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OBSERVATIONS AND MEASUREMENTS OF FLOW IN A CAVITATING VENTURI

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PREFACE

This report is a re-issue of Internal Report No. 6, Project 03424 (Summarization of 03424-2-T and 03424-3-T) as a Project Technical Report. It was felt that the material contained herein is of sufficient interest to substantiate this re-issue.

ABSTRACT

This report presents observations and measurements on the flow of water in geometrically similar cavitating venturis. It discusses the general nature of such flow, and presents measurements which are correlated in terms of non-dimensional parameters. It is shown that cavitation number correlates fairly well with Reynolds' number while venturi loss coefficient does not. It is suggested that a true correlation will include Reynolds' number, but that other dimensionless groupings will also be required.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following personnel who had a significant part in the studies leading to this report: A. Ahles, Wm. Beckman, E. Brower, E. Flanigan, P. Houtman, S. Peres, E. Rupke, M. Robinson, J. Schmidt, J. Summers, and A. Travers.

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I. INTRODUCTION

Cavitation is an important phenomenon from the viewpoint of its effect upon the fluid-dynamic behavior of a flowing system and also its effects relating to the damaging of materials. Important present-day technological applications involve cavitation in fluids other than water, and often at depressed or elevated temperature and/or pressure. The present project is an effort to investigate this phenomenon in fluids other than water (specifically liquid metals), and to relate the data so obtained to water. To accomplish this result, a small tunnel facility, capable of handling liquid metals, and including a venturi test section, has been constructed.

In order to provide a meaningful basis for comparison of liquid metal cavitation data with that applying to water, it was first necessary to obtain as complete an understanding as possible of the phenomena in this particular facility with water. It was soon apparent that departures from ideal theory and from prior expectations were considerably more significant with water than had been anticipated, so that an extensive investigation using water was necessary. This paper is concerned with the observations and measurements made in the water investigation.

In some cases the measurements are less precise than might be desired. This is a result of the fact that the design of the facility was compromised in many ways to allow operation with liquid metals at high temperatures. However, the data are of sufficient precision that the various results discussed are statistically significant.

II. GENERAL DESCRIPTION OF FLOW

Generally, the flow in the cavitation region of a cavitating venturi is characterized by a jet, more or less completely liquid, surrounded by a more or less vaporous region.[1,2,3,4] Because of the cylindrical throat (Figure 1) of the venturis used in the present tests, the minimum pressure, in the absence of cavitation, occurs at the entrance to the diffuser. If the streamlines were to follow the wall of the venturi at the diffuser entrance, a radial pressure gradient toward the wall would be necessary. This cannot exist if the pressure at the diffuser entrance is close to vapor pressure, so that separation is to be expected at this point, giving the central free-jet flow pattern. At a certain axial position in the diffuser, depending upon the pressure maintained at the diffuser discharge, the vaporous region terminates, and is replaced by a complete liquid flow. The region of termination is characterized by a relatively abrupt pressure rise, analogous to a hydraulic jump or condensation shock (i.e., standing wave).

Figure 2 shows two photographs of such flow. The first is from a two-dimensional venturi,[1] and the second from the present circular venturi with an inserted impact tube in the stream. This latter picture is included to show the general nature of the flow, and the localized condensation shock caused by the impact tube (clear area in front of and above the tube).

Several methods have been utilized in the present work to verify the general existence of a central jet flow pattern and to measure the details of the flow pattern more precisely than heretofore. These were:

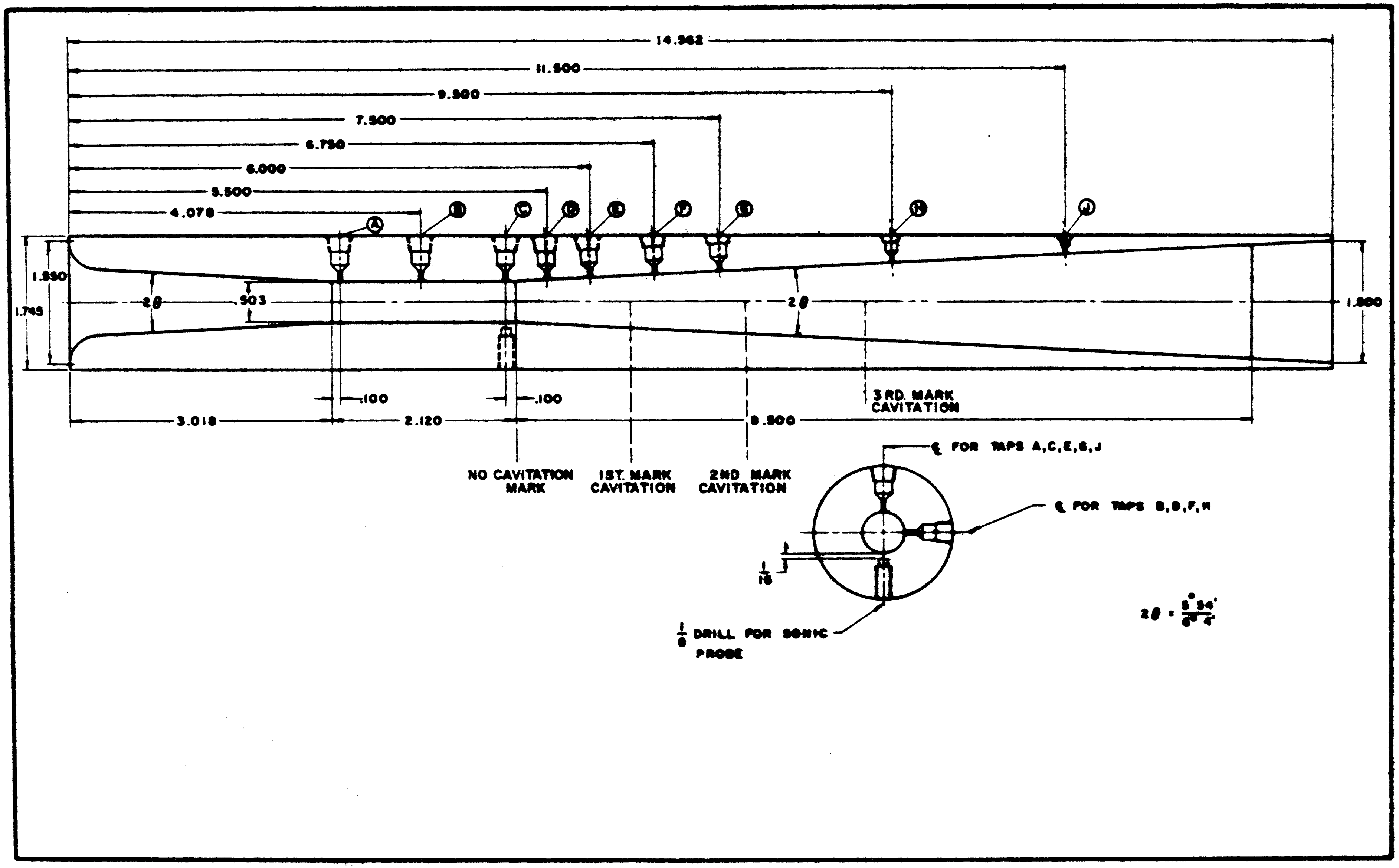

Figure 1. 1/2" Cavitating Venturi Test Section

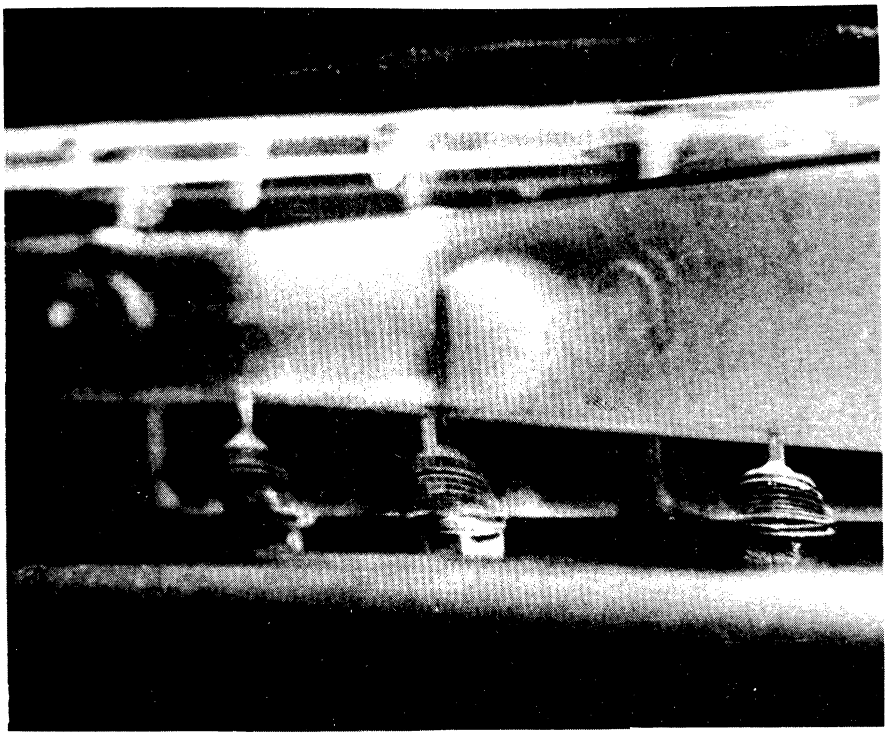

Figure 2a. Photograph of a Condensation Shock on an Impact Tube

Figure 2b. Flow in a Cavitating Venturi

i) Velocity profile measurements with micro-impact tube.

ii) Void-fraction* measurements using gamma-ray densitometer.

iii) High-speed motion pictures.

iv) Static pressure measurements.

Additional, more precise investigations, using the first three techniques, would be useful. However, the rather preliminary experiments herein reported have resulted in significant and meaningful information.

A. Venturi Test Section

The larger of the two venturi test sections used is shown in detail in Figure 1 (nominal 1/2 inch throat diameter, 6° included diffuser angle, cylindrical throat of length to diameter ratio of approximately 4, nozzle symmetrical with diffuser in vicinity of throat). The smaller was geometrically similar, but with nominal 9/32 inch throat diameter. Both are of plexiglass. Static pressure taps (1/16 inch diameter) are located along the axis as shown.

B. Cavitation Condition

The cavitation condition (for all tests) is defined in terms of "degree of cavitation," referring (except for initiation) to the extent of the cavitating region.

i) Sonic Initiation - First sonic manifestation beyond that of single-phase flow. This was detected either by ear or electronically using a piezo-electric crystal. In the water tests the results of these two methods were the same. In all cases sonic initiation occurred at a higher throat pressure than visible initiation.

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*A vapor region is considered as effectively void from the viewpoint of gamma-ray absorption.

ii) Visible Initiation - First appearance of a more or less complete ring of cavitation at the throat exit.

iii) First Mark - Cavitation region approximate termination at "first mark" downstream of throat exit, i.e., 1-3/4 inches in large venturi and approximately 1 inch in small (as is required to maintain geometric similarity).

iv) Second Mark - Definition analogous to First Mark - 3-1/2 inches downstream of throat exit in large venturi.

v) 2-3/4 Mark - Analogous definition - 4-13/16 inches downstream of throat exit in large venturi, greatest extent attainable.

Since the termination is not sharp, the setting of conditions becomes a matter of visual judgment. Actually, it was found to be quite repeatable and not a predominant source of error.

C. Impact-Tube Measurements

Impact-tube measurements were made for various axial positions and for various cavitation degrees and flow conditions (velocity and temperature). It was realized that the meaning of such measurements in the vaporous region would be uncertain because of the existence of condensation shocks around the probe (Figure 2), but it was felt that evidence of the extent and existence of a liquid core could be obtained.

The impact tube to be used was severely restricted by the small size of the venturi and of the holes through which it could be inserted. In order to avoid complication, a simple hypodermic needle was used with a radial hole near the tip (which was flattened). Static pressure was taken to be that existing in the absence of the probe. The details of this, and the other experiments to be described which were designed to delineate the flow pattern, are given in reference 5. The experimental set-up, though crude, was believed sufficient for the purpose of confirming the existence and extent of a central jet.

The resulting radial velocity profiles, taken at taps C, E, and G, respectively (see Figure 1) in the large test section, for zero cavitation and cavitation to 1st, 2nd, and 2-3/4 Mark, and for a given flow rate, are shown in Figures 3, 4, and 5. Tap C is just upstream from the throat exit. As shown in Figure 3, the velocity profiles for all cavitation conditions measured at tap C are identical, showing a flat profile in the central section. The profiles near the wall are repeatable, although probably inaccurate because of the probe configuration. The velocity magnitude is consistent with the expected velocity as calculated from flow and area.

Tap E (Figure 1) is located approximately midway between the throat exit and the 1st Mark position. Hence, it would be expected that the jet would exist at this point for all the cavitation degrees, and that this jet would still show a velocity equal to that in the throat. On the other hand, the zero cavitation profile should show diffusion consistent with the flow area at that point. Examination of Figure 4 shows that this is substantially the case, although the jet velocity has decreased by about 3% from the throat, presumably due to the frictional effects.

The results at tap G (Figure 5) are also consistent with the jet model. Tap G is located approximately 1/3 the distance from the 1st to the 2nd Mark position. Hence, the full jet would be expected for the 2nd and 2-3/4 Mark cavitation, and this is seen to be the case although the velocity has fallen about 8% from the throat. On the other hand, the zero cavitation velocity has fallen almost 50% because of the diffusion of the single-phase flow. The 1st Mark velocity is significantly less than that of the more

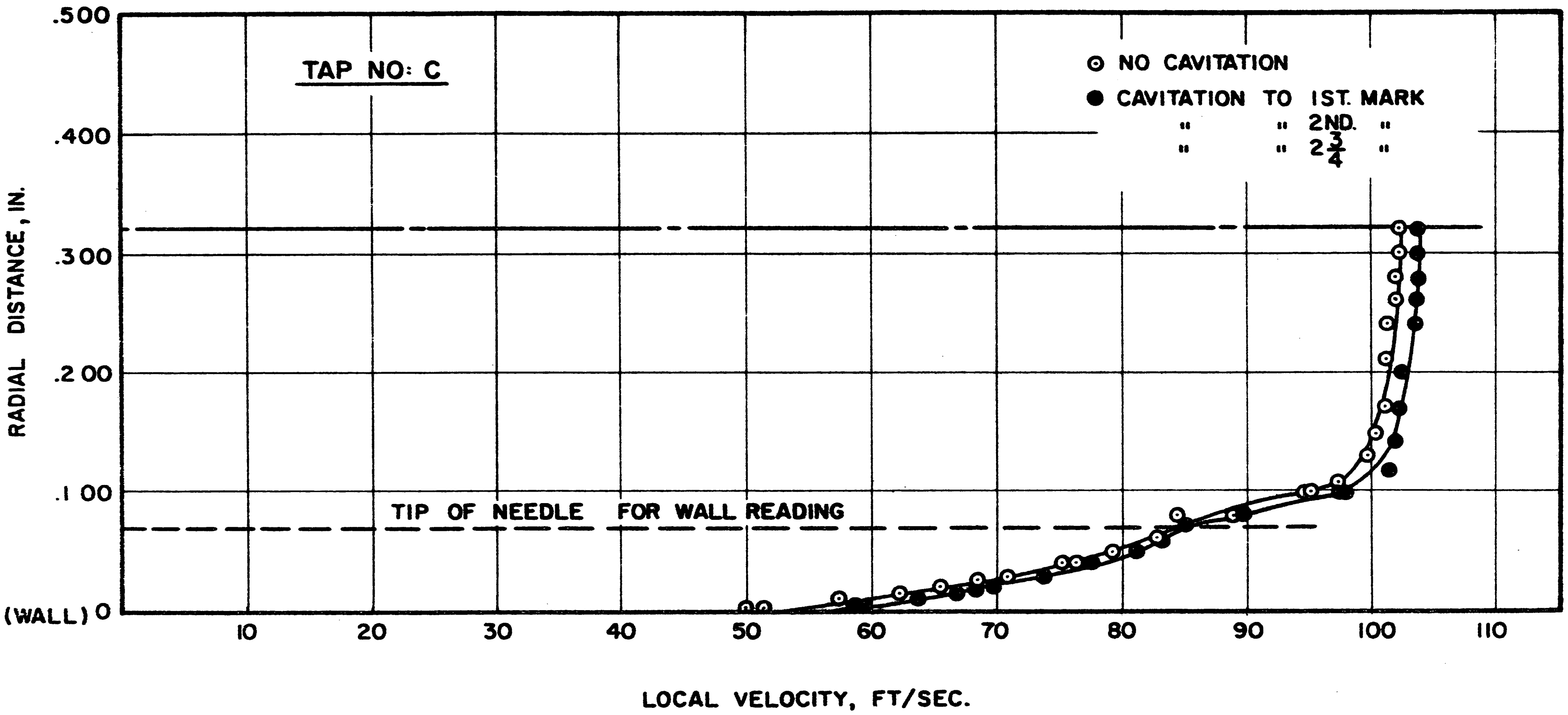

Figure 3. Velocity Profiles as a Function of Radial Position and Cavitation Condition, Tap Position C, Cold Water, 1/2" Test Section

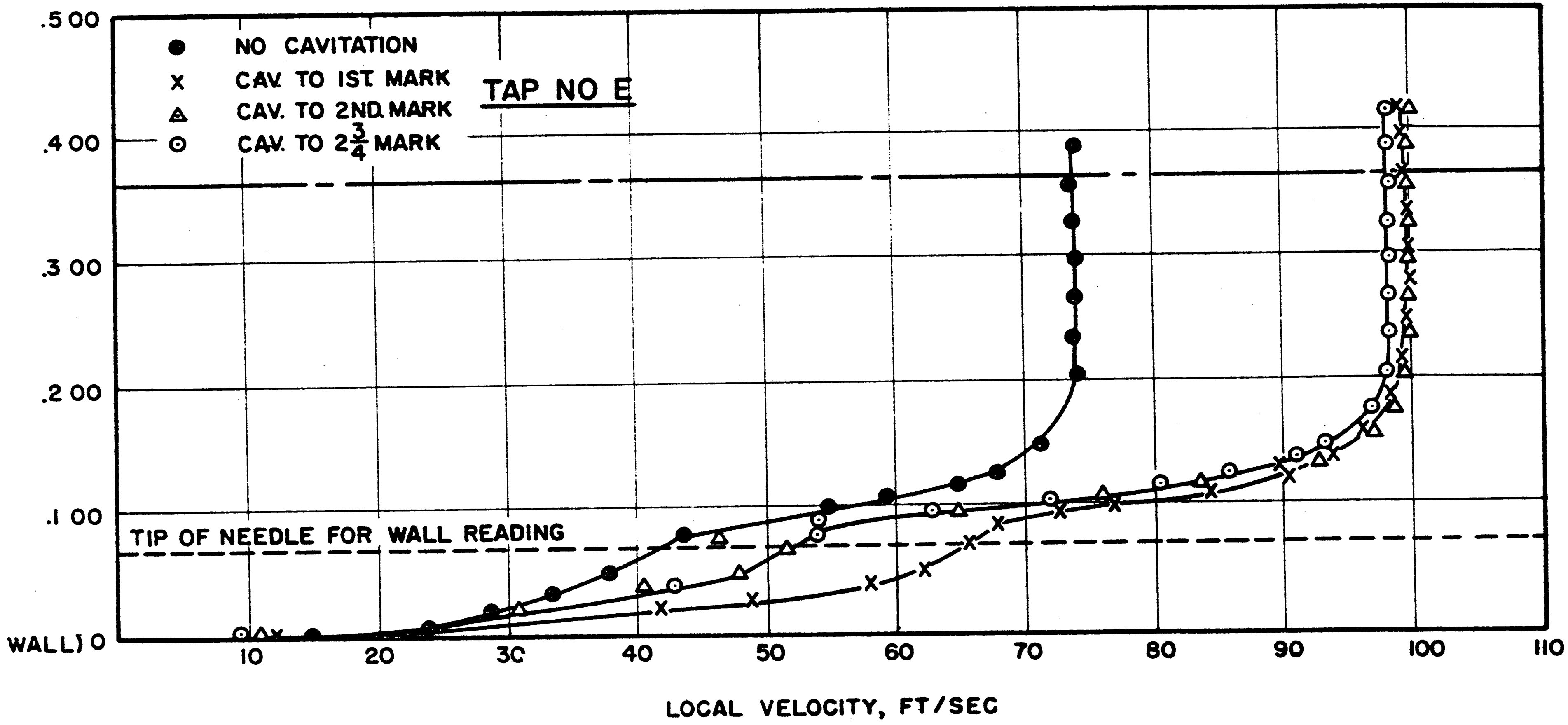

Figure 4. Velocity Profiles as a Function of Radial Position and Cavitation Condition, Tap Position E, Cold Water, 1/2" Test Section

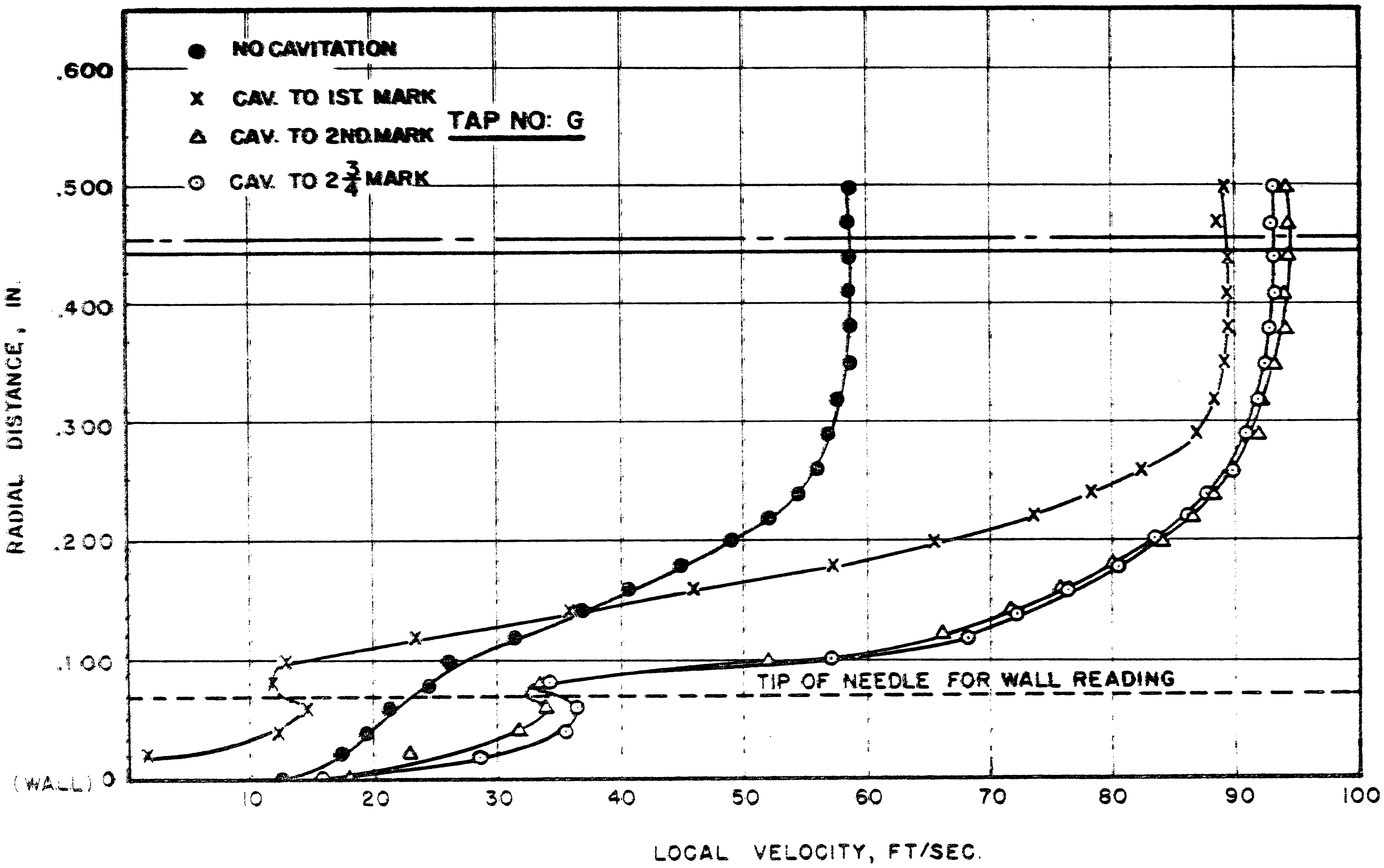

Figure 5. Velocity Profiles as a Function of Radial Position and Cavitation Condition, Tap Position G, Cold Water, 1/2" Test Section

extensive cavitation conditions, since this is now presumably almost single-phase flow and is being diffused as such.

It is noted from Figure 5 that there is some indication of reversal of velocity gradient near the wall for the cavitating flow patterns. This might be expected on the basis of the severe axial pressure gradient in the region of cavitation termination.

To summarize these results, the velocity profile is nearly flat over the extent of the jet, and is not a function of the extent of cavitation downstream of the position of observation. However, the velocity does not appear to fall off as sharply in the radial direction at the edges of the jet as might be expected. This may be the result of the fact that the measured impact pressure in a two-phase region probably exceeds the actual total pressure because of condensation shocks induced by the velocity probe, itself.

The maximum radial extent of the jet may be calculated according to continuity considerations if an average velocity is assumed in the peak region. This appears to be a fairly realistic approach for the following reasons. In a single-phase region, the rather crude impact-tube could easily be assumed to give low readings. However, high readings do not seem possible. If the region actually contains a significant proportion of vapor, the readings would be reduced. Since the readings obtained show a pure liquid velocity almost equal to the known throat velocity, they can be neither significantly high nor low.

The jet diameters calculated as above are shown in Figure 7 for different cavitation conditions at different observer positions. It is noted that the jet diameter remains fairly constant at a value somewhat less than throat diameter to approximately the point of the visual cavitation termination (which is, of course, not sharp but appears to cover an

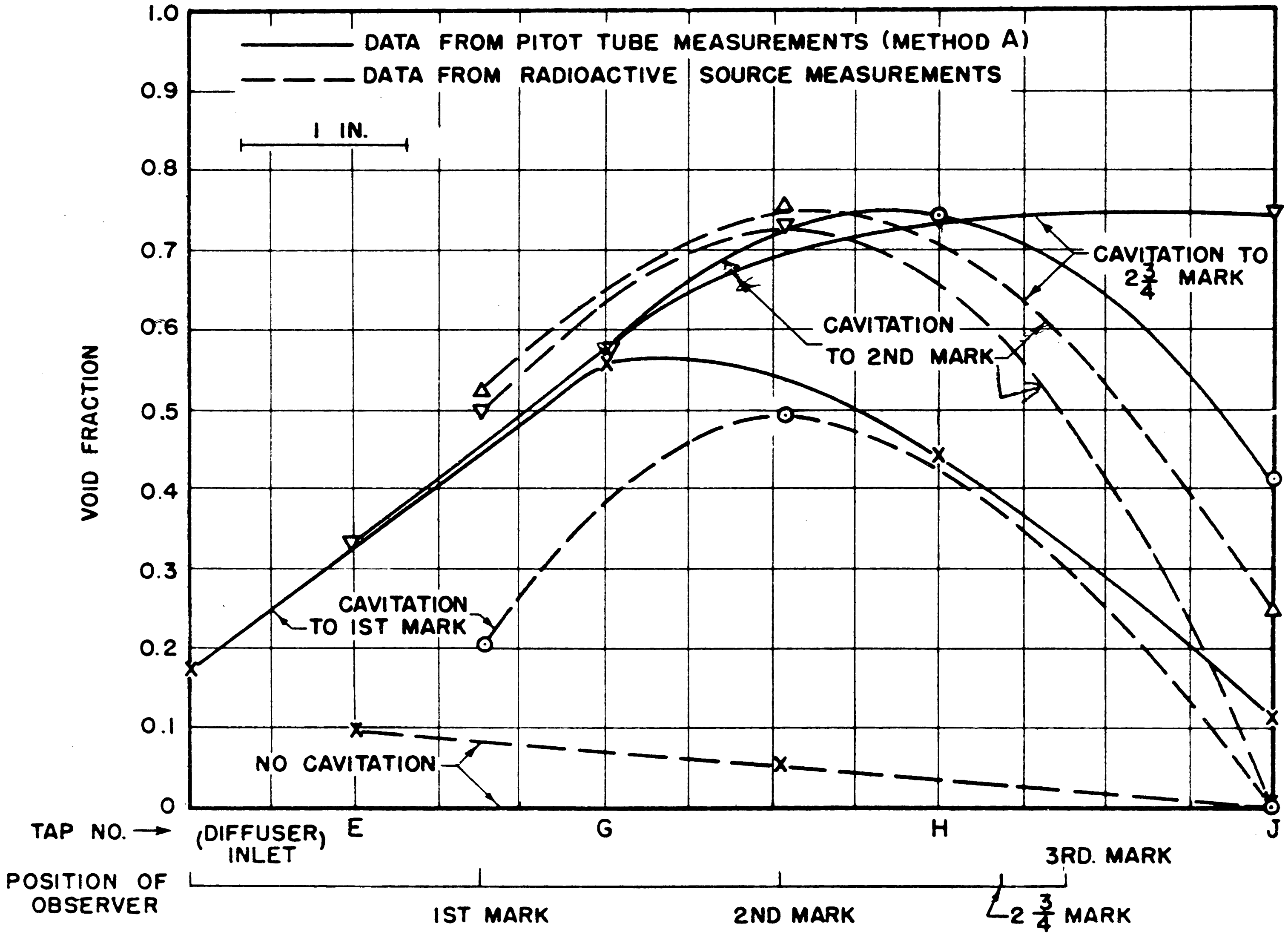

Figure 6. Void Fraction as a Function of Position of Observer and Cavitation Condition

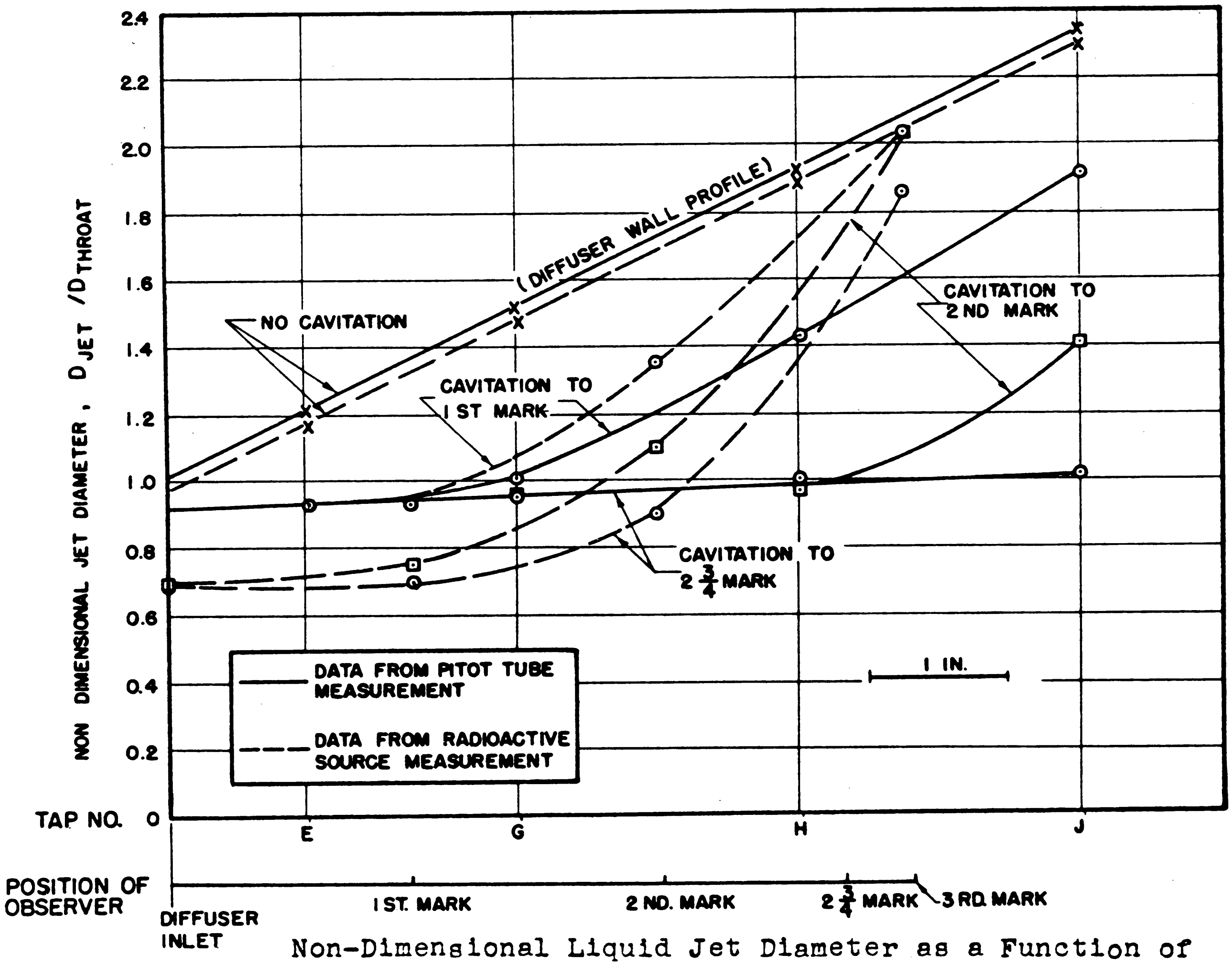

Figure 7. Non-Dimensional Liquid Jet Diameter as a Function of Axial and Cavitation Condition, Cold Water Data, 1/2" Test Section

axial extent of perhaps 1/2 inch), and then tends toward the actual diffuser diameter as the observer position moves downstream. However, it does not attain this value for some distance, indicating that the termination is not analogous to a normal shock wave in being a sharp discontinuity. The data from the impact-tube are compared in this figure with those from the gamma-ray densitometer which are discussed next.

D. Gamma-Ray Densitometer Measurements

A gamma-ray densitometer, with gamma (or X) rays of about 67 Kev, was constructed using a promethium-tungstate source-target mixture. Details of the construction and the reason for the choice of this type of source are given in reference 5. Since the first readings were regarded as preliminary, and merely an attempt to see if the method would be feasible, no effort to achieve good collimation was made. Hence, the measurements give only average density of fluid in the venturi at a given axial position, rather than local values. Nevertheless, if the jet model is assumed for calculation of jet diameter, it is found that the readings are approximately consistent with those from the impact-tube (Figures 6 and 7). Some of the differences may well be experimental error. However, there are basic, inherent reasons for which differences might be expected.

The densitometer measures directly the ratio of vapor volume to total volume, but is insensitive to velocity. The impact-tube is sensitive to the product $(\text{velocity})^2(\text{density})$. If it is supposed that in the vicinity of cavitation termination the region directly downstream of the vapor portion is filled with a relatively stagnant liquid-vapor mixture, but contains a considerably higher proportion of liquid than the region immediately upstream, then the densitometer would indicate a greatly reduced void fraction in this area, indicating the termination of the central jet. On the other hand, the impact-tube would indicate the continued existence of the jet, since the stagnant region around it would not show a significant velocity, even though it were predominantly liquid. Thus the impact-tube would tend to indicate cavitation termination further downstream than the densitometer. Examination of Figures 6 and 7 shows that this is actually the case.

Stated in slightly different terms, the densitometer measures the location of termination of significant vapor in the stream, whereas the impact-tube measures the termination of the central high-velocity jet. These two termination points do not necessarily coincide according to the data presented, as well as according to intuition based on physical reasoning.

E. High-Speed Motion Pictures

High-speed motion pictures of the cavitating flow in the larger venturi were taken using a 16 mm Fastax camera with a framing rate of about 8000 frames per second. Due to imperfect lighting conditions, only the region of bubble growth was viewed. The details of the apparatus and procedures, as well as typical frames, are given in reference 5.

The significant items of information which resulted from these motion picture studies are:

i) The "vaporous region" is actually filled with more or less spherical bubbles of sizes ranging from the minimum which could be observed up to about 1/4 inch with the mean at about 1/8 of an inch. The size distribution is shown in Figure 8. In this connection, no clear cavity was evident to the naked eye either. Rather the entire cavitating region appeared frothy.

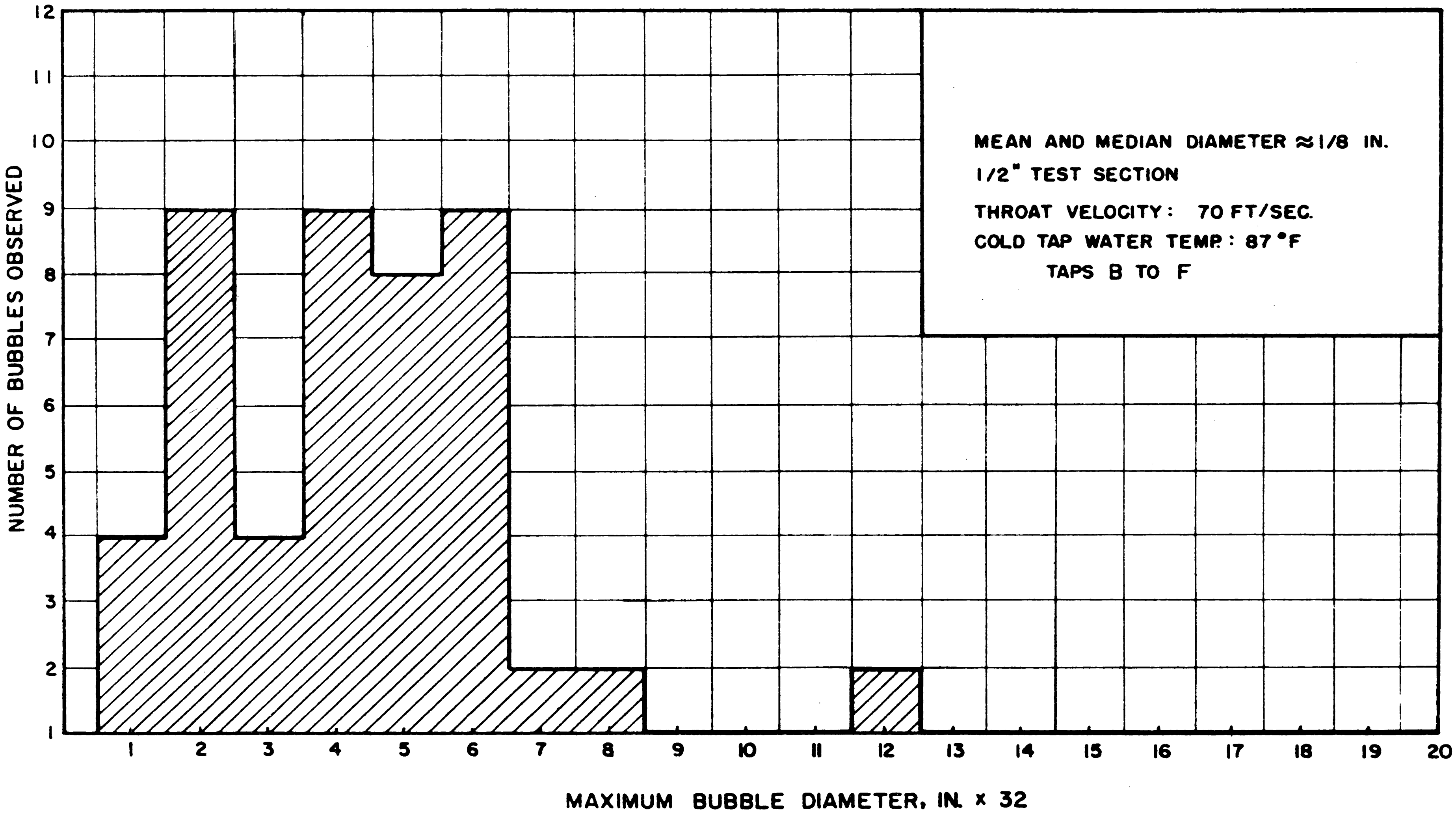

Figure 8. Bubble-Maximum-Growth Diameter Distribution

ii) The downstream velocity of the bubbles is, on the average, about 87% of the mean stream velocity at the throat. The picture covers the region between taps B and F (Figure 1), i.e., from midway through the cylindrical throat to near the 1st Mark position. However, the flow condition was such that the apparent cavitation termination was further downstream (as for example 2nd Mark cavitation), so that the jet velocity in the region of the picture was close to throat velocity (Figure 4). Thus, it appears that there is significant "slip" between vapor bubbles and liquid stream, with the bubbles lagging. The velocity distribution of the bubbles observed is shown in Figure 9.

iii) The rate of growth of the bubbles has also been observed and the distribution is shown in Figure 10, where it is shown that the average rate of increase of bubble diameter is on the order of 3 to 4 feet/second.

iv) The extent of the vapor region oscillates very rapidly with time.

Unfortunately, it is not possible in these pictures to determine the radial extent of the jet or the density of bubble packing, either in the jet itself or in the surrounding regions, because of the circular nature of the test section. However, it is felt that the information presented in Figures 8, 9, and 10 will be useful in verifying theoretical treatments of bubble dynamics which may be made, as well as in increasing the general understanding of the actual flow pattern.

III. PRESSURE MEASUREMENTS AND NON-DIMENSIONAL PARAMETER CORRELATIONS

A. Static Axial Pressure Profiles

Static pressures along the axes of the large and small venturis were measured for various cavitation conditions, velocities, fluid

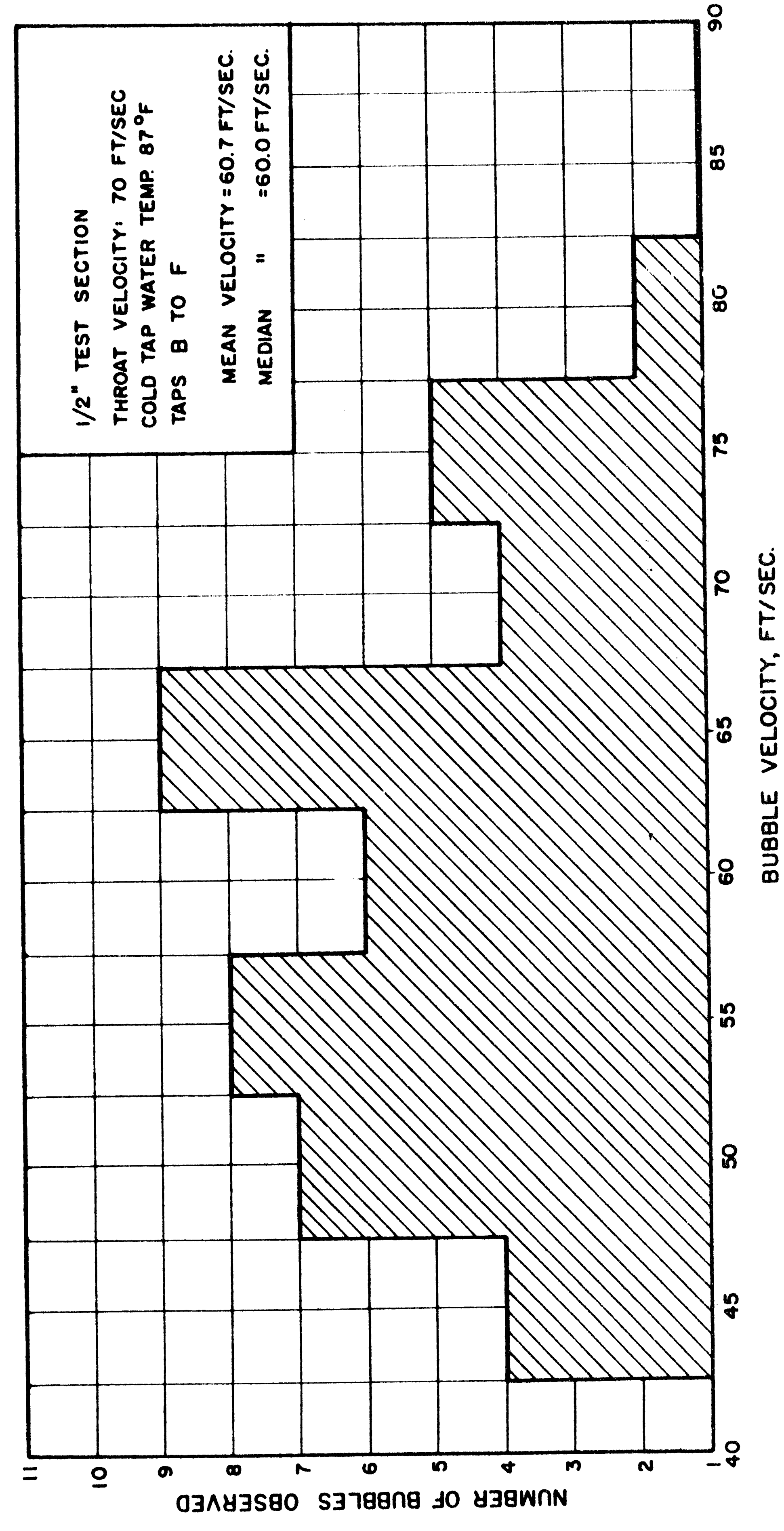

Figure 9. Bubble Velocity Distribution

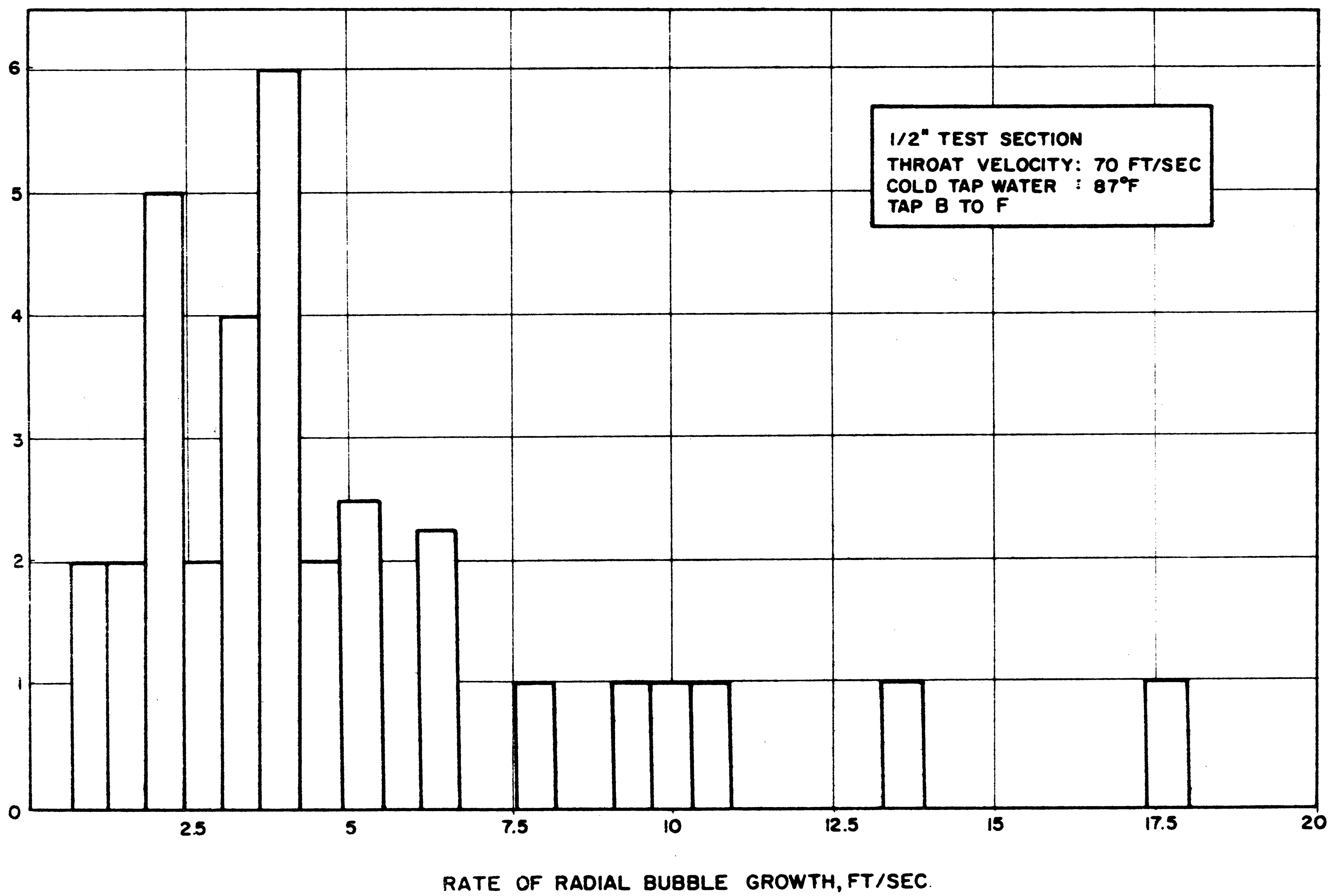

Figure 10. Bubble-Growth-Rate Distribution

temperatures, and gas contents. The detailed description of the apparatus and instrumentation is given in reference 6. The limiting values of these parameters which could be attained are approximately as follows:

i) Velocity - 50 to 95 feet/second, depending to some extent on cavitation conditions (no minimum for single-phase flow; but about 90 feet/second maximum).

ii) Temperature - 50 to 165°F.

iii) Gas Content - 30% saturation at room temperature and pressure to about 20% in excess of above saturation condition. (Measured by a Van Slyke gas content analyzer.)

1. Effects in Large Venturi

The resulting axial pressure profiles for sonic initiation for the large venturi are shown in Figure 11 for different Reynolds' numbers. It is noted that the diffuser efficiency is increased as expected by increasing Reynolds' number. It appears that nozzle efficiency is slightly reduced for higher Reynolds' number, for which no explanation other than possible experimental error, or the detailed rearrangement of velocity profile with acceleration through the nozzle, is available. The above results, relative to both the diffuser and nozzle, were also observed for the smaller venturi.[6]

The pressures are normalized through division by the kinetic pressure in the throat. The normalized vapor pressure is subtracted so that the vertical coordinates of this and subsequent curves is actually the normalized net positive suction head at a given axial position. This becomes the cavitation number at the point of minimum pressure. Other than through the use of vapor pressure as a datum, the curves of Figure 11 apply to single-phase flow in the venturi at any arbitrary pressure level.

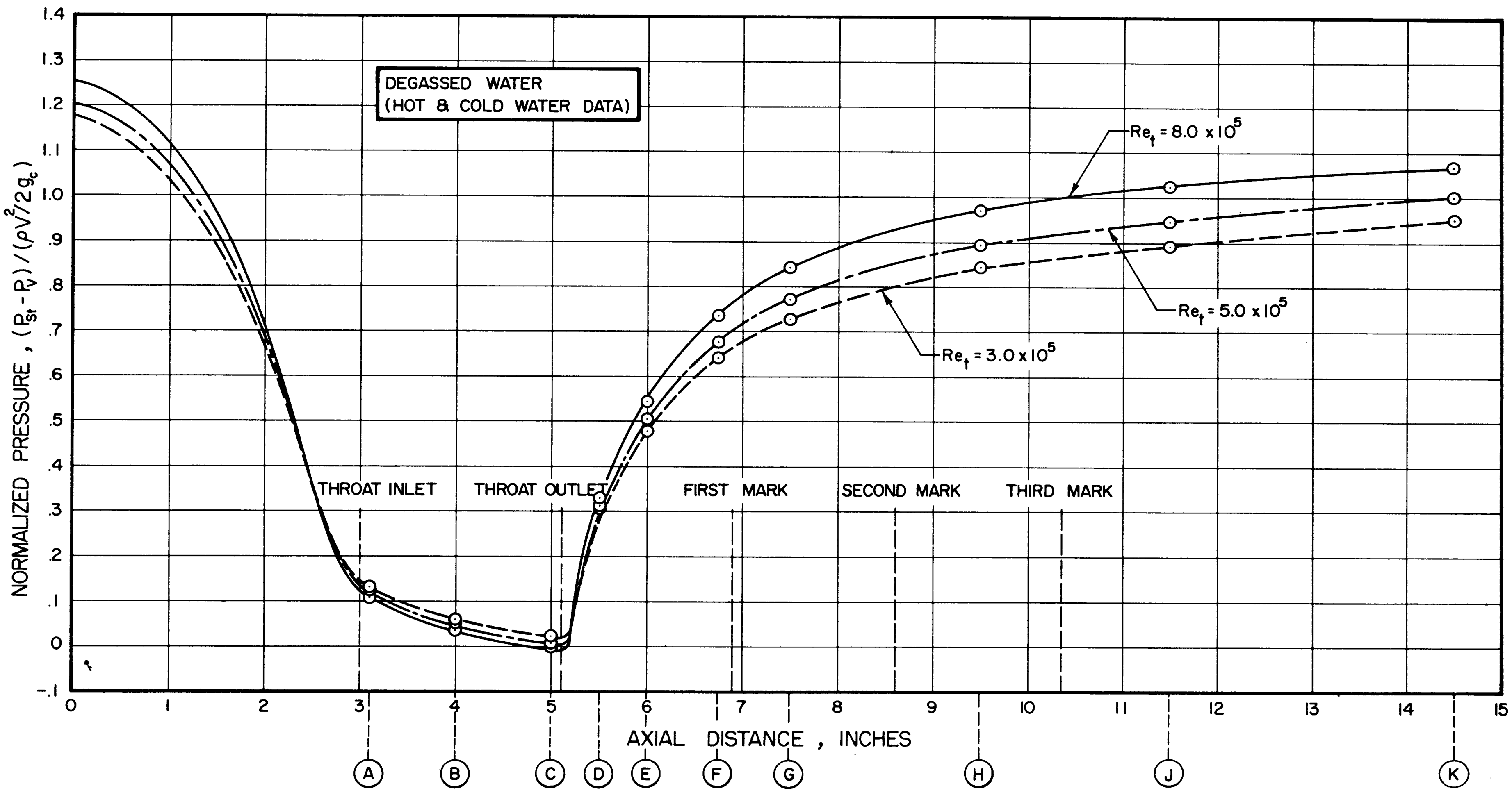

Figure 11. Normalized Pressure vs Axial Position, Sonic Initiation, 1/2" Test Section

As shown in Figure 11, there is a very sharp positive axial pressure gradient in the diffuser inlet region, as well as a significant pressure decrease through the cylindrical throat. Because of the latter, cavitation is initiated approximately at the throat exit (except for very localized cavitation observed at times around the pressure taps).

The pressure profiles for visible initiation[6] are not included since their shape and the axial location of the minimum pressure points is practically identical to those for sonic initiation.

Figure 12 shows the pressure profiles in the large venturi for 1st Mark cavitation and Figure 13 for 2nd Mark. The following points relative to these conditions appear significant:

i) The minimum pressure occurs about 1 to 2 inches downstream of the throat exit (i.e., well into diffuser; more so for 2nd Mark), indicating a vena-contracta type of flow, even though the throat is cylindrical.

ii) For these cases of well-developed cavitation the pressure recovery in the diffuser (diffuser efficiency) is greater for low than for high Reynolds' number (i.e., opposite to trend with sonic initiation, which is virtually single-phase flow).

iii) The pressure gradient is approximately centered about the point of visual termination of cavitation. However, this gradient is not so steep as that achieved with sonic initiation or single-phase flow, for which the gradient is strongly influenced by the diffuser angle. Hence, this result may not be general, but merely a function of the particular geometry.

iv) The minimum pressures observed are close to the fluid vapor pressure, both above and below (discussed in detail later).

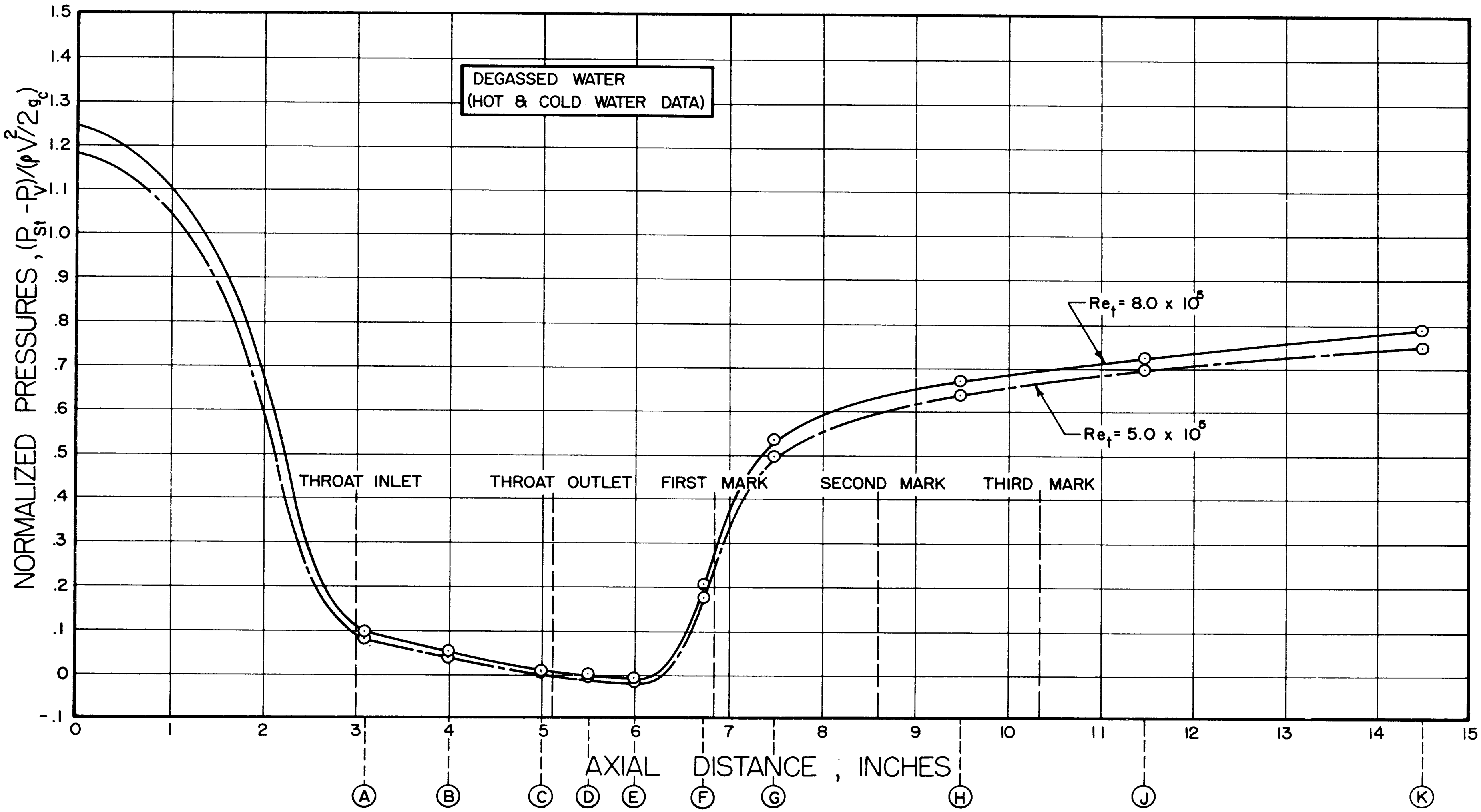

Figure 12. Normalized Pressure vs Axial Position, Cavitation to First Mark, 1/2" Test Section

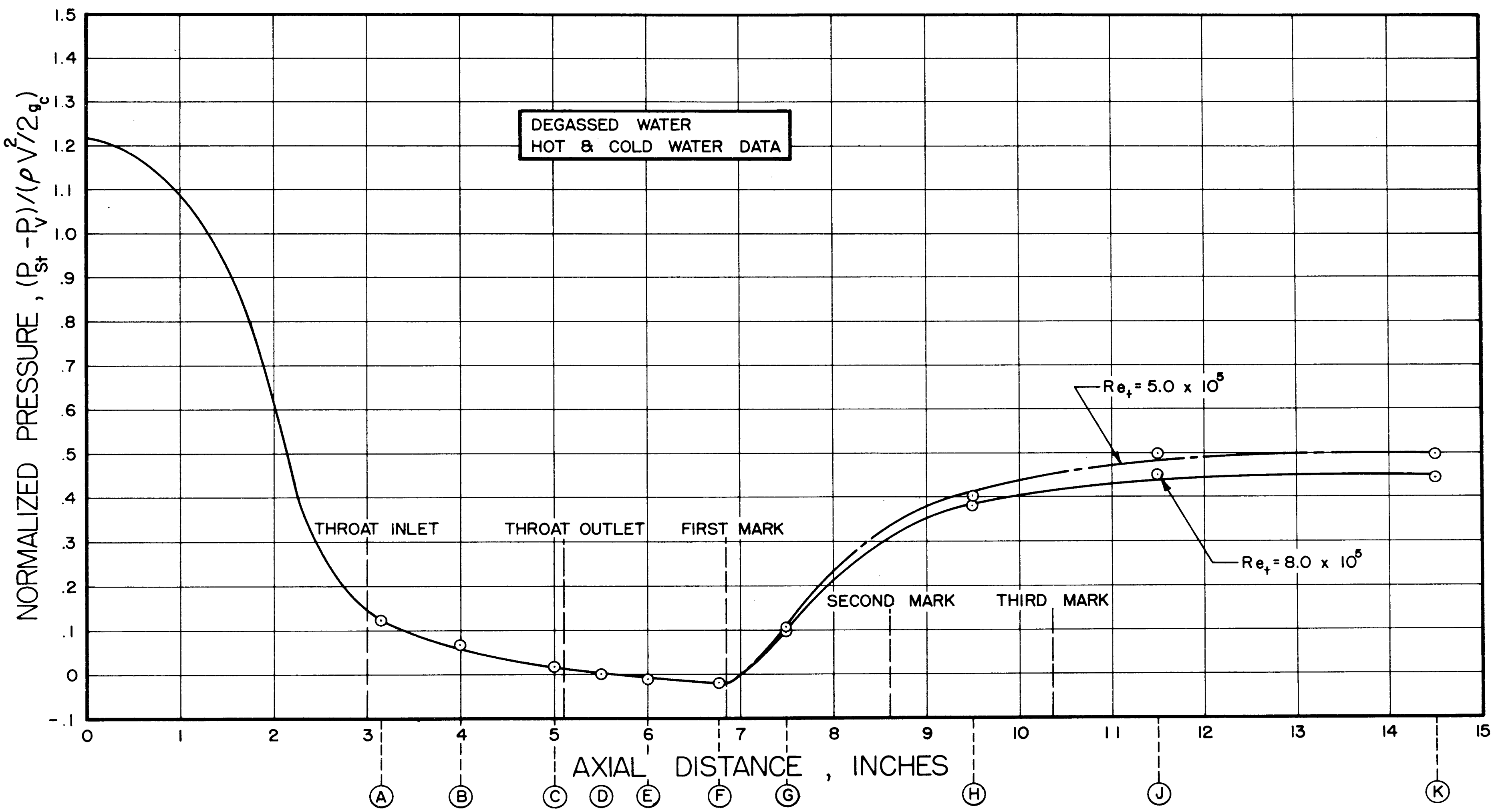

Figure 13. Normalized Pressure vs Axial Position, Cavitation to Second Mark, 1/2" Test Section

v) Nozzle efficiency is not a function of cavitation condition. A comparison of Figures 11 and 12 indicates that the decrease in normalized pressure between venturi inlet and throat inlet does not change for cavitation degree within the accuracy of the experiments. Since cavitation is not observed in this region, this is to be expected.

vi) There is a small additional pressure drop in the well-developed cavitation conditions between throat exit and minimum pressure point.

2. Comparison of Large and Small Venturis

A comparison between large and small venturis showing pressure profiles for initiation and well-developed cavitation is given in Figures 14 and 15. Although the venturis are geometrically similar, it is noted that the pressure profiles are not identical; rather, recovery is greater and more rapid with the smaller test section. Thus, the same effect with Reynolds' number for developed cavitation is indicated as was noted for tests in the large venturi alone where Reynolds' number variation was obtained by velocity or temperature variation. However, the comparison does not hold for the sonic initiation case in that the pressure recovery for the small venturi is greater than that for the large, perhaps because of differing relative surface roughnesses between the two venturis. It seems likely that roughness effects would be more influential in single-phase flow than in well-developed cavitation.

B. Cavitation Number Correlation

Cavitation number for this study is defined as the ratio between minimum static pressure above vapor pressure to kinetic pressure based on mean throat velocity. The minimum pressure is taken from axial pressure

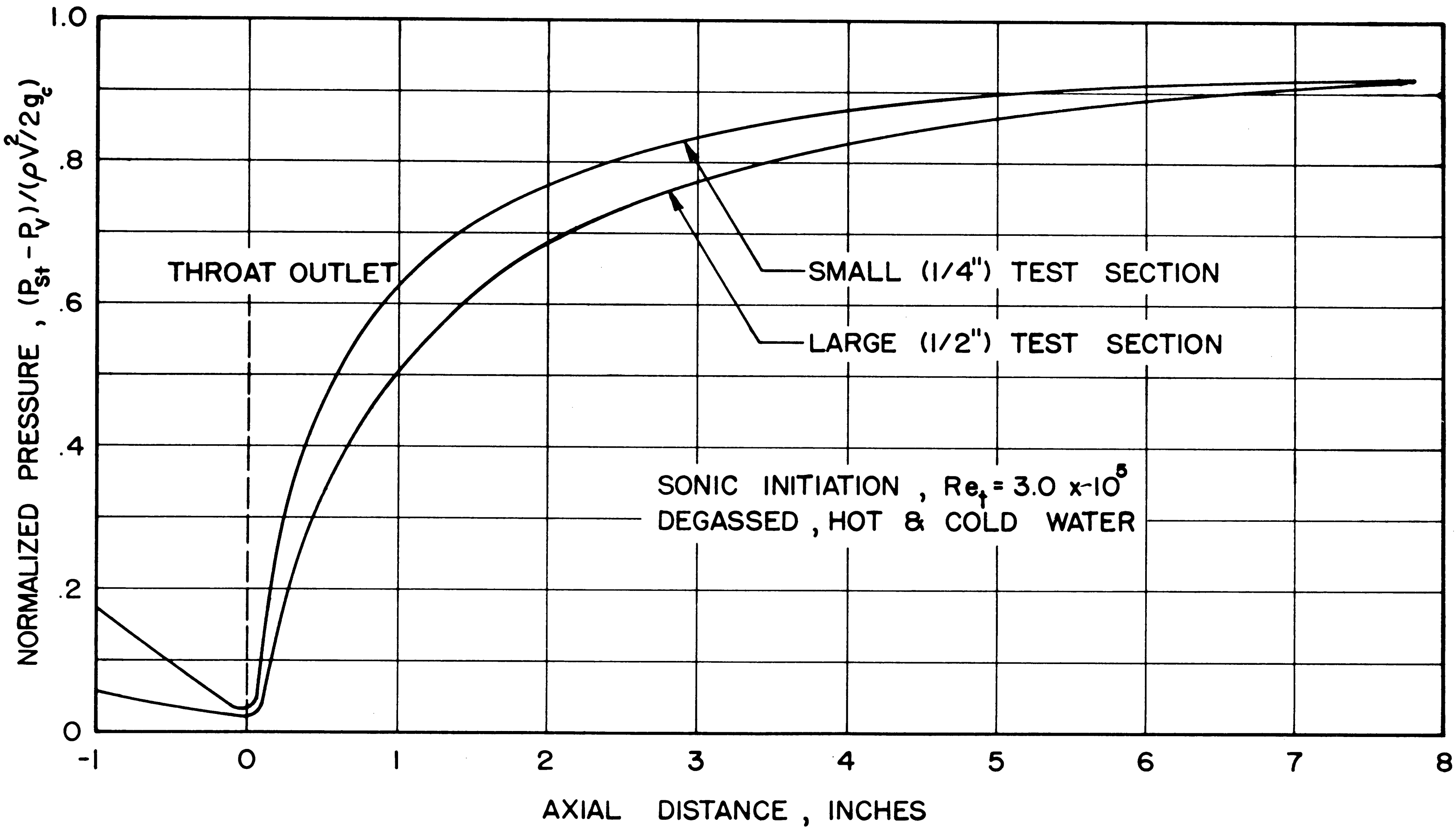

Figure 14. Comparison of Axial Pressure Profile in Different Test Sections

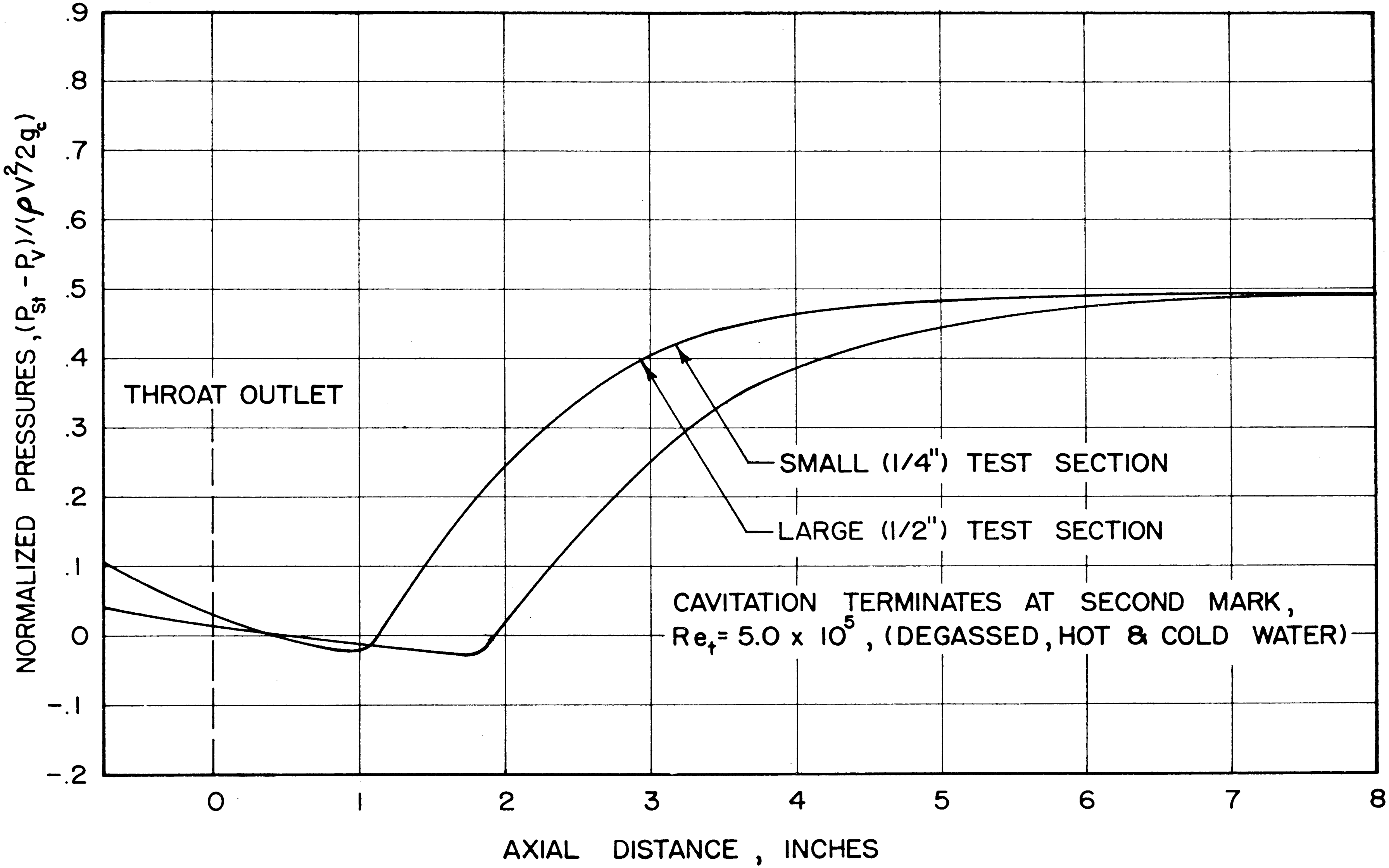

Figure 15. Comparison of Axial Pressure Profile in Different Test Sections

profile plots, and may not correspond to an actual measurement or tap position.

In the past it has been shown that at least in some cases cavitation number can be correlated in terms of Reynolds' number. The past experimental evidence is summarized in reference 7. There are good theoretical reasons to indicate that this may be the case:

i) Cavitation nucleation probably occurs largely in the boundary layer[8] where the bubbles grow initially until swept downstream. Boundary layer thickness depends on Reynolds' Number.

ii) The magnitude of local pressure depressions in a noncurving stream (below measured wall pressure) depends upon the degree of turbulence, which, in turn, also depends on Reynolds' number.

There are numerous other possible mechanisms whereby fluid or flow parameters would be thought to influence cavitation number even with constant geometry. These include the common non-dimensional groupings[6] involving surface tension effects, heat transfer, etc. In addition, the possibility of effects relating to time of exposure to tension and absolute magnitude of tension, as well as finite evaporation, condensation, and solution rates are involved. Hence, it would not be surprising if it were found that Reynolds' number alone is not a sufficient correlating parameter. As a result of the data herein reported, it is believed that this is actually the case.

Figures 16 through 19 show cavitation number plotted against Reynolds' number for sonic and visible initiation, 1st Mark and 2nd Mark cavitation, respectively, Reynolds' number variations are attained through variation of velocity, throat diameter, and viscosity (by temperature variation) over about a 2:1 range in all cases. Within this rather limited range

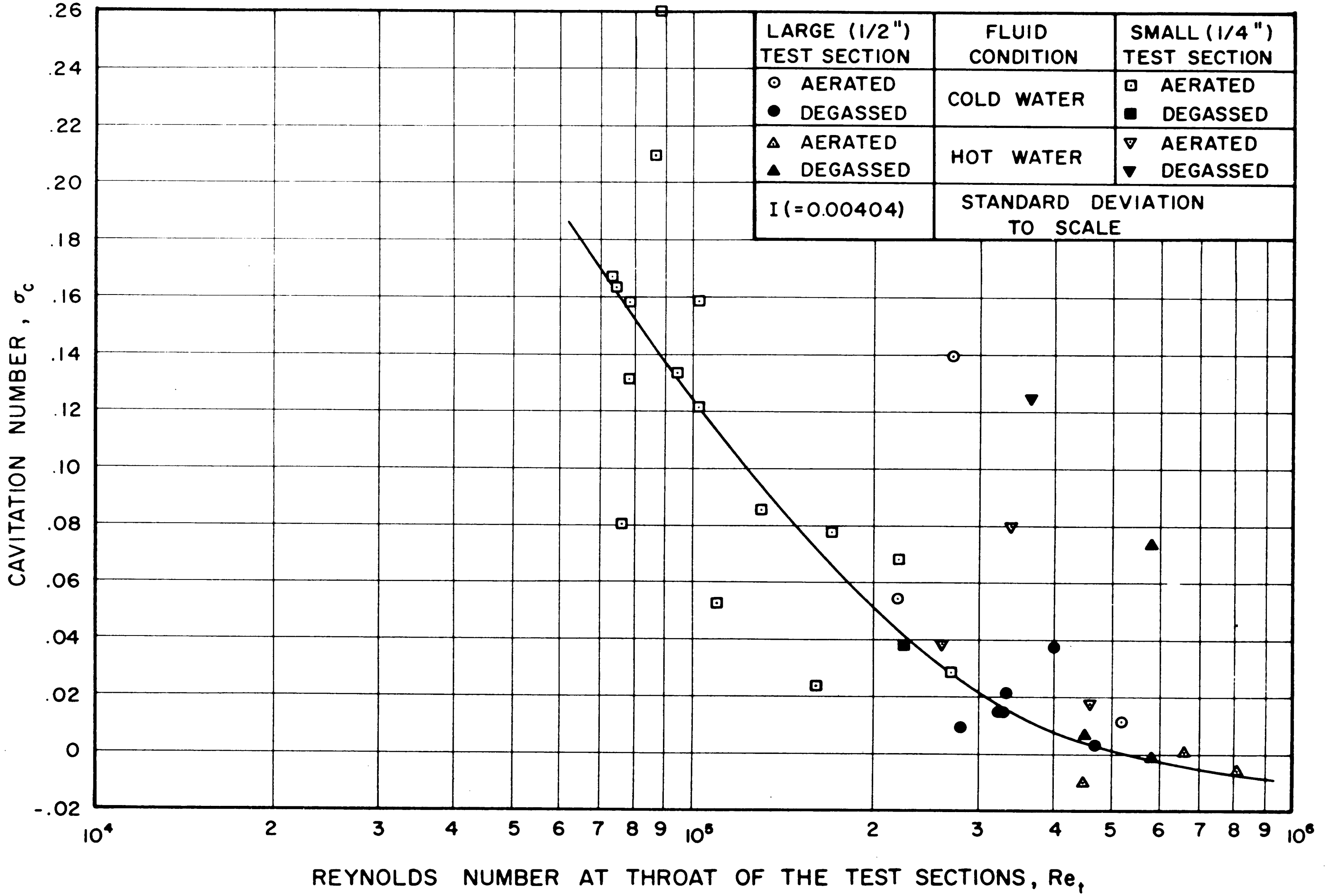

Fig. 16 Cavitation Number vs. Throat Reynolds' Number in a Cavitating Venturi for Sonic Initiation.

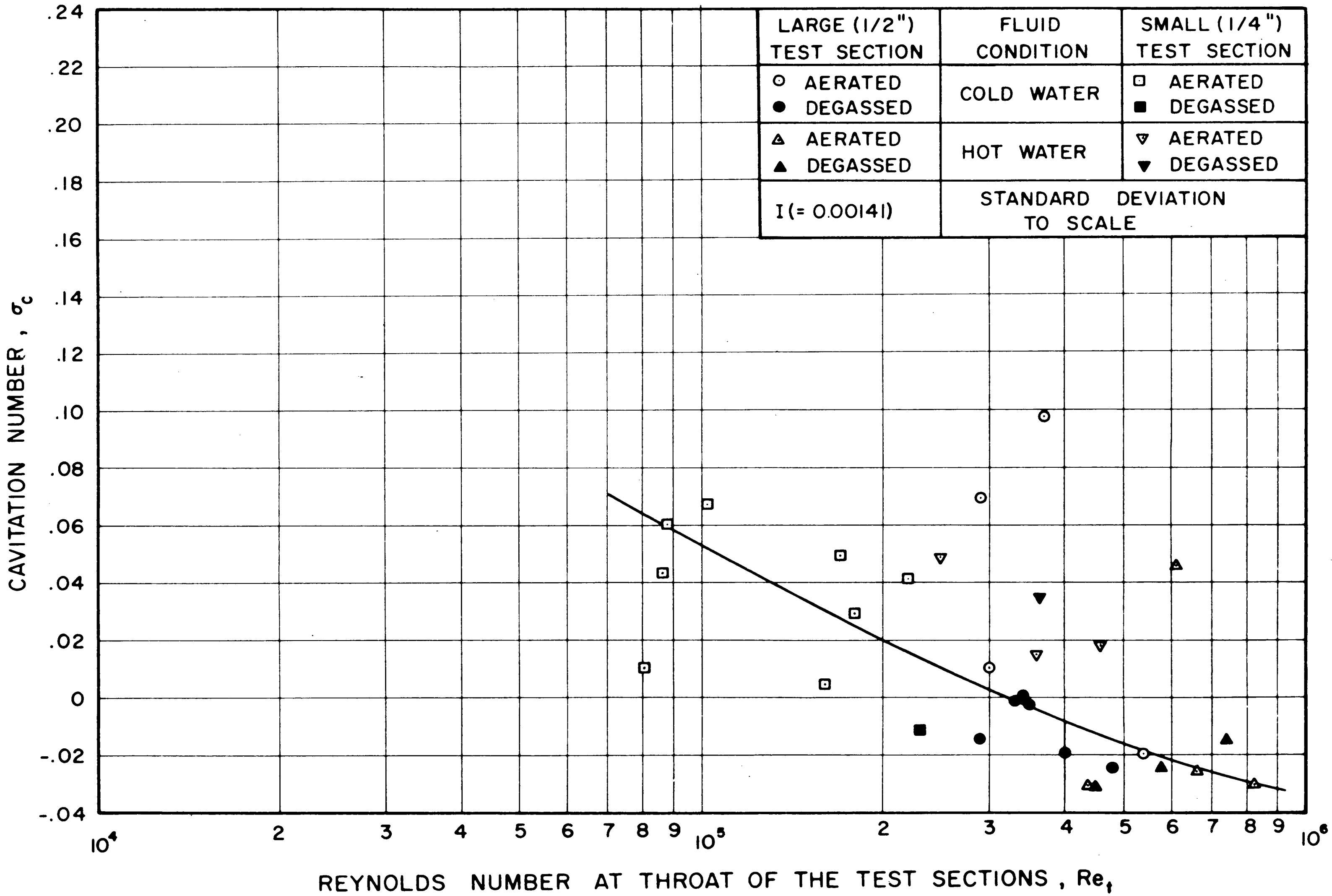

Fig. 17 Cavitation Number vs. Throat Reynolds' Number in a Cavitating Venturi for Visible Initiation.

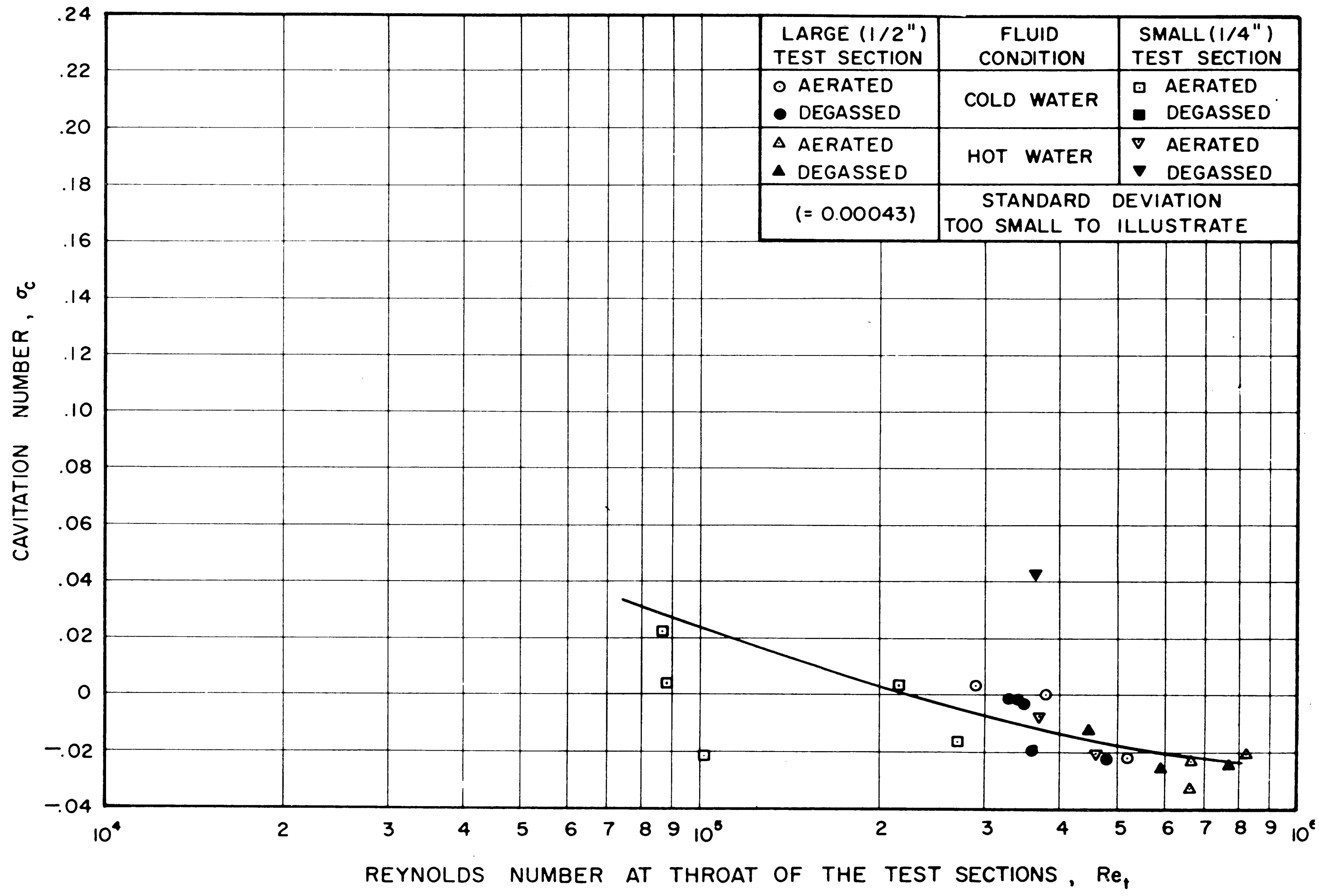

Fig. 18 Cavitation Number vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to First Mark.

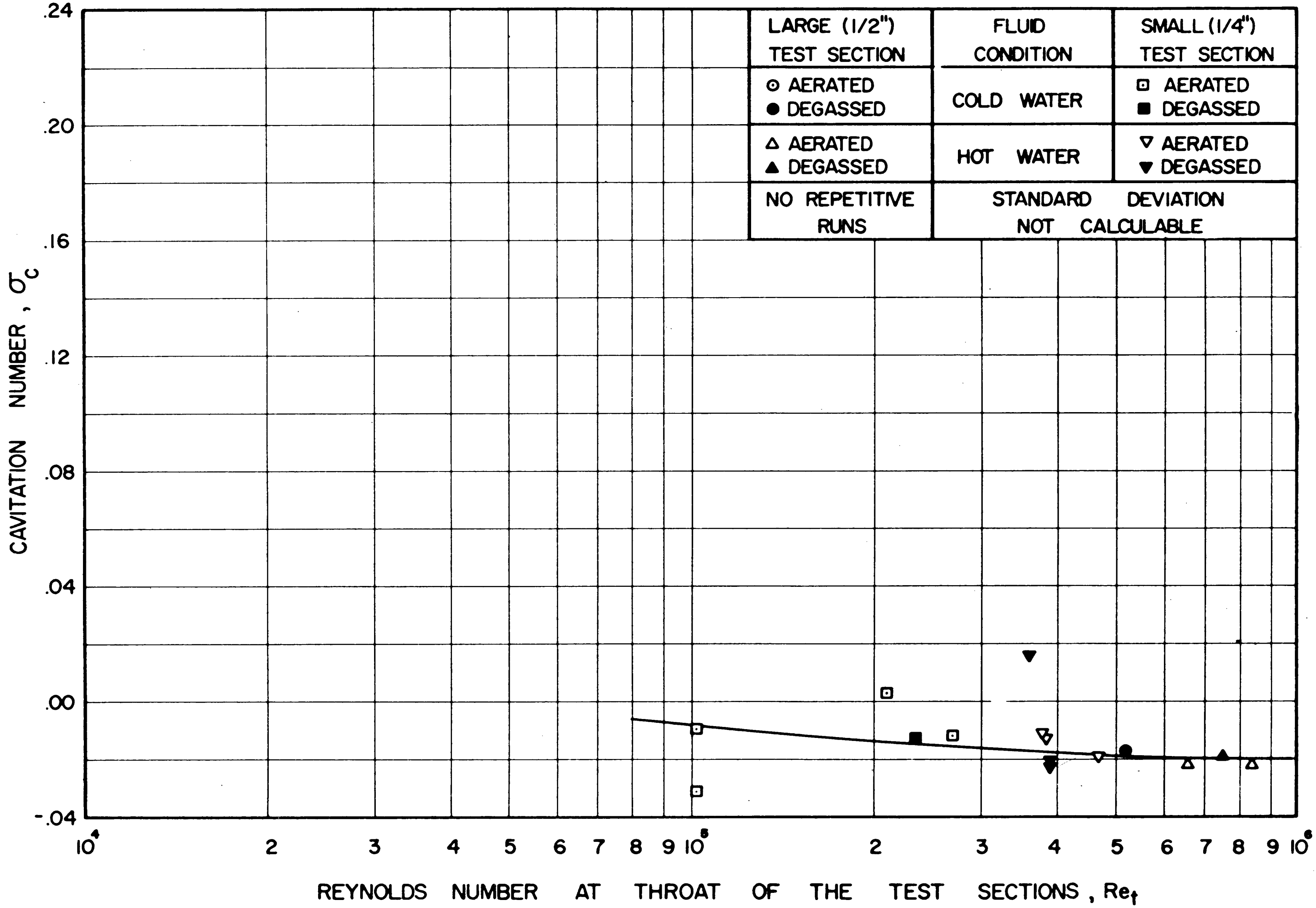

Fig. 19 Cavitation Number vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to Second Mark.

of parameter variation, and for a single fluid (water), a fairly good correlation with Reynolds' number is obtained for all the cavitation degrees. However, the scatter of points around the best curve is much greater than can be explained on the basis of experimental error (the standard deviation is shown on each curve - it is derived from repetitive tests at a single flow-rate in which all adjustments were made anew for each run). It thus appears that, while Reynolds' number is a useful correlating parameter, it is not in itself sufficient. When more comprehensive data are available, including data for other fluids, it may be possible to specify better non-dimensional groupings.

Examination of these curves and Figures 20 and 21, where the comparisons are given, discloses these additional significant facts:

i) The sensitivity of cavitation number to Reynolds' number is considerably reduced as cavitation becomes more fully developed.

ii) The measured cavitation numbers are sensitive to gas content (within the rather restricted range of the experiments) only for the cold-water initiation conditions, where increased scatter is noted for the tap water points. However, no consistent trend with gas content within the precision of the experiments was noted.

iii) The smoothed curves show the existence of pressures below the vapor pressure for all cavitation conditions but only in the high Reynolds' number range except for 2nd Mark where the entire curve is below vapor pressure. A close examination of the curves shows that within the range where tension is recorded the gas content has no measurable effect. The tension measurements are discussed in the next section.

In a region such as the exit of a cylindrical venturi throat, it might be thought that cavitation would occur at approximately vapor

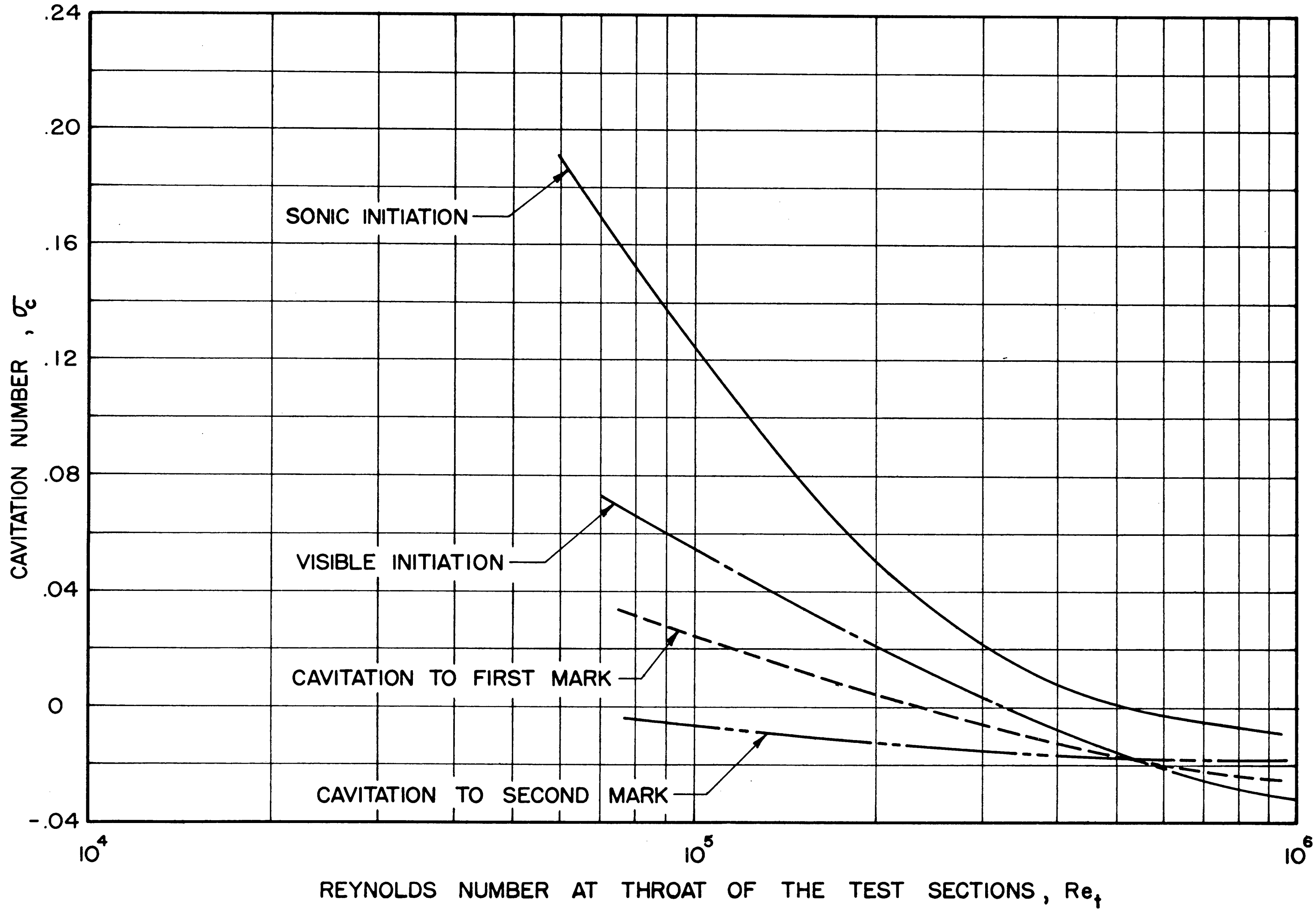

Figure 20. Comparison of Cavitation Number vs Throat Reynolds Number for Various Degrees of Cavitation

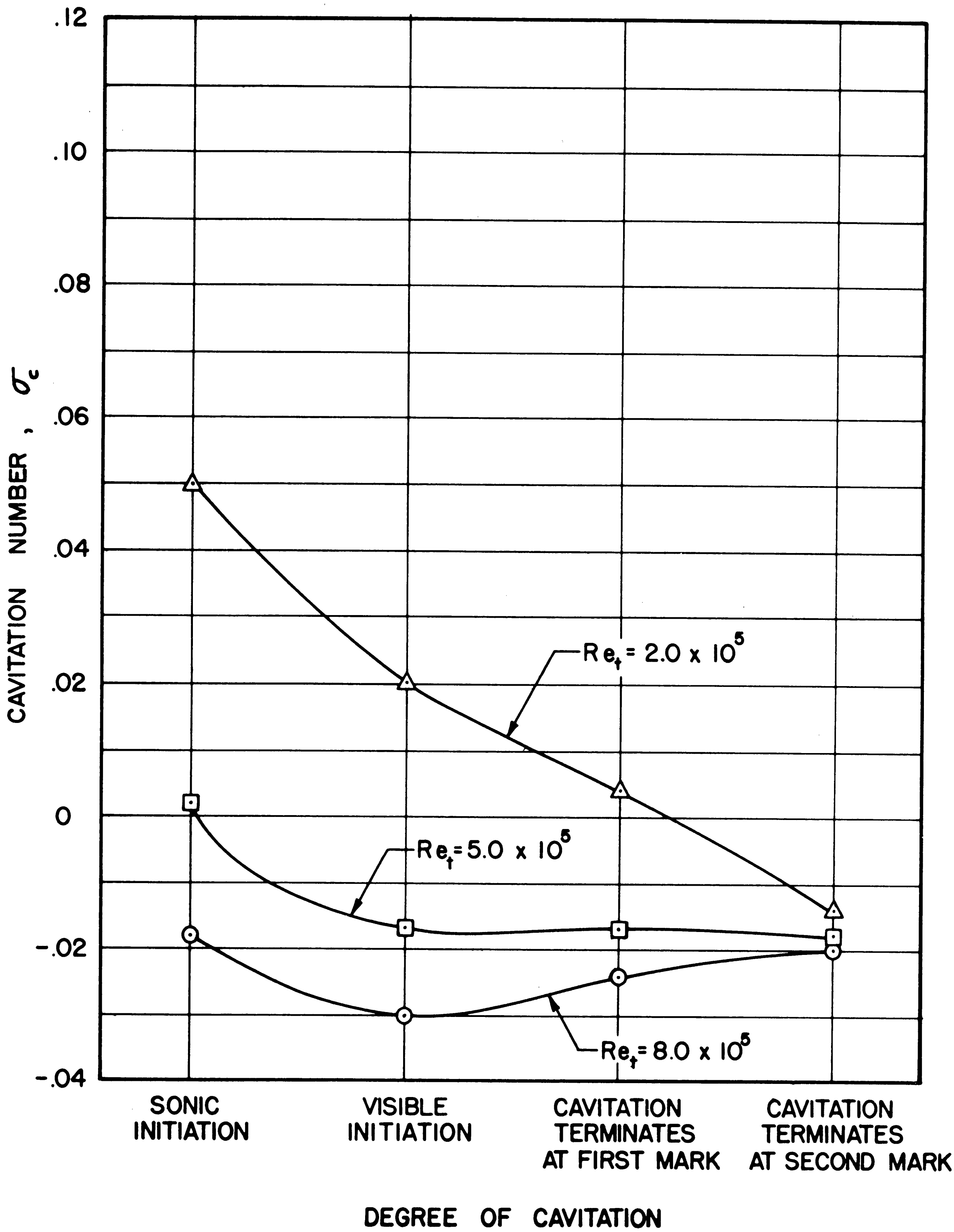

Figure 21. Cavitation Number vs Degree of Cavitation at Various Reynolds Numbers

pressure at any velocity, and that the decrease in cavitation number shown with increased velocity (Reynolds' number) perhaps merely reflects the increase of kinetic pressure as it affects the cavitation number parameter. However, plotting of the data as net positive suction head vs. Reynolds' number[6] reveals that no correlation is obtained in this manner.

C. Tension Observations

Direct readings at the various tap positions indicated tension at high Reynolds' number for all cavitation conditions with the exception of sonic initiation. The maximum tension occurred for 1st Mark and was of the order of 11 inches of H_2O at the maximum velocity. These are listed in Table I.

TABLE I

DIRECT PRESSURE MEASUREMENTS

Cavitation Condition	$(p - p_v)^*$ min
Sonic Initiation	6.1 inches H_2O
Visible Initiation	-6.1 " "
1st Mark	-11.3 " "
2nd Mark	-2.6 " "

*Applies at maximum velocity tested.
No consistent trend with gas content.

If it is assumed that the pressure drop in the cylindrical throat is independent of degree of cavitation (since in no case is there substantial cavitation in the cylindrical throat), then the pressures measured at the throat exit are incorrect and are too high, possibly because of vapor formation around the taps and in the lines. In terms of cavitation number, the error is quite constant (though peaking at visible initiation) and averages to about 0.022, giving the corrections, listed in Table II which depend on velocity:

TABLE II

CORRECTIONS TO DIRECT PRESSURE MEASUREMENTS

V Throat	Δp Correction
55 ft/sec	-12.3" H_2O
70 "	-19.8" "
90 "	-32.9" "

All figures involving cavitation number have been plotted using the correction indicated above.

No significant consistent distinction for this correction between degrees of cavitation, throat diameters, water temperatures, or air contents, within the range and precision of the data, is found.

It has been shown[9] that turbulence within the stream can result in pressures in the turbulent boundary layer significantly less than measured wall pressure. A typical[9] correction in terms of cavitation number has been given as .025. However, no correction of this type has been included in the plots.

Summing the maximum indicated tension with the measurement error, and the above turbulence correction, the following is noted for maximum velocity.

a) Wall static pressures: 3 ft of water below vapor pressure;

b) Boundary layer pressures: ~ 6 ft of water below vapor pressure.

It seems likely that almost any cavitating water tests probably will show small amounts of tension, since the gas content for the pressure tests ranged up to saturation and no attempt was made to reduce impurities. Ordinary tap water (sometimes later degassed) was used. In lieu of more exact knowledge, it has been assumed that all taps within the cavitating region are affected to the same extent. The only precise method for obtaining a pressure measurement in a region of highly developed cavitation known to the authors involves the use of a flexible membrane between the tunnel fluid and the test gage fluid as developed by Kermeen, et al.[10]

Previous literature[10,11,12,13] shows

a) The existence of underpressures of the same order of magnitude observed here.[10,12,13]

b) An increase of underpressure with velocity nearly sufficient[11] to give constant negative cavitation number; a greater velocity effect;[12] a smaller velocity effect.[10]

c) An increase of underpressure with decrease in air content;[11,12] no significant change.[10]

d) Much higher negative pressures if great care is taken to minimize undissolved gases.[13,14]

D. Venturi Loss Coefficient Correlation

Venturi loss coefficient is herein defined as the ratio between static pressure drop across the venturi and kinetic pressure based on average throat velocity. It is very sensitive to cavitation condition, beyond the initiation stages, because of the deterioration of diffuser efficiency with increased cavitation. Figures 22, 23, and 24 show this parameter plotted against throat Reynolds' number for sonic initiation, First Mark,

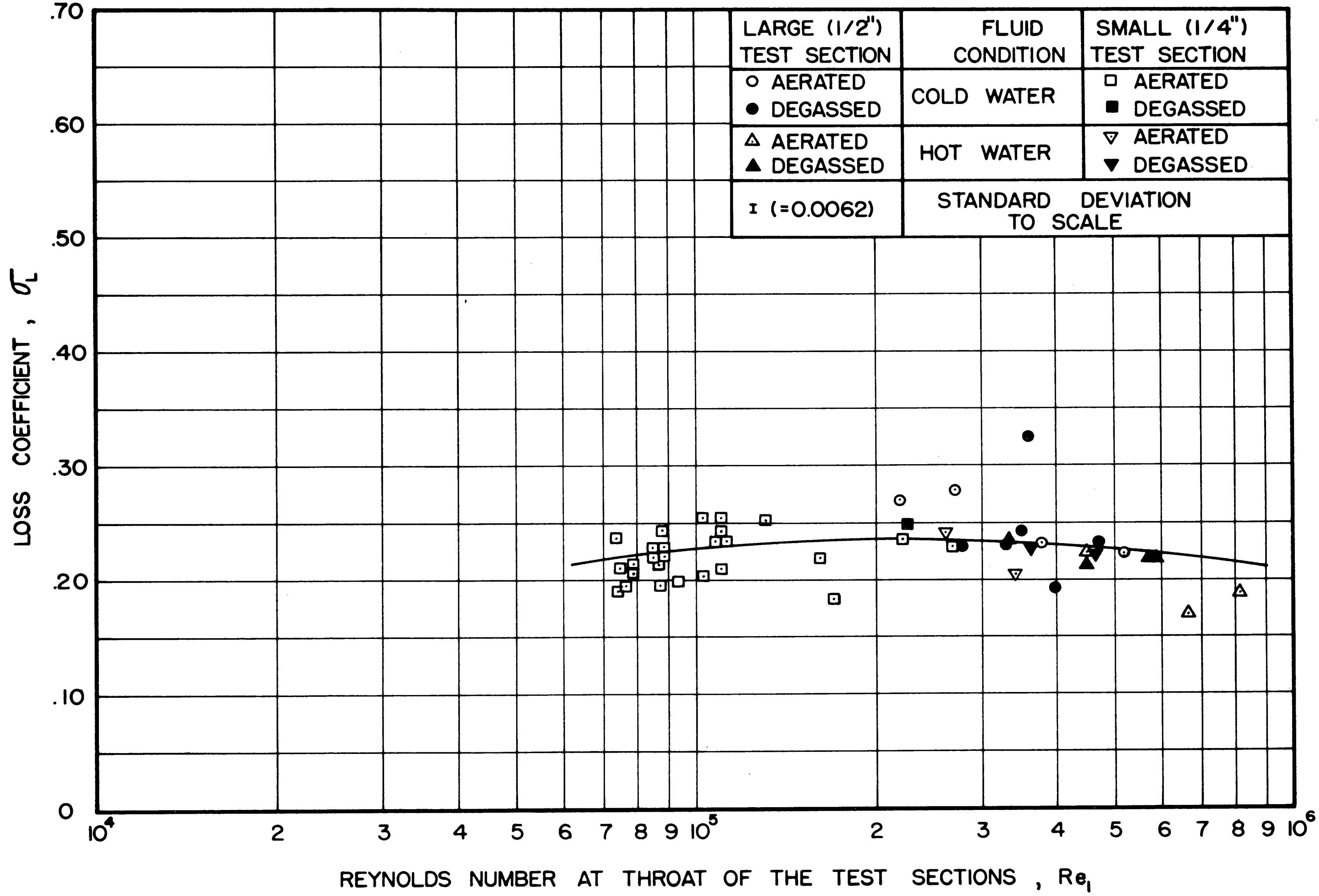

Figure 22. Loss Coefficient vs Throat Reynolds Number in a Cavitating Venturi for Sonic Initiation

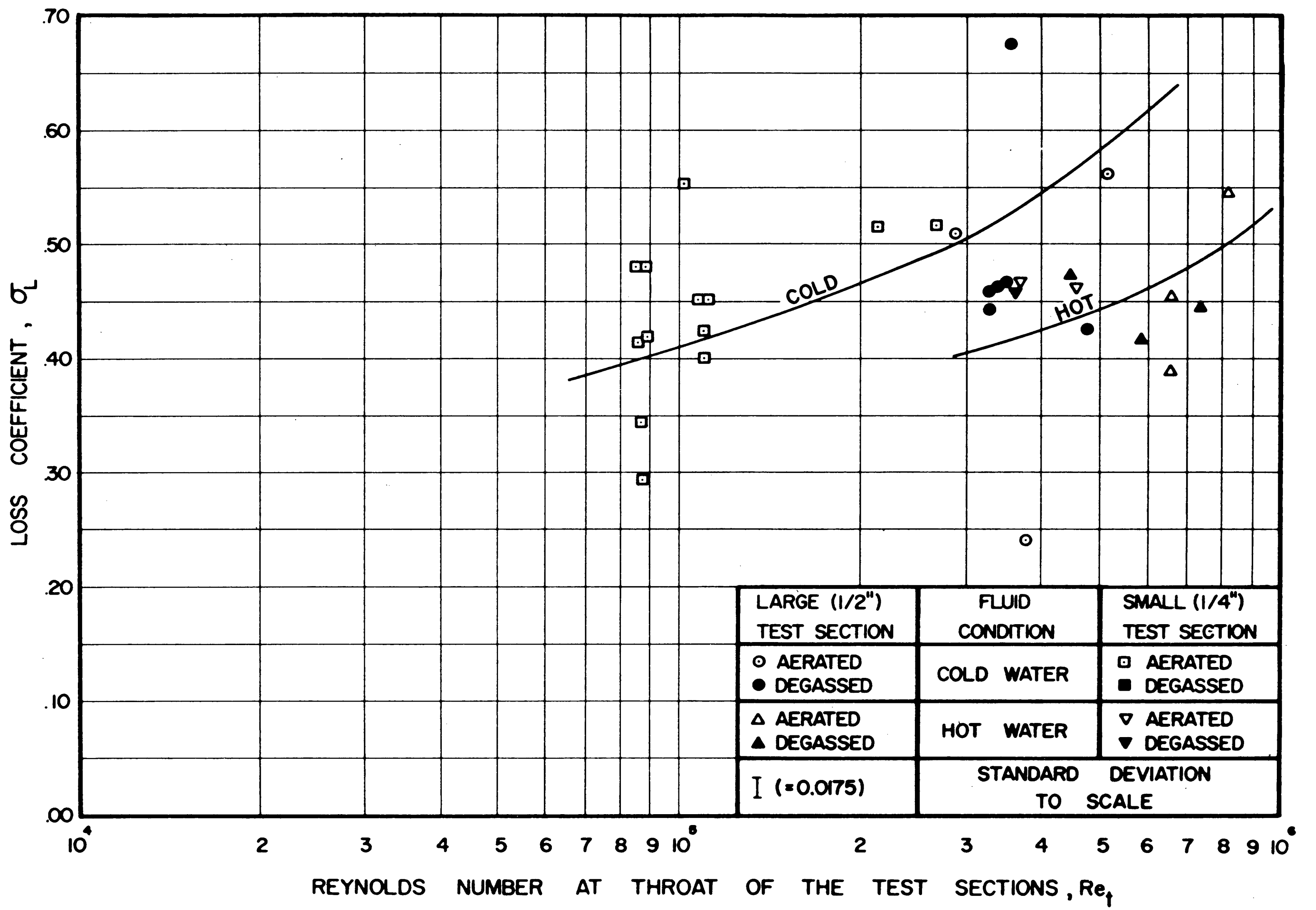

Fig. 23 Loss Coefficient vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to First Mark.

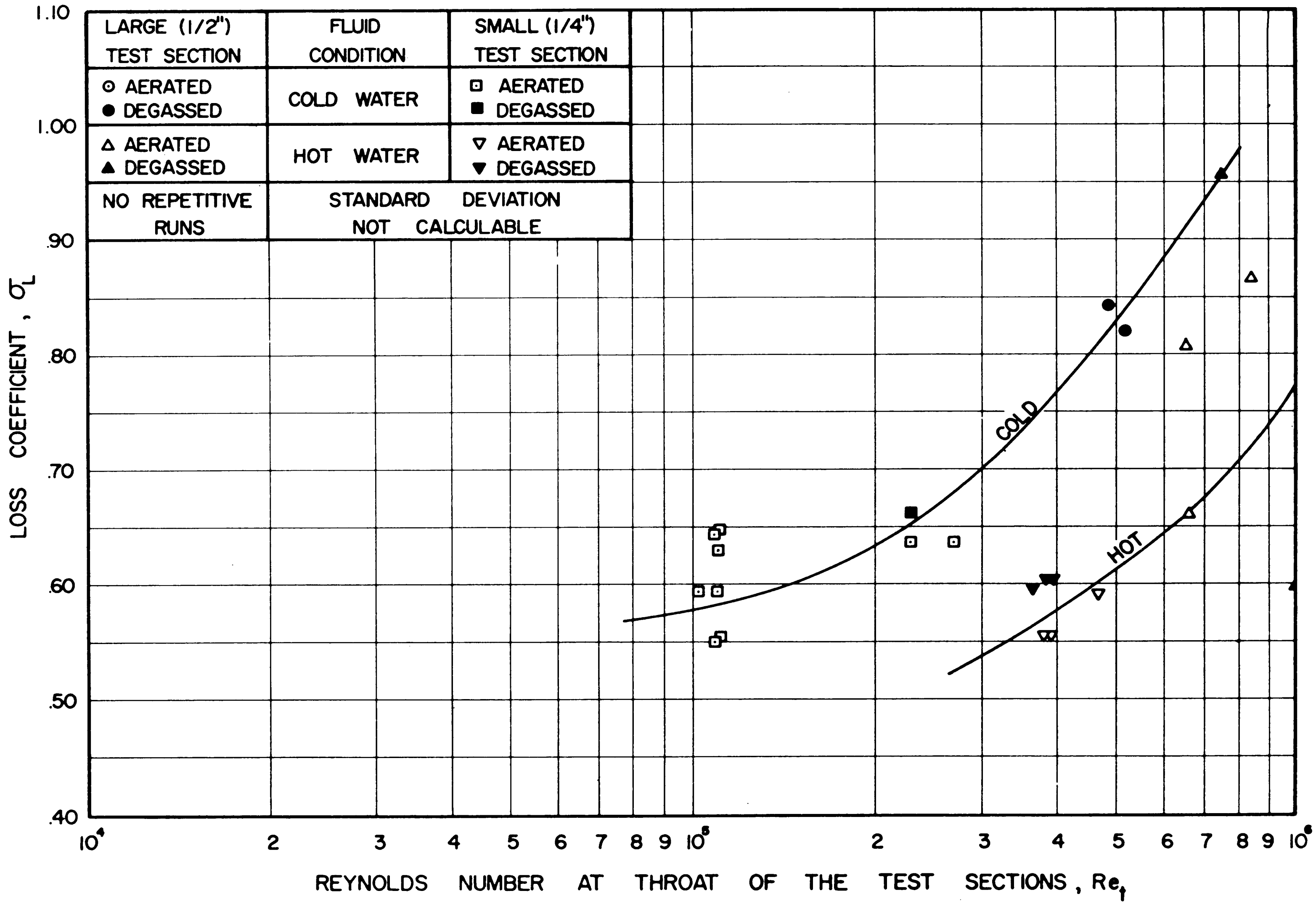

Fig. 24 Loss Coefficient vs. Throat Reynolds' Number in a Cavitating Venturi for Cavitation to Second Mark.

and Second Mark cavitation, respectively.[6] Sonic initiation is more or less indistinguishable from single-phase flow, as expected, while visible is somewhat similar but shows considerably more scatter. The loss coefficient increases from approximately 0.23 for sonic initiation to the order of 0.5 for First Mark, and the order of 0.75 for Second Mark. Hence, it is apparent that, at least for well-developed cavitation, venturi loss coefficient is a much more sensitive index than cavitation number, and might well be used as an indication of the extent of cavitation in experiments with opaque test sections. Also, it might be expected to show more clearly than cavitation number the significant correlating parameters (Reynolds' number, etc.). An index of the same type is commonly used in describing the cavitation degree in a turbomachine, where a given percentage head loss is considered to coincide with a given extent of cavitating region.[15,16]

For the cases of cavitation initiation (or single-phase flow), loss coefficient correlates well with Reynolds' number as expected (Figure 22). However, the correlation for First Mark and Second Mark is much poorer than it is with cavitation number, requiring separate curves for hot and cold water. Generally, the loss coefficient in these cases appears to increase significantly for increased Reynolds' number as opposed to single-phase flow.

The lack of correlation with Reynolds' number alone, as opposed to the behavior of cavitation number, is believed due to the increased sensitivity of loss coefficient as an index. For this reason, the obtaining of more comprehensive loss coefficient data to assist in the specification of correlating dimensionless groups appears a fruitful approach.

1. Thermodynamic Effects

It is shown in Figures 23 and 24 that, for a given visually determined extent of cavitation, and for a given throat Reynolds' number, the loss coefficient is greater for cold than for hot water. This implies a greater vapor volume for cold water than hot under these conditions, and hence is consistent with vapor volume calculations based on equilibrium conditions, using the approach suggested by Stahl and Stepanoff[15] and others. Such a difference between cold and hot water vapor volumes for a given cavitation condition was actually measured in the void fraction tests.[5]

IV. CONCLUSIONS

The most significant conclusions from this report appear to be the following:

i) The flow pattern in cavitating venturis of the general configuration tested (cylindrical throat, 6° diffuser angle, throat Reynolds' number well above laminar-turbulent transition), with water at moderate temperature as fluid, is substantially that of a separated jet, followed by a "hydraulic jump" or "condensation shock," after which ordinary single-phase diffusion proceeds. However, the vaporous region around the jet is not a clear cavity but rather a region filled with numerous vapor bubbles, ranging from very small to diameters approaching 1/2 the venturi throat diameter, travelling at velocities only slightly less than jet velocity. The extent of the vaporous region is not sharply defined, and oscillates very rapidly with time.

ii) Cavitation number for various degrees of cavitation can be correlated approximately with Reynolds' number, generally decreasing as Reynolds' number increases. However, the scatter of the data around the best curve on such a plot is considerably greater than can be explained by experimental error (increasing for low Reynolds' number, and decreased cavitation degree), so that it appears that parameters other than Reynolds' number must be of substantial significance.

iii) Cavitation number applying to sonic initiation as well as the more advanced cavitation degrees, has been observed with minimum wall static pressure substantially above vapor pressure (except 2nd Mark) as well as substantially below (depending on Reynolds' number); maximum of about 6 feet above for sonic initiation. The effect of gas content was not significant. High gas contents appeared within the limited data to create more scatter but only for cavitation initiation conditions, especially at low Reynolds' number. The tests covered ranges of about 2:1 in velocity, throat diameter, and viscosity. Temperature was varied from about 50 to 160°F.

iv) Venturi loss coefficient could only be correlated in terms of Reynolds' number for cavitation initiation and single-phase flow. For more developed cavitation conditions, separate curves were required for throat diameter and water temperature, so that the only correlation was with velocity. That cavitation number correlated with Reynolds' number, and loss coefficient did not, is believed due to the fact that loss coefficient is a much more sensitive index.

v) The differentiation between hot and cold water in the loss coefficient (and void fraction) tests was in the direction predicted by thermodynamic equilibrium calculations.

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