GAS ENTRAINMENT EFFECTS ON CAVITATION NUMBER IN MERCURY IN 1/2" VENTURI TO 400° F

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LIST OF FIGURES

I. INTRODUCTION

A realtively comprehensive series of cavitation number vs. gas content tests has been recently completed in "dry" mercury, using a 1/2" throat diameter stainless steel venturi (flow-passage dimensions identical to 1/2" venturis previously used,[1, e.g.]). Tests have been conducted at room temperature, ~ 270°F, and ~400°F*, in all cases using the throat velocity (34 ft./sec.) which has been most frequently used in previous tests[1, e.g.]. A total of 81 previously unreported pressure profiles have been measured, resulting in as many cavitation number vs. gas content data points, and covering a gas content range (for argon) between ~ 0.2 and ~4.0 ppm. (by mass). Corresponding mass ppm values for hydrogen, assuming the same volumetric contents for the two gases, would be less by the ratio of the molecular weights, i.e., a factor of 20.

Since the presently available results are quite comprehensive and indicate trends which are believed to be of interest, it was believed desirable to present them at this time even though they are in a rather preliminary form. Later it is planned to issue a formal Technical Report which will include the present data and also complementary data as will be explained in the report necessary to achieve a more

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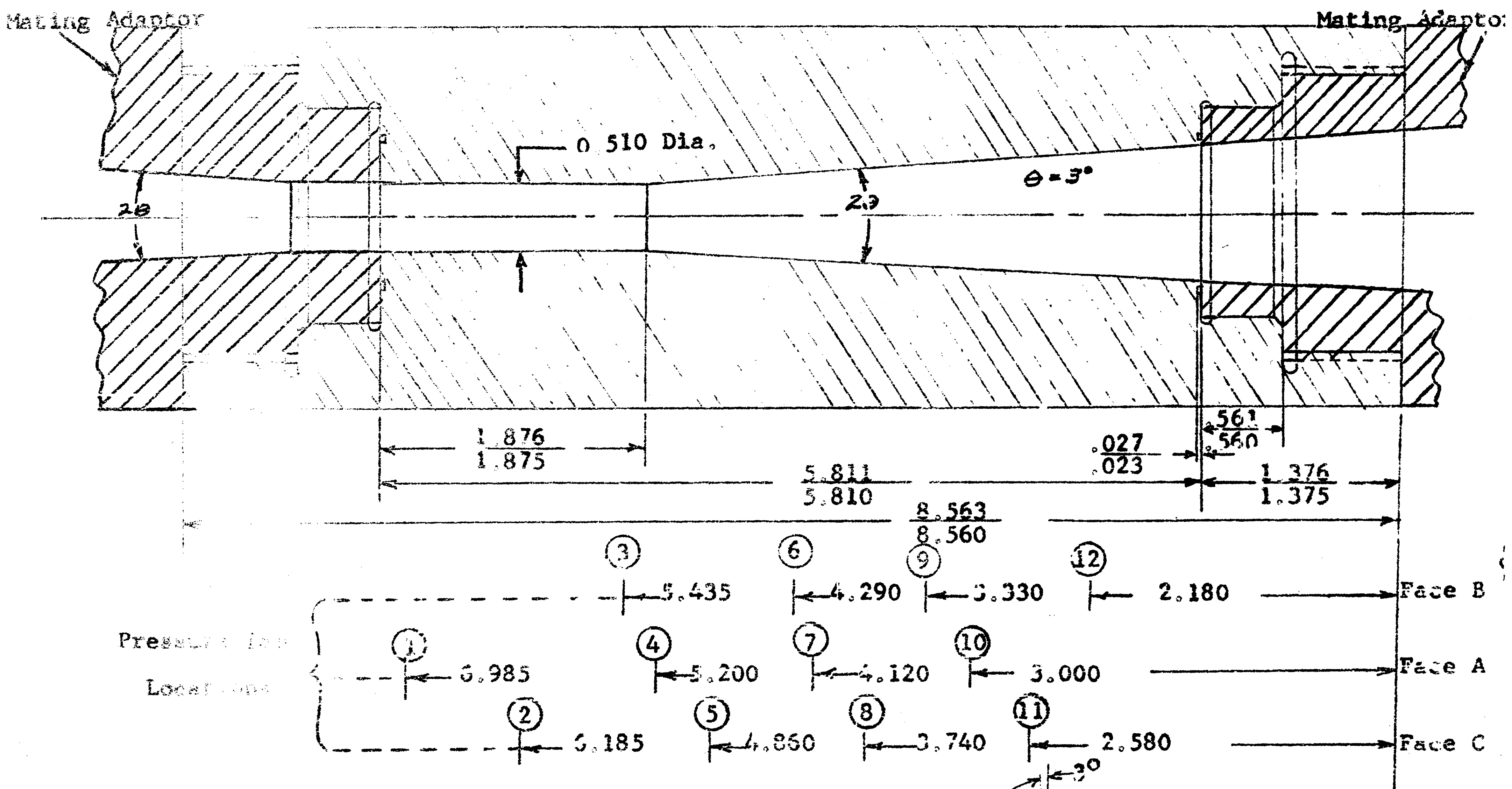
* The maximum temperature was reduced from the previously discussed 500°F to 400°F at the suggestion of Mr. James Howard of A.I. The lower temperature is now felt to be more applicable to the expected pump conditions. However, if desirable, tests at 500°F can be made with the presently available equipment.

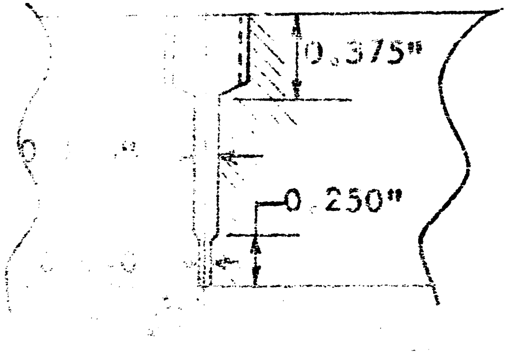
desirable and comprehensible form of presentation.

II. EXPERIMENTAL DATA

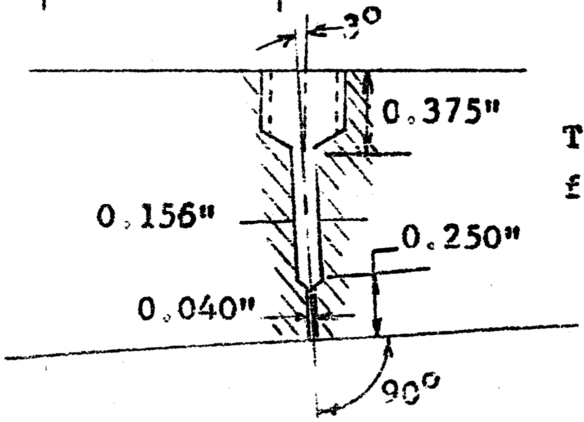
As already stated, 81 axial pressure profiles have been run for cavitation initiation for a "standard" 1/2" stainless steel venturi[1] (Fig. 1 shows the nominal flow-path dimensions) in "dry" mercury, covering gas contents from the minimum presently attainable (about 0.2 ppm) up to approximately 4.0 ppm of argon, and including room temperature, ~ 270°F, and ~400°F, all at a "standard" throat velocity. Since some of the mercury temperatures were too high for plexiglas, it was necessary to use a stainless steel venturi. This same venturi had been previously tested at minimum gas content with room temperature mercury, and the results compared to those from the 1/2" plexiglas venturi, which had previously been used for gas content vs. cavitation number tests with room temperature mercury.[2,3]

As has been frequently discussed in past correspondence[3], e.g. there are several methods by which cavitation initiation can be characterized, and, considering the present state of the theory, it is not possible to define precisely the relation between them; e.g., in a transparent system the first visible indication of two-phase behavior can be used (and often is). However, this "visible initiation" may not precisely correspond to "sonic initiation", i.e., the first manifestation of a change in audible signal (as observed by stethescope or electronically) from that characteristic of single-phase flow. A further possible definition of cavitation initiation, which





Typical Tap Detail for Taps in Throat



Typical Tap Detail for Taps in Diffuser

may have more meaning for the pump designer, is that flow condition for which a given change in the gross flow parameters occurs. The parameter loss coefficient i.e., the proportion of throat kinetic head which is not recovered in the diffuser, has been previously used in the present investigation for such a purpose, since it has been found to be very sensitive to the cavitation condition ("degree of cavitation").

For the plexiglas venturis of the present study, "visible initiation" has been used, and it has been attempted to obtain a correlation between this and "sonic initiation" using the signal from an "acoustic probe" displayed on an oscilloscope[3]. In the present tests with a stainless steel venturi, "sonic initiation" only can be detected, and hence the comparison with previous results from the plexiglas venturis involves the personal interpretation of a relative noise signal on an oscilloscope. However, to obtain a more precise and repeatable determination of cavitation initiation, comparison to conditions of constant loss coefficient, which could then be taken as a definition of a given "degree of cavitation", as, e.g., initiation, might be preferable. For fixed loss coefficient, it could then be assumed, from the viewpoint of the designer, that there existed a given "disturbance" due to cavitation of the predominently single-phase flow.

There is information in the literature indicating that an increase in gas content in a cavitating fluid may result in a reduction of noise[4]. The same observation has been made in this laboratory in the water tunnel when it was observed that the noise from cavitation, as judged by the human ear, decreased by orders of magnitude when a small amount of air was injected upstream of the cavitatiog region. It has also been a relatively common observation, found both in the literature^5, and in discussion with powerplant engineers, that injection of substantial quantities of air into a cavitating region may very strongly reduce cavitation damage. This is also taken as confirmation that noise may be expected to decrease for a given "degree of cavitation" for higher entrained gas contents. Hence, the approximately constant sonic signal used to describe the initiation point for the present data, would indicate more cavitation at higher gas contents, which would result in a larger venturi loss coefficient as has been observed. Then the measured cavitation number would be too low, since the "degree of cavitation" corresponding to "initiation" would actually be greater for high than for low gas contents. Hence it is felt that the high gas content cavitation numbers shown in the present data (Fig. 2, 3, 4) should actually be corrected upward. It is expected that this correction will be accomplished at a later date, when constant loss coefficient curves at fixed gas contents become available.

Figures 2, 3, and 4 show cavitation number plotted against gas content for room temperature, ~270°F, and ~400°F, respectively. The number of axial pressure profiles, which are averaged to form each point shown, is indicated by the number

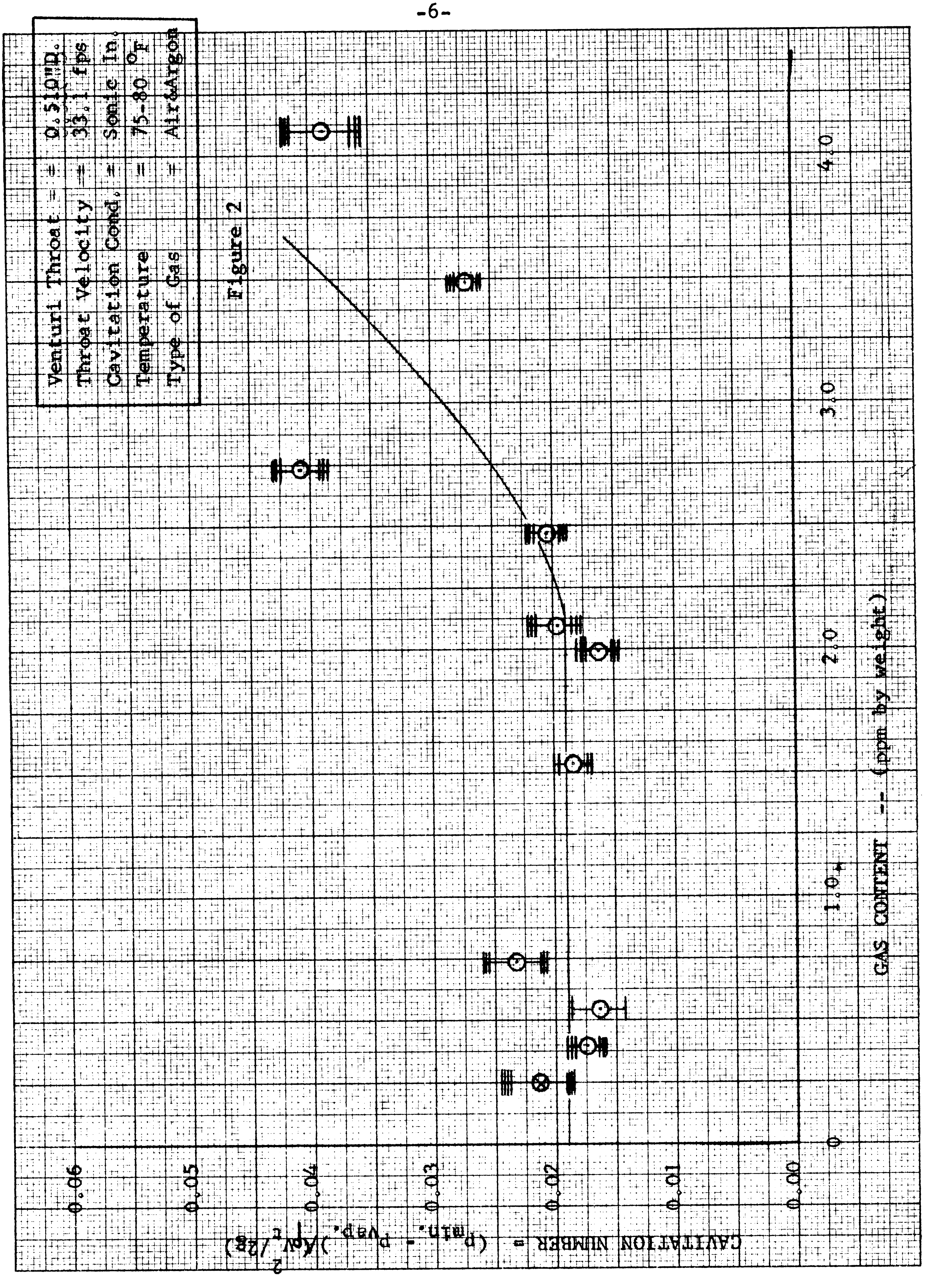

Venturi Throat = 0.510"D.
Throat Velocity = 33.1 fps
Cavitation Cond. = Sonic In.
Temperature = 75-80 °F
Type of Gas = Air&Argon
0.06
0.05
0.04
0.03
0.02
0.01
0.00
CAVITATION NUMBER = $(p_{min.} - p_{vap.})/(\rho V_t^2/2g)$
0
1.0
2.0
3.0
4.0
GAS CONTENT -- (ppm by weight)

Figure 2

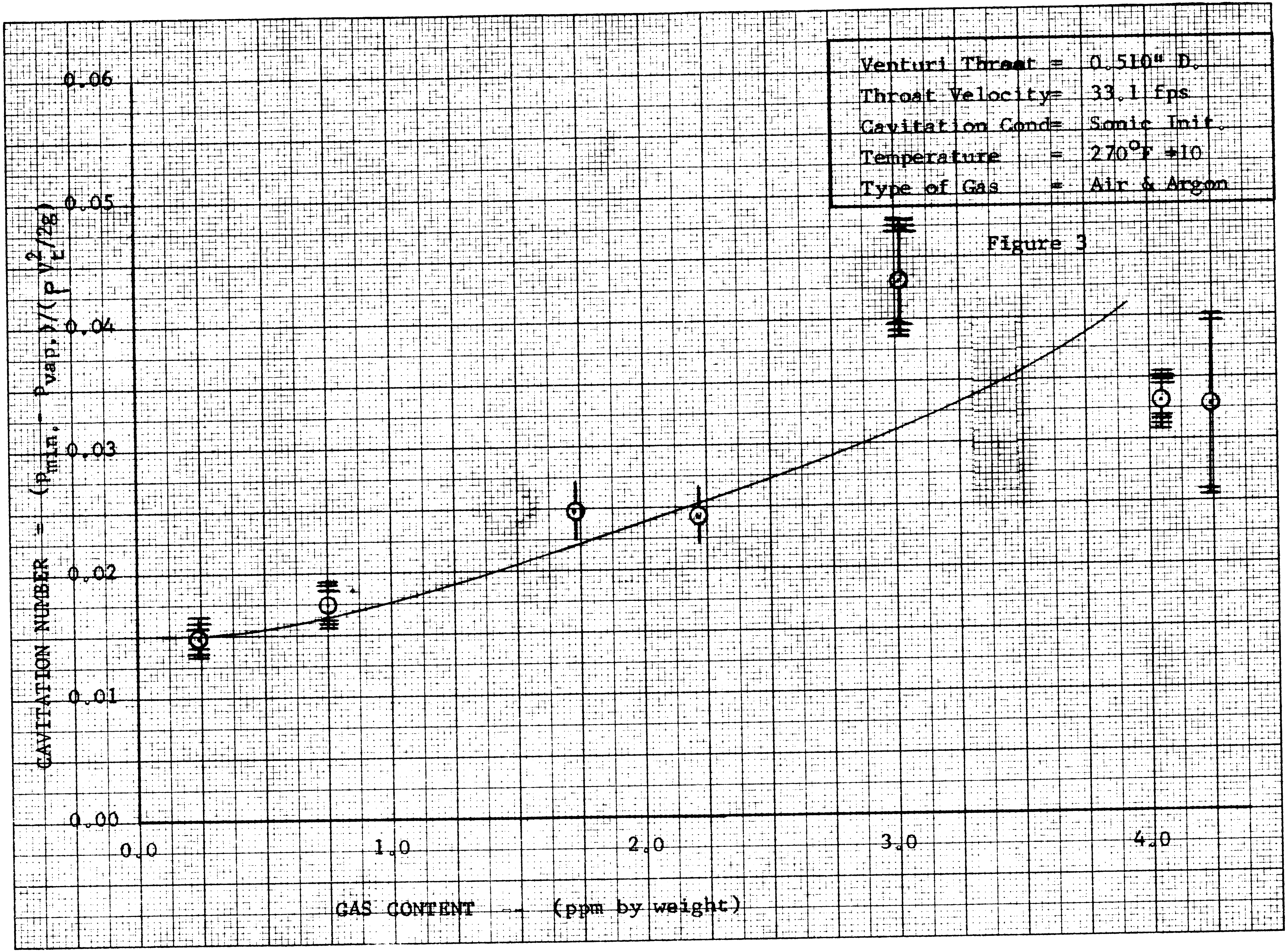

Venturi Throat = 0.510" D.
Throat Velocity = 33.1 fps
Cavitation Cond = Sonic Init.
Temperature = 270°F ±10
Type of Gas = Air & Argon
CAVITATION NUMBER = $(P_{min.} - P_{vap.})/(\rho V_t^2/2g)$
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.0
1.0
2.0
3.0
4.0
GAS CONTENT -- (ppm by weight)

Figure 3

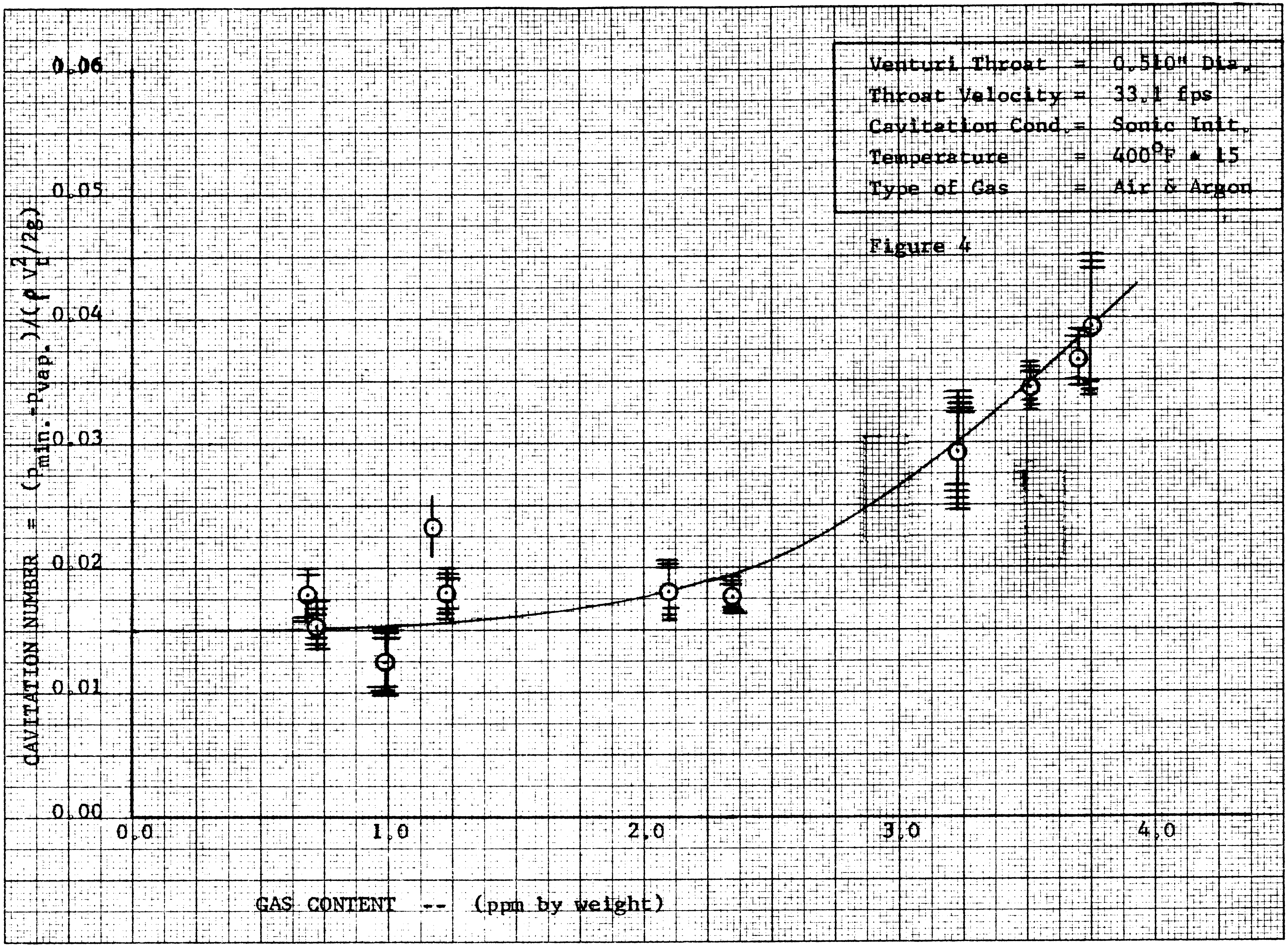

Venturi Throat = 0.510" Dia.
Throat Velocity = 33.1 fps
Cavitation Cond. = Sonic Init.
Temperature = 400°F ± 15
Type of Gas = Air & Argon
CAVITATION NUMBER = $(p_{min.} - p_{vap.})/(\rho V_t^2/2g)$
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.0
1.0
2.0
3.0
4.0
GAS CONTENT -- (ppm by weight)

Figure 4

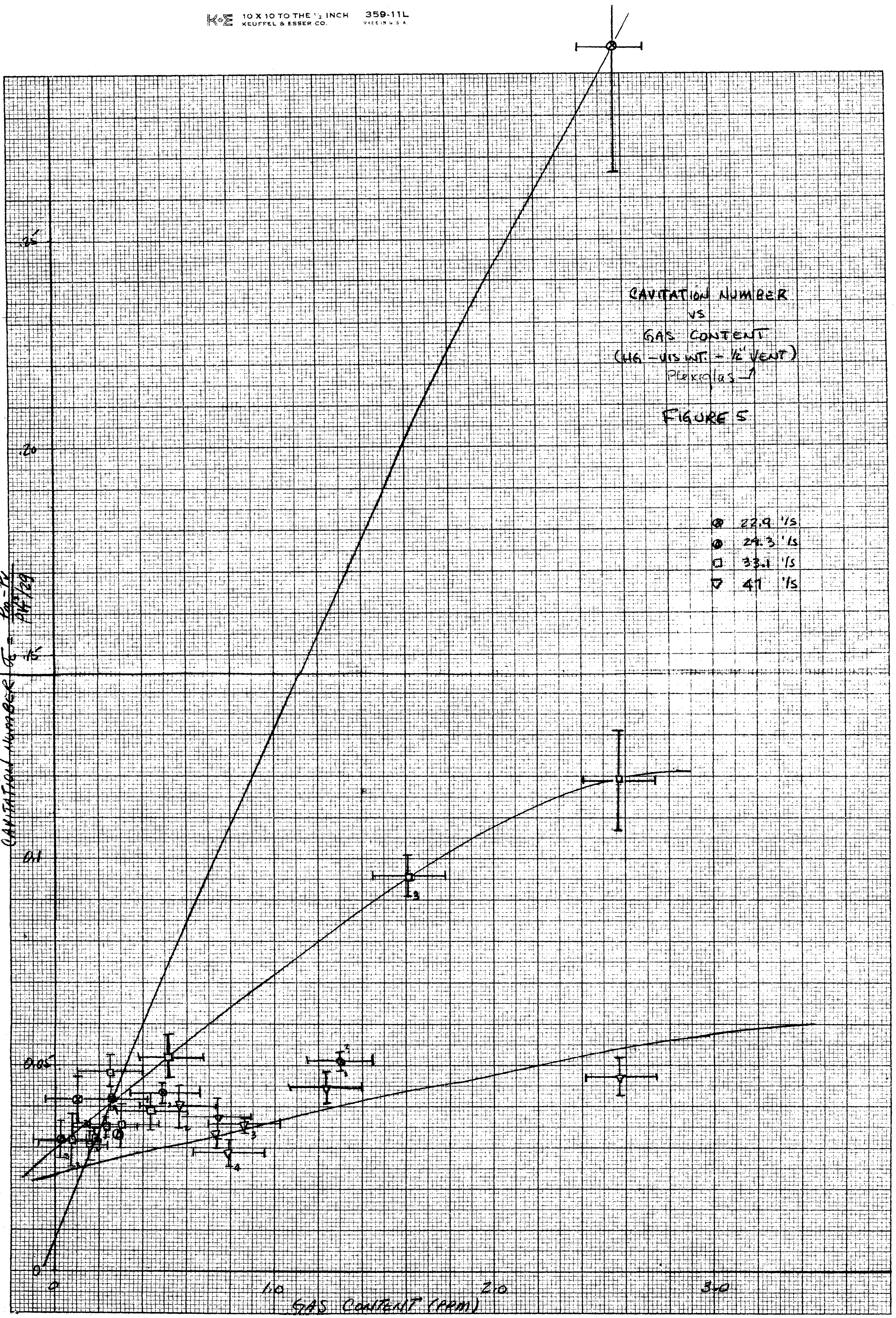
of cross-marks above (or below) the point (usually 3). Pressure profiles, taken over such a time period that it is believed that the gas content cannot have varied appreciably between measurements, are averaged together; their corresponding gas contents are also averaged to form the composite points which are shown. It is believed that this method of reduction is desirable, since on physical grounds it is known that the gas contents for such a series of points must actually be close. The vertical length of the line through the points indicates the standard deviation as calculated for that particular data set, thus showing the approximate range of repeatability of the cavitation number data.

As indicated above, for all these points cavitation initiation is "sonic initiation" as determined by the acoustic probe and oscilloscope, and the loss coefficients vary, generally increasing for increasing gas content. The assumed explanation for this latter trend has been already discussed. Fig. 5, shows the previously reported cavitation number vs. gas content data from the 1/2" plexiglas venturi.[2] For these tests cavitation initiation was visually determined.

III. DISCUSSION OF RESULTS

A. Comparison of Plexiglas and Stainless Steel Data

Comparison of Fig. 2 for the room temperature stainless steel venturi data with Fig. 5 for the plexiglas venturi room temperature data (considering for comparison only the 33 ft./sec. curve of Fig. 5) indicates that the trend is the same for each venturi in that the cavitation number increases



CAVITATION NUMBER
VS
GAS CONTENT
(HG - VIS WT. - ½" VENT)
Plexiglas

FIGURE 5

substantially with gas content over the range tested, which is about the same in either case. However, the actual cavitation number values obtained in the plexiglas venturi (Fig. 5) are considerably greater over the entire gas content range. It is believed that this discrepancy in cavitation number values is the result primarily of two factors:

1. The relative roughness of the venturis is different, and since the plexiglas is subject to relatively rapid cavitation damage in mercury, it is probably the rougher, thus tending to cavitate at higher cavitation numbers (i.e., higher pressures). Cavitation is often triggered by local roughnesses, and it may also be that burrs or other irregularities around the pressure taps in the plexiglas venturi are greater than in the stainless steel unit.

2. "Visible" rather than "sonic" initiation was used for the determination of cavitation initiation in the plexiglas. In a previous attempt to correlate cavitation initiation in the two venturis[3] by setting flow conditions so that the oscilloscope signal from the acoustic probe would be the same in the two cases, a somewhat similar discrepancy in cavitation numbers was found.* However, it was also found that the loss coefficient for the stainless steel venturi was considerably larger, indicating that there was actually a higher "degree of cavitation" in that unit, so that the lower cavitation numbers

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* Although these tests were with "wet" rather than "dry" mercury as in the present case, the results are believed applicable in the context used.

would be expected. The significant values are summarized in Table I.

TABLE I

COMPARISON OF PLEXIGLAS AND STAINLESS STEEL VENTURIS[3]

Venturi	Cavitation Number	Loss Coefficient
Plexiglas	0.0484 ± 0.0066	0.215
Stainless Steel	0.0262 ± 0.0006	0.2468

In both cases, gas content is about 0.2 ppm and H_2O content about 370 ppm. The indicated precision of the cavitation number values are equal to the standard deviations calculated.

As already mentioned, in order to procede further in systematizing the data, it is necessary to obtain the partial derivative of cavitation number with respect to loss coefficient around the applicable point, so that results can be presented on a constant loss coefficient basis. This will require supplementary tests. The fact that the absolute values of cavitation number depend upon geometrical factors as relative roughness, etc. is not a substantial difficulty if the correction to be applied to the basic, minimum gas, cavitation initiation number can be obtained. If such a correction is found to be relatively independent of roughness, etc., then the necessary data, relative to gas content effects from the viewpoint of the design engineer, is at hand. This possibility is further discussed in a later section.

B. General Gas Content Effects from Present Data

On theoretical grounds it would be expected that for very low entrained gas content the cavitation number would decrease markedly, very likely becoming negative, and for very high entrained gas content, it would increase substantially, resulting eventually in a break-down of stability of the flow as may be encountered in high void-fraction, two-phase flows. The low gas content effect would be due to the inherently substantial tensile strength of the pure liquid, which is not attained ordinarily because of entrained gas "nuclei", as has been discussed in the literature for many years[4, e.g.] In addition, since the effects of gas upon bubble nucleation, growth, and collapse are primarily volume rather than mass effects, it would be expected that similar results would be attained with the same entrained volume of different gases. Previous to the present investigation, however, these effects have not been generally investigated experimentally for cavitating flows.

The present data can be taken as confirmation of some but not yet all of the above expectations. However, it is not inconsistent with any of the above.

Examination of Fig. 2, 3, 4, and 5 shows the following:

1. Over the gas content range from ~ 0.2 to ~ 4.0 ppm (argon), the cavitation initiation number (at 34 ft./sec. throat velocity) increases by a factor of at least 2 for all temperatures

investigated (room, 270°F, and 400°F), and for both stainless steel and plexiglas venturi (where tested).

2. The consensus of the data now available is that the effect is not large below about 2.0 ppm, (~ 2.0% by volume) and then becomes substantial between 2 and 3 ppm. This is definitely demonstrated in Fig. 2 and 4 (room temperature and 400°F mercury in stainless steel venturi). A more continuous slope is shown in Fig. 3 (270°F mercury in stainless steel venturi), but this interpretation rests only upon two single-run data points at about 2 ppm, whereas Fig. 2 and 4 show many more repetitive data points in the same area. Fig. 5 is also inconclusive regarding mid-range effects, since there is only a single point in this region.

3. Non-stable loop flow (strongly oscillating pump and venturi inlet pressures) for gas contents above about 4 ppm (the approximate limit of stability is shown by a vertical dotted line on the figures) was observed. Some instability was first noticed at about 3 ppm but not to a great extent. The instability at high gas content was greater for the higher temperatures. It is believed that this observation is important in indicating an approximate maximum limit for gas content, consistent with proper component operation. It is not implied that the numerical limits found herein for the cavitating venturi loop are directly applicable to other components, but it is believed likely that such a limit exists for all such systems, and it

may be that the present tests will eventually indicate its probable order of magnitude.

4. Between 3 and 4 ppm of entrained argon there is an indication (Fig. 2 and 3 for the two lower temperatures in the stainless steel venturi) that the cavitation number actually decreases for increasing gas contents. This is not shown in Fig. 4 (400°F mercury), perhaps because the influence of gas is less in this case, in that the non-condensible gas is a smaller portion of the total gas within a bubble, including vapor, which becomes relatively more significant at the higher temperatures. Also, it is not directly confirmed in Fig. 5, since the highest gas content thereon is less than 3 ppm; however, the standard deviation on the higher gas content points are large which is consistent with above.

It is believed that the apparent decrease of cavitation number with gas contents above 3 ppm (argon) is a result of the method of determining cavitation initiation through the attainment of a given signal from the acoustic probe. As was mentioned earlier, there is evidence that the noise from a given "degree of cavitation" decreases with gas content. Hence to obtain the required noise signal for these very high gas contents a considerably greater "degree of cavitation" may have been required, explaining the lower cavitation numbers. This is verified by an examination of the loss coefficients for the higher gas contents, which increase substantially with gas content, thus indicating the above increased "degree of cavitation". (Table II shows typical values).

When these points have been corrected to the same loss coefficient as exists for the lower gas content points, it is believed that the cavitation number curve will continue to rise for higher gas contents.

Also, as previously mentioned, the flow conditions are not stable for these higher gas contents so that the data points are the result of considerable averaging of pressure readings, and hence, may be subject to error in this respect, however the repeatibility of cavitation number is still indicated by the calculated standard deviations.

5. There is no observable decrease of cavitation number for low gas content, previously mentioned as a theoretical expectation. It is believed that such a fall-off would require considerably lower gas contents than are presently attainable, since substantial tensile strength of liquids has previously been observed only under very carefully controlled laboratory conditions. Under such conditions, however, theoretical values of the order of -300 atm. in water are reported[4], e.g. It is conceivable that some improvement in cavitation performance due to this tension effect might be achieved in liquid metal systems where very high purity exists. However, it is believed that this cannot be expected in the presence of even very small quantities of entrained gas, or, perhaps, in the presence of radiation flux, which can also serve as a nucleating agent (indicated by previous rough tests here, and perhaps elsewhere,

TABLE II

Averaged Cavitation Number Data in Mercury

	σ	$\bar{\sigma}=\sigma/\sigma_{mingas}$	GAS Conc.	Loss Coef.	Temp.	Venturi	Velocity	Weight
Ericson Data (From Fig. 29 - 06110-2-T)	.032	.970	.06		75°F	1/2" Plex.	33 Ft/sec	3
	.031	.940	.085					3
	.030	.910	.130					1
	.035	1.06	.230					2
	.046	1.39	.250					3
	.038	1.15	.450					1
	.053	1.60	.540					1
	.095	2.88	1.63					3
	.118	3.58	2.45					1
	.0176	1.005	0.40	0.250	75°F	1/2" SS	33 Ft/sec	3
	.0216	1.235	0.50	0.268				4
	.0164	0.935	0.59	0.270				1
	.0250	1.430	0.74	0.242				3
	.0183	1.045	1.57	0.210				2
	.0166	0.950	1.99	0.233				3
	.0196	1.120	2.09	0.267				3
	.0203	1.160	2.47	0.263				3
	.0416	2.380	2.72	0.277				3
	.0270	1.540	3.48	0.297				3
	.0389	2.220	4.10	0.307				3
	.0148	0.988	0.230	0.355	270°F	1/2" SS	33 Ft/sec	3
	.0172	1.150	0.760	0.278				3
	.0249	1.665	1.690	0.261				1
	.0241	1.610	2.219	0.261				1
	.0431	2.880	3.02	0.302				3
	.0332	2.220	4.09	0.273				4
	.0321	2.140	4.238	0.266				2

TABLE II

Averaged Cavitation Number Data in Mercury (Continued)

σ	$\bar{\sigma} = \sigma / \sigma_{min\,gas}$	Gas Conc.	Loss Coef.	Temp.	Venturi	Velocity	Weight
.0153	1.010	0.691	0.273	400°F	1/2" SS	33 Ft/sec	3
.0179	1.195	0.691	0.215				2
.0124	0.827	0.982	0.256				3
.0233	1.550	1.165	0.259				1
.0180	1.200	1.220	0.245				3
.0180	1.200	2.112	0.228				3
.0177	1.180	2.349	0.265				3
.0292	1.950	3.195	0.255				5
.0344	2.290	3.510	0.281				3
.0365	2.440	3.692	0.269				2
.0391	2.605	3.739	0.286				3

and also by the existence and use of "bubble chambers").

6. For any gas content, a decrease in cavitation number for an increase in temperature would be expected (cavitation "Thermodynamic parameter" concept originated by Stepanoff[6].) It was reported earlier[3] that this effect was observed for minimum gas content tests at room temperature and 270°F using the present 1/2" stainless steel venturi. A comparison of Fig. 2, 3, and 4 shows the same effect for various gas contents (cavitation number values from a "best curve" for 0.5, 2.0 and 3.0 ppm are listed in Table III). The two higher gas content points at 270°F (2.0 ppm and 3.0 ppm) do not exhibit this effect. However as previously mentioned, the data in Fig. 3 in this region is not conclusive, while the other two figures are consistent in this regard, and are well documented in this range.

The present data cannot show effects due to change in the entrained gas, since only argon and air have been used, and they do not differ sufficiently in their properties. However, some indication of the likelihood of the importance of volumetric rather than mass effects is afforded by comparison of previous tests carried out with entrained water[2] with the present entrained gas data.

Very roughly, 1 ppm of entrained air or argon in mercury is a gas mass equal to that provided by 1% by volume at STP. Under such conditions, the volume percent of gas in the cavi-

TABLE III

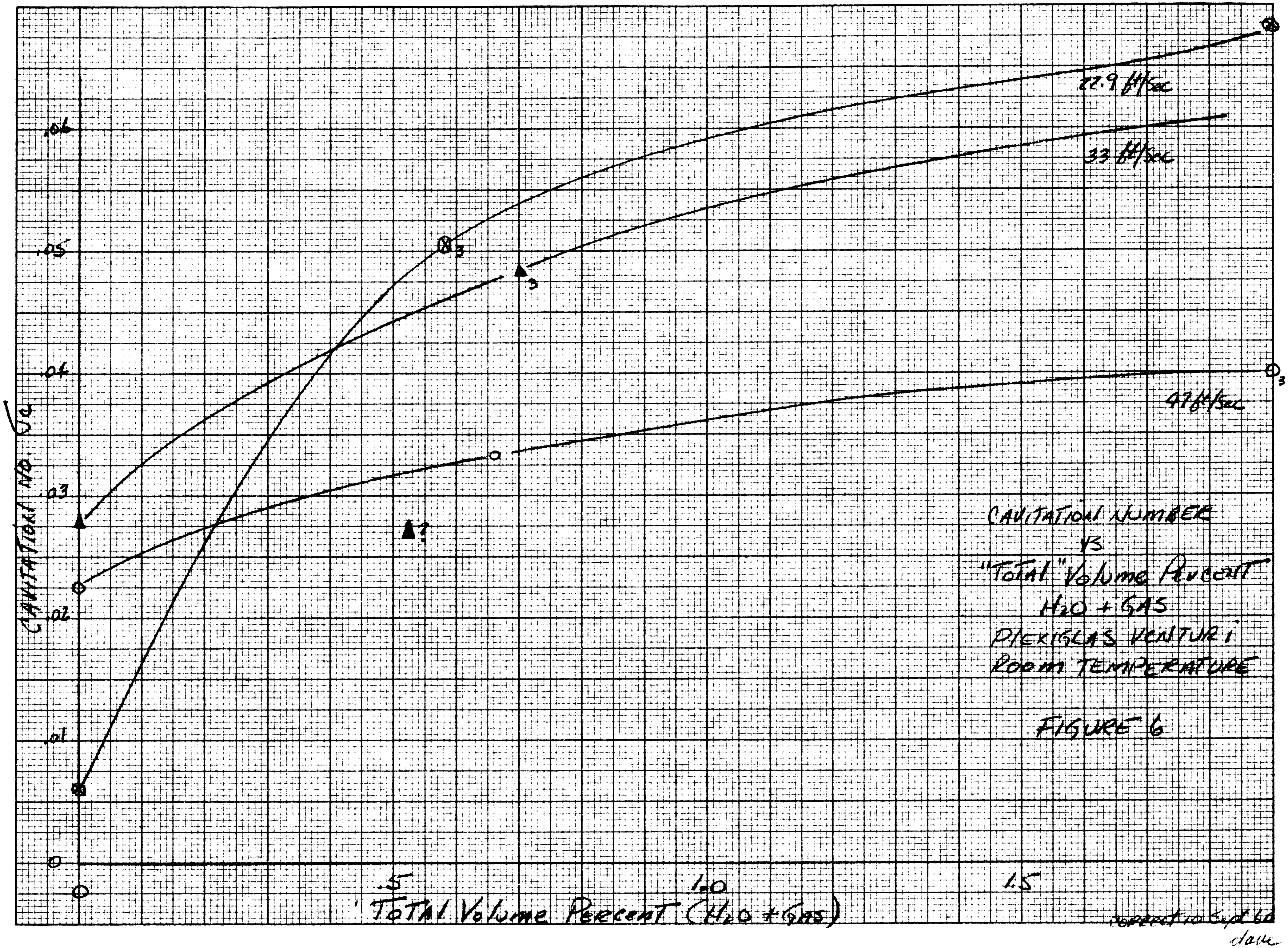
Thermodynamic Parameter Effects in Cavitation Number in Mercury

Temperature (^oF)	Cavitation Number $(p_{min}-p_v)/ V_T^2/2g$	Gas Content (ppm by mass Argon)
75	.0190	0.5
270	.0170	0.5
400	.0160	0.5
75	.0200	2.0
270	.0230	2.0
400	.0175	2.0
75	.0255	3.0
270	.0285	3.0
400	.0245	3.0

tation region would be much greater than 1% since the absolute static pressure would be near zero, and, conversely, it would be much less than 1% in the high-pressure portions of the loop. Fig. 6, previously reported[2], shows the effect upon cavitation number of water contents in mercury (in a 1/2" plexiglas venturi) ranging from near zero to about 2.0 volume percent (gas volume percent for these tests is believed near 0.2%). The volume percents shown, if the entrained fluid were gas rather than water, range in mass equivalent from about zero to ~ 2.0 ppm (argon); hence they are approximately comparable in range to the gas data shown in Fig. 2 - 5. It is noted that the proportionate increase in cavitation number over this range is also similar to that in the gas data (Fig. 2 - 5). The proportionate increase at 34 ft.sec. (chosen to compare with the gas data) is, however, somewhat greater than that for the gas data. Since, in the low-pressure cavitation region, it is presumed that the water will be largely vaporized and hence will behave as a gas, it is significant that its effect, when compared on a volume basis, is roughly comparable to that of a gas (the mass contents of water and gas in this example differ by a factor of 1000). Hence, this is taken as a relatively strong confirmatory evidence of the predominance of the volumetric effect.

C. Normalized Composite Curve

The previous discussion has emphasized the similarity in data obtained for the different temperatures and the two ven-



CAVITATION NUMBER
VS
"TOTAL" Volume PERCENT
H_2O + GAS
PLEXIGLAS VENTURI
ROOM TEMPERATURE

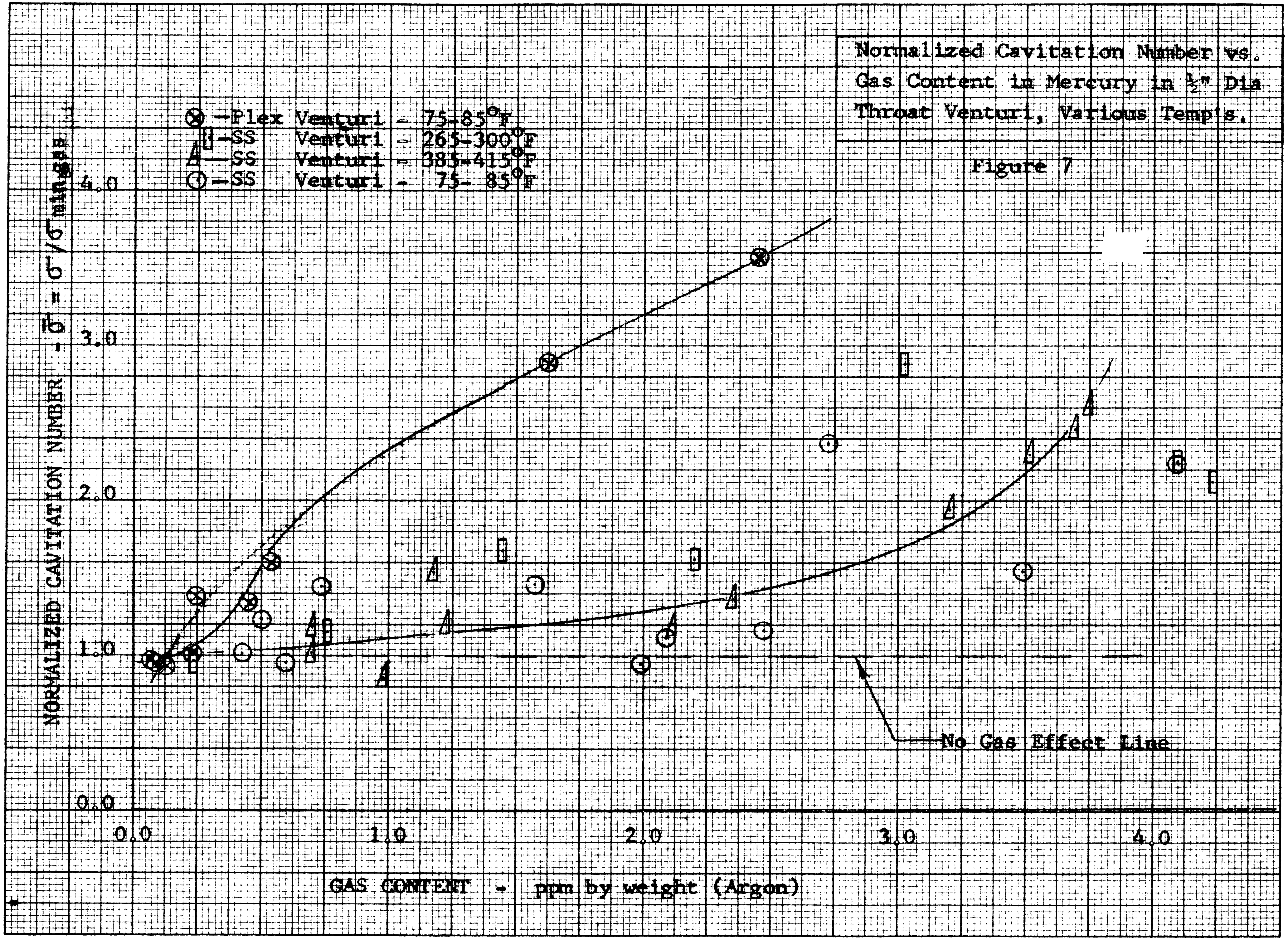
FIGURE 6

corrected to Sept 60
dale

turis. It has also been indicated that further data on the slope of a loss coefficient vs. cavitation number curve around the points of interest would allow a correction of the data to a constant loss coefficient basis, which it is believed would be more consistent and significant from the viewpoint of a pump designer. Of course, similar detailed information on the effects of velocity, size, and geometry, as well as gas content are also required by a pump designer, but these are not within the scope of the present discussion, although data relevant to them is being produced in this investigation, and has been discussed in other project reports[1,2,7,8].

Even though the present data are incomplete and not yet analysed and modified as believed desirable, it is believed useful to attempt a method of presentation which could be used as a first approximation for estimating the effect of gas content in a given component design, as, e.g., a centrifugal pump. It is expected that the available data, as applied in this form, will become considerably more precise and meaningful as the investigation proceeds.

Fig. 7 shows all the averaged data points from Fig. 2, 3, 4, and 5, in terms of "normalized" cavitation number vs. gas content. The numbers of points and standard deviations for each point are listed in Table II as previously mentioned for the individual figures. The cavitation numbers are normalized by dividing through for each set of data by the approximate cavitation number corresponding to minimum attainable gas con-



Normalized Cavitation Number vs. Gas Content in Mercury in ½" Dia Throat Venturi, Various Temp's.

Figure 7

tent for that set, as taken from the "best curves".[*] The value of the cavitation number, normalized in this fashion, can be taken to be a correction factor to the cavitation initiation number (or to NPSH, for a given velocity), presumed to be known experimentally or theoretically, for minimum gas content. Thus a first-order approximation is afforded a pump designer. Since this cannot be taken to be at all precise at the present time, still, in the absence of any other applicable approximation, it may have some value.

When a "best curve" is drawn through the data points shown on Fig. 7, it is noted that it follows the general trends previously discussed for the individual curves, showing essentially only a small effect in the stainless steel venturi for all test temperatures up to about 2 ppm, and then an accelerating effect for the higher gas contents. The "correction factor" to the minimum gas content cavitation initiation number would, e.g., be about 2 for 3.25 ppm argon. In the absence of gas effect, the cavitation number, so normalized, would of course remain at unity for the entire gas content. range. The curve for the plexiglas venturi shows an almost immediate and approximately linear effect perhaps due to roughness effects etc. as explained earlier.

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[*] It is expected eventually to process the data for a least mean square fit to a simplified polynomial curve, so that precisely-defined "best curves" will be available.

IV. CONCLUSIONS

Many detailed conclusions from the present data have been drawn throughout the report. The following are believed most significant.

1. The effect of gas content upon cavitation initiation number for mercury in a 1/2" venturi appears to be relatively small between the minimum attainable gas (~0.2 ppm) and ~2 ppm of argon, but becomes a factor of ~X2 or more for gas contents in the 3 - 4 ppm range. This has been demonstrated by the present data to be the case for mercury temperatures ranging from room temperature to about 400°F, at a single velocity and in the steel venturi. Previous work[1,2,7] has also indicated strong velocity and size effects for constant gas content.

2. The present tests afford some experimental verification of the theoretical expectation that gas volumetric rather than mass effects control.

3. A curve showing rough correction factors, derived from the present data (i.e., for one velocity, size, and gross geometry,* but over the full temperature range to ~400°F, to allow an estimation of the effect of gas content on cavitation initiation number is presented.

4. Various inconsistencies between the present data and theoretical expectations are believed to result partially from the lack of precision in the definition of "cavitation

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* Detailed geometry differences in roughness, etc., do exist between the plexiglas and stainless steel venturi, as explained in the report.

initiation". It is believed that this can be largely remedied by referring cavitation number measurements to a constant loss coefficient basis (as explained in the report), and it is anticipated that the additional data necessary to effect this transformation will be obtained.

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