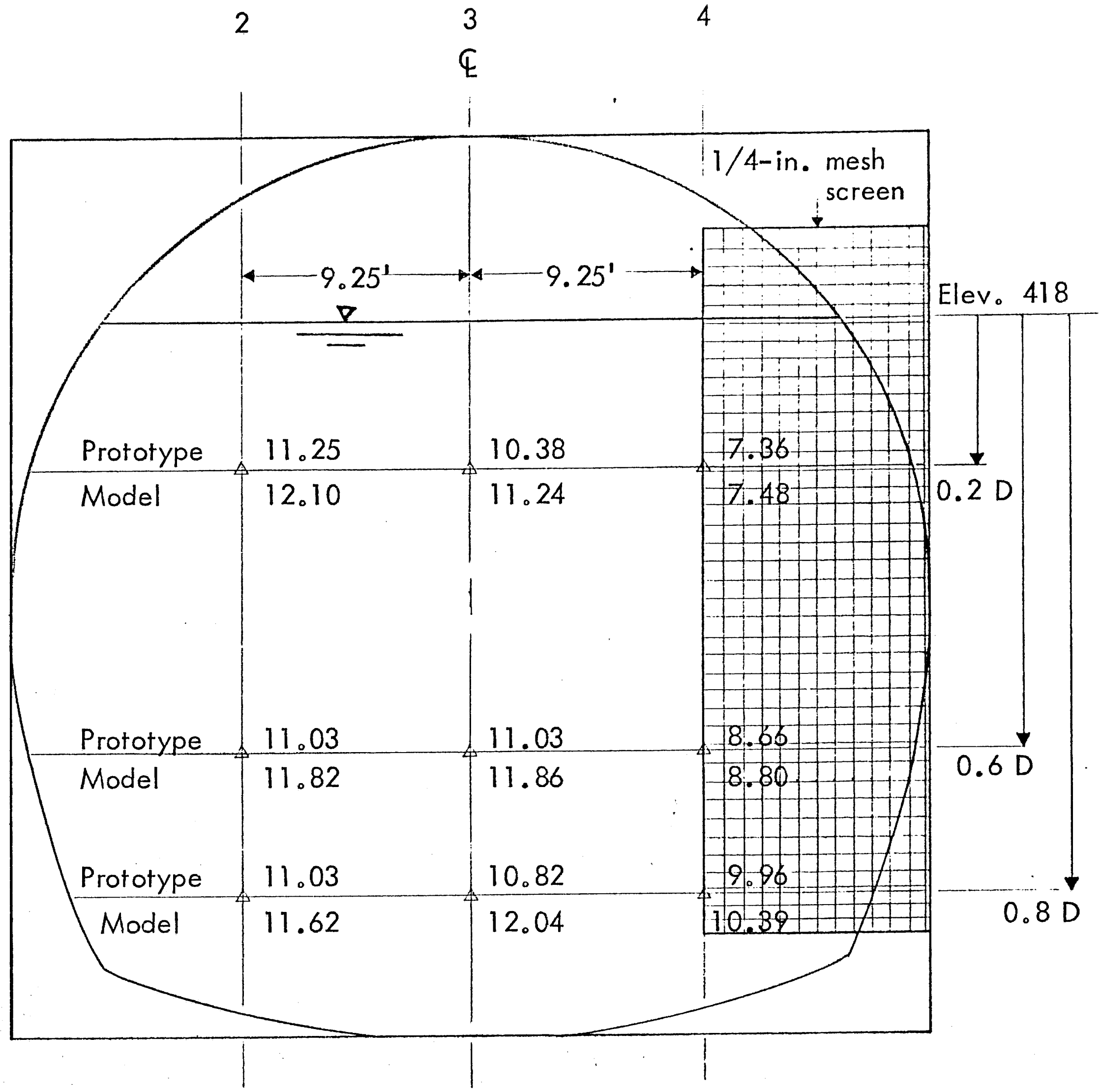


Fig. 5 - (Ser. No. 228-115) Photograph showing flow separations and reverse currents near tunnel portal



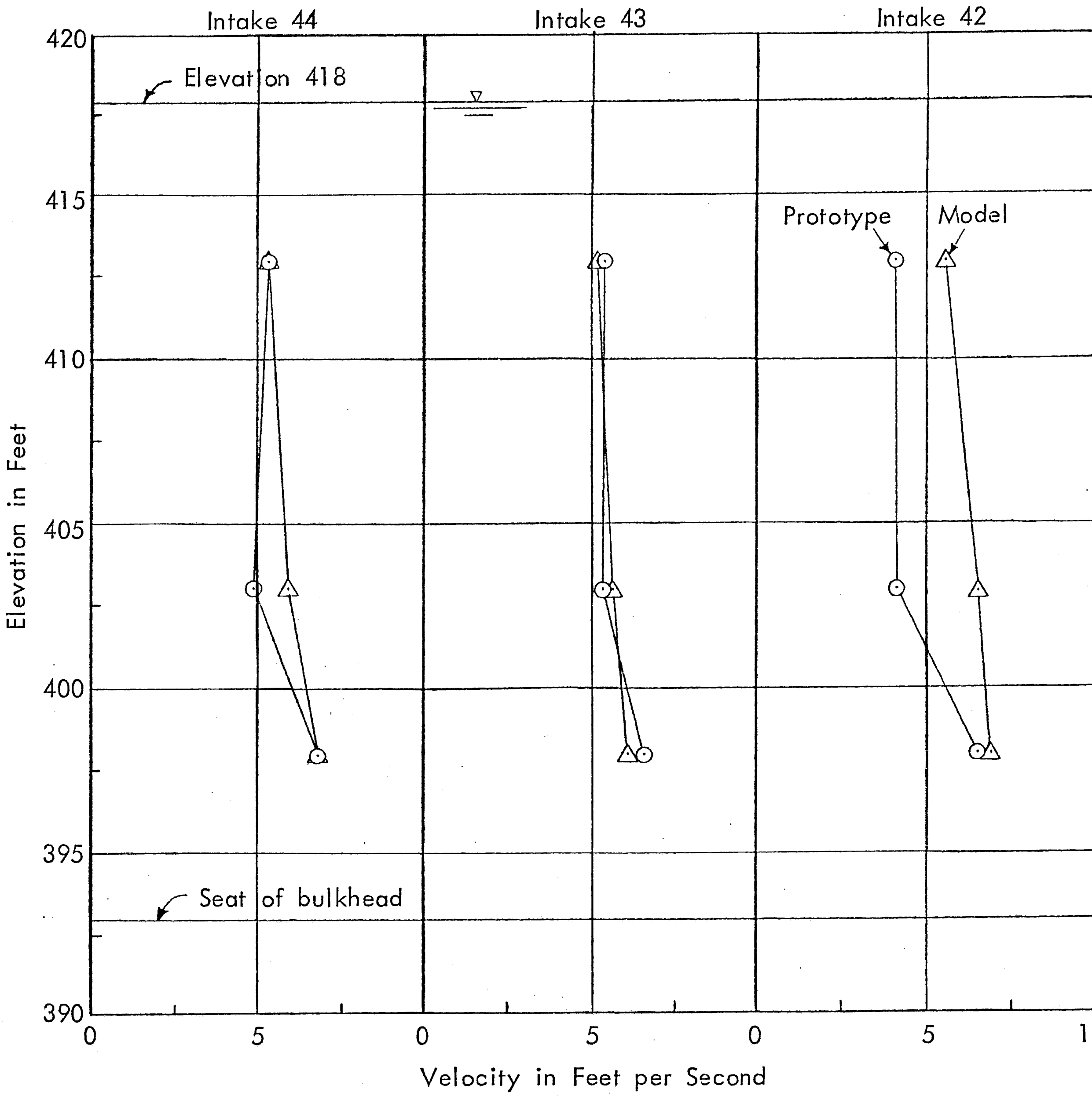
Water Surface Elevation 418

Q = 3500 cfs for Units 42, 43, 44

Q = 0 for Unit 41

Velocities in feet per second

Fig. 6 - Comparison of velocity distributions near tunnel portal for prototype and model (with portal screen)



Forebay water surface elevation of 418
Q = 3500 cfs for each unit

Fig. 7 - Comparison of velocity distributions near penstock intakes for prototype and model (with portal screen)

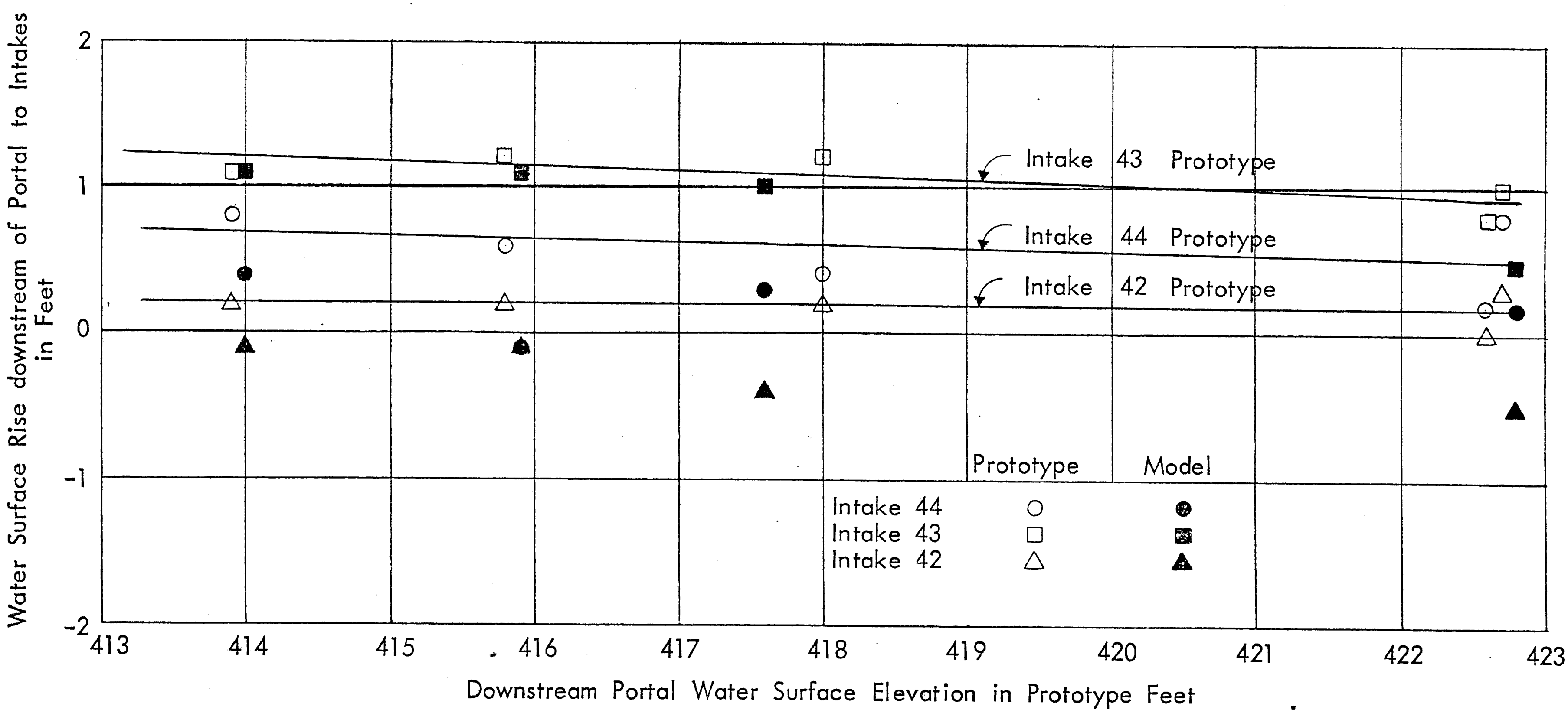


Fig. 8 - Comparison of water surface rises from portal to intakes, three existing units

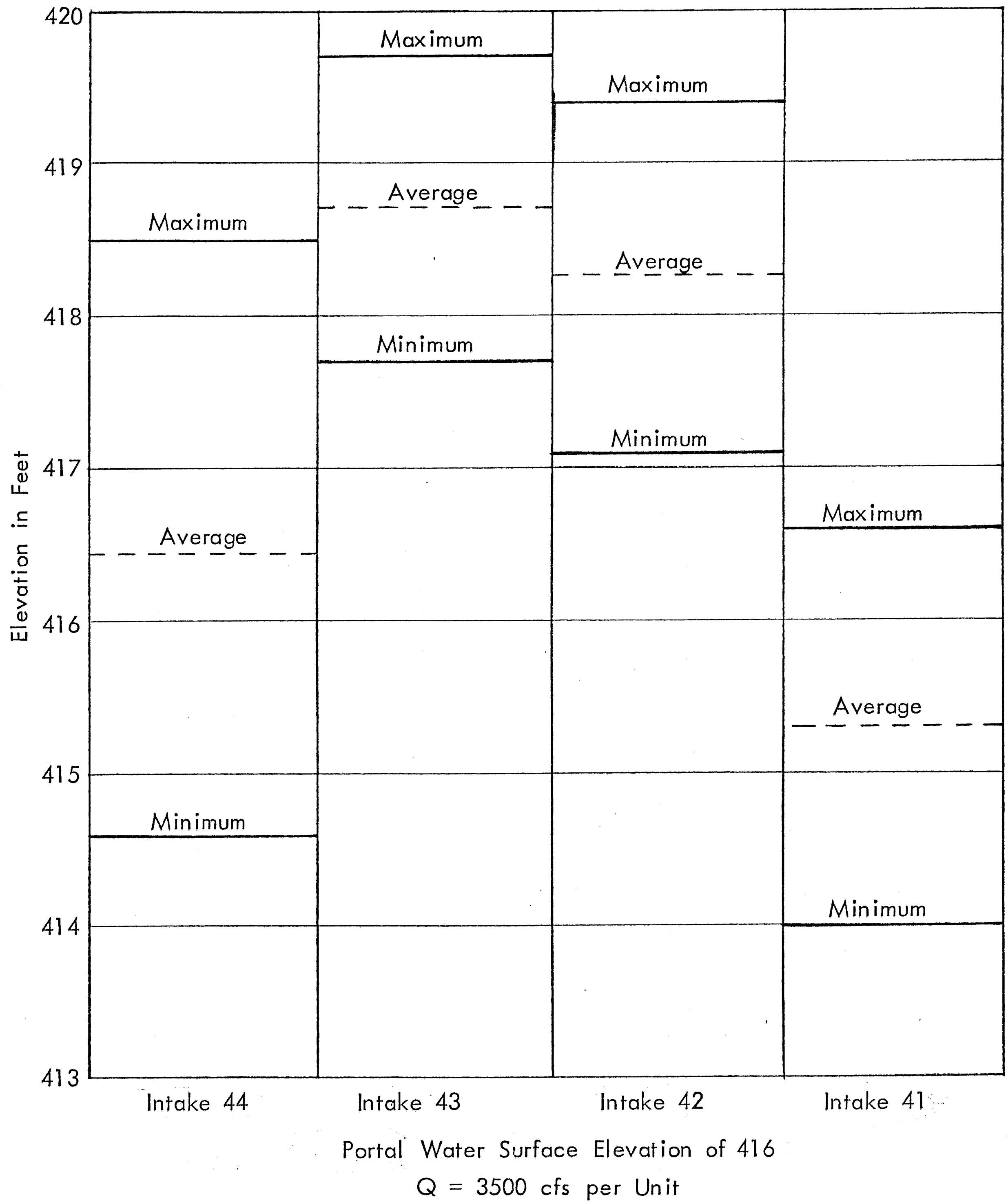


Fig. 9 - Water surface profiles at intakes, four units in operation, without guide vanes

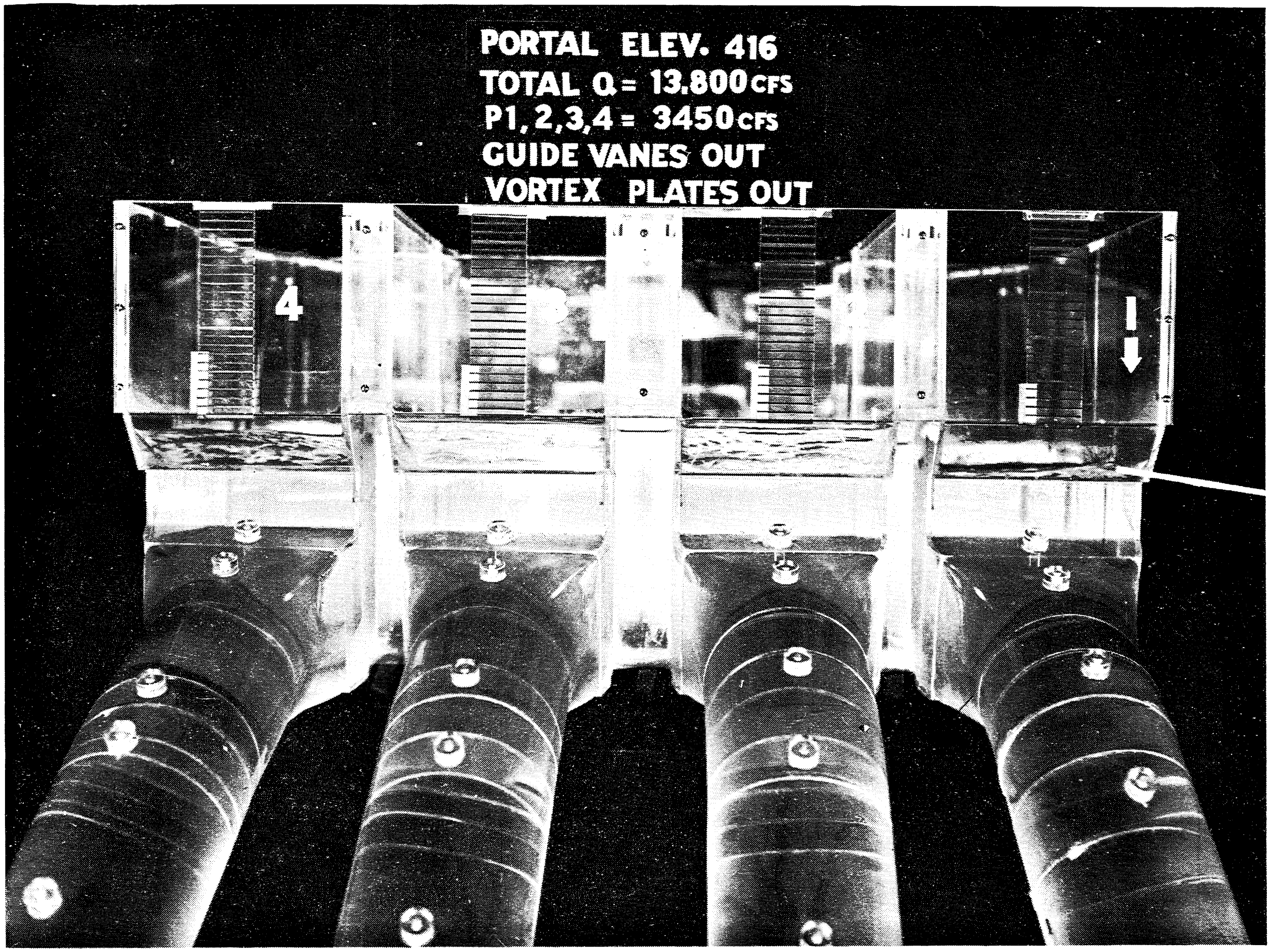


Fig. 10 - (Ser. No. 228-37) Typical photograph showing uneven water surface at the intakes, four units in operation, average water surface elevation at portal = 416.0

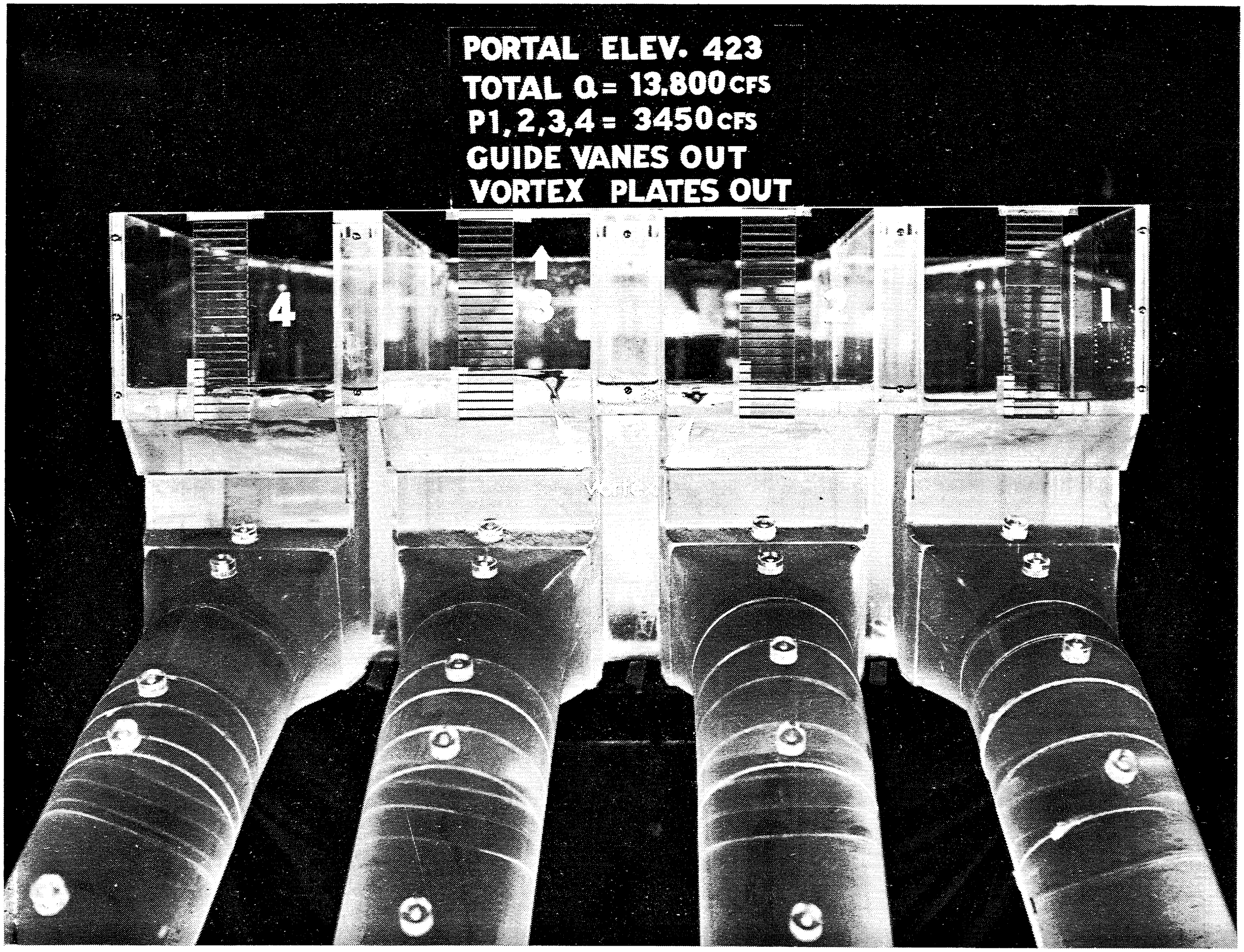
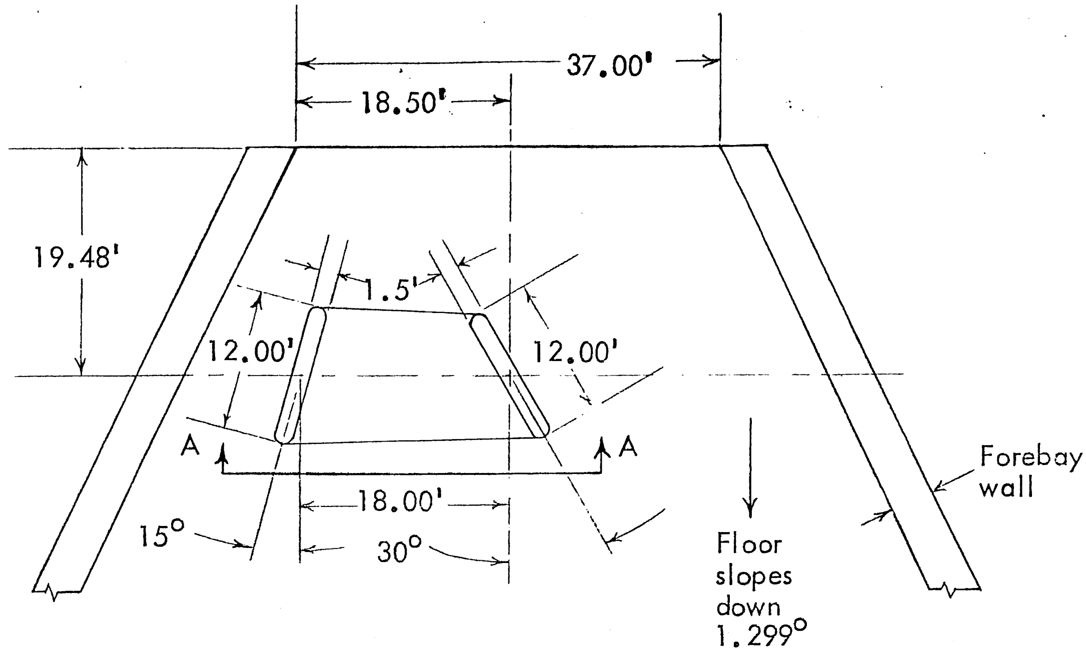
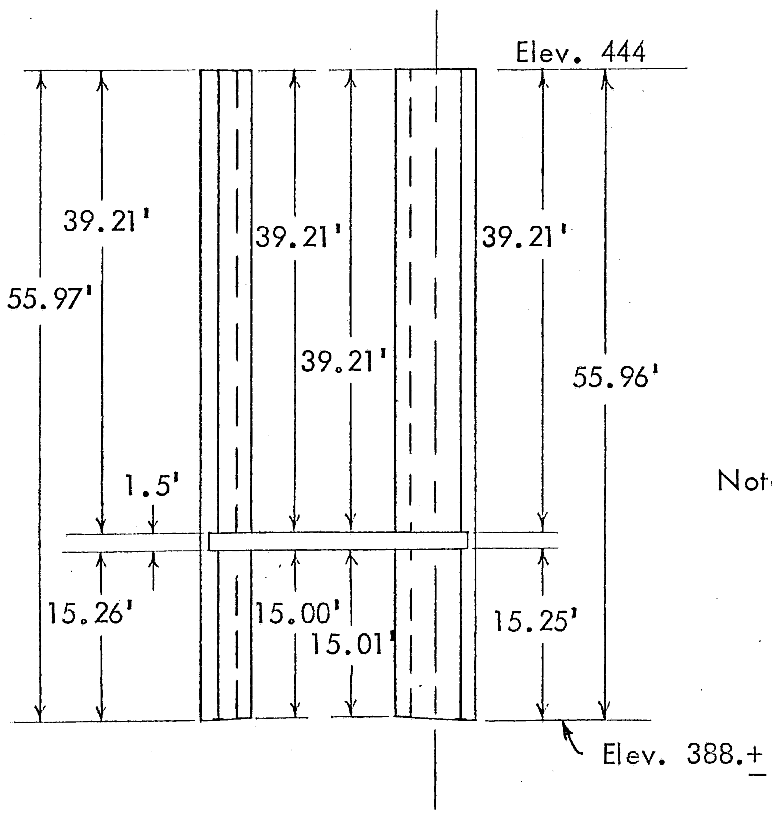


Fig. 11 - (Ser. No. 228-116) Typical photograph showing vortices in intake bays



Plan View of Upstream Portion of Forebay



Note: Bracing plate has rounded edges.

Section A-A

Scale: 1" = 16'

Fig. 12 - The configuration of two 12-ft-wide full-height guide vanes

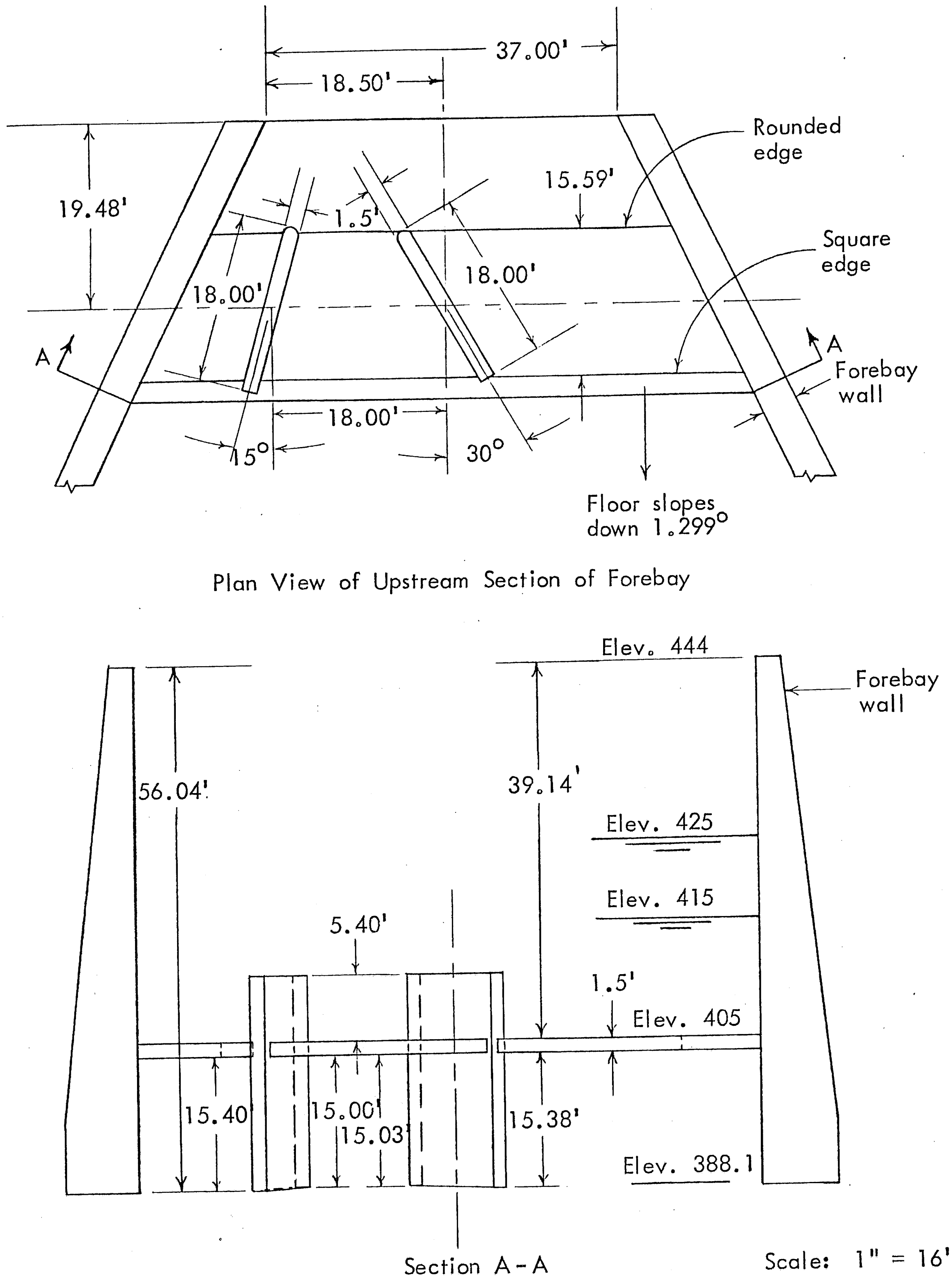


Fig. 13 - The final design configuration, two 18-ft submerged guide vanes

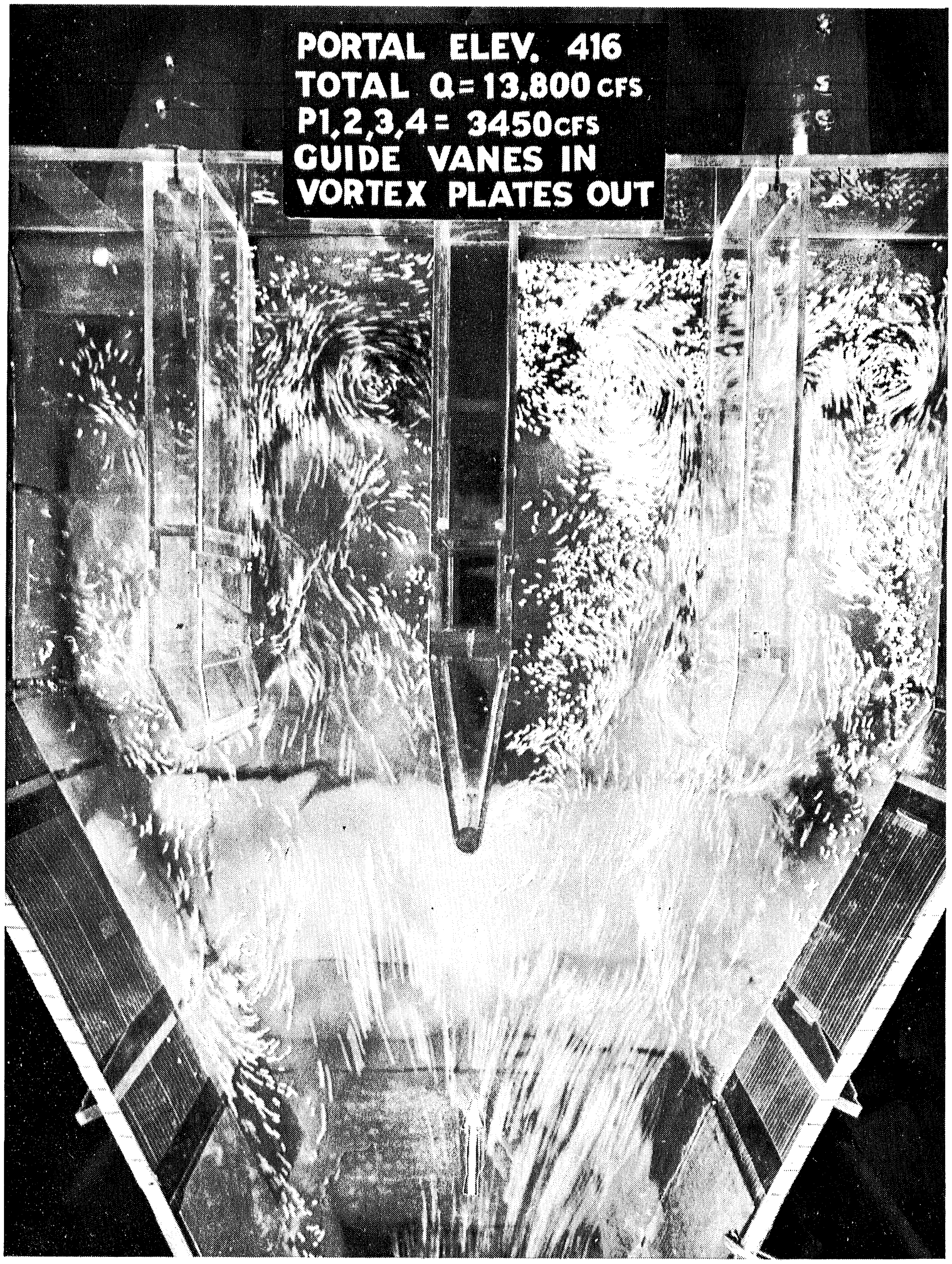


Fig. 14 - (Ser. No. 228-70) Surface eddies with submerged guide vane, but without vortex suppressor

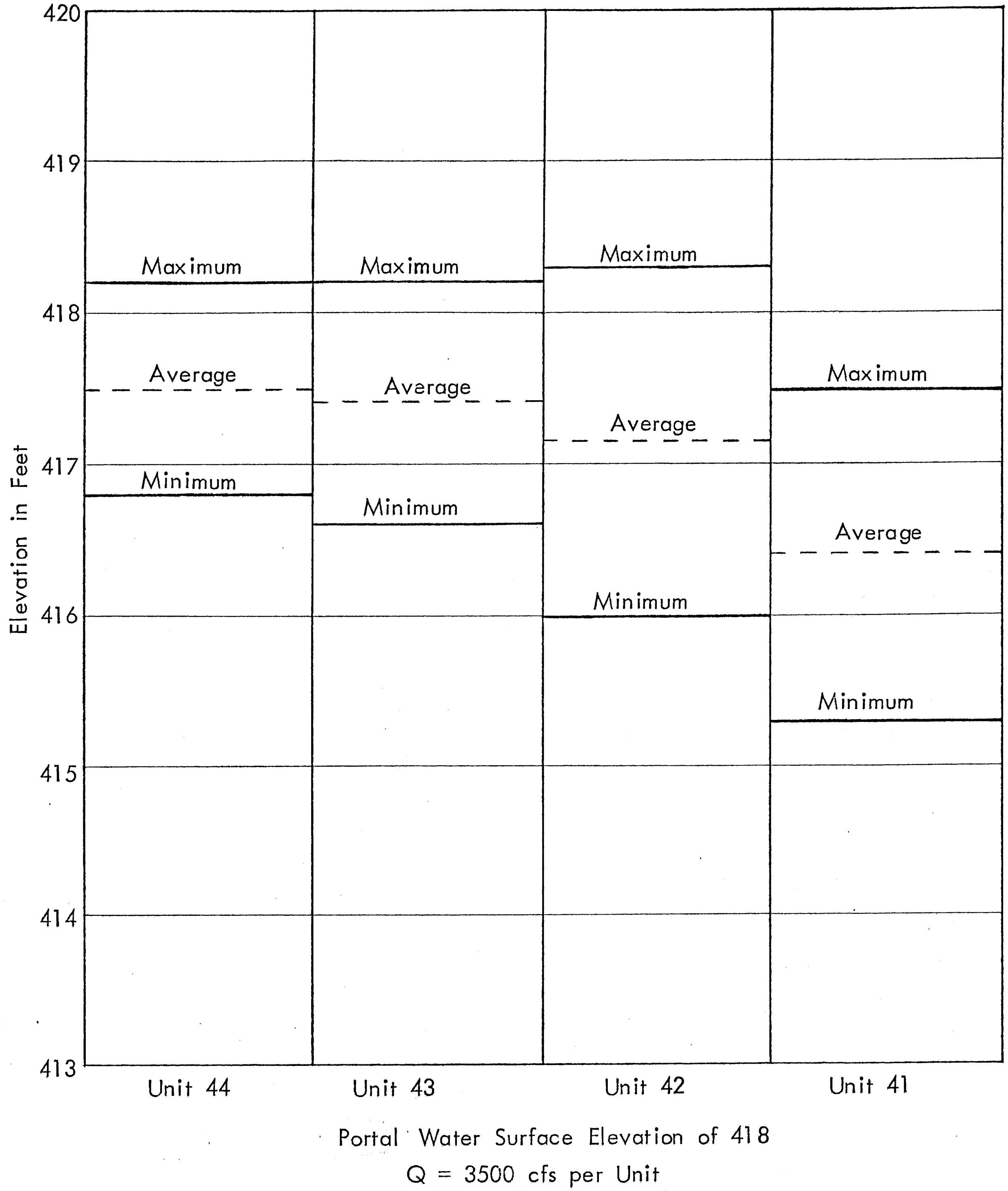


Fig. 15 - Water surface profiles at intakes, four units in operation, with submerged guide vanes

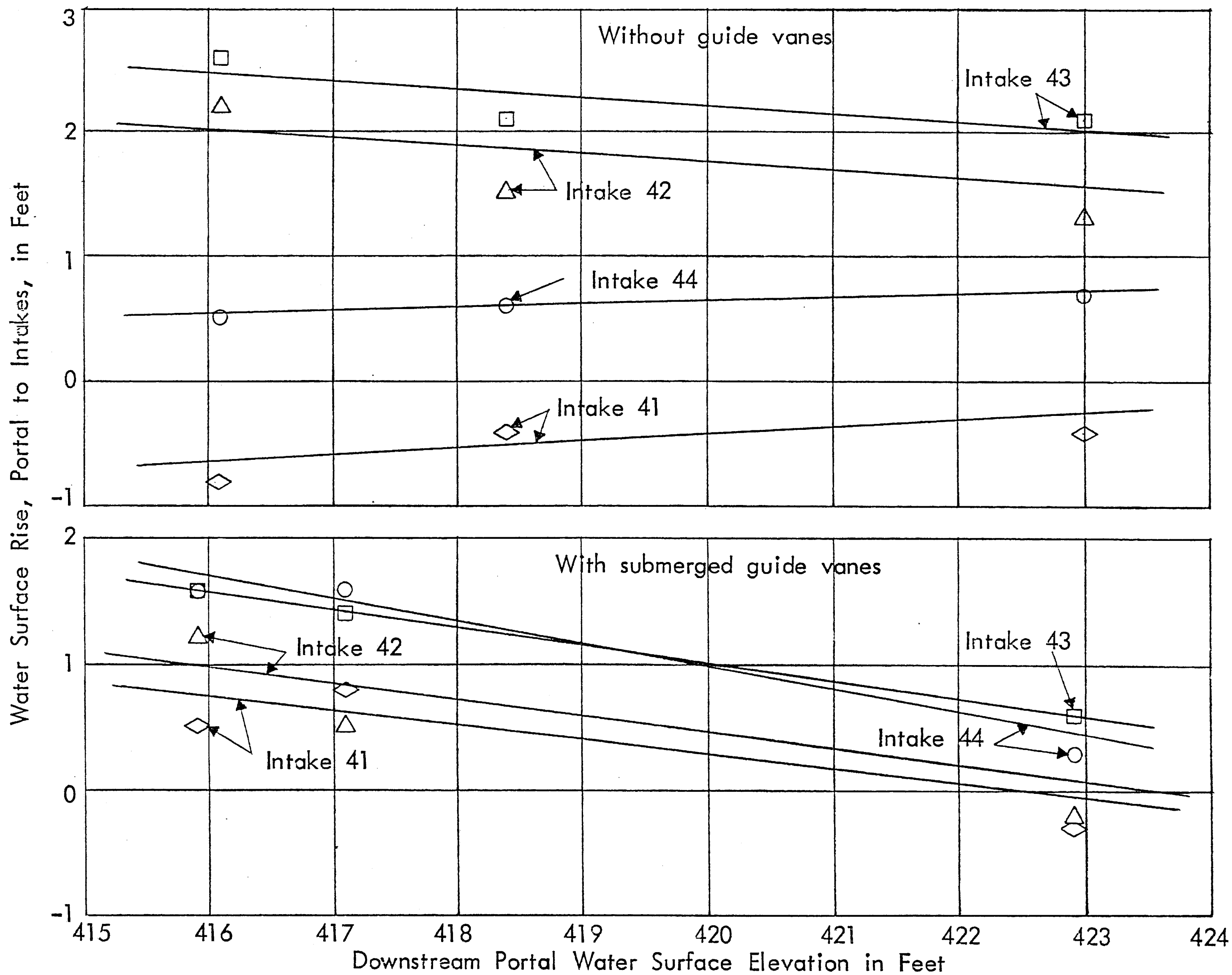


Fig. 16 - Predicted water surface rises at intakes, four-unit operation with and without guide vanes

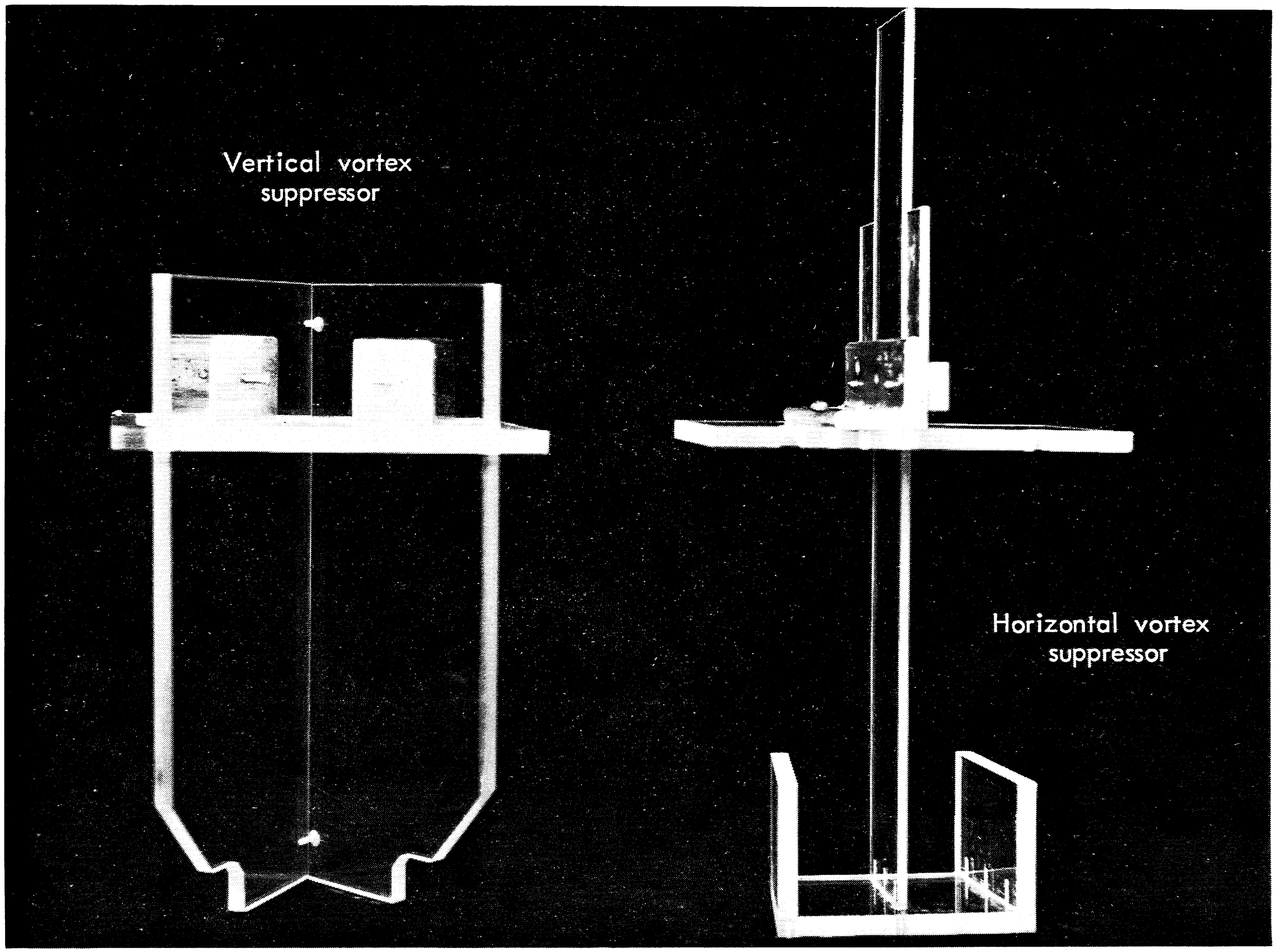
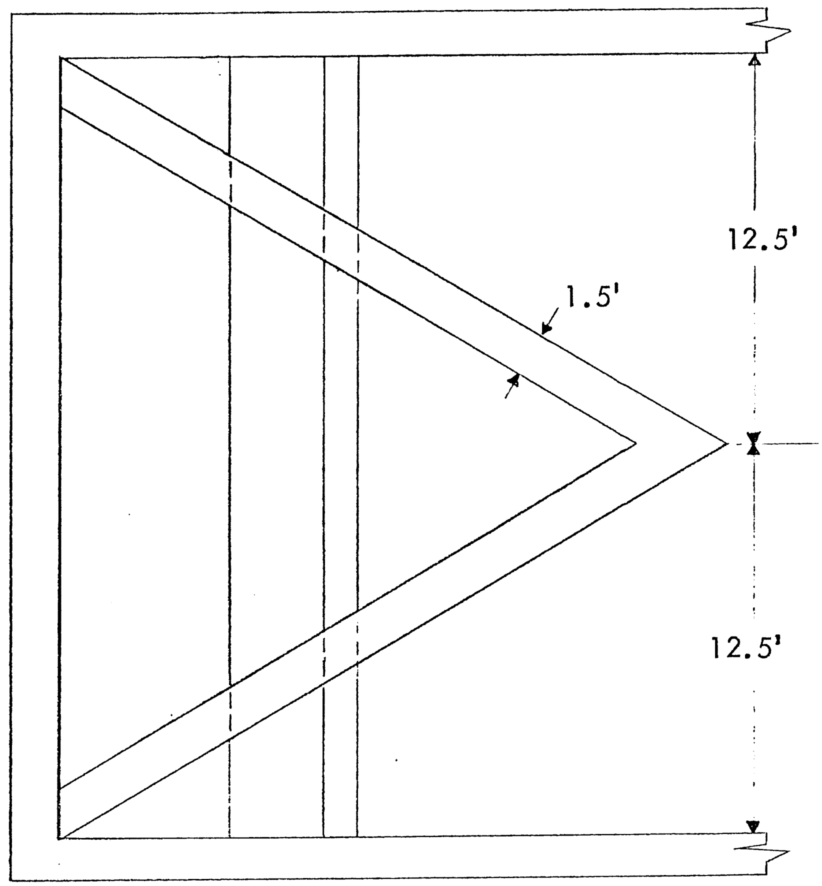
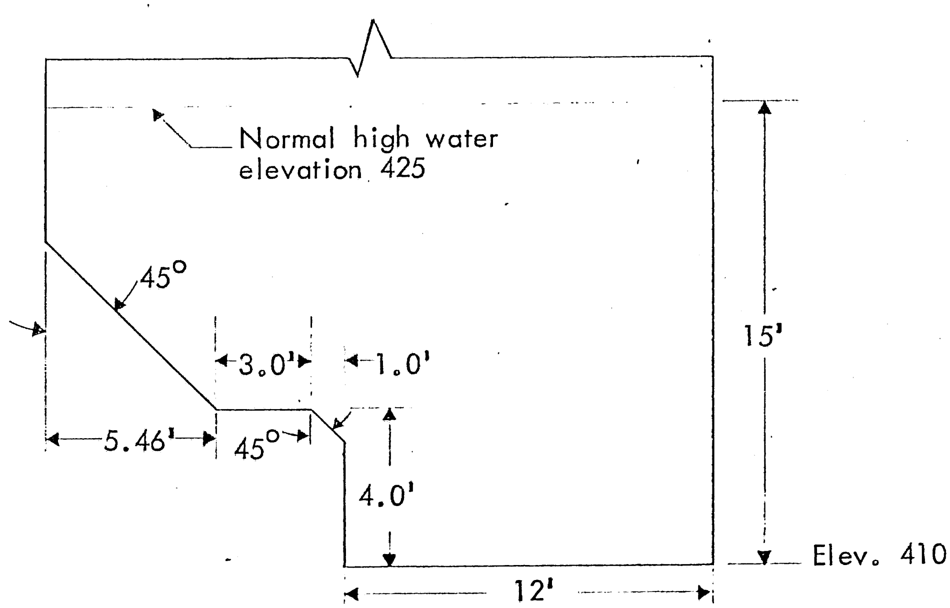


Fig. 17 - (Ser. No. 228-79) Photograph of vortex suppressors



Plan View



Side View

Fig. 18.- Dimensions of V-shaped vertical vortex suppressor

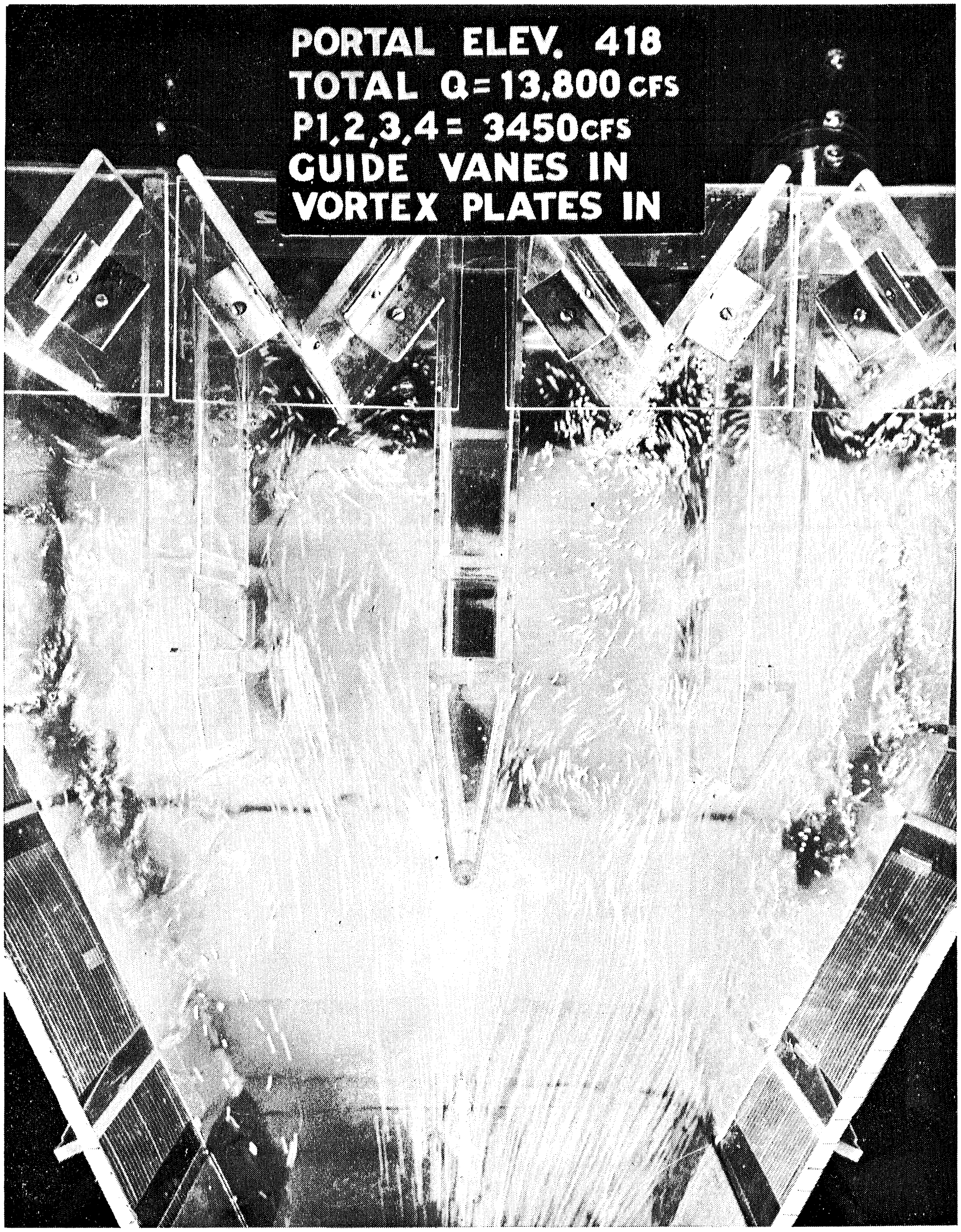


Fig. 19 - (Ser. No. 228-92) Flow pattern at the water surface with vortex suppressor in place