St. Anthony Falls Hydraulic Laboratory
University of Minnesota

Project Report No. 194

HYDRAULIC MODEL STUDY
OF THE
COOLING WATER INTAKE
RUSH ISLAND PLANT
UNION ELECTRIC COMPANY

by

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Prepared for

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PREFACE

The St. Anthony Falls Hydraulic Laboratory was approached by representatives of Union Electric Company concerning two problems occurring in the cooling water intakes of their Rush Island Plant. The problems involved vibrations of the intake pipe and sand accumulation on the floors of the intake bays. In discussions, it was agreed that a model study could be effective in helping to solve the vibration problem but that a separate model study would be necessary to study the sand problem, and it was not so likely that a satisfactory solution could be obtained from such a model. The model to study the vibration problem was then authorized late in August, 1979, and construction of the model began in September.

During October there were further discussions as to what might be done about the sand accumulating in the intake bays. After the alternative of a second model was discarded, it was decided to do some modeling on the original model by enlarging it. Authorization to do this was received late in October; construction of the enlarged model was completed at the beginning of December, 1979. Operation of the model occupied the months of December, 1979 and January through March, 1980.

The model study was conducted under the supervision of Professor E. Silberman. Operation was Mr. C. Shanmugham's responsibility. Mrs. Patricia Swanson handled preparation of the report.

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HYDRAULIC MODEL STUDY OF THE COOLING WATER INTAKE RUSH ISLAND PLANT UNION ELECTRIC COMPANY

I. INTRODUCTION

The Rush Island Plant is an operating plant in which problems have occurred in the cooling water intake bays. The intake is located on the west bank of the Mississippi River about 40 miles south of St. Louis. It is on a straight reach of river about 2000 ft wide.

The intake consists of four identical bays, each drawing 151,000 gpm from the river. The water is pumped out of the bays through a vertical pipe suspended from the top deck near the back of each bay. The floor of the bays is at elevation 336.5 ft, the approximate level of the river bed at the intake site, and the deck is at elevation 412 ft. The lowest predicted river stage at the intake is 356.0 ft. Normal river stage is about 368.0 ft and highest flood stage, 408.0 ft.

The more immediate of the intake problems is the occurrence of vibrations and loosening of bolts in the pipe columns. A second problem is that sand collects to considerable depth in a portion of each bay making maintenance and dewatering difficult. The model was originally designed to look specifically at the first problem but, before it was placed in operation, it was altered to also examine the second problem.

In designing the model, the symmetry of the bays suggested that only one bay need be modeled in detail with partial bays upstream and downstream to represent the intake flows to those bays. A plan view of the model designed in accordance with this concept is presented in Drawing 286-14. A scale of 1:12 was selected to facilitate study of the flow conditions that might be causing pipe column vibrations. (The scale of 1:12 permits reading dimensions on the drawings, which are in inches for the model, as feet for the prototype.) When the model design was changed to accommodate study of the sand ingestion problem, the same scale was retained but this permitted including only 40 ft of the 2000 ft river width at the site.

Model design and operation are elaborated upon in subsequent sections. Other details of the model are shown in Drawings 286-15, -16, -17, and -18, and in Photos 1 and 2. A sketch showing sand deposition measured following dewatering of one bay in the prototype is reproduced in Fig. 1.

II. MODEL DESIGN

A. Scale

The model was originally designed to examine the hydraulics of flow in one intake bay with the objective of eliminating vibrations in the intake pipe. Vibration problems are frequently associated with vorticity or rotation in the flow approaching the intake pipe. The model was designed to look for possible vorticity. It is not feasible to model pipe vibrations directly because to do so requires both a different scaling of the model than is required for vorticity and also the modeling of the elastic properties of the pipe and its supports.

Vorticity in a large scale river flow is controlled largely by gravitational phenomena. Thus, the Froude Model Law governs the model scale. Using this relationship, velocity and time are proportional to the square root of the length scale and discharge is proportional to the 5/2 power of the length scale.

Vorticity, however, may be damped by viscosity in the model if the model is not large enough to generate turbulence comparable to that in the prototype. Thus, it is desirable to make the model scale as large as possible; scale is limited by the physical size and water flow rate required in the model. In this case the head room required to model the 75 ft depth of the intake forced selection of a 1:12 length scale. This implies velocity and time scales of close to 1:3.5 and a discharge scale of 1:500, and these are the scales which apply to this model. The 151,000 gpm intake at each bay, for example, corresponds to 0.67 cfs in the model.

Later, is was proposed that the model also be used for studying the sand ingestion problem. To do this adequately, it would be desirable to model a large part of the 2000 ft width of the river opposite the intake.

But, if the model river becomes very wide, the model scale is limited by the available water supply in the Laboratory. The ideal solution would be to build two models, one at large scale to study the hydraulics of flow in the intake and the other at about 1/10 of that scale to study the sand transport problem in the river approaching the intake.

Since construction of the original model at 1:12 scale had been nearly completed when the desirability of incorporating some modeling of the sand ingestion process became evident, and since it was not desired to delay the study further or to increase its cost significantly, it was decided to model as much of the sand ingestion process as could be done using the completed portions of the 1:12 model and extending its size to encompass more of the river. Because of limitations in the water supply, the river width opposite the intake in the model had to be limited to 40 ft prototype. The river was also extended upstream at the same time to model the approach flow better. Drawing 286-14 is a plan view of the model as enlarged.

B. Discharge Required

Union Electric Company supplied point velocity measurements (speed and direction),taken at several depths along transects parallel to the intake at distances of 20, 40, and 80 ft from the intake into the Mississippi River. The measurements were made at different times of the year when the stages were 360.0, 367.0, and 385.5 ft.

The Laboratory integrated these velocity measurements to obtain estimates of the downstream discharge when the river is cut off at 40, 60, and 80 ft away from the intake. The estimated discharges were extrapolated to the maximum model study stage of 408.0 ft and to the minimum of 356.0 ft. It was these estimates that resulted in limiting the river width that could be accommodated in the model to 40 ft. Table 1 lists flow quantities required in the model for the 40 ft river width. At the 408.0 ft stage, whereas about 14 cfs was required, only 8 cfs could be delivered by the Laboratory water supply. It was decided to run with a smaller river discharge than required at maximum flood stage so as to avoid making the model river any narrower. In the actual tests, various combinations of larger flows into the center bay and past the intake were used (at less than flood stage).

TABLE 1. Flow Quantities Required in Model, cfs

Stage, ft	Past Intake	Into Center Bay	Total Side Bays	Total
408.0	12.0	0.67	1.34	14.0
368.0	1.38	0.67	1.05*	3.1
356.0	0.5	0.67	0.93*	2.1

*The 4 in. I.D. pipes used for intakes in the side bays could not carry the required 0.67 cfs at low heads.

C. Some Model Features

The model is shown in plan and elevation in Drawings 286-14 and -15. Photo 1 shows the model from the land side during operation, while Photo 2 is a view looking toward the intakes of the partially completed model before it was enlarged. The center bay of the model was provided with windows on three sides to facilitate observation and illumination of the flow into the intake pipe. (The need for these windows was one of the reasons for using shortened intake bays adjacent to the test bay in the model.)

The suction bell and intake transition were constructed of transparent plastic and provided with a built-in vortimeter as shown in Drawing 286-16; the vortimeter was visible through the viewing windows as may be seen in Photo 3.

The vortimeter was an important measuring device for studying the flow. Another device was a ring of 12 yarns installed around the periphery of the suction bell; this may also be seen in Photo 3. The yarns are on pins placed at 30 degree intervals at mid-height between the bottom of the bell and the floor. Yarns were also placed at the ends of long rods which could be inserted through the water surface to explore flow direction at various places in the model. Dye was inserted in the model at critical places using a long tube supplied by a squeeze bottle containing the dye at its upper end. Photo 5 is an example of dye injection. Free surface flow patterns were observed by floating confetti. Some flow velocity measurements were made in the model river using a current meter on a staff for speed measurements and by observing yarns for direction.

The water supply line and intake pipes were provided with precalibrated orifice meters. All pipe flows, including that from the waste pipe which was not metered, were controlled by valves. The model was supplied with water by gravity flow from the Mississippi River outside the Laboratory, about 40 ft above the model water surface. Intake pipes operated under suction head created by immersing their discharge ends in the waste channel below the model floor.

The water stage in the model was controlled by establishing the inflow discharge first and then manipulating the waste valve along with the intake valves until the correct intake flows were achieved at the correct stage. This trial and error process was quite rapid and once the flow was established, stage and discharge remained very steady.

D. Sediment

Two grades of sand were used in the model. A coarse sand was selected to reproduce the geometry of the deposit found in the bays as reported in Fig. 1. This sand was immobile and was only intended to establish the flow boundaries for the hydraulic tests of intake performance.

A finer sand was used to study the ingestion problem. It was selected by trial from several sand piles available in the Laboratory so as to be partly transported as suspended load and partly as bed load. The sand's sieve analysis is shown in Fig. 2a. Sieve analyses of sand found in an intake bay and in the river bed about 10 ft outside the intake in the prototype were provided by Union Electric Company and are shown in the same figure. For comparison, typical analyses of sand found at St. Louis, about 40 miles upstream, and reported by the U. S. Geological Survey, are shown in Fig. 2b where the bed sand analysis at Rush Island is replotted from Fig. 2a for comparison.

Sand transport can only be modeled qualitatively, at best. An important quantity in modeling sand transport is the fall velocity of the particles; this should be modeled at proper scale. This means that the model sand should have a fall velocity of about 1/3.5 times the prototype fall velocity. For model sand grains of the same specific gravity as those in the river (as is the case here), this velocity ratio may be obtained if the model sand grain diameters are approximately $1/\sqrt{3.5}$ times the prototype grain diameters. Inspection of Fig. 2a will show this relationship is roughly satisfied for the river bed sand at Rush Island for particles finer than the 50 per cent size; it is even better satisfied with respect to the sand deposited in the intake.

In studying bedload transport, the shear stress on the particles moving along the bed should also be modeled. This is roughly proportional to water velocity squared and to cross sectional area of the particles. Since model velocity is less than prototype velocity, model sand particles must be larger than prototype particles to satisfy this criteria; to satisfy the fall velocity criterion at the same time requires that model particles have smaller specific gravity than sand--like coal, for example. Since sieve analyses of the prototype sands were not available when the model was being designed and tested, it was not possible to design the model sediments to the extent required for good modeling of bedload transport. Thus, the available stock sand as already described was used in the model.

III. MODEL OPERATION

A. Hydraulics of Flow

As already noted, the model study consisted of separate studies of the hydraulics of flow in the intakes first and then of sediment ingestion into the intakes. The hydraulics were eventually re-examined with the proposed sediment control devices in place.

Model Verification - It is desirable to verify a model by comparing model measurements with corresponding prototype measurements. The only comparable measurements that were available in this case were velocity measurements in the river outside the intake at approximately normal river stage. The comparisons are shown in Fig. 3 for two different levels in the flow. In the model, velocity direction fluctuated wildly and the direction finally plotted in Fig. 3 is a "best guess"; the same may be true of the river measurements. The agreement between model and prototype is far from perfect but acceptable. Comparisons were made for this same flow at two other levels, 360.0 ft and 339.5 ft with similar results. Prototype river measurements were also made at stages of 360.0 ft and 385.5 ft, but model measurements were made at the low flow stage of 356.0 ft and flood stage of 408.0 ft so that no other comparisons are available. There was also some verification of the sand deposition pattern reported in Fig. 1 as described below.

Tests at Existing Conditions - The first tests examined operating behavior under existing conditions. These tests were conducted using coarse sand on the bottom of the test bay as in Fig. 1. Photo 3 is illustrative of the flow into the intake pipe in these tests. The principal discovery was that there is a strong, clockwise (as seen from above) prerotation of the flow in the suction bell. The vortimeter appears stationary in the picture only because an exposure of 1/60 sec was used; the vortimeter was blurred and almost invisible at an exposure of 1/8 sec. The prerotation was continuous at all 3 test stages. Such prerotation is capable of forcing the pipe vibrations that have been observed in the prototype.

Crossed-Plate Flow Diverter - A simple means of damping prerotation is to use a crossed-plate flow diverter. The diverter shown in the lower part of Drawing 286-18 was constructed and installed under the suction bell in the model, together with a divider wall, 2 x 6 x 3/4 ft, between the suction bell and back wall of the bay as shown in Drawing 286-17. Photo 4 shows the model in operation with this installation at normal river stage. It may be noted that the vortimeter is at rest in the picture even though the exposure is 1/8 sec. Measurements showed occasional spinning rates of up to 8 rpm in a clockwise direction (looking from the top), but the vortimeter was at rest most of the time. The threads at the periphery of the suction bell showed that the flow was generally steady and radial. There was also a general clockwise circulation at the water surface northeast of the intake pipe. An occasional vortex formed here, but it would disappear almost immediately without becoming fully developed like the vortex in Photo 5. It was observed for this flow that most of the river water entered the test bay downstream of the center pier; there was occasional circulation around the pier at the free surface. The flow pattern was little influenced by whether the fish gates were open or closed.

The flow condition used in taking Photo 4 is not one of those listed in Table 1. Rather, as previously indicated, the model was operated at normal and higher than normal intake flows and at normal and higher than normal river discharges, as well as in combinations of these. Table 2 shows maximum flow quantities used at each stage. The flow for Photo 4 was 4.65 cfs in the river and 0.92 cfs through the intake pipe in the center bay at the stage of 368.0 ft.

TABLE 2. Maximum Flow Quantities, cfs

Stage, ft	Past Intake	Into Center Bay	Total Side Bays
408.0	6.66†	0.92*	1.34
368.0	4.65	0.92*	1.05
356.0	3.67	0.84#	0.93

† Limited by available supply

* Corresponds to 206,500 gpm

Corresponds to 188,500 gpm

The model with the crossed-plate flow diverter was studied extensively with and without sand on the bottom of the intake and with and without sand in the river. The description of the flow associated with Photo 4 is applicable with minor variations to all flow conditions at all stages. At the more normal design discharges listed in Table 1, the water surface was somewhat less disturbed than described above and the circulation at the surface was less noticeable.

At the high intake flows listed in Table 2, the model intake pipe vibrated noticeably (but did not vibrate at normal flows). The only significance this has for the prototype is to warn that there are instabilities present which could cause pipe vibration under suitable circumstances. As already mentioned, the model does not reproduce elastic behavior. It is believed that the simple crossed-plate flow diverter is a useful divice to control the pipe vibrations being experienced in the prototype.

Modified Flow Diverter - The pump manufacturer suggested a more elaborate flow diverter which is shown in the upper part of Drawing 286-18, and it may be seen during operation of the model in Photo 6. The advantage of this design is that it provides points of anchorage for the suction bell. Anchorage may be useful in controlling pipe vibration.

This diverter was not studied for as many flow conditions as the original design. However, enough conditions were examined to know that its hydraulic performance is very much the same as that of the crossed-plate diverter. Only one test was made with both the back divider wall and this modified flow diverter while all the rest were made without the divider wall. The divider wall is not necessary when using the modified flow diverter.

B. Sand Ingestion

At various times during the hydraulic tests described above, sand, whose gradation was shown in Fig. 2a, was introduced into the model just upstream of the fender pile. This was dumped into the river through the surface. Much of this sand settled to the bottom and moved as bedload. Some bedload entered the test bay, especially on the downstream side of the center pier. Suspended sand was also drawn into the test bay, some depositing on the floor and the remainder passing through the intake pipe. The deposition pattern in the model was similar to that reported for the prototype as shown in Fig. 1, except that the depth was much less in the model (to scale) and no deposit was found under the suction bell. To reproduce the thickness reported in Fig. 1, it would have been necessary to run the model for a much longer time than was practicable or to have used larger, lighter sediment particles. The result obtained is indicative, however, that the model is functioning properly.

Observations during the above tests, supported by study of the sieve analyses plotted in Fig. 2a, and the river velocity measurements obtained just above the bottom suggest that most of the sand being deposited in the bays of the prototype comes from the river bed just outside the intakes. One way to control ingestion of bedload is to place a barrier across the bottom of the intake. This was done in the model. At first, a 3 ft high barrier was used and then a 6 ft high barrier was used, both being placed at the bottom of the trash racks as shown in Drawing 286-17. Most of the tests were conducted with the 6 ft barrier.

The barrier caused the sand deposition pattern to be more uniform and the sand to accumulate at a lesser rate than was the case without the barrier. This indicates qualitatively that a barrier can be useful in reducing the rate of sand ingestion, but there is no basis for quantitative prediction. A 6 ft high barrier placed at the bottom of the gate slots was also tried, but this was less satisfactory than the barrier at the trash racks.

To make a more complete and definitive test of the effectiveness of the barrier would again require continuous operation of the model for longer periods than was practicable or use of larger, lighter particles. As in the case of the original condition, this was not done.

While the model was being operated with the sand barrier, it was discovered that the hydraulic flow pattern was altered by the barrier. The most obvious change was that a strong, persistent, rope-like vortex developed northeast of the intake pipe. This may be seen in Photo 5. As noted earlier, an incipient vortex had been observed in the same place without the barrier, but that occurred so infrequently that it could not be photographed. This vortex existed in the model close to half the operating time. This vortex cannot be tolerated for it will undo the solution already proposed for damping the pipe vibrations.

Possibly there are other ways to reduce sand ingestion that would not disturb the hydraulics of the flow into the intake pipes. One possibility is to build guide vane structures into the river bed or on the surface outside the intakes. The model covers too little of the river to permit modeling such structures. Since a possible solution had been found for the sand ingestion problem using barrier walls that was at least partly testable in the existing model, it was decided to rest with this solution. The remaining testing effort would then need to be directed at eliminating the rope-like vortex.

C. Skimmer Wall

Several devices were tried to eliminate the vortex. It was found that increasing the headloss on the downstream side of the central pier of a bay would stop the vortex. Headloss could be increased by placing a perforated screen on the downstream side, only, of the pier or by placing a wall in the gate slot at the downstream side, only. Such unsymmetrical devices are generally undesirable.

Eventually, it was found that a skimmer wall was very effective in eliminating the vortex; it also improved the appearance of the surface flow around the intake. The skimmer wall that was tested is shown in Drawing 286-17. The wall extends from the top of the bay down to elevation 353.0.

The measured headlosses for the 6 ft barrier and for the skimmer wall are given in Table 3.

TABLE 3. Measured Headlosses, Prototype, ft

Stage	6 ft Barrier	Skimmer Wall
408.0	0.19	0.25
368.0	0.13	0.41
356.0	0.23	0.42

Much more model operation data is available than has been reproduced herein. However, the data have been summarized by the discussion. A project log is available in the records of the St. Anthony Falls Hydraulic Laboratory containing specific test results for each of the test conditions.

IV. SUMMARY AND RECOMMENDATIONS

A 1:12 scale model of the Rush Island Plant intake structure was constructed and operated in accordance with the Froude Model Law. The model sought causes and remedies for the intake pipe column vibrations and also explored the problem of sand injection from the river.

The model was verified using the limited field data that could be obtained. This consisted of certain velocity traverses outside the intake for which the comparison is illustrated in Fig. 3 and in reproducing the sand pattern found in one of the intake bays as reported in Fig. 1.

Operation under existing conditions indicated that there is a strong prerotation in the flow entering the suction bell. This could be the cause for pipe column vibration. Flow diverters as shown in Drawings 286-17 and -18 worked well in damping the prerotation.

It is recommended that such a diverter be installed under each bell. This should be done whether or not any steps are taken to control sand ingestion. Both diverters shown in Drawing 286-18 work equally well; the modified one shown at the top of the drawing may be preferable because it provides a firm anchorage for the bottom of the suction bell. If the simpler crossed-plate diverter is used, a divider wall as shown in Drawing 286-17 should also be installed between the suction bell and back wall of each bay.

The model scale was too large to be capable of examining all aspects of the sand ingestion problem. However, it was found that a 6 ft high barrier wall placed at the bottom of the trash racks at the entrance to each bay will reduce the rate of sand ingestion. This conclusion is partly due to model observation and partly to the result of examination of the sieve analyses of sands found in an entrance bay and in the river outside; the analyses, shown in Fig. 2a, indicate that most of the ingested sand comes from the river bed outside rather than from suspended sand in the water. It must be recognized that some sand will be carried over the barrier by vortices and secondary currents in the river. There may also be some erosion of the river bed adjacent to the wall at the intake. But overall, the barrier should be useful in materially alleviating the sand ingestion problem.

If the barrier is installed, it is necessary to also install a skimmer wall in each intake bay. The model installation is shown in Drawing 286-17. The wall is located just downstream of the downstream nose of the central pier. It is possible to install it somewhat further upstream, say up to 6 ft, without negating the model results. The wall is required to still a rope-like vortex that results from the barrier at the trash racks; in addition to eliminating this vortex, the skimmer wall also improves the general behavior of the flow around the pipe column.

If it is desired to reduce the rate of sand ingestion, it is recommended that the 6 ft high barrier at the trash racks and the skimmer wall, as shown on Drawing 286-17, be installed in each bay. Whether or not a sand barrier is used, it is necessary to install a flow diverter under the suction bell as previously described.

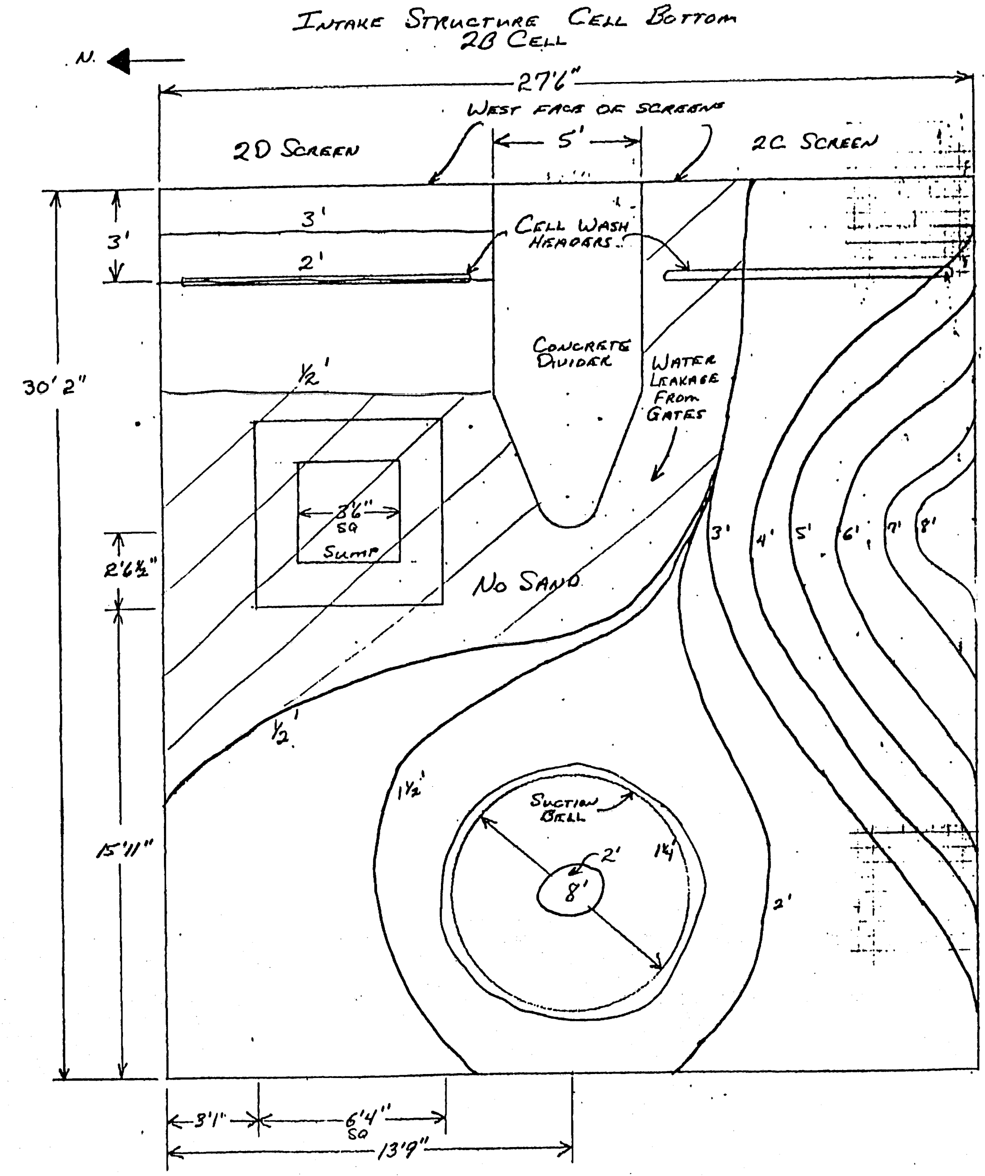
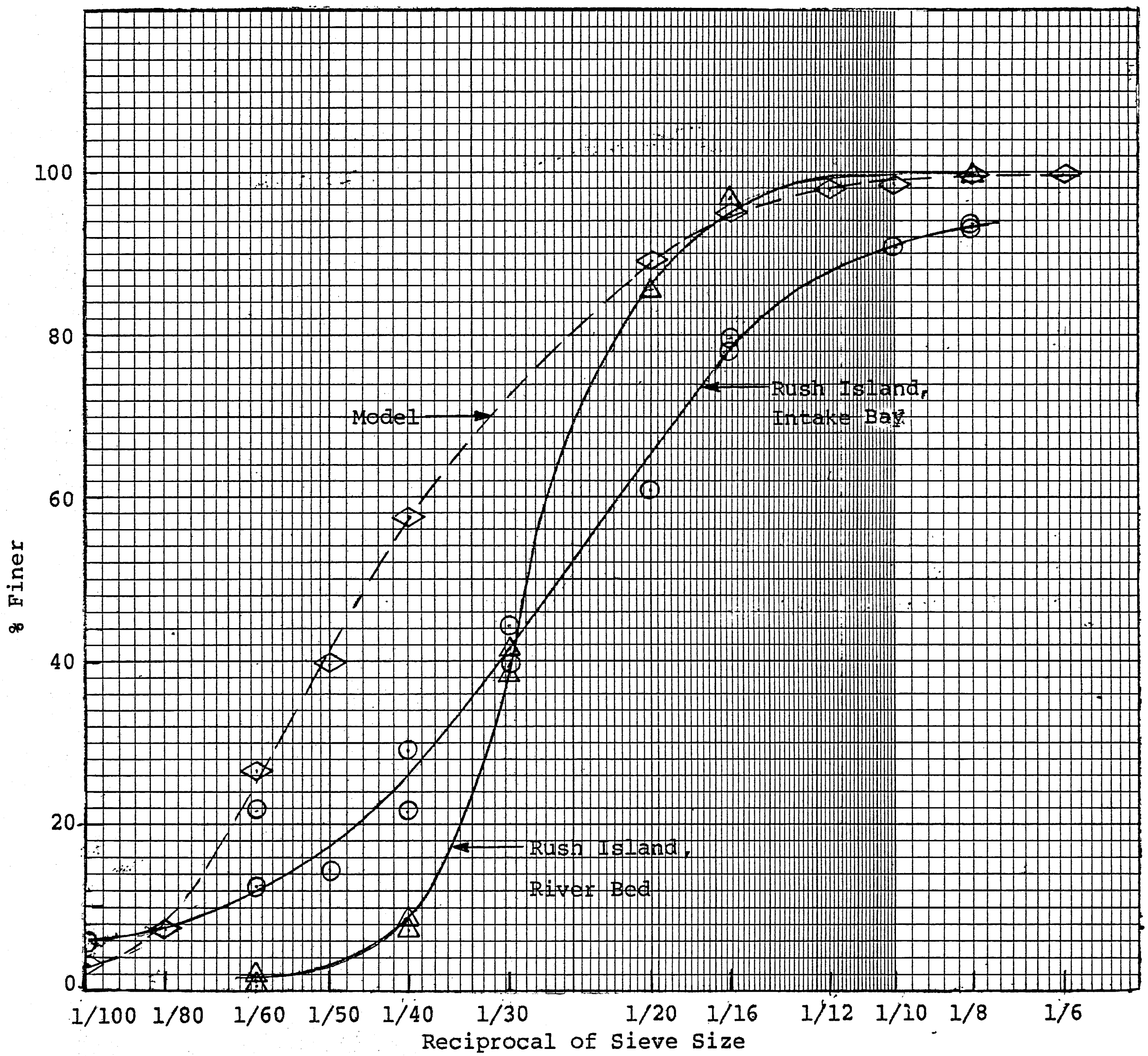
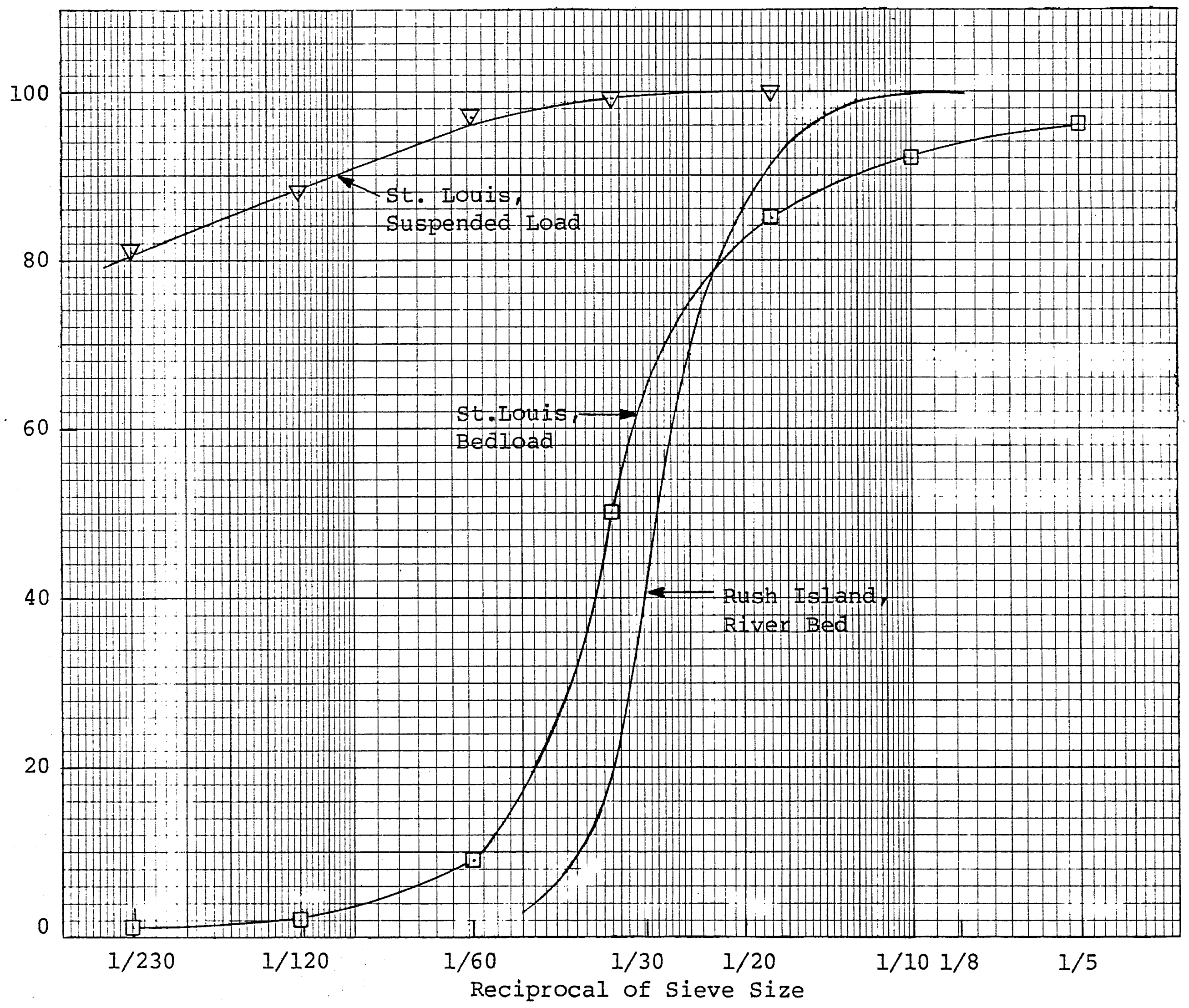


Fig. 1. Sand Deposit Measured in Prototype Bay. (Contours in feet above bottom.)



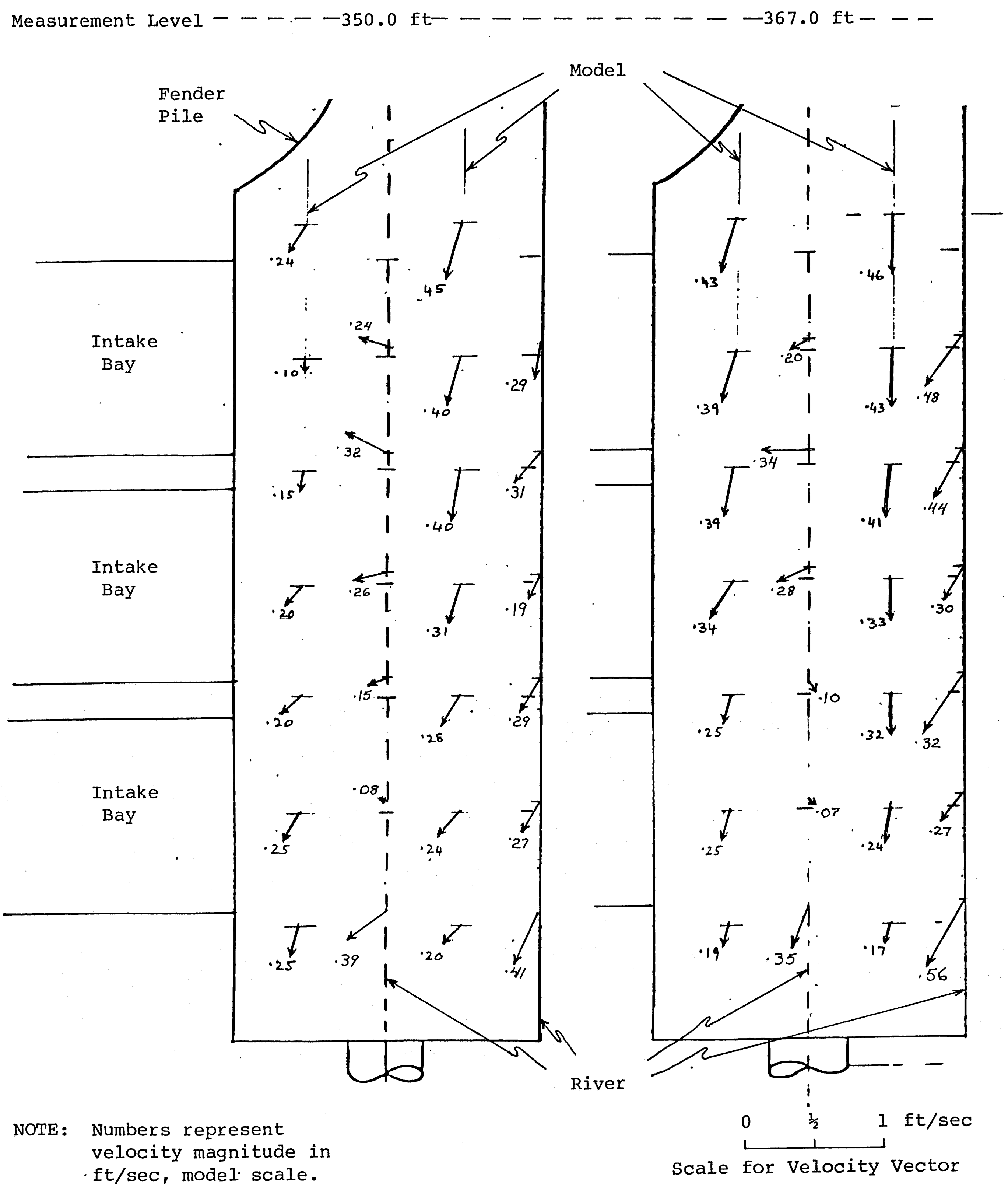
a) At Rush Island and in Model

Fig. 2. Sand Gradation.



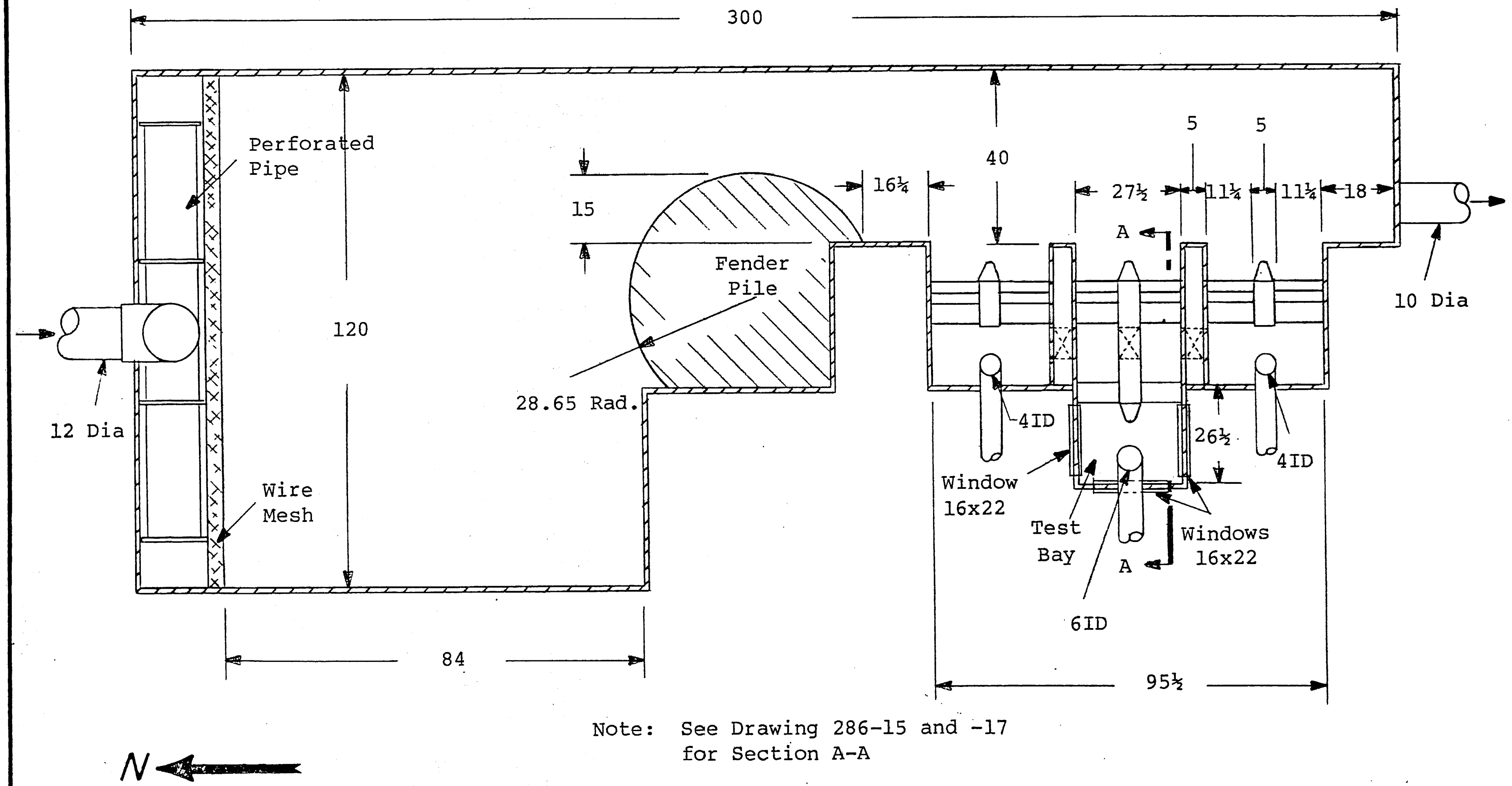
b) At St. Louis

Fig. 2. Sand Gradation.



NOTE: Numbers represent velocity magnitude in ft/sec, model scale.

Fig. 3. Velocities Measured in Model and River.
Stage 368.0 ft, Model; 367.0 ft, River



Note: See Drawing 286-15 and -17
for Section A-A

PLAN

RUSH ISLAND INTAKE MODEL

Model Scale 1:12
Read all dimensions in inches, model
or feet, prototype (where applicable).

SAINT ANTHONY FALLS HYDRAULIC LABORATORY **UNIVERSITY OF MINNESOTA**		
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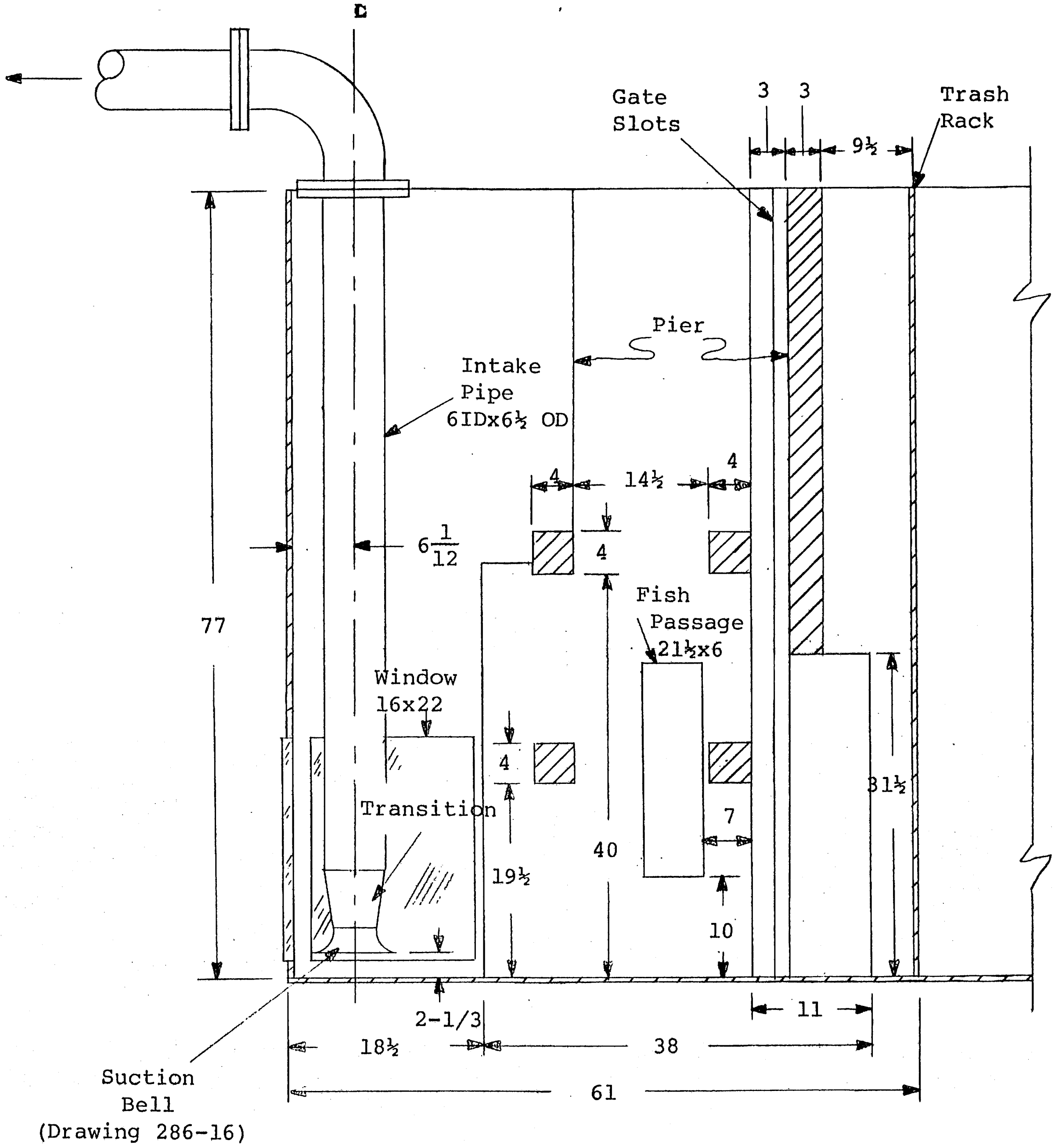
SCALE 1"=36"	DATE 3/20/80	NO. 286-14



ELEVATION, SECTION A-A

RUSH ISLAND INTAKE MODEL

Model Scale 1:12
Read all dimensions in inches, model
or feet, prototype (where applicable).

SAINT ANTHONY FALLS HYDRAULIC LABORATORY **UNIVERSITY OF MINNESOTA**		
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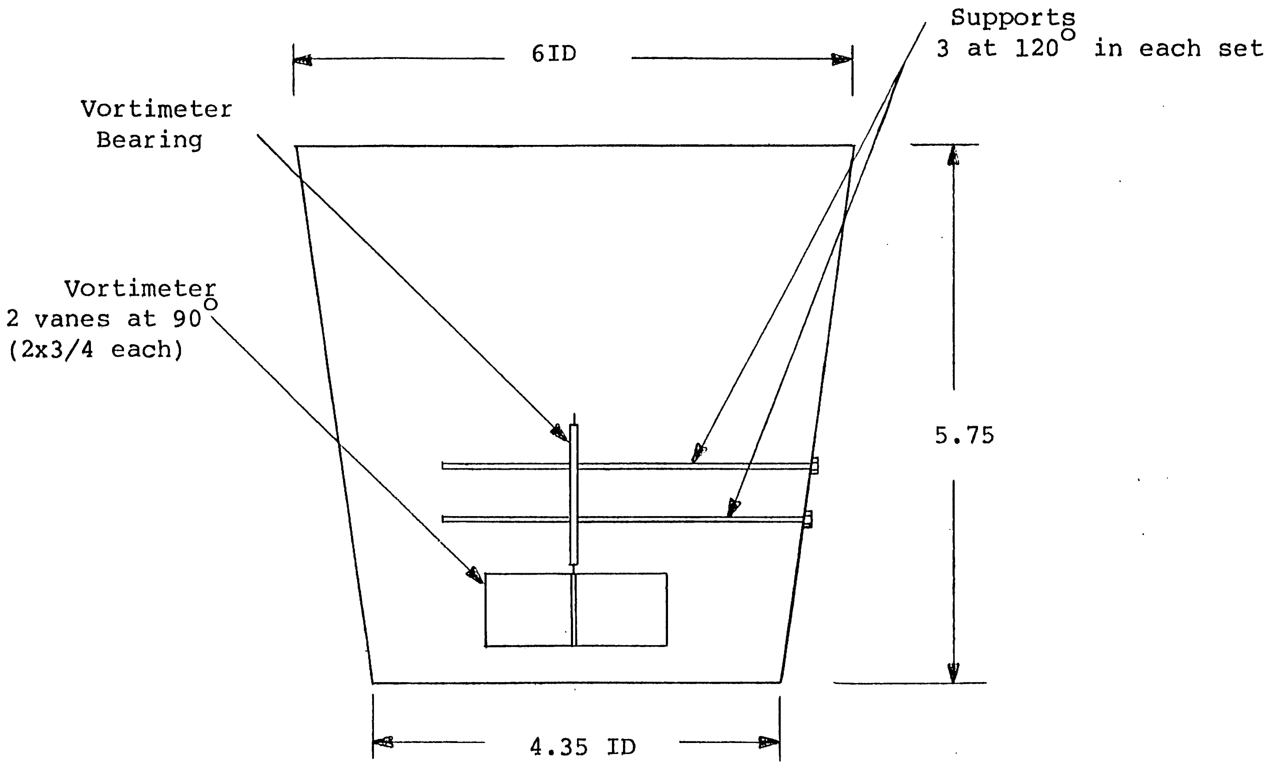
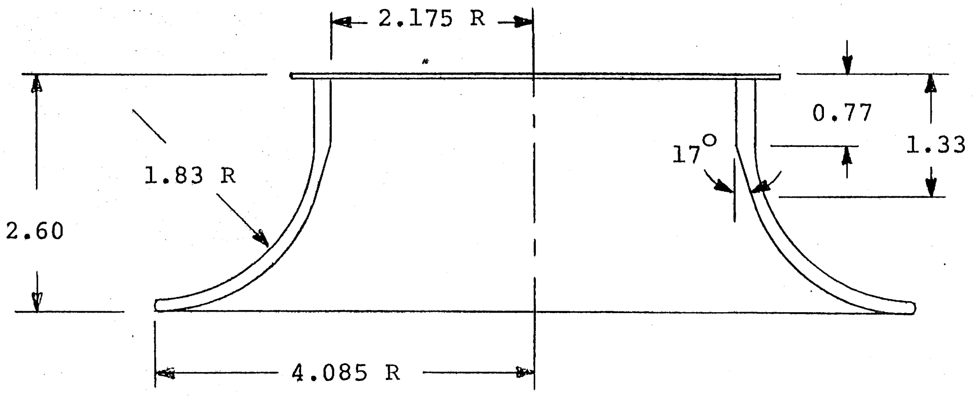


TRANSITION AND VORTIMETER



SUCTION BELL

SUCTION BELL & TRANSITION

RUSH ISLAND INTAKE MODEL

Model Scale 1:12
Read all dimensions in inches, model
or feet, prototype (where applicable).

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UNIVERSITY OF MINNESOTA

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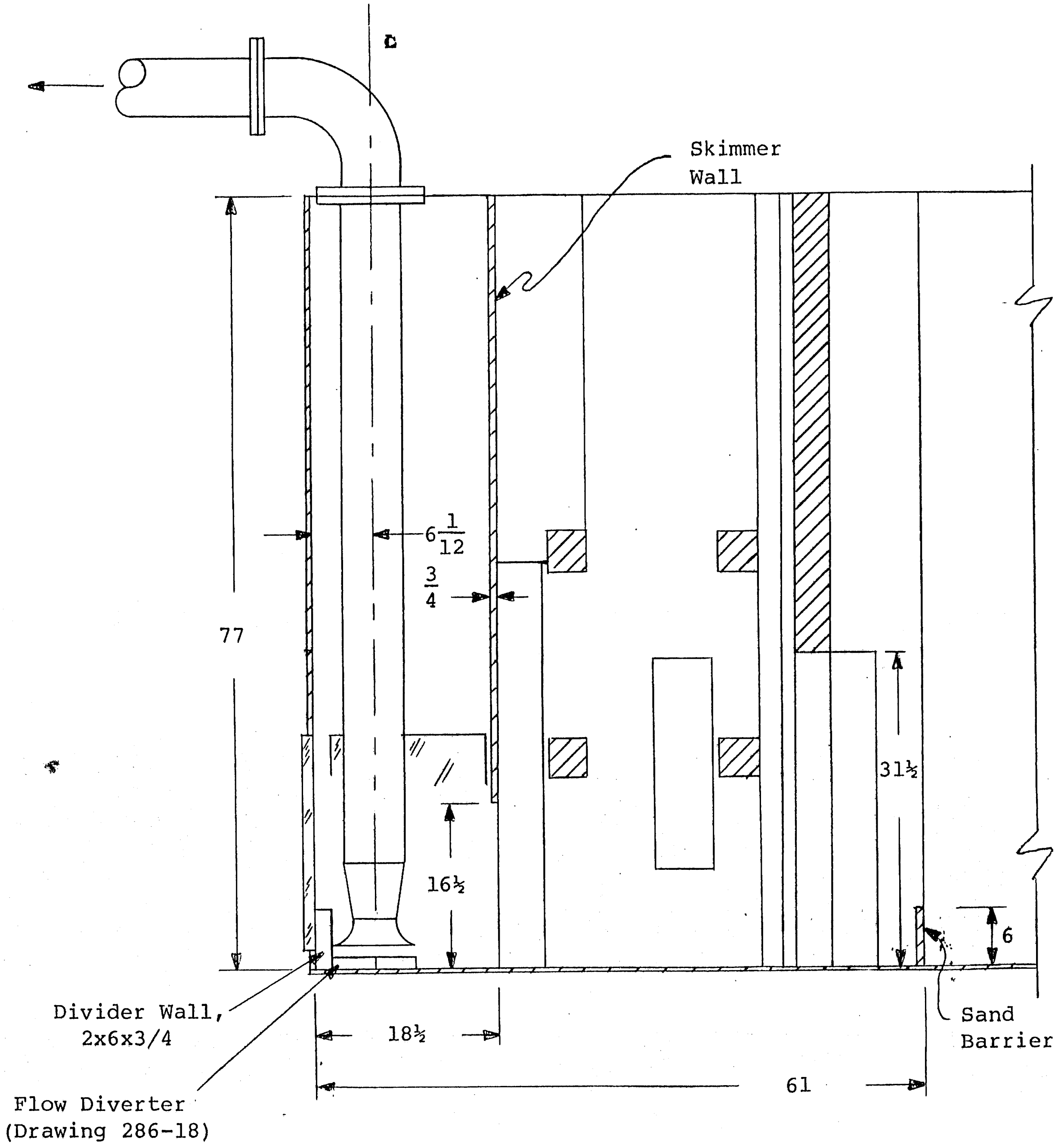


MODIFIED MODEL

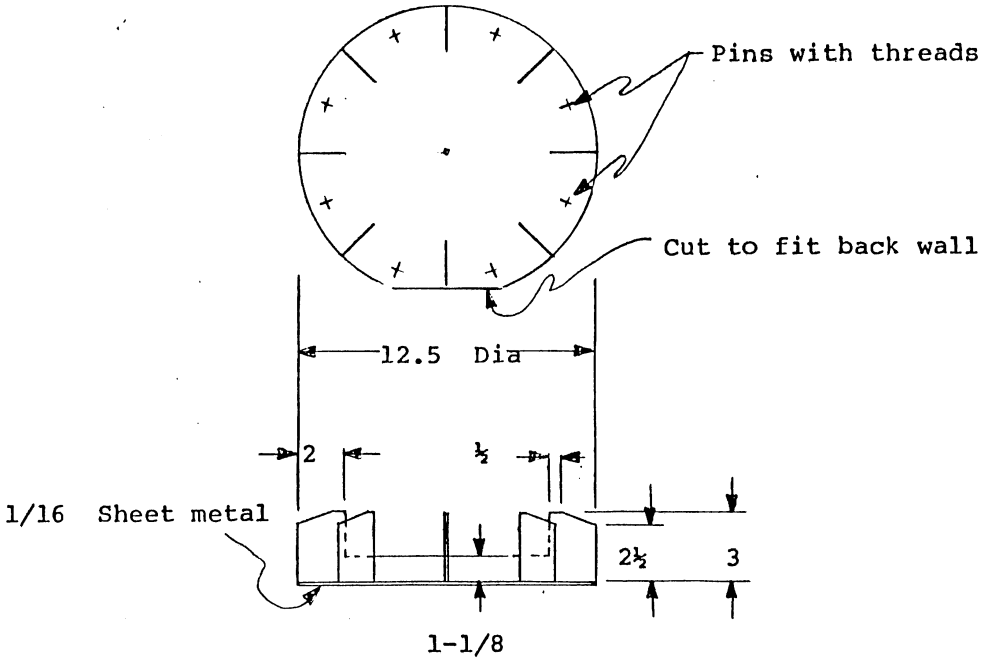
ELEVATION, SECTION A-A

RUSH ISLAND INTAKE MODEL

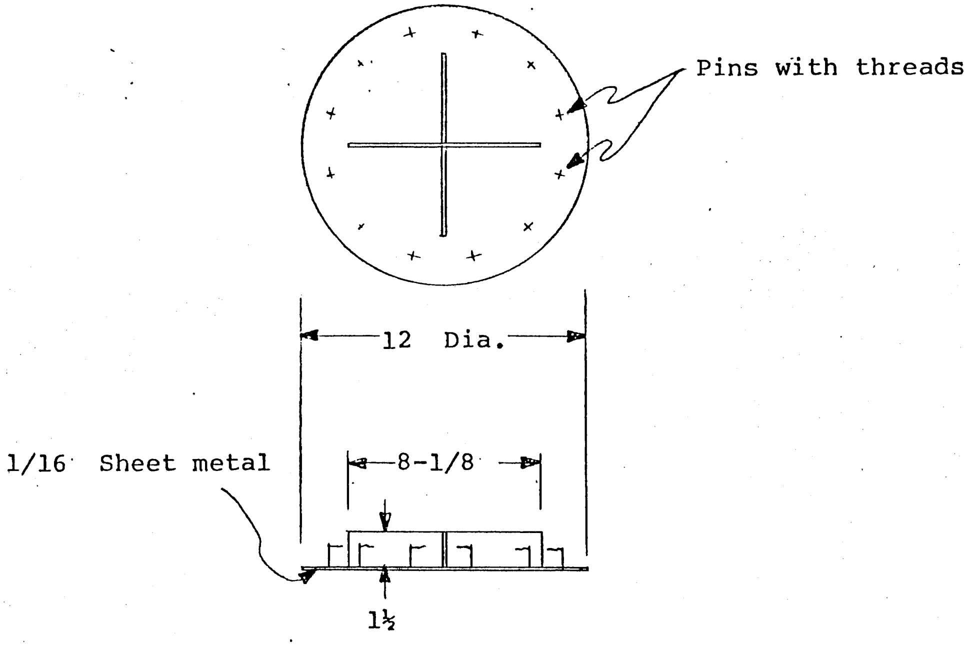
Model Scale 1:12
Real all dimensions in inches, model
or feet, prototype (where applicable).

SAINT ANTHONY FALLS HYDRAULIC LABORATORY
UNIVERSITY OF MINNESOTA

DRAWN DA	CHECKED	APPROVED ES
SCALE 3/4"=12"	DATE 3/20/80	NO. 286-17



MODIFIED FLOW DIVERTER



FLOW DIVERTER

RUSH ISLAND INTAKE MODEL

Model Scale 1:12

Read all dimensions as inches, model or feet, prototype (where applicable).

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DRAWN D.A.	CHECKED	APPROVED ES
SCALE 1/8"= 1"	DATE 3/20/80	NO. 286-18

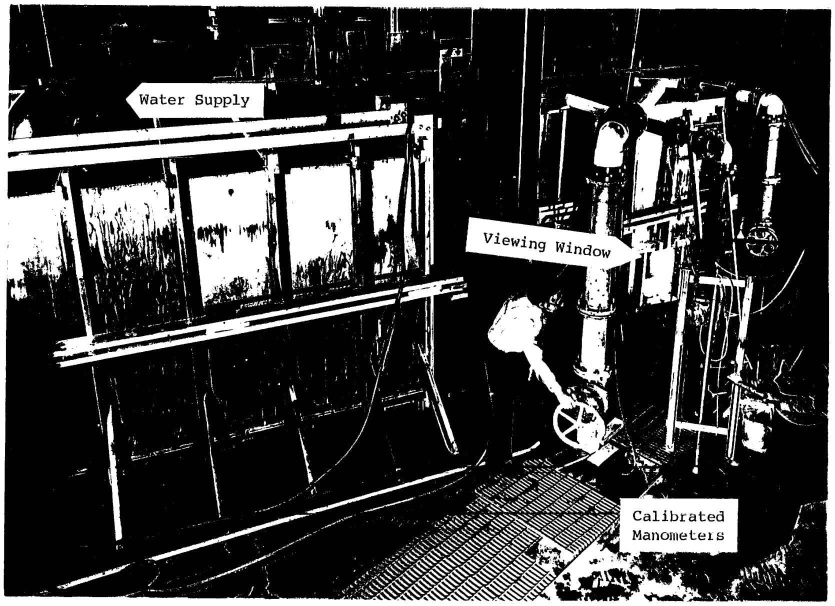

Photo No. 1 (286-26). Model from Shore Side.

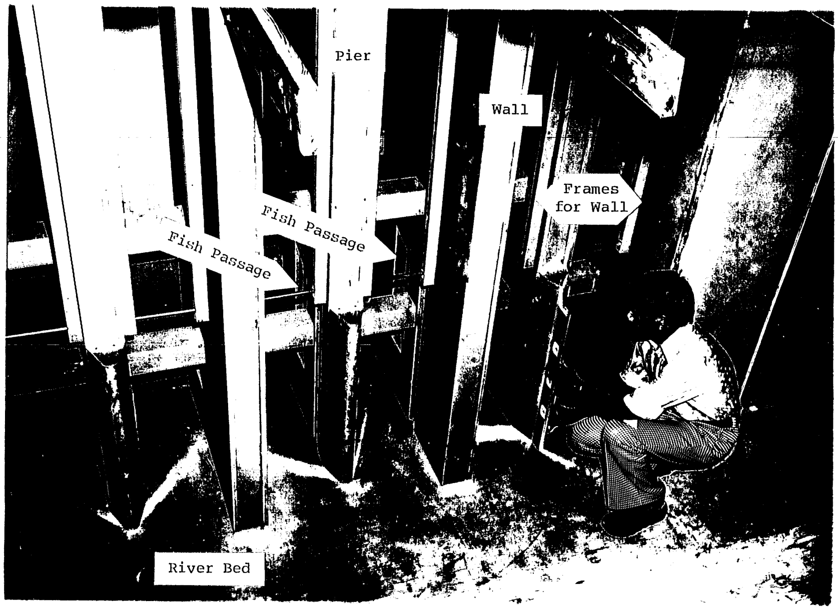

Photo No. 2 (286-8). Model Under Construction from River Side.

Photo No. 3 (286-11). Intake, Original Conditions.

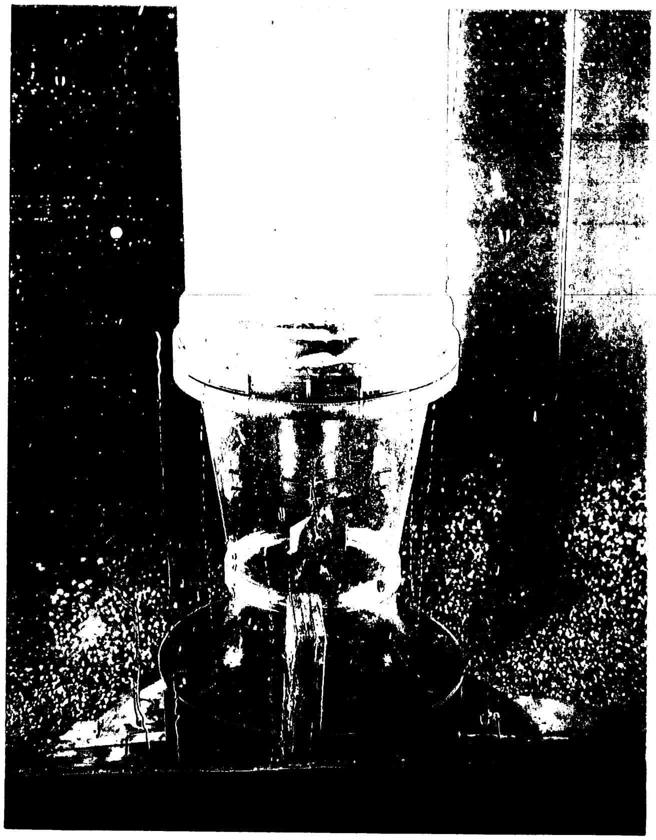

Photo No. 4 (286-14). Intake with Cross-Plate Flow Diverter.

Photo No. 5 (286-23). Rope-Like Vortex.

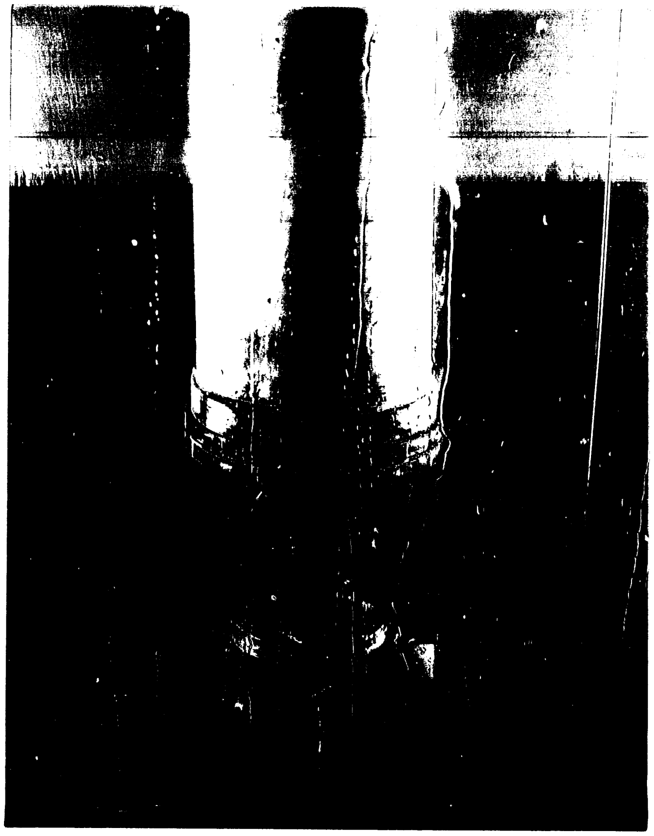

Photo No. 6 (286-31). Intake with Modified Flow Diverter.