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GAS CONTENT, SIZE, TEMPERATURE AND VELOCITY EFFECTS ON CAVITATION INCEPTION

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ABSTRACT

The results of a comprehensive investigation into the effects of several variables on cavitation inception primarily, in a venturi, are reported. These include total air content, venturi throat size and velocity with water as the test fluid. The effects of gas content, venturi throat size, surface roughness, velocity, and fluid temperature, with mercury as the test fluid are also examined. The data was correlated using a computerized least mean square regression analysis. A final correlation of all measured cavitation numbers with Reynolds number, based on venturi throat diameter and velocity, is also included.

ACKNOWLEDGMENTS

The authors would like to thank Michael P. Rothstein, Dr. Willy Smith, Richard A. Robinson, and Ronald Koopman for their work with the computer programs used for the correlations of the data and for the performance of some of the tests. Financial support for this investigation was provided by both NASA and Atomics International under Atomic Energy Commission sponsorship. Much auxilliary equipment was provided by the Nuclear Engineering Department of the University of Michigan.

TABLE OF CONTENTS

NOMENCLATURE

σ_c	Cavitation Number
P_{min}	Minimum Observed Static Pressure
P_v	Vapor Pressure of Working Fluid
ρ	Density of Working Fluid
V_t, Vel., V.	Free Stream Velocity in Venturi Throat
σ_L, L.C., l.c.	Loss Coefficient
Vol%, G.C.	Gas Content in Volume Percent
Temp., T	Temperature of Fluid

LIST OF TABLES

LIST OF FIGURES

Figure | Page

CHAPTER I

INTRODUCTION

In the past there have been only a few attempts to examine the effect of gas content on cavitation in fluid-handling machinery such as centrifugal pumps, hydraulic turbines, etc. However, it is to be expected that there are significant influences both upon cavitation damage and performance effects. The present paper is concerned only with these latter aspects.

The effect upon cavitation number, both for inception and more fully-developed cavitation, of varying gas contents in cavitating venturis in both water and mercury is examined. Venturis were used for this purpose since they provide a relatively simple flowing system but still one which is similar enough to the flow geometry of many fluid-handling components so that the results should add to the basic understanding of the cavitation phenomena as it exists in such devices. In addition, the venturi results are compared where possible with results obtained in pumps.

While no clear-cut understanding of the effects of gas content upon a flowing cavitating system exists, it is evident that the relationships are very complex, and are bound up with the general group of phenomena usually labelled "scale effects," i.e., the observed departures from classical scaling relations in cavitating systems due to changes in velocity, size, temperature, etc. Thus the effects of variation in gas content cannot in general be looked upon apart from the effects of varying the other parameters which together control the cavitating flow regime.

It is expected on theoretical grounds that entrained gas rather than dissolved gas will be important in influencing cavitation inception in a flowing system. Since the lifetime of a cavitation bubble in such systems is typically very short (order of milliseconds), essentially only that dissolved gas which is within the liquid volume which actually vaporizes to form the bubble can be involved. Since the saturation content of most gases in liquids is only a few ppm by mass, the dissolved gas can in most cases form only a small portion of the bubble contents. Entrained gas, however, is of very great importance in bubble nucleation since it provides the interface (or "nucleus") necessary for rupture of the liquid to occur under the very limited tensions which have been observed to exist in such systems. Assuming that in most cases a cavitation bubble will grow from such an entrained gas nucleus, the entrained gas portion of the contents of the bubble may be relatively substantial. Thus in any investigation of gas content effects upon cavitation initiation it is obviously desirable to measure the entrained and dissolved portions of the total gas content separately.

Under the present state of the art a good determination of the entrained portion of the total gas content in most liquids is difficult. It cannot be well inferred from the total gas using known solubility coefficients, since the dissolved gas is typically almost the entire quantity, and the existence of an equilibrium gas-liquid solution in a flowing system cannot be assumed due to pressure and/or temperature gradients within the system. Thus the development of a simple laboratory instrument capable of measuring only the entrained gas content is highly desirable. Approaches for the development of such an instrument have used either the absorption of acoustic energy in appropriate frequencies by gas bubbles[1] or visual techniques.

The use of mercury as a test fluid, as herein discussed, provides the investigator with an inherent advantage in this respect, since the solubility of most common gases in mercury is essentially zero. Thus the total gas and entrained gas quantities are equal. This fact has been utilized in the present investigation.

CHAPTER II

EXPERIMENTAL FACILITIES AND TECHNIQUES

A. Major Facilities

Two closed loop venturi facilities,[2] one suited for mercury operation up to 600°F and 55 ft./sec., and one for water to 150°F and 220 ft./sec. have been used. Both were fitted with devices for injecting gas[3,4] and both have the capability for limited degassification. This is provided in the water facility by a cold-water vacuum deaerator in a bypass loop, and occurs naturally in the mercury facility due to the disentraining action of the impellor of the centrifugal sump pump which drives the loop. Thus in both facilities it is possible to obtain steady-state gas content either by achieving a balance between injection and degassification rate, or, in the water loop, by attaining a desired gas content and then shutting down both injection and deaeration equipment.

B. Venturi Flow-Paths

Geometrically similar venturis (Fig. 1) were used for all the tests. The throat diameters ranged from nominal values of 1/8 to 3/4 inches. The length to diameter ratios of the cylindrical throats, and the converging and diverging cone

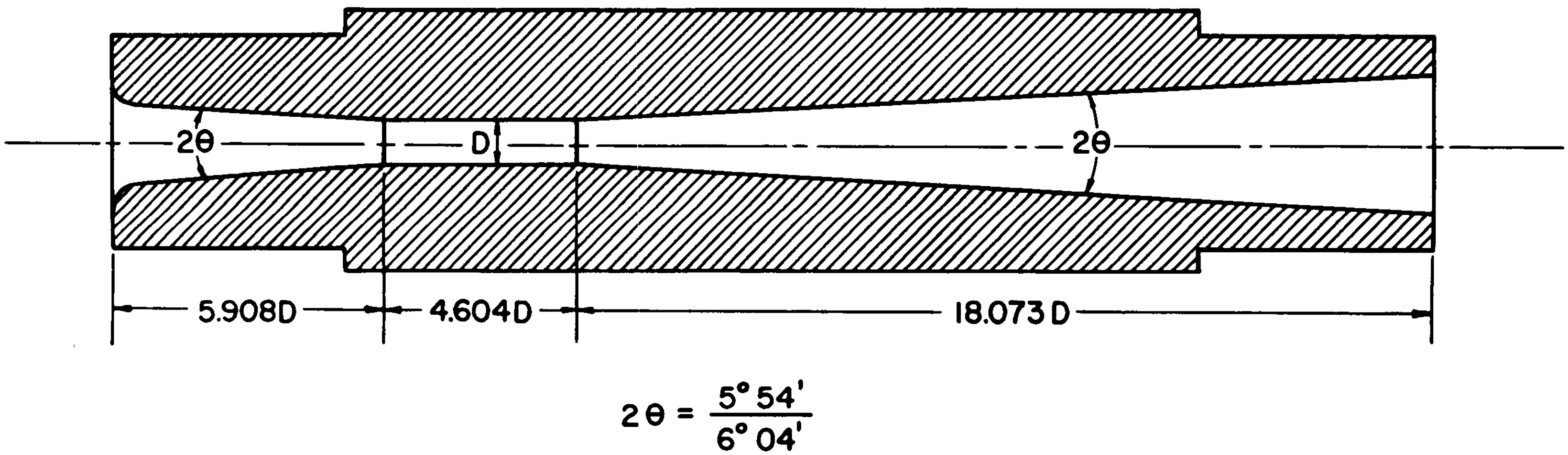

Fig. 1.--Basic venturi flow path dimensions.

angles in the vicinity of the throat, were maintained the same for all throat diameters. Detailed drawings, showing tap locations, adaptor configurations, etc. are presented elsewhere.[4] Pressure taps are located near the inlet and exit of the throat as well as being suitably spaced along the diffuser. Axial pressure profiles were obtained for all tests, and the minimum pressure from these profiles used for the calculation of cavitation number, here defined as

$$\sigma_c = (p_{min} - p_v)/\rho V_t^2/2g_o \quad - \; - \; - \; (1)$$

In general plexiglas venturis were used for the water tests and for the room temperature mercury tests. For the high temperature mercury tests (270°F and 400°F), stainless steel venturis with the same basic flow-path (Fig. 1) were used.

C. Gas Measurement Techniques

For the water tests the total gas content only was measured using a conventional Van Slyke apparatus. A fluid sample is removed from the loop from a tap near the venturi outlet and a measured volume subjected to vacuum in the Van Slyke. The sample is then agitated under vacuum to free the dissolved and entrained gas, which is then driven into a small calibrated volume wherein its pressure and temperature are measured. Assuming that the gas molecular weight is known, or can be estimated, it is then possible to compute the mass of gas which was associated with the original sample, and hence both the volume percent gas in the liquid and the mass percent (or ppm).

An entirely similar procedure was adopted for the mercury, using a suitably modified water Van Slyke. With these devices it was found possible to measure gas content in water down to about 0.1 volume percent with a precision of about ± 10% which is equivalent with air to about 1 ppm by mass. The same minimum volume percent could be measured in mercury with about the same precision. Due to the density difference between mercury and water, this is the equivalent of about 0.1 ppm in mercury.

It was also found possible to measure the volume of gas in mercury to about the same precision by allowing the gas in a mercury gas mixture within a standard capsule to expand from loop pressure to ambient and thus displace a volume of mercury into a calibrated capillary. By a comparison of this volume measurement to the mass measurement from the Van Slyke, it was found possible to infer the actual pressure under which the gas must have existed within the loop at the sampling point. By a comparison of this pressure with the measured loop pressure at that point and the use of the known value of surface tension in mercury, it was possible to estimate the mean bubble diameter of the entrained gas in the loop, assuming spherical bubbles.

D. Gas Injection Techniques

Only air was used for the water tests. It was admitted as desired by simply slightly opening a fitting located in a region where the pressure was sub-atmospheric. The water-gas mixture was then allowed to become homogenized by operating the loop for a few minutes. If it were desired to reduce the air content, the deaerator was used. It was found in general that no gas bubbles were visible under stroboscopic light illumination when the gas content was appreciably below saturation at STP (1.87 volume percent). Entrained gas was visible upstream of the cavitating region, which normally commences at throat discharge, for higher gas contents (Fig. 2). The mean radius of these bubbles is about 5 mils.

For the mercury tests the gas (air, argon, and hydrogen all were used) was injected through a hypodermic needle with tip flattened into a slit with an opening on the order of 0.1 mils. Preliminary tests in water showed that small, well-dispersed bubbles could be obtained in this manner. A typical bubble cloud in mercury upstream of the cavitating region of a plexiglas venturi has an average bubble radius of about 8 mils (Fig. 3). This is of the same order of magnitude computed using surface tension from the gas content measurement data previously discussed, if correction is made for the difference between the pressure at the loop sampling point and at the venturi throat where the bubbles were observed.

E. Cavitation Detection in Steel Venturi

In this study, cavitation number has been measured primarily for the inception* condition. It was established that "visible initiation" and "sonic initiation" (defined in the

*For these closed loop facilities, except for those cases where prepressurized water was used, it has not been possible to detect any difference between cavitation "incidence" and "desinence" as defined in the literature.[5]

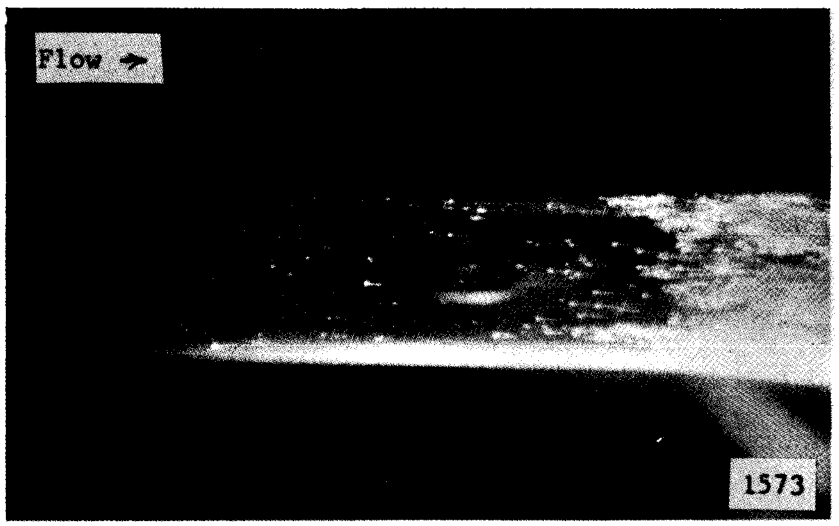

Fig. 2.--Typical photograph of air bubbles in 1/2" plexiglas venturi with water.

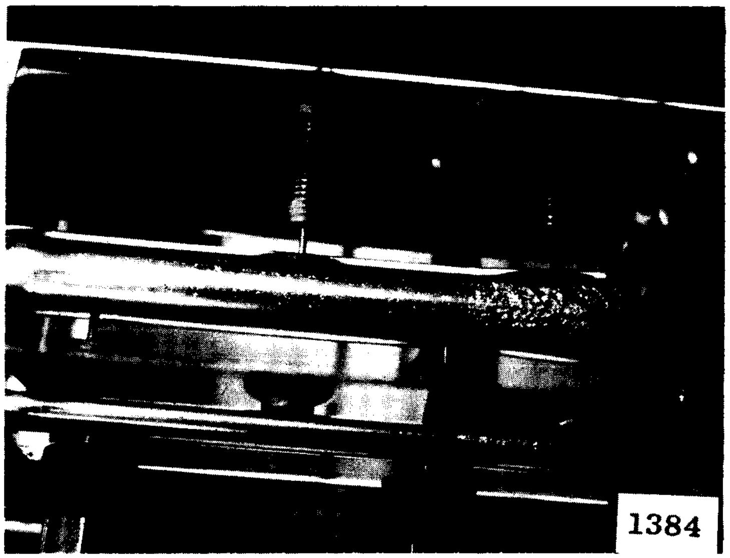

Fig. 3.--Photograph of argon bubbles in 1/2" plexiglas venturi with mercury as test fluid.

appendix) coincided within the experimental accuracy for those cases where it was possible to use a transparent (plexiglas) venturi. However, for the high-temperature mercury runs it was necessary to use a stainless steel venturi which is, of course, opaque. Due to the high-temperature, it was also not possible to use a simple stethoscope to obtain a sonic indication of cavitation as had been done for the low-temperature tests. Consequently, a "sonic probe", i.e., a 1/4 inch diameter steel rod, 12 inches in length with piezoelectric wafer cemented to one end, was firmly affixed to the venturi at the other end. The voltage signal generated by the wafer was observed on an oscilloscope and used to give an indication of cavitation inception. The details of this arrangement and the resulting signal for various cavitation conditions are reported elsewhere.[3] The signal was increased substantially by even very slight cavitation so that this method was a good indication of cavitation initiation. This was confirmed in the plexiglas venturi where it was found that cavitation inception as indicated by the sonic probe corresponded to "visual initiation."

CHAPTER III

SCOPE OF EXPERIMENTAL DATA

A. Water Tests

The scope of the data obtained in water is shown in Table I where it is indicated that 4 different venturis having nominal throat diameters of 1/8, 1/4, 1/2, and 3/4 inch were used. For each of these, data was obtained for 3 cavitation conditions as defined in the appendix, ranging from inception to well-developed.

As shown, the temperatures range from 50°F to 140°F and the throat velocities from 55 to 220 ft./sec. It was not always possible to obtain precisely a desired velocity, temperature, or gas content, although the cavitation conditions were set as precisely as possible. The effect of gas content variation over a range of about 1 to 3.5 volume percent for the other parameters approximately fixed as indicated in the table was explored. The lack of precise fixing of these variables necessitates the use of a computerized correlation to determine the effect of single variable changes, when all other variables are held constant as will be explained later.

TABLE I

DATA SET GROUPINGS AND RANGE OF EXPERIMENTAL VARIABLES FOR WATER TESTS

Venturi Number	Cavitation Condition	Temperature °F	Velocity ft./sec.	Problem Vol.%	Number L. C.
534	Sonic	80	70	1	
		80	100	2	4,5,6
		80	180	3	
534	Standard	60	100		
		80	70		
		80	100		
		80	182		
534	1st Mark	80	70	35	
		80	100	35	
		90	180	35	
412	Sonic	50	63	7	
		50	100		
		80	220		
		120	63	9	
		120	100	8	11,12,13
		120	220	10	
412	Standard	55	65		
		80	210		
		113	65		
		100	55	23	24,25,26
		100	120		
		140	212		
412	1st Mark	55	65		
		55	100	36	
		77	200		
		105	65		
		120	100		
		135	200		
614	Sonic	70	68	14	
		70	96	15	
		82	195	16	
614	Standard	65	70		
		65	100	27	29,30,31
		85	200		
		100	100	27	29,30,31
614	1st Mark	70	67		
		70	100		
		85	200		

TABLE I (Continued)

Venturi Number	Cavitation Condition	Temperature °F	Velocity ft./sec.	Problem Vol.%	Number L. C.
818	Sonic	65	75	17	
		65	100	18	20,21,22
		65	150		
		80	200	19	
		100	80		
		100	100		
818	Standard	60	76	32	
		65	100	33	
		75	200	34	
		100	80	32	
		100	100	33	
818	1st Mark	65	75		
		65	100		
		70	200		

B. Mercury Tests

The scope of the mercury tests is shown in Table II. Five venturis were used (2 of steel). These include 1/8, 1/4, and 1/2 inch nominal throat diameters. The injected gases were argon and hydrogen. These were mixed in the loop with a residue of air which could not be entirely removed, and in some cases, as will be explained later, with a trace residue of water. Due to loop limitations the throat velocity range used is only from 22 to 48 ft./sec. so that no overlap with the water data was obtained. Tests at about 80°F, 270°F, and 400°F were made. The gas content range investigated for the other loop parameters fixed was about from about 0.2 to 4.0 volume percent. Only the inception cavitation condition was investigated. The difficulty of obtaining precise selected values of variables other than cavitation condition for repeated runs necessitates computerized correlation of the data as already mentioned in connection with the water tests.

TABLE II

DATA SET GROUPINGS AND RANGE OF EXPERIMENTAL VARIABLES FOR MERCURY TESTS

Venturi No.	Gas	Temperature (°F)	Velocity (Ft/Sec)	Data Set No.
712	A	80	22	1
			34	2
		270	22	3
			34	4
		400	34	5
	H_2	80	34	6
		400	34	7
412	A	80	22	8
			34	9
			48	10
614	A	80	22	11
			34	12
			48	13
818	A	80	34	14
918	A	80	34	15
		400	34	16
	H_2	80	34	17
		400	34	18

CHAPTER IV

DATA REDUCTION

A. Experimental Measurements and Variables

The independent variables of the experiment are: cavitation condition, fluid, gas, throat velocity, throat diameter, throat roughness, temperature, gas content, and previous pressure history of the fluid, in that this latter effect may influence the distribution and size of gas "nuclei," and also their population density in the case of the water tests. The dependent variable is the axial pressure profile. As previously mentioned, the cavitation number, σ_c as defined by eq. (1), is computed from the axial pressure profile and throat velocity. In addition a loss coefficient, σ_L is defined:

$$\sigma_L = (p_{in} - p_{out}) / \rho \, V_t^2 / 2g_o \qquad - - - - \quad (2)$$

and computed from the same data.

Since the loss coefficient is highly sensitive to diffuser efficiency, it is a good measure of the degree of cavitation. It could then be used as a definition of cavitation condition, alternative to the visual or acoustic appearance of the flow, and ideally a one-to-one correspondence between these methods of definition should exist. The present data, however, shows that this is not always the case, partly due presumably to experimental error and partly to "scale effects." Since the pressure and flow measurements required to measure the loss coefficient are probably more precise than the subjective visual or acoustic signals used to set the cavitation condition, it may be argued that the data for presumably similar test conditions should be "corrected" to a constant loss coefficient basis. This procedure has indeed been followed in the computerized correlations to be described.

B. Preliminary Data Reduction

Various "preliminary" tests were conducted in both fluids designed to measure single-variable variation effects, e.g., in a specific venturi at a set velocity, etc., the effect of gas content change might be examined. These tests were generally run over a short time span and in a single venturi. Thus the condition of the fluid (especially important in water with its highly variable "nuclei" content even for a constant total gas content), the roughness of the venturi, etc. did not change. Hence, in retrospect, the data so obtained shows a higher degree of consistency than that derived from the computer correlations explained later. While these results are reported in detail elsewhere[3,4,11], the more significant curves are reproduced herein.

C. Computerized Data Correlations

As indicated in Tables I and II, a very comprehensive series of tests has been made over a long time period and using a large number of "geometrically-similar" venturis (but of course not exactly so when consideration of surface roughness, possible small discontinuities around pressure taps, etc. is made). As previously discussed, there are a very large number of independent variables, none of which can be set precisely, but which can indeed be measured quite precisely. In fact, the characteristics of the equipment are such that it is not feasible to obtain for some tests precise, preselected values of gas content, velocity, or, in some cases, temperature. For these reasons a computerized data correlation procedure, previously explained in detail[3,6], was employed.

The data (for each fluid) was grouped into several sets according to cavitation condition and venturi size. For water, e.g., with 3 cavitation conditions and 4 venturi sizes, 12 such sets result. It was then considered that cavitation number (within each set) was a function of velocity, gas content, temperature, and loss coefficient. A least mean square fit regression analysis was then used to generate a power series expression giving cavitation number in terms of these other variables:

$$\sigma_c = C_0 + \sum_{i=0}^{3} C_i(\sigma_L)^i + \sum_{i=0}^{3} C_i(\text{Vol.\%})^i + \sum_{i=0}^{3} C_i V^i + \sum_{i=0}^{3} C_i T^i \cdots \quad (3)$$

The effect of a single variable variation can then be determined easily by simply assigning "typical" constant values to the other variables in eq.(3). A relation between cavitation number and the variable of interest then results.

The data sets under each group were combined into "problems" (Tables I and II) where the cavitation number is a function of the independent variable of interest, and the remaining variables are held constant at their average value for the data of that problem. The actual group equations are reported elsewhere[4,6] and will not be repeated here.

CHAPTER V

RESULTS AND DISCUSSION

A. Preliminary Data Results

As already mentioned, "preliminary" data of limited scope was obtained, primarily with water, to explore and illustrate the effect of different single-variable variations. Since these tests were conducted over a short elapsed time period, several pertinent variables which affect the overall data set were effectively eliminated as previously explained. Hence, this data is in some cases more successful in illustrating anticipated trends that that which results from the more comprehensive data which was used for the computer correlations. A few of these "preliminary" results which seem especially significant will be presented. The remainder are found in references 3 and 4.

1. Gas Content Effects

Fig. 4 shows gas content versus cavitation inception number for water for 3 velocities in a 1/2 inch venturi. It shows clearly that cavitation number increases with increased gas content, but that the variation decreases for increased velocity. The first effect is certainly to be anticipated, while the second may result from the fact that dissolved gas,

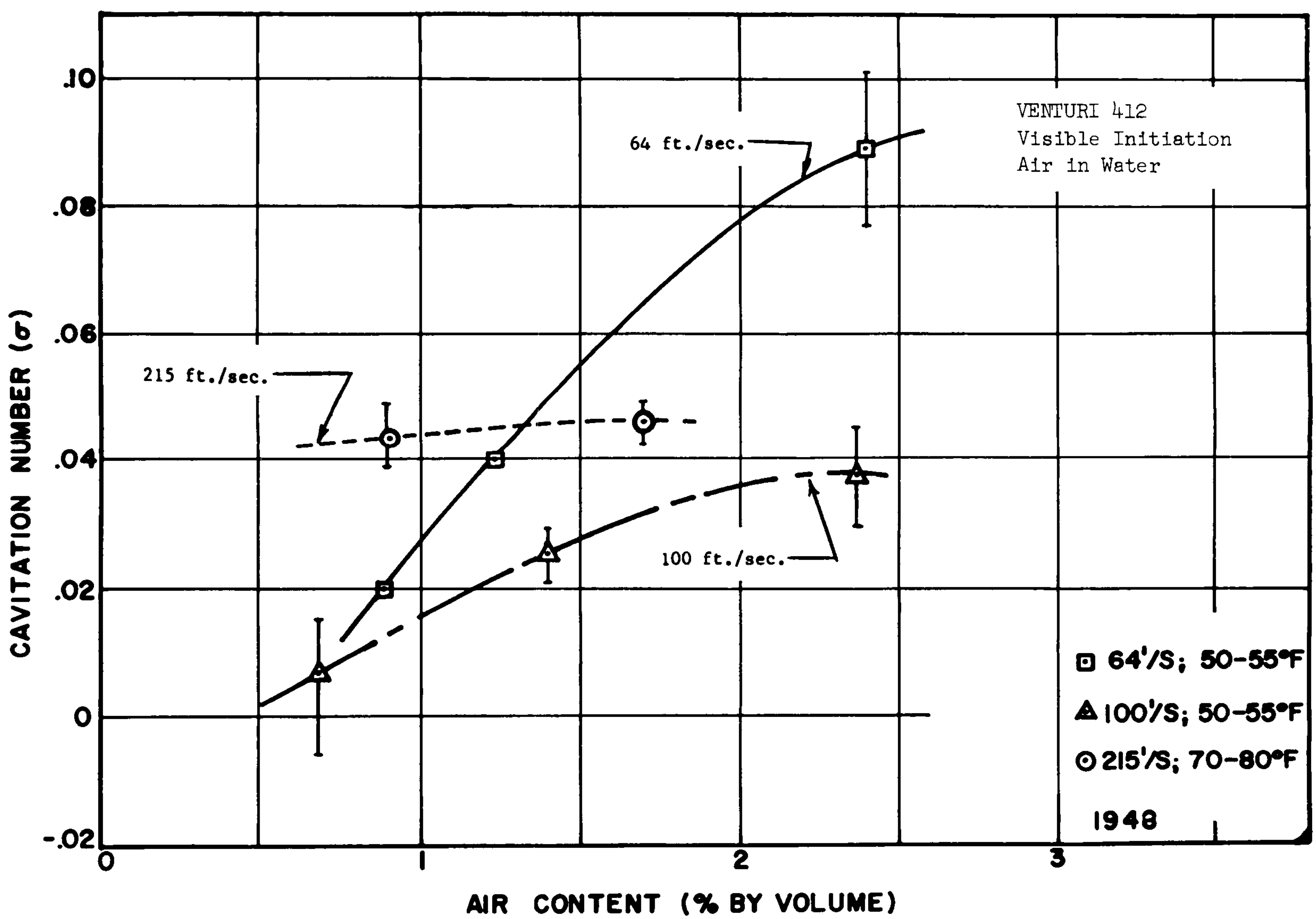

Fig. 4.--Cavitation number versus gas content for 1/2" plexiglas venturi with water at several gas contents..

which predominates in the water tests over the entrained portion, may have less influence at the higher velocities, since the time for solution effects is reduced.

A cross-plot of the same data into the form of cavitation number vs. throat velocity results in Fig. 5*, showing clearly the dependence of the velocity effect (upon cavitation number) on the total gas content. The higher gas content curves are typical of those previously obtained in this laboratory with air-saturated water[7], but over only the lower portion of the velocity range, where a substantial decrease of inception cavitation number with increasing throat velocity was shown. However, as indicated in Fig. 5, this trend only applies for the lower velocity, gas-saturated water, while the deaerated water generally shows an increase of cavitation number with velocity over the whole range tested. Since the minimum air content actually obtained in this data set was about 0.7 volume percent, the lower air content curves are extrapolations of the data and hence their reliability is somewhat in question.

Further confirmation of the behavior of approximately air-saturated water (in a 3/4 inch venturi) is afforded by Fig. 6.

Fig. 7 shows that the effect upon cavitation number of trace quantities of water in mercury, when taken on a volume percent basis, is much like that of gas. As in Fig. 4, the sensitivity of cavitation number to the impurity content is reduced as the velocity is increased. That water traces in mercury

*Reproduced from reference 8 for convenience.

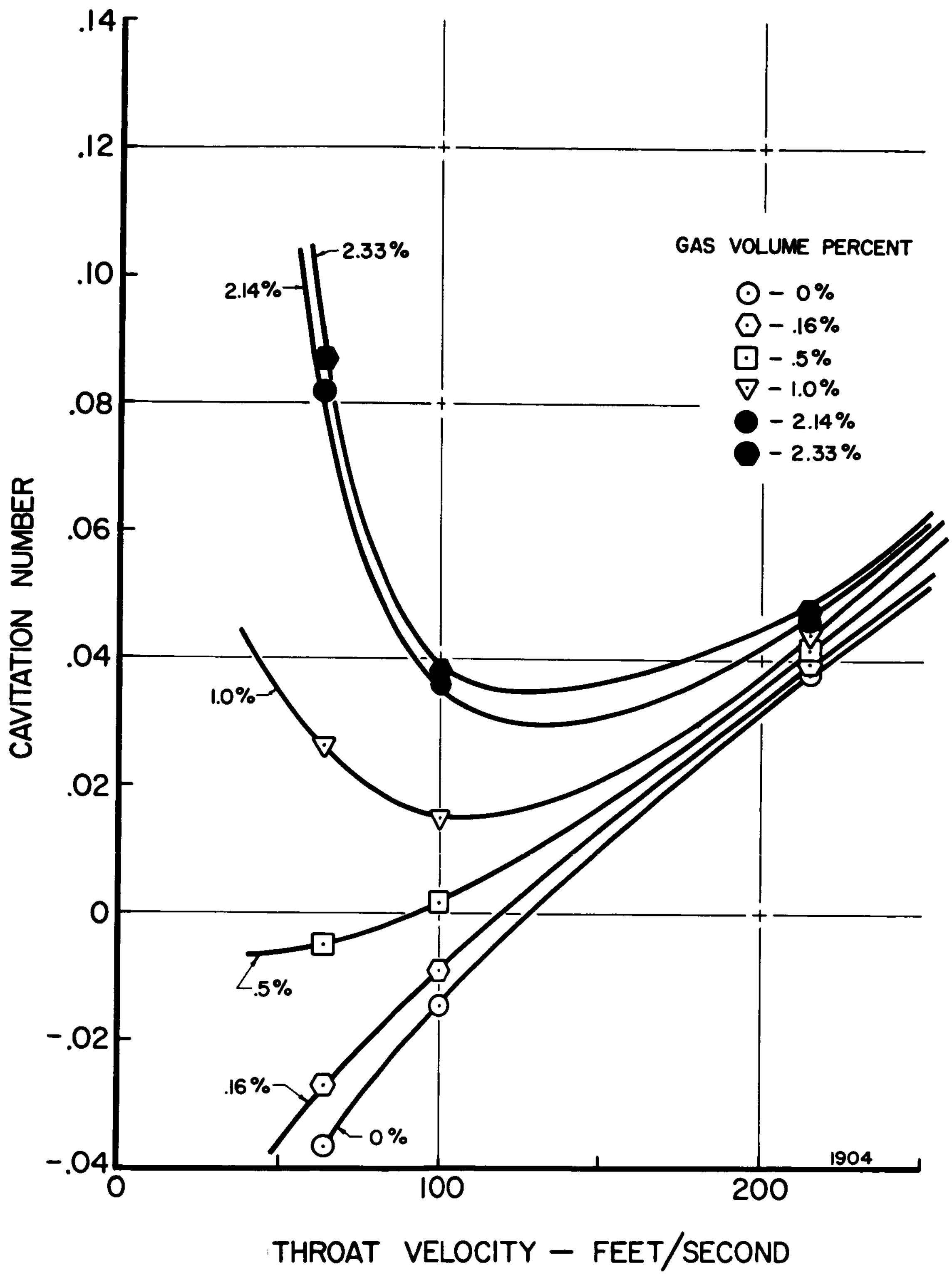

Fig. 5.--Cavitation number versus throat velocity for 1/2" plexiglas venturi with water at several gas contents.

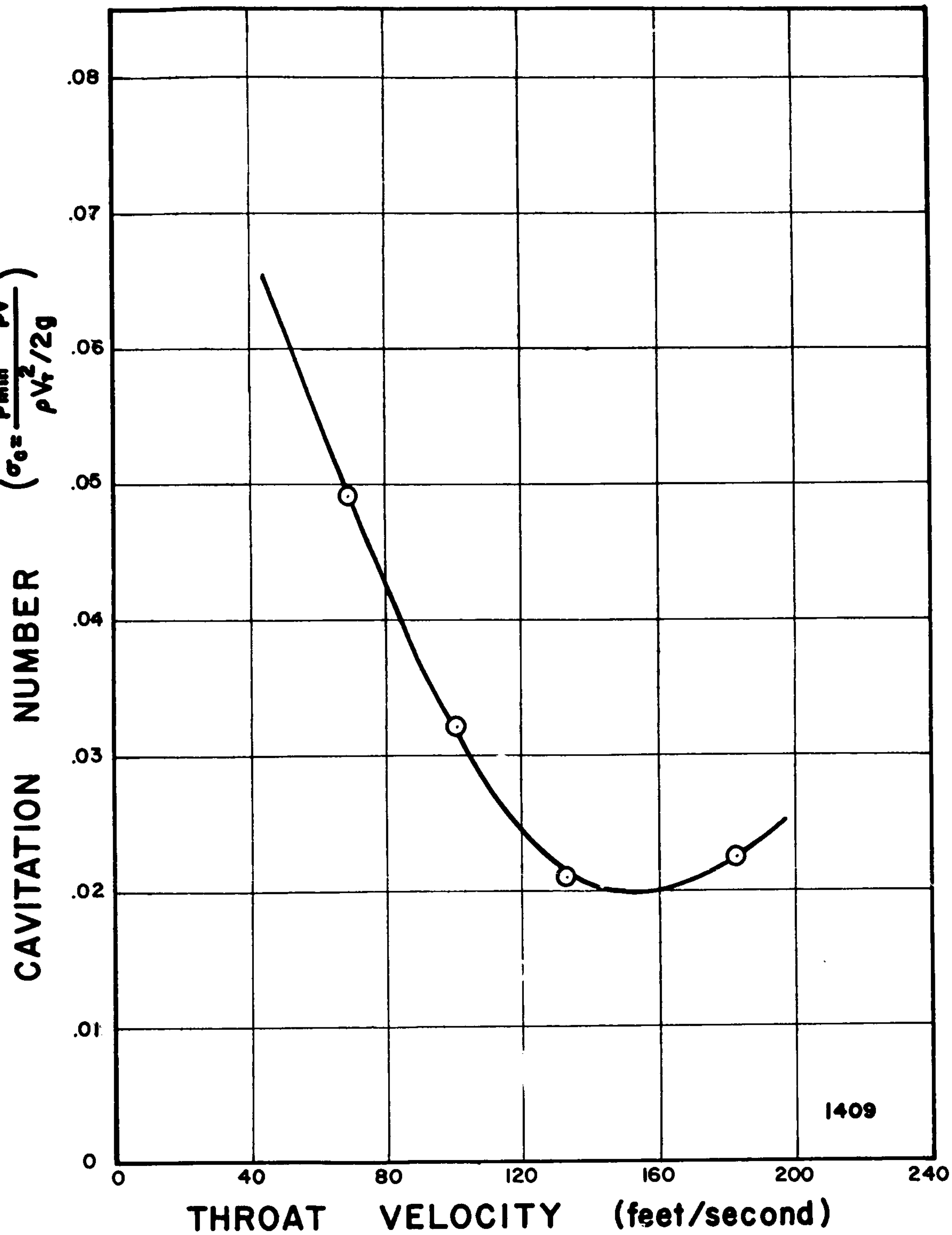

Fig. 6.--Cavitation number versus throat velocity for 3/4" plexiglas venturi with water.

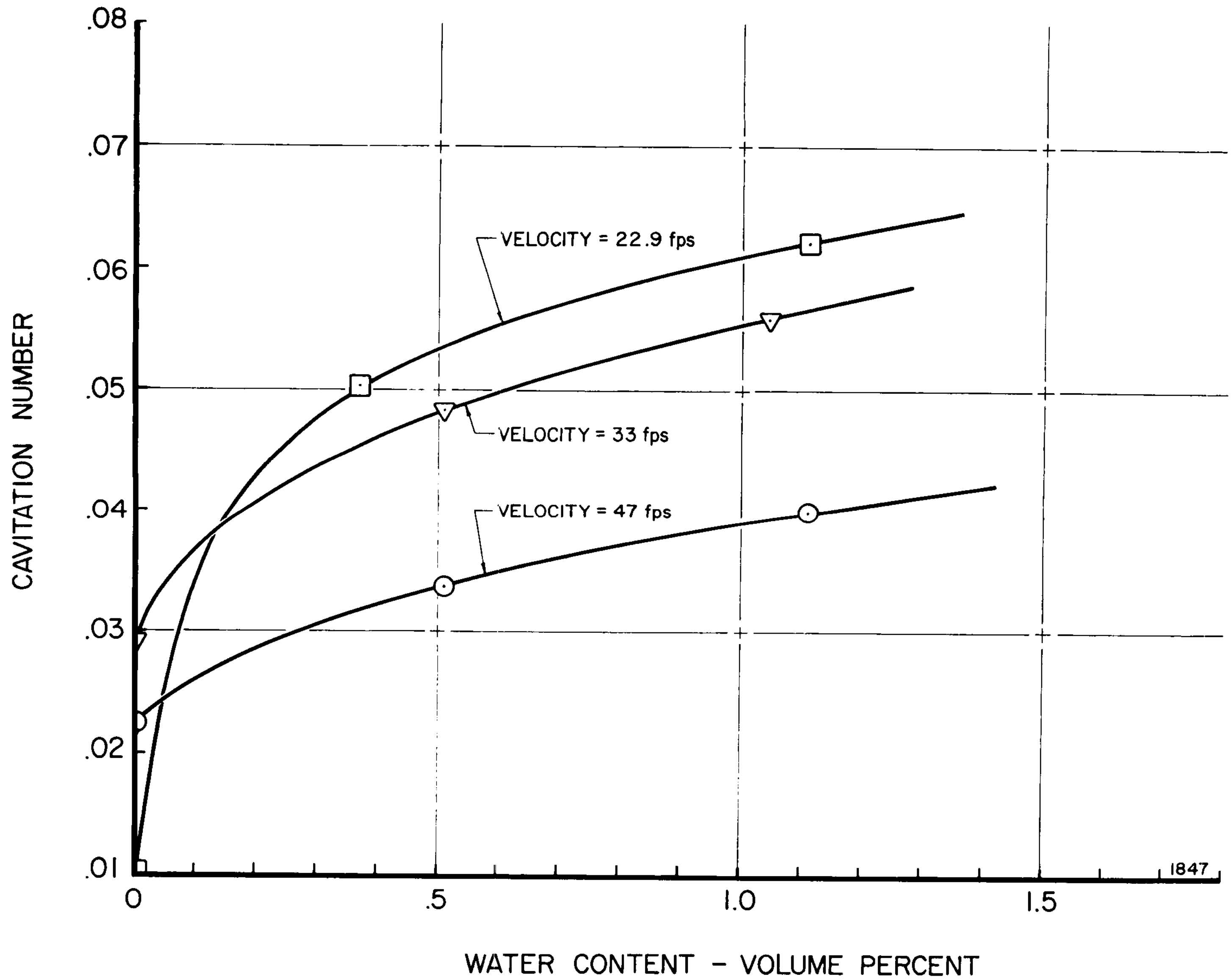

Fig. 7.--Cavitation number versus water content for 1/2" plexiglas venturi with mercury at several velocities.

act in a manner similar to gas is not surprising, since vapor pressure of water is so much greater than that of the mercury.

Fig. 7 also shows that the velocity effect in mercury for fixed volatile impurity content is similar to that for the low-velocity portion of the water data, in that cavitation number decreases as velocity increases. This is not surprising since all the mercury velocities are below the minimum water velocity.

2. Prepressurization Effect

Fig. 8 shows the effect of various prepressurization conditions of the loop water, which was approximately air-saturated at STP, upon cavitation inception number as a function of time after start of test. Cavitation inception was determined by approaching from the non-cavitating side, and then returning very quickly to non-cavitating operation once the inception pressure had been noted. As indicated in Fig. 8, the procedure was repeated several times after an appropriate elapsed time interval for each case. The significant variation of cavitation number with time as well as the substantial tensions measured in the water in one case are of interest.

Although no such tests were made in mercury, it would be expected that no prepressurization effect would be found due to the lack of significant gas solubility in mercury.

B. Computerized Correlation Results

The complete computerized correlation results are reported in references 3 and 4, so that only sample results illustrating the major trends will be included here.

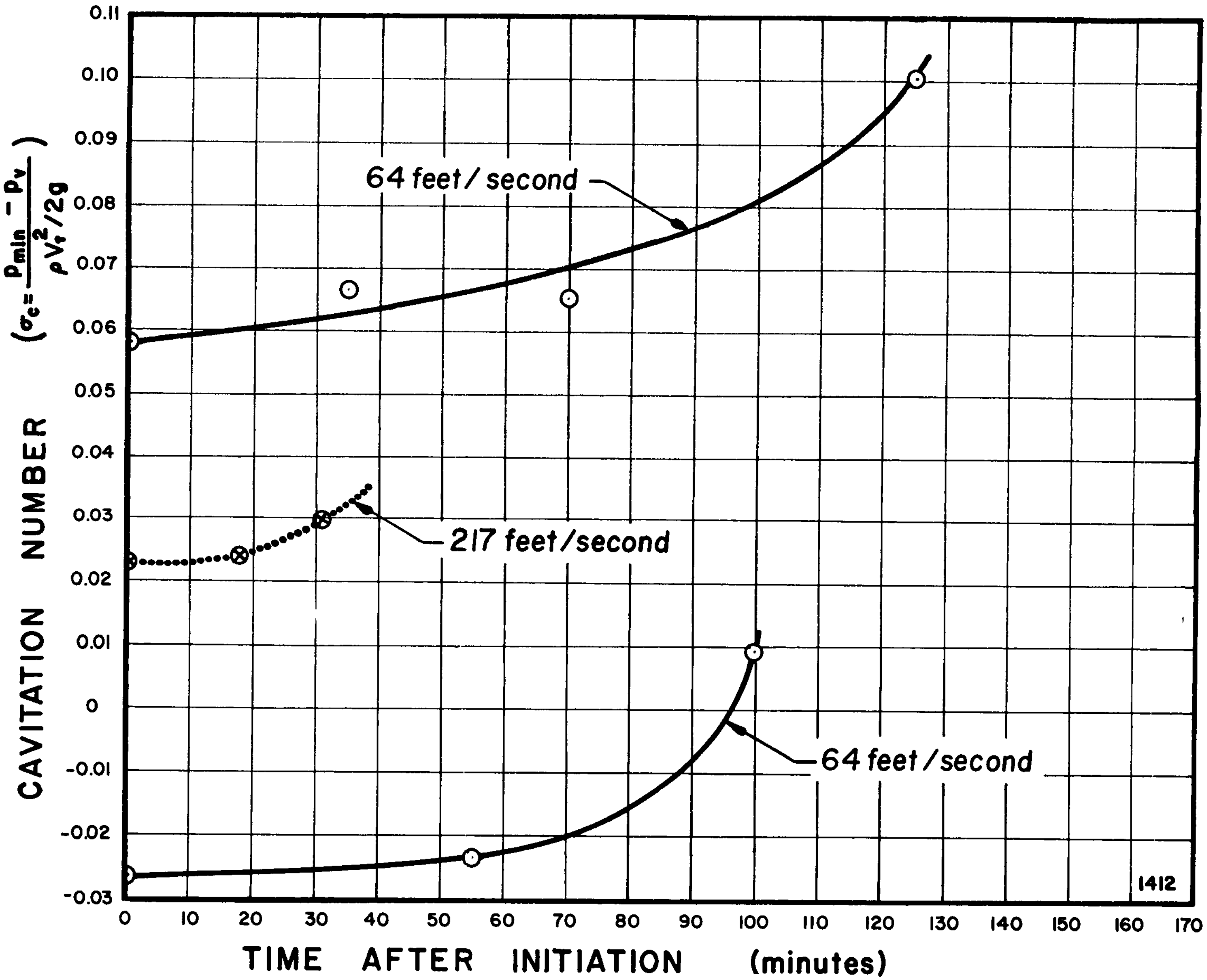

Fig. 8.--Cavitation number versus time after initiation for 1/2" plexiglas venturi with water at several velocities.

1. Mercury

A typical cavitation inception number vs. gas content curve, as generated from the computer correlations, is shown in Fig. 9 for argon at room temperature in a 1/2 inch steel venturi. As would be expected the cavitation number increases substantially with gas content over the range up to about 4% by volume. Of course, the zero percent point is unreliable since it is merely extrapolated from the minimum gas content actually obtained of about 0.2%.

Fig. 10 shows similar but more comprehensive information for the plexiglas venturi of the same size. This indicates that cavitation inception number decreases for increased velocity as with the high gas content low velocity water data (Fig. 5). However, in the mercury test this occurs for all gas contents. The different influence of gas content in mercury as compared to water on the velocity effects may be a result of the fact that the gas largely dissolved in water and entrained in mercury. Thus no time-dependent solubility effects exist in mercury.

Fig. 11 shows the effect of temperature on the cavitation number for various gas contents. For all gas contents, the cavitation number reaches a maximum for an intermediate temperature and then decreases substantially at 400°F. While the curve shown is for argon, similar results were noted for hydrogen. It is noted that the effect is most pronounced for the lower gas contents. The existence of the decrease in cavitation number for increased temperature is presumably a result of the well-

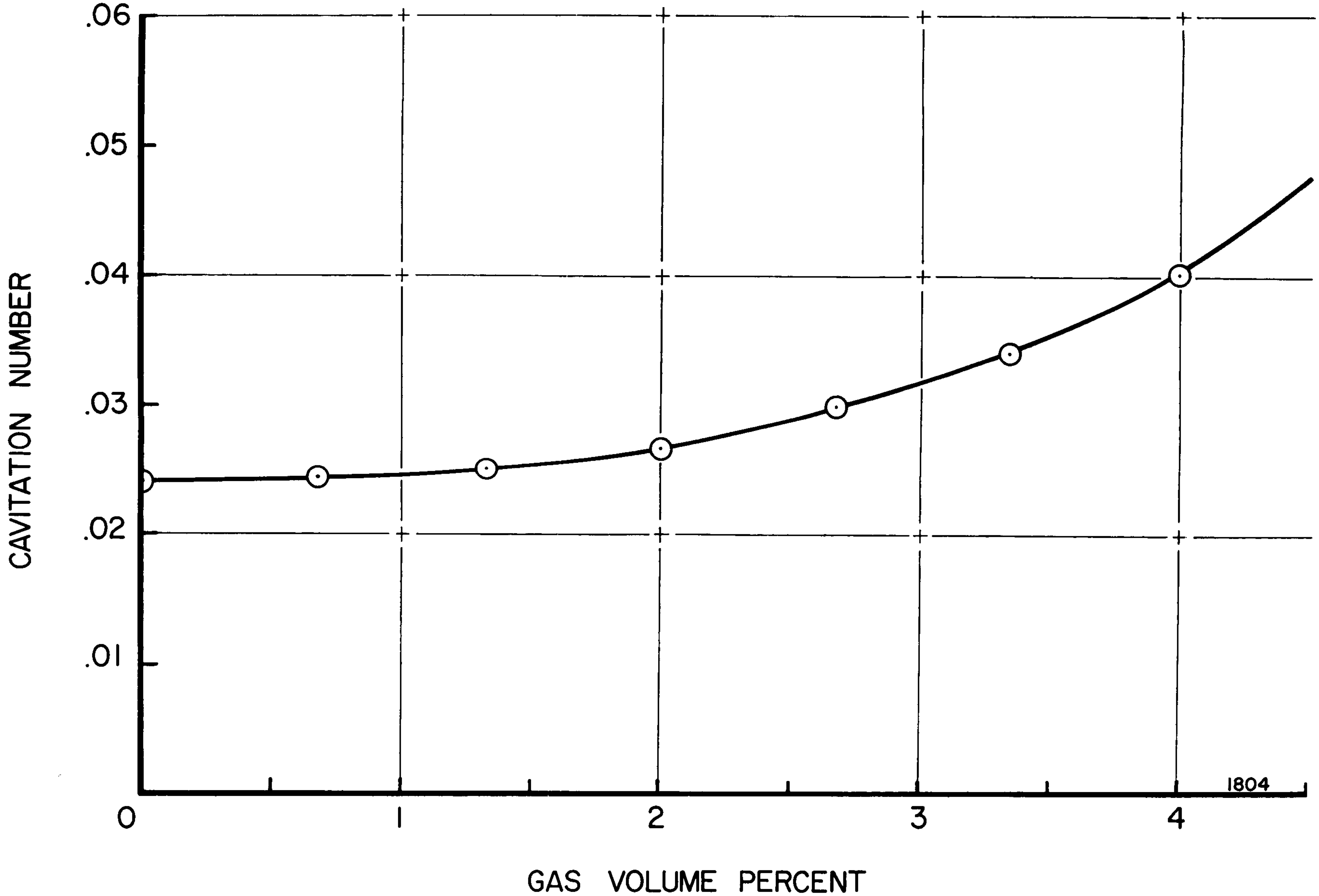

Fig. 9.--Cavitation number versus argon volume percent for 1/2" stainless steel venturi with mercury as test fluid.

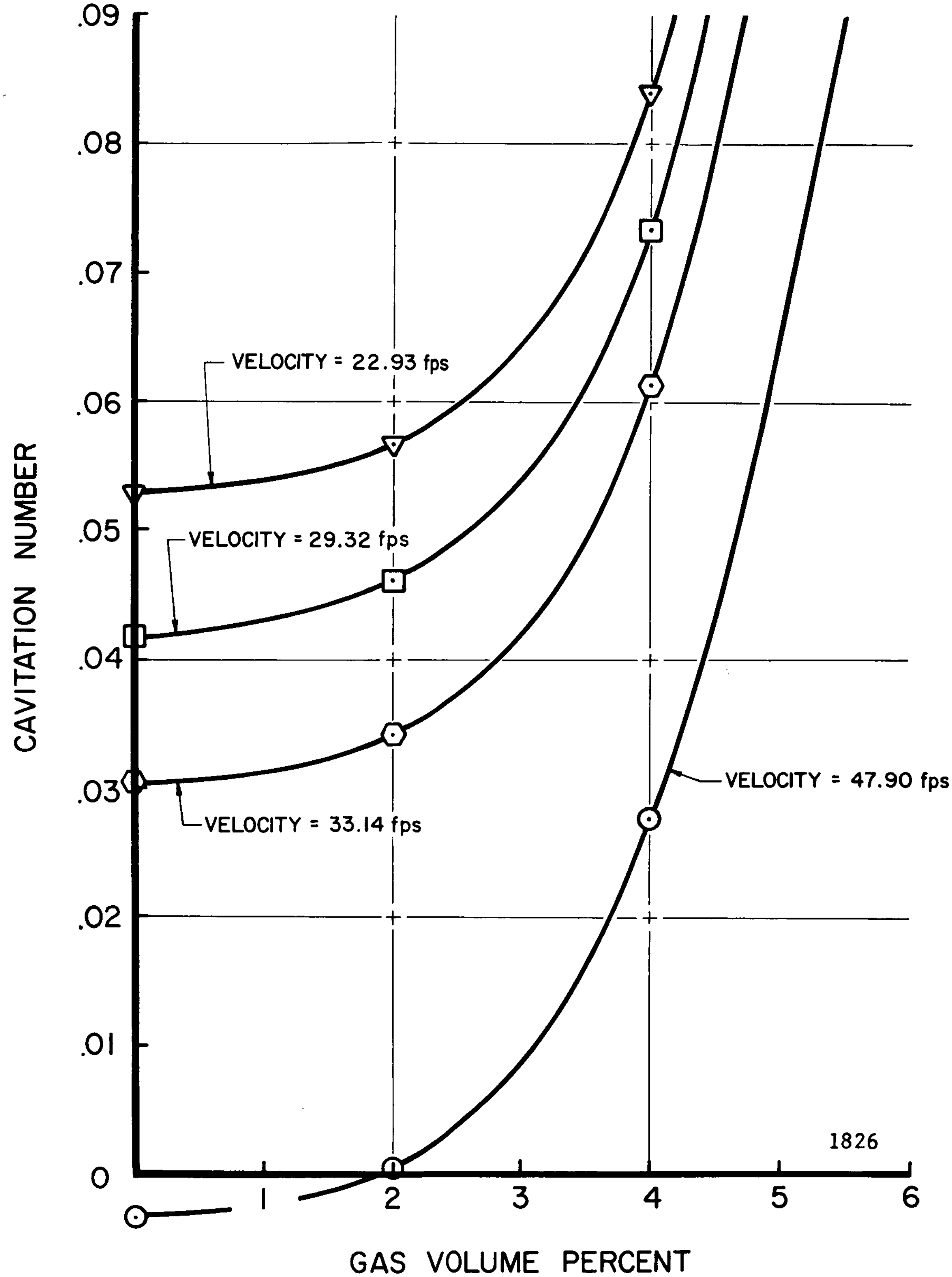

Fig. 10.--Cavitation number versus argon volume percent for 1/2" plexiglas venturi with mercury at several velocities.

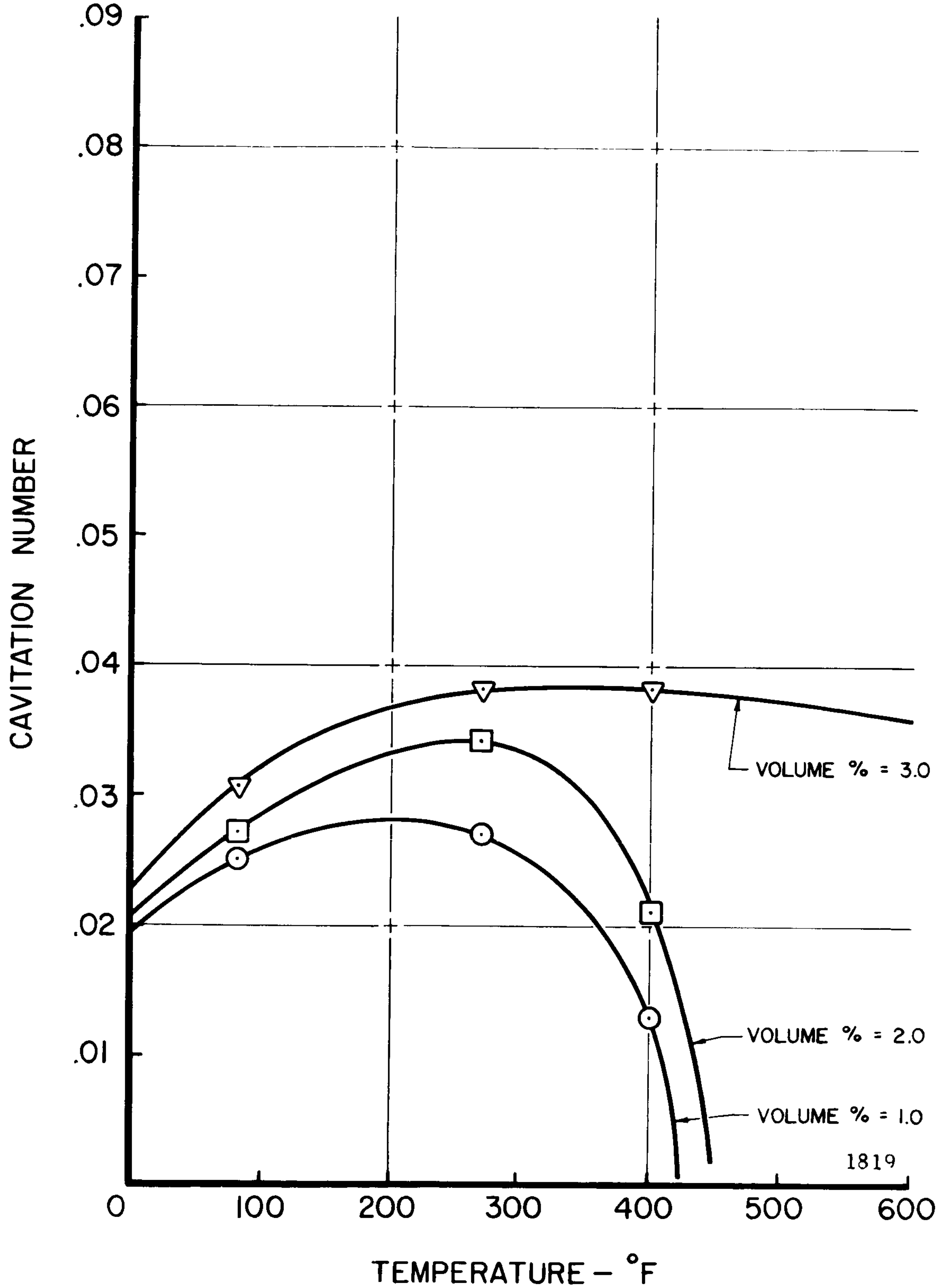

Fig. 11.--Cavitation number versus temperature for 1/2" stainless steel venturi with mercury at several argon volume contents.

recognized "thermodynamic effects"[9] since the vapor pressure of mercury at 400°F is becoming quite substantial. The fact that the effect is reduced for higher gas content is reasonable in that the effect of the vapor itself is proportionately reduced at higher gas content.

The effect of throat diameter upon cavitation number for various gas contents in the plexiglas venturi is shown in Fig. 12, while the typical effect in the stainless steel venturi is shown in Fig. 13. There is a net decrease in cavitation number with increasing throat diameter for the stainless steel venturi while for the plexiglas venturi there is a decrease in the range between 1/8 and 1/4 inch, but an increase again between 1/4 and 1/2 inch. As will be noted later (Fig. 17) the effect in the water data, also using a plexiglas venturi, is similar to that for the plexiglas mercury venturi. The difference observed in this regard between the plexiglas and steel venturis may be due to differences in relative roughness. Note that the effect of increasing diameter for the plexiglas venturis is similar to that previously mentioned for increasing velocity in gas-saturated water (Fig. 6) in that the cavitation number goes through a minimum. This similarity suggests the possibility of Reynolds number as a correlating parameter, as will be discussed later.

Fig. 14 shows large differences in cavitation number between tests using argon and those using hydrogen as injected gases, when compared, on a fixed volume percent basis. Although

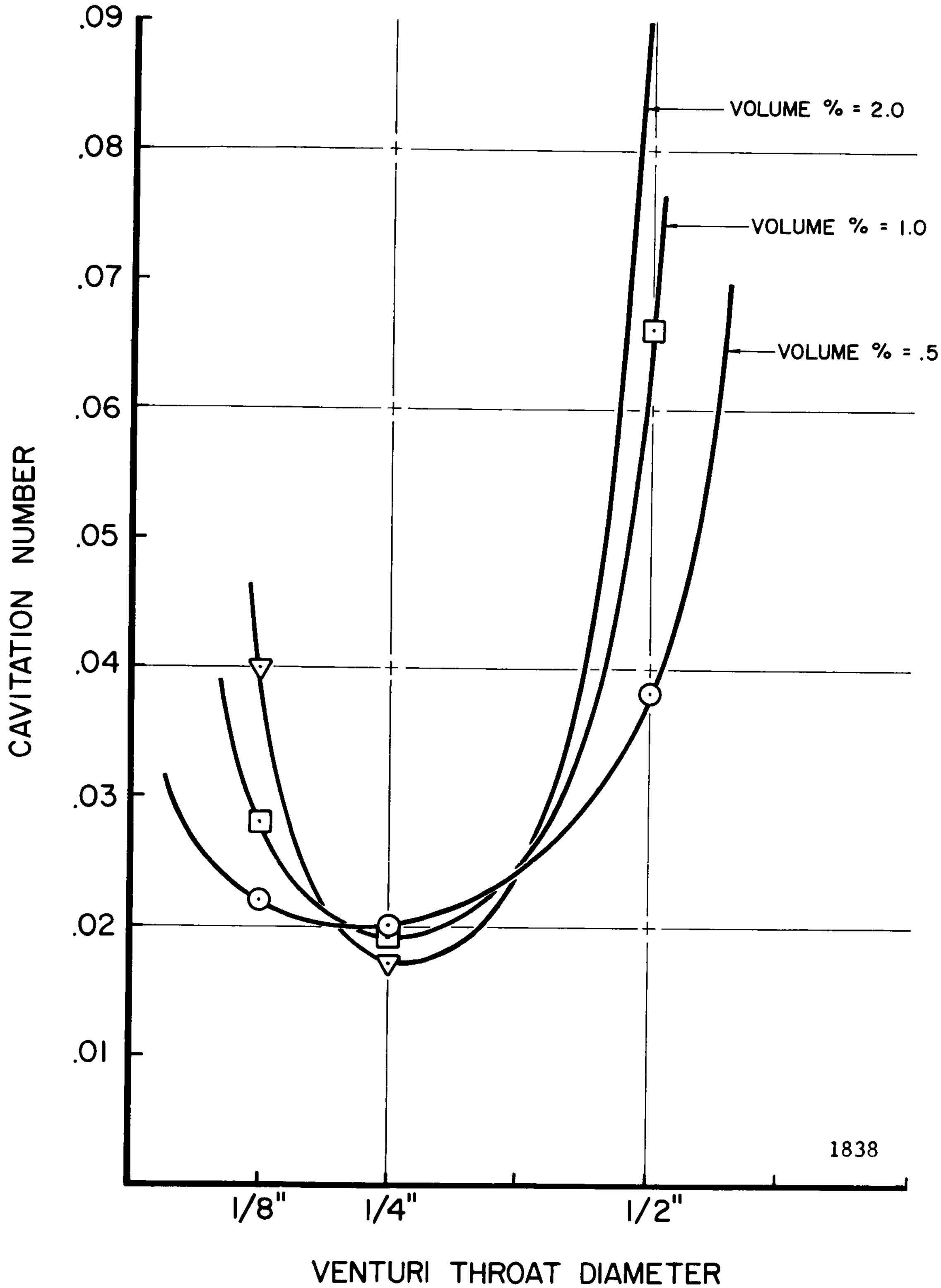

Fig. 12.--Cavitation number versus venturi throat diameter for plexiglas venturis with mercury at several argon-air volume contents.

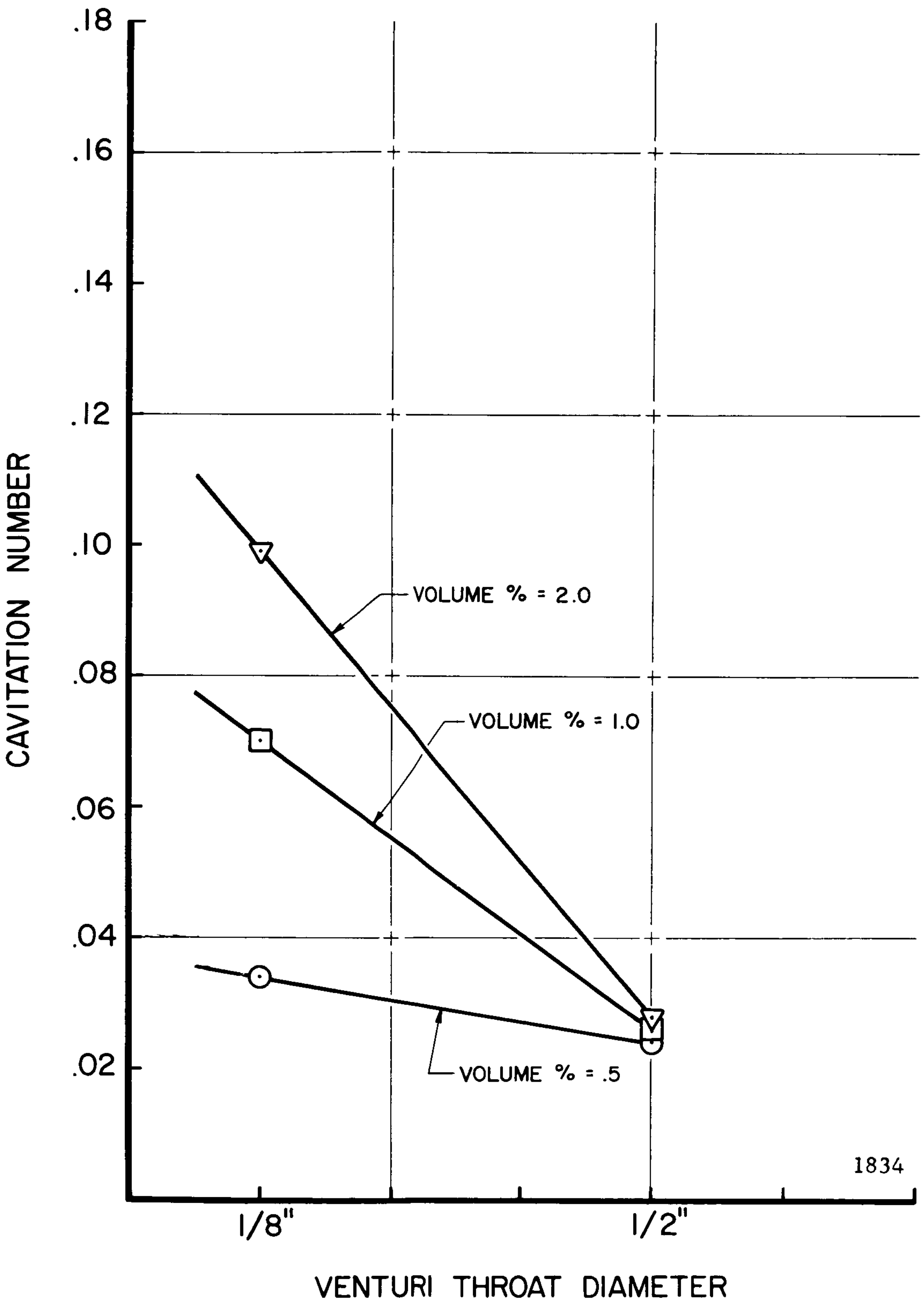

Fig. 13.--Cavitation number versus venturi throat diameter for stainless steel venturis with mercury at several argon-air volume contents.

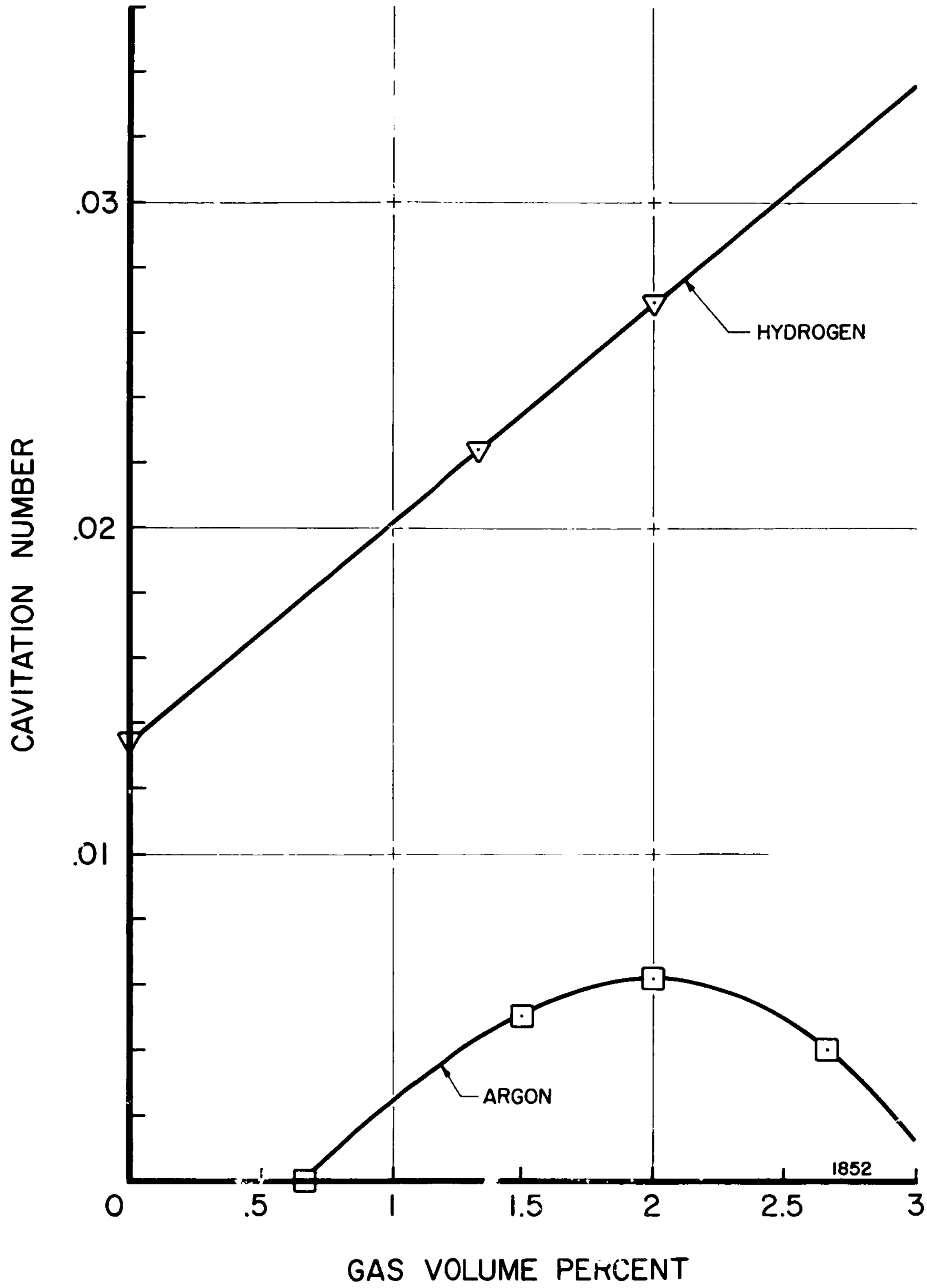

Fig. 14.--Cavitation number versus gas volume content for 1/8" stainless st-el venturi with mercury, argon-hydrogen comparison.

substantial differences were encountered in all the tests between these two gases, the difference is most exaggerated in Fig. 14. This difference was unexpected, and the explanation is not known. It is believed that it may be due to a difference in mean bubble size between the two fluids, perhaps due to differences in interfacial tension between the two gases and mercury, although the same injection equipment was used.

2. Water

The computerized correlation results with water are not as consistent as those obtained with mercury, or as the "preliminary" water results already discussed. It is believed that in general the water results are less consistent than those for mercury, because of the uncontrolled variable in the water tests (and not in the mercury tests) of the ratio between dissolved and entrained gas. It is also believed, as previously mentioned, that the "preliminary" water results are more self-consistent since the variables of water condition and venturi surface roughness are partially eliminated by the fact that the test series occur in only single venturis and over a small time span so that the same loop water sample is used. Although tap water was used in the loop, it is believed that solid impurity content is not of primary importance.

Full results are found in reference 4, and only typical results illustrative of significant trends are included here.

Fig. 15 shows typical curves of cavitation number vs. gas content. While the curves rise considerably toward the high

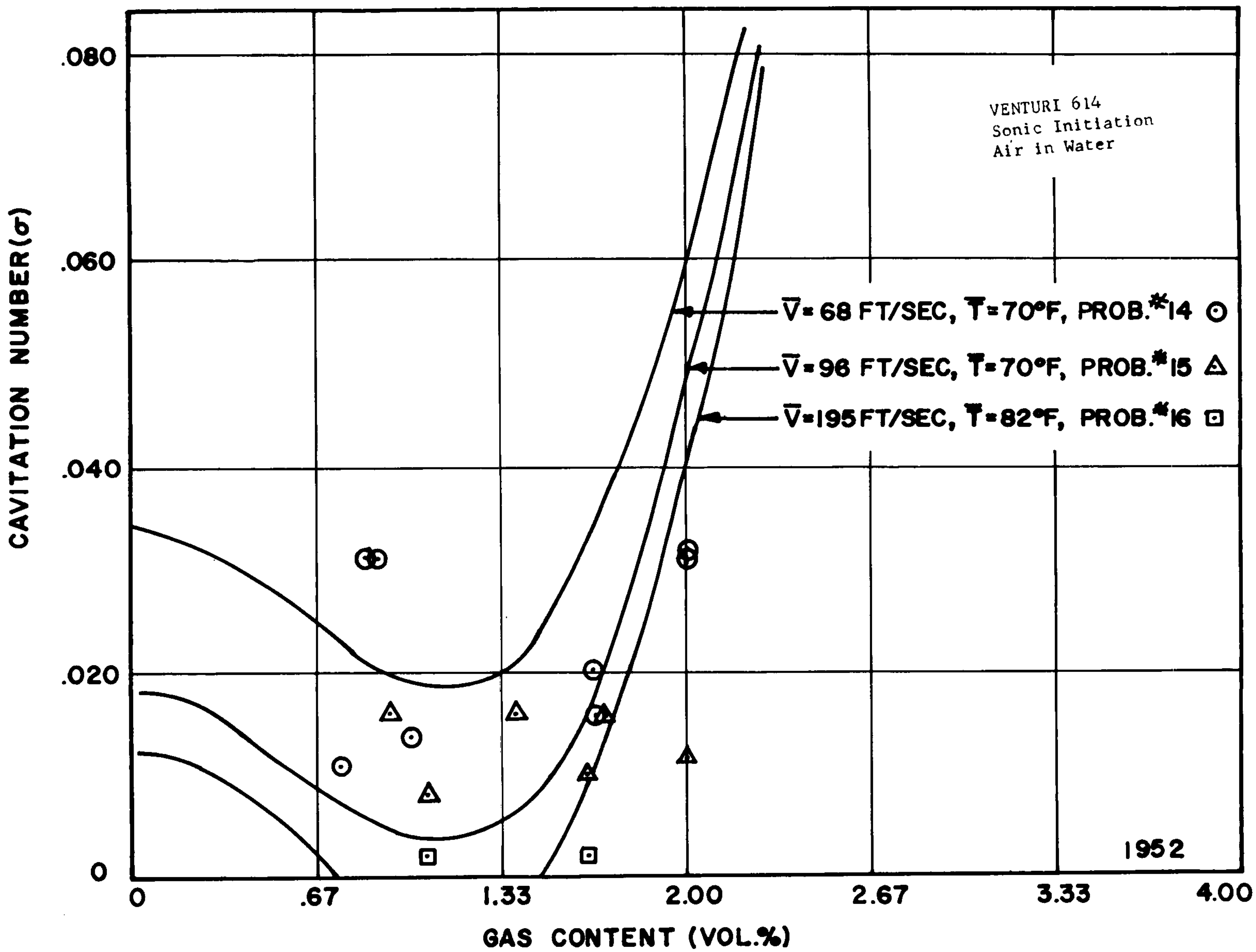

Fig. 15.--Cavitation number versus air content for 1/4" plexiglas venturi with water at several velocities.

gas content end, they also, in many cases, show a tendency to rise somewhat on the low pressure end. It is not believed that this latter trend represents physical reality, but rather that it is a result of the curve-fitting technique employed. It is felt that the computer-generated polynomial is influenced premarily by the high-gas content end where the bulk of the data exists, and that the rising "tail" of the polynomial at the low gas content end is not physically meaningful.

Fig. 15 also indicates the velocity effects already discussed in that the higher velocities correspond to the lower cavitation numbers.

Fig. 16 illustrates the effect of gas content upon cavitation number for more fully-developed cavitation. It is noted that cavitation number in this case decreases with increasing gas content, i.e., the pressure in the cavitating "void" region is reduced for higher gas content. No explanation for this unexpected observation is available.

A typical effect of throat diameter upon cavitation inception number for various gas contents is shown in Fig. 17. As previously noted, this result for a plexiglas venturi is quite similar to that obtained for mercury in plexiglas (Fig. 12).

3. Reynolds Number Correlations

A previous investigation from this laboratory[7,8] indicated that a reasonable correlation could sometimes be obtained between cavitation number and Reynolds number for both mercury and water both in venturis (of the same geometry used in the

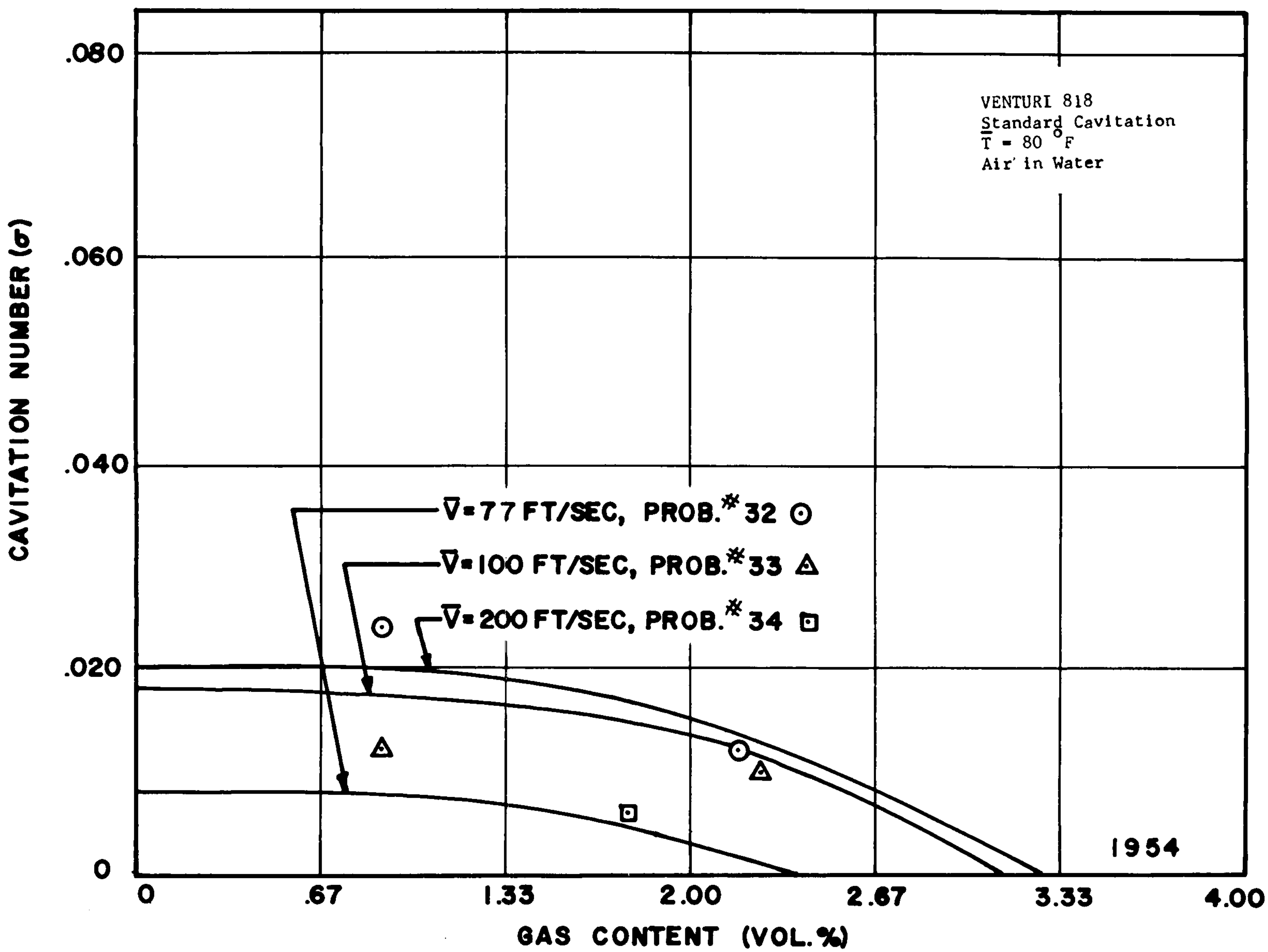

Fig. 16.--Cavitation number versus air content for 1/8" plexiglas venturi with water at several velocities.

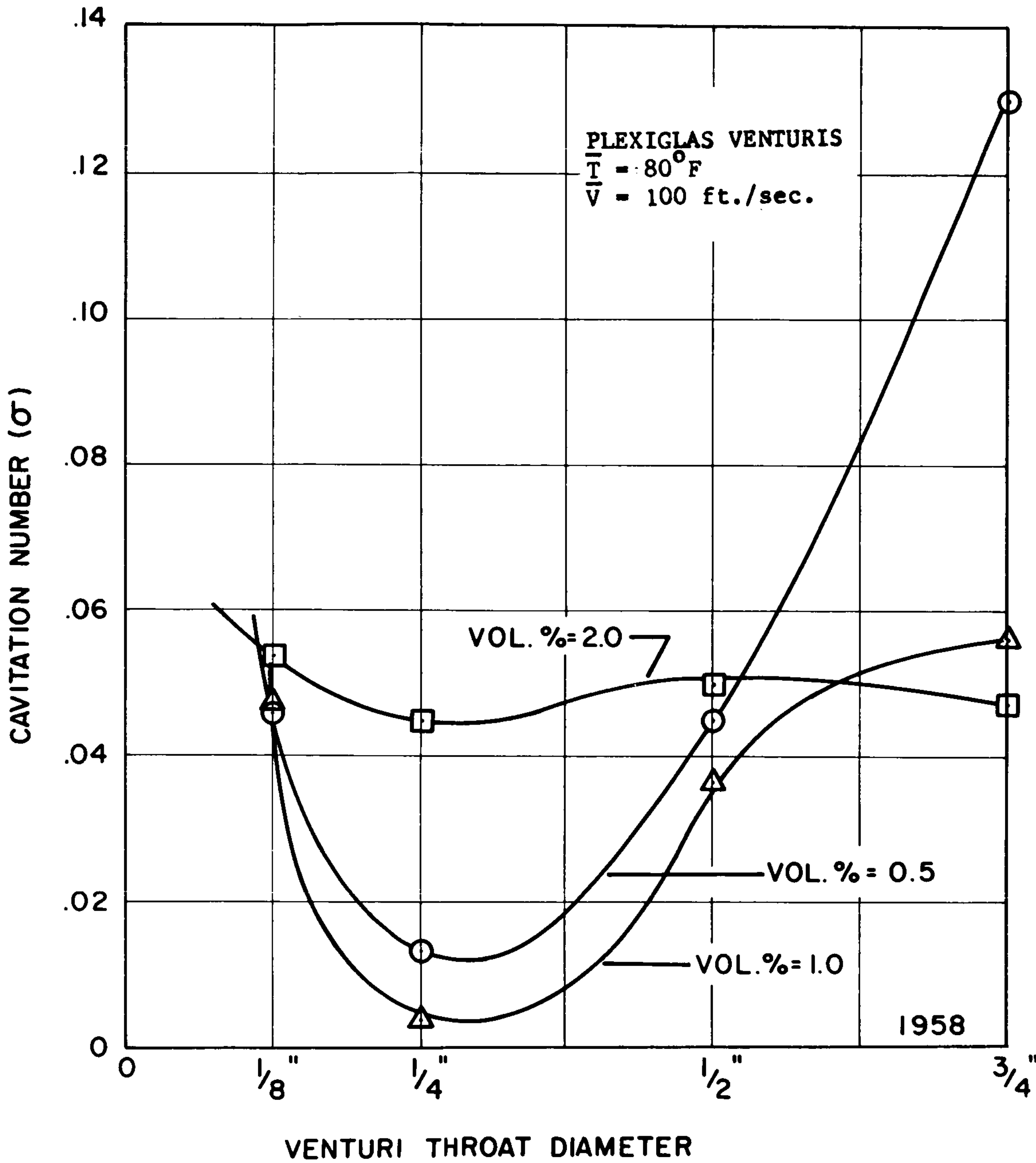

Fig. 17.--Cavitation number versus venturi throat diameter for plexiglas venturis with water at several air contents

present tests) and in a low specific speed centrifugal pump which was available for test. The use of Reynolds number appeared to properly group points obtained for different temperatures and passage diameters. In these tests it was observed that for both cavitation inception and well-developed cavitation, the cavitation number decreased as Reynolds number was increased. However, the mercury and water data were not brought together by this form of presentation, so that clearly parameters other than Reynolds number were significantly involved. Fig. 18, reproduced for convenience from ref. 8, summarizes this previous data for the venturi.

More recently, Jekat[10] showed somewhat similar results from tests on a cavitating axial inducer in water. However, his tests showed that the cavitation parameter passed through a minimum as Reynolds number was increased and then increased again at high Reynolds number.

A similar overall trend to that of Jekat[10] is indicated by the present water data (Fig. 19). This is consistent with our own previous tests in that the rise in cavitation number occurs for Reynolds number greater than 10^6, which was the limit of the previous data (Fig. 18). However, the curves for the different venturi sizes do not coincide in the present water data.

Fig. 20 indicates the present mercury data as plotted against Reynolds number for different gas contents for both hydrogen and argon injection. As previously mentioned there is

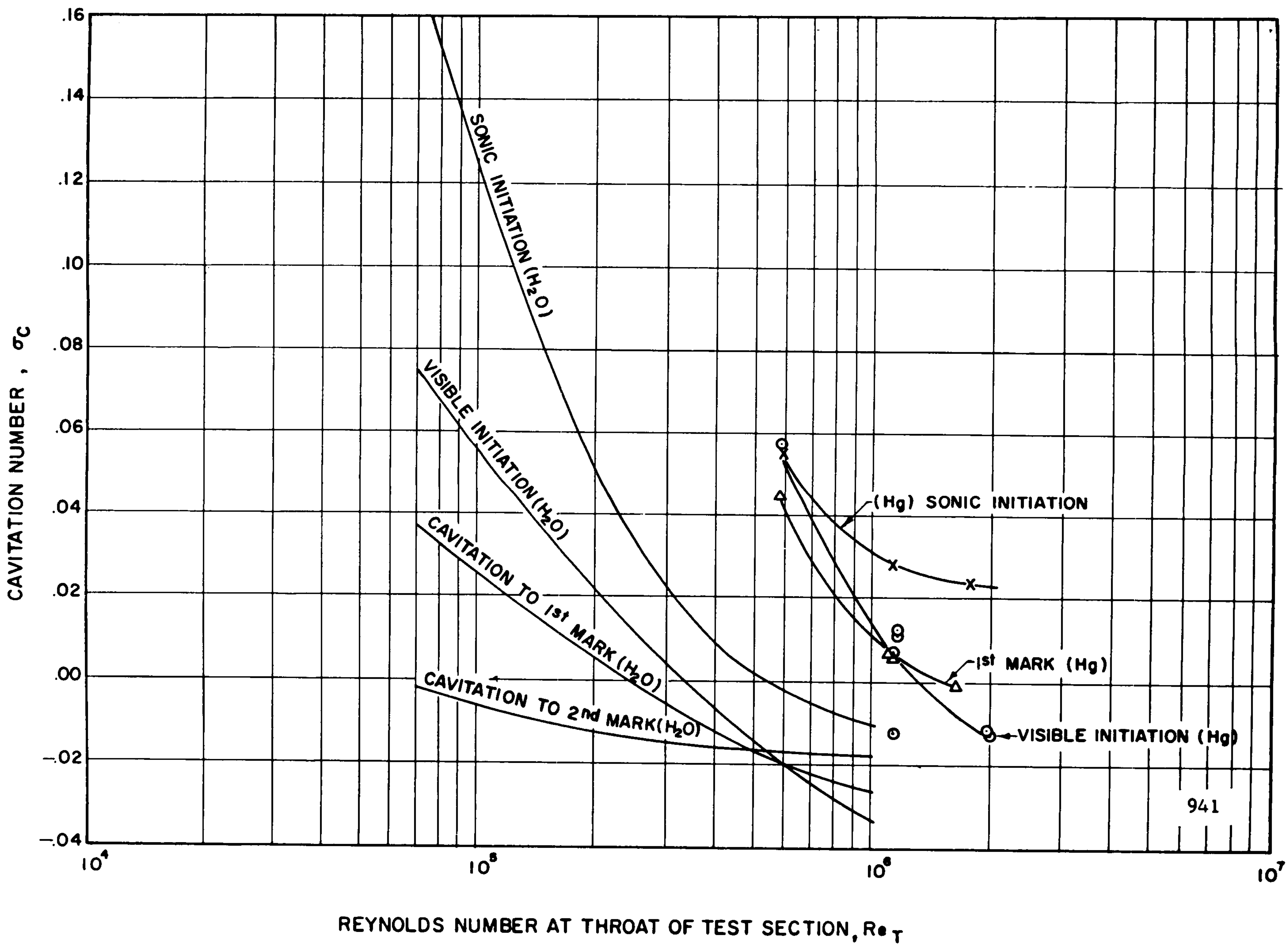

Fig. 18.--Cavitation number versus throat Reynolds number for several cavitation conditions in 1/2" plexiglas venturi with water and mercury.

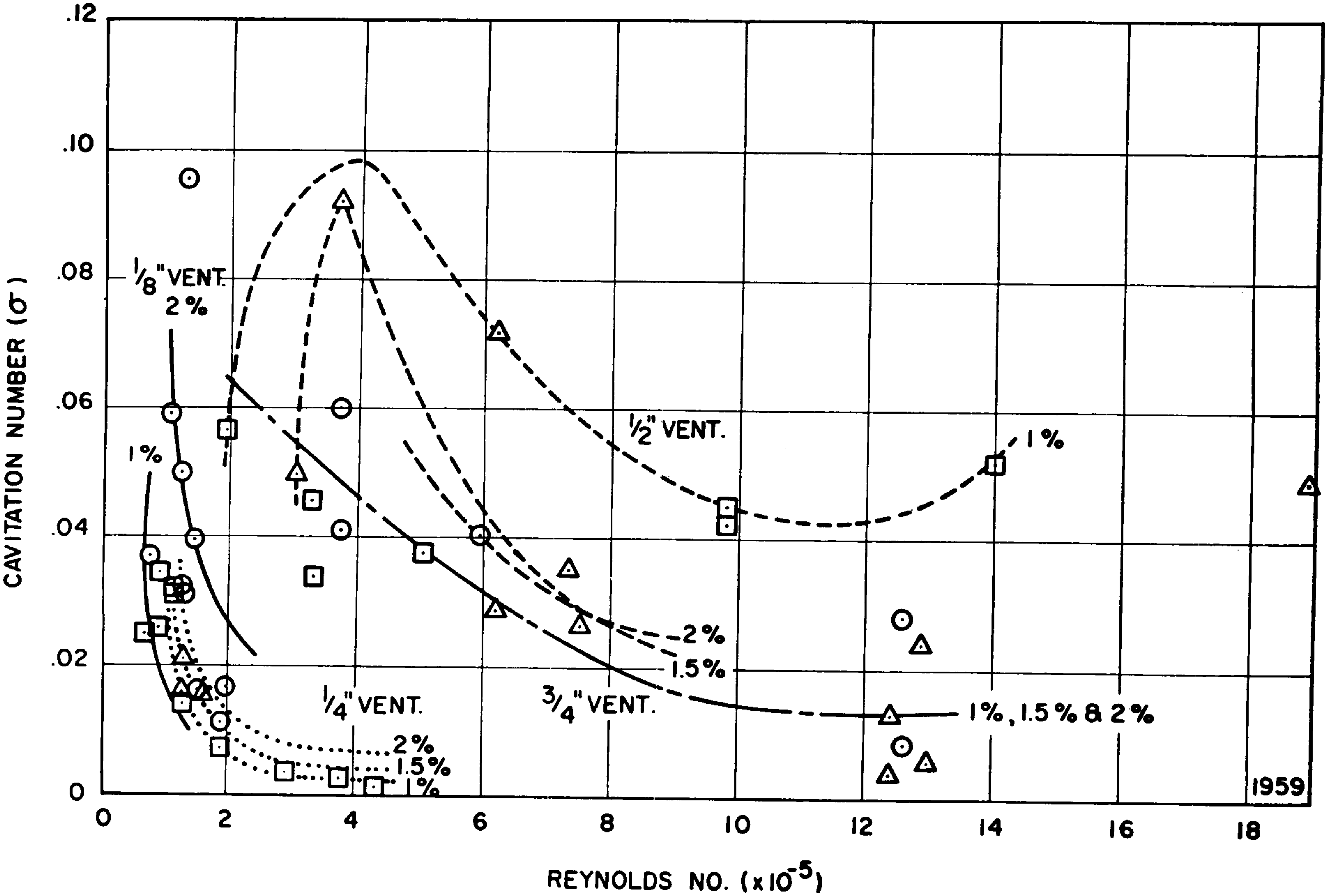

Fig. 19.--Cavitation number versus throat Reynolds number for plexiglas venturis with water at several air contents.

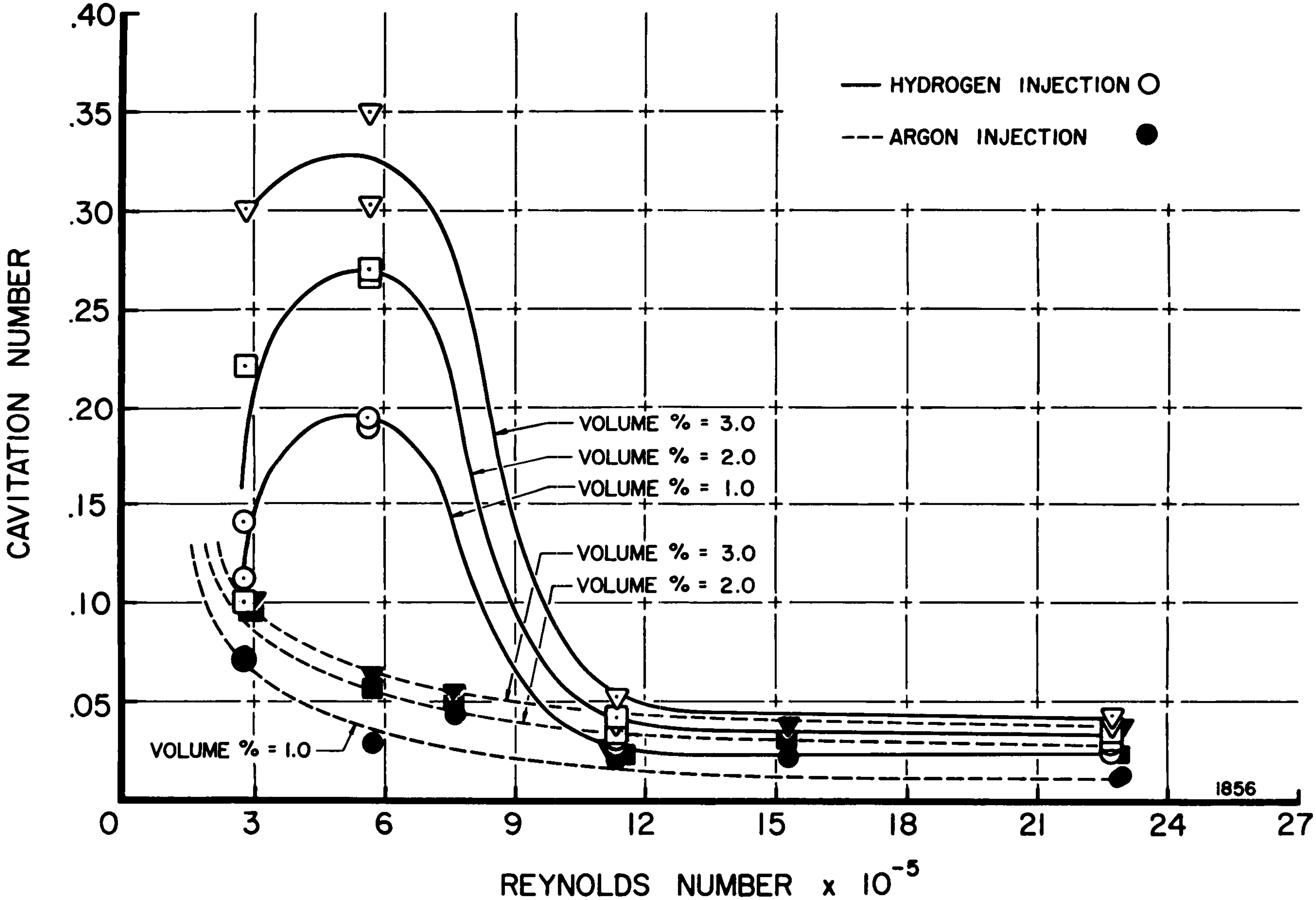

Fig. 20.--Cavitation number versus throat Reynolds number for stainless steel venturis with mercury at several argon and hydrogen gas contents.

a considerable discrepancy between the two gases. This is particularly pronounced in the low Reynolds number end. Although the curves are carried to a somewhat larger Reynolds number than was obtained with water, the data shows no indication of an upturn for high Reynolds number. However, there is considerably more consistency between the different sized venturis in mercury than was the case for water, so that no differentiation according to venturi size is indicated in the curves.

It is felt that the large effect of gas content upon cavitation number for hydrogen-mercury at the low Reynolds number end (small venturi data) may be due to the fact that the bubble size does not scale with throat diameter. The bubbles become of appreciable diameter compared with the throat opening for the small throats (particularly 1/8 inch). Thus, even though the venturis are geometrically similar, the flows do not scale properly, and substantial bubble "blockage" of the small venturi throat may exist.

Fig. 21 shows the mercury-argon Reynolds number plot superimposed upon the water curve. The hydrogen data is not included since the cavitation numbers in the low Reynolds number range are of a different order of magnitude. It is noted that the mercury data lies generally above and to the right of the water data on this plot, as it did in the earlier tests where gas content variation was not involved (Fig. 19). The hydrogen-mercury data (not shown) is generally displaced further from the water data in the same direction.

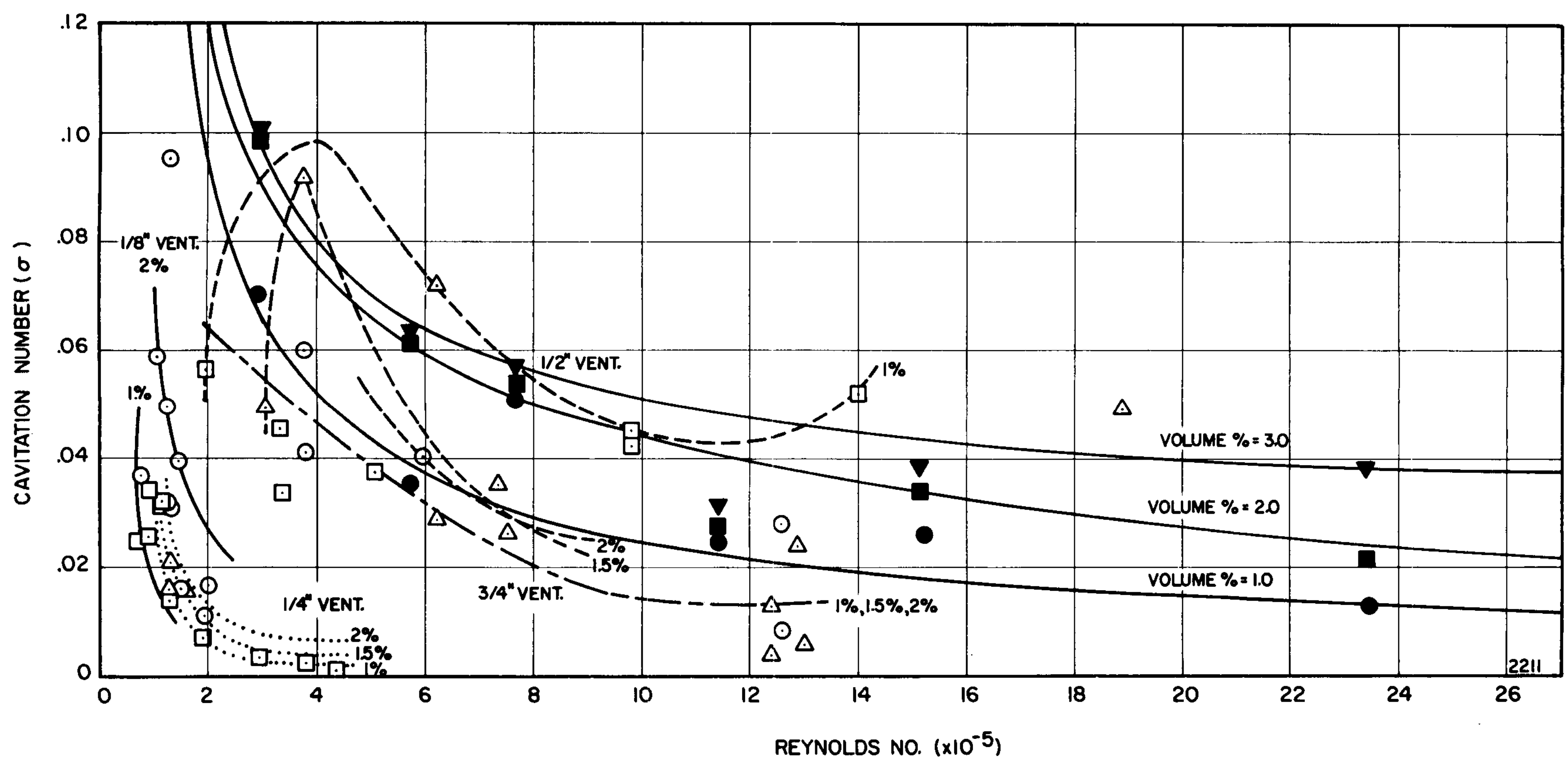

Fig. 21.--Cavitation number versus throat Reynolds number for plexiglas and stainless steel venturis with water and mercury at several gas contents.

CHAPTER VI

CONCLUSIONS

The following general conclusions relative to cavitating venturis can be drawn from this study:

1) There is a substantial effect of gas content upon cavitation inception number for both water and mercury. For water the effect was greatest at low velocity, although this differentiation was not noticed with mercury.

2) There is a substantial effect of velocity and passage size upon cavitation inception number for both fluids. In general the cavitation number tends to decrease with increasing velocity or size, although the trend may be reversed for large size and diameter. While the foregoing applies to water with gas content near STP saturation, it was noted that cavitation number increased with velocity throughout the range for well-degassed water.

3) The effect of the temperature variation in the mercury tests (60°F to 400°F) was as great as that of gas content, size, or velocity variation. Generally, the cavitation inception number decreased at high temperature as would be expected from consideration of the "thermodynamic parameter." No temperature effect was noted in the water tests since the temperature range was insufficient.

4) The effect of surface roughness differences and minor surface discontinuities, as around pressure taps, upon cavitation inception number can be substantial.

5) An improved correlation of cavitation number data can be achieved if it is plotted against Reynolds number rather than velocity, diameter, temperature, etc. singly. This appears to be more the case for mercury than for water. Inception cavitation number for both fluids appears to decrease with increasing Reynolds number up to about 10^6. Above that value, there is some indication of an increase of cavitation number with increased Reynolds number.

6) Velocity, size, and gas content effects are reduced at high Reynolds number.

APPENDIX

DEFINITION OF CAVITATION CONDITIONS

The following are the definitions of the degrees of cavitation as used in this investigation:

Sonic Initiation* ------	first visible or sonic manifestation of cavitation in the venturi.
Visible Initiation* ----	continuous ring of cavitation at the throat outlet, about 1/8" long.
Standard Cavitation ----	cavitation cloud extends from throat outlet to termination at 1.520(D) inches downstream.
First Mark Cavitation --	cavitation cloud extends from throat outlet to termination at 3.440(D) inches downstream.

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*The flow conditions corresponding to these two inception conditions are the same for this set of tests, so that both conditions are called "cavitation inception in the paper.

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