Silberman

UNIVERSITY OF MINNESOTA
ST. ANTHONY FALLS HYDRAULIC LABORATORY
LORENZ G. STRAUB, Director

Technical Paper No. 16, Series B

The Six-Inch Water Tunnel at the St. Anthony Falls Hydraulic Laboratory and Its Experimental Use in Cavitation Design Studies

Limited Distribution of Paper Presented at
The National Physical Laboratory Symposium on Cavitation in Hydrodynamics
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A B S T R A C T

A recirculating model water tunnel has been devised at the St. Anthony Falls Hydraulic Laboratory for the purpose of determining prototype design data for use in the planning of various types of cavitation test facilities. The test section of the model is 6 in. in diameter, and various boundary geometries have been studied in their relation to the test stream flow quality. Special emphasis has been given to the cavitation test limits imposed by the test section boundaries and various other tunnel components. This paper describes the basic tunnel, the critical cavitation tests made on the tunnel, and some cavitation studies made in the tunnel. Observations made on closed (cylindrical and diverging), open, and slotted-wall test sections are discussed. A minimum cavitation index of about 0.023 can be achieved in the diverging closed-jet test section at a velocity of 50 fps.

Some cavitation studies indicate how the cavitation susceptability of the tunnel water varies, and show that the critical cavitation index of a slender body is more constant when based on a measured pressure than when based on vapor pressure.

C O N T E N T S

L I S T O F I L L U S T R A T I O N S

LIST OF SYMBOLS

d - Diameter of test body.

D_o - Diameter of test section at upstream end ($x = 0$).

P - Piezometric pressure on test body, psf.

P_c - Measured cavitation pressure in psf absolute.

P_o - Piezometric pressure at upstream end of test section in psf.

P_v - Vapor pressure of water in psf absolute.

P_x - Piezometric pressure along axis or wall of test section in psf.

s - Distance from nose of test body along surface.

V_o - Test section velocity in fps.

x - Distance downstream of beginning of test section.

w - Specific weight of water, lb per cu ft.

ρ - Density of water, slugs per cu ft.

σ_c - Cavitation index based on P_c.

σ_v - Cavitation index based on P_v.

σ_{min} - Minimum cavitation index for tunnel component.

THE SIX-INCH WATER TUNNEL AT THE ST. ANTHONY FALLS HYDRAULIC LABORATORY AND ITS EXPERIMENTAL USE IN CAVITATION DESIGN STUDIES

INTRODUCTION

The performance of bodies intended to move at high speeds in water can seldom be predicted by analytical methods alone, but must depend to a large extent on experimental model tests. Towing basins, rotating booms, circulating or non-recirculating water channels, and open water or prototype test ranges are suitable test facilities for studying many problems. However, if cavitation is to be present in the prototype, it must also occur in the model; therefore, a controllable- and variable-pressure flow stream must be provided. A test facility which provides this is called a variable pressure water tunnel, and is usually built as a recirculating system in order that the power requirements be a minimum.

The primary objective of a water tunnel is the production of a test stream of a quality such that the flow around a test body effectively simulates the relative flow around a prototype body under natural, still-water conditions. Various forms of test sections are used to provide this test stream. In the closed jet the test stream is guided by fixed solid boundaries. In the open jet the test stream is surrounded by a reservoir of water. A slotted wall is rather like a combination of both, wherein the test stream is bounded by longitudinal guide bars and is surrounded by a reservoir of water. A free jet is surrounded by air. Special emphasis is given to the design so that cavitation will occur on or around the test body without prior or simultaneous cavitation occurring at some other point in the tunnel.

This paper discusses the mechanical design and operational characteristics of a 6-in. recirculating, variable-pressure model water tunnel at the St. Anthony Falls Hydraulic Laboratory and some of the cavitation studies which have been conducted in it. All work has been sponsored by the David Taylor Model Basin of the United States Department of the Navy.

The 6-in. SAF water tunnel (the size indicates the upstream diameter of the test section) was originally used as a model in studying optimum or favorable designs for three different large cavitation tunnels for the David

Taylor Model Basin. In addition, it has also been used as a test facility for making various cavitation studies.

The first arrangement was a model of a 60-in. closed-jet tunnel whose test section was to be 25 ft (5 diameters) in length. This first model is shown in Fig. 1. The second was a model of a 24-in. open- or closed-jet tunnel, the open jet being 1.6 diameters long and the closed jet 0.46 diameter long, as shown in Fig. 2. The third arrangement simulates a 36-in. tunnel equipped with an air-bubble resorber, and the present 6-in. tunnel is of this form. It alternately permits a cylindrical and diverging closed-jet test section 2.18 diameters long, an open-jet test section 1.6 diameters long, and a slotted-wall test section 2.4 diameters long. The present arrangement of the model water tunnel is shown in Fig. 3. Inasmuch as the various successive setups of the model tunnel, to simulate different designs for proposed longer water tunnels, involve analogous problems, only the present arrangement is discussed in detail in this paper.

DESCRIPTION OF THE TUNNEL

The various tunnel components are designated in Fig. 4. Three test sections (the diverging closed jet, the open jet, and the slotted-wall) are shown in detail in Figs. 5-7. In order to observe cavitation, walls in the test-section regions are made of a transparent acrylic resin (Lucite or Plexiglas) about 1-in. thick. Two half cylinders were formed from flat sheets and cemented along longitudinal joints. Critical portions were machined with tolerances of the order of 0.002 in. and have maintained excellent dimensional stability. One closed-jet test section is cylindrical and the other (Fig. 5) diverges about 0.2 degree to produce a constant-pressure core flow by correcting for the boundary-layer growth. Anodized aluminum end flanges support the large reservoir cylinders for the open-jet and slotted-wall test sections. Anodizing reduces surface deposits from the tunnel water; a black color was chosen for photographic reasons.

The test sections are followed by a 7-degree diffuser with a 1-to-4 area ratio. Parabolic transitions join the test section to this diffuser. The recirculating conduit includes four turning elbows containing guide vanes made from airfoil shapes of extruded aluminum (Fig. 8). A 15-hp electric motor driving a 3-bladed propeller-type pump produces test-section velocities from 8 to about 54 fps. After leaving the pump, the water passes through a third diffuser to the nominal 18-in. diameter recirculating conduit, through a flow model of an air-bubble resorber, and into the contraction cone. This resorber is a 1/6-scale flow model of a prototype resorber and is not optimum from an air-bubble resorption point of view. It does operate as a low efficiency resorber, however, and may be bypassed if desired. The contraction cone was machined from cast aluminum and has an anodized surface. It has a 9-to-1 area reduction with a concave curvature over the upstream 22 per cent of its length and a convex curvature over the remaining 78 per cent.

The tunnel was designed and constructed by the Laboratory staff. It was fabricated of steel weldments in the low-velocity portions of the tunnel circuit, and the inner surfaces were galvanized or (in the case of the resorber) painted with a synthetic enamel.

The basic test-section diameter of 6 in. and the velocity range from 8 to 54 fps were selected as a practical compromise of a number of factors. These factors include: achieving a definitely turbulent Reynolds number (2.4 to 29 x 10^5 over the range of operating temperatures and velocities) in the test section, components of convenient fabrication and handling size, a reasonable cost (varies roughly as the square of the size), and reasonable power demands (varies approximately as the cube of the velocity).

Test-section velocities are controlled by varying the pump shaft speed through a mechanical transmission from the driving motor, and are indicated by means of a calibrated pressure measurement across a part of the contraction cone. Test-section pressures are controlled by raising or lowering the free surface of a water leg which is flexibly connected to the tunnel wall either in the contraction or in the test section itself. Values from one psig down to vapor pressure can be attained in the test section.

The total capacity of the tunnel with the air-bubble resorber is about 1600 gal, and is filled directly from the city water supply without further treatment. This supply water is nearly saturated with air at temperatures from below 40 F in the winter, to above 70 F in the summer. The air content of the tunnel water is varied and controlled from about 45 per cent to over 100 per cent saturation (based on atmospheric pressure at the operating temperature).

Wall piezometer taps are located on the walls of the tunnel at numerous points, especially in the test-section regions. Stuffing glands are also located at the upstream and downstream ends of all tunnel components to allow insertion of Pitot cylinders for making velocity traverses (Fig. 4). Numerous traverses can be made in the test section. Provision is made for measuring the axial pressures in the test sections and boundary pressures on test bodies mounted in the test sections through hollow axial shafts extending through the ends of the upper horizontal leg of the tunnel. During early design studies, surface pressures on the guide vanes were also measured.

Cavitation is observed visually through the transparent walls of the test sections and through viewing ports placed near the vaned elbows and the pump impeller.

OPERATIONAL CHARACTERISTICS OF THE TUNNEL

Extensive measurements were made in the models of the three prototype tunnels in order to predict the flow quality in the test sections, the energy losses in the various tunnel components, and the cavitation characteristics of the tunnels. Estimates of prototype water tunnel performance were made on the basis of these measurements and have been given in various reports prepared for the David Taylor Model Basin. Some of the actual measurements from the 6-in. tunnel will be given.

A. Test-Section Flow Quality

It is desirable that there be no pressure or velocity gradients in the test-section flow and that the turbulence level be as low as possible. By its nature, the open jet has rather large gradients, but is well suited for short, large-diameter bodies such as propellers. The axial pressures for four different test sections are shown in Fig. 9. The pressures are expressed as a dimensionless coefficient relative to the conditions existing at the upstream end of the test-section axis. Those for the diverging closed jet are uniform within 1/10 per cent of the dynamic pressure for nearly two test-section diameters.

Velocities are uniform within 1 per cent of the maximum over 90 per cent of the diameter for the open jet, the closed jet, and the slotted-wall bare test sections at a plane 3 in. from the beginning of the test section.

Typical velocity profiles are shown in Fig. 10. Measurements of the longitudinal velocity fluctuations at the outlet from the resorber indicated rms (root mean square) values of the order of 5 per cent of the mean. These are higher than customary for fully-developed flow, and are reduced as the water passes through the contraction. Turbulence sphere tests indicated a critical Reynolds number of 254,000 in the test section for the tunnel without the resorber.

B. Power Loss

The minimum input power required from the pump varies from 17 to 32 per cent of the jet power, depending on the tunnel assembly. Table I gives the loss coefficients in terms of the power in the test jet.

TABLE I

SIX-INCH WATER TUNNEL POWER REQUIREMENTS AT 50 FPS

Test Section	Without Resorber	With Resorber
Closed Jet	0.17	0.215
Open Jet	0.245	0.29
Slotted Wall	0.275	0.32

Results of measurements across each tunnel component (Fig. 4) are given in Table II as approximate losses in per cent of total losses for each assembly. The data apply only to the tunnel with the resorber.

TABLE II

APPROXIMATE LOSSES IN TUNNEL COMPONENTS

Per Cent of Total Loss with Resorber

Type of Test Section	Closed Jet	Open Jet	Slotted Wall
Test Section	8	} 52	} 56
Diffuser I	31		
Elbow I	9	9	8
Diffuser II	5	3	3
Elbow II	10	7	6
Diffuser III	5	4	4
Elbow III	1	1	1
Resorber	20	15	14
Upcomer Extension, Elbow IV	1	1	1
Contraction	10	8	7

C. Cavitation Characteristics

It is desirable that the tunnel be capable of running at a test-section cavitation index as low as possible in order that bodies of low incipient cavitation can be tested without cavitation occurring elsewhere in the tunnel. The minimum cavitation index applies when cavitation is incipient and is defined as

$$\sigma_{min} = \frac{P - P_c}{\rho V^2/2}$$

where P_c = cavitation pressure of the water, ρ = density of the water. P and V are the absolute pressure and velocity, respectively, applying at the upstream axis of the test section, the guide vanes, or the pump, as the case may be. For the pump, $\rho V^2/2$ is replaced by the total head across the pump, and the pressures are expressed as head.

1. The Test Section

Incipient cavitation occurs as intermittent bubbles at the top of the test-section diffuser transition for the closed jet (Fig. 11). The value of the minimum cavitation index is thus determined largely by the wall pressures. These wall pressures for bare test sections are shown in Fig. 12 for both cylindrical and diverging closed jets and result in a minimum cavitation index of 0.07 (evaluated at the upstream axis of the test section) for the cylindrical and 0.023 for the diverging closed-jet test sections.

The open jet cavitates at a cavitation index of about 0.4 in the form of vortex cavities in the region of high shear at the boundaries of the diffusing jet (Fig. 13).

The slotted-wall test section cavitates at an index of about 0.6 to 0.9 in the form of vortex cavities in the wakes of the guide bars at the higher value, and along the slots between bars at the lower value (Fig. 14).

2. The Guide Vanes

The only guide vanes likely to cavitate are those in the first elbow, since the pressures are lower and the velocity (in the core) greater than for any other elbow. Measurements of vane boundary pressures indicated a critical cavitation index of 2.25 for these guide vanes, while the lowest cavitation index at which they are operated is greater than 5.9, and thus are free from cavitation. Visual observations confirmed this.

3. The Pump

The model tunnel pump consisted of a three-bladed propeller-type impeller preceded by a faired drive shaft and elbow vaning and followed by an anti-rotation blading and diffuser. Despite the use of a standard commercial impeller and a relatively low vertical static head at the pump intake of the model tunnel, incipient tunnel cavitation occurred in the test section (for all types) before visual or sonic cavitation evidence occurred on the impeller.

Computation of the cavitation index occurring at the pump intake when incipient cavitation occurs in the test section establishes that the least of these values (3.0) is greater than the generally accepted critical cavitation index values (1.0 to 2.0) which may be expected with commercial propeller pumps.

SOME TESTS CONDUCTED IN THE SIX-INCH TUNNEL

Although the tunnel was built as a model of other tunnels and not as a test facility in itself, it has been used for this purpose in a number of instances.

There are numerous direct and indirect measurements reported in the literature which indicate that boundary pressures in incipient-bubbling cavitation zones in water, range from values considerably above vapor pressure to below absolute zero (liquid tension).

Tests have been conducted to study some of the factors believed to affect the cavitation susceptability of water in a water tunnel and to determine if the use of a measured cavitation index would result in more consistent values in tests of incipient bubbling cavitation on slender bodies. Factors studied included total gas content of the water, the free carbon dioxide, the nitrogen-oxygen ratio, changes in surface tension (measured statically), temperature, and velocity. The total gas content and temperature were the only known factors which changed the measured cavitation pressure significantly at a given velocity, although one or more unknown factors were effective since tests with different waters at a given air content and temperature were not always reproducible. The cavitation pressure was measured on the wall of the tunnel test section, in the diffuser transition region, when cavitation was visually observed to be incipient. No hysteresis effects (cavitation appearance or disappearance occurred at the same pressure) were observed.

Typical cavitation pressures measured for two values of relative saturation are shown in Fig. 15. The cavitation pressure increased with increasing air content and with velocity.

Incipient cavitation tests were run on 3- and 6-caliber ogive head forms for various water conditions. Cavitation inception was determined visually, and the critical cavitation index was computed with vapor pressure and with the measured cavitation pressure as a datum. Typical test results are shown in Fig. 16. The incipient cavitation index based on the measured cavitation pressure was quite constant at 0.083, and when based on vapor pressure it varied from about 0.090 to 0.115, on the average.

Figure 17 shows the pressure distribution along a short cylinder of 2-in. diameter and hemispherical head form. The pressures were measured in a 10-in. diameter free jet and in 6-in. diameter test sections of the slotted wall and the closed jet type. The measurements show the ability of the slotted wall test section to provide approximately free-field flow conditions, using the free jet as a basis for comparison.

These are typical of tests which can be conducted in a high-quality, relatively small water tunnel where flow and water parameters can be readily varied.

A P P E N D I X

Figures 1 to 17

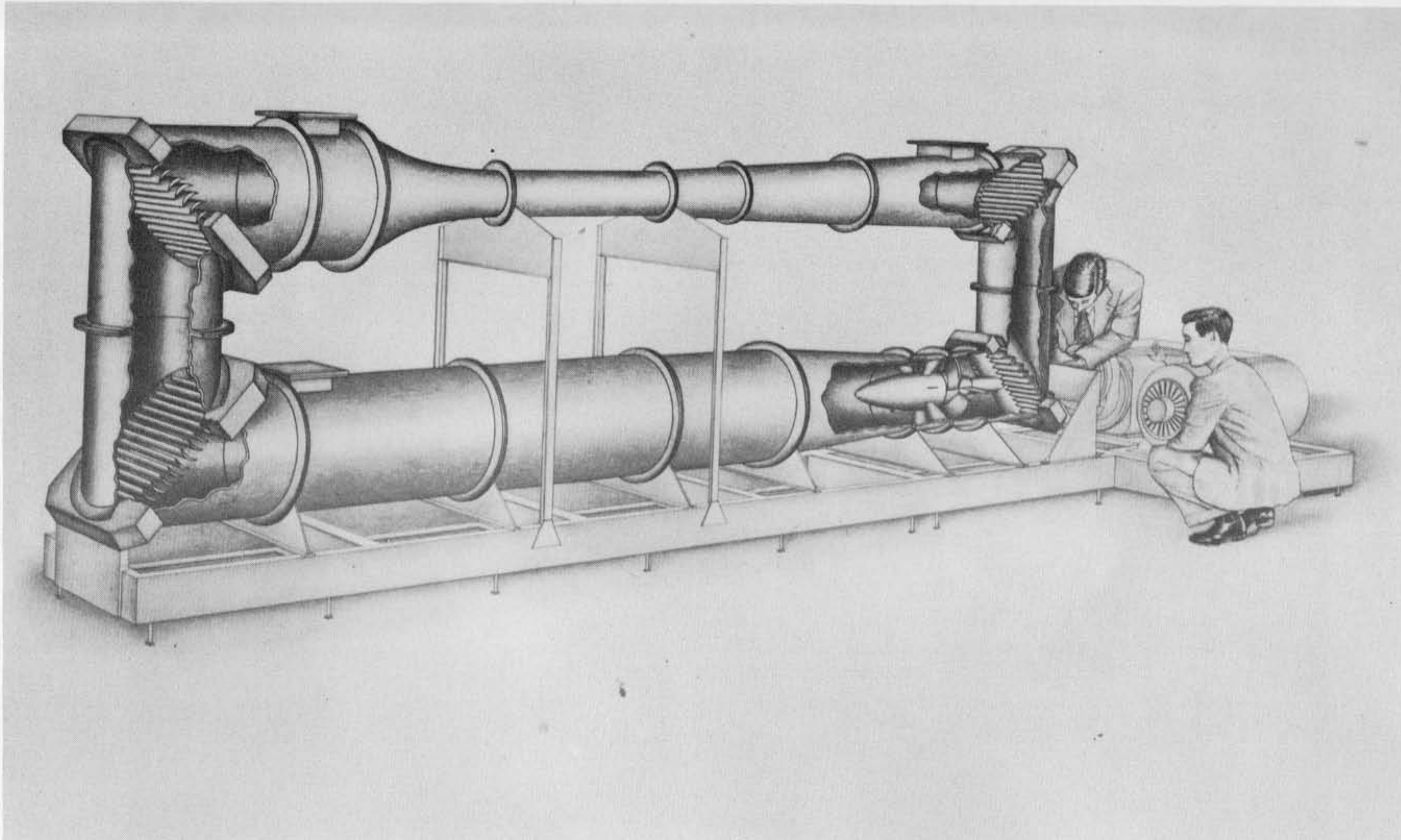


Fig. 1 - Model of 60-inch Water Tunnel

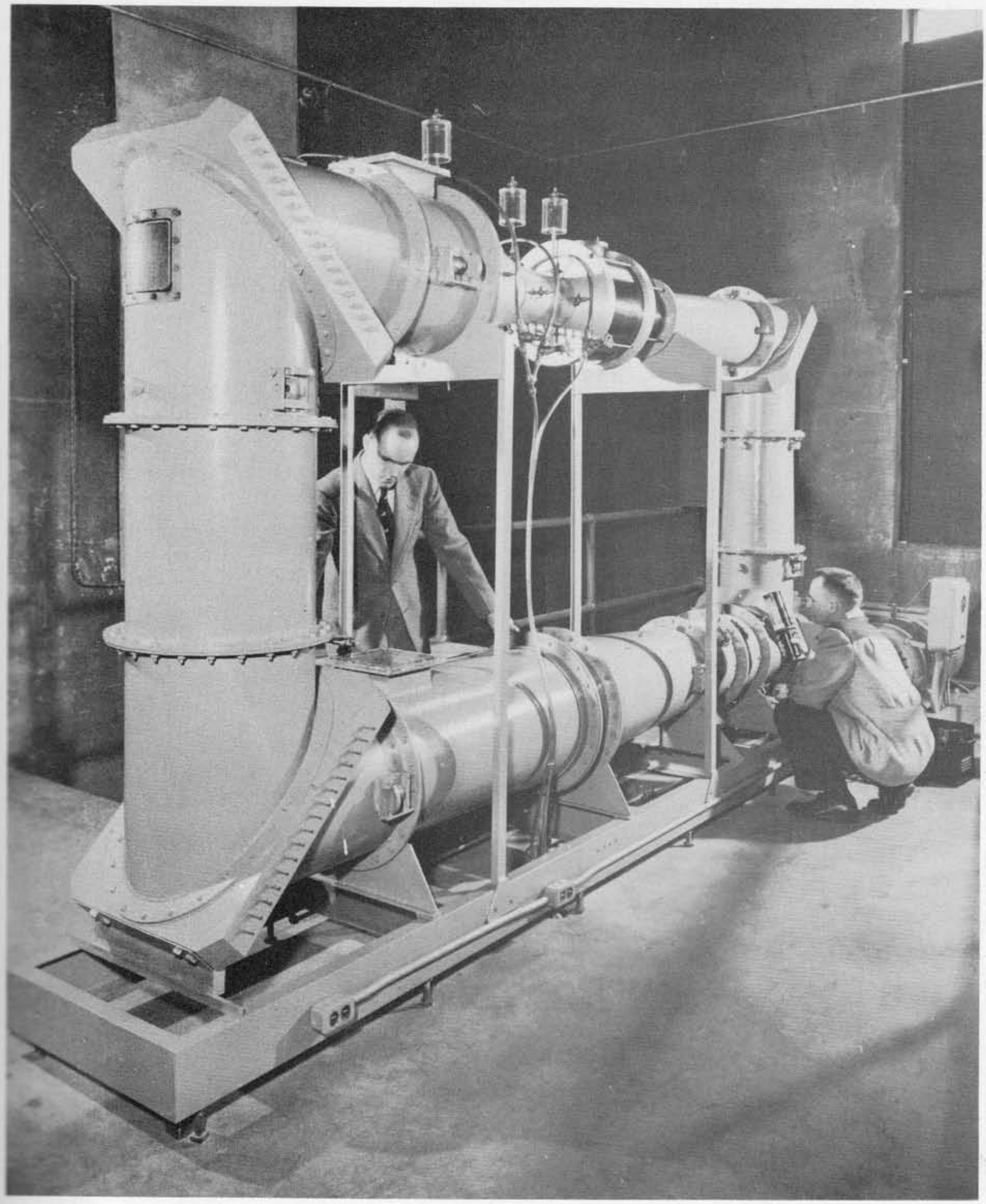


Fig. 2 - Model of 24-inch Water Tunnel

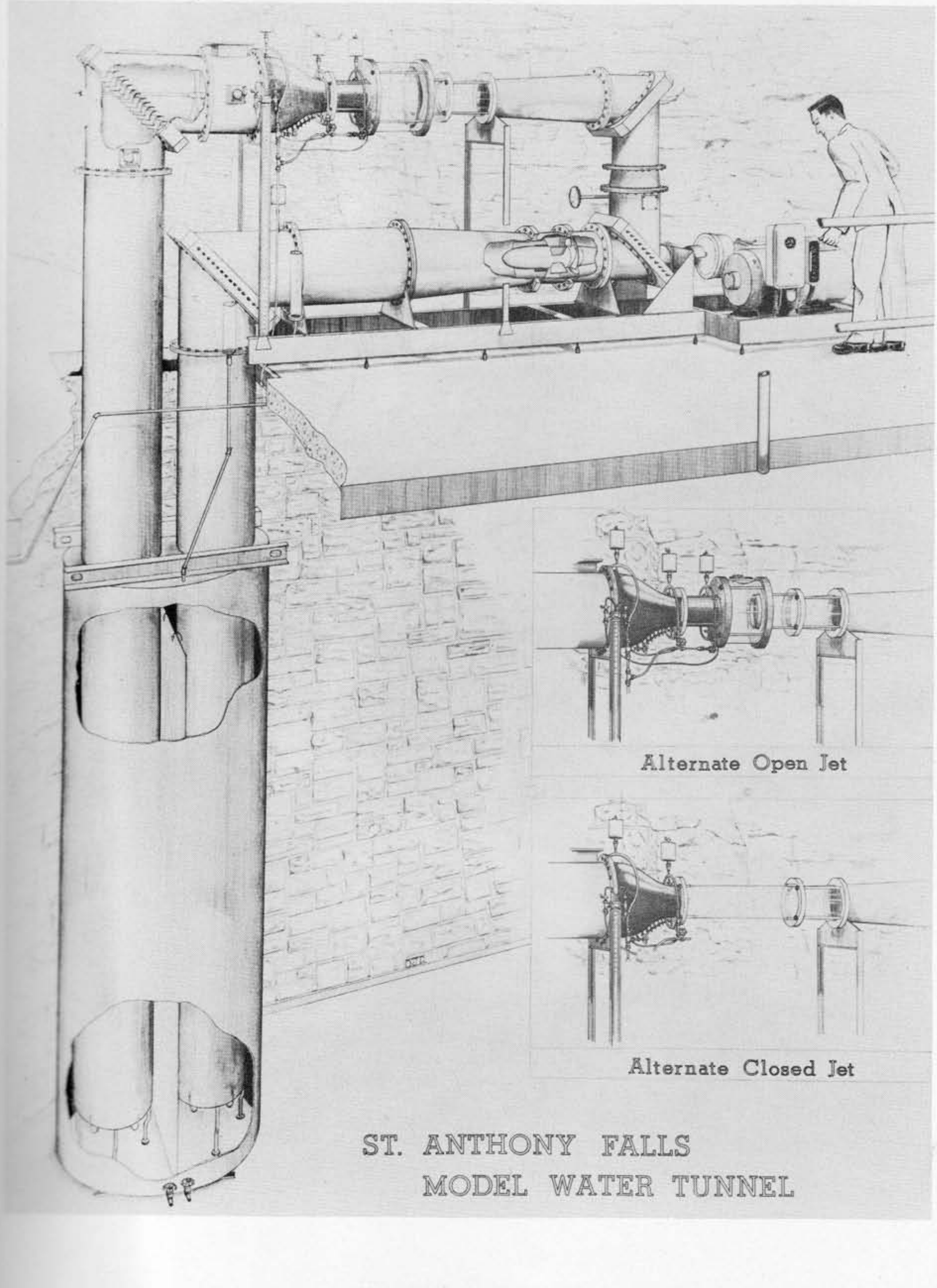


Fig. 3 - St. Anthony Falls 6-inch Water Tunnel with Slotted-Wall Test Section

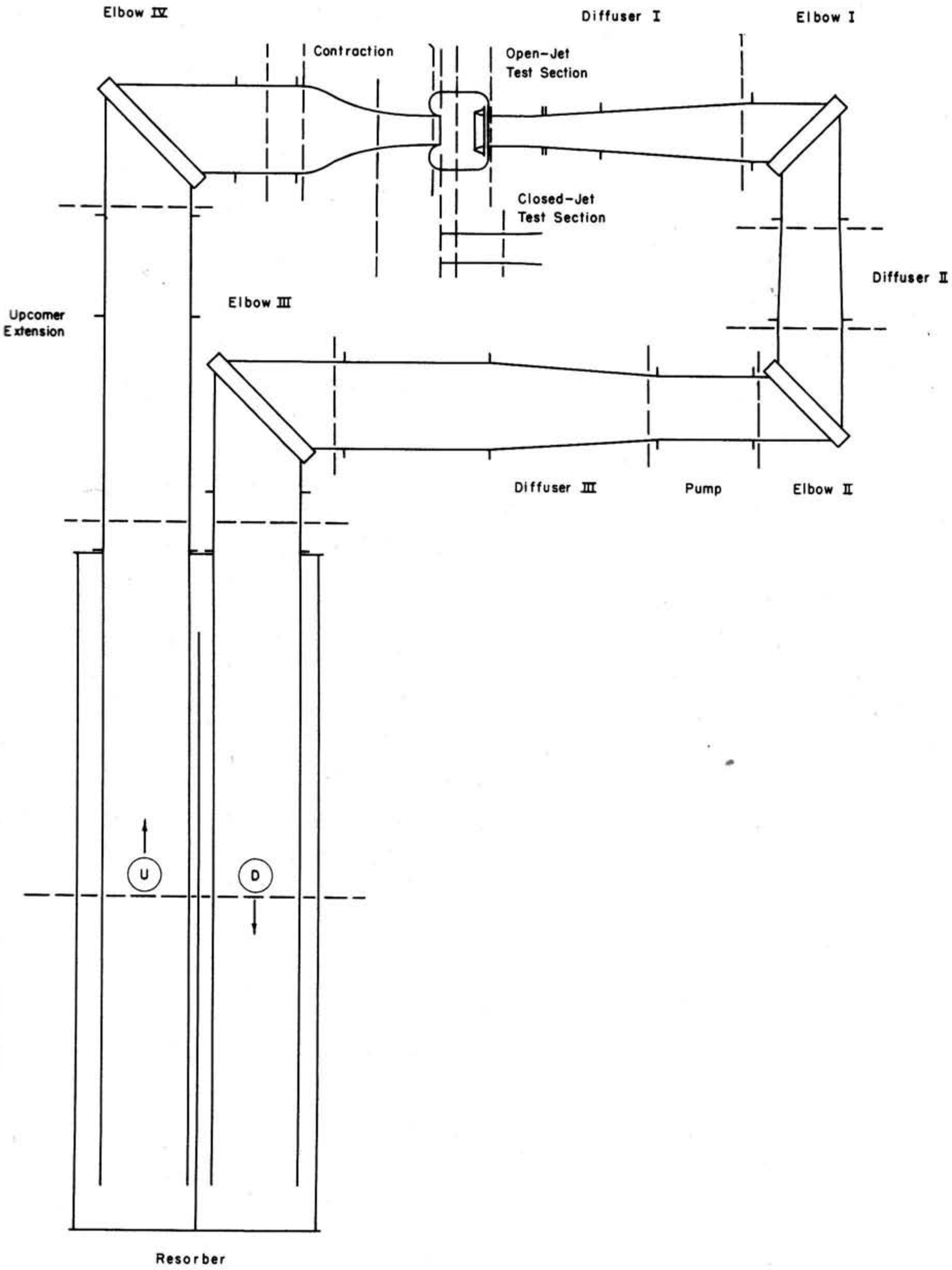
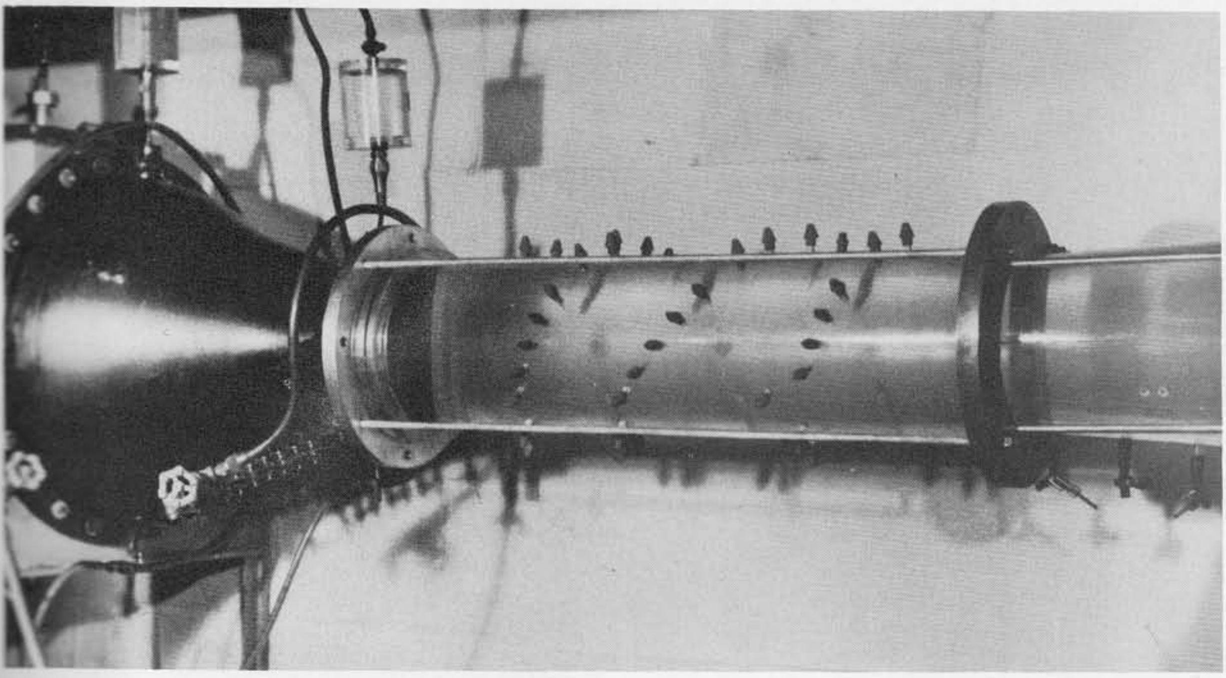
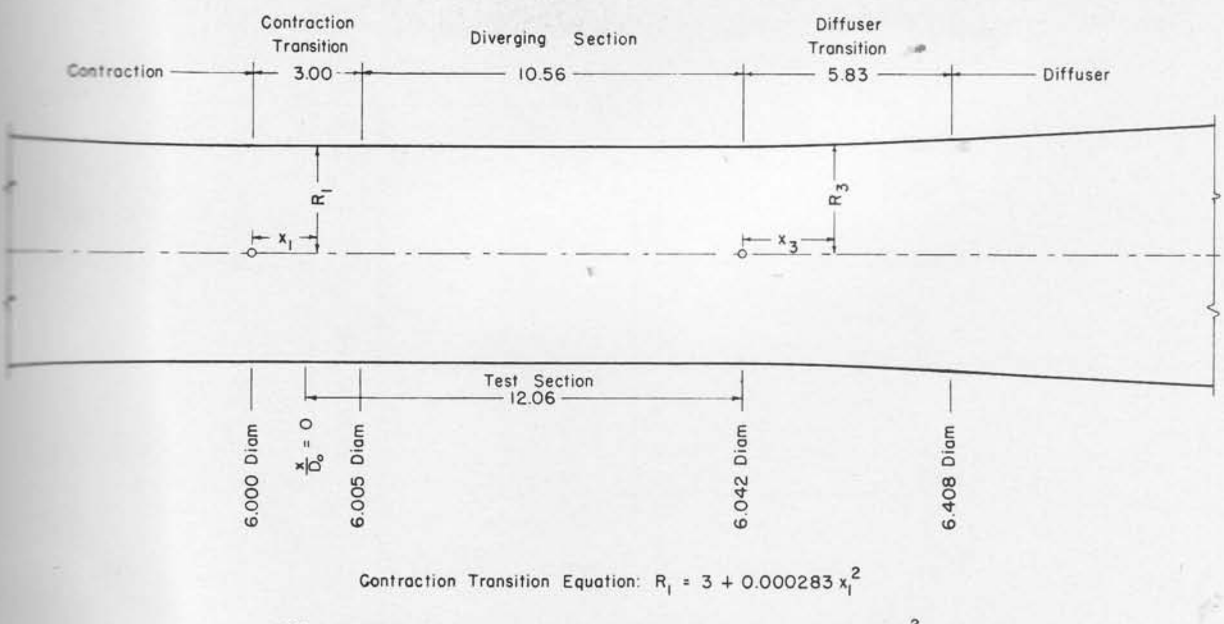


Fig. 4 - Model Tunnel Components and Measuring Stations



(a) Bare Test Section

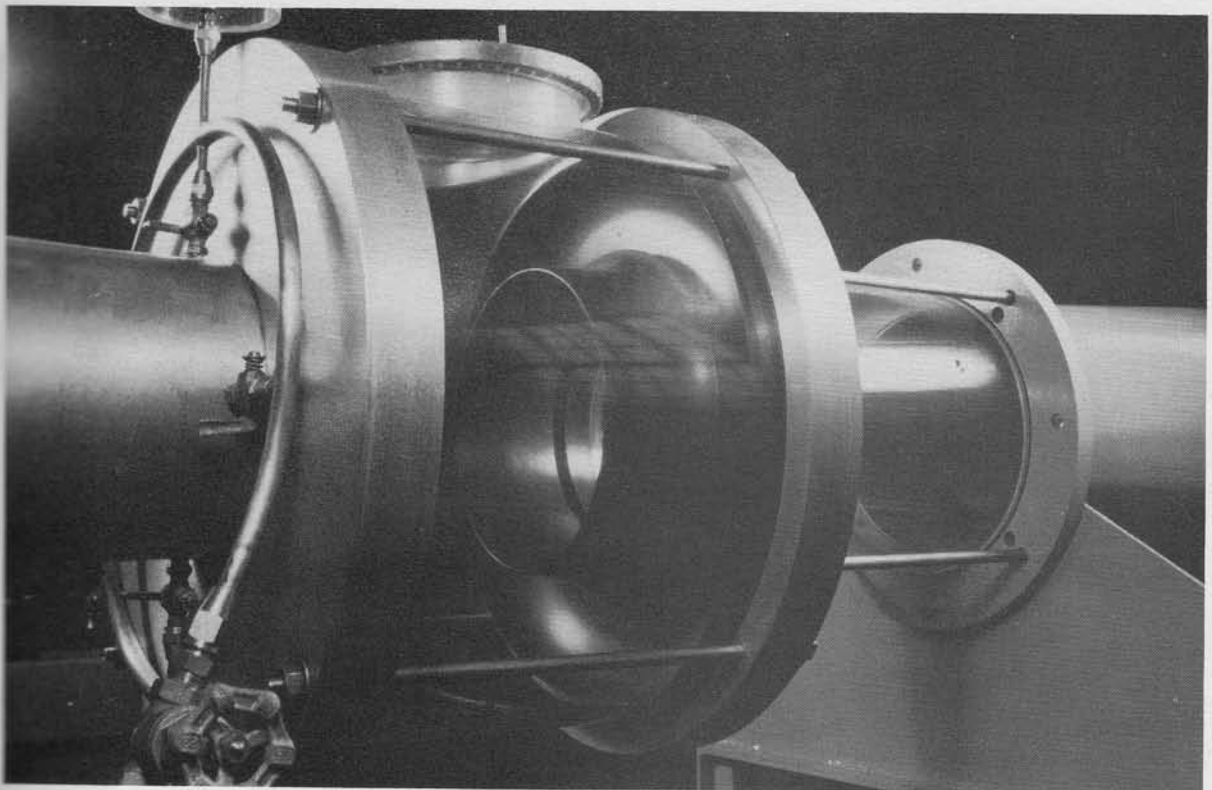


Contraction Transition Equation: $R_1 = 3 + 0.000283\,x_1^2$

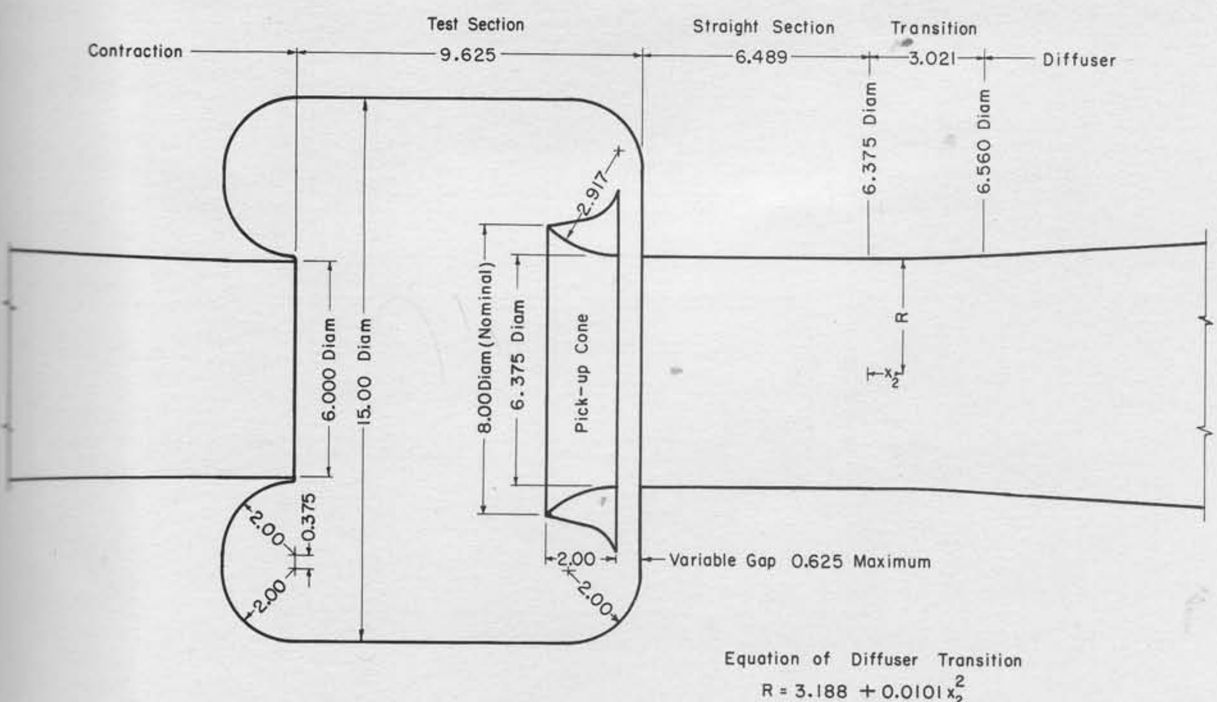
Diffuser Transition Equation: $R_3 = 3.021 + 0.001701\,x_3 + 0.00510\,x_3^2$

(b) Boundary Profile

Fig. 5 - The Diverging Closed-Jet Test Section

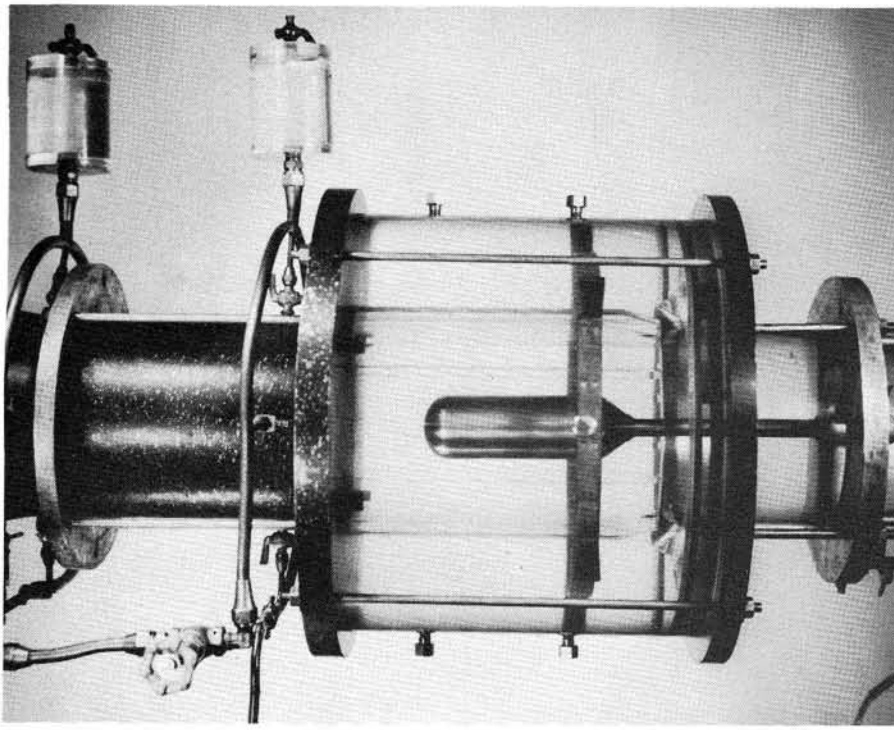


(a) Assembly

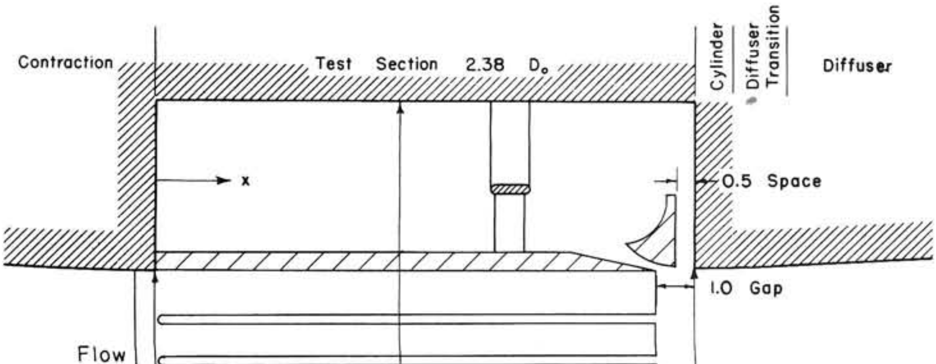


(b) Boundary Profile

Fig. 6 - The Open-Jet Test Section

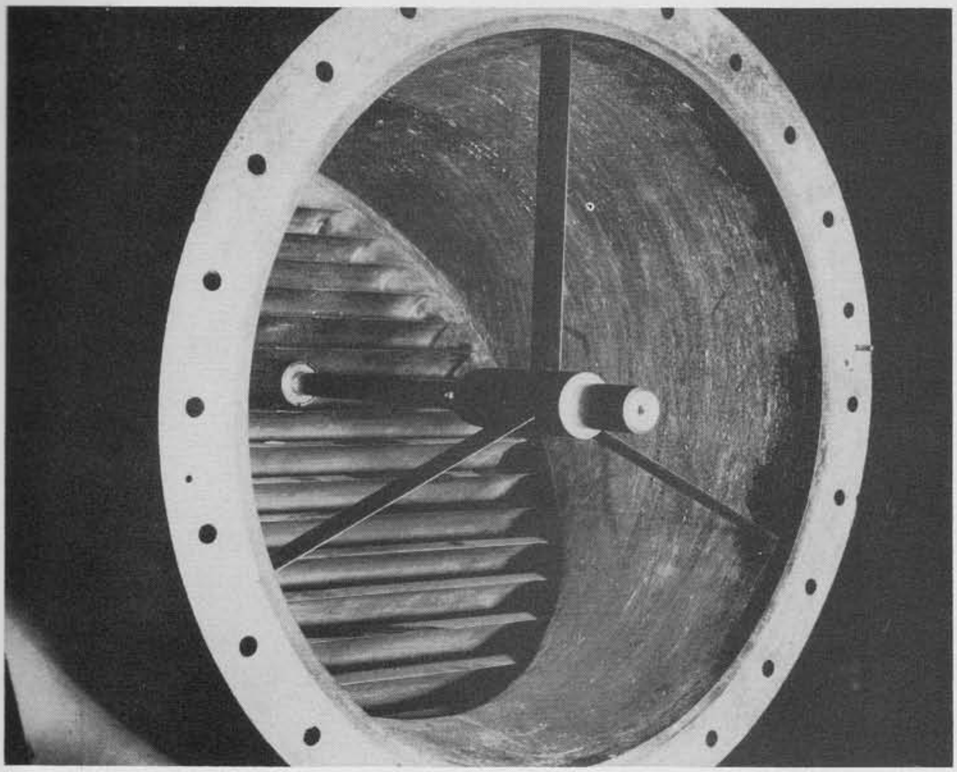


(a) With Hemispherical Head Form

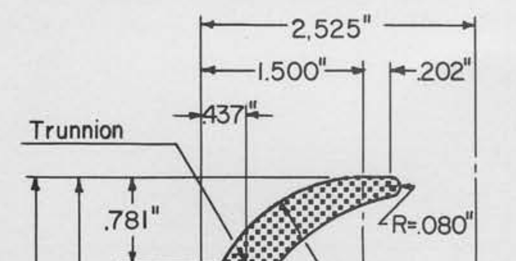


(b) Boundary Profile

Fig. 7 - A Slotted-Wall Test Section



(a) Vaned Elbow IV with Measuring Shaft Housing and Strut Supports



(b) Vane Profile

Fig. 8 - Vaned Elbow

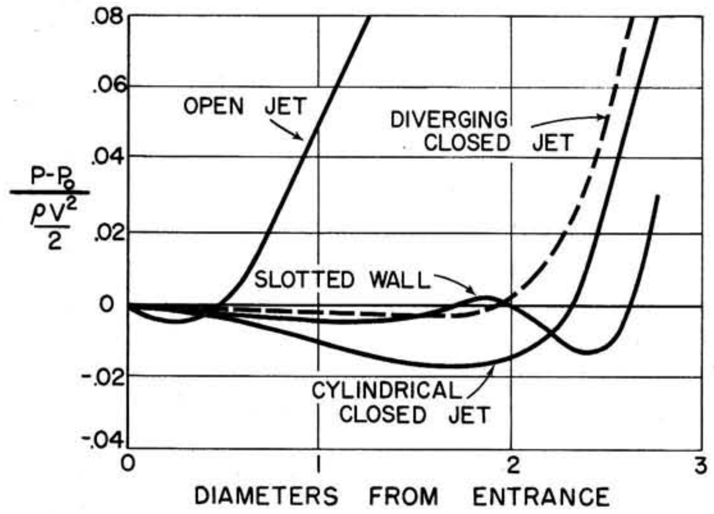


Fig. 9 - Axial Pressures for Various Types of Test Sections

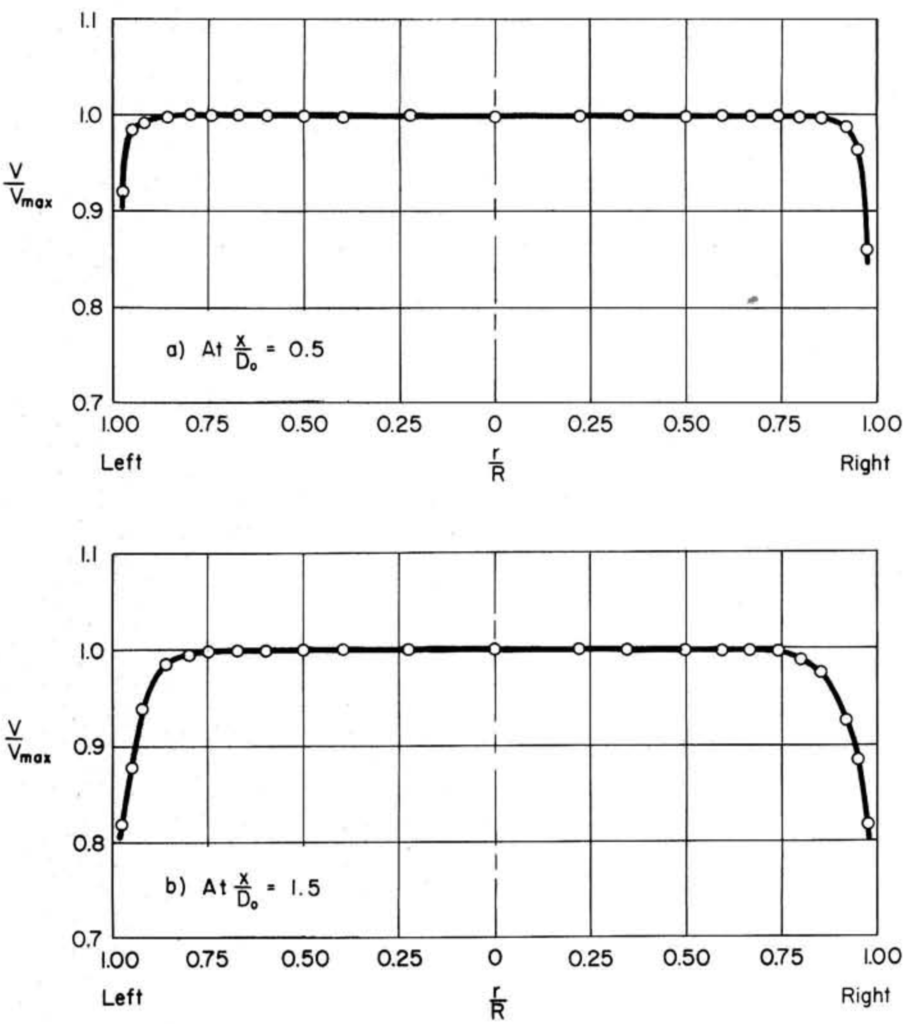
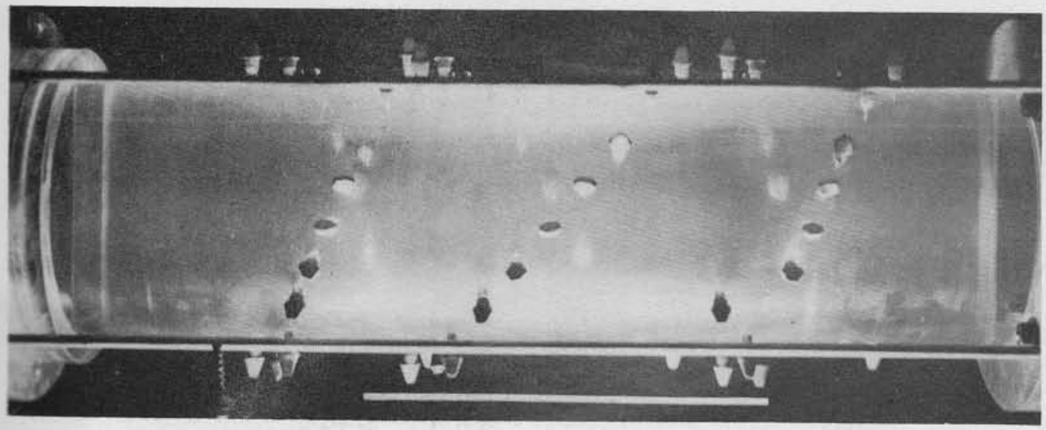
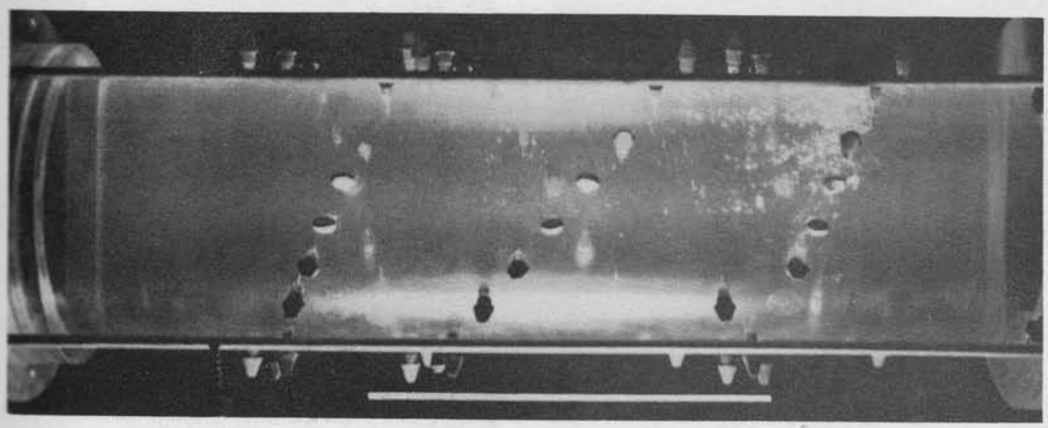


Fig. 10 - Horizontal Velocity Profiles in Slotted-Wall Test Section



(a) σ_o = 0.06 (no cavitation)



(b) σ_o = 0.014

Fig. 11 - Cavitation in Diverging Closed-Jet Test Section

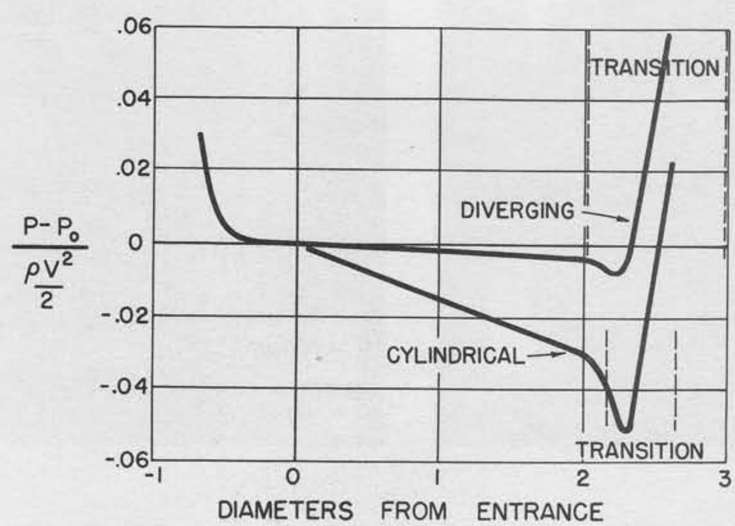
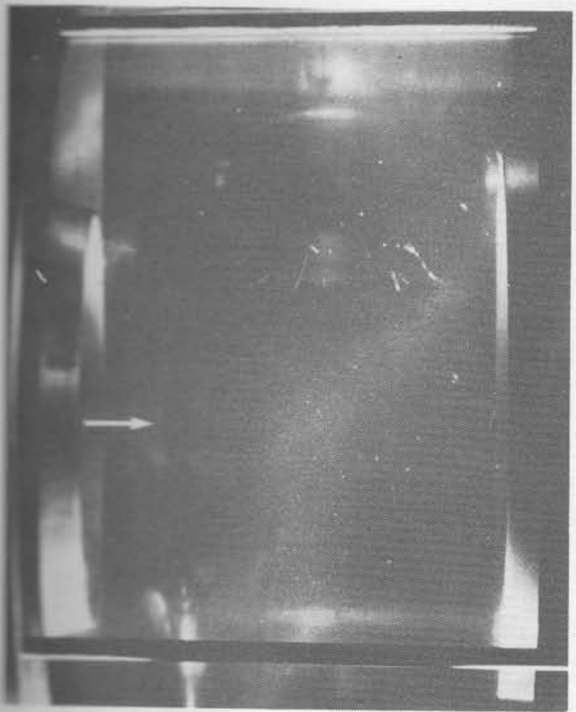
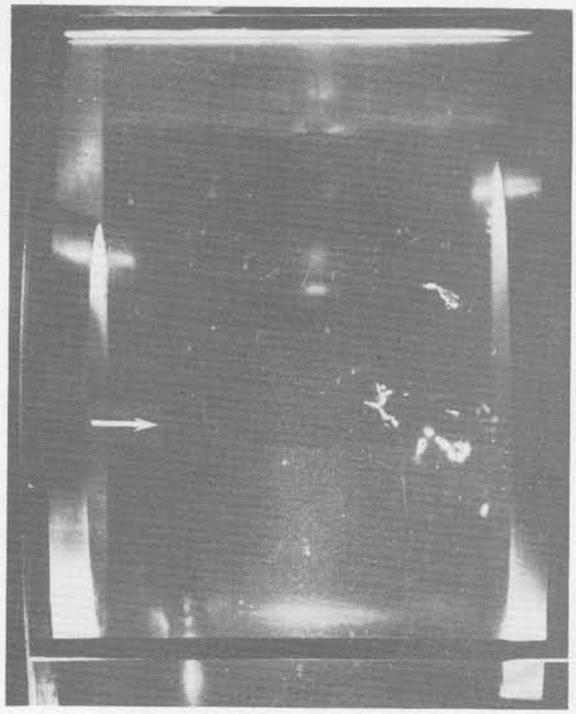


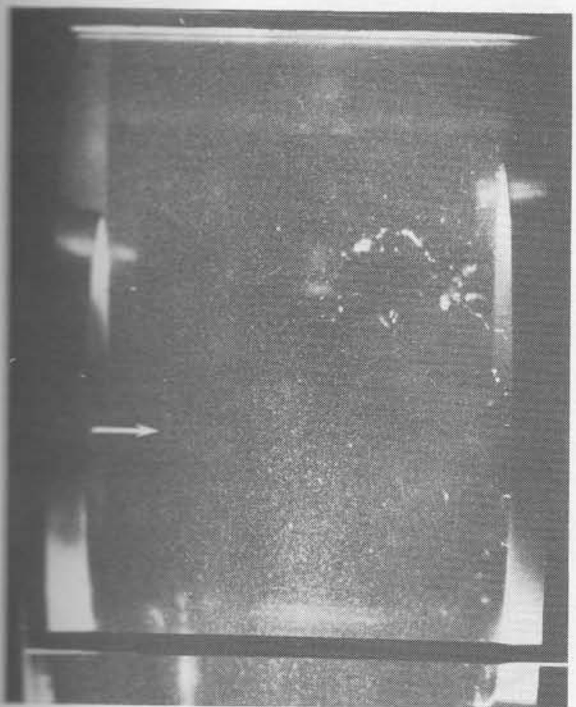
Fig. 12 - Wall Pressures in Closed-Jet Test Sections



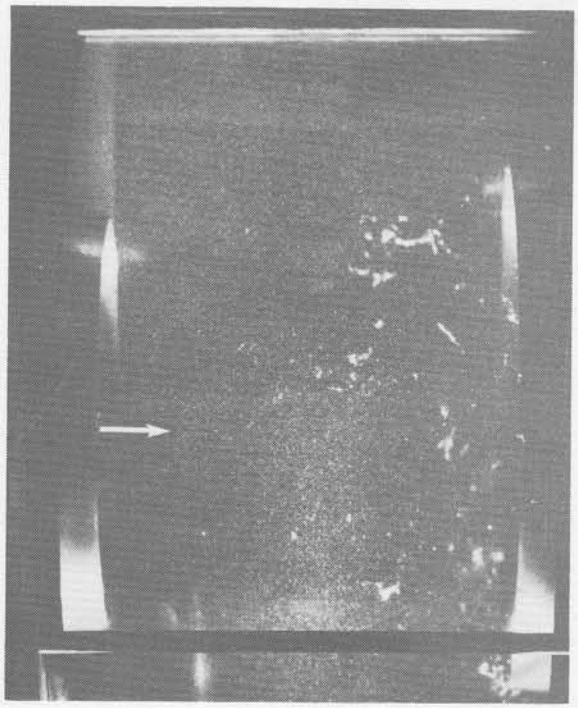
σ = 0.410



σ = 0.375

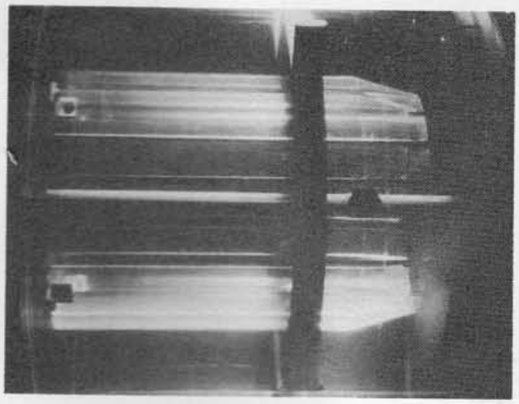


σ = 0.320

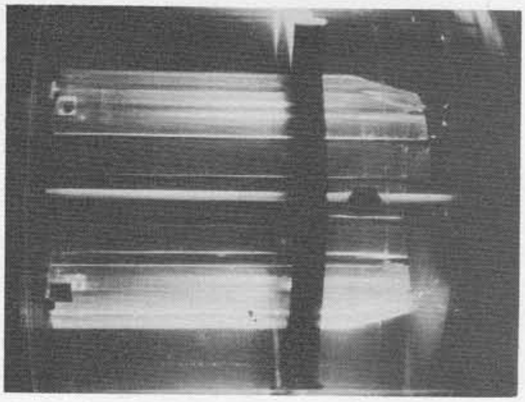


σ = 0.285

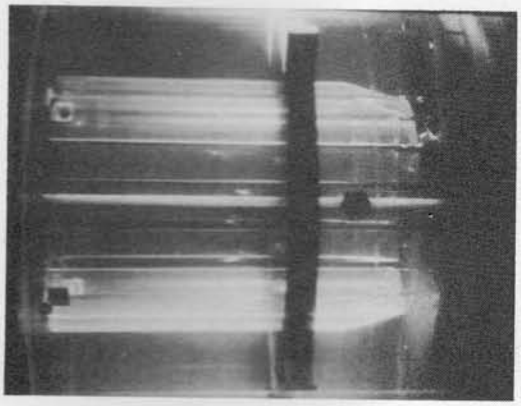
Fig. 13 - Cavitation in Open-Jet Test Section



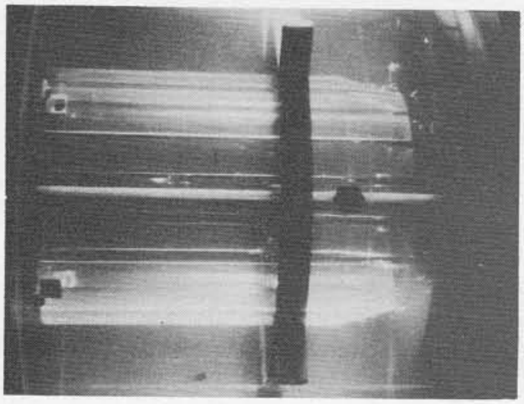
a) σ_o = 0.7



b) σ_o = 0.6



c) σ_o = 0.5



d) σ_o = 0.4

e) σ_o = 0.35

CAVITATION WAS INCIPIENT AT A CAVITATION INDEX OF σ_o = 0.70 AS VORTEX CAVITIES IN THE WAKES OF THE ENDS OF THE GUIDE BARS. CAVITATION FURTHER UPSTREAM NEARER THE CENTER OF THE TEST SECTION BEGAN AT A CAVITATION INDEX OF ABOUT 0.50. BELOW THAT THE RESERVOIR BECAME CLOUDED.

Fig. 14 - Cavitation in the Slotted-Wall Test Section

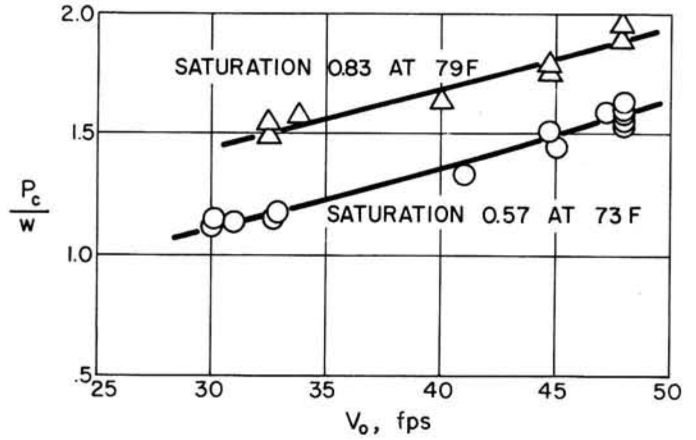


Fig. 15 - Cavitation Pressures of Tunnel Water

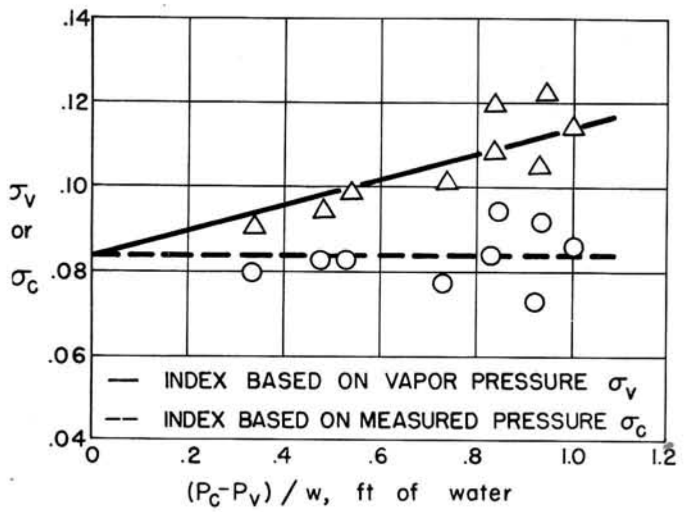


Fig. 16 - Incipient Cavitation Index for a 6-Caliber Ogive Head Form

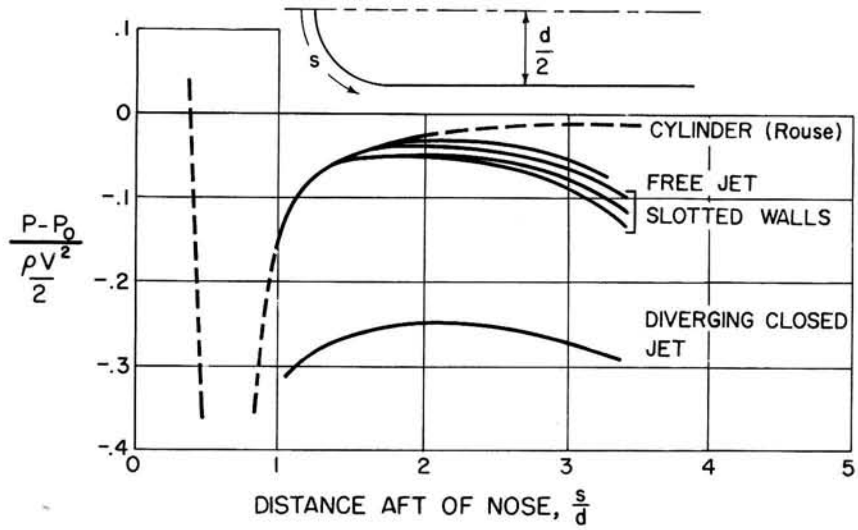


Fig. 17 - Pressure Distribution Along a Short Cylindrical Body Placed in Various Types of Tunnel Test Sections