MASSACHUSETTS INSTITUTE OF TECHNOLOGY

HYDRODYNAMICS LABORATORY

DEPARTMENT OF CIVIL AND SANITARY ENGINEERING

TECHNICAL NOTE No. 3

DESIGN OF A CLOSED JET, OPEN CIRCUIT WATER TUNNEL FOR THE STUDY OF WAKE MECHANICS

by

G. H. TOEBES, F. E. PERKINS AND P. S. EAGLESON

APRIL 1958

PROGRESS REPORT
PREPARED UNDER
CONTRACT No. Nonr–1841 (12)
DAVID TAYLOR MODEL BASIN
U. S. DEPARTMENT OF THE NAVY
WASHINGTON, D. C.

HYDRODYNAMICS LABORATORY

Department of Civil and Sanitary Engineering
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The design and much of the construction was carried out at the Hydrodynamics Laboratory of the Massachusetts Institute of Technology by Messrs. G. H. Toebes, F. E. Perkins and C. A. Givler, Research Assistants, under the general direction of Dr. A. T. Ippen, Professor of Hydraulics, and under the technical supervision of Dr. P. S. Eagleson, Assistant Professor of Hydraulic Engineering.

The large steel weldments were fabricated in local commercial shops.

ABSTRACT

This Technical Note describes the design of an open-circuit water tunnel with a 7-1/2 inch by 9 inch closed-jet working section. The maximum velocity obtainable in the empty test section is approximately 50 fps.

The water tunnel was built for the purpose of investigating wakes behind objects placed in its test section. In particular, a study is to be made of the relationship between the trailing edge geometry of two-dimensional flat plates, the frequency of vortex shedding from them and the resulting elastic response of the plates when placed at zero angle of attack.

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I. INTRODUCTION

1. Program Objectives

Wake phenomena have been found responsible for many of the operational difficulties with structures, structural components, propellers and turbines. Periodicities in the wake may bring about excitement of elastically responsive structures to transverse oscillations of sometimes destructive amplitude. Von Karman early defined the mechanism of disturbances created by submerged bodies in the "vortex-street" bearing his name. While much has been done to investigate the decay of these vortex streets into random turbulence, the detailed mechanism of the flow field adjacent to the generation area of the vortices has not received much attention. It is believed that design information of considerable value may be obtained by exploring the characteristics of such vortex streets in more detail.

An investigation directed at the flow conditions in the immediate neighborhood and downstream of the submerged body was initiated in the Hydrodynamics Laboratory at the Massachusetts Institute of Technology in June, 1957, under the sponsorship of the Office of Naval Research for the David Taylor Model Basin.

The objective of the program is limited to the detailed study of the wake behind a two-dimensional flat plate held at zero angle of attack in a high velocity stream. This objective will permit consideration of such experimental factors as: correlations between frequency of vortex shedding and flow parameters; correlations between free and induced vibrations of the plate and the wake structure; correlations between total plate drag, trailing edge modification, and flow parameters. Also cavitation in the cores of vortices shed from the plate may have to be considered.

This note is a description of the design of a water tunnel of moderate size which is needed for conducting the investigation outlined above.

2. Basic Design Considerations

The experimental facilities at the Hydrodynamics Laboratory include three circulation pumps connected in parallel to an 18-inch header. The design of the water tunnel proceeded on the basis of using these pumps for the water supply.

The capacity of the pumps was thus defined beforehand. Because of the fixed distance between floor openings at the water tunnel location the horizontal dimension of the water tunnel was fixed. Within these restrictions, it was necessary to balance riser and draft tube dimensions, contraction ratio, maximum velocity obtainable in the test section, needed diffuser length and the loss of head in all components.

Several possible tunnel designs were investigated. The estimated head losses for each, compared with the combined pump characteristics suggested a test section of 60 to 70 square inches in order to obtain velocities up to 50 fps.

The circulating pumps receive water from a large basin beneath the main floor of the laboratory. It is preferable that all pumps remain available for other uses in the laboratory; therefore, the tunnel was designed as an open circuit, single-pass tunnel in which the water supply is a free surface reservoir.

Although the study will be primarily concerned with the wake near its point of generation it is expected that conditions further downstream of the object will eventually become of interest. It is therefore not appropriate to employ an open-jet design as instabilities of the jet occur if it is made much longer than one jet diameter. Also, since cavitation is not a primary concern in this investigation, the use of a free-jet tunnel was not considered. The selected closed-jet working section has the disadvantage of possible wall interference and also produces axial nonuniformity in the jet due to boundary layer growth.

The latter effects may readily be kept small in this case due to the thin nature of the bodies to be tested. The latter effect may be further reduced by flaring the test section in the direction of flow.

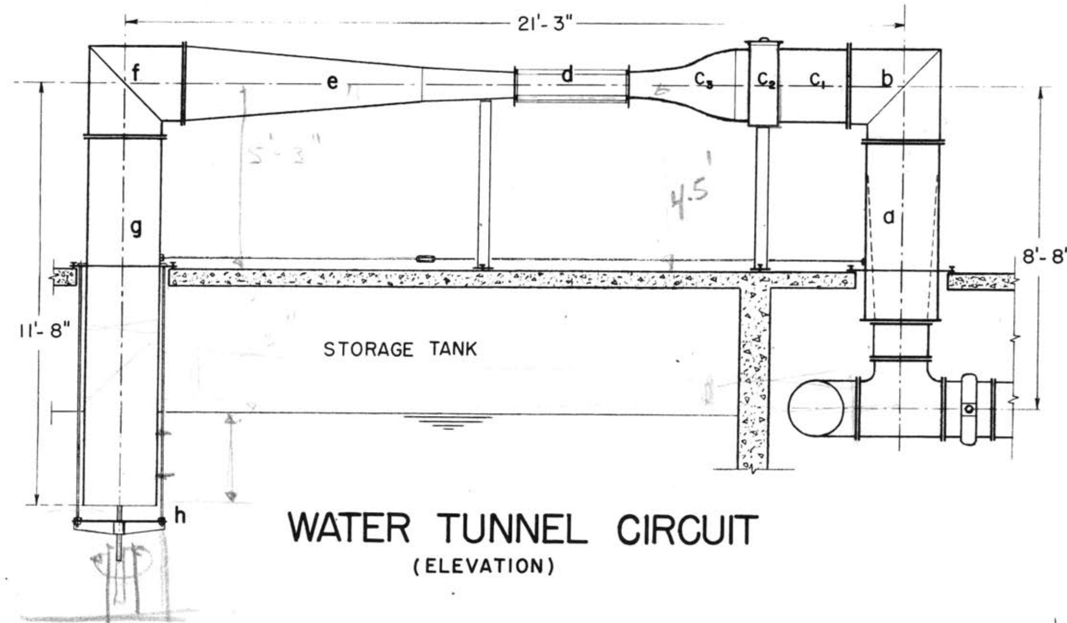
II. TUNNEL COMPONENTS

1. General Description

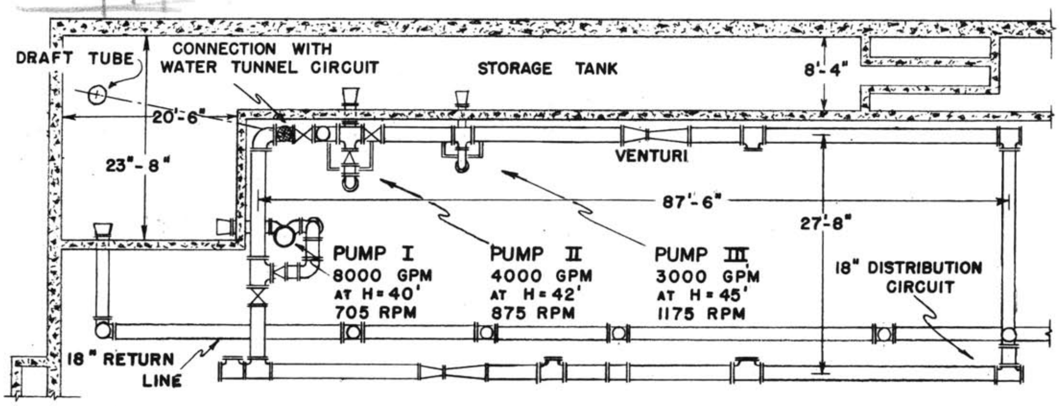
The flow circuit may be divided into two main parts which are indicated schematically in Figure 1.

The first of these lies in a horizontal plane and consists of an 18-inch header pipe in the form of a closed loop having overall dimensions of 25' x 90'. This circuit is suspended just below the ceiling in the basement of the laboratory and is intended for the distribution of flow to all parts of the main laboratory hall. It may receive water from any or all of three centrifugal pumps which have rated capacities of 8,000; 4,000; and 3,000 gallons per minute, respectively, at heads of approximately 40 feet. The flow rate may be varied by means of remotely controlled motor-operated valves located on the discharge side of the pumps. All pumps draw water from a common 75,000 gallon free surface storage tank in the basement and are so placed as to have a positive suction head.

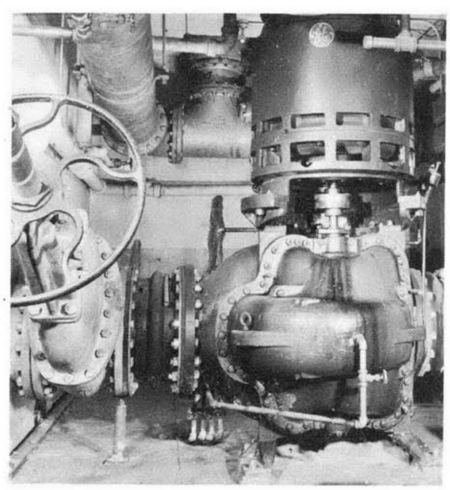
The second part of the flow circuit has overall dimensions of 12' x 21' and lies in a vertical plane. It consists of a series of elements designed



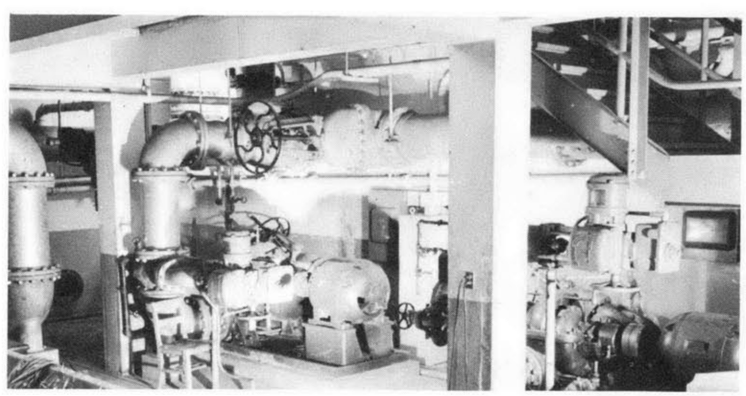
WATER TUNNEL CIRCUIT
(ELEVATION)



CIRCULATION PUMPS AND DISTRIBUTION CIRCUIT
(PLAN)



Pump I



Pump II and III

Figure 1. Water Tunnel, Pressure Circuit and Circulation Pumps

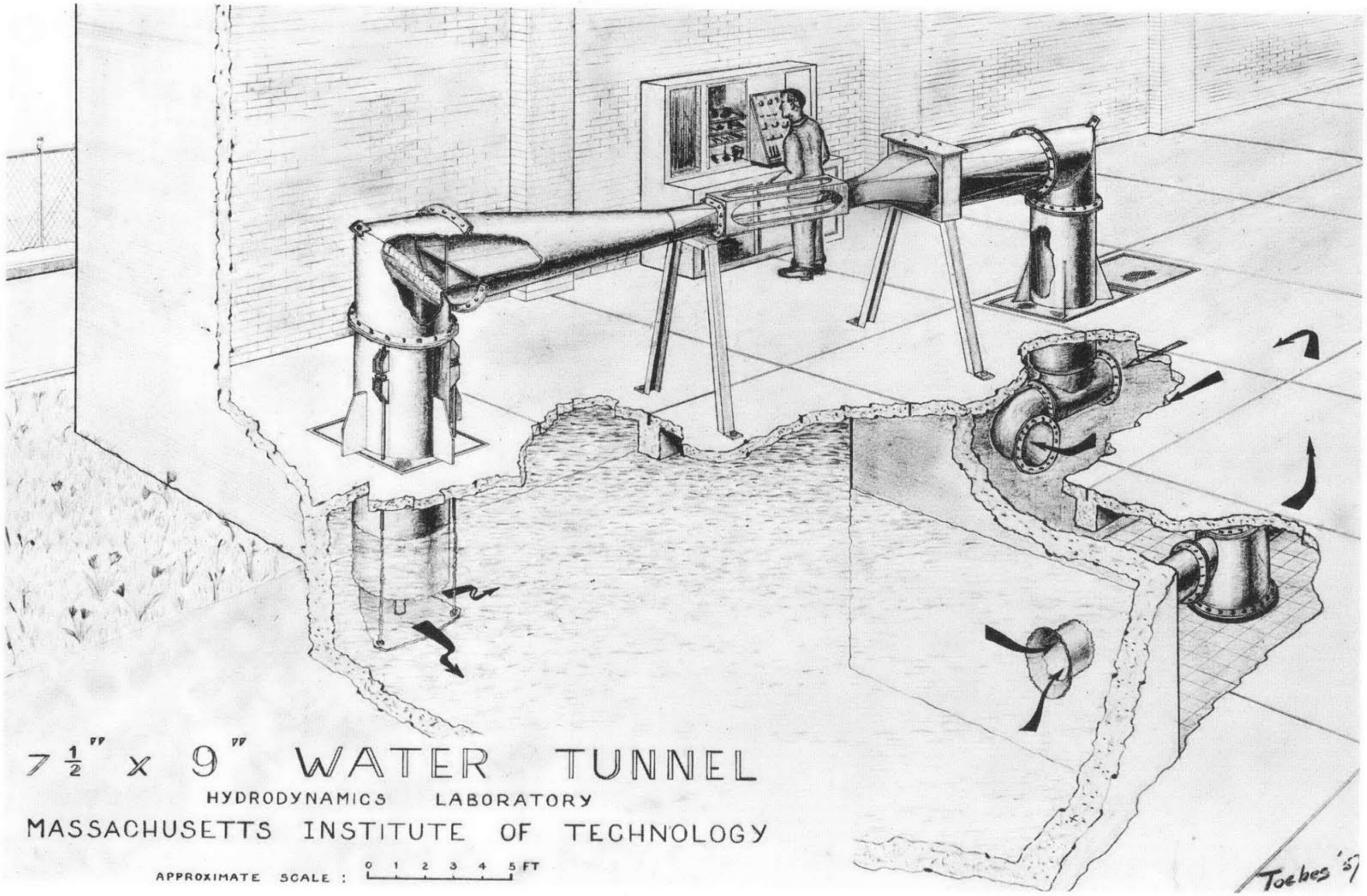


Figure 2. Design of Water Tunnel

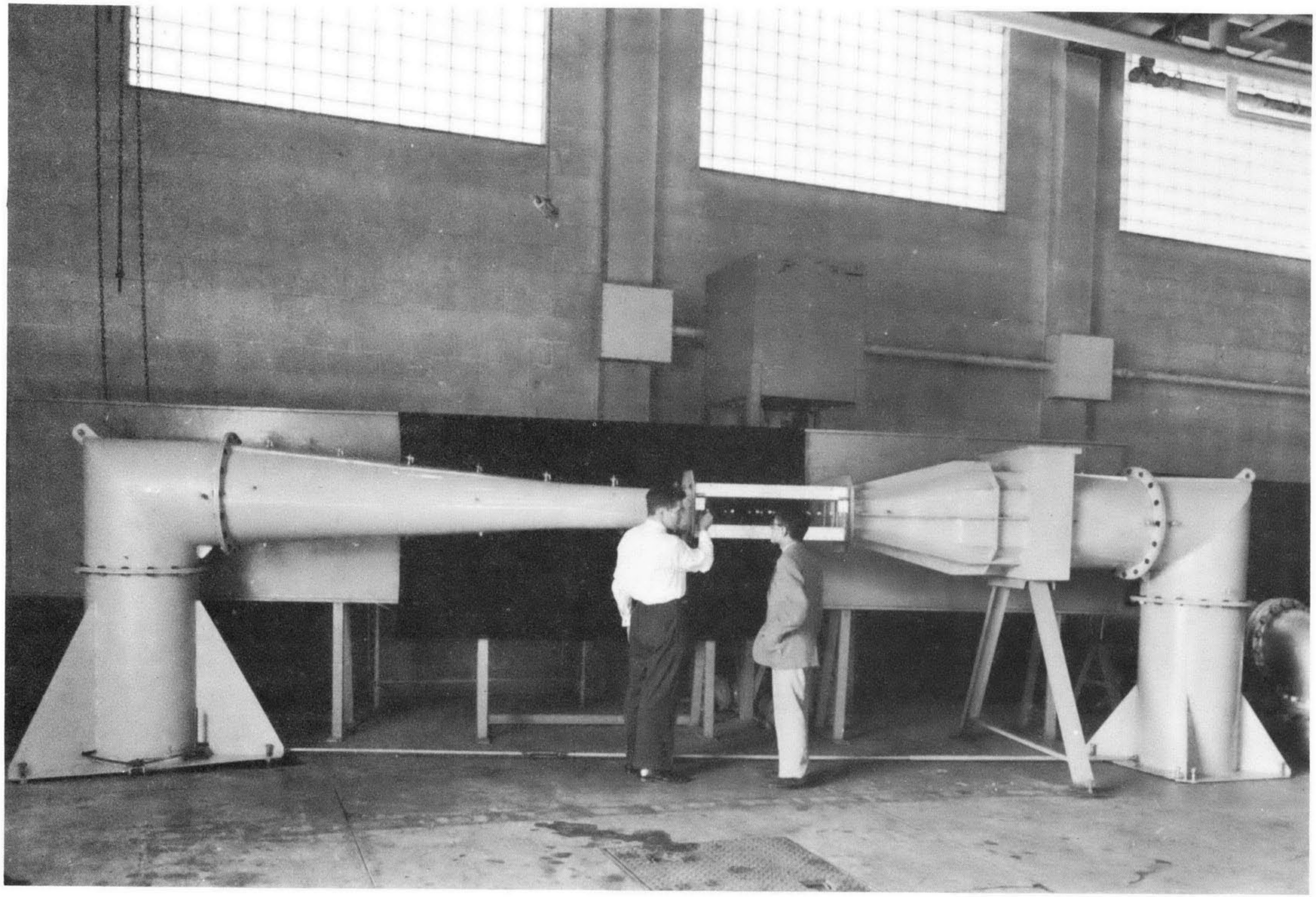


Figure 3. Assembled Water Tunnel

to produce a flow of desired character in the test section. Proceeding downstream from the junction with the header pipe and referring to the lettered items of Figure 1 there are:

a. An expanding riser which brings the water from the 18-inch header up to a 24-inch diameter at a suitable elevation above the main floor of the laboratory hall.

b. A 24-inch mitered elbow fabricated from 24-inch pipe and including 15 guide vanes situated in the mitered plane.

c. A composite transition, screen housing and contraction with overall length of 6' 2". This item includes:

   1. A 24-inch long transition from the 24-inch round elbow section to an octagonal one of slightly larger area.

   2. A screen assembly housing.

   3. A 33-inch long contraction composed of 8 pieces of thin steel plate dressed to carefully shaped ribs. This unit provides a transition from the octagonal screen section to the filleted rectangular test section

d. A 36-inch long test section of essentially rectangular shape, 9 inches high and 7 1/2 inches wide. This unit is fabricated from 1 inch thick plexiglass reinforced by external aluminum members.

e. A 9-foot long diffuser fabricated from steel plate and divided into four equal flow channels by two continuous orthogonal splitter vanes. By means of this unit the 7 1/2 inch x 9 inch test section is brought back to a circular section of 24-inch diameter.

f. A second mitered elbow similar to the bend mentioned under b.

g. A 10-foot long draft tube of circular cross section 24 inches in diameter. The downstream end of this unit is below the free surface in the water storage tank.

h. A plate valve for regulation of pressure level within the tunnel.

In some cases it will be desirable to mount the test plate horizontally rather than vertically as is currently planned. Although the positions of the transition, contraction, test section, plate and diffuser are fixed relative to one another, this entire assembly may be rotated 90° at the mitered elbows thus allowing the desired rotation of the test plate.

Pressure taps have been provided along the axis of both elbows, the transition, contraction and the diffuser.

All steel components of the water tunnel were joined employing a "sandwich" consisting of a 1/16 inch rubber gasket between two 1/16 inch asbestos gaskets.

2. Riser

The 5 foot long riser forms the connection between the 18-inch header suspended below the laboratory floor and the first 24-inch mitered bend. The actual method of construction followed from the availability of 24-inch O.D. steel pipe. The pipe has a wall thickness of 5/16 inch and a length of 5' 2" and was used as the structural element of the riser. Inside this pipe a 5 foot high truncated cone fabricated from 12 gage steel plate is tack welded to provide the necessary transition between tee and elbow, (see Figure 1).

The desire not to add additional structural load to the header line, the possibility of vibration isolation and the need for easy adjustment in elevation resulted in resting the riser on the laboratory floor via jacking bolts. These bolts are held in nuts welded to the underside of a square 1/4 inch collar plate around the riser pipe. In this fashion a vertical adjustment of the riser of several inches is possible if a suitable filler between riser and tee is provided for.

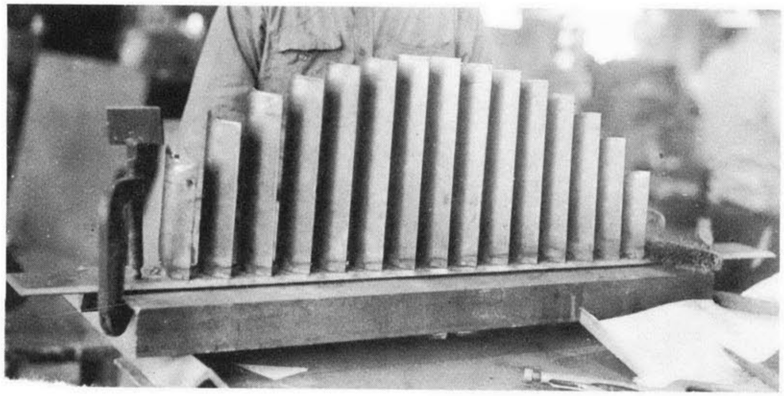
In order to prevent local separation of the flow a circular groove which remained at the connection of riser and tee was filled with a commercially available hardening compound of plastic resin and steel particles.

3. Mitered Elbow

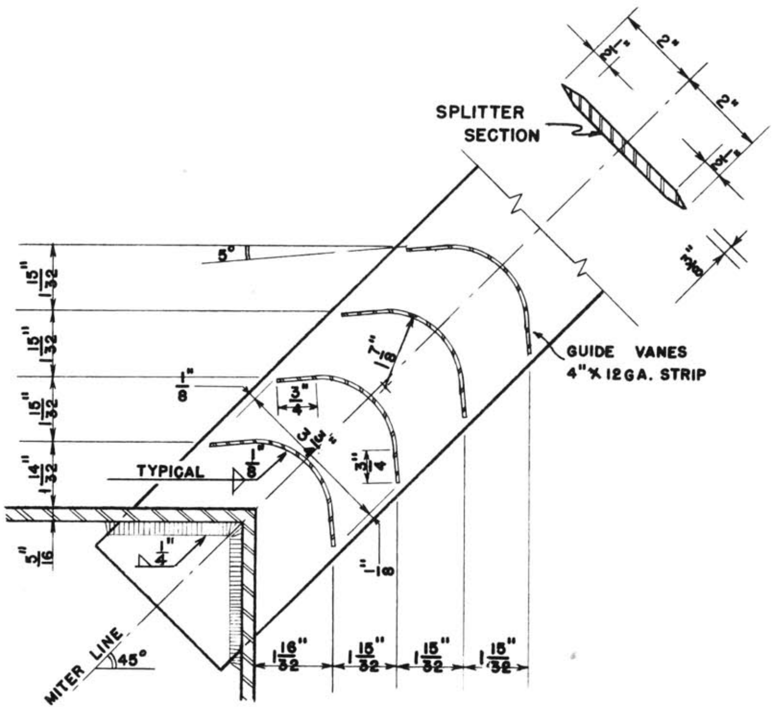
The mitered elbow, which connects the riser to the transition piece in the horizontal part of the water tunnel, turns the flow through a right angle with a minimum of separation and secondary motions. A length of 24-inch pipe was flame cut at a 45 degree angle, one end turned over and the two parts butt-welded together. After this, flanges were welded to both ends of the formed elbow.

The 15 guide vanes which form an integral part of the mitered elbow are made from 12 gauge, 4 inch wide steel strips and are welded to a faired splitter vane (see Figure 4). The vane is located in the plane of symmetry of the bend. It projects through slits in the walls and is welded to the outside of the elbow. At the other end the guide vanes are tack welded to the wall of the elbow.

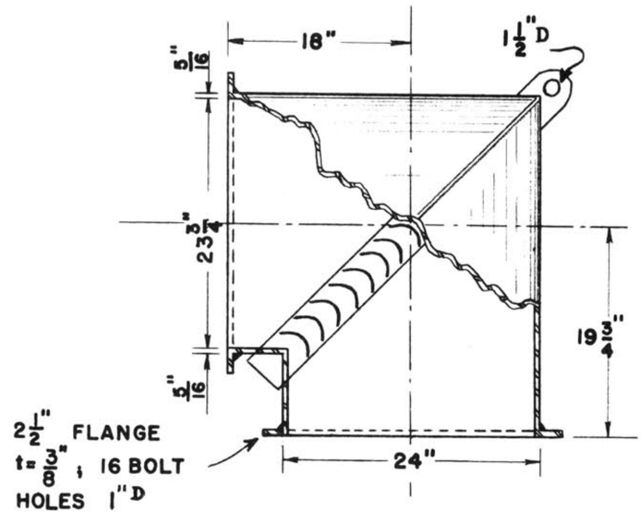
The cross sections of the vanes are of the circular segment type with a 1-7/8 inch radius for the circular segment and 3/4 inch tangents. Their center to center spacing was taken as 1-15/32 inch. Following recommendations of Ripken (1) the angle between vane chord and the miter plane was set at 95°in order to insure axial flow immediately before and after the turn.



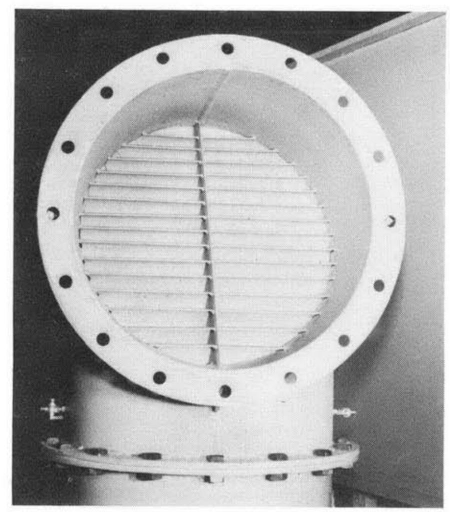
Welding of Set of Vanes



DETAILS OF VANES AND SPLITTER



LOCATION OF GUIDE VANES



Completed Elbow

Figure 4. Mitered Elbow

4. Screen Installation

It is reasonable to expect that the 24-inch elbow at the upstream end of the water tunnel circuit will give rise to a rather nonuniform velocity distribution. Provisions for the insertion of damping screens upstream of the test section have therefore been made. The screens are placed in the low-velocity approach section upstream of the contraction to break up large eddies into smaller ones which attenuate more rapidly. Consequently, the velocity distribution tends to become more uniform. The design of the screen assembly has been based on pertinent literature about damping screen characteristics (2, 3).

The housing for the screens consists of a U-shaped frame of 10 inch steel channel. This frame connects the two foot long transition (upstream) and the three foot long contraction (downstream) into an integral unit (see Fig. 5). The open side of the channel frame is closed off with a removable cover plate and sealed with a rubber gasket. The transition which connects the mitered elbow with the screen housing was fabricated by welding together two symmetrical developments formed from 10 gauge steel plate. The contraction will be discussed in the next section.

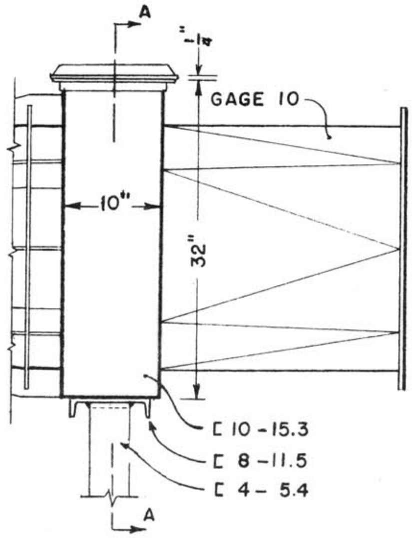
The stainless steel screening is clamped between screen frames made from 3/8 inch steel strip. The frames are drawn together in pairs by means of counter sunk brass screws. The insides of these frames which form a part of the flow conduit when the screens are in place were all carefully aligned. In total the screen housing can accomodate a sandwich of nine such screens. Since a proper choice for the make-up of the screen assembly can only be made empirically it has been decided to adopt for the initial tests an assembly of four screens. If proven necessary this number can be increased later. This flexibility calls for fillers between the screen frames which also form a part of the wall of the flow passage. Three of these fillers made of 1-1/2 x 2 inch air-dried mahogany were combined with three screens to form one sandwich.

To increase their life and minimize swelling, the mahogany fillers were given several coats of marine-type spar varnish. Since some swelling will inevitably occur a 1/2 inch thick neoprene sponge rubber filler was added between the screen frames.

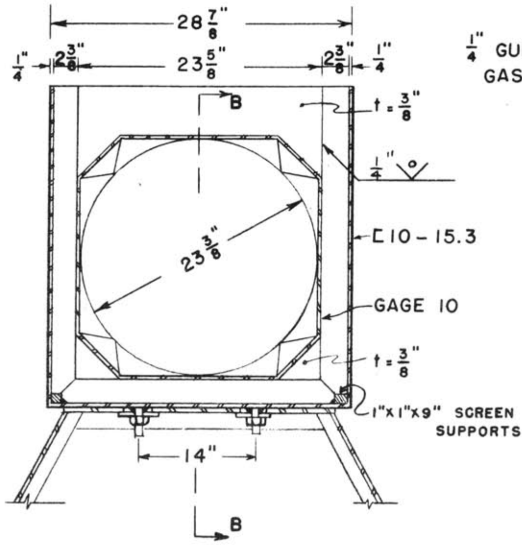
Upstream from this unit a single steel-framed screen is inserted. This screen, which is made with a very fine mesh, will retain most suspended solids in the water and can readily be taken out, cleaned and replaced.

During assembly of the screens, the wire mesh was pretensioned by means of a steel frame specially made up for this purpose.

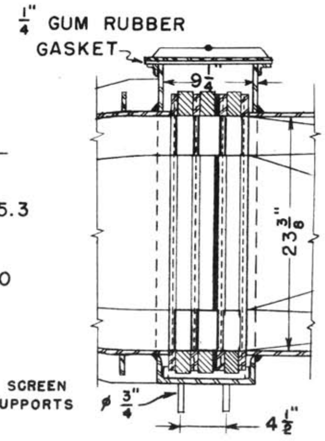
The most efficient screen assembly consists of a large number of screens each having a relatively low head loss. However, having limited the number of screens (for the initial tests at least) to four, it was deemed advisable



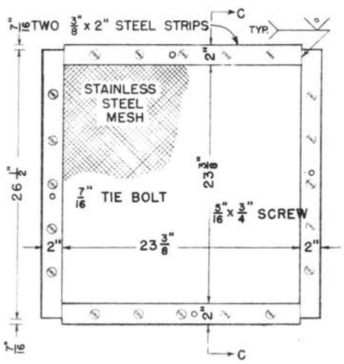
SCREEN HOUSING



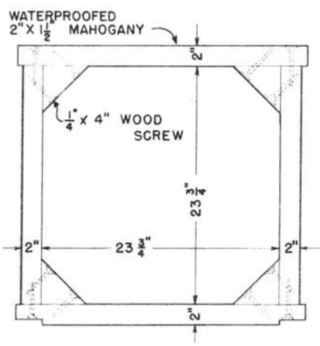
SECTION A–A



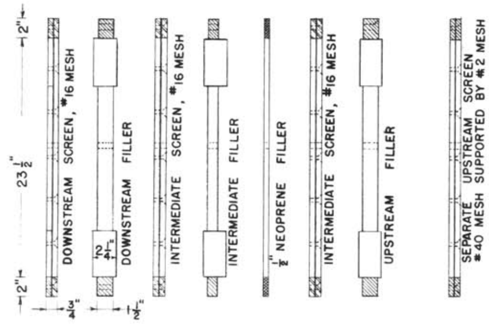
SECTION B–B



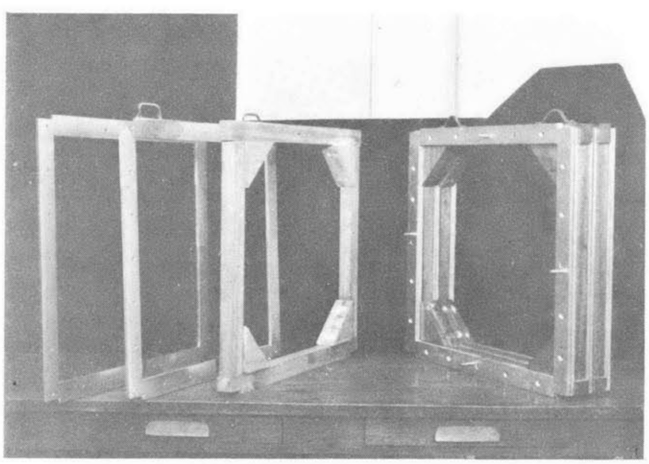
STEEL SCREEN FRAME



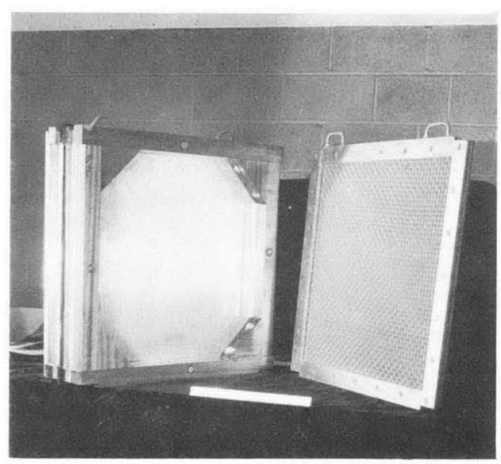
WOODEN FILLER



SCREEN ASSEMBLY



Metal and Wooden Frames



Screen Assembly

Figure 5. Screen Housing and Screen Assembly

to use screens with as high a head loss as possible. The greatest head loss is associated with the finest mesh screens (largest mesh number). However, other factors restrict the use of extremely fine mesh screens:

a. The solidity ratio of the screen should not exceed 0.5 as distortion of the velocity distribution may result.

b. Excessive deformation or even structural failure of the screen limits the finest mesh that can be used without additional support. In this case it was felt that 16 mesh was the limiting size.

c. The total head loss through the screen assembly must of course be less than the maximum allowable which in this case was estimated to be 6 feet for a 50 fps velocity in the test section.

d. Clogging of the screen due to impurities in the water will cause nonuniformities in the flow and despite provisions to clean them regularly presents a practical lower limit to mesh size.

With these points in mind the initial stage design, Figure 5, was adopted. It will be noted that this design consists basically of a 40 mesh screen followed by three 16 mesh screens, approximately equally spaced.

The head loss through a screen may be estimated by the following expression (4):

$$\frac{\Delta p}{\rho V^2/2} = \left(\frac{1}{C_C[1 - S]}\right)^2$$

where Δp is the pressure drop through the screen, V is the mean velocity upstream of the screen, C_C is the coefficient of contraction of the jets passing between two screen wires and S is the solidity ratio of the screen, defined as the metal area of the screening divided by the total area.

The 16 mesh screen has a wire diameter of 0.018 inches and mesh opening of 0.045 inches which gives a solidity, S, of 0.490. Assuming V constant between screens and $C_C = 0.90$ the total head loss through the three 16 mesh screens is 2.9 ft. at a flow corresponding to a velocity of 50 feet per second in the test section.

The 40 mesh screen was chosen to make use of the 3.1 feet of head still available for damping. The head loss through the 40 mesh screen is 2.5 feet giving a total loss through the screen assembly of 5.4 feet. The 40 mesh screen has a wire diameter of 0.010 inches, mesh opening of 0.016 inches and a solidity equal to 0.622. It is felt that by placing this screen on the upstream side of the assembly any undesirable effects of this rather high solidity will be damped by the 3 remaining screens. The 40 mesh screen is backed up with a very coarse 2 mesh screen for added support against deformation.

The distance between the 16 mesh screens is equal to 125 wire diameters. From Ref. 4 it is estimated that about 85% of the turbulence intensity generated by the screens will have decayed in this distance. The distance between the 40 mesh screen and the first 16 mesh screen is 225 wire diameters which gives about 91% decay.

From the last screen to the beginning of the contraction is a distance of 9.37 inches or 520 wire diameters resulting in about 95% decay.

5. Contraction

The most effective tool to obtain a low turbulence test jet of uniform velocity distribution is a well designed contraction.

Since the available funds for this structurally expensive unit were modest, considerable attention was paid to its design. Both the contraction ratio as well as the shape of the boundary curves from which the contraction is composed, are of importance. In general, the larger the contraction ratio the lower the turbulence level and the more uniform the velocity distribution in the test section will be. Although wind and water tunnels with contraction ratios of about 25 are to be found, for most water tunnels design values of 6 to 9 have been chosen. In this case, the selected area ratio of 7.6 represents the maximum value as dictated by spatial and economic limitations.

The shape of the boundary curve for many tunnel contractions built in the past is the result of intuitive fairing rather than an analytic approach. The requirements for a proper contraction are:

a. For a given contraction ratio the contraction should be as short as possible since a long contraction adds to the cost of the water tunnel and tends to increase the boundary layer thickness at the entrance of the test section.

b. Along the boundary of the contraction adverse pressure gradients should be minimized in order to prevent boundary layer separation and resulting flow disturbances.

These requirements are conflicting since the necessary change in the direction of flow near the entrance and exit of the contraction creates local adverse pressure gradients. Only lengthening of the contraction may minimize these effects sufficiently to prevent separation.

In the pertinent aeronautical literature several design approaches are to be found. Greidanus and Van Heemert (5) and Goldstein (6) warn that superposition of solutions to the LaPlace equation will not lead to a sufficiently simple determination of short contractions in three and two-dimensional cases respectively. The solution given by Tsien (7) is tedious in its application and for an axially symmetrical case the centerline velocity distribution must be chosen arbitrarily. The length of the contraction is infinite leading to an arbitrary choice of the points of tangency. Successful application of this analysis for water tunnels built by the California Institute of Technology and the University of Minnesota is reported.

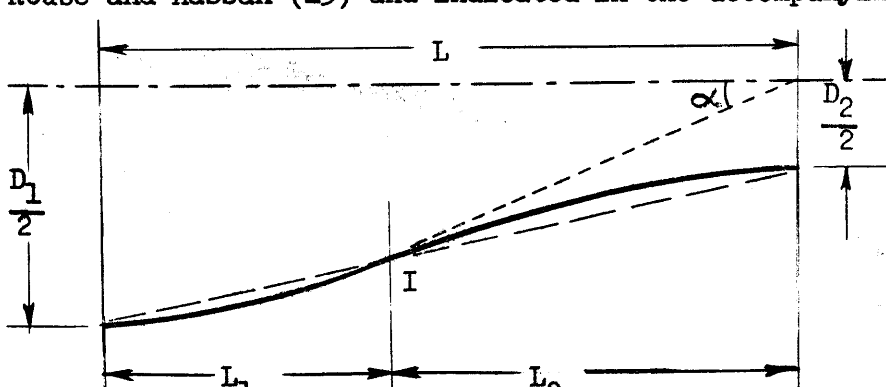
Szczeniowski (8) also offers a solution for an axially symmetrical case for which the axial velocity distribution is presumed. This solution was applied in 1928 in a Polish wind tunnel.

Batchelor and Shaw (9) started from an arbitrary choice of a curve near the to be determined boundary and made use of relaxation methods.

Thwaites (10) offers a series solution for the axially symmetrical case based on potential flow and selecting the entrance and exit sections of the transition as two equipotential planes. Again this is equivalent to a choice of the axial velocity distribution, this time expressed in terms of a Fourier Series. The contractions thus formed are finite. The selected solution may also be tested inexpensively by means of the electric tank technique. The author states that the computations involved are less time consuming than those given in either References (7) or (8).

All approaches mentioned above lead to contractions of generally similar shape, but Cheers (11), using the transformation technique, offers a two-dimensional transition of markedly different form in which the high velocity section is very short relative to the transition length. Again the solution is given in a series form. A successful application of this method for a small wind tunnel has been reported by Holder and North (12).

It appears that as many expressions for the complete flow field may be obtained as there are "reasonable" initial assumptions, none of which can be claimed as being ideal. Or, on the other hand, since particular attention has to be given only to sections near the entrance and exit of the contraction, a transition with "reasonable" entrance and exit portions may be as satisfactory as those mentioned above. In this regard a transition curve of finite length can be called reasonable if it possesses continuous first and second derivatives, such as a curve composed of cubic arcs, $y = ax^3$, suggested by Rouse and Hassan (13) and indicated in the accompanying inset.



I = Inflection point

L = Contraction length

$D_{1,2}$ = Diameter

It appears that for a given D_1 and D_2 there remain three degrees of freedom: L/D_1; L_1/L and α. The choice of L/D_1, and α was based on comparison of the contraction cones found in the literature and those accompanying the above mentioned papers, while the ratio L_1/L was chosen according to Batchelor and Shaw (9). It can be expected that by using this technique the cone will yield a contracting flow field which is not easily described mathematically but is of a quality comparable to those found satisfactory by other investigators. In this respect, it is well to realize that a solution for the transition curve cannot be better than the accuracy with which the contraction cone can be fabricated. For larger cones, this accuracy cannot be expected to be expressible in more than four or five significant figures. Moreover it should be borne in mind that the offered solutions, based on potential flow and a chosen initial condition, are all restricted to either axi-symmetrical or two-dimensional cases. In the case considered, as well as in most wind tunnels, the test section will be octagonal or rectangular rather than circular. It follows that the solutions given in References (7) through (11) may serve only as a guide for actual design.

The cubic equation:

$$y = a\,x^3 \qquad [1]$$

has to be modified so that it will contain two parameters in order that the curve may satisfy two boundary conditions at point I. (See inset). Adopting the expression developed at the Pennsylvania State College (14) for a transition to the diffuser in a 48-inch water tunnel, the modified equation may be written as:

$$y = a\,x^3\,e^{\left[b\,[1 - (x/L_1)^2]\right]} \qquad [2]$$

Soon after the formulation of the desirable dimensions of the water tunnel it became clear that casting a contraction of the visualized size would be prohibitively costly. The alternative was to fabricate the contraction from plate material. Since the plate can only be bent in one direction (which is necessarily the axial one) all cross sections of such a contraction will have transverse sections bounded by straight lines and will be more or less similar in shape. A test section of truly rectangular shape would then lead to a contraction with rectangular cross section. This represents the simplest solution. However, the chance that eddy motion would develop in the 90-degree corners is great. Therefore, the corners of the rectangular test section were filleted calling for a contraction of octagonal shape. This gave rise to eight parts (4 fillets and 4 sides) comprised of three basic configurations. Each part was fabricated from plate material carefully bent in its longitudinal direction according to a curve following from equation [1]. The contraction was so dimensioned that only two different curves were used, thus reducing the amount of computational work and, especially, the fabrication cost and time. The edges of these bent plates were then cut along three-dimensional curves in such a manner that all eight parts fitted well together to form the contraction. Since practicality of construction required the final shape of the parts to be laid out two dimensionally on the flat plate, the choice of a computationally amenable expression for contraction curvatures was imperative.

In order to be certain about the correctness of the computations a half-size cardboard model was constructed before the plates were actually cut.

After the eight parts were outlined and trimmed to size they were dressed and welded to template strips which by careful flame cutting and subsequent grinding conformed to the design curves with an accuracy of ±1/50 inch. In order to minimize distortion of the thin wall plate, two strips were welded perpendicular to each template strip. In the final welding these strips then formed a circumferential stiffening rib and, at the test section end served also as a flange. The first step in assembly was to tack weld all eight plates to their respective stiffening ribs and then to each other (see Figure 6). Subsequently, the contraction was thoroughly annealled after which the welding work was completed. The maximum distortion of the final contraction curves amounted to ± 1/32 inch.

The effectiveness of the contraction in reducing the turbulence is not entirely a function of its configuration, but is also dependent upon the characteristics of the flow entering it. Therefore, a number of screen assemblies and modifications to the flow circuit may have to be made before a final evaluation of the performance can be given.

6. Test Section

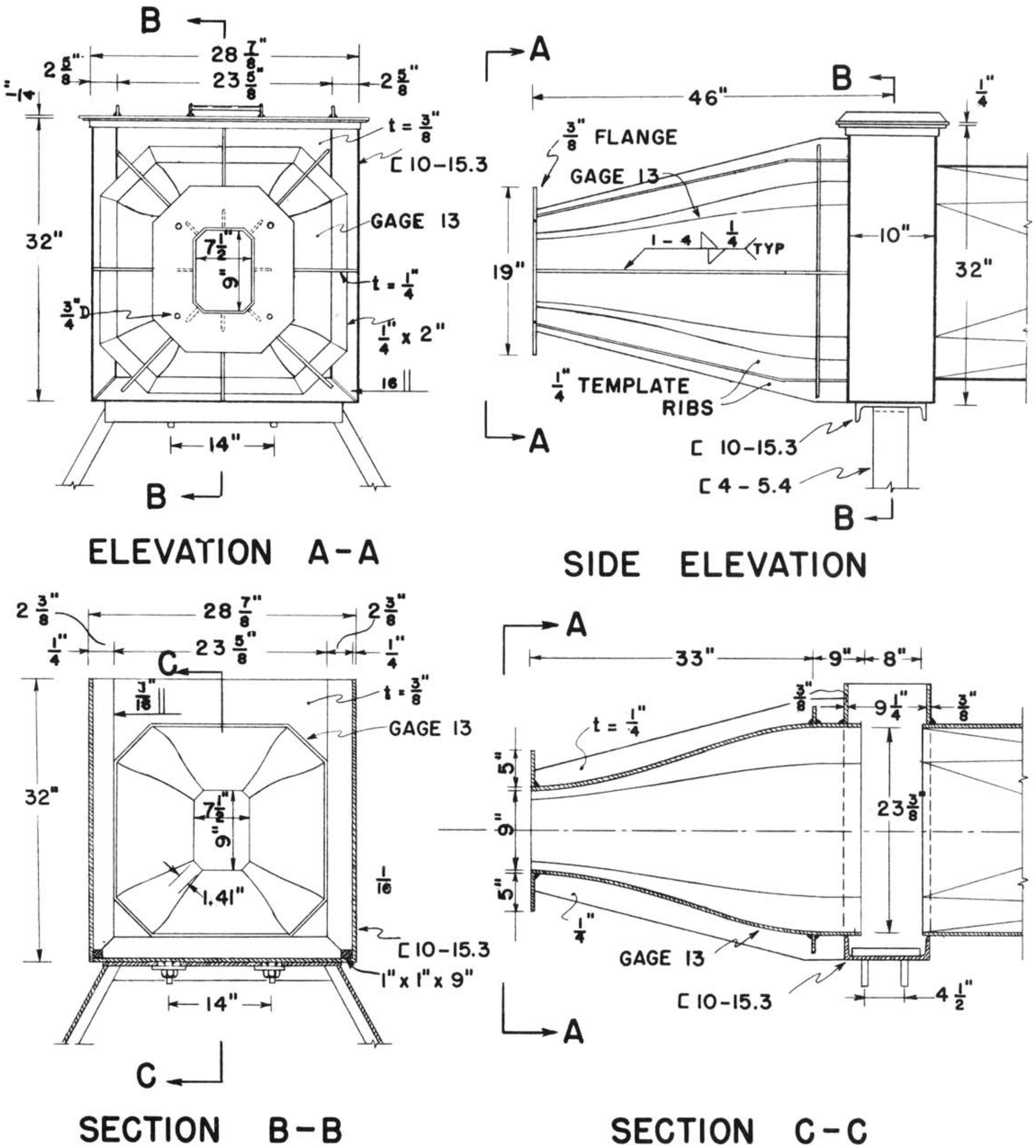
As has been set forth in the introductory section of this report the most advantageous cross sectional area of the test section was found to be about 65 square inches.

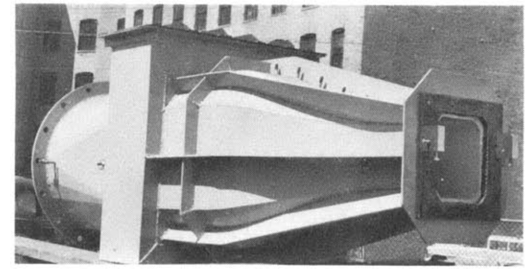
The ratio of test section height to width is controlled by conflicting requirements concerning the length of the test plate.

In order to determine accurately the forces, per unit of span, exerted on the test plate by the fluid, it is necessary that two-dimensional flow conditions exist. In a test section of limited width this requires a short plate (large aspect ratio). In addition, the test plates should be short enough with respect to the test section height to minimize free stream accelerations resulting from boundary layer development on the plate and wall.

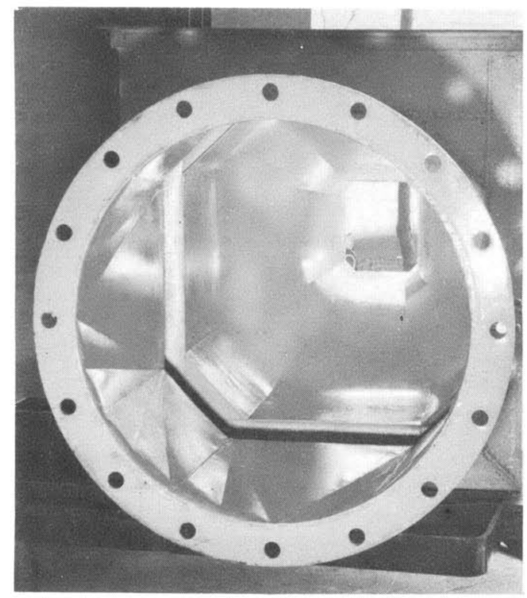
On the other hand, the test plates should be long enough to develop measurable resistance forces and should be significantly extensible to permit determination of the effect of variable trailing edge boundary layer thickness for constant free-stream conditions.

Based on the above as well as on structural considerations, a 7-1/2" x 9" section was adopted with the test plates to be mounted in the plane of symmetry parallel to the long side of the rectangle.





Exterior of Contraction



Interior of Contraction

Figure 6. Contraction

To prevent pronounced eddy motion in the corners these were filleted. The long side of the fillet used measures 1.41 inches. The length of the test section is 36 inches.

For the structural design of the test section the following main criteria were adopted:

a. Ease of observation of wake and test object.

b. Versatility in illumination of flow (photography).

c. Strength to withstand a positive differential pressure (highest pressure inside) of 25 psi and a negative differential pressure (lowest pressure inside) of 13 psi.

d. Ease in making modifications (pressure taps, etc.)

The first two requirements led to the design of a rectangular conduit formed entirely from 1 inch thick, flat sheets of plexi-glass, the transparency of which will greatly facilitate observations and optical measurements.

Plexi-glass can be quite easily machined and thus meets the fourth requirement mentioned above. The material, when not aged, is fairly elastic. Redistribution of stress in composite parts as a result of yielding is unlikely. The design should therefore be quite conservative and local stress concentrations in the plexi-glass should be kept to a minimum. In the course of time, the material tends to become brittle. Small cracks and some discoloration may occur.

The test plates are mounted by means of a force balance. To preserve two-dimensional conditions, the plate is mounted at both ends. The symmetrical force balance components are placed outside the cross sectional area of the test section and each holds a small portion of the plate which protrudes through the test section wall. Since a test plate with dimensions of say 1/4 x 6 x 9 inches, has to be readily replaceable, one of the walls through which the plate protrudes is removable (see Figure 7).

When the pressure in the tunnel reaches 25 psi the calculated stresses at the bonded joints far exceed the design value of 2000 psi adopted for the plexi-glass. Glued construction, while beneficial from the standpoint of watertightness, is thus not sufficient. These and other considerations such as the connection between test section and water tunnel led to the use of 1-inch thick aluminum bars to form angle shaped members which support the plexi-glass plates along the full length of each longitudinal joint. After gluing, the plastic is bolted permanently to the aluminum strips. Transfer of load to the strips is thus assured in case of either positive or negative pressure in the test section (see Figure 7).

Correction of the cross sectional area to remove the fluid-accelerating effect of boundary layer growth was not considered feasible with the adopted prismatic section. The easiest method would have been to bring about a downstream enlargement of the cross sectional area by tapering the triangular fillers in the corners. For this purpose the given fillers are too small, however. It was felt that tapering the test section walls would lead to structural difficulties and costs which would outweigh all advantages.

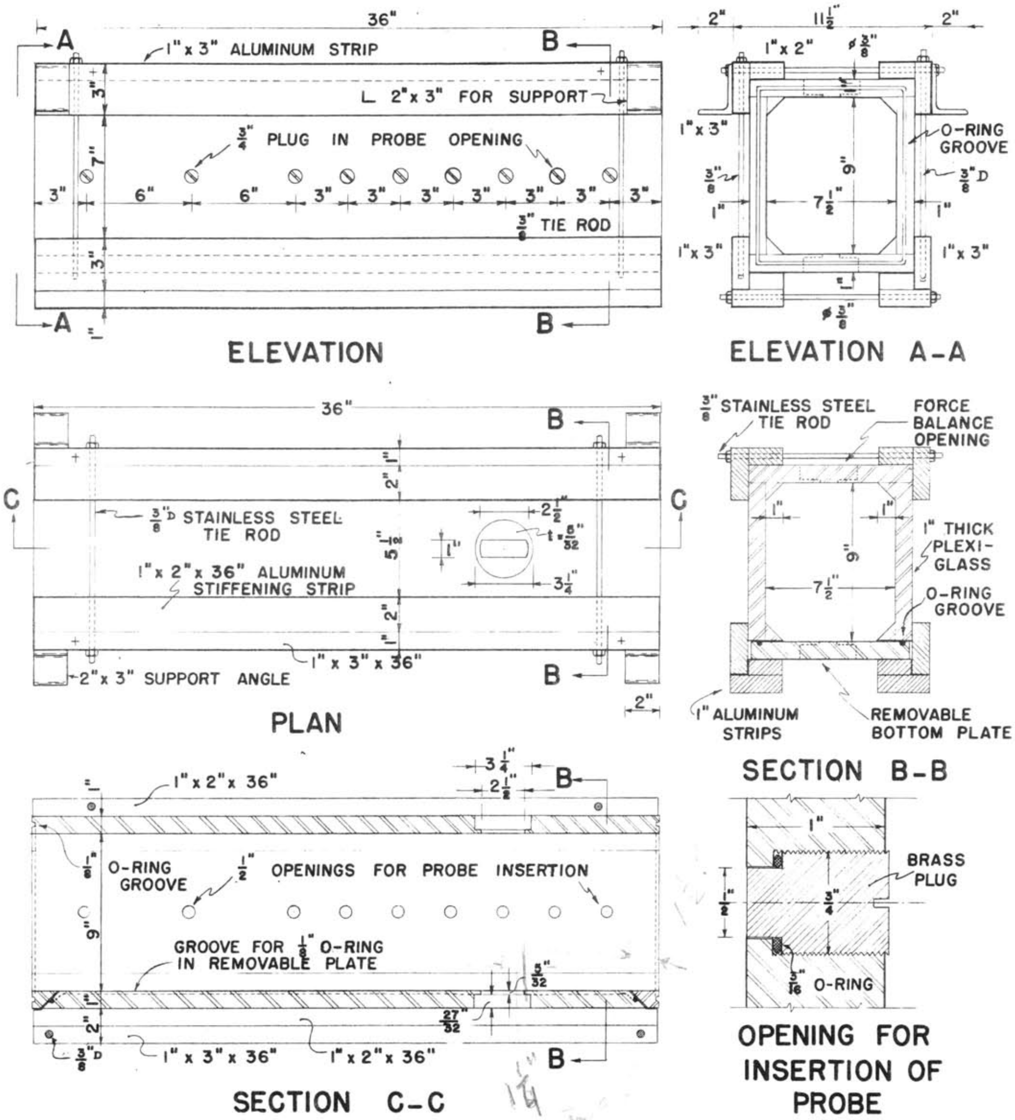
Watertightness of the removable bottom plate was insured as indicated in Figure 7. At both ends the bottom plate was cut at a 45 degree angle. A continuous "O"-ring groove was milled in these faces and in the inside of the plate near its edges. With the "O"-ring in place the bottom plate may be drawn onto the U-shaped part of the test section by fastening two rows of bolts in the aluminum strips.

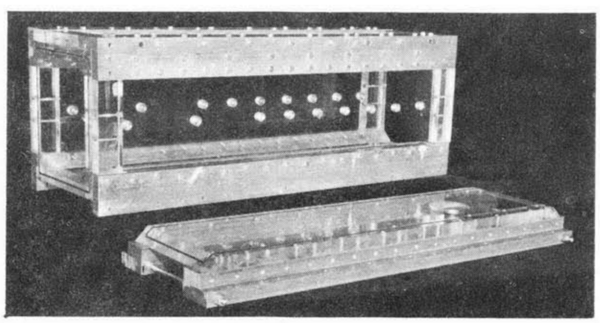
Whereas working to narrow tolerances such as 5/1000 inch is possible in the construction of the test section it is obvious that similar accuracy cannot be obtained for either the welded contraction or diffuser. At the transition from contraction to the test section the flow already has the tendency to separate on account of the adverse curvature of the boundary whereas the joint from test section to diffuser is the most likely location for the inception of cavitation. Both transitions therefore need to be perfectly smooth and continuous. Local differences of up to 3/32 inch were noted between the matching end sections.

Correction of this condition by grinding off the inside of the contraction or diffuser was not practical. Two steel filler plates with flame cut openings larger than the contraction (diffuser) opening and with a composite thickness equal to the chosen transition length were bolted to the contraction (diffuser) flange. A 1/4 inch aluminum plate with a machined opening which exactly matched the test section entrance was then fastened to the steel plates. The broad groove thus formed was filled in with "plastic steel" and this material was carefully faired out into the contraction (diffuser).

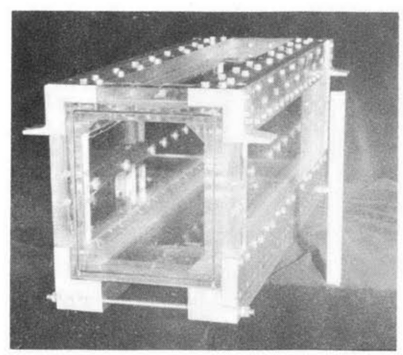
The aluminum plates which facilitated the finishing of the contraction exit and diffuser entrance to the test section dimensions served a second purpose. The smooth faces were utilized to compress an "O"-ring put in a groove in the plexi-glass end faces of the test section. In this fashion watertightness of the joints between the test section and the water tunnel was obtained (see Figure 9).

The actual connection between the test section and the water tunnel is effected by resting the test section on four jacking bolts which are supported in aluminum blocks fastened to the steel filler plates mentioned above. After positioning of the test section by means of eight jacking bolts (4 vertical, 4 horizontal) the two parts of the water tunnel were drawn together by means of a tie rod and turnbuckle installed between riser and tailrace, thus compressing the "O"-rings. This solution for the mounting of the test section is not only precise and convenient but it also prevents the test section material from becoming additionally stressed by relative movements of the tunnel parts at either side of the test section. Furthermore, this manner of "suspension" of the test section will make vibration isolation of this unit fairly simple if it should appear necessary (see Figure 8).





Bottom of Test Section



End Face of Test Section

Figure 7. Test Section

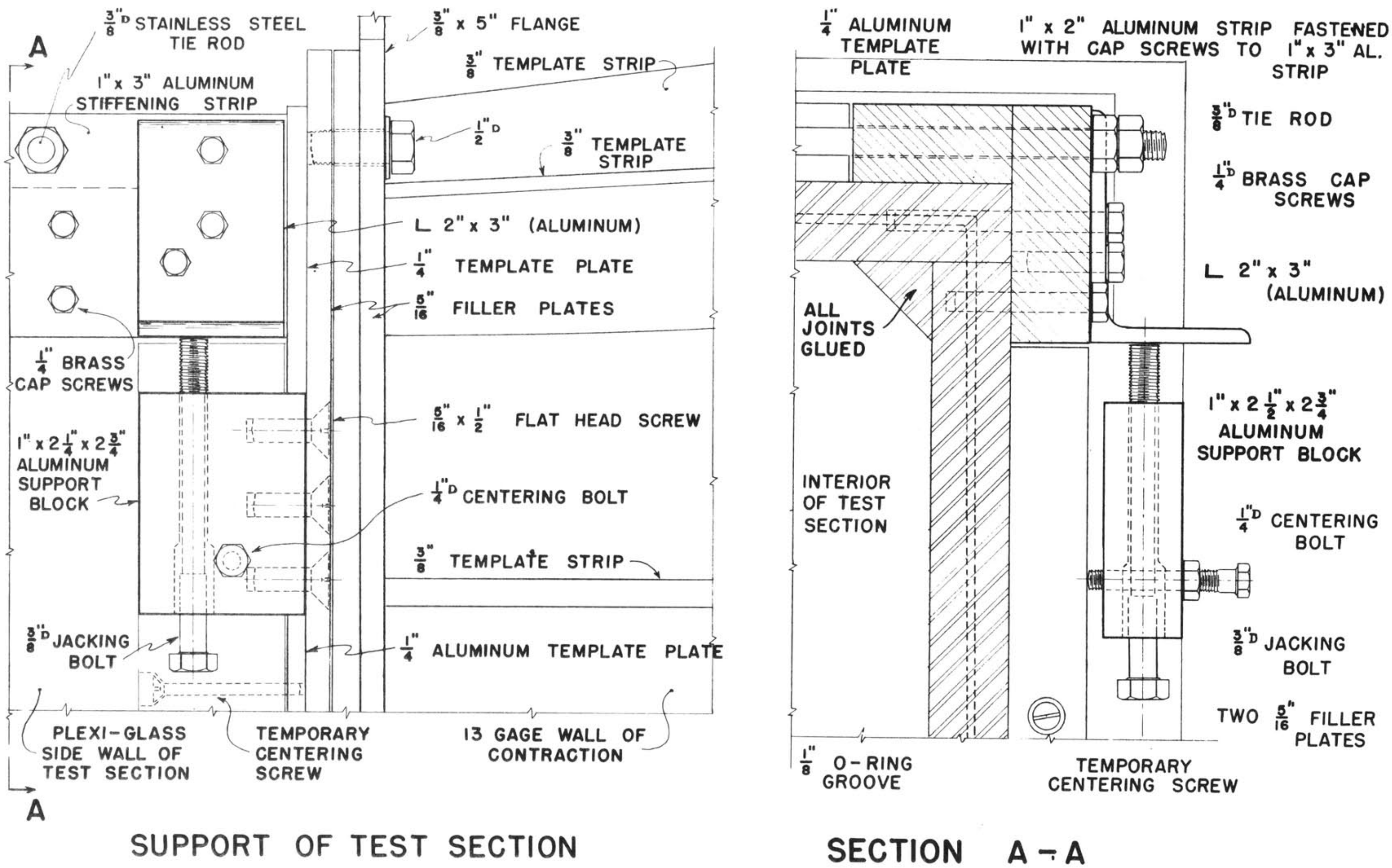
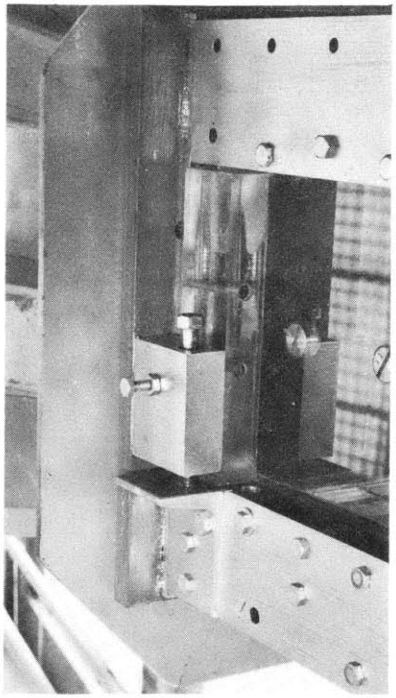
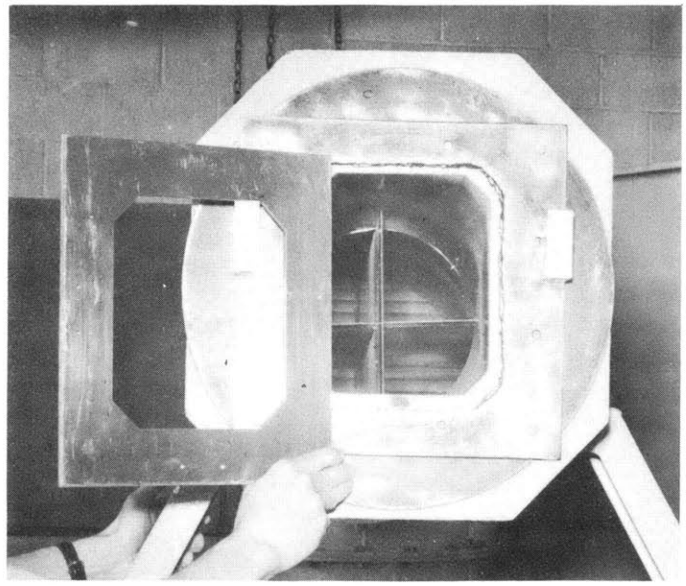


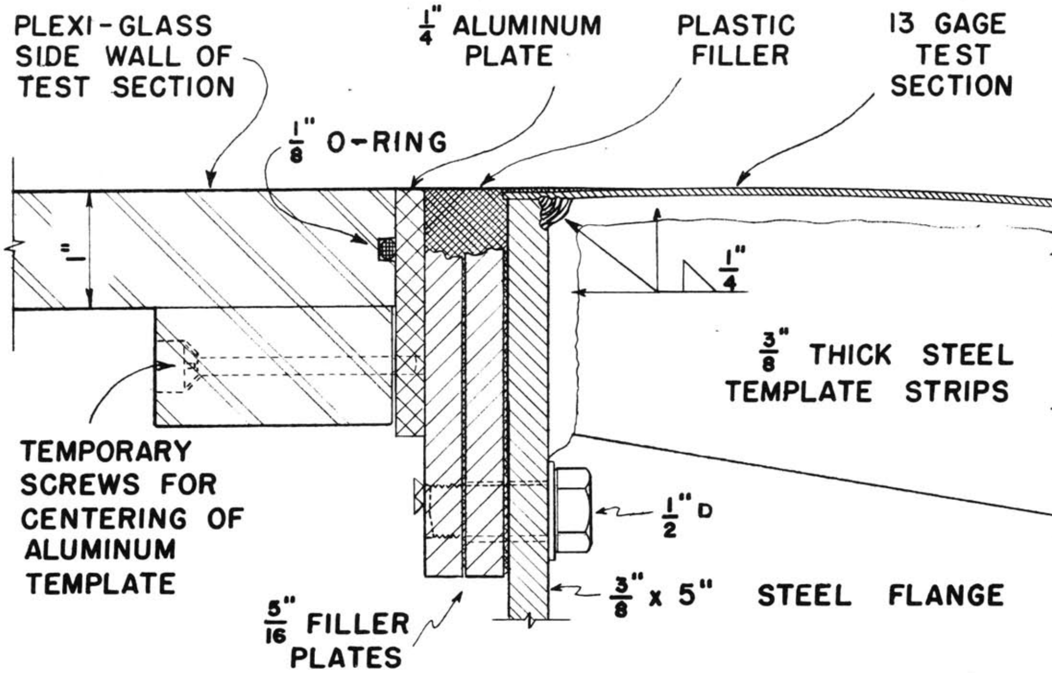
Figure 8. Support of Test Section





Filler Plates

Support of Test Section



MEETING OF TEST SECTION AND CONTRACTION

Figure 9. Joint of Test Section and Water Tunnel

7. Diffuser

The function of the diffuser is to lower the high velocities of flow in the test section without producing flow separation with its accompanying pressure fluctuations. This reduction is essential since at the exit of the tunnel the water is returned to the storage basin where a full velocity head is lost. If no diffuser were present this expansion loss, for test section velocities of 40 to 50 fps., would amount to 50 to 80% of the total head delivered by the pumps. This compares to 1 to 1.6% for the given case where the draft tube has a 24-inch diameter section.

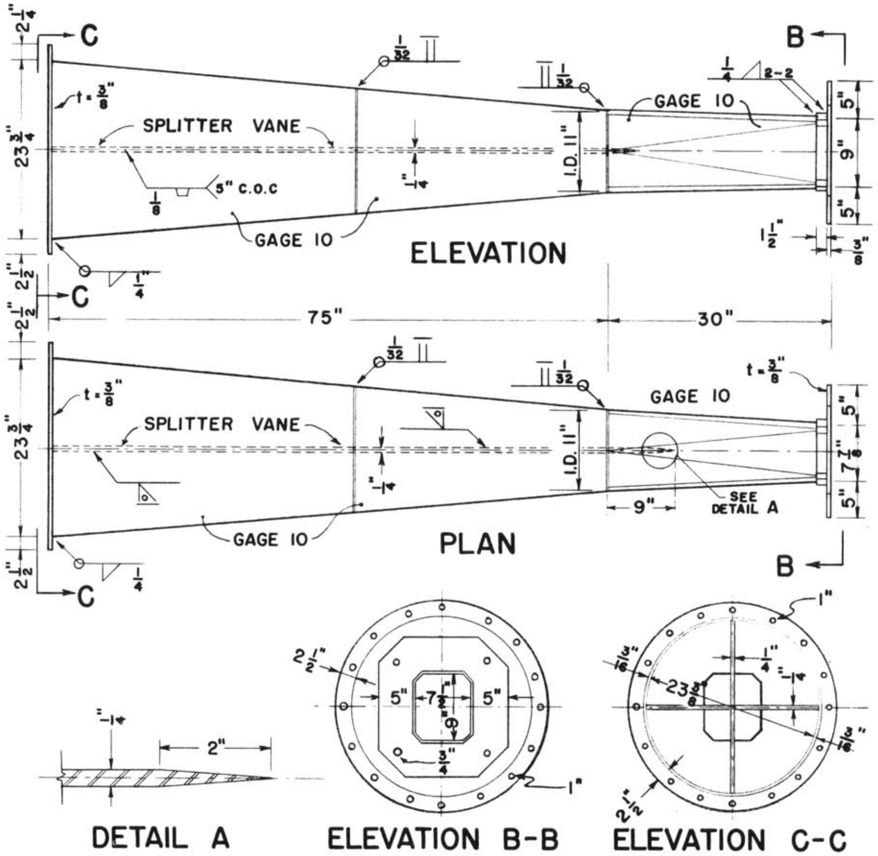
Comparison of several designs in the manner outlined in Section 2 of Part I indicated that fairly large diffuser losses were acceptable but that the available space was strictly limited. This resulted in the design of a conical diffuser having two orthogonal splitter vanes running its entire length (see Fig. 10). In this fashion the diffuser is divided into four channels for each of which the included wall angle remains acceptable.

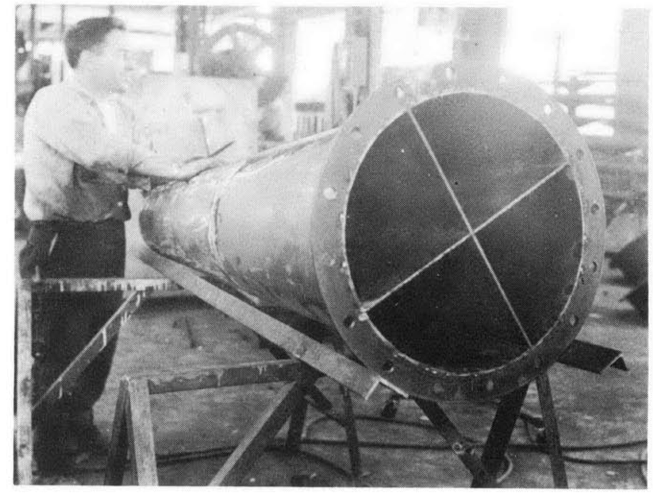
Between the actual diffuser and the test section a transition is needed to modify the "rectangular" test section opening to the circular cross section of the diffuser cone (see Figure 9). This transition is 30 inches long and has a maximum included wall angle of 4 degrees. It is fabricated from 10 gage cold rolled steel plate. The transition is welded to the smaller opening of the diffuser which is a truncated cone, 75 inches long and also made of 10 gage steel plate. The total included angle of the diffuser is 10 degrees. The cross formed by the long 1/4 inch splitter vanes is fastened to the cone by means of plug welds. The upstream ends of the plates which will be in a zone of high velocity have been well sharpened. By means of the vanes the maximum included angle of each flow passage has been kept to 5 degrees.

8. Draft Tube and Plate Valve Assembly

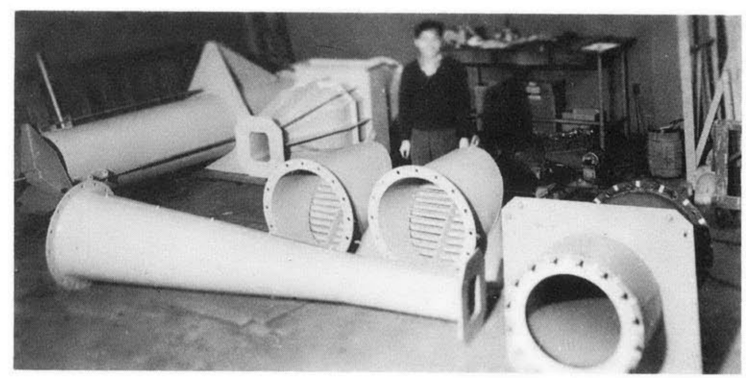
Leaving the diffuser unit the flow is turned 90 degrees and vertically downward by a second elbow identical in construction to the one discussed before. Following this elbow is a 10 foot long draft tube made from standard rolled steel pipe with an inside diameter of 23-3/8 inch and a wall thickness of 5/16 inch. The function of the draft tube is to preserve available head in the water tunnel. The downstream end of the draft tube will always be below the elevation of the water level in the storage tanks (see Figure 10).

The draft tube is supported on the floor of the laboratory hall via a triangular shaped collar plate which, together with stiffening gusset plates, is welded to the pipe. As in the case of the riser, the draft tube may be aligned readily by means of three pairs of jacking bolts which are held in nuts welded to the underside of the triangular collar plate. In this way vertical adjustments of several inches are possible, whereas the 30 x 30 inch floor opening permits ample horizontal motion of the 24-inch pipe. Horizontal adjustments may be made by means of a tie rod and turnbuckle connecting draft tube and riser.





Diffuser Construction



Diffuser and Other Components

Figure 10. Diffuser

In order not to inactivate that part of the loop formed by the 18-inch diameter header to which the water tunnel circuit is connected, a valve is needed in the latter circuit. If this valve is located downstream of the test section, it can also serve as a regulator of the pressure level within the tunnel during operation. Such regulation is important when inducing or preventing cavitation.

The valve, consisting of a flat plate and a bronze bushing attached thereto,is mounted at the downstream end of the draft tube. The more or less triangular shaped plate is stiffened by ribs. These ribs also serve to hold the bronze bushing by means of which the plate valve may move along a 1-1/2 inch diameter stainless steel shaft parallel to the centerline of the draft tube. The shaft is supported by three splitter vanes welded to the pipe wall. The valve plate can be moved up and down by means of three stainless steel lifting rods. To prevent rotational vibration of the plate around the central shaft the lifting rods slide through three radially aligned slotted holes in support plates placed near the end of the draft tube (see Figure 11). The lifting rods are connected to threaded brass rods, carrying small cylinders to which sprockets are fastened. Rotation of the sprocket cylinders by means of a chain drive causes the plate valve to move vertically. The cylinders rest in radial thrust bearings mounted on the collar plate.

9. Protection against Corrosion

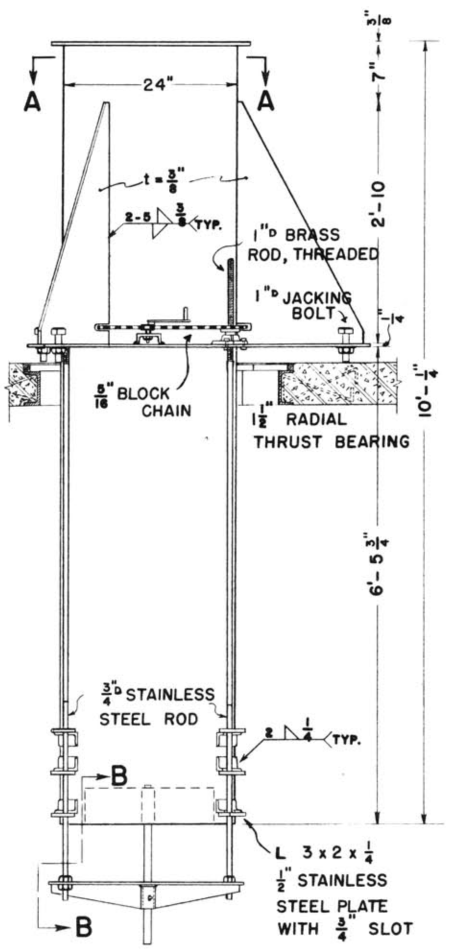
The water tunnel components have been protected against corrosion by the application of a plastic coating.

Since the structural elements were formed from thin gage steels it was feared that the heat of galvanizing might lead to excessive distortions. Electrolytic plating was not possible due to the excessive size of the units.

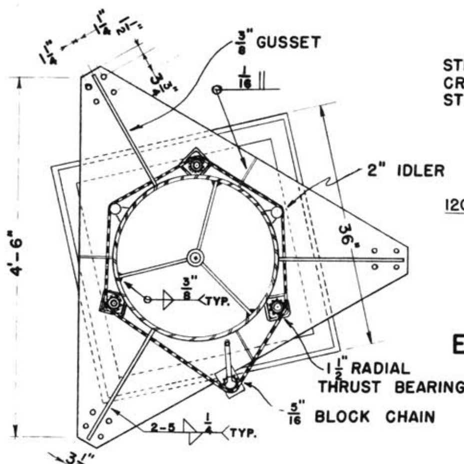
Except for the riser and the draft tube all components were pickled and "bonderized." The truncated cone of the riser was fabricated from cold rolled steel plate and did not need this pretreatment. The draft tube was sand blasted since no pickling tank of local shops could contain this unit. Subsequently, all parts were sprayed with three layers of "Profilm," each in a thickness of 0.0015 inch. The corrosion resistant layer of "Profilm" consists of a ceramic silicate with a resin employed as the vehicle. The finished surface is very smooth. For smaller parts which could not be protected in this fashion stainless steel was employed.

10. Vibration Isolation

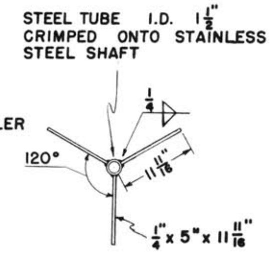
Vibrations originating at the centrifugal pumps will be transmitted through the 18-inch header to which these pumps are more or less rigidly connected (see Figure 7). At present the riser of the water tunnel is bolted to a tee in the header. By making this connection less rigid the amount of vibration of the tunnel itself may be decreased. If need be, this can be realized by in-



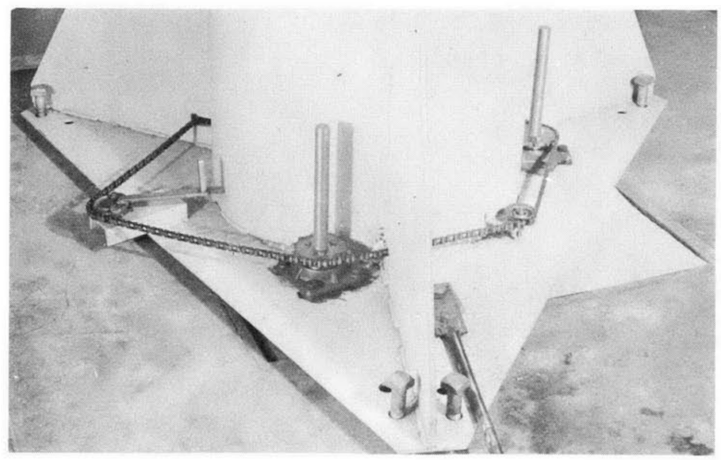
ELEVATION OF DRAFT TUBE



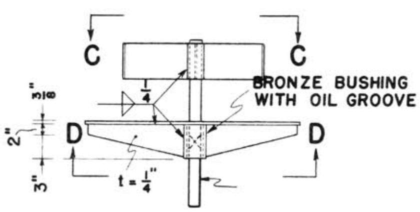
SECTION A-A



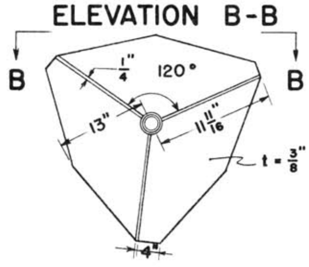
ELEVATION C-C



Valve Lift Mechanism



ELEVATION B-B



ELEVATION D-D

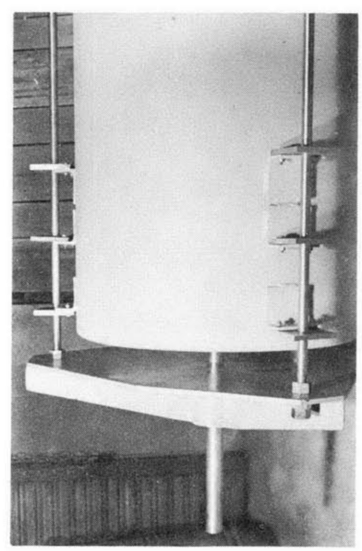


Plate Valve

Figure 11. Draft Tube and Plate Valve Mechanism

serting a flexible coupling between the tee and the riser. It will be recalled that the riser is supported on the laboratory floor by means of jacking bolts so that the presently rigid connection between riser and tee merely serves to obtain a watertight joint.

Even if the rigidity of the connection between water tunnel and header is minimized, vibrations objectional from the standpoint of measurements with a pressure transducer may be found to occur in the water tunnel structure. These vibrations may be transmitted through the tunnel supports from the laboratory structure which, due to features of its construction, responds actively to external shock loadings. The few points of contact between the tunnel and the laboratory structure will facilitate shock mounting if the need arises.

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