ST. ANTHONY FALLS HYDRAULIC LABORATORY
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CAVITATION TESTING IN WATER TUNNELS

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PREFACE

Cavitation generally occurs in a flowing liquid when the pressure at some point in the liquid is reduced to a critical value near the vapor pressure. The cavities which result may occur in various forms: either as intermittent bubbles, more-or-less steady cavities which form on a body and then leave with the fluid as it passes the body; or as essentially steady cavities which completely envelop at least a part of the submerged body.

Cavitation manifests itself in different ways: It affects the performance of pumps, turbines, and propellers, and is commonly detected by sudden changes in some of the performance characteristics. It produces vibration in hydraulic machinery. It causes pitting of surfaces in cavitation zones. It affects the drag of an underwater body. Finally, it produces noise which is often used to detect cavitation inception on bodies.

In some instances it is not important to know whether cavitation occurs at vapor pressure, as is often assumed, or at some slightly different pressure. In other instances this information is believed to be necessary--for incipient cavitation, it is especially important for bodies having low critical cavitation indices. For tests of bodies under partial cavitating conditions (some propeller tests) it may also be significant.

This report deals with water-tunnel testing of incipient cavitation of the intermittent-bubbling type on bodies having low critical cavitation indices.

Contract Nonr-710(06) between the University of Minnesota, St. Anthony Falls Hydraulic Laboratory, and the Department of the Navy, David Taylor Model Basin, provided for studies of some factors believed to affect the cavitation susceptibility of water in water tunnels and to determine whether or not a measured cavitation pressure is more suitable than the vapor pressure in defining a cavitation parameter for incipient cavitation of the intermittent-bubbling type. This report contains the results of the studies.

The program was carried out under the general direction of Dr. Lorenz G. Straub, director of the St. Anthony Falls Hydraulic Laboratory, and was supervised by R. M. Olson. The apparatus for the water analyses was set up by N. R. Ziemke, and most of Part V is a digest of an informal report prepared by him. Dr. A. G. Anderson performed the tests on the effects of surface tension. C. D. Christopherson made some analyses of experimental and analytical results found in the literature and conducted some exploratory tests in a 10-in. free jet. Most of the experimental work was done by R. S. Dart, D. W. Rolschau, R. P. Wengler, N. R. Ziemke, and R. M. Olson.

ABSTRACT

There are direct and indirect measurements reported in the literature which indicate boundary pressures in incipient-bubbling cavitation zones in water ranging as high as a foot or more of water above vapor pressure to below absolute zero (liquid tension).

Tests have been conducted to study some of the factors believed to affect the cavitation susceptibility of water in a water tunnel and to determine if the use of a measured pressure instead of vapor pressure in computing the cavitation index would result in more consistent results 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, colloidal solid nuclei added to the water, 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 were seldom reproducible.

Incipient cavitation tests of the tunnel test section, and of a 3- and 6-caliber ogive head form, indicated that the incipient cavitation index was more constant when based on a measured pressure than when based on the conventional vapor pressure.

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

h - Piezometric head on a body surface in feet of water.

h_c - Measured cavitation pressure head in feet of water absolute.

h_v - Vapor pressure of water in feet of water absolute.

h_o - Pressure head at axis of upstream end of test section in feet of water.

P_c - Measured cavitation pressure in pounds per square foot absolute.

P_v - Vapor pressure of water in pounds per square foot absolute.

P_o - Pressure head at axis of upstream end of test section in pounds per square foot absolute.

V_o - Test-section velocity in feet per second.

σ - Cavitation index = $(h_o - h_v)/(V_o^2/2g)$ when based on vapor pressure.

σ_c - Cavitation index based on h_c.

σ_v - Cavitation index based on h_v.

CAVITATION TESTING IN WATER TUNNELS

I. INTRODUCTION

The purpose of the cavitation studies at the St. Anthony Falls Hydraulic Laboratory has been to study some factors believed to affect the cavitation susceptibility of tunnel water and to determine whether there is a measurable pressure at which cavitation occurs which is a better indication of the cavitation susceptibility of the water than is vapor pressure. The vapor pressure is customarily used as the datum in defining the cavitation index. The ultimate objective would be to use this measured pressure in computing the cavitation index. If this were done, it was believed that perhaps the cavitation index would be, at least for incipient cavitation if not generally, more a characteristic of a body shape (and perhaps size) and independent of the cavitation susceptibility of the water in which the body is tested.

Interest in this problem was developed in conjunction with earlier model tests of a diverging closed-jet test section for a water tunnel conducted for the David Taylor Model Basin, Department of the Navy. It was necessary to determine the minimum cavitation index at which the tunnel could be run. This index was defined in the customary manner as applying to the upstream axis of the test section when cavitation had just begun at some other point in the tunnel. The point of cavitation inception was at the top of the diffuser transition between the test section and the main diffuser immediately following. Measurements were made with tunnel water at different, but unknown, air contents, and the results showed a minimum cavitation index varying between 0.049 and 0.102 when cavitation was assumed to occur at vapor pressure. However, when based on the pressures measured at the point of cavitation inception, the index was constant at 0.023. It was believed that the cavitation index should be largely a function of the geometry of the flow boundaries and, for a given boundary shape, should be relatively independent of the ease with which the water cavitates.

Cavities may be of various forms:

(1) Intermittent bubbles which grow and collapse within a very short time.

(2) Steady cavities which peel off the tips of propeller blades, for example, or which form about an immersed body.

(3) Large cavities which completely envelop a body for a short period of time, such as when a body enters a free water surface.

The present studies were concerned almost entirely with the inception or disappearance of intermittent-bubble cavitation. One series of tests was run on an essentially steady cavity behind a probe.

The experimental program was divided into four phases:

(1) The establishment, measurement, and control of some of the factors believed to affect the cavitation susceptibility of water in a water tunnel.

(2) A study of the effect of these factors on the measured pressure at which water cavitates.

(3) The use of various body shapes to measure the cavitation pressure and the determination of whether the method of measuring this cavitation pressure is important.

(4) A comparison of the cavitation index for incipient cavitation (of the intermittent-bubble type) for some typical body shapes based on vapor pressure and on a measured cavitation pressure under various conditions in both a closed- and a free-jet water tunnel.

The program, as originally outlined, was not completed within the time and funds allotted. Phases (1) and (2) above were completed as planned, but only preliminary tests were run for phases (3) and (4). The idea of using a measured pressure rather than the vapor pressure as the cavitation pressure datum in defining the cavitation index has received support from the tests on cavitation inception, but more extended experimental work is necessary to establish it completely.

This report will include a brief discussion of the work of other individuals and laboratories in so far as it relates to the aspect of the cavitation problems being studied. It will be followed by details of the experimental program carried out at the St. Anthony Falls Hydraulic Laboratory.

II. THE CAVITATION PRESSURE AND THE CAVITATION INDEX

When the pressure in a liquid is reduced to a low enough value gaseous or vaporous cavities are formed. Such a low pressure may occur in a flowing fluid as a result of low ambient static pressures, from dynamic effects, or from a combination of both. It has generally been considered that when the pressure reaches the vapor pressure of the liquid corresponding to its temperature, cavitation will occur. Thus, the vapor pressure would be considered as a critical pressure above which the liquid would be free of cavitation.

A quantitative parameter used in cavitation testing is the cavitation index:

$$\sigma = \frac{(P_o - P_v)/w}{V_o^2/2g} = \frac{h_o - h_v}{V_o^2/2g}$$

where p_o, h_o, and V_o are the absolute pressure, absolute pressure head, and velocity at a point in the fluid; w is the specific weight of the fluid; g is the acceleration of gravity; P_v is the vapor pressure; and h_v is the vapor pressure head in feet of water. This index is seen to be simply a dimensionless pressure coefficient, and a numerical value can be applied to any point within a flowing liquid, whether or not cavitation exists at that point or elsewhere in the flow circuit. This general value may or may not be significant. Convention has established certain points of interest which may be implied rather than specified in all instances. For a water tunnel, the minimum cavitation index of the test section refers to the index at the upstream axis when cavitation inception occurs at some other point, usually in the diffuser transition. For a solid body in a fluid, the index refers to a point in the free stream, upstream of the body and at its axis. This index is commonly called the critical cavitation index for the body if it applies when cavitation is incipient at some point on the body. For a propeller, the same location as for a solid body is implied. For a pump, the point of interest is the axis of the pump at its suction side. In the discussion thus far the reference pressure for cavitation has been the vapor pressure.

Suppose it is desired to determine the critical cavitation index for an axisymmetric body. It would be necessary to determine the cavitation index for point "O" when cavitation is incipient at point "B" in Fig. 1. It is possible to measure the absolute pressure and the velocity at "O" and the water temperature to obtain the vapor pressure; and if cavitation inception on the body can be reliably determined by some means or another, the critical cavitation index can be computed. However, the pressure at point "B" on the body at cavitation inception may not be the vapor pressure but may be some other pressure which depends not only on the temperature of the liquid, but also on the air content, the size and distribution of gas nuclei, and perhaps the surface tension of the fluid. It may depend on the size and surface finish of the body as well. If it is assumed that the pressure difference between points "O" and "B," expressed dimensionlessly, is constant regardless of the ambient pressure of the system, P_o can vary considerably when cavitation begins at "B" if the cavitation pressure at "B" varies. Thus, if the cavitation index for incipient cavitation is based on the vapor pressure, it will also vary when P_o varies.

A. Some Direct Measurements of the Cavitation Pressure of Water

There have been a number of proposals for using a pressure other than the vapor pressure as the datum in defining the cavitation index. One of the earlier sets of experiments on measuring the cavitation pressure P_c of distilled, salt, and sea water was that conducted by Numachi and Kurokawa in Japan and reported in abridged form in 1936 and more completely in a series of papers in 1938 [1, 2, 3, 4]*.

Numachi [1] suggested that the cavitation pressure be the saturation pressure of the gas contained in the water, and he attempted to show that there was a fixed cavitation pressure for specified water and flow conditions in his apparatus. His work showed that cavitation became more likely as the air content of water was increased, and that the vapor pressure was not the critical pressure for cavitation.

Gutsche [5] suggested that the cavitation pressure be the pressure observed by Numachi as a function of the water temperature at various values of relative air content. Edstrand [6] in Sweden compared some propeller tests conducted at a cavitation index of 2.0 on this basis with those at a value of 2.0 based on vapor pressure as the cavitation pressure, and

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*Numbers in brackets refer to the Bibliography on p. 31.

found a reversal of the effect of air content on the propeller thrust and torque coefficients and on the propeller efficiency. Both Numachi and Crump [7] show that a fixed value of Edstrand's critical pressure with relative air saturation at agiven temperature is unlikely.

Eisenberg [8] and Edstrand [9] suggest that P_c be a function of the gas saturation pressure from Henry's law. Edstrand used a factor θ with this; this factor depended on the time the water was in the low-pressure region (the water velocity), the water purity, the type of cavitation (bubble or sheet cavitation), and the geometry of the particular water tunnel. His tests indicated that it also depended on the static pressure of the water. He concluded that much experimental work would be necessary before results of model tests could be transferred to prototype ship propellers, but that model tests at different air contents could be compared using a cavitation index based on this cavitation pressure.

B. University of Iowa Tests of Cavitation and Pressure Distribution on Head Forms

Measurements by Rouse and McNown [10] of the pressure distribution on head forms indicate, indirectly, that the cavitation pressure of their tunnel water was above vapor pressure at cavitation inception.

The difference in pressure between two points in a flowing liquid should not be a function of the ambient pressure level as long as the liquid remains homogeneous. Thus, as the ambient pressure of a liquid flowing past a body at constant velocity is lowered, the dimensionless pressure difference between some upstream point and the point on the body surface at which cavitation will eventually be incipient (points "O" and "B" in Fig. 1) should be constant down to, but not necessarily at, the appearance of cavitation. The value of this dimensionless pressure coefficient at the appearance of cavitation should be equivalent to the critical cavitation index for the body if the index is based on the actual cavitation pressure. If this differs from the critical cavitation index based on vapor pressure, the difference is a dimensionless measure of the difference between the cavitation pressure and vapor pressure since

$$\sigma_v - \sigma_c = \frac{(h_o - h_v)}{V_o^2/2g} - \frac{(h_o - h_c)}{V_o^2/2g} = \frac{(h_c - h_v)}{V_o^2/2g}$$

Cavitation inception can be defined as occurring when the minimum pressure coefficient of the body changes from its constant value under noncavitating conditions. If so, some interesting comparisons may be made with pressure measurements taken just before cavitation occurred and at various stages of cavitation on the surfaces of 2-, 1-, and 1/2-caliber (hemispherical), 2:1 ellipsoidal, and half-body head forms [10]. It is believed that for only these five head forms, of the many reported, did cavitation occur on the surface of the bodies; while for the others, cavitation was incipient in vortex cores in the fluid at some distance away from the bodies themselves.

Figures 35, 36, 37, 46, and 50 of [10] indicate that the minimum pressure coefficients were not equal to the cavitation index (based on vapor pressure) at cavitation inception. Figure 2 shows the essential part of Fig. 37 of [10] to illustrate this for the hemispherical head form. In this instance the difference between the cavitation index at incipient cavitation and the minimum pressure coefficient is 0.065, and for all five bodies considered, it ranges from this value up to 0.077 with an average value of 0.070. Since the maximum velocity of this tunnel was given as 35 fps, the maximum difference between the pressure on the head-form surfaces and vapor pressure (based on the average 0.070 value) is 1.3 ft of water. At 30 fps this would be less than 1.0 ft, and at 25 fps, 0.7 ft of water. It is not stated at what velocities the tests were run, but these values suggest that the cavitation pressure of the water may have been above vapor pressure by those amounts. If so, the cavitation index for incipient cavitation based on this cavitation pressure would be the same as the minimum pressure coefficient at cavitation inception. Under cavitating conditions, however, this cavitation index would then be less than the minimum pressure coefficient. This does not appear to be reasonable: the measured data indicate that the minimum pressure on the bodies was equal to the vapor pressure since the cavitation index based on vapor pressure was equal to the minimum pressure coefficient after cavitation was well established.

Thus, there is evidence that for cavitation inception, the cavitation pressure was above the vapor pressure, while after cavitation was well established, the cavitation pressure was equal to the vapor pressure.

C. California Institute of Technology Tests of Cavitation on Hemispherical Head Models

Kermeen [11] reports some observations of cavitation on hemispherical head forms. In these tests intermittent incipient cavitation was defined as the point of maximum acoustic noise for the disappearance of cavitation. Some tests were concerned with scale effects--the effects of model size and flow velocity on the critical cavitation index (based on vapor pressure)--for incipient cavitation as defined above. The cavitation index increases with velocity for a given body diameter. If it is assumed that some cavitation pressure other than vapor pressure exists, the cavitation indices given (based on vapor pressure) for a given body size at various velocities can be examined, and an estimate made of the necessary cavitation pressure for an essentially constant cavitation index for all velocities. For example: If the cavitation index based on vapor pressure is

$$\sigma_v = \frac{h_o - h_v}{V_o^2/2g}$$

then, if based on a truer cavitation pressure, it is

$$\sigma_c = \frac{h_o - h_c}{V_o^2/2g} = \sigma_v - \frac{h_c - h_v}{V_o^2/2g}$$

Values for a 0.5-in. diameter hemispherical head form at four velocities taken from [11] are shown in Table I. It is assumed that all values of the

Table I

CAVITATION INDICES FOR 0.5-IN.-DIAMETER HEMISPHERICAL HEAD FORMS

V_o fps	σ_v	$\sigma_c = \sigma_v - \frac{(h_c - h_v)}{V_o^2/2g}$	$(h_c - h_v)$ ft water
20	0.47	$0.47 - (h_c - h_v)/6.2$	-0.69
40	0.55	$0.55 - (h_c - h_v)/24.9$	-2.31
60	0.60	$0.60 - (h_c - h_v)/56.0$	-3.96
80	0.63	$0.63 - (h_c - h_v)/99.2$	

cavitation index based on the actual cavitation pressure are equal, and if so, the equations for the cavitation index based on this pressure may be solved simultaneously to obtain the values of $(h_c - h_v)$ given in the last column. The last column shows the difference between the cavitation pressure and vapor pressure.

Two things are indicated: (1) there is no single value of $(h_c - h_v)$ which results in a constant value of the incipient cavitation index for all velocities; and (2) the necessary values of $(h_c - h_v)$ are negative so that the cavitation pressure is below the vapor pressure, and possibly less than absolute zero (a tension). In a later report [12] Kermeen, McGraw, and Parkin indicate that tensions of about 2.7 ft of water were actually measured on the surface of a 2-in. hemispherical head form for cavitation inception defined at maximum acoustic noise.

In these tests, the cavitation index based in vapor pressure was less than the minimum pressure coefficient as shown by Parkin and Holl [13], when incipient cavitation was considered to occur at the point of maximum acoustic noise. The opposite was true at very low velocities.

Thus, it appears that the cavitation pressure was not a unique pressure. The tests of Numachi and Kurokawa, Crump, and Rouse and McNown, indicated that for cavitation inception, the cavitation pressure was above vapor pressure. The tests of Rouse and McNown on hemispherical head forms indicate that after cavitation was established, the cavitation pressure was equal to the vapor pressure. Tests on hemispherical head forms reported by Kermeen, McGraw, and Parkin at the California Institute of Technology indicated a cavitation pressure below vapor pressure and actually below absolute zero (a tension) for incipient cavitation defined somewhat differently than in the other tests. It should be emphasized that different water was used by the various investigators, and thus it is quite reasonable to expect that the cavitation pressure would be different for the various series of tests. It is indicated in the tests of Rouse and McNown, however, that the water was essentially the same for all their tests. If so, their results suggest that there may be a transition regime between cavitation inception and well-established cavitation in so far as the cavitation pressure is concerned.

III. THE EXPERIMENTAL STUDIES

While it is generally realized that the cavitation pressure is not the vapor pressure, it is common practice in cavitation studies, for lack of a definite knowledge regarding its actual value to assume that it is the vapor pressure in defining the cavitation index.

A number of questions arise concerning the cavitation pressure:

(1) What is the best way to measure the cavitation pressure P_c?

(2) What fluid properties affect P_c and to what degree do they affect it?

(3) What are the effects of velocity on P_c?

(4) What effect does the past history of the water have on P_c?

(5) How constant in time is P_c for a given fluid in a water tunnel?

(6) What criterion should be used for defining cavitation inception?

(7) Would cavitation studies based on a cavitation index using the measured cavitation pressure P_c correlate substantially better than those based on a cavitation index using the vapor pressure?

An experimental study of these questions for incipient cavitation of the intermittent-bubbling type in a water tunnel constituted the basic program at the St. Anthony Falls Hydraulic Laboratory. The studies were originally grouped into a number of phases as outlined on p. 2.

Phases (1) and (2) were completed as originally planned, while only a limited number of tests were conducted in Phases (3) and (4). The factors believed to affect the cavitation pressure which were studied included the gas content of the water (total gas, nitrogen-oxygen ratio, dissolved oxygen, and carbon dioxide), the surface tension, the temperature, and solid nuclei. The cavitation pressure was measured on the wall of the tunnel test section and indirectly with a form of Reichardt probe which created a steady cavity.

A comparison of the incipient or critical cavitation index based on a measured cavitation pressure and on vapor pressure was made for three bodies: the tunnel test section itself, a 3-caliber ogive head form, and a 6-caliber ogive head form.

IV. TEST FACILITIES AND TECHNIQUES

A. Test Facilities

The tests have been conducted in the 6-in. water tunnel at the Laboratory. This tunnel is shown in Fig. 3. It has a range of velocity up to 50 fps and a pressure control system with a range varying from +2 to -18 ft of water with respect to the test-section centerline. The pressure system was connected to the upstream end, center, or downstream end of the contraction which precedes the test section; and the pressure in the test section is, in the first two instances, determined by the setting of the pressure-control system and the pressure drop through the contraction. Thus, the pressure is not always independent of velocity. The velocity is varied by means of a mechanical transmission with an electrically driven speed-changing system. Thus, while the speed is theoretically infinitely variable, changes in velocity occur in finite steps, however small. The pressure-control system is electrically operated, and while any desirable setting may be obtained, it is not always possible to do this without a slight amount of "hunting." These factors become important in the determination of the incipient cavitation index of a body based on cavitation inception (approaching cavitation from a noncavitating condition) or on cavitation disappearance (approaching noncavitating conditions from a cavitation condition).

The tunnel is equipped with an air-bubble resorber which is a 1/6 scale flow model of a prototype resorber, and was not designed to be optimum in itself from a bubble-resorption point of view. The total capacity of the tunnel is 1600 gal, and was supplied directly from the city water supply without further treatment. The water was near saturation at temperatures below 40° F in the winter to above 70° F in the summer. Thus, the air content of the tunnel water could be increased either by bleeding in air or by replacing some of the water with tap water. De-aeration was done by running the tunnel under conditions which caused severe cavitation in the test section and removing the air which collected in various points in the tunnel circuit. Water properties could be varied quite readily with the relatively small total volume of water in the tunnel. Tap water was used without filtering.

The test-section region is made of Plexiglas, formed in the shape of a cylinder, the inside following the contour of Fig. 4 and the outside being cylindrical. The wall thickness is about 1.25 inches.

B. Test Techniques

Two methods have been used to measure the pressure at which the tunnel water cavitates (apart from the vapor pressure). In one, the tunnel test section itself was used as the cavitating body. The test section was the diverging closed-jet test section [14] shown in Fig. 4. Incipient cavitation occurred at the top of the test section near the beginning of the diffuser transition. Cavitation inception or disappearance was determined visually, with an overall accuracy in the measured pressure within 0.05 to 0.10 ft of water. Figure 5 shows two photographs of the diffuser transition region of the tunnel test section taken near the point of incipient cavitation on the walls. The streaks in the right-hand photograph actually appeared as flashes rather than as steady streaks of intermittent-bubble cavitation. A pressure difference of about 0.03 ft of water existed between the left and right photograph, indicating the visual method of observation to be quite sensitive. Wall tap 26-R (Fig. 6) was located at this point of minimum wall pressure but near the bottom of the test section so that the plastic manometer connecting tubes would be free of air or vapor cavities. Figure 6 indicates that this piezometer tap was about 0.007 test-section velocity head below the mean pressure at that plane, and all measurements were corrected for this difference.

The second method used to measure the cavitation pressure of the water was with a form of "Reichardt" probe. This involved the measurement of the pressure in a steady-state cavity produced behind a cylinder normal to the flow stream with a 45° flat nose oriented to face downstream. The cavity pressure was measured indirectly with an evacuated air system separated from the cavity by a thin rubber membrane. It was necessary to reflect light through the water and off the membrane carefully in order to observe the membrane position. A null position of the membrane was used to establish an equilibrium of pressure in the cavity and in the air system.

Incipient cavitation on the 3- and 6-caliber ogive head forms was also observed visually by using transmitted light through the test section in a darkened room. It was more difficult to decide when cavitation was incipient for the head forms than for the test-section wall; and although two or three determinations were made and averaged for each test condition there was an increased scatter of data for the head forms. The test bodies were 0.542 inch in diameter.

Two other methods of determining cavitation inception were tried but were considered less satisfactory than visual observations: One involved measuring the change in resistivity of the fluid surrounding the body due to the change in fluid characteristic (resulting from a change from a liquid to a liquid-gas or liquid-vapor mixture) accompanying cavitation. This was tried in a 10-in. free-jet tunnel, and was not considered sensitive enough, probably because the region which began to cavitate was small compared to the total region surrounding the test body. An acoustic method was also tried. A Brush VM-1 Vibromike contact microphone, with a frequency response from 30 to 6000 cps, was taped to the outer surface of the Plexiglas test-section wall of the 6-in. water tunnel at the point of incipient cavitation. The output of this microphone was amplified with an audio amplifier and the rms or peak-to-peak output voltage read on a voltmeter. There was a twelvefold increase in voltage from a noncavitating condition to a cavitating condition, but the exact point of incipient cavitation was difficult to determine.

The pressure at the upstream end of the test section was measured by means of tap 6-R (Fig. 6). This tap was essentially the mean pressure at its section, and since the longitudinal variation was essentially zero at the upstream portion of the test section, readings from this tap referred to the axis were considered to be the upstream axial pressure.

The test-section velocity was determined by measurement of the pressure drop (with a mercury manometer) across the upstream portion of the contraction immediately preceding the test section. This had been previously calibrated. The reading accuracy was about 0.1 fps; the overall accuracy is estimated to be about 1 per cent.

All cavitation pressures were measured with respect to the atmosphere by use of mercury manometers and were corrected to absolute pressures by means of the barometric pressure, also measured with a mercury barometer.

V. MEASUREMENT AND CONTROL OF SOME WATER PROPERTIES

Among the water properties varied in a study of the change in the cavitation susceptibility of the water were the air or gas content, the temperature, and the surface tension. The solid nuclei content was increased by the addition of white china clay.

A. The Gas Content in General

The dissolved or entrained gas in a water tunnel may be assumed to be made up of those components which are present in atmospheric air--nitrogen, oxygen, and carbon dioxide being the most predominant ones. The weight ratio of nitrogen to oxygen in the atmosphere at normal temperature and pressure is about 3.31, and since the absorption coefficient of oxygen is about twice that for nitrogen, the weight ratio of nitrogen to oxygen in saturated water under ordinary conditions is about 1.7. Although the carbon dioxide content of ordinary air is only about 0.03 per cent, it is highly soluble in water, and since it is also produced in water by bacterial decomposition, the concentration of carbon dioxide in many natural waters may be higher than that equivalent to atmospheric saturation.

It exists in three forms: as normal carbonates, bicarbonates, and as free carbon dioxide. The latter is actually ionized carbonic acid. In relatively pure fresh water the free carbon dioxide may be only 2 or 3 ppm, but at low gas contents this may be 10 to 15 per cent of the total and must be considered.

The saturation concentration of gases in water is directly proportional to the pressure (following Henry's law), and as the water flows around the tunnel circuit, it is exposed to an ever-changing set of pressure conditions and thus to changing relative saturation conditions as well. In this report the relative saturation of the water is the ratio of the total weight of gases contained in a given water sample to the weight of nitrogen and of oxygen in that sample if it were saturated at atmospheric pressure. Since the saturation concentration of gas decreases with increasing temperature, a given water sample will change in relative saturation as the temperature changes.

No attempt was made to separate the dissolved gases from the entrained gases; the two were considered together.

1. Measurement of Total Gas

Total gas was measured by the conventional Van Slyke method in which the gas from a 10-cc water sample is extracted in two steps, and the pressure and temperature of these two 2-cc volumes of extracted gas and water vapor are used to compute the weight of the gas extracted. Tests indicated that a 2-min shaking time for each extraction was sufficient to establish equilibrium conditions and a 3-min interval was established as a standard procedure in order to provide a factor of safety. The accuracy of the method depends on a knowledge of the gas composition. For a nitrogen-oxygen ratio between 1.9 and 7 the equation

$$\text{Total gas} = [3.13\Delta P + 0.35 \times \text{ppm } CO_2] \text{ ppm}$$

gives results within 1 per cent. The term ΔP is the partial pressure of the 2-cc samples of gas (actual readings were corrected for vapor pressure) in centimeters of mercury. The overall accuracy is considered to be about 3 per cent if the carbon dioxide content is low.

2. Measurement of Oxygen

The standard Winkler chemical test for dissolved oxygen was used. A 200-cc water sample treated with manganous sulphate, an alkaline potassium iodide solution, and concentrated sulphuric acid was titrated with 0.025 N sodium thiosulphate so that the oxygen concentration in parts per million was equal to the volume of titrating solution in cubic centimeters. The accuracy is considered to be about 2 per cent.

3. Measurement of Free Carbon Dioxide

The free carbon dioxide was measured indirectly by calculation from measurements of the pH and the alkalinity of the water. Measurements of pH were made with a Beckman glass electrode pH meter, model H2, and with a Hellige Standard Comparator, Type 607-A, with a 180-D color disc having a pH range of 6.8 to 8.4. The accuracy of determining the carbon dioxide was about 15 per cent.

4. Determination of Nitrogen

The nitrogen concentration was obtained by subtracting the oxygen and free carbon dioxide from the measured value of total gas.

B. Nitrogen-Oxygen Ratios in Water

Tests were conducted for study of the changes in the nitrogen-oxygen ratio in the tunnel water. The purpose was two-fold: first, to determine whether the total gas could be determined by making an oxygen determination and use of a constant factor to obtain total gas; and second, if significant changes occurred it was of interest to determine if the cavitation susceptibility of the water was related to this nitrogen-oxygen ratio. It has been presumed that if the gas content of an under-saturated water were increased by aeration with air, the nitrogen-oxygen ratio would increase because this ratio for air is greater than that for saturated water.

1. Distilled Water and Tunnel Supply Water

The experimental techniques were verified by measuring the nitrogen-oxygen ratio for saturated distilled water and comparing the results with those reported by Fox [9]. Values ranging from 1.67 to 1.70 were measured, and these compare favorably with a value of 1.7 given by Fox.

The tap water used to supply water to the tunnel maintained a rather constant total gas content of 22.8 to 24.7 ppm at 71° F (0.93 to 1.0 relative saturation) over a 2-week test period, but the nitrogen-oxygen ratio varied between 1.87 and 2.60.

2. Tunnel Water

Five series of tests were conducted over a 3-week period to determine the minimum and maximum air contents obtainable in the tunnel and to determine the effects of cycling the air content on the nitrogen-oxygen ratio. Results are shown in Table II.

Water had been in the tunnel for about one month and had been subjected to considerable cavitation at the beginning of the tests. Attempts were made to further de-aerate this water, but the total gas remained at about 0.43 to 0.51 relative saturation (Series I). The dissolved oxygen decreased from 1.20 ppm to just a trace (probably from biological decomposition) during the tests and the nitrogen-oxygen ratio increased from 6.3 to over 100. Apparently the gas content was at a minimum.

Table II

EFFECT OF AERATION AND DE-AERATION ON GAS CONTENT OF TUNNEL WATER

Temp	Total Gas	Dissolved Oxygen		Free Carbon Dioxide		Nitrogen		$\frac{N_2}{O_2}$	Date 1953
°C	ppm	ppm	per cent	ppm	per cent	ppm	per cent		
TUNNEL WATER									
Series I Attempts at De-aeration by Cavitation at Minimum Air Content, D.O. Changing but Total Gas Content Constant									
23	11.2	1.20	10.7	2.4	21.4	7.60	67.9	6.29	Aug. 19
23	10.5	0.60	5.7	3.0	28.6	6.90	65.7	11.50	Aug. 20
23	10.6	0.35	3.3	2.5	23.6	7.75	73.1	22.20	Aug. 20
22	11.6	0.35	3.0	2.5	21.5	8.75	75.5	25.10	Aug. 21
22	12.1	0.10	0.8	2.5	20.6	9.50	78.6	98.10	Aug. 24
23	12.5	Tr	<0.1	2.4	19.2	10.00	80.0	∞	Aug. 25
Series II Aeration by Bleeding in Tap Water									
23	13.7	1.95	14.2	2.0	14.6	9.75	71.2	5.01	Aug. 25
23	16.4	3.20	19.5	1.4	8.5	11.80	72.0	3.70	Aug. 25
23	17.7	3.90	22.0	1.4	7.9	12.40	70.0	3.18	Aug. 26
23	19.4	4.85	24.0	1.0	5.2	13.55	69.8	2.90	Aug. 26
22	21.3	5.50	26.8	1.0	4.7	14.80	69.5	2.60	Aug. 26
22	22.3	6.10	27.4	0.8	3.6	15.40	69.0	2.52	Aug. 26
22	22.7	6.30	27.8	0.8	3.5	15.60	68.7	2.47	Aug. 27
21	23.8	7.00	29.4	0.7	2.9	16.10	67.6	2.30	Aug. 27
22	23.7	7.00	29.7	0.8	3.4	15.90	67.1	2.26	Aug. 27
Series III Aeration by Bleeding in Air									
22	28.0	8.10	29.0	0.7	2.5	19.20	68.2	2.35	Aug. 27
Series IV De-aeration by Cavitation									
24	19.3	6.10	31.6	0.9	4.7	12.30	63.7	2.02	Aug. 28
24	17.5	5.25	30.0	0.9	5.1	11.35	64.8	2.16	Aug. 28
24	15.1	3.90	25.8	1.0	6.6	10.20	66.8	2.59	Aug. 31
25	13.2	3.35	26.3	1.0	7.6	8.85	67.5	2.56	Sept. 2
25	10.9	2.95	27.1	1.0	9.2	6.95	63.8	2.36	Sept. 2
26	10.7	2.90	27.1	1.0	9.3	6.80	63.6	2.35	Sept. 2
27	10.1	2.40	23.8	1.0	9.9	6.70	66.3	2.78	Sept. 3
Series V Aeration by Bleeding in Air									
27	18.5	5.20	28.1	1.0	5.4	12.30	66.4	2.36	Sept. 3
27	23.1	6.50	28.1	1.0	4.3	15.60	67.5	2.40	Sept. 3
25	26.8	7.85	29.3	0.9	3.4	18.05	67.4	2.30	Sept. 4

In Series II tap water was bled into the top of the tunnel at the same rate at tunnel water was drained out at the bottom of the resorber. The free carbon dioxide decreased from an abnormally high value of 2 ppm to about 0.8 ppm, the air content increased to 23.8 ppm (relative saturation 0.96), and the nitrogen-oxygen ratio decreased to a value of 2.3 which was more representative of tap water than the initial value of 5.0.

The tunnel water at the end of Series II was essentially the same as tap water, and in Series III air was bled into the tunnel to determine the maximum concentration possible. The total gas reached a relative saturation of 1.16 (28 ppm), and it can be seen that the nitrogen-oxygen ratio remained essentially the same after the air had been dissolved.

In Series IV the tunnel was de-aerated by running the tunnel with severe cavitation in the test section. The total gas dropped to a relative saturation of 0.45 (10.1 ppm), but in this instance the nitrogen-oxygen ratio increased from 2.02 to 2.78. The ratio actually dropped initially from 2.35 at the end of Series III to 2.02 for the first analysis made in Series IV, and then increased.

In Series V air was again bled into the tunnel, and the nitrogen-oxygen ratio remained essentially constant as the total air increased to a relative saturation of 1.16 (26.8 ppm).

It therefore appeared that the nitrogen-oxygen ratio in the tunnel was always higher than that for saturated distilled water (1.7) and that it varied throughout a wide range as the tunnel was aerated or de-aerated or if the tunnel water remained in the tunnel for a period of time. This wide variation would preclude the possibility of computing the total gas content by the nitrogen-oxygen ratio from a measurement of only the oxygen. There has been some interest in making continuous measurements of the air or gas content of tunnel water, but until a recent method for measuring this directly was reported by Fitzpatrick and Harkleroad [15], the only known methods were either by measurement of the oxygen continuously by polarographic methods or by use of a Cambridge gas-content meter. The latter device measures total gas continuously but has some disadvantages, one of which is inaccuracies caused by high free carbon dioxide concentrations at low total gas concentrations.

C. The Vapor Pressure, Surface Tension, and Nuclei Content of the Water

The vapor pressure of the tunnel water was determined (in steam tables) from direct measurements of the water temperature. A calibrated dial thermometer was inserted into a well, located just upstream of the pump elbow. Temperatures varied between 55° and 81° F.

The surface tension of the water was measured by the bubble method with a manometric-type CENCO surface tension apparatus. In nearly all tests the value measured statically was about 4.9×10^{-3} lb per ft, the value for distilled water, but in some tests it was reduced to 2×10^{-3} lb per ft.

The tunnel was not equipped with a filter, and some foreign particles were undoubtedly nearly always present. The inner surfaces of the steel parts of the tunnel proper were galvanized, and the aluminum parts anodized, but the resorber tank was coated with a synthetic enamel which had a tendency to flake. Also, mineral deposits were found in small amounts on some of the galvanized inner surfaces and therefore were probably present in the water as well. The tunnel was flushed frequently when the tests permitted, maintaining the water as clean as possible. In some tests white china clay was added as a source of gas nuclei formation. The size-distribution of this clay was measured by the standard hydrometer analysis and was found to consist of 94 per cent by weight smaller than 10 microns and 64 per cent smaller than 1 micron and was thus considered colloidal.

VI. VARIATIONS IN THE MEASURED CAVITATION SUSCEPTIBILITY OF TUNNEL WATER

As a preliminary step in the study of the use of a measured cavitation pressure in tests of incipient-bubbling cavitation on bodies, it was considered desirable to examine the variation of a measured pressure with gas content of the water, temperature, time, and velocity. It was also of interest to know what property of the water would permit the best controllable variation in the cavitation pressure.

A. Hysteresis Effects

Kermeen [11] indicates a considerable difference between the cavitation index for the inception and disappearance of cavitation on hemispherical head models. Cavitation disappeared at a much higher cavitation index than it appeared, the difference being about 0.4 at 20 to 60 fps for a 3/8-in. head form. The point of appearance or disappearance was determined on the basis of maximum acoustic noise.

In 32 pairs of measurements of this difference for cavitation determined visually at the top of the test section, wherein the cavitation pressure was measured by means of a wall piezometer tap, the measured pressure for cavitation disappearance averaged 0.03 ft of water below that for inception. The standard deviation was 0.08 ft of water from this mean difference. Thus, within the limits of measurement accuracy, cavitation inception occurred at essentially the same point as cavitation disappearance, either slightly above or slightly below. It was considered that basing inception on cavitation appearance was no more consistent than basing it on disappearance; so data for these 32 tests were averaged and subsequent tests averaged or run on the basis of cavitation inception. All tests represent at least two and usually three independent measurements of the cavitation pressure.

As mentioned previously in the description of the tunnel pressure and speed-control systems, it was not always possible to approach cavitation inception or disappearance unidirectionally. However, it is believed that the hysteresis effects were truly small, since even in those instances when the inception or disappearance of cavitation was slightly overshot, only a slight change in pressure or velocity in the opposite direction brought the water back to its original condition. This suggests that the test section was a very stable form for use in measuring the cavitation pressure.

B. Effect of Total Gas Content

The air content of the tunnel water was varied in four cycles, with de-aerated tap water initially in the tunnel. These cycles were:

(1) Aeration with tap water.

(2) De-aeration following aeration with tap water.

(3) Aeration with air.

(4) De-aeration following aeration with air.

At various values of air content in the above sequences, the cavitation pressure of the water was measured at cavitation inception on the tunnel test-section wall. Test results on the effect of air content are shown in Figs. 7 to 11, Fig. 11 being a composite of Figs. 7, 9, and 10. In all tests of aeration or de-aeration, except de-aeration following aeration with tap water (Fig. 8), there was very little scatter of data for a given test run, and the difference between the measured cavitation pressure and vapor pressure was a linear function of the relative saturation.

It is interesting to note that the data obtained for a given aeration or de-aeration cycle under the same conditions of velocity and relative saturation, but on different dates, were not reproducible except for de-aeration following aeration with air (Fig. 10). This suggests that some parameter other than relative saturation affected the cavitation pressure, perhaps the previous history of the tunnel water in so far as its aeration or de-aeration cycles were concerned, or the form or proportions of the component gases which made up the total. If the data were plotted as a function of absolute air content instead of relative air content, the results would be essentially the same, since the saturation values on which the relative values are based differed by only about 10 per cent.

The nitrogen-oxygen ratios for the tests of Figs. 7 to 11 varied from about 1.3 to more than 5.6. In Figs. 7, 8, and 9 the curves for higher cavitation pressures were at higher nitrogen-oxygen ratios than those for lower cavitation pressure for similar test cycles. In Fig. 10 the results were essentially reproducible and the nitrogen-oxygen ratios were about the same. This may or may not be significant. For the top curve of Fig. 7 during aeration with tap water the nitrogen-oxygen ratio decreased from over 100 to 2.4. Because of the linear relation between relative air content and the cavitation pressure, it is not believed that the nitrogen-oxygen ratio is a significant parameter. If the data were plotted as a function of nitrogen content rather than relative saturation, results were no more reproducible on different days with different water than those shown in Figs. 7 to 11. At any rate, the nitrogen-oxygen ratio varied over a wide range, and measurement of oxygen to indicate total gas was found to be an unreliable method.

It is considered especially significant that the measured cavitation pressure was generally a linear function of the relative saturation for a <u>given sample of water</u>. If the water was changed, a linear relationship also existed, but it was generally a different one. This indicates that control of total air content will not control the cavitation susceptibility of tunnel water, although it will most likely vary it.

C. Effect of Free Carbon Dioxide

The effect of free carbon dioxide on the cavitation susceptibility of the tunnel water was studied for two reasons: First, the higher curves of Figs. 7 and 8 (at 46 fps) were at higher carbon dioxide contents than the lower curves, although the content for the two curves of Fig. 9 and the nearly identical curves of Fig. 10 was about the same. Secondly, it has been suggested by Silberman, as a result of studies on air-bubble resorption [16], that one way to increase resorption in a tunnel circuit would be to substitute another gas with a high product of solubility and diffusivity for air. Carbon dioxide has a product of solubility times diffusivity about 20 times that for air. It was considered that if carbon dioxide resorbed much more readily than air, it might also enhance cavitation more readily as well.

Measurements of the cavitation pressure made at 46.5 fps from carbon dioxide concentrations increasing from about 1 to 55 ppm varied between 1.07 and 1.46 ft of water. Similar measurements while the concentration was being reduced from 55 ppm down to 1.3 ppm indicated a variation in the measured pressure between 1.53 and 1.35 ft of water. This reduction in concentration was accomplished by adding sodium hydroxide to the tunnel water.

It may be concluded that concentrations of carbon dioxide up to 55 ppm had no significant effect on the cavitation pressure of the water.

D. Effect of Surface Tension

Surface tension is generally considered to be significant in the occurrence of bubble cavitation. In some early tests, the surface tension was decreased to one-half normal (measured statically) by adding a commercial wetting agent, Alconox, to de-aerated water after it had been aerated with air. The results, shown in Fig. 12, indicate essentially no change in the cavitation pressure when increasing amounts of Alconox were added.

The surface tension was not the only water property changed. The pH changed from 7.8 to 9.2 when the first small amount of Alconox was added and remained at 9.2 to 9.4 during the rest of the tests. This meant that that there was no longer any free carbon dioxide present after the first amount of Alconox had been added.

E. Addition of White China Clay

It was thought that perhaps the addition of solid nuclei on which cavities might form would change the cavitation susceptibility of the water in the tunnel. The clay was a white china clay considered colloidal. Fresh water was put into the tunnel and clay was added in four steps up to a concentration of 3.1 ppm; then fresh water was added again and the concentration increased from its residual value of 1.8 ppm up to 7.8 ppm.

The results of the measurements of the cavitation pressure at 40 and 50 fps are shown in Fig. 13. Each plotted point is the average of 3 to 6 individual measurements, the maximum variation in the measured pressure being 0.11 ft of water within any series. The data are plotted as the difference between the measured cavitation pressure and the vapor pressure $(h_c - h_v)$ to eliminate some variations in temperature. No significant effect was produced by the addition of the clay.

F. Variation with Time

It was of interest to determine if a given water with supposedly constant parameters would have an essentially constant measured cavitation pressure. Fresh water was added to the tunnel and this water was de-aerated to a total gas content of 14.5 ppm. This resulted in a relative saturation of 0.53 based on total gas, compared to the total solubility of oxygen and nitrogen at the same temperature. Measurements of the cavitation pressure were made over a 5-day period, and the results are shown in Fig. 14. Again, the value of $(h_c - h_v)$ is plotted to correct for slight temperature changes. The measured cavitation pressure remained essentially constant over the 5-day period.

G. Variation with Water Temperature

It was not known whether the measured cavitation pressure would increase at the same rate as the vapor pressure if the temperature of a given water were increased, all other absolute properties remaining the same. (The relative saturation would, of course, increase with temperature.) This rise in temperature occurred frequently from normal tunnel operation when cold water was added to the tunnel. Water at 48° F near saturation was placed in the tunnel and the tunnel was run almost continuously during the normal working hours over a 4-day period at about 48 fps. Measurements of the cavitation pressure (measured at 48 fps) were made from time to time as the temperature increased. The results are shown in Figs. 15 and 16. Each plotted point represents a single measurement.

The air content was 29.9 ppm; and as the temperature increased from 48° to 78° F, the relative saturation increased from about 0.99 to 1.30. The vapor pressure increased from 0.38 to 1.10 ft of water, but the measured cavitation pressure increased from about 1.20 to 2.02 ft of water, more than the increase in vapor pressure. This greater increase is shown in Figs. 15 and 16 as $(h_c - h_v)$. This change in $(h_c - h_v)$ with temperature was used to adjust other data when slight temperature changes occurred.

H. Effect of Velocity

Figures 7 to 9 indicate that the measured cavitation pressure was higher at a higher velocity. No detailed measurements on the effect of velocity were made; but during later tests on some ogive head forms, the cavitation pressure of the water was measured over a range of velocities for each change of water in the tunnel. Some typical measured cavitation pressures taken during tests of cavitation on a 3-caliber ogive are shown in Fig. 17 for two values of relative saturation. In each instance the cavitation pressure was about 0.4 ft of water greater at 45 fps than at about 30 fps, which was about the same as in the earlier tests shown in Figs. 7 to 9.

I. Dependency of Cavitation Pressure on Method of Measurement

In all the tests reported thus far, the measured cavitation pressure of the tunnel water was determined from visual observations of cavitation on the top of the test-section wall at its downstream end. One aspect of the project (Phase 3) was the use of various body shapes for measurement of the pressure at which cavitation occurred and the determination of the importance of the method of pressure measurement.

Among the shapes suggested or considered were

(1) a 6-caliber ogive,

(2) a circular disc normal to the flow,

(3) a venturi shape in the test section,

(4) a venturi shape in parallel with the test section, and

(5) a Reichardt probe.

It was believed that, since the studies were concerned with intermittent-bubble cavitation on a surface, the measuring probe should be associated with that type of cavitation. The lack of hysteresis effects and apparent stability of the tunnel test section in measuring the cavitation pressure indicated that some body with small pressure gradients in the region of minimum pressure would probably be desirable. Thus, the 6-caliber ogive and the venturi were judged to be promising in that respect. A circular disc would measure boundary pressures when cavitation was incipient in vortex cores in the wake flow and thus would measure pressures much higher than the cavity pressures. Direct measurements by Kermeen, McGraw, and Parkin [12] showed this to be the case. A Reichardt probe creates a steady cavity rather than intermittent bubbles and it was this cavity pressure which was measured in the present tests. A test setup for measuring boundary pressure on test bodies was made, but the experimental program was terminated before measurements were taken.

The form of Reichardt probe found most successful for observations is that shown in Fig. 18(a). The probes were stainless steel cylinders 1/4-in. OD and 1/8-in. ID, with a 45° flat face at one end. Some probes with a 1/32-in. ID were tried but were not considered satisfactory. The left probe in Fig. 18(a) has an open end, and the right probe has a piece of dental dam cemented to its surface. This dental dam is a natural rubber about 0.007 in. thick. Some 3M Trim Cement, manufactured by the Minnesota Mining and Manufacturing Company, and thinned with chloroform, was used to cement the rubber diaphragm to the face of the probe. This probe was inserted into the test section so that the slanted face was downstream, and the resulting cavities appeared as in Fig. 18(b). The inside of the probe was connected to an aspirator, and the internal pressure regulated by bleeding atmospheric air into the aspirator circuit. The air pressure was measured with a mercury manometer when the rubber diaphragm on the probe was judged to be in a neutral position. The air pressure was then considered to be equal to the cavity pressure, within limits of measuring accuracy.

These measured cavity pressures were compared with cavitation pressures measured on the test-section wall at various cavitation susceptibilities of the tunnel water. This variation was obtained by varying the air content of the water.

Tests were not run at what might be judged incipient cavitation for the probe because it was not possible to see the rubber diaphragm clearly and the incipient point was not well defined. Observations were generally made on the smallest cavity considered to be visually useful and on a larger cavity at test-section velocities of about 31 and 48 fps. There was no significant difference in test values between the two cavity sizes, and the results for both were considered together. Measurements were made of the cavitation pressure of the water at various air contents using the Reichardt probe, and these were compared to the measurements made on the tunnel test-section wall. The results are shown in Fig. 19 as the difference between the measured pressures and vapor pressure in order to correct for slight changes in temperature during a test series. The range of Reichardt probe values is shown for various mean values of wall-cavitation values. There is some scatter, but the general tendency was for the cavitation pressures measured with the Reichardt probe to decrease with an increase in the cavitation pressures measured on the tunnel wall. In almost all instances, the Reichardt probe indicated pressures below vapor pressure. All the data of Fig. 19 were taken by the same observer. There seemed to be more variation in the observations of different observers when measurement of the cavitation pressure was made with the Reichardt probe than when it was measured on the test-section walls.

Cavitation pressures measured with the Reichardt probe were the only ones which were not measured on the test-section walls of the water tunnel.

VII. INCIPIENT CAVITATION INDEX FOR DIFFERENT BODY SHAPES BASED ON VAPOR PRESSURE AND ON A MEASURED CAVITATION PRESSURE

Tests were run to determine incipient cavitation on three body shapes. These were the test section itself, a 3-caliber ogive head form, and a 6-caliber head form. In all instances, incipient cavitation was observed visually, and there was no detectable or significant difference between cavitation inception and cavitation disappearance. Actually, attempts were made to determine cavitation inception rather than disappearance. Datum pressures for the cavitation index were vapor pressure and the pressure measured on the test-section wall for incipient cavitation on the wall.

A. The 6-in. Diverging Closed-Jet Test Section

The minimum cavitation index for a water tunnel is customarily defined as the cavitation index at the axis of the test section at its upstream end when cavitation commences at some other point in the tunnel. For a well-designed closed-jet tunnel, this other point is at the top portion of the transition between the test section proper and the diffuser immediately downstream. Direct measurements in the test section showed that the dimensionless pressure coefficient between the upstream axis and the point of cavitation inception was constant to the point of actual cavitation inception, as inception was being approached from a noncavitating condition. Thus, the minimum cavitation index (based on the measured cavitation pressure) was equal to this pressure coefficient. This was to be expected if the cavitation index was defined in that way. It would not be true if the index was based on vapor pressure unless the cavitation pressure was equal to the vapor pressure.

The minimum cavitation index for a water-tunnel test section should be a measure or an indication of the cavitation characteristics of the shape of the test-section boundaries and should not be a measure of the cavitation susceptibility of the water in the tunnel. Preliminary measurements made during design tests of a diverging closed-jet test section indicated that the minimum cavitation index varied from 0.049 to 0.102 when based on vapor pressure, but that it was constant at 0.023 when based on the measured pressure at which cavitation occurred. Tests were made at a test-section velocity of 46 fps, and it was believed that the major change in the water properties during the tests was in the air content of the water. These preliminary data have been verified by many tests wherein some of the factors believed to affect the cavitation susceptibility of the tunnel water have been systematically varied and the cavitation pressures measured as previously described. Some of the data are shown in Figs. 20 and 21. In Fig. 20 the minimum cavitation index is plotted against the relative air saturation of the tunnel water. The minimum cavitation index is designated at the axis of the test section and thus varies with the test-section velocity. The cavitation index is plotted against the same abscissas in Figs. 20 and 21. However, in Fig. 21 the index is referred to the top of the test section, so that it is constant with velocity and needs no correction for the static head from the top to the axis of the test section. This is common practice for quoting incipient cavitation indices for similar bodies of different size in order that true scale effects can be indicated.

Although the data are shown as a function of relative saturation of the tunnel water it is believed that some other property of the water varied also, since most of the test runs were not reproducible when the water was changed and adjusted to given values of relative saturation. Nevertheless, it is clearly indicated that for the test section of the tunnel as a cavitating body, the critical cavitation index for incipient cavitation was constant regardless of the cavitation susceptibility of the water when based on the measured cavitation pressure and was very erratic in magnitude when based on the vapor pressure. The same is true for the minimum cavitation index for the test section as a test facility.

The above results are to be expected as long as the minimum pressure coefficient for the test section remains constant and the cavitation pressure is measured on the test-section wall itself. It remains to be determined whether the incipient cavitation index for a body remains essentially constant and independent of the cavitation pressure of the water when the cavitation pressure is not measured on the body itself but on some other body surface.

B. Axisymmetric 3- and 6-Caliber Head Forms

Incipient cavitation tests were run on 3- and 6-caliber ogive head forms, each 0.542 inch in diameter, for various water conditions. Cavitation was observed visually, and the critical cavitation index was computed with vapor pressure and with a measured cavitation pressure as a datum. This measured pressure was that measured by means of wall tap 26-R (Fig. 6) for cavitation inception at the top of the diffuser transition.

The 3-caliber ogive was mounted on the diffuser dynamometer shaft housing, the tip of the nose being 1/2 test-section diameter from the upstream end of the test section (2.18 diameters long). The shaft was supported by struts of 1.1-in. chord, 5 per cent thick, located nearly 1/3 test-section diameter upstream of the diffuser transition. Thus, they were in the test section proper. These struts cavitated to such an extent that the testing time for a given test run was quite short. It was not possible to determine cavitation explicitly; the tunnel velocity and test-section pressure were set at a predetermined value, and as soon as equilibrium conditions were reached, an observation was made to determine whether or not the body was cavitating. Thus, a series of "go, no-go" tests was necessary to determine the actual incipient cavitation index for the 3-caliber ogive.

The 6-caliber ogive was mounted on the same shaft but supported by struts of 2-in. chord, 10 per cent thick, located in the diffuser downstream of the test section. The nose of the 6-caliber ogive was 1.0 test-section diameter downstream of the location of the nose of the 3-caliber ogive, at about the downstream quarter point. These struts did not cavitate before the test body, and thus it was possible in these tests to approach cavitation inception gradually without resorting to the go, no-go type of test used for the tests of the 3-caliber ogive head form.

Measurements of incipient cavitation on the test bodies were taken over a range of measured cavitation pressures of the water. Results are shown in Figs. 22, 23, and 24. (Figure 17 shows some typical measured cavitation pressures of the tunnel water taken during tests of the 3-caliber ogive. Slight corrections were applied to the measured values to apply them to conditions existing during the tests on the head forms. About 6 per cent of the tunnel water had to be drained from the tunnel in order to remove the test bodies, and when the tunnel was refilled with fresh tap water, slight changes in air content and temperature resulted.) Results of the go, no-go tests of the 3-caliber ogive are shown in Fig. 22. Some additional tests at a lower velocity were made, but the results were considered less reliable and were not complete since the tunnel clouded rather quickly and made reliable observations difficult. The difference between the measured cavitation pressure and vapor pressure, $(h_c - h_v)$, ranged from a minimum of 0.52 to a maximum of 0.81 ft of water. It was difficult to obtain water which cavitated at higher pressures--much more so than in the earlier tests discussed in Part VI. At higher air saturations the water became too cloudy to allow reliable observations. The data of Fig. 22 were usually taken with two observers verifying whether or not cavitation occurred for a given test. Each plotted point for the 6-caliber ogive tests is the average of at least two, and usually three or more independent measurements, the maximum variation from the plotted points from any single observation being equivalent to a variation of 0.006 in the cavitation index. The average maximum variation was equivalent to a variation of 0.002 in the cavitation index.

The data of Fig. 22 and the results of two series of tests on the 6-caliber ogive are shown in Figs. 23 and 24. There is some scattering of the data. However, if the results at $(h_c - h_v) = 0.6$ ft of water for the

3-caliber ogive tests are disregarded, the incipient cavitation index σ_c, based on the measured cavitation pressure of the water, is quite constant at about 0.128. If this is so, then the cavitation index based on vapor pressure σ_v should increase along the line indicated. The test points do follow that trend quite well. The results of the first tests on the 6-caliber ogive (Fig. 23) are not so convincing. Half the pairs of test points have to be disregarded in order that the cavitation index based on h_c, the measured cavitation pressure, be essentially constant at about 0.082 and for the index based on vapor pressure to increase along the line indicated.

Results of the second series of tests on the 6-caliber ogive head form, conducted about 4 months after the first, are shown in Fig. 24. The incipient cavitation index based on the cavitation pressure measured on the tunnel wall was quite constant at 0.083, and when based on vapor pressure varied essentially as shown, from about 0.090 to 0.115 on the average.

A certain amount of scatter is to be expected in all these tests. Although each plotted point represents an average of two or three independent measurements, the exact determination of incipient cavitation was rather difficult. Also, the scatter about the horizontal lines for the points based on the measured cavitation pressure are the same as that about the sloping lines for the points based on vapor pressure. This is a direct result of the method of plotting the data. The important result is the relatively constant cavitation index obtained for incipient cavitation when it is based on a measured pressure as compared to the relatively variable index when it is based on vapor pressure; the trend rather than the scatter of the data is important.

It is believed that the results of tests on the 3-caliber ogive and the second series of tests on the 6-caliber ogive indicate quite conclusively that a measured pressure was a more reliable datum on which to base the cavitation index for cavitation inception than was the vapor pressure. A termination of the test program precluded further investigations along this line.

VIII. CONCLUSIONS

On the basis of test results included in this report the following conclusions may be drawn:

1. There were no significant or detectable hysteresis effects for incipient cavitation on the tunnel walls or on the 3- and 6-caliber ogive test bodies.

2. Measurement of total air content or of oxygen to obtain the total air content, as is often done, is not a satisfactory basis for evaluating the cavitation susceptibility of tunnel water.

3. The total gas content and temperature of the tunnel water were the only known water properties which influenced the cavitation susceptibility of the water. An unknown factor had some influence because tests when gas content and temperature were controlled were seldom reproducible.

4. Neither nitrogen-oxygen ratios from 2 to over 100, carbon dioxide contents from about 0.7 to 55 ppm, surface tension (measured statically) from one-half normal to normal values, nor colloidal nuclei added to the water up to a maximum concentration of 7.8 ppm had any significant effect on the measured cavitation pressure of the water.

5. The usual method of writing the cavitation index based on vapor pressure is frequently improper for accurate cavitation studies.

6. It appears that the Reichardt probe creates a "steady" cavity and that it does not provide a satisfactory means of measuring the cavitation pressure for studies involving intermittent-bubble cavitation.

7. Tests of a 3- and a 6-caliber ogive for incipient cavitation indicated that, although there was some scatter in the results, the cavitation index was more constant when based on a measured cavitation pressure than when based on vapor pressure.

8. There probably is no unique cavitation pressure of water which can be used as a pressure datum for defining the cavitation index for all types of cavitation.

BIBLIOGRAPHY

[1] The Pennsylvania State College School of Engineering Ordnance Research Laboratory. "On the Appearance of Cavitation with Especial Reference to the Air Content of the Water." Translation and Commentary on F. Numachi's Articles on "The Effect of Air Content on the Appearance of Cavitation in Distilled, Salt, and Sea Water." Report Serial No. NOrd 7958-27, August, 1946. 85 pages.

[2] The Pennsylvania State College School of Engineering Ordnance Research Laboratory. "Supplement to the Paper 'On the Appearance of Cavitation with Especial Reference to the Air Content of the Water.'" Translation and Commentary on F. Numachi's Articles on "The Effect of Air Content on the Appearance of Cavitation in Distilled, Salt, and Sea Water." Report Serial No. NOrd 7958-27, August, 1946. 85 pages.

[3] The Pennsylvania State College School of Engineering Ordnance Research Laboratory. "On the Effect of Air Content on the Appearance of Cavitation in Salt Water." Translation and Commentary on F. Numachi's Articles on "The Effect of Air Content on the Appearance of Cavitation in Distilled, Salt, and Sea Water." Report Serial No. NOrd 7958-27, August, 1946. 85 pages.

[4] The Pennsylvania State College School of Engineering Ordnance Research Laboratory. "On the Effect of Air Content on the Appearance of Cavitation in Sea Water." Translation and Commentary on F. Numachi's Articles on "The Effect of Air Content on the Appearance of Cavitation in Distilled, Salt, and Sea Water." Report Serial No. NOrd 7958-27, August, 1946. 85 pages.

[5] Gutsche, F. "Cavitation Formation in Water Containing Air." [Hohlsog - (Kavitations-) bildung in lufthaltigem Wasser.] Schiffbau, Vol. 11.

[6] Edstrand, Hans. The Effect of Air Content of Water on the Cavitation Point and upon the Characteristics of Ships' Propellers. Swedish State Shipbuilding Experimental Tank Publication No. 6, Goteborg, 1946. 50 pages.

[7] Crump, S. F. Determination of Critical Pressures for the Inception of Cavitation in Fresh and Sea Water as Influenced by Air Content of the Water. David Taylor Model Basin Report 575, October, 1949. 37 pages.

[8] Eisenberg, Phillip. On the Mechanism and Prevention of Cavitation. David W. Taylor Model Basin Report 712, July, 1950. 70 pages.

[9] Edstrand, Hans. Cavitation Tests with Model Propellers in Natural Sea Water with Regard to the Gas Content of the Water and Its Effect upon Cavitation Point and Propeller Characteristics. Swedish State Shipbuilding Experimental Tank Publication No. 15, Goteborg, 1950. 80 pages.

[10] Rouse, Hunter and McNown, John S. *Cavitation and Pressure Distribution, Head Forms at Zero Angle of Yaw.* University of Iowa, Studies in Engineering Bulletin 32, 1948. 70 pages.

[11] Kermeen, R. W. *Some Observations of Cavitation on Hemispherical Head Models.* California Institute of Technology, Hydrodynamics Laboratory Report No. E-35. 1, June, 1952. 30 pages.

[12] Kermeen, R. W., McGraw, J. T., and Parkin, B. R. *Mechanism of Cavitation Inception and the Related Scale-Effects Problem.* The American Society of Mechanical Engineers Paper No. 54-Mex-1. 8 pages.

[13] Parkin, B. R. and Holl, J. W. *Incipient-Cavitation Scaling Experiments for Hemispherical and 1.5-Caliber Ogive-Nosed Bodies.* A Joint Study by The Hydrodynamics Laboratory, California Institute of Technology, and Ordnance Research Laboratory, The Pennsylvania State College, May 15, 1953. 33 pages.

[14] Olson, R. M. *A Diverging Closed-Jet Test Section for a Water Tunnel (Supplement 1 to Model Studies of a Water Tunnel with an Air-Bubble Resorber, Project Report No. 29).* University of Minnesota, St. Anthony Falls Hydraulic Laboratory Project Report No. 32, June, 1952. 33 pages.

[15] Fitzpatrick, H. M. and Harkleroad, M. F. A Meter for Continuous Indication of Dissolved Air in Water. David W. Taylor Model Basin Report 867, October, 1954. 19 pages.

[16] Silberman, E. *Air-Bubble Resorption.* University of Minnesota, St. Anthony Falls Hydraulic Laboratory Technical Paper No. 1, Series B, August, 1949. 32 pages.

APPENDIX A

(Figures 1 - 24)

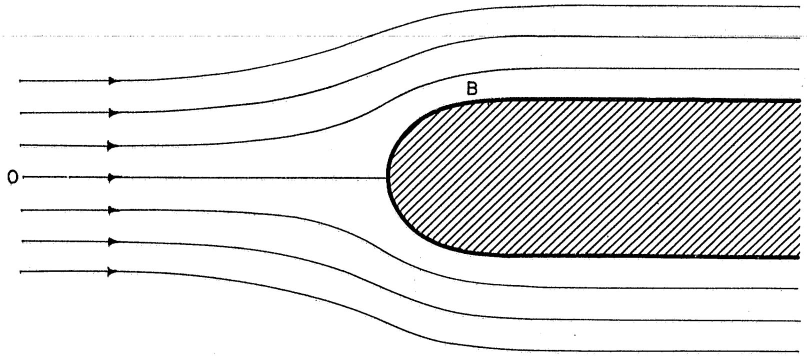


Fig. 1 - Incipient Cavitation on an Axisymmetric Streamlined Body

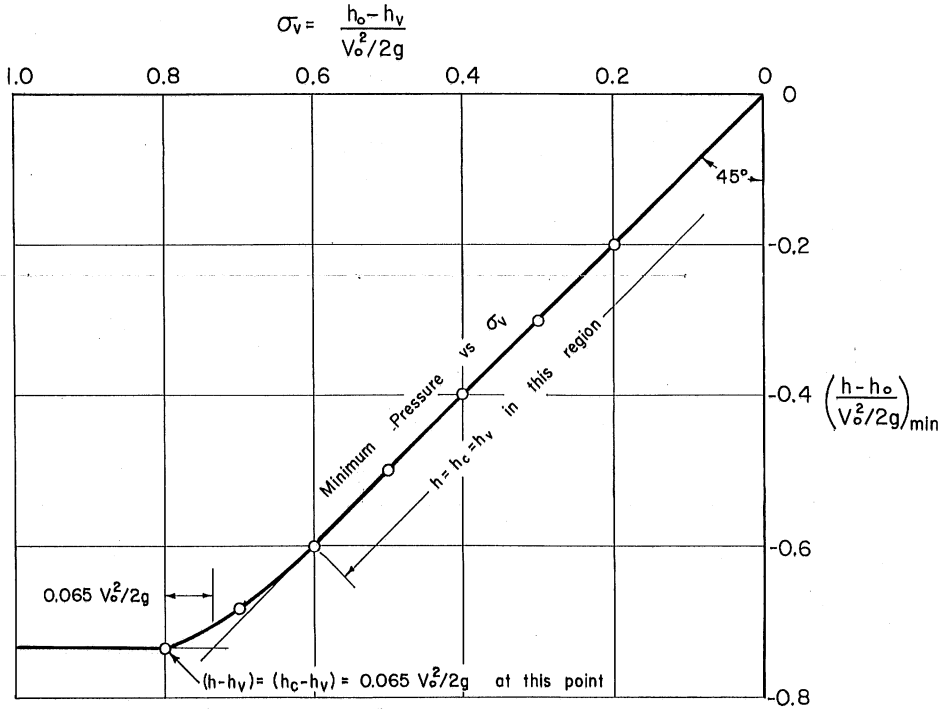
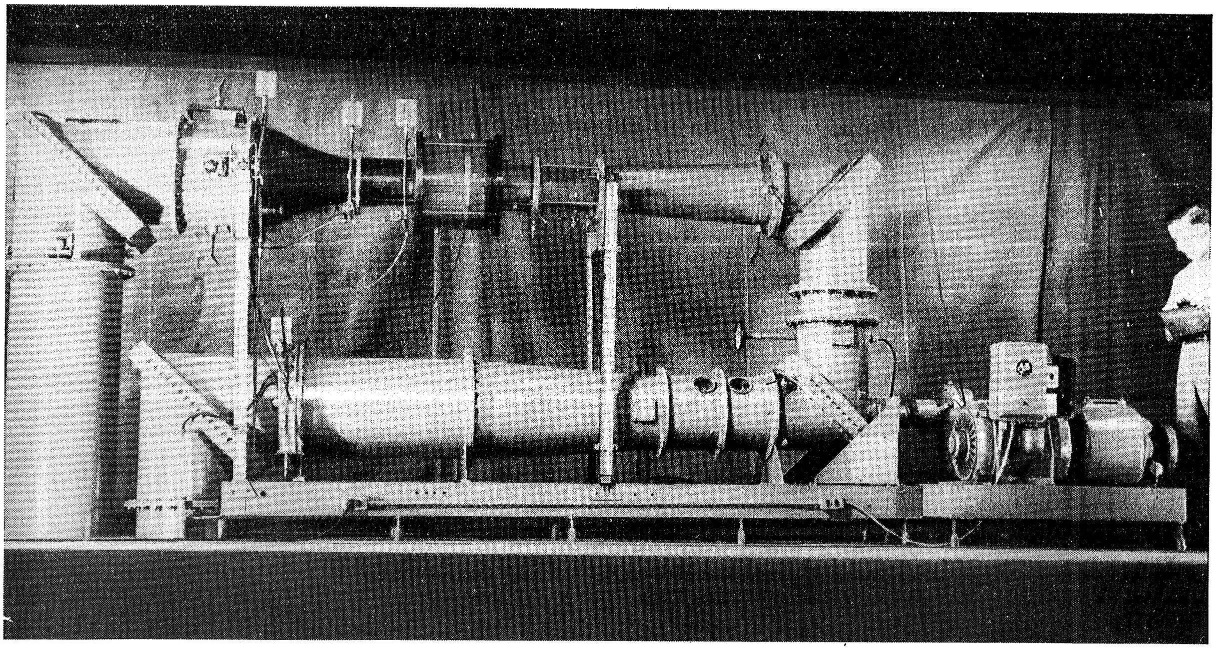
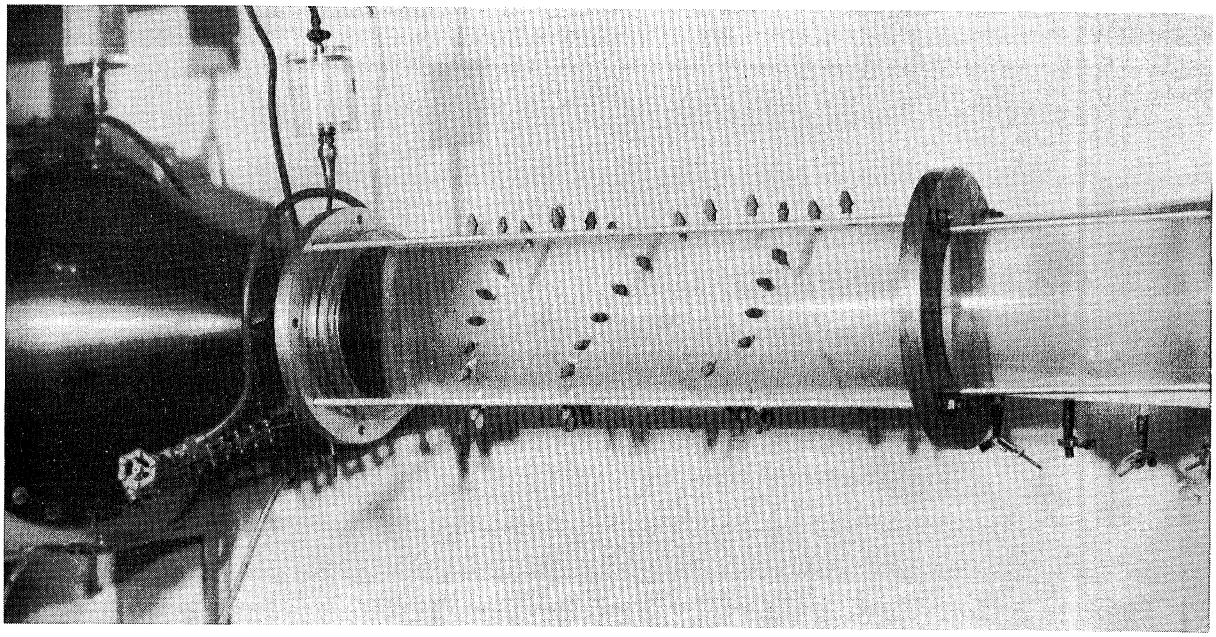


Fig. 2 - Effect of Cavitation on the Minimum Pressure Coefficient for a Cylindrical Body with a Hemispherical Head [10]

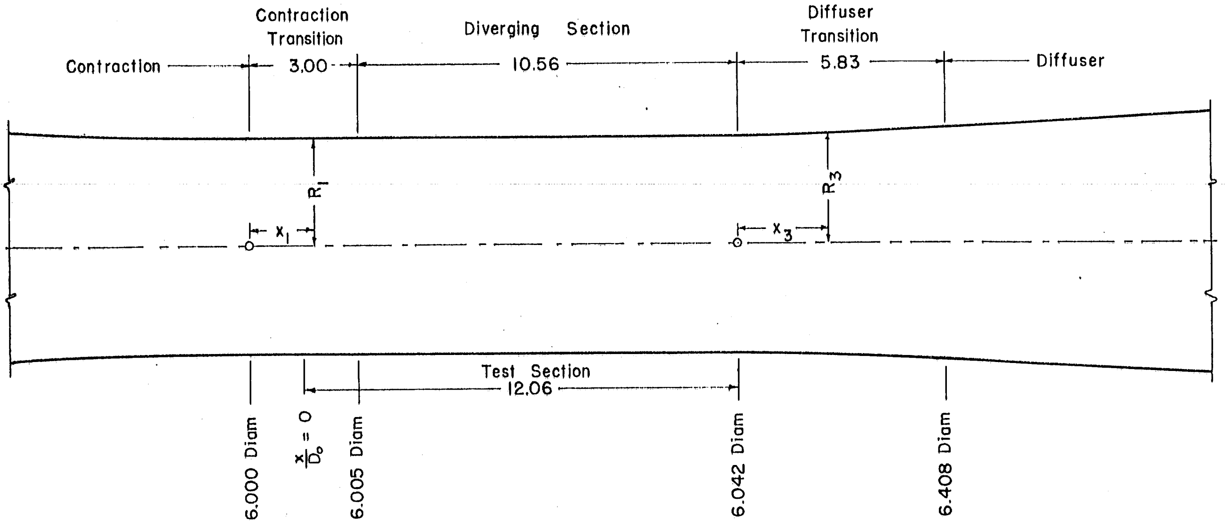


(a) Water Tunnel with Slotted-Wall Test Section



(b) Diverging Closed-Jet Test Section used for Cavitation Studies

Fig. 3 - Six-Inch Water Tunnel

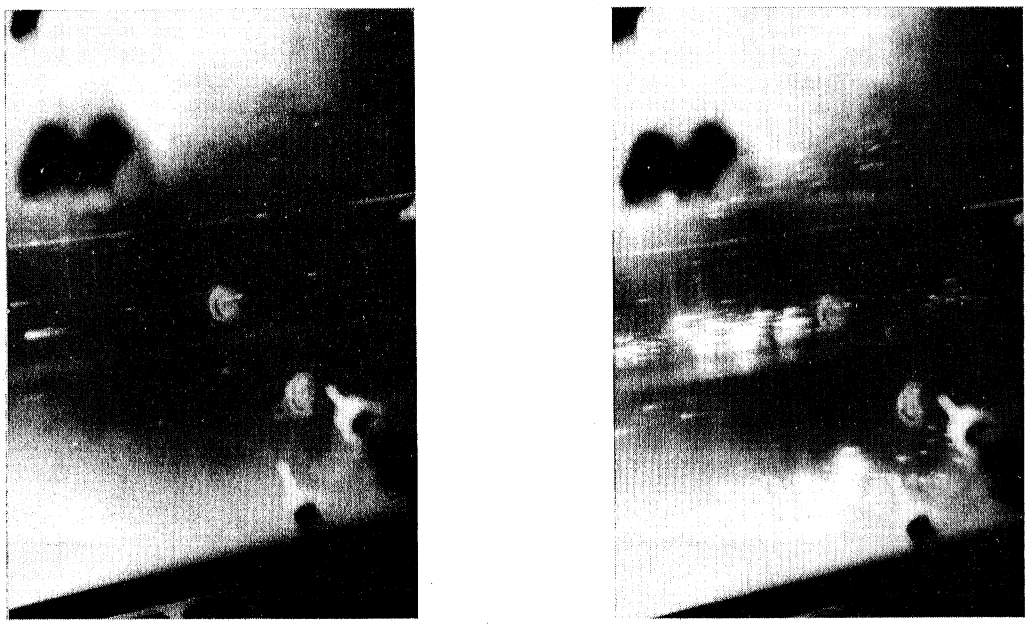


Contraction Transition Equation: $R_1 = 3 + 0.000283\,x_1^2$

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

Fig. 4 - Diverging Closed-Jet Test-Section Boundary Profile

Dimensions in inches



(a) Just before cavitation. Flow is from left to right at 41 fps.

(b) Just beyond cavitation inception. Flow is from left to right. Measured wall pressure was about 0.03 ft of water less than that in photo at left.

Fig. 5 - Incipient Cavitation in Diverging Closed-Jet Test Section of Model Water Tunnel

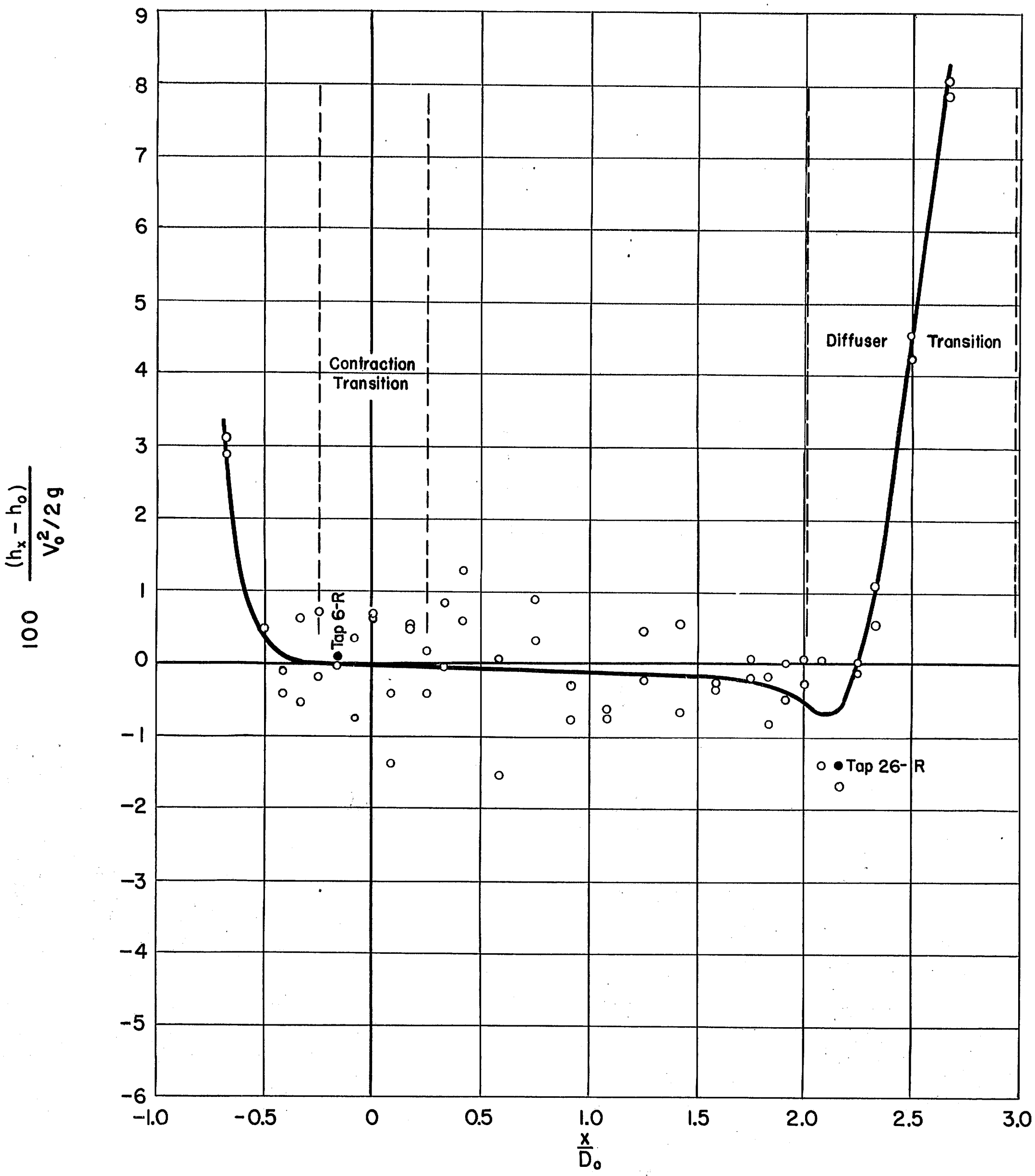


Fig. 6 - Measured Wall-Pressure Variation in Diverging Closed-Jet Test Section

$V_o = 49$ fps

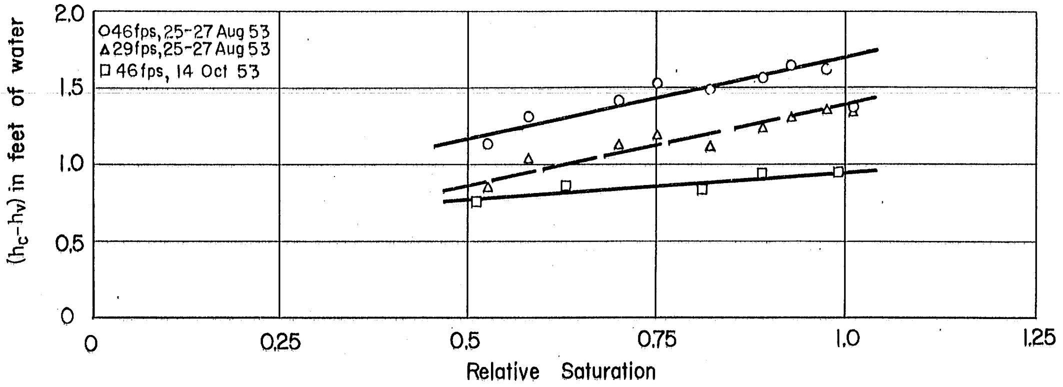


Fig. 7 - Effect of Aerating Tunnel Water with Tap Water on the Measured Cavitation Pressure

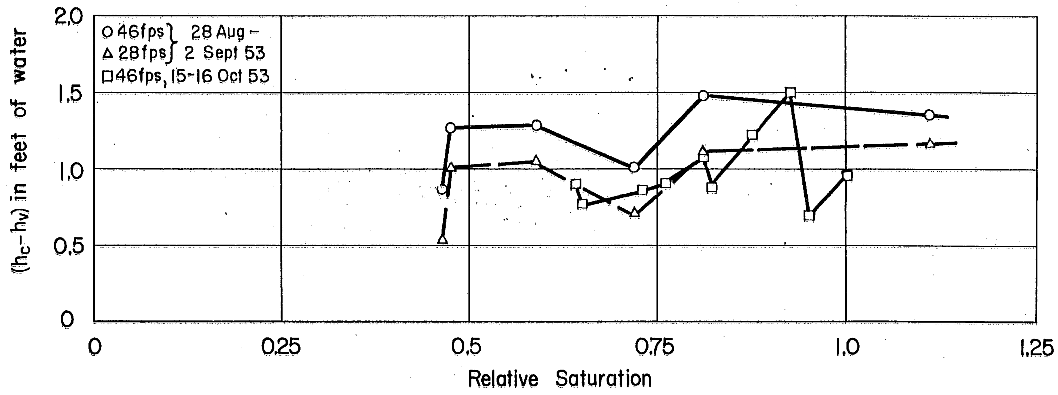


Fig. 8 - Effect of De-Aeration of Tunnel Water Following Aeration with Tap Water on the Measured Cavitation Pressure

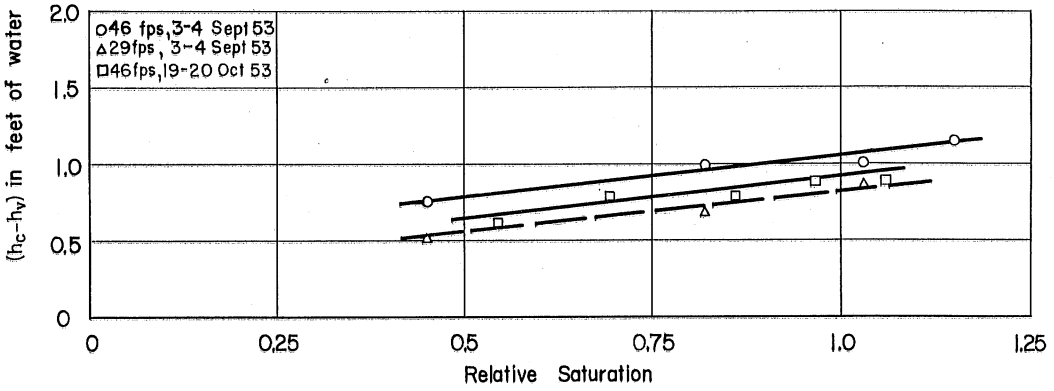


Fig. 9 - Effect of Aerating Tunnel Water with Air on the Measured Cavitation Pressure

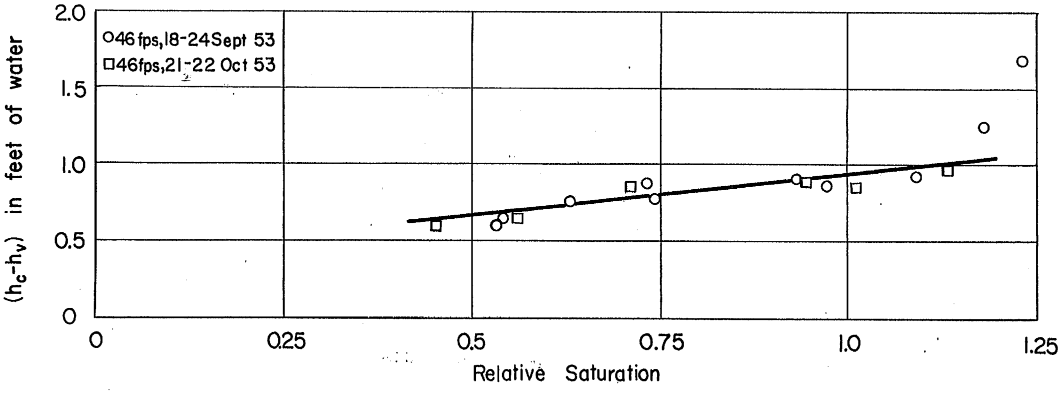


Fig. 10 - Effect of De-Aeration of Tunnel Water Following Aeration with Air on the Measured Cavitation Pressure

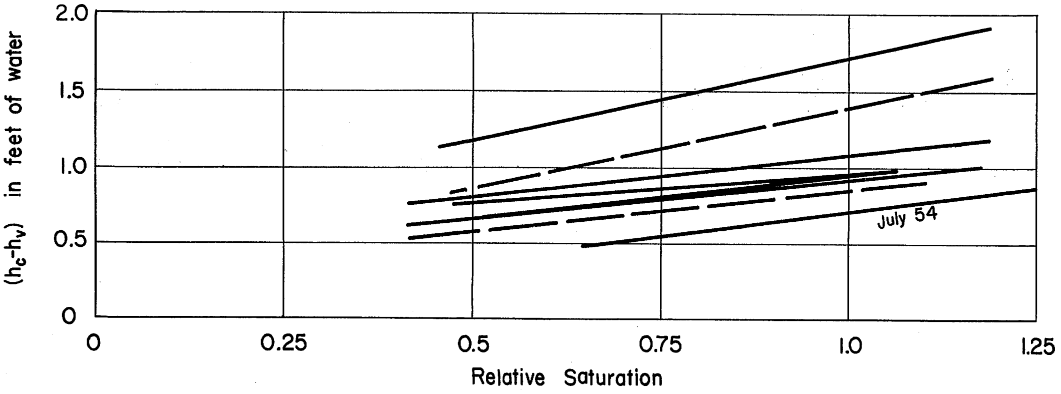


Fig. 11 - Composite Effect of Aerating and De-aerating Tunnel Water on the Measured Cavitation Pressure

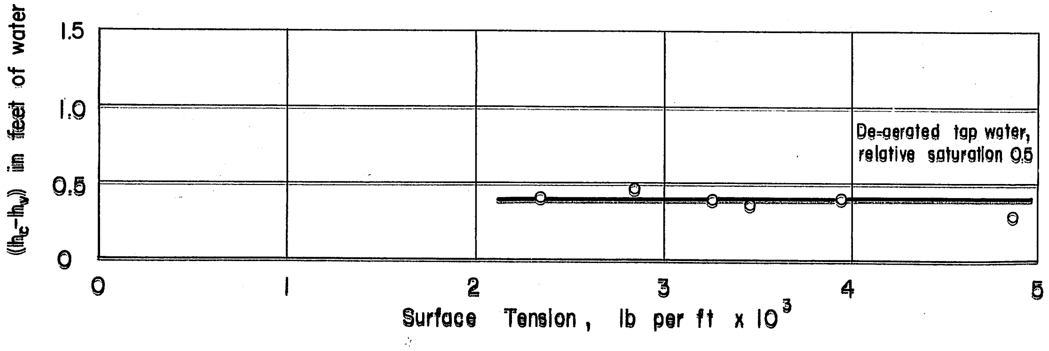


Fig. 12 - Effect of Adding Wetting Agent (Alconox) to Tunnel Water on the Measured Cavitation Pressure

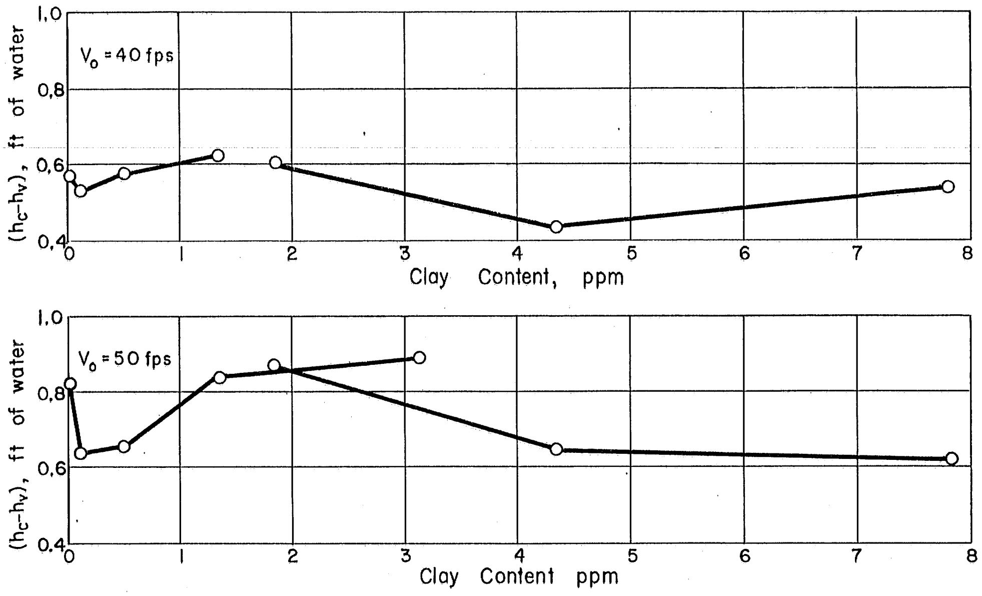


Fig. 13 - Effect of Adding White China Clay to Tunnel Water on the Measured Cavitation Pressure

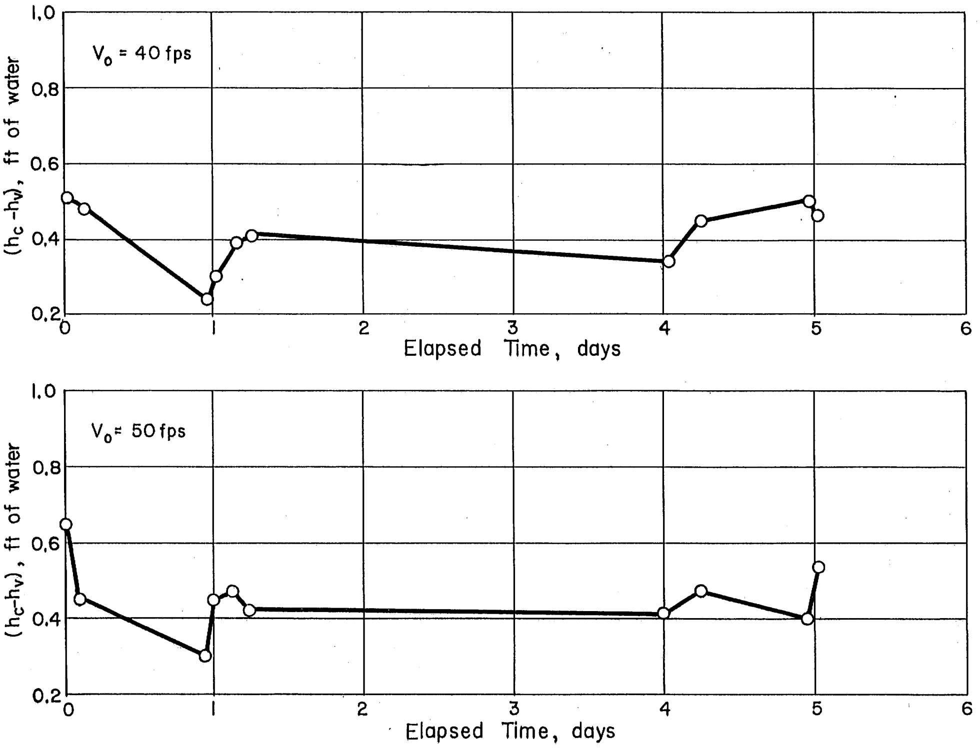


Fig. 14 - Variation with Time in Measured Cavitation Pressure of Tunnel Water

Total Gas Content = 14.5 ppm; Relative Saturation about 0.53

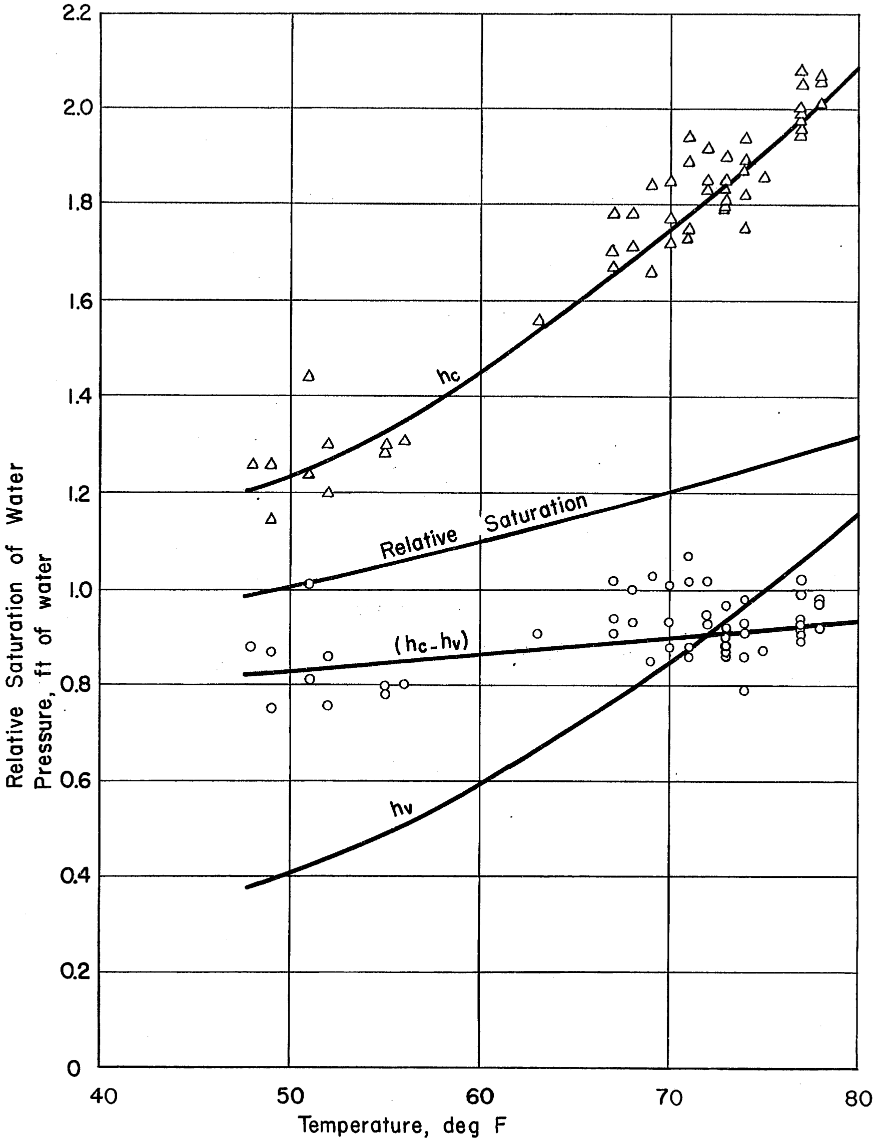


Fig. 15 - Effect of Increasing Temperature on the Measured Cavitation Pressure of Tunnel Water

Air Content = 29.9 ppm; V_o = 48 fps

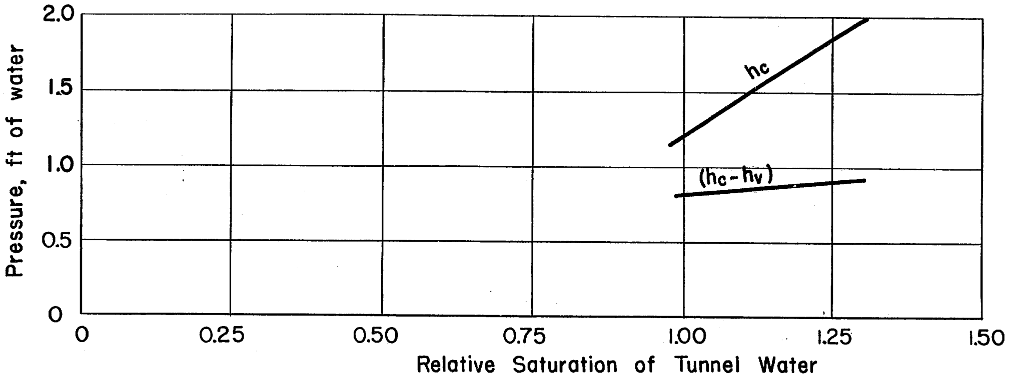


Fig. 16 - Effect of Relative Saturation (Increased by Increasing Temperature) on the Measured Cavitation Pressure of Tunnel Water

Air Content = 29.9 ppm; V_o = 48 fps

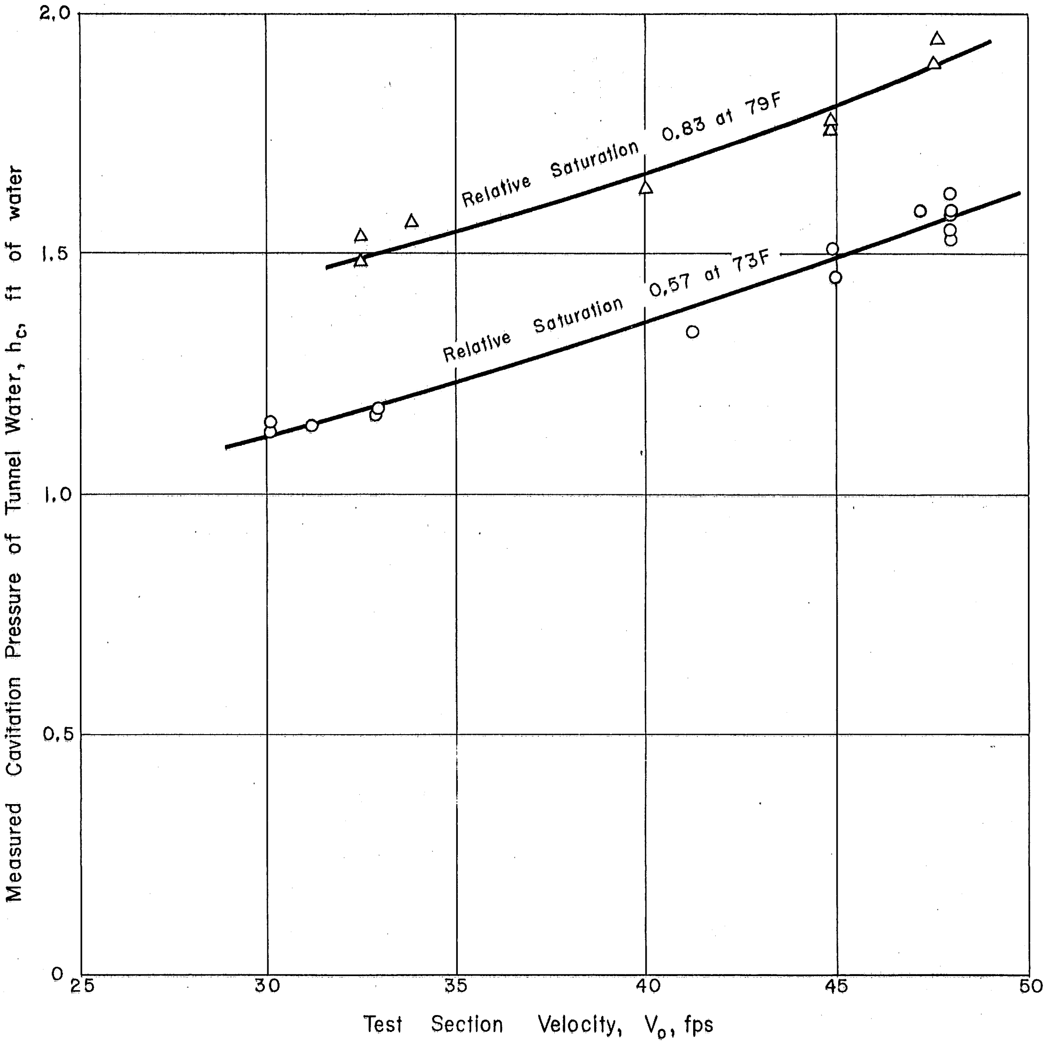
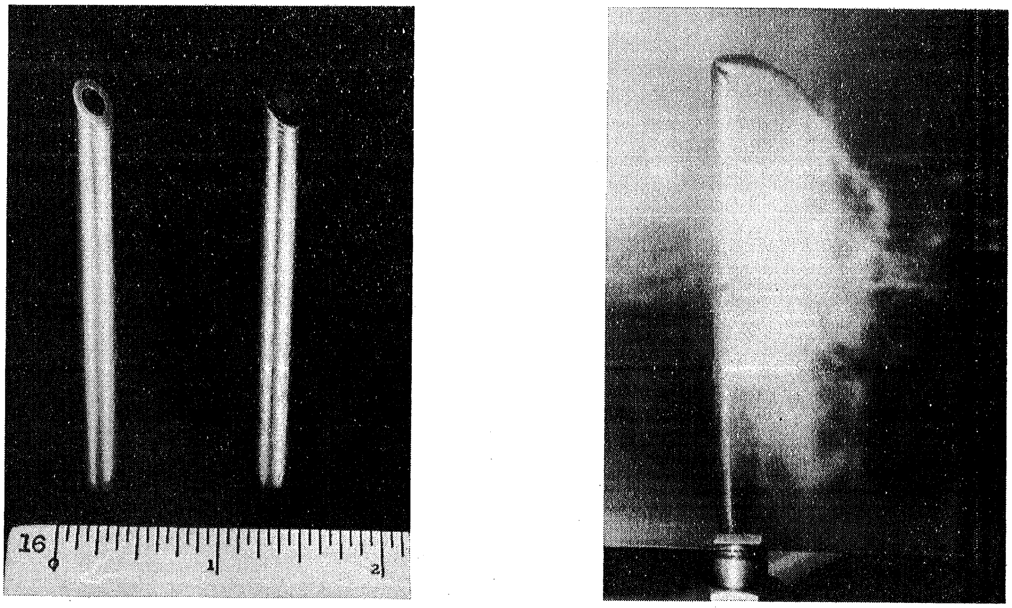


Fig. 17 - Typical Measured Cavitation Pressures of Tunnel Water Taken During Cavitation Tests of 3-Caliber Ogive Head Form



(a) Probe at right has rubber diaphragm cemented to face.

(b) Close - up of cavity
$V_0 = 43$ fps
$\sigma = 0.66$

Fig. 18 – Reichardt Probes for Measuring Cavitation Pressures

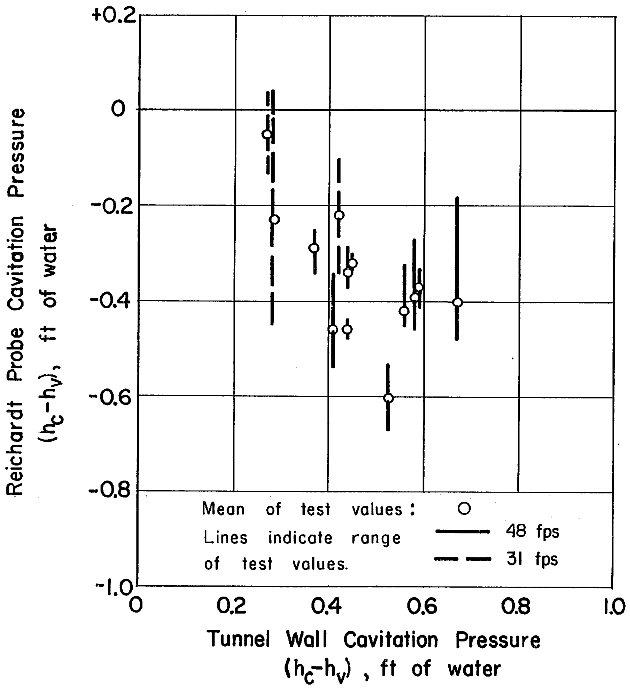


Fig. 19 – Measurements of Cavitation Pressure of Water on Tunnel Walls and with Reichardt Probe

Lines indicate range of test values , circles the mean

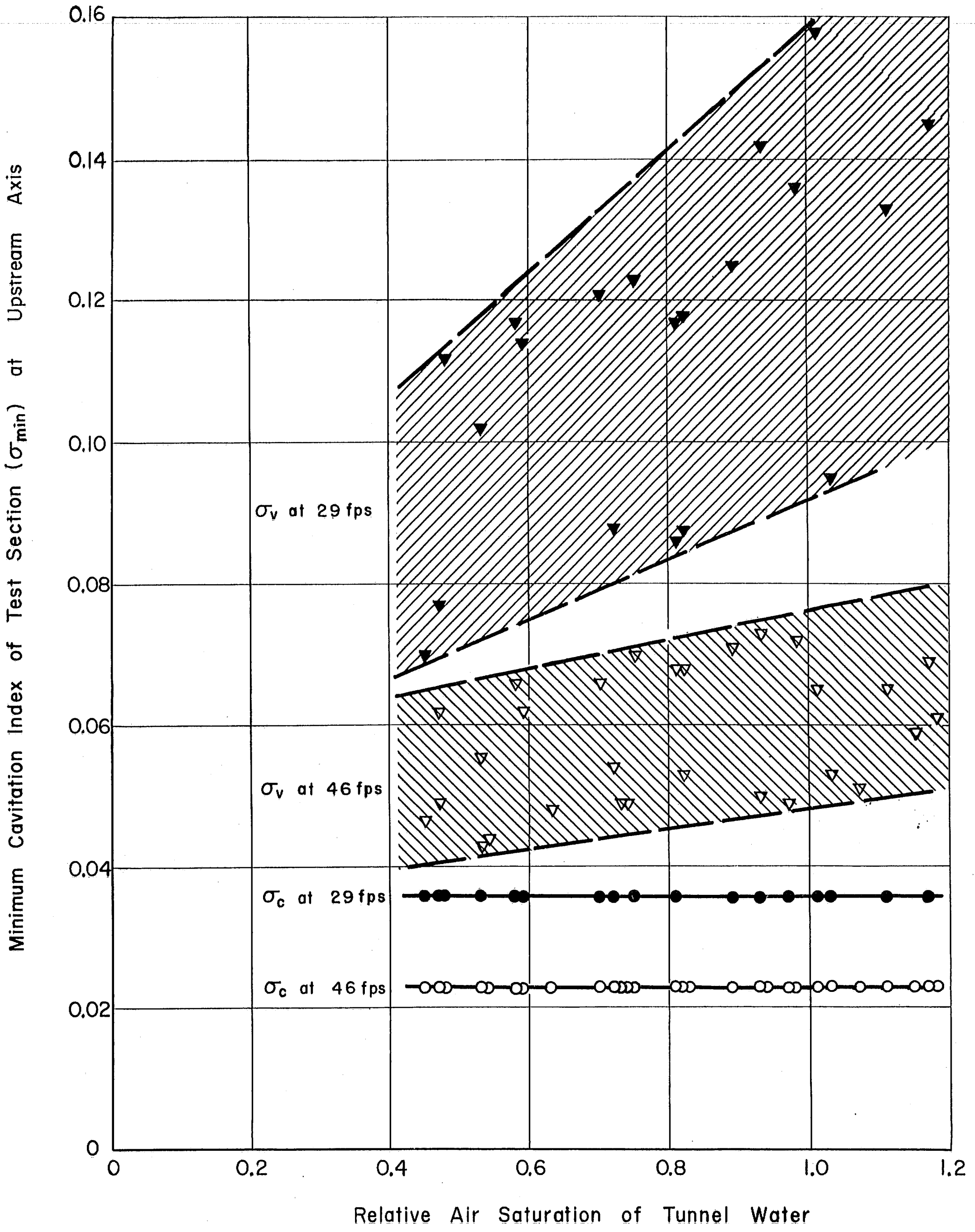


Fig. 20 - Minimum Cavitation Index of 6-in. Diverging Closed-Jet Test Section Used as a Testing Facility

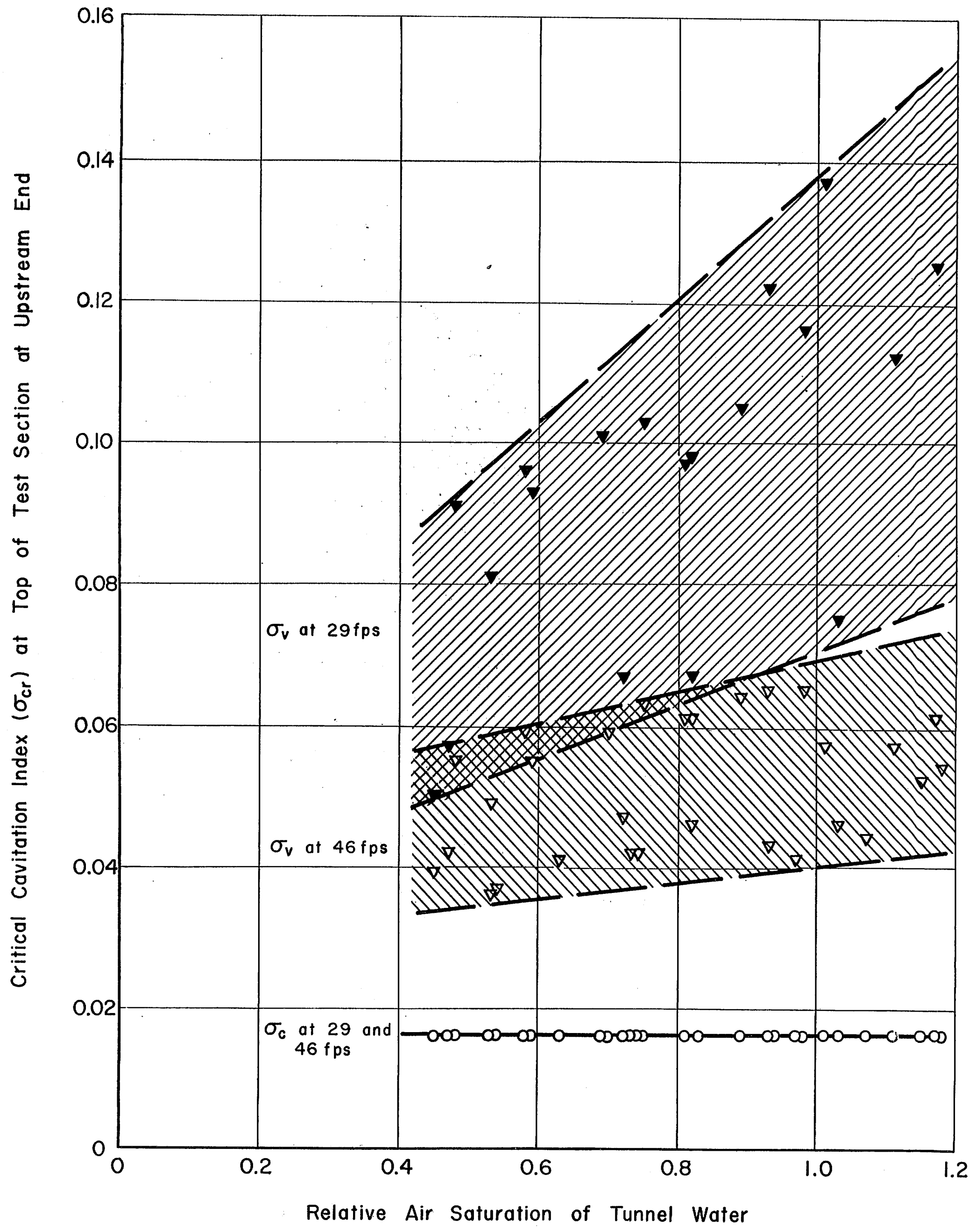
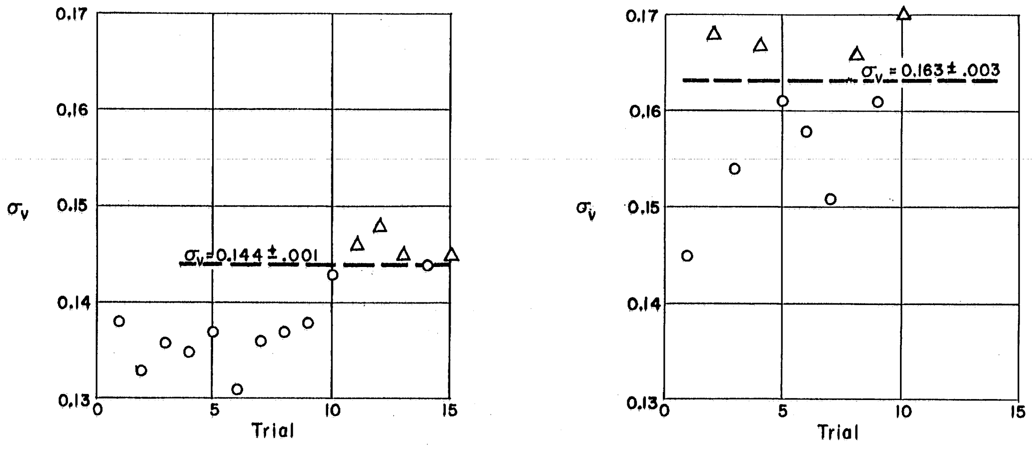
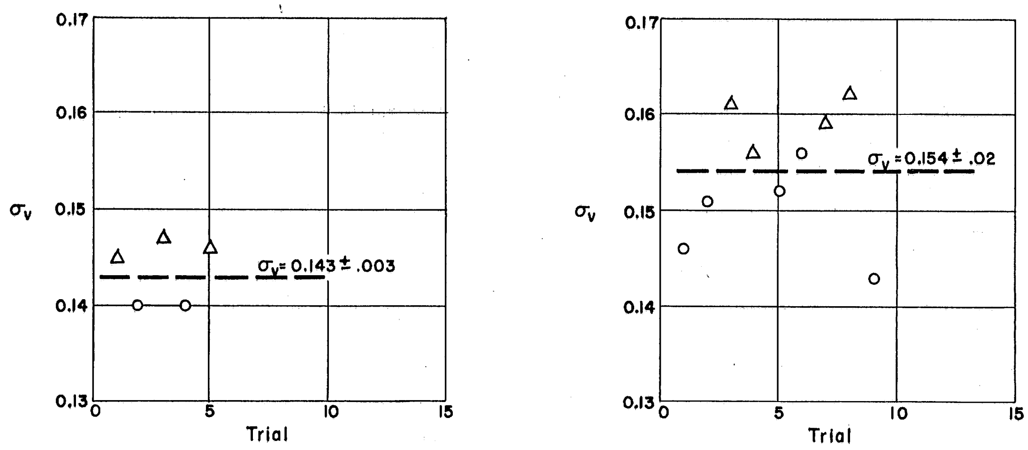


Fig. 21 - Critical Cavitation Index of 6-in. Diverging Closed-Jet Test Section Used as a Cavitating Body



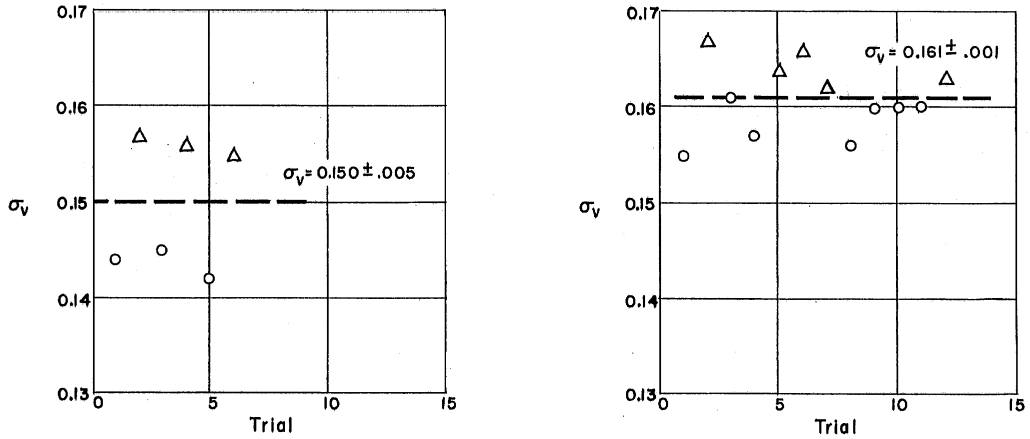
$(h_c - h_v) = 0.52$ ft water

$(h_c - h_v) = 0.60$ ft water



$(h_c - h_v) = 0.69$ ft water

$(h_c - h_v) = 0.73$ ft water



$(h_c - h_v) = 0.79$ ft water

$(h_c - h_v) = 0.81$ ft water

Fig. 22 - Incipient Cavitation on 3-Caliber Ogive Head Form

△ No Cavitation; ○ Cavitation; $V_o = 44.5$ fps

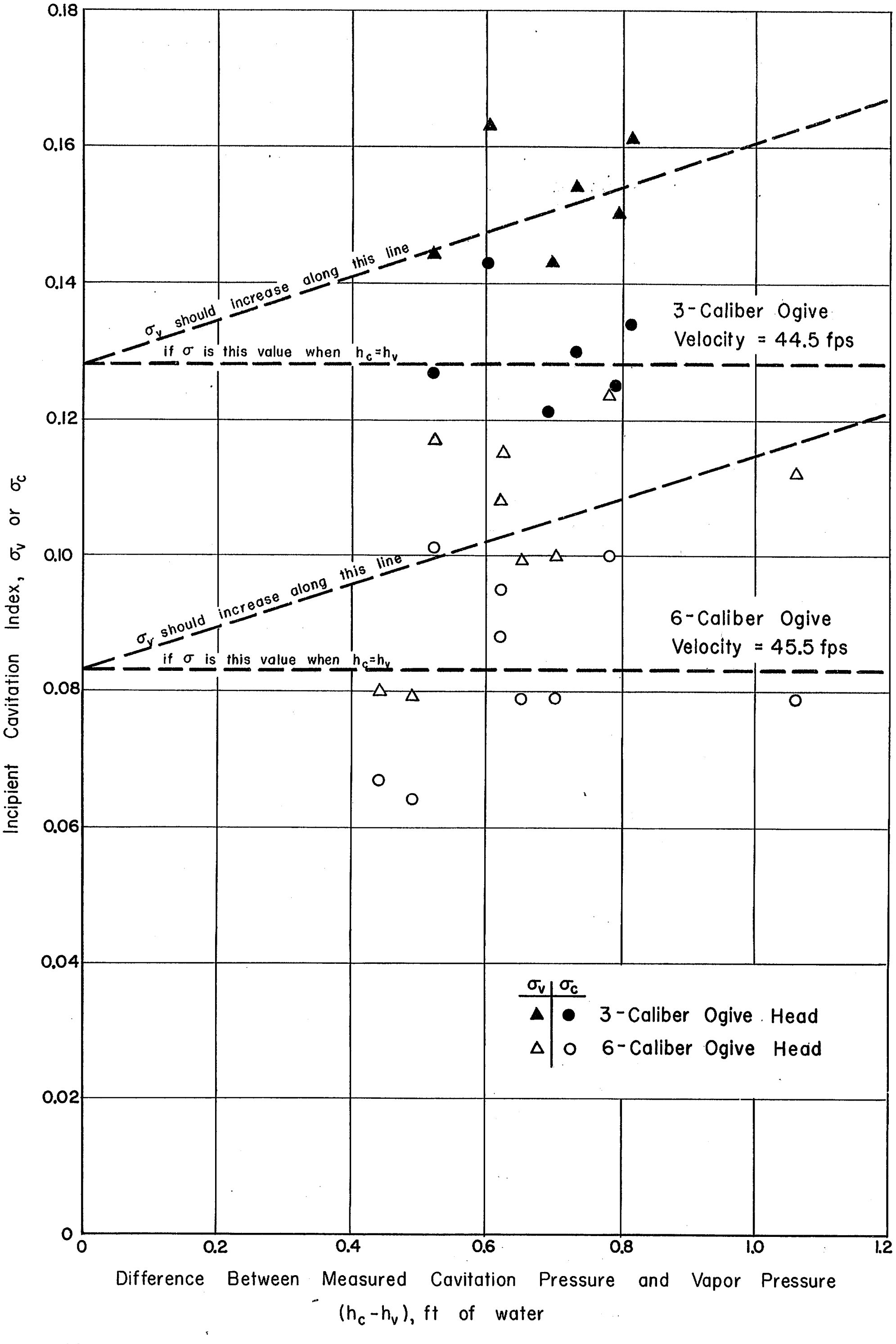


Fig. 23 - Incipient Cavitation Index for 3- and 6-Caliber Ogive Head Forms Based on Vapor Pressure and on a Measured Cavitation Pressure (Test I)

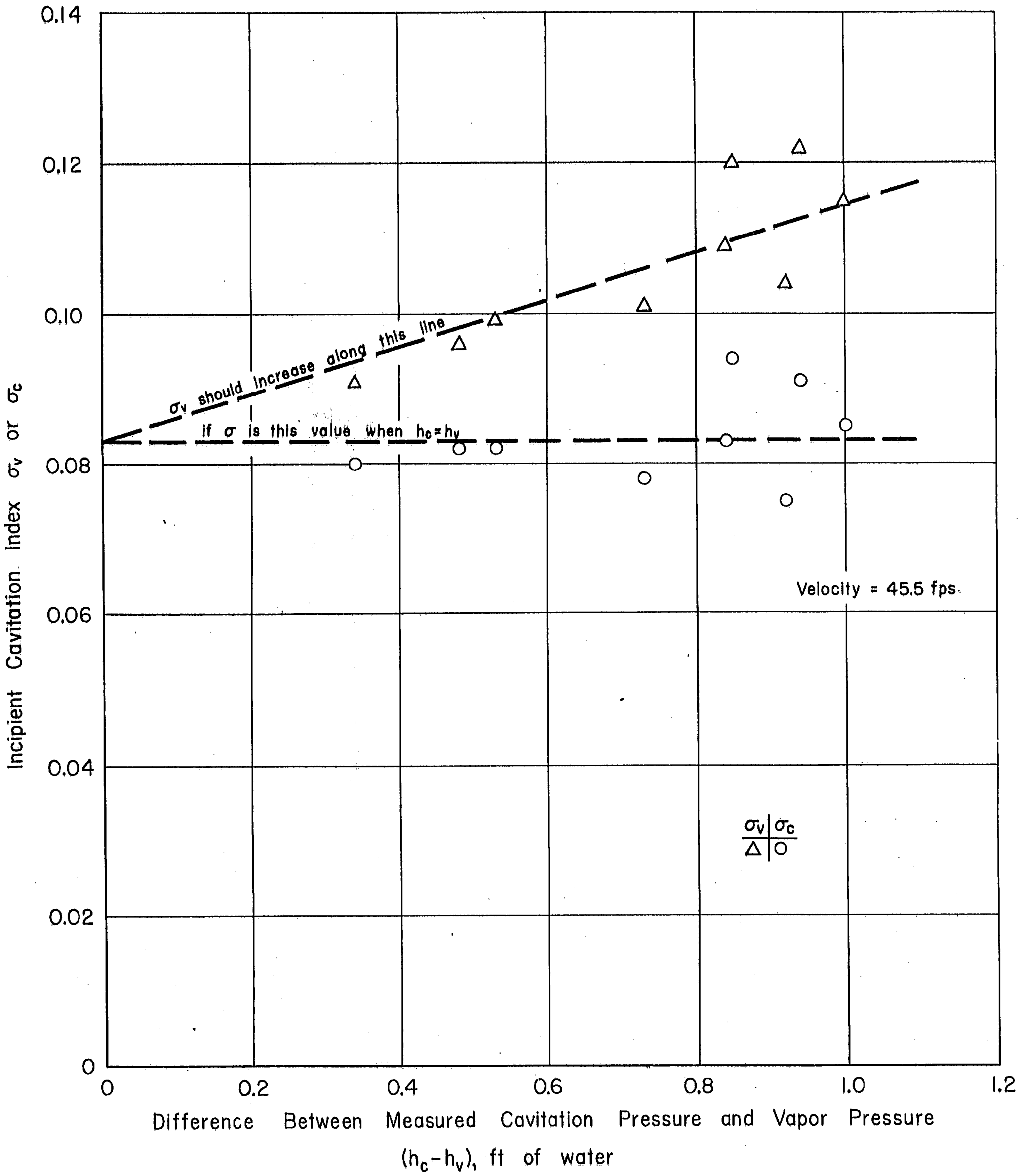


Fig. 24 - Incipient Cavitation Index for a 6-Caliber Ogive Head Form Based on Vapor Pressure and on a Measured Cavitation Pressure (Test II)

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