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A STUDY OF THE INFLUENCE OF GAS NUCLEI ON CAVITATION SCALE EFFECTS IN WATER-TUNNEL TESTS

(With an Appendix,
A Sonic Method of Measuring the Concentration
of Undissolved Gas Nuclei in Water)

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PREFACE

Marine designs with performance limited by critical cavitation are an important naval problem. Design studies with performance predictions based on model studies in a cavitation tunnel have long been plagued with substantial scale effects. To further the understanding of these scale effects, fundamental studies have been made of the basic test facilities with emphasis given to controlling the characteristics of the cavitation nuclei present in the test water. The major effort under the program has been given to the development of a new type of test facility. The data from this facility are still preliminary in nature but give promise of contributing to the reduction of scale effects.

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ABSTRACT

The gas content of water employed in a cavitation tunnel is known to influence the conditions under which cavitation will be initiated.

This study gives emphasis to the importance of the portion of the gas content which is in the form of free-gas bubbles. It is shown that these cavitation nuclei are inhibited from forming in existing types of water tunnels and that such inhibition may contribute to scale effects in model testing.

The report describes a new modification to tunnel construction that promotes and controls the presence of gas nuclei in the water.

The increased concentrations of nuclei provided by the new tunnel were evaluated by a very promising new instrument developed specifically for such measurements.

Scale effects evident in cavitation-inception tests in other tunnels were substantially reduced in comparable tests in the new tunnel.

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I. INTRODUCTION

The designers of dynamic hydraulic machinery and underwater bodies have for many years regarded the cavitation tunnel as a primary facility in the determination of the performance criticals established by the occurrence of cavitation in a given design. The effectiveness of these facilities is attested to by the increasing number, size, and speed of the new units of this character which are being built to pursue cavitation studies both here and abroad.

These facilities have been most useful in those hydraulic fields where the size and nature of the prototype make it economically desirable to conduct design studies on a model scale. This is particularly true in the study of large marine propellers, underwater ordnance, and hydroelectric turbines. In all of these fields there has been a continuing effort to improve the reliability of the model studies as an index of prototype performance. However, despite this effort, significant sources of error still remain in the results obtained from cavitation studies in water tunnels.

While there are many tunnel environmental conditions which are known to differ significantly from the prototype, variation in the gas concentration of the tunnel water has long been suspected as a major contributor to prediction errors relating to incipient cavitation studies. A number of studies [1, 2, and 3]* have been made of the influence of the gas content as measured by the dissolved gas. These studies have indicated that the dissolved-gas concentration is influential but is not in itself a sufficiently reliable index to cavitation susceptibility. More recently it has been conjectured that possibly only the entrained, free-gas nuclei in the flow are important to the modeling of cavitation inception.

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*Numbers in brackets refer to the corresponding numbers in the List of References on p. 24.

The study described herein was initiated on the premise that cavitation-inception tests involving water enriched with many nuclei would be significantly different from tests involving water depleted of gas nuclei.

Proof of this premise necessitated the development of a practical tunnel facility permitting substantial control of the nuclei existing in the tunnel flow and the development of a meter to evaluate the concentration of nuclei. These developments are described.

Cavitation-inception tests of a preliminary nature were conducted in the new tunnel with accompanying measurements of gas-nuclei concentration. The tests indicate a substantial reduction in the scale effect apparent in other comparative studies.

II. A RESUME OF CURRENT CONCEPTS ON THE INFLUENCE OF GAS CONCENTRATION

The growth of vapor or gas bubbles in a liquid under varying conditions of temperature, pressure, and gas concentration has been the subject of considerable study over a long period of time. If one examines the literature of these studies with a view toward clarifying the basic mechanisms involved in the cavitation-inception process, certain obscurities and acceptable concepts appear.

The following important points appear to have a basis in demonstratable concepts:

1. Water which is gas free and at temperatures common in nature has a substantial resistance to internal tensile rupture or to being pulled free from a solid boundary.
2. In gas-free water, resistance to tearing forces is sufficient to prevent cavitation under the limited negative pressure values normally found in good hydrodynamic designs.
3. A free surface or gas-liquid interface within the liquid is essential to the inception of cavitation. The interface may exist as a gas bubble either entrained in the liquid or trapped in a fissure of the solid boundary. Natural waters give evidence of having substantial numbers of such discrete free surfaces or nuclei.

4. Cavitation or the large-scale growth of a gas nucleus under reduced pressure conditions occurs either as the result of the diffusion of dissolved gas through the interface and into the nucleus or from vaporization at the interface.

5. In most hydrodynamic design problems, the bulk of the flow stream and its entrained nuclei are exposed to reduced pressure so briefly that the slow, gaseous diffusion processes are unable to contribute materially to the nuclei growth. The resulting gaseous cavitation is therefore of minor importance.

6. Vaporization at the nuclei interface can and apparently does serve as the principal support for rapid growth or true cavitation of the original nuclei under reduced pressure conditions.

7. The gas nuclei in the water are directly involved in the inception of cavitation and the dissolved gas is only indirectly involved.

8. A large number of factors contribute to initiating and supporting the rapid, vaporous growth of a nucleus, but chief among these is a critical balance between net pressure forces across the interface and the surface-tension force in the interface. Because of this latter force, the inception of cavitation is dependent on the size of the nucleus when it enters the region of low pressure.

9. The stable size of a gas nucleus under a given condition of sustained pressure in a given liquid is dependent on the dissolved gas in the liquid and the previous history of pressurization.

The concepts involved in the last three items constitute the basis for the investigation described herein. Important to the understanding of these concepts is the following rationalization.

The elementary static equilibrium conditions pertinent to the expansion of a gas bubble in a liquid have been analyzed [4] to yield the expression

$$p_g + p_v - p = 2 \frac{\sigma}{r}$$

or

$$p - p_v = \frac{K}{r^3} - 2 \frac{\sigma}{r}$$

where p_v is the liquid vapor pressure, p is the ambient liquid pressure, p_g is the partial pressure of gas (which equals K/r^3 for a perfect gas at a constant temperature where K varies with the weight of gas in the bubble), σ is unit surface tension, and r is bubble radius.

If arbitrary values of K are selected together with a typical $\sigma = 0.005$ lb per ft for water at 68 F, the relationship between the pressure differential $p - p_v$ (expressed in feet of water) and the bubble diameter has been calculated [4] to be in accord with Fig. 1.

The idealized differential pressure values shown in Fig. 1 may be only a qualitative approximation to the relationship for cavitation under dynamic conditions in a water tunnel. However, the figure is important in that it shows the way in which pressure must be lowered to a critical value before the rapid expansion of true vaporous cavitation can be experienced by a given bubble. This critical expansion size is approximated by the dashed curve of the figure. The plotting demonstrates that rapid vaporous expansion or cavitation will readily occur at moderate differential pressures if the nucleus is relatively large but will occur only under very low pressures if the nucleus is very small. The plotting also serves to demonstrate that the usual method of writing the cavitation index is erroneous if vapor pressure is presumed to exist in the cavity.

It is apparent from these pressure curves that the value of the cavitation parameter for inception conditions on a given test body should be significantly affected by the size of nuclei available in the test water. From this it follows that water-tunnel studies of incipient cavitation on a model will produce a reasonable approximation to prototype cavitation only if the nuclei are in some way comparable. If wide dissimilarities exist between nuclei in the model and prototype, it is reasonable to expect disparities or "scale effects" to be in evidence in model-prototype comparisons.

are produced by use of a high flow speed. In the case of rotary blading systems, the low pressures on the blades are produced by the through flow augmented by the velocity of rotation.

Since the cost of operating the tunnel varies as the cube of the flow speed, and the loads imposed on models vary as the square of the speed, it is economically desirable to conduct cavitation model studies at the lowest permissible speed. Use of a low speed requires, in turn, the use of a low ambient pressure for similarity in accord with the conventional cavitation parameter.

In the conventional water tunnel, which recirculates the test water in a closed conduit loop, the test speed is usually independently controlled through the pump speed, and the test-section pressure is independently varied by superimposing static variations on the entire tunnel loop. The establishment of a desired test-section speed and pressure is therefore quite straightforward.

If, in accord with the foregoing discussion on nuclei, one decides that it is also desirable to control the size of gas nuclei present in the test section, a new complication is introduced.

Gas nuclei in a given liquid increase or decrease in size in accord with the dissolved-gas concentration of the liquid and the ambient exposure pressure. Under steady test conditions, diffusion processes continue until an equilibrium condition stabilizes the size of the nuclei. Brown [7] found that the rate of change of nuclei size was quite rapid for a substantial oversaturation or undersaturation condition and asymptotically approached a stable size as saturation was approached.

This means that a water saturated with dissolved gas consistent with a selected mean tunnel pressure must be maintained if nuclei are to be stably maintained.

If a tunnel water is saturated with dissolved gas for a given mean pressure condition and passes through the low-pressure test section, any entrained nucleus will increase locally in size and decrease again as it passes into regions of higher pressure in the tunnel loop. If this repeating cycle of expansion and contraction is augmented by heavy cavitation in the test section, the combined mechanism appears to afford a coalesence or collection of nuclei into larger bubbles which may not be able to return to nucleus size in a single pass through the tunnel loop. A continuation of this procedure may ultimately result in a new stability pattern which allows substantial numbers of larger bubbles to recirculate in the flow.

In the practical operation of a water tunnel, these recirculating larger bubbles constitute an obscuring abnormality in the flow and it is desirable that they be eliminated.

If an attempt is made to maintain a dissolved-gas content consistent with normal atmospheric saturation, larger bubbles will usually appear in continued tunnel operations. This happens with a conventional water tunnel because the circuit time, for which reabsorbing high pressures exist, is too limited to achieve complete reabsorption.

In the case of the simple tunnel, the undesirable accumulation of large bubbles can be alleviated by reducing the dissolved-gas content until the undersaturation inhibits the evolution of the bubbles and accelerates reabsorption sufficient to accommodate the available time-pressure cycle of the circuit. For tunnel studies involving light or incipient cavitation, the necessary undersaturation may be quite moderate, whereas with heavy cavitation, the undersaturation must be substantial. Unfortunately, efforts to undersaturate for the elimination of larger bubbles will eliminate quite effectively all but the smallest of the nuclei and will, in turn, adversely influence a subsequent critical expansion pressure in accord with Fig. 1.

In the case of the Cal Tech resorber tunnel, a remedy is provided by increasing both the time and pressure in the return circuit sufficiently to reabsorb the offending larger bubbles. Unfortunately, the high pressures necessary to bring the larger bubbles under control will leave only very small nuclei and will again adversely influence the critical expansion pressure in accord with Fig. 1.

From the foregoing, it is apparent that cavitation studies in existing types of water tunnels will generally be involved with either excessive numbers of obscuring large bubbles or with a deficient number of suitable nuclei. In either case the model inception test data may be considered somewhat abnormal for use in prototype predictions.

IV. A NEW FORM OF WATER TUNNEL

The problem of providing a tunnel flow that contained a near normal or controllable content of nuclei without the presence of large bubbles evidently called for a material change in the physical make-up of existing tunnel types. A review of the total problem indicated that the problem of providing suitable nuclei might be solved if means could be found for screening out or separating only the extraneous large bubbles from a tunnel flow with otherwise satisfactory control.

The problem of mechanically separating gas bubbles from the flow in a water-tunnel test section could conceivably be approached in a variety of ways. However, the solution of similar gas-separation problems in other technical fields appeared in the practical cases to employ either gravity or centrifugal force in producing the desired result. The application of a centrifugal force might produce a powerful, rapid-acting separation suitable to a small installation, but with the large flow volume involved in a water tunnel, centrifuging did not seem a practical solution. The problem, therefore, resolved itself into consideration of simple methods of gravity separation.

A study of the literature relating to the gravitational rate of rise of individual gas bubbles through water indicates that the rate of rise varies from a small value (0.0075 fps at diameter = 0.001 in., 0.075 fps at diameter = 0.01 in.) to a terminal value near 1.0 fps for bubbles with diameter = 0.10 in. or larger. The initial design of a practical gravity separator then requires a selection of that size range which is to be passed and that which is to be retained. The size of bubble to be passed by the separator to serve as test-section nuclei has been discussed previously. No preferred top size of nucleus has as yet been established, but a number of factors indicate that it would be desirable to separate bubbles larger than about 0.01 inches in diameter.

From the above figures, it is evident that the simplest type of gravity separation using a vertical downflow tank would require a flow cross-sectional area and associated diffuser conduit of very large size.

As an alternate to separation in a vertical downflow, it was rationalized that separation of gas bubbles could be accomplished by passing the flow through a bundle of small bore tubes in a near-horizontal position. The vertical rise rate of the bubbles would permit them to ascend to the tops of the tubes as the water moved axially through the tubes. The gas would then accumulate at the tops of the tubes where it might be withdrawn by secondary gravity effects or other means. Since the rise distance could be kept small by use of tubes of small height, collection at the tube top could presumably be accomplished in a relatively short flow length.

The tube diameter and length required to collect all bubbles above a certain arbitrary size may be calculated simply by using the previously mentioned rates of rise. These simplified calculations do not, however, account for the diffusion or exchange characteristics of the fluid turbulence which may produce forces dominant over the gravitational separating force. The result of these forces and other secondary forces will support a stable state of suspension of bubbles below a certain critical size. Accordingly, the critical size of bubbles which will pass through the separator will be dependent not only on the configuration of the separator tubes but also on the inherent turbulence of the approach flow system. Since the latter is not, in practice, subject to close control or analysis, it was decided to establish the design of the separator structure on the basis of experimental studies.

A conventional form of water tunnel of 6-in. test-section diameter was available at the St. Anthony Falls Hydraulic Laboratory. The characteristics of this tunnel were well known from previous cavitation studies and the tunnel was easily adapted to physical modification. In light of this, the separator development program was designed around use of this tunnel.

Selection of the configuration of tubes to be tested represented a a compromise between those which might be preferred for flow control and those which could be practically fabricated for mass installation in a water tunnel.

Those configurations which offered promise of development were fabricated to prototype size and in a small-tank test setup were exposed to gasified flow conditions approximating those to be expected in the tunnel.

These comparative tests eventually lead to the selection of a flow tube with a crown shaped to a sharp, inverted V in which a greatly thickened boundary layer develops. Bubbles, which manage to gravitate upward into this boundary layer within the length of the tube, are exposed to relatively low velocities and a weakened transporting system. With the tube axis tilted downward in the direction of flow, the bubbles collecting in the crown of the tube will be subject to a gravitational-force component acting upstream along the top of the tube.

With appropriate adjustment of the tube slope and the mean flow velocity, it has been established that it is practical to promote the collection and upstream movement of all but the smallest sizes of bubbles passing through the tube. To promote general collection of the bubbles, the individual tubes are provided with holes near the upstream end. These holes permit the bubbles to gravitate from one tube to the next above. In the case of the water tunnel, the bubbles progress upward through the tube stack to the top of the tunnel conduit where they are collected and drawn off for disposal or controlled return to the tunnel.

Pilot studies of various tube configurations and arrangements lead to use of standard, galvanized, corrugated steel sheets stacked to produce the desired tube arrangement, as shown in Figs. 2 and 3.

The pilot studies showed that a tube length of 3 ft having a tube slope of about 20 degrees with the horizontal and a mean velocity of not more than 1.0 fps would collect substantially all of the bubbles larger than about 0.03 inches in diameter. While it would have been desirable to reduce this minimum separation value to the preferred 0.01-in.-maximum nucleus size, the higher value appeared to be a practical limit.

The separator tubing of Fig. 3 is introduced into the circuit of the tunnel in the low-velocity region upstream of the contraction, as shown in Fig. 4. At the downstream end of the separator, a flow-straightening honeycomb is provided. This honeycomb, of thin sheet metal, is composed of cells of about 1/4 inch in diameter and 3 inches in length with axes parallel to the tunnel test section. This serves both as a flow straightener and a turbulence suppressor. The flow straightener is followed by a contraction approach chamber which allows some turbulence decay in the flow before entrance to the contraction.

The contraction is a quadrant of an elongated, simple ellipse designed to be free of cavitation in accord with Reference [8]. This form permits a compact, economical construction with excellent flow properties and may be safely employed because of the large area ratio involved in the contraction. In modifying the 6-in. tunnel, the contraction was fabricated of Lucite.

The low velocity required in the separator necessitated substantial velocity reduction in the portion of the tunnel circuit following the pump. This velocity reduction is fixed by the maximum test-section velocity for which bubble-free operation is desired as compared to the maximum 1.0-fps velocity which must prevail in the separator. In the case of the 6-in. tunnel the ratio was selected as 32. This was selected to allow substantial overload test studies at the top tunnel speed of 50 fps.

The form of the conventional 6-in. tunnel, which was being modified for this study, provided an excessive velocity in the region in which the separator was to be installed and necessitated the provision of additional diffuser action employing an area increase of about 4. This diffuser ratio was very large in relation to the values usually encountered in diffuser design practice and necessitated a new concept in diffuser design in an effort to achieve economical construction and desirable flow characteristics. A study accompanied by tests was made on a number of diffuser forms. This finally resulted in the combined turning vane and two-dimensional diffuser arrangement shown in the upper left-hand corner of Fig. 4 and detailed in Fig. 5.

This diffuser provided a compact arrangement with relatively good characteristics, but as with all diffusers some maldistribution of velocity developed on the discharge side. Since a nonuniform velocity entering the flow separator would lead to local bubble transport in any high-velocity region, an adjustment of the velocity profile was necessary. This was accomplished by experimental fitting of suitable resistance screening across the entrance to the turning vanes and the entrance to the separator tubes.

The arrangement shown in Fig. 4 provided a flow which was visually bubble free at low velocities and gradually showed more evidence of test-section bubbles as the velocity increased. However, even under heavy cavitation and with velocities exceeding the separator design critical by a factor of nearly 2, the number of test-section bubbles was judged as not being excessive for most types of tunnel tests.

The over-all performance of the tunnel with the air-separator modifications shown in Fig. 4 was quite satisfactory. The separator fabrication introduced substantial new boundary areas to the tunnel flow and additional diffuser action, but because of the low absolute velocities involved, the modifications gave no bulk evidence of significant energy losses.

A basic assumption of the entire program was that cavitation-inception studies with water enriched with many nuclei would be significantly different from tests with water depleted of gas nuclei. To test this assumption, it was then required that the tunnel or the tunnel procedures must be modified to assure maintenance of large numbers of nuclei in the flow.

In the initial phases of the program, it was felt that the desired nuclei would have to be supplied by introducing them into the tunnel through a bubble generator. In a stable equilibrium condition, these nuclei would be recirculated with an origin at the tunnel separator and collection system. If an equilibrium condition with a higher nuclei concentration were desired, additional outside gas would have to be introduced at the generator, and if an equilibrium with a lower content were desired, a suitable amount of collected gas would have to be removed to the outside.

In support of this concept, a nuclei-generator development was undertaken. Several different forms of shear-type generators were designed and built. These proved capable of producing substantial volumes and controlled bubble sizing but failed to produce the desired smaller nuclei sizes. It is believed that additional development of a generator would have achieved the desired ends. However, preliminary tests indicated that even with a nucleus generator, a stable high level of nuclei concentration could not be maintained in a water unless a near-saturation content of dissolved gas existed in the water. In view of this, development of a nuclei generator was suspended in favor of a parallel study which established that pressure control of the tunnel could inherently produce the desired nuclei.

The alternate method consisted of depressing the tunnel pressure to the point where the liquid became supersaturated with gas and gas evolution began. The amount of freed gas could be regulated by the pressure. The absolute pressure at which a desired nuclei concentration occurred was dependent on the initial dissolved-gas content of the given water.

The maintenance of a stable level of nuclei concentration by such a procedure would be difficult in a static water, but the small nuclei remained in stable suspension in the turbulent tunnel flow and any change in pressure was followed by a rapid shift (less than 1 minute) to stability at a new level of nuclei concentration. This rapid shift to a new stability appears to be in general agreement with the time-pressurization effects noted in Reference [3]. Duration tests were not made on the long-time stability of the air content of such water, but conditions were observed to remain constant for the 10 or 15 minutes involved in each of the inception tests, which are described later. These observations were made in the tunnel using a new type of nuclei-concentration meter, which will be described later.

Some complications result in application of this procedure because the average pressure in the tunnel circuit is not varied exclusively by the test-section pressure regulator but is also a function of the speed. These difficulties are believed to be minor once preconditioning and test procedures are properly established for a given tunnel.

Since the above procedure appears to offer a means of providing the necessary nuclei without externally generating them, some question arises as to what should be done with the gas that may be collected at the separator. Actually no real problem developed in the current inception studies because the coalescence of bubbles in the test section was minor, and their collection and removal did not significantly affect the measured stability of the nuclei concentration. Under prolonged operation or at higher rates of removal associated with heavy cavitation, the loss of gas would, however, eventually be reflected in the saturation stability and the collected gases should be returned to the flow to maintain that stability.

Some explanation for the relative stability may be found in the fact that the gas entrained as useful nuclei in the tests did not exceed 100 parts per million of water volume. In contrast to this, the volume of gas in solution is probably normally equivalent to no less than about 20,000 parts per million. With these values it is apparent that even a fairly rapid turn-over in the entrained 100 ppm will not readily affect or exhaust the dissolved 20,000 or more ppm.

While a maximum useful concentration of entrained nuclei of 100 ppm was obtained in the tests, it is presumed that additional tests using even higher dissolved-gas concentrations would produce still higher entrained nuclei concentrations.

For the current tests the physical removal of the separated gas was achieved by application of a controlled vacuum at the collection slot in the tunnel roof above the separator. Control of this vacuum constituted the ambient pressure control for the entire tunnel.

V. A NEW FORM OF NUCLEI-CONCENTRATION METER

Recognition of the importance of gas content on the inception of cavitation is by no means new. Earlier the dissolved-gas content was generally thought to be the significant measure of influence, whereas more recent thinking gives emphasis to the possible importance of only the freed gas.

In support of the earlier thinking, considerable effort has been devoted to the development of practical air-content meters, and a number of types have evolved for measuring various components of the dissolved-gas content. None of these have selectively measured the entrained gas nuclei. As part of the present gas-control study, it was originally proposed to make preliminary studies of a nuclei-concentration meter.

Several general methods of approach originally appeared to offer promise and these were made the starting point of a development under this general program. The end result of this development was an instrument which is described in detail in the appendix attached to this report. The general features of this instrument are briefly described in the following.

The selected instrument employs a measurement of the changes in the bulk modulus of compressibility in accord with a suggestion by Eisenberg [9]. This is accomplished by measuring the ratio of the acoustic velocity of a homogeneous gas-water mixture to the acoustic velocity of water free of gas. This ratio is a sensitive function of the nuclei concentration of the water.

The acoustic velocity was in each case evaluated by measuring the time of transit of a sound pulse traveling through the test fluid between a sound source and a sound pickup.

The sound source was a specially designed magnetostriction transducer which emitted pulses having a selected frequency. The sound pickup was a standard barium titanate ceramic crystal.

The pickup signal wave was imposed on a standard oscilloscope for direct reading of the sound wave transit time. The trace length was a measure of the transit time. The ratio of the trace length in gas-free water to the trace length in the gasified test water served as the acoustic velocity ratio.

Initial confirmatory studies of the instrument were conducted in a static-water tank; in later adaptations the transducer and pickup were attached directly to the exterior of the tunnel test section.

The sound coupling between the selected instrument components and the Lucite test-section walls was simple and effective, and secondary sound transmission through the walls was found to have a negligible effect on the signal. Measuring the sound-transit time of the nuclei-free water prior to a test and the subsequent transit time for any selected flow condition permitted ready evaluation of the nuclei concentration. The fact that these measurements could be made instantaneously, continuously, and directly in the test section without disturbing the flow made the instrument very promising.

For each frequency of sound pulse, there is a certain size of bubble which is resonant to that frequency, and the presence of even a few such bubbles in the sound beam will seriously attenuate the signal. In the current pilot design of the tunnel, a few bubbles of the larger resonant size are passed through the separator when the test-section velocities are in excess of 30 fps. These bubbles proved sufficient to destroy the signal for velocities above 30 fps in the current tests.

Available time did not permit fabricating transducers of other frequencies, nor did it permit revision of the tunnel to eliminate extraneous bubbles from the flow. Therefore, the sound system was moved from the test section to a submerged position in the contraction chamber where the influence of extraneous bubbles was minor.

The nuclei-concentration measurements, which were made as part of the inception studies (to be discussed later), were thus actually made in the contraction chamber. The test-section nuclei concentration values were then calculated from the contraction chamber readings by assuming the isothermal expansion of a perfect gas, using the measured pressure drop through the contraction. These values are, therefore, considered as an approximation to the nuclei concentration which might actually have existed.

It was believed that with relatively minor changes in the tunnel circuit and transducer unit, most of the difficulties encountered in these nuclei-concentration measurements could be remedied.

VI. CAVITATION TESTS IN THE NEW WATER TUNNEL

The previous discussion has pointed out the possibility that the nuclei concentration of a tunnel water may be a clue to abnormalities in model observations of cavitation inception. Accordingly, the tunnel described in Section IV, preceding, was assembled to provide nuclei control and the instrument described in Section V and the Appendix was developed to measure the nuclei concentration. It remained then to establish by test the extent to which nuclei concentration influences cavitation inception or contributes to scale effects.

Many cavitation tests might be conceived to demonstrate the influence of nuclei on inception scale effects, but a relatively simple yet informative test procedure had already been defined by earlier studies. These studies

[10] were conducted in the 48-in. conventional tunnel at the Ordnance Research Laboratory and the 14-in. resorber tunnel at the California Institute of Technology. The tests evaluated the average conditions for the inception of cavitation on hemispherical and 1.5-caliber, axially symmetric ogival (a pointed-bullet shape formed by a circular arc of radius 1.5 times the body diameter) head forms for a range of sizes exposed to a range of flow velocities. The tests were run with a dissolved-air content equivalent to about half-saturation at atmospheric pressure. The end result of the tests is shown in Fig. 6 which is taken from Reference [10].

It is to be noted that the figure contains a horizontal line representing the value of the minimum dimensionless pressure coefficient ($C_{p_{min}}$) for each of the two body shapes. The $C_{p_{min}}$ values had been previously measured in noncavitating flow at a high Reynolds number. The lack of agreement between the measured $C_{p_{min}}$ curve and a measured incipient-cavitation curve for a given size of body was presumed to constitute a scale effect. It is apparent that on this basis marked scale effects do exist in the CIT-ORL tests, and this same method of gaging scale effects will be used in reference to the tests of the new tunnel which is to be described.

For comparison with the CIT-ORL tests, the studies of the new separator tunnel employed a 1/2-in.-diameter, 1.5-caliber ogive head form. The ogive was located at the upstream end of a 1/2-in. sting placed on the tunnel axis at the downstream end of the contraction. The sting was supported by a spider of three streamlined struts positioned 6.5 in. downstream of the ogive.

In the separator-tunnel tests, the stream speed was varied from a minimum useful value slightly over 20 fps to a maximum obtainable value slightly over 50 fps. During cavitation tests the test pressure at the tunnel axis was varied from about 2 to 11 ft of water absolute by the application of controlled air pressure at the crown of the separator chamber. The dissolved-gas content of the water was varied by a preconditioning procedure.

In the case of the lowest dissolved-gas content, the entire tunnel was subjected to the highest obtainable vacuum for a period of several hours. The gases evolved under the vacuum gravitated to the top of the tunnel and were removed. The vacuum was applied to the tunnel water at rest, but periodically the tunnel was run at a high speed to produce heavy cavitation and gas evolution. It is noteworthy that even after four hours of exposure to a high vacuum, numerous small nuclei could be seen forming and rising in the water. There was evidence of leakage of air into the tunnel at joints and packings so the evacuation process was discontinued after about four hours and inception tests were then run.

An intermediate dissolved-gas content was created by exposing an air dome at the top of the tunnel separator to atmospheric pressure while air was bubbled through the rising leg of the tunnel with the tunnel operating at low speed. The exposure lasted about two hours. The extraneous gas not absorbed by the water was removed through the gas separator and recirculated through the bubbler.

A high dissolved-gas content was created by exposing the air dome at the top of the tunnel separator to a pressure of 2 atmospheres absolute while air was again bubbled through the rising leg of the tunnel. The exposure lasted two hours.

The above preconditionings were terminated just prior to a given test series. The test series was then begun by establishing a desired test-section speed (usually the maximum) and then progressively lowering the pressure until cavitation occurred on the test body. The pressure was then gradually raised until the cavity disappeared. This was considered the critical cavitation-inception condition. The critical pressure and nuclei concentration were then read and the run repeated for reproducibility. The speed was then changed to the next lower selected setting and a new cavitation-inception value noted. This progression was continued to the lowest speed at which cavitation could be initiated. In two of the series, the sequence of tests was rerun to establish further the reproducibility and long-term stability.

The nuclei-concentration meter, which is described separately in the Appendix, was mounted near the top of the contraction chamber. This meter had two arbitrary scales or sensitivities, but because of its elementary form, one of them had to be elected prior to a given run. Since large gas-content effects were initially being sought, the cruder, less sensitive instrument hookup was employed in these tests.

In each of the test series, the initial comparative transit time evidenced on the oscilloscope was noted for the undisturbed but freshly preconditioned water. The transit time on the oscilloscope was again read for the water condition existing at the time of an observed inception condition. The ratio of these transit times could then be converted to relative nuclei-concentration values in accord with the procedure described in the Appendix.

It is to be noted that the test conditions in general employed water which visually appeared to be free of gas. However, for those runs where the nuclei-concentration reading was comparatively high, the water had a definitely cloudy or milky appearance.

The inception of cavitation was observed visually in the low-pressure region on the top side of the ogive. For tests involving low nuclei concentration and low speed, inception was noted under rising pressure conditions by the sudden disappearance of a steady-state cavity having a clear forward portion and a foamy after portion. For the very lowest pressure and speed, the inception cavity was as much as 2 in. long. Hysteresis was noted in the pressure conditions relating to the appearance and disappearance of the cavity at low pressures.

As the speed and pressure of inception increased, the steady inception cavity shortened in length and the pressure hysteresis progressively diminished to zero.

For the tests with the lowest obtainable dissolved-gas content, the inception was nearly always in the form of the above-described steady cavities. However, as the dissolved-gas content was progressively increased, the tendency to inception with a steady cavity was replaced by inception with transient-bubble cavities.

In the transient-bubble cavitation, a small bubble visibly appeared and disappeared in the flow passing over the low-pressure region of the ogive. The length of the ogive over which the bubble was visible and the size of the bubble increased as the pressure decreased. For a water with an intermediate dissolved-gas content, cavitation sometimes appeared in two phases--the first phase was the transient bubble eventually followed by a steady cavity (second phase) as the pressure was progressively diminished. For tests with high dissolved-gas content, only the first phase appeared for the speeds obtainable in the tunnel.

The transient-bubble cavitation gave no evidence of pressure-hysteresis effects, and the appearance and disappearance of the cavity was measured by a wholly arbitrary visibility index. The index in this case was established by holding the visible length to about 1/8 in. when viewed with the naked eye under a strong crosslighting and against a dark background.

In the CIT-ORL test data of Fig. 6, the inception condition is apparently confined to steady-state cavities. The occurrence of the two types of inception cavitation had, however, been noted by Crump [2] in earlier dissolved-gas-content studies.

The test data acquired by the above procedures are plotted in Fig. 7.

In Fig. 7 Curve A is a duplication of the 1/2-in. ogive curve of Fig. 6 and is introduced for comparative purposes.

Curve B is the result of preconditioning by prolonged evacuation of the water prior to the test run. This represents a relative condition of under-saturation (atmospheric pressure datum) of dissolved gas. The test points are drawn as circles.

Curve D is the result of preconditioning the water at 1 atmosphere of pressure. This, therefore, represents a condition of approximate saturation of dissolved gas. The test points are drawn as x's.

Curve F is the result of preconditioning the water at 2 atmospheres of pressure. This represents a relative condition of gas enrichment or over-saturation (atmospheric pressure datum). The test points are drawn as squares.

Curves C and E represent other in-between conditions of pressure preconditioning. The test points are drawn as triangles and diamonds.

The numbers adjacent to the plotted test points are approximations of the nuclei concentration in parts per million by volume as calculated from the meter oscilloscope readings.

The most noteworthy features of these data are:

1. Increasing the dissolved-gas content of the water produced a marked influence on the inception of cavitation. The influence is such as to reduce the scale effects evident in the comparative tests of Fig. 6. This is in accord with the related findings of References [1] and [2].

2. For a water of given preconditioning, the inception condition appears to be influenced by the nuclei concentration of the water. Except for the scatter at the extreme left end of each curve, the data appear orderly but are in need of correlation through extension and refinement of quantitative measurements.

3. At the lower speeds or left end of each curve, the inception conditions are extremely erratic. A clue to the cause

of this erratic behavior is to be found in the sudden shift to a very high nuclei concentration as indicated by the measured values. The mechanics of this transition are in need of further clarification but are presumed to be related to critical nuclei sizing in accord with Fig. 1.

4. The basic nature of the cavity form varies at inception. In the low dissolved-gas region represented by Curves B and C, the cavity was nearly always a small steady-state cavity of abrupt appearance and disappearance. For the higher dissolved-gas curves--D, E, and F--the cavity was a transient-bubble streak. Steady-state cavities were rare in the high dissolved-gas region, but in the low-gas region a streak-bubble inception could frequently be noted prior to the appearance of the steady-state cavity. The data entries in Fig. 7, which are connected by a vertical dotted line, represent these dual inceptions.

5. The influence of the nuclei concentration in reducing previously noted scale effects appears to be most powerful at low test speeds and of diminishing influence at high speeds. This appearance is partially the result of employing a cavitation index falsely based on the assumption that vapor pressure exists in the cavity and is partially due to the complex way in which mean circuit pressure varies with velocity in a tunnel circuit.

6. Figure 7 clearly shows that a separator type of tunnel will permit an effective variation of nuclei-concentration conditions by suitable regulation of the relation between the preconditioning saturation pressure and the actual testing pressure. However, the figure does not directly indicate that the nuclei are sufficiently stable to permit tunnel tests of a reasonable duration. In this respect, it is of considerable significance that the numerous data points for Curve B span a test period of 150 minutes and the data of Curve E span a period of 75 minutes. The data points were mixed in sequence during these periods. It would appear that the control procedure provides adequate stability for the usual type of tunnel test.

7. Earlier studies of dissolved-gas content [11] conducted in the 6-in. St. Anthony Falls tunnel prior to the separator modification established that the dissolved-gas content could be reduced to a minimum of about 10 parts per million by weight and increased to a maximum of about 28 ppm. These values assume significance if it is recognized that the saturation value at atmospheric pressure is approximately 25 ppm by weight or about 20,000 ppm by volume. If these earlier values are compared with the range from 10 to about 200 ppm by volume of nuclei concentration (as measured in the current tests), it is apparent that the nuclei concentration is a relatively minute quantity. These values may also shed light as to why the CIT-ORL inception tests [10], the results of which are summarized in Fig. 6, failed to show significant changes with variation of gas content. The gas content in the CIT-ORL tests was varied from about 7 to 12 ppm by weight or, in other words, the highest value represented only about 50 per cent of normal saturation. Failure to show gas-content effects in the CIT-ORL tests may also be attributed to the high preconditioning pressures to which both tunnels subjected the water. Analysis [7] of the combined dynamic and static pressure in the CIT tunnel indicates that the average circuit pressure varies from about 3 to 7 atmospheres depending on speed. The ORL tunnel, being without a reabsorber, did not possess circuit pressures as high as the CIT tunnel but was stated [10] to have been manipulated to subject the water to 3 atmospheres of pressure for 10 minutes prior to each run. Since Strasberg [5] found that even 1 atmosphere of preconditioning pressure produced substantial changes in the critical cavitation-inception pressure, it seems quite reasonable that the gas-content effects appeared negligible for the limited CIT-ORL tests. The combined effect of a low dissolved-gas content and high preconditioning pressure probably also accounts for the fact that Curve A of Fig. 7 is lower than Curve B.

VII. CONCLUSIONS

The facilities and procedures described herein have been subjected only to limited tests and the resulting data are accordingly fragmentary. It is intended that these studies be extended with a view toward confirmation, but pending such additional studies, the following tentative conclusions appear to be in order:

1. A conventional water tunnel can be provided with a gas-bubble separator system which will permit the tunnel to be effectively operated with a water of controlled high nuclei concentration.

2. The nuclei concentration of a water (for concentrations above 0.1 ppm by volume) can be measured with great sensitivity by measuring the ratio of the acoustic velocity of the test water to the acoustic velocity of water without nuclei.

3. Cavitation-inception tests using water with a high concentration of air nuclei are significantly different from tests using low concentrations. Scale effects previously noted in other tunnel studies were found to be substantially decreased in the current tests which used high nuclei concentrations.

4. Cavitation inception in the form of steady-state cavities of abrupt appearance and disappearance tends to occur in water having a relatively low nuclei concentration.

5. Cavitation inception in the form of transient bubbles tends to occur in water having a relatively high nuclei concentration.

6. Hysteresis effects associated with the appearance and disappearance of inception cavitation resulted from the use of waters of low nuclei concentration and were not apparent in waters of high nuclei concentration.

7. The portion of the gas content of a water which is in the form of nuclei is probably much more influential in cavitation-inception processes than the portion in the dissolved

form, despite the fact that the mass of the former is probably less than 0.5 per cent of the mass of the latter.

8. The maintenance of a high nuclei concentration in the tunnel water required maintenance of a high dissolved-gas content.

9. The control of water-tunnel cavitation inception by preconditioning the nuclei concentration of the water appears definitely to improve certain previously noted scale effects. The improvement was greatest for the low speeds common to propeller tunnels. For body studies in a high-speed stream, the control appears less effective. The loss in effectiveness is presumed to be associated with the high circuit pressures that inherently attend high test-section speed. It is possible that use of even higher dissolved-gas contents might also improve the effectiveness at high speeds.

10. It would appear that gas-content instrumentation yielding data regarding the size of nuclei might better characterize cavitation-inception conditions than instrumentation yielding either dissolved- or free-gas volume. The gas volumes may eventually prove to be significant factors in studies of extensive cavitation or performance breakdown but are believed to be of lesser importance than nucleus size in inception studies.

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[11] Olson, R. M. Cavitation Testing in Water Tunnels. University of Minnesota, St. Anthony Falls Hydraulic Laboratory Project Report No. 42, December 1954. 49 pages.

FIGURES

(1 through 7)

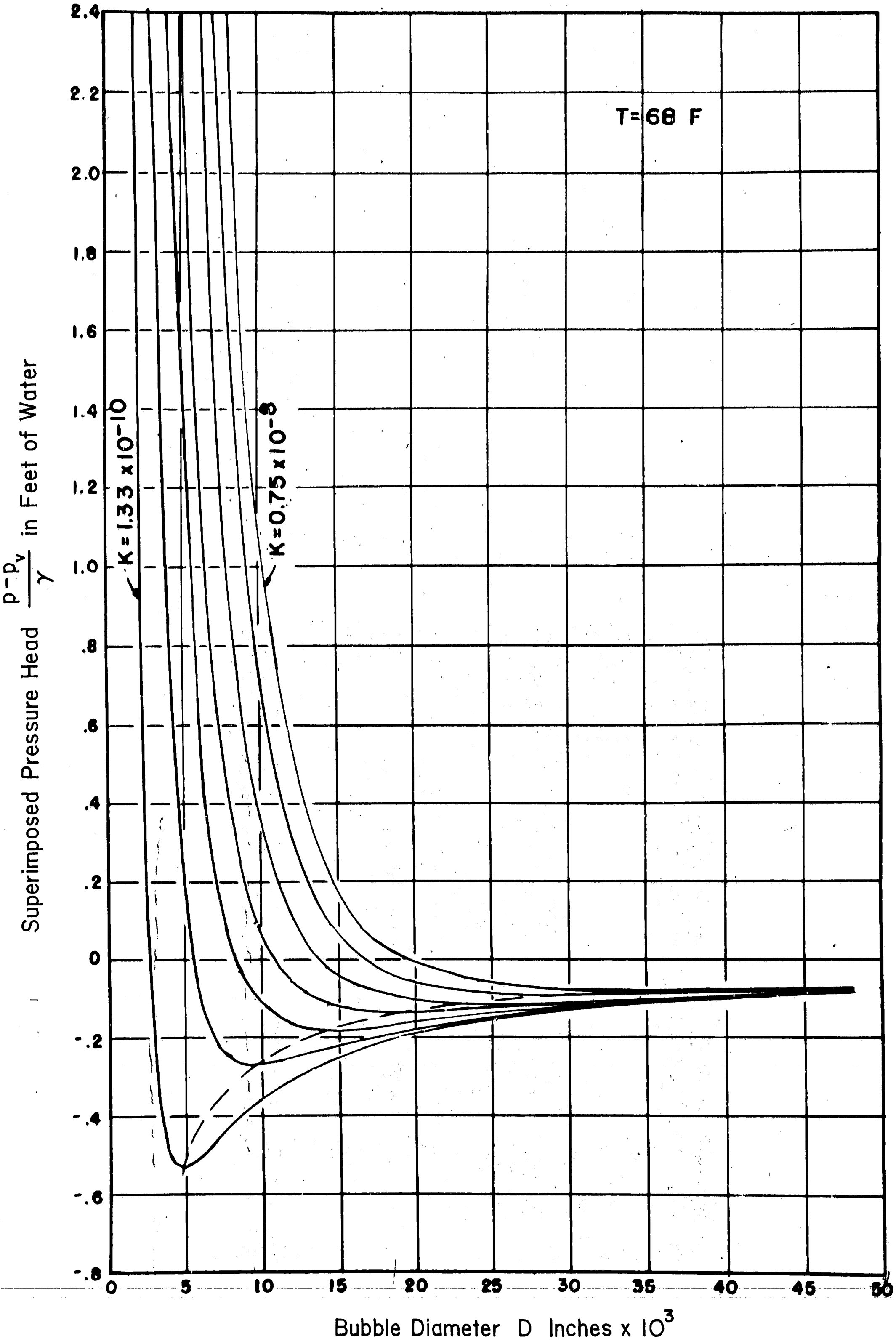


Fig. 1 - Relation Between Bubble Size and Superimposed Pressure as Influenced by Gas Content of the Bubble (From Reference [4])

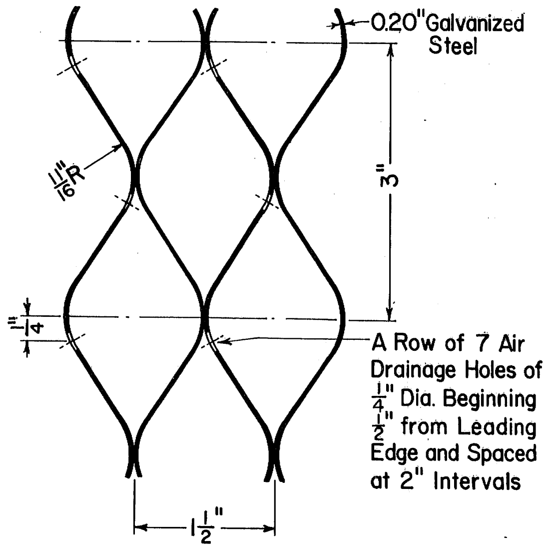


Fig. 2 – Configuration of Gas-Separator Tube Employed in Tunnel Tests

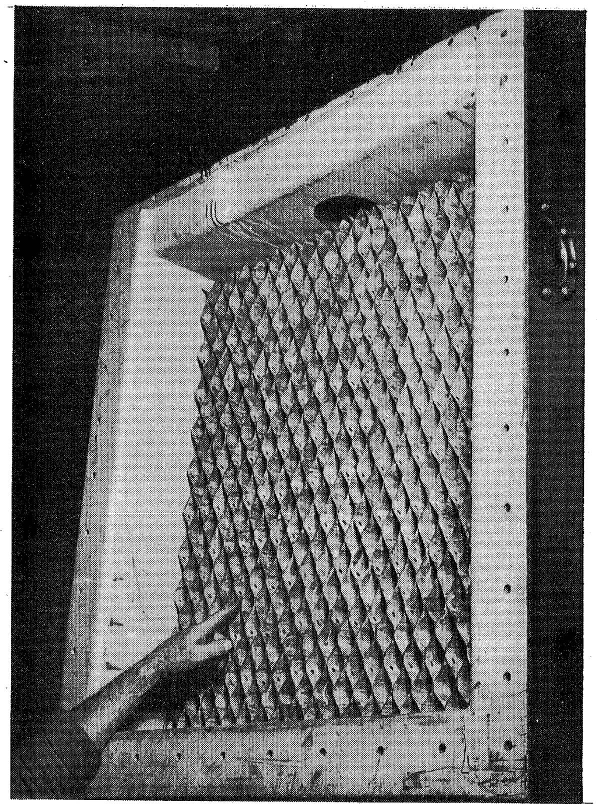


Fig. 3 – General Arrangement of Separator Tubes in Tunnel Cross Section as Viewed From Upstream

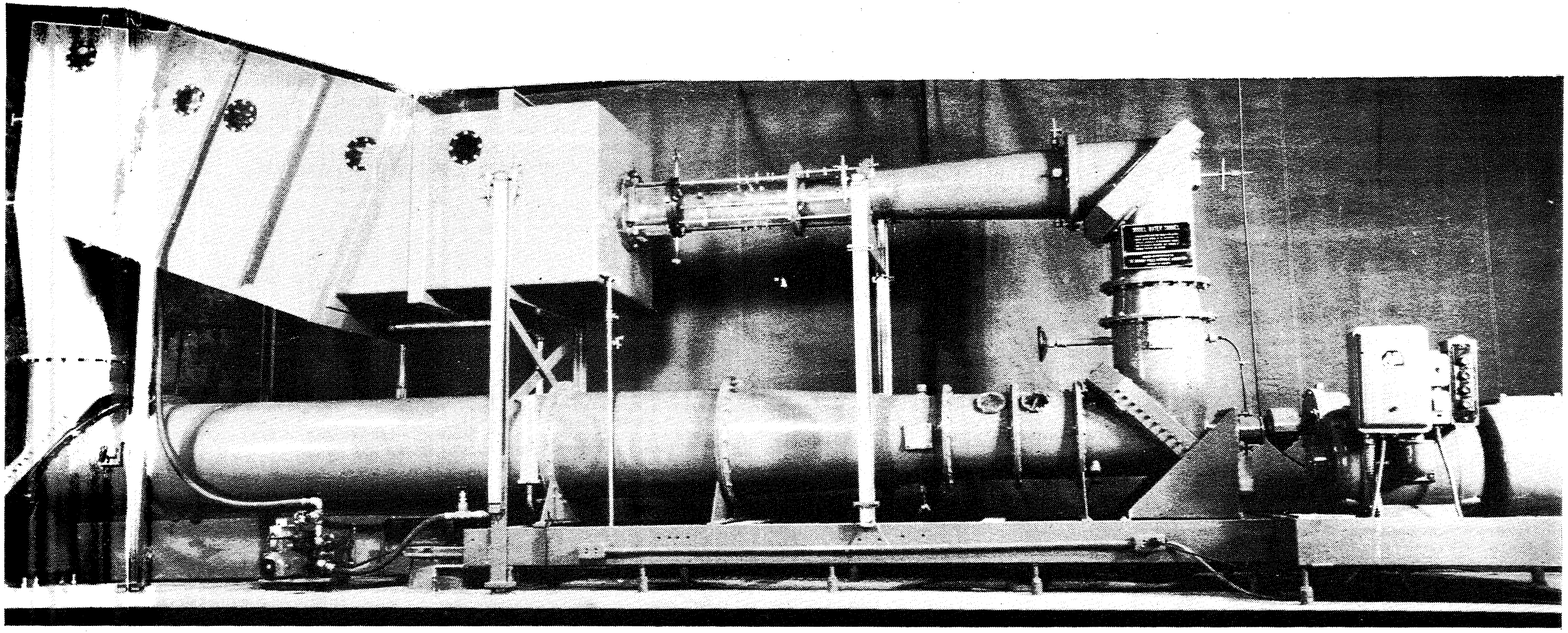
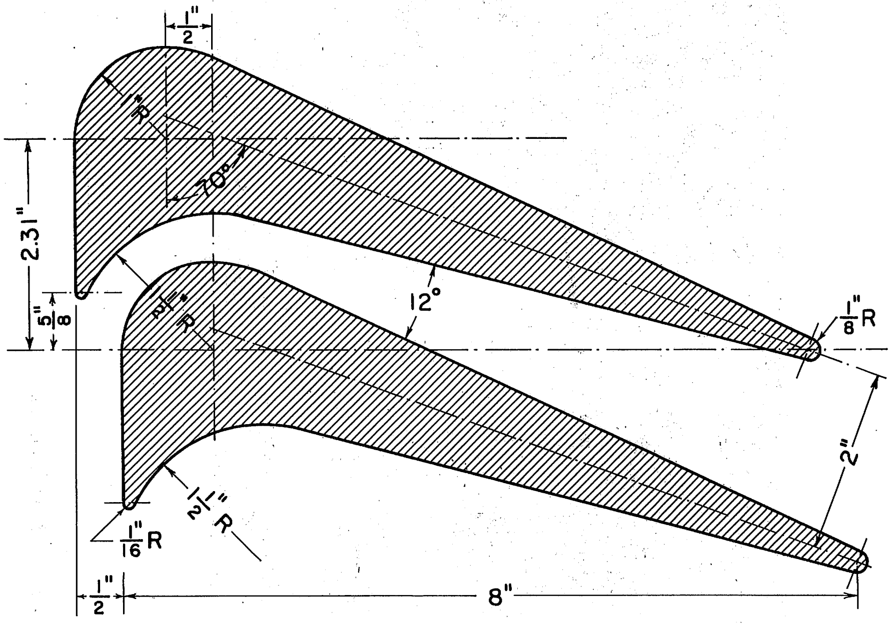
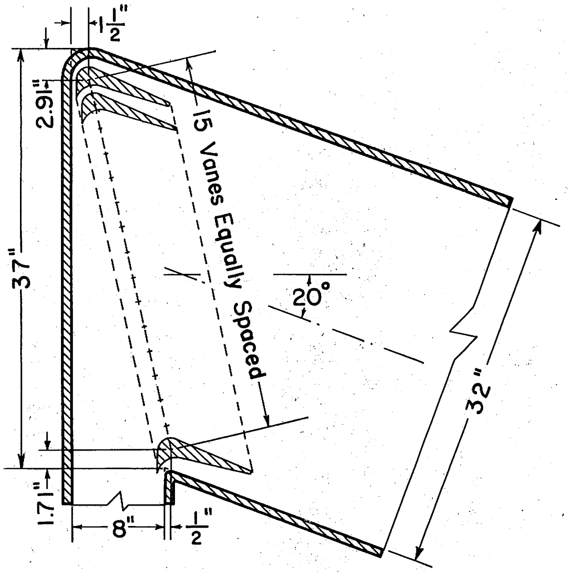


Fig. 4 – The 6-in. Water Tunnel with Gas-Separator Modifications



Vane Detail



Elbow Assembly

Fig. 5 - Arrangement of the Two-Dimensional Combined Turning Vane and Flow Diffuser

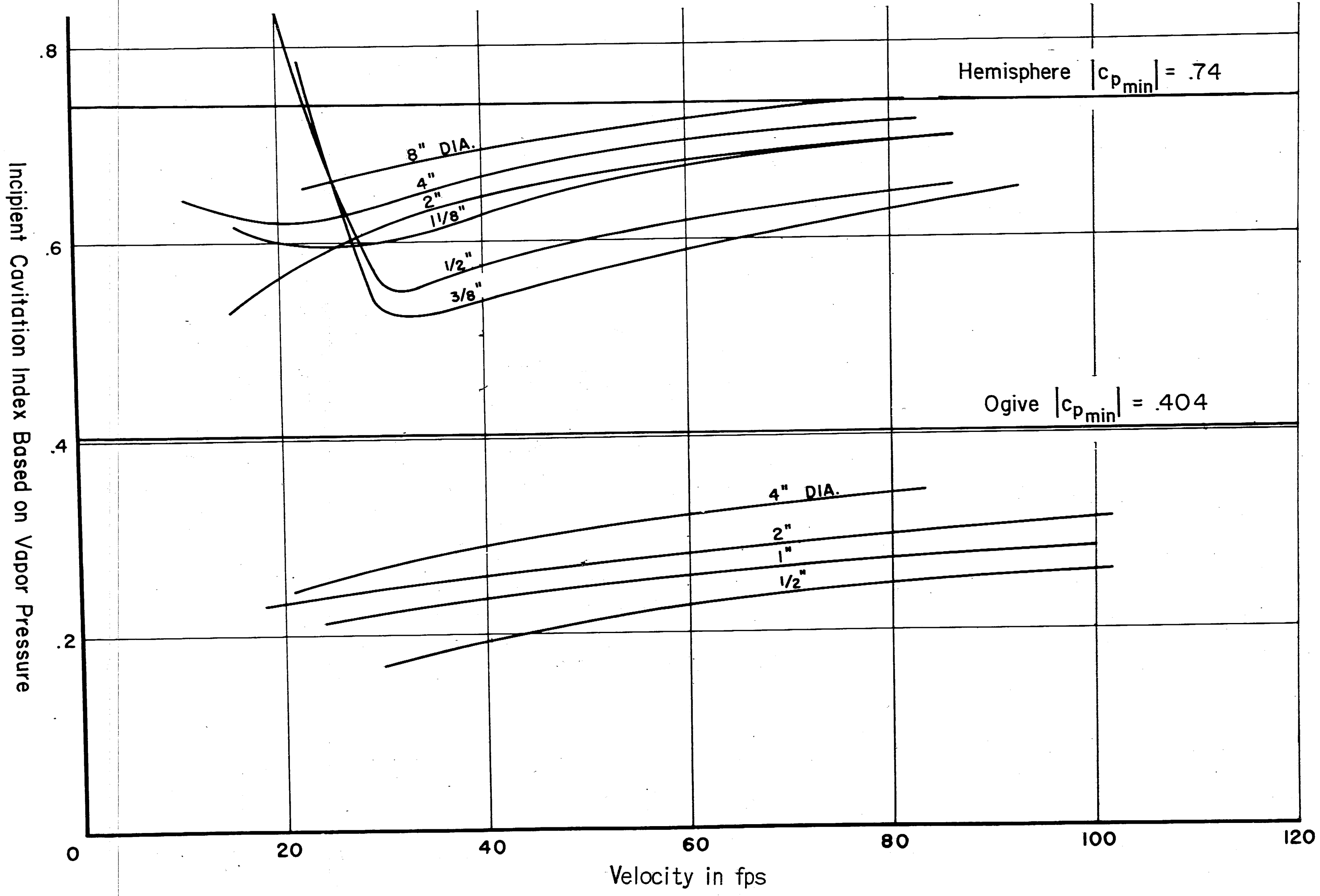
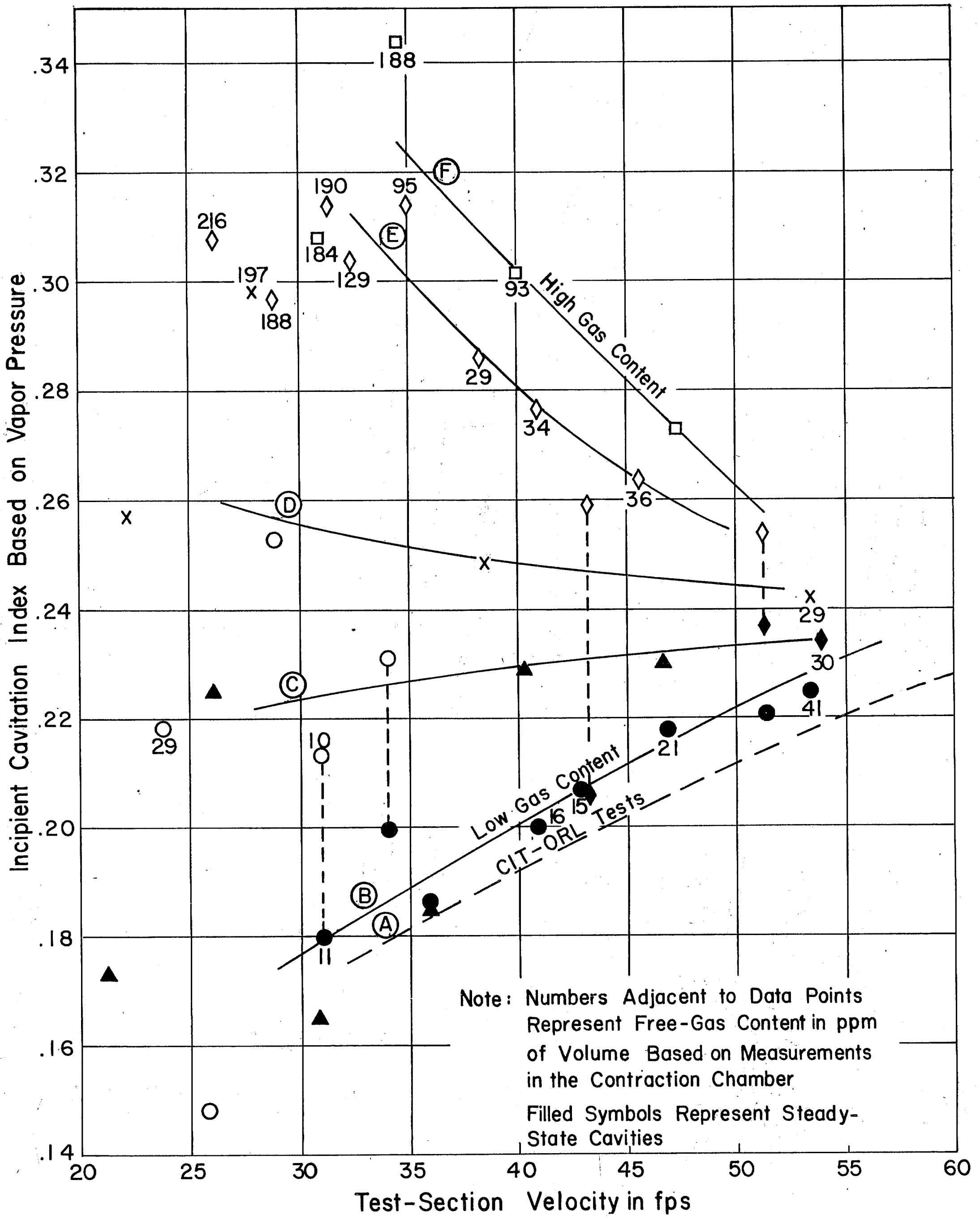


Fig. 6 – Relation Between Incipient Cavitation Index and Test-Section Velocity for Various Sizes of Hemisphere and 1.5-Caliber Ogive Head Forms (From Reference [10])



Note: Numbers Adjacent to Data Points Represent Free-Gas Content in ppm of Volume Based on Measurements in the Contraction Chamber

Filled Symbols Represent Steady-State Cavities

Fig. 7 - Relation Between Incipient Cavitation Index and Test-Section Velocity for an 0.5-in.-Diameter, 1.5-Caliber Ogive Head Form as Influenced by the Gas Content of the Water

APPENDIX A

A SONIC METHOD OF MEASURING
THE CONCENTRATION OF
UNDISSOLVED GAS NUCLEI IN WATER

I. INTRODUCTION

Various sonic methods might be used to detect undissolved gas nuclei in water. The reverberation decay rate at ultrasonic frequencies and the intensity of ultrasonic sound necessary to initiate visible cavitation were both used to detect gas-bubble nuclei by Strasberg [A-1]*. Wood [A-2] indicates the effect of gas bubbles on the velocity of sound in gas-water mixtures, and this suggested a third method wherein the nuclei concentration itself could be determined.

The third method was developed to measure low concentrations of gas nuclei in water. Preliminary measurements were initially made in open water at rest and were followed with tests in moving water in a 6-in. water tunnel. This appendix describes this work.

II. THEORY

The acoustic velocity c in any homogeneous medium is given in terms of its elasticity E and its density ρ as

$$c = \sqrt{E/\rho} \tag{1}$$

Let subscripts m, w, and a refer to mean property values, those for water, and those for gas, respectively; let x be the proportion of gas by volume; then the mean density is

$$\rho_m = x\rho_a + (1 - x)\,\rho_w$$

The mean elastic modulus can be calculated by treating its reciprocal, the compressibility, in a like manner. Thus,

---

*Numbers in brackets with prefix A refer to the List of References on p. 44.

$$\frac{1}{E_m} = \frac{x}{E_a} + \frac{1 - x}{E_w}$$

and

$$E_m = \frac{E_a E_w}{xE_w + (1 - x)\, E_a}$$

Experimental verification of the result

$$c = \sqrt{E_m/\rho_m}$$

at a pressure of 1.1 atmospheres and a temperature of 80 F reported by Silberman [A-3] indicates that at the low gas concentrations to be expected in tunnel operations (below 1 per cent by volume), the phenomenon is isothermal rather than adiabatic. The elastic modulus for the gas then becomes equal to the absolute pressure p_a.

The ratio of sound velocity in a nonresonant gas-water mixture to that in pure water becomes

$$\frac{c_x}{c_{x=o}} = \sqrt{\frac{p_a \rho_w}{[xE_w + (1 - x)\, p_a]\ [x\rho_a + (1 - x)\, \rho_w]}} \qquad (2)$$

which is always less than unity and depends primarily on the reduction in the elastic modulus at low gas concentrations. (The mixture is more elastic or more compressible than pure water.) For gas concentrations less than 10^{-3}, this velocity ratio becomes

$$\frac{c_x}{\boxed{c_o}} \approx \sqrt{\frac{p_a}{xE_w + \underbrace{(1 - x)}\, p_a}} \simeq \sqrt{\frac{1}{1 + x(E \div P_a)}} \qquad (3)$$

because $x\rho_a << (1 - x)\, \rho_w$ and $(1 - x)\, \rho_w \approx \rho_w$.

This velocity ratio is plotted for a range of gas concentrations from 10^{-7} to 10^{-2} at a pressure of 15.94 psia and a temperature of 80 F in

Fig. A-1. The confirming measured values reported in Reference [A-3] are indicated. The lesser agreement between measured and calculated values at the lower gas concentrations is attributed to the difficulty in making direct measurements of the extremely small gas volume contained in a given volume of a mixture.

A. Effect of Pressure

The acoustic velocity in a nonresonant gas-water mixture is reduced either by an increase in gas concentration (at the low values of interest) or by a reduction in pressure of the mixture. The effect of reduced pressures on amplifying the reduction of acoustic velocity, as shown in Fig. A-2, is especially advantageous for measurements in water tunnels where cavitation testing is usually done at subatmospheric pressures.

For example, if there are 10^{-5} parts of entrained gas by volume in a water-tunnel test section at a pressure nearly atmospheric (32-ft pressure head), the velocity ratio is 0.90, whereas this same gas concentration at an absolute pressure head of 2 ft results in a velocity ratio of 0.46. Very small concentrations of gas nuclei are therefore more easily detected and measured as the lower pressures more commonly associated with cavitation testing in water tunnels are approached.

B. Effect of Temperature

Temperature affects the elastic modulus of water slightly. In the range from 60 F to 100 F, the variation is about 2.9 per cent from the mean value at 75 F, the temperature at which Fig. A-2 applies. Calculations indicate that for temperature variations in this 60 F to 100 F range, the velocity ratio given by Eq. (3) will differ from that plotted in Fig. A-2 by less than 1.5 per cent at gas concentrations less than 10^{-4}, and by less than 1 per cent for gas concentrations less than 10^{-5}. These statements are valid for pressures above 0.2 atmospheres.

C. Measuring Frequencies

The preceding theory is valid only if the frequency of the sound transmission is nonresonant for the gas bubbles involved. In order that these gas-bubble nuclei be nonresonant, the impressed frequencies should be no greater than one half the resonant frequency of the bubbles [A-3].

(Frequencies well above resonance may also be useful but were not investigated.) These resonant frequencies f_r are approximated by [A-4]

$$f_r = \frac{1}{\pi D} \sqrt{3kp/\rho_w}$$

where D is the diameter of the gas nuclei, k is the specific heat ratio for the gas (1.4 for air), p is the average absolute pressure, and ρ_w is the water density--all in consistent units.

The interrelationships between the pressure, size of nuclei, and resonant frequency are shown in Fig. A-3. Superimposed on this family of curves is another group relating the usual cavitation number (based, in this instance, on a vapor-pressure head of 0.9 ft of water) with the test-section velocity and pressure for a water tunnel. From this graph can be determined the non-resonant frequency at which the acoustic velocity in a gas-water mixture may be measured. For example, if tests at 40 fps at a cavitation number of 0.5 are to be run, the test-section pressure head is 13.2 ft. If the largest nuclei present are 0.008 inches in diameter, their resonant frequencies are 23.4 kcps (interpolation between frequency curves is linear), and acoustic measurements should be made at a frequency of 11.7 kcps or less in order that resonance be avoided. Equation (3) will then apply.

III. BUBBLE SIZES OF INTEREST

For the proper selection of impressed frequency for a nuclei-concentration instrument, it is necessary to know the maximum size of nuclei to be expected in the test section of the cavitation tunnel.

Currently there is a scarcity of information regarding the size of nuclei essential to the promotion of cavitation and what information is available is largely conjectural. In addition, there is a considerable question as to the actual size that can be maintained in the tunnel flow under practical operating conditions and pressure variations. The selection of a limiting frequency of transmission is therefore complex.

Available information [A-1 and A-5] and laboratory experience with gas-nuclei-and-water mixtures where the nuclei were below 0.006 to 0.008 inches in diameter indicates (further conjecture) that it is unlikely that nuclei or bubbles larger than 0.010 inches in diameter would (or should) be present in the test section of a water tunnel. If test-section velocities are 30 fps or more, Fig. A-3 indicates that resonant frequencies will rarely be below 15 kcps. Thus a 7.5-kcps measuring frequency was believed to be satisfactory.

IV. METHOD OF MEASUREMENT

The acoustic velocity in water or in a nuclei-and-water mixture was determined by measuring the transit time of sound pulses between a transducer and a pickup. Actually, the transit time in a mixture was compared with that in pure water to give the velocity ratio of Eq. (3). The gas-nuclei concentration was then obtained from Fig. A-2.

A. Transducers

Two pure-nickel-core magnetostriction transducers were used, each having a natural frequency in the audio range (15 and 7.5 kcps, respectively). This type of transducer was chosen because of its excellent coupling qualities both in preliminary tests in direct contact with water and in its adaptability to water-tunnel use. The transducers were designed from data given in Reference [A-6] and were made at the Laboratory because they were not available commercially. Both were driven at a repetitive rate variable from about 6 to 30 pulses per second by a circuit shown in Fig. A-4.

B. Pickups

Pickups included a Brush Measurement Hydrophone, Model BM-101A, with a frequency range of 0.1 to 100 kcps and a barium titanate ceramic crystal. This crystal was 1/4 in. long and 1 inch in diameter with a natural frequency of about 500 kcps.

C. Oscilloscope and Oscillogram Interpretation

An oscilloscope with a trigger sweep is required. In these tests a Dumont 208 oscilloscope with an added trigger sweep was used for transit-time measurements.

For direct measurements of the velocity ratio given in Eq. (3), the length of the oscilloscope traces (Figs. A-5 and A-6), L_o and L_x, were measured, since they were direct indications of transit time of a sound wave between transducer and pickup. The "knee" at L_o became more rounded (and less easily located with precision) as the concentration of nuclei increased. The sinusoidal portion of the oscillogram did not expand but merely shifted in position with a change in transit time, and therefore $L_x' - L_o'$ was measured directly (with more precision than $L_x - L_o$) and was used to determine the increase in L_o to L_x. Then, if T refers to transit time, for a fixed path length from transducer to pickup,

$$\frac{c_x}{c_o} = \frac{T_o}{T_x} = \frac{L_o}{L_x} = \frac{L_o}{L_o + (L_x - L_o)} = \frac{L_o}{L_o + (L_x' - L_o')}$$

For velocity ratios below 0.9, this velocity ratio could be determined with a maximum error of about ±0.01.

For velocity ratios near unity, a delay circuit was set up, such that the increase in transit time of a sound pulse between transducer and pickup was indicated directly on the oscilloscope. This circuit consisted of a ZA-8886 plug-in unit (Electronic Engineering Company of Los Angeles) as indicated in Fig. A-4. Typical oscillograms are shown in Fig. A-7.

For example, if the first circuit (without pulse delay) were used, and the oscillograph trace increased 1.8 units ($L_x' - L_o'$) from an initial length of 30 units (L_o) as a result of adding a certain concentration of nuclei, then

$$\frac{c_x}{c_o} = \frac{30}{30 + 1.8} = 0.943$$

and the nuclei concentration could be obtained from Fig. A-2 for the appropriate ambient pressure. The sensitivity in this instance is rather poor.

If the delay circuit were used, the sensitivity and accuracy would be much better. Calibration in this instance is readily illustrated if the transducer and pickup are immersed in water free of nuclei. An increase in spacing between transducer and pickup increases the transit time of a sound pulse between them just as would the presence of nuclei. For example, suppose the spacing between transducer and pickup were increased from 6.00 to 6.60 in., which results in a lengthening of the oscillograph trace of 20 units. Then, if the transducer-pickup spacing is set at 6.00 in. and the addition of nuclei lengthens the oscillograph trace 12 units ($L_x' - L_o'$ of Fig. A-7), the ratio of sound velocity in the mixture to that in pure water becomes

$$\frac{c_x}{c_o} = \frac{1}{1 + \left(\frac{6.60 - 6.00}{20}\right) 12} = 0.943$$

The increase in sensitivity with the delay circuit is more than six-fold in this example.

V. PRELIMINARY MEASUREMENTS IN OPEN WATER AT REST

The instrumentation was checked out and the sensitivity of the method was initially confirmed by suspending the transducer and the Brush hydrophone in water contained in a long glass-sided open tank 6 in. wide and about 12 in. deep. Small and well-dispersed nuclei were supplied to the tank by recirculating some of the water through a pump with a 3/4-in. gate valve in the discharge line adjusted for a 40- to 50-psig discharge pressure. Nuclei less than 0.008 inches in diameter resulting from (it is believed) valve cavitation were dispersed throughout the water in the open tank.

When the nuclei were being supplied at a constant rate, velocity ratios (Eq. 3) as low as 0.5 were recorded. (This same value was also obtained in the water-tunnel tests.)

A number of measurements were made to check the response of the measuring system in quasi-steady states of gas-water mixtures in an open tank. Nuclei were supplied to the water between and surrounding the transducer and pickup, and when this supply was shut off, it was expected that these nuclei would disappear by gravitating upwards or by dissolving into the water at a continuous (though not constant) rate. Their presence was measured by comparing the acoustic velocity at various instants with the acoustic velocity when the nuclei were considered to have disappeared. Typical curves are shown in Fig. A-8.

The sensitivity of the measuring system was checked with the smooth end of the transducer core and the barium titanate ceramic crystal pickup placed in direct contact with the opposite outer surfaces of the glass walls of the tank. Coupling was improved by adding a drop of castor oil to the glass surfaces. Nuclei were generated in the water as before, and the amplitude and lengthening of the oscilloscope trace indicated excellent sensitivity. This was considered a significant point. It indicated that a magnetostriction transducer and a simple ceramic pickup could be mounted in contact with the external surfaces of a water-tunnel test section. This would preclude any interference with the internal boundaries of the tunnel and would permit measurements to be made with no disturbance to the flow.

VI. ADAPTATION TO WATER-TUNNEL MEASUREMENTS

To confirm the above indications, the transducer and pickup were mounted externally near the beginning of a closed-jet test section of the 6-in. water tunnel at the Laboratory. Two diametrically opposite flat surfaces were milled in this acrylic resin plastic piece, and the transducer and pickup were mounted in good contact with these flat surfaces, castor oil being used at the interface to improve coupling.

Initial concern regarding the effect of tunnel vibration was dispelled when the oscillograms showed good wave form. At only one tunnel speed did the wave form become unstable, and this was due to the vibration of a nearby mounting strut.

The system showed good response to the addition of nuclei into the tunnel water, and further tests are described in the main body of this report.

Consideration should be given to possible interference from sound pulses traveling circumferentially through the tunnel walls to the pickup in addition to a diametrical path. In the mounting described, this occurred at a velocity ratio (Eq. 3) of about 0.5 to 0.6.

VII. SUMMARY

Although the nuclei-concentration meter described herein has not been tested under a range of conditions which clearly establishes its role in water-tunnel programs, it is believed that some significant conclusions may be drawn:

1. The method of measuring the velocity of sound in a mixture of gas nuclei and water described herein was demonstrated both in open water at rest and in a water tunnel with flowing water and with a flowing water-nuclei mixture and proved to be a practical and accurate method of determining the concentration of minute gas nuclei in water.

2. The somewhat unconventional use of a magnetostriction transducer in the audio range permits the installation of a workable nuclei-concentration meter on a water tunnel with no interference with the flow through the tunnel.

3. The principle of operation of this meter permits essentially instantaneous indications of the nuclei concentration.

4. It is believed that the method is very promising, and additional instrument development work should be pursued. Such development will contribute materially to studies of the influence of nuclei concentration on cavitation and to eventual control in a water tunnel.

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[A-4] Anonymous. The Physics of Sound in the Sea. Summary, Technical Report of Division 6, NDRC, Vol. 8. 1946.

[A-5] Daily, J. W., and Johnson, V. E., Jr. "Turbulence and Boundary Layer Effects on Cavitation Inception from Gas Nuclei." Transactions of the American Society of Mechanical Engineers. November 1956. 19 pages.

[A-6] Anonymous. Design of Nickel Magnetostriction Transducers. The International Nickel Co., Inc.

FIGURES

(A-1 through A-8)

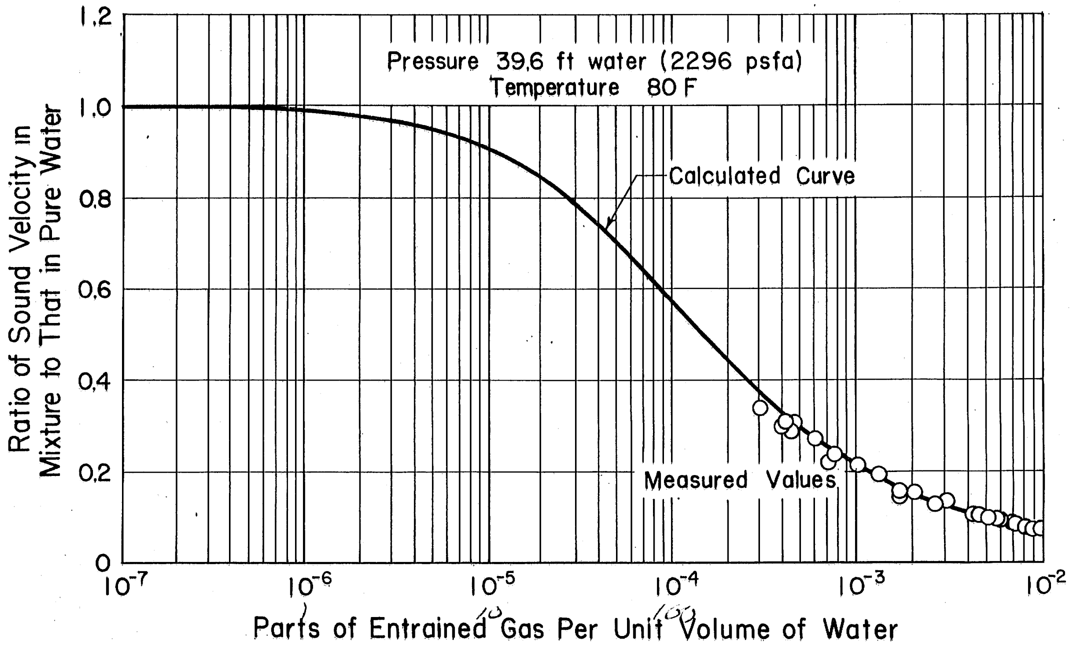

Fig. A-1 – Reduction in Acoustic Velocity in Gas-Water Mixtures

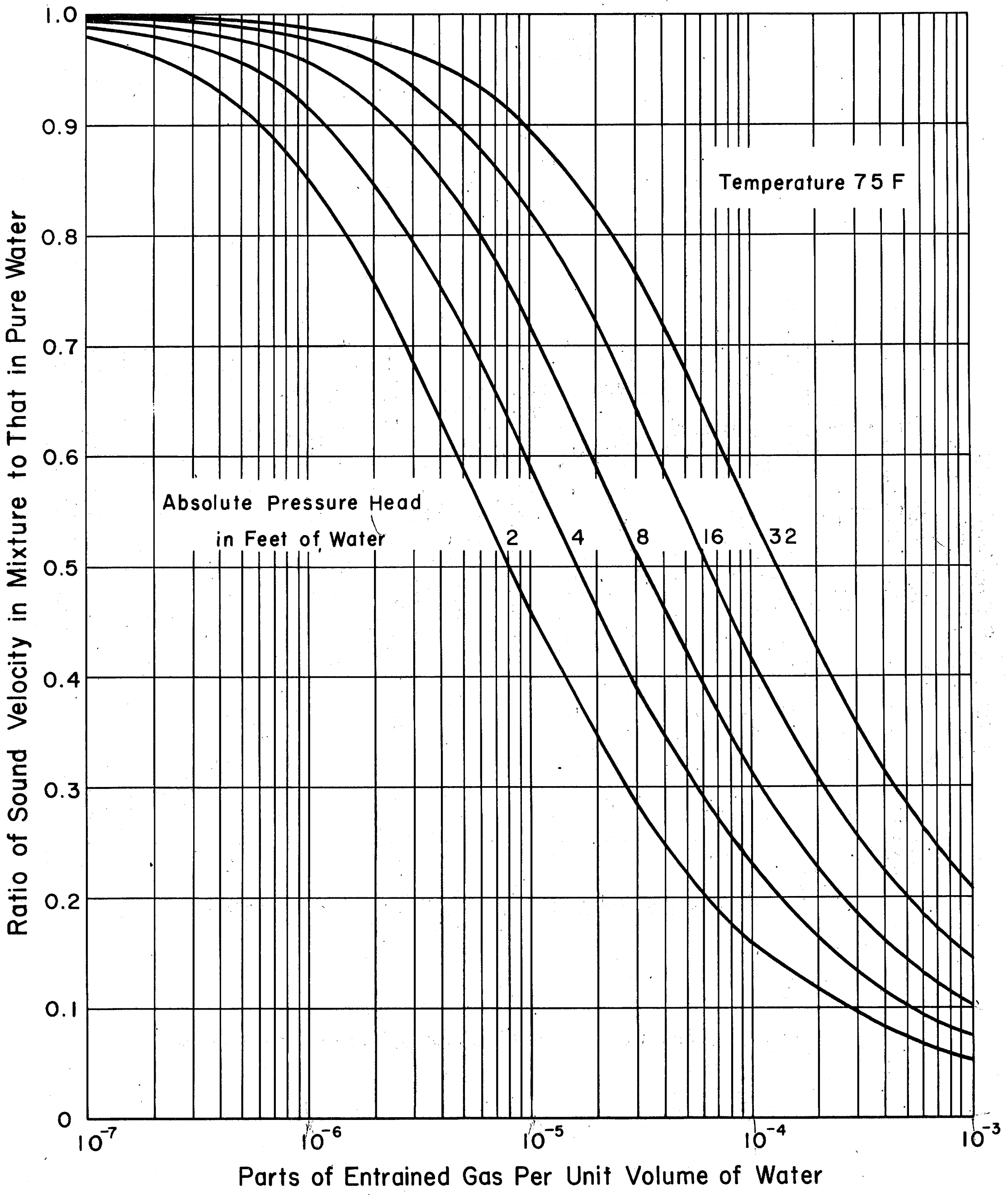

Fig. A-2 – Effect of Pressure on the Reduction in Acoustic Velocity in Gas-Water Mixtures

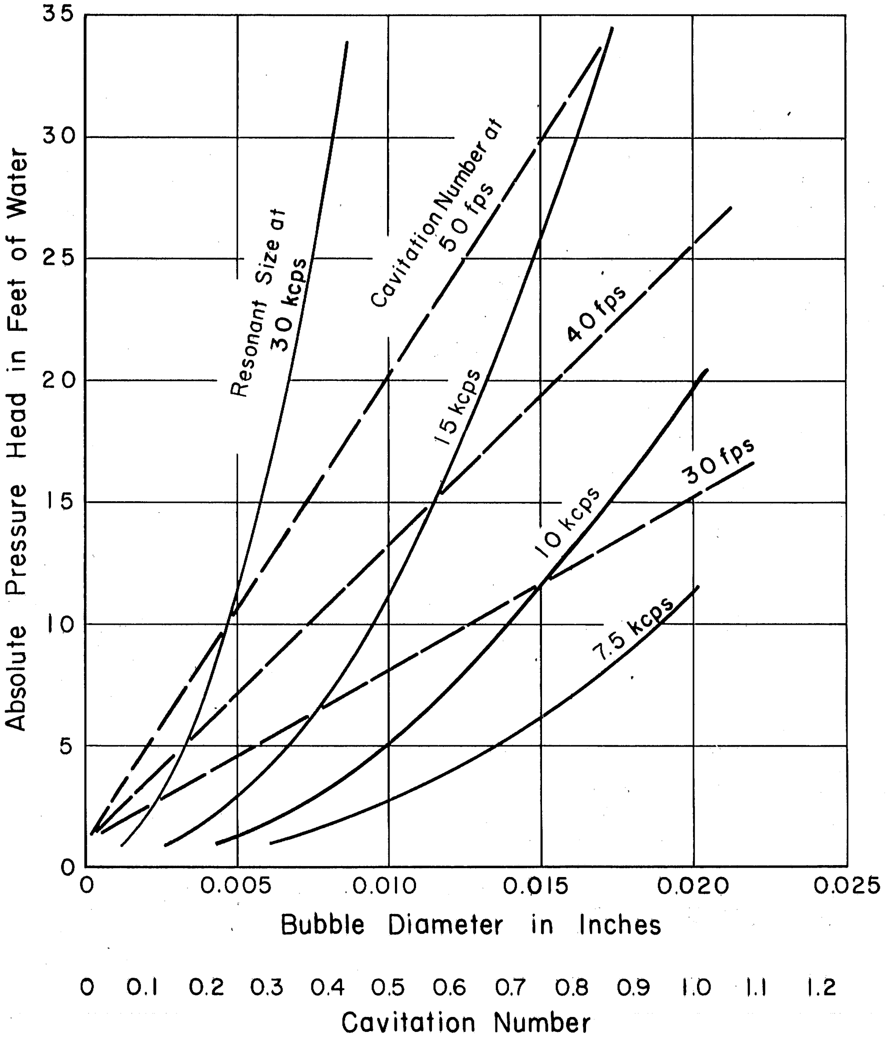

Fig. A-3 – Resonant Bubble Size at Various Frequencies and Water-Tunnel Test-Section Conditions for Various Cavitation Numbers

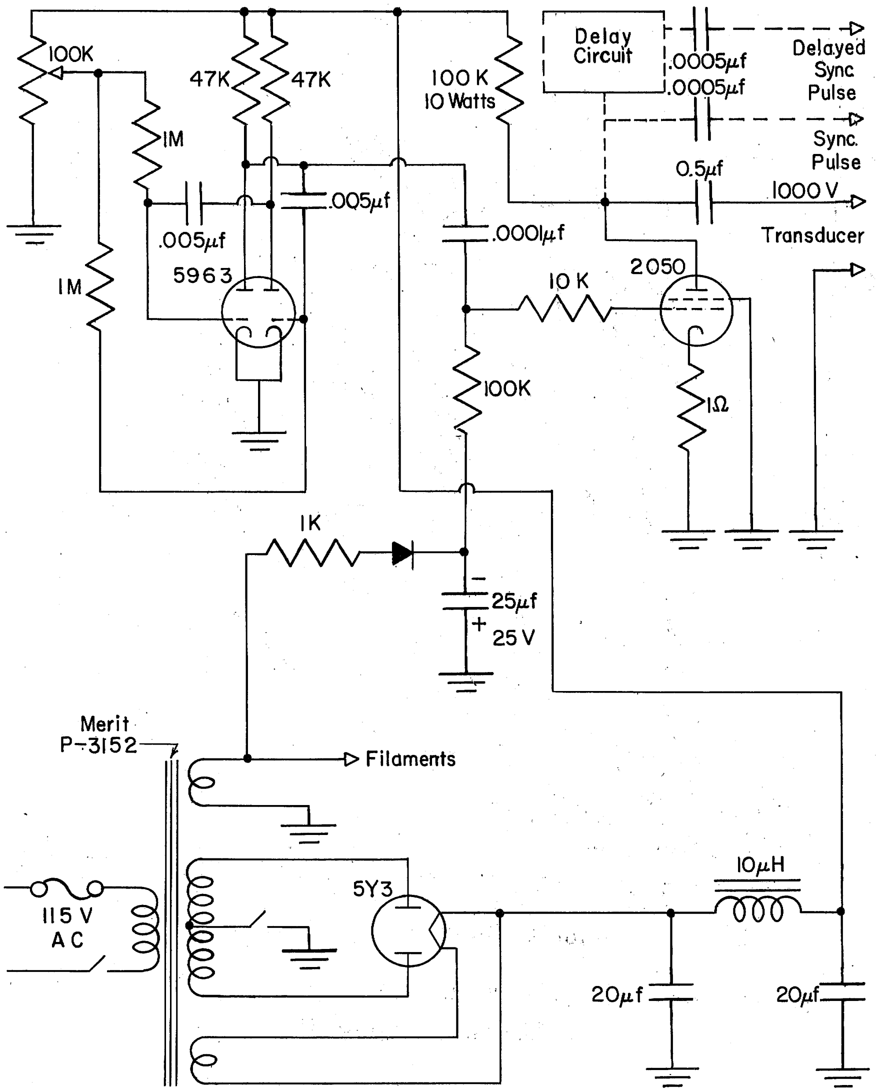

Fig. A-4 – Pulse Circuit

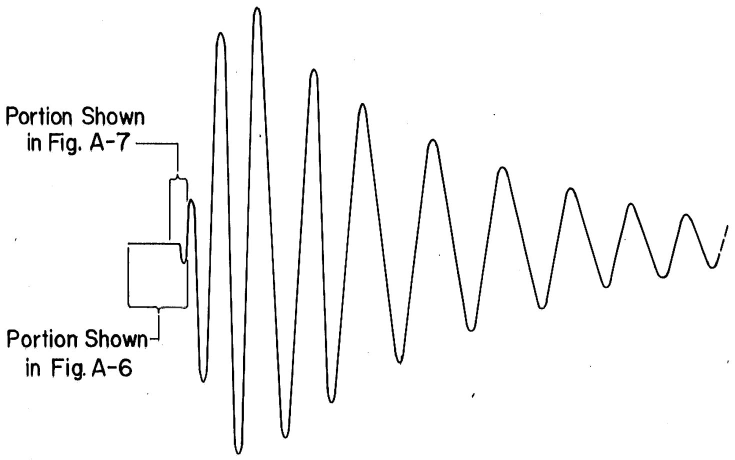

Fig A-5 – Oscillogram of Wave Form

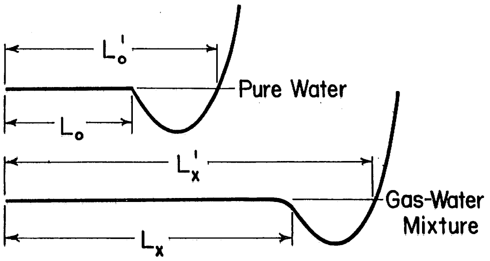

Fig. A-6 – Oscillograph Traces for Direct Measurement of Transit Time of Acoustic Wave

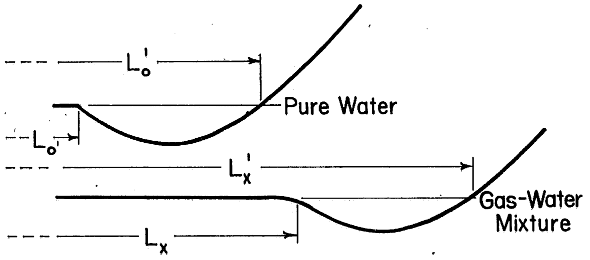

Fig. A-7 – Oscillograph Traces with Delay Circuit

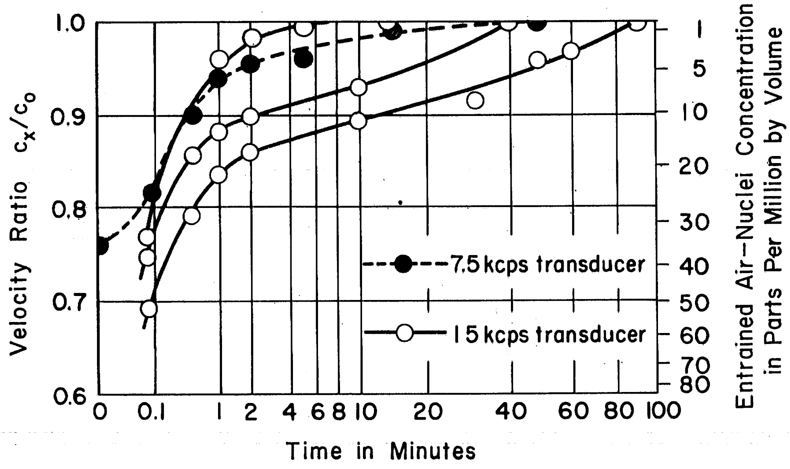

Fig. A-8 – Measured Gas Concentration in Nuclei in Open Water at Rest at Various Instants After Supply of Nuclei Was Cut Off

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