University of Michigan
Department of Mechanical Engineering
Cavitation and Multiphase Flow Laboratory
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CAVITATION NOISE FOR DAMAGE PREDICTION

(Question No. 2)

by

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I. INTRODUCTION

This report is presented in reply to "Question No. 2" in partial fulfillment of "Application Article 2" of Contract No. C 620.107 between the CEA and myself.

In brief, the general form of "Question No. 2" is as follows:

> "How can the noise from cavitation be used to study and predict cavitation erosion?"

Sub-questions to be considered particularly should include:

1) Does there exist a correlation between the "spectrum" of cavitation noise and the rate of erosion?

2) Can one differentiate acoustically between an eroding flow and one which is not?

3) Can one make a correlation between the erosion potential of a specific flow regime and the "level of nucleation"?

The "general question" will be considered in the following, particularly through a discussion of the "sub-questions". These will be treated in the same order as they are listed above.

II. CAVITATION NOISE AND EROSION

A. Spectrum of Cavitation Noise and Rate of Erosion

1. General

The use of noise in general for the detection of cavitation has been an accepted practice for years, and more recently attempts have been made to correlate overall noise with erosion (1-7, eg). Some success has been obtained in specific experiments with individual pumps. However, it appears that useful general correlations are not likely to be attained in this way. For this reason we have here* attempted to develop a technique whereby bubble collapse pressure pulse "spectra" are measured. If it is assumed that bubble collapse

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*at the University of Michigan

pressure pulse durations are roughly uniform (or at least uniquely related to the pressure magnitudes) then the area under such a spectrum curve provides a measure of the total impulse delivered to the damaged surface, or to a probe located at a position equivalent to that of the surface to be damaged, from the viewpoint of the cavitation field. Such a technique is sensitive to not only the number of "blows" delivered to the surface, but also to their strength. It thus appears to provide vital information beyond that provided either by a simple total noise measurement or a noise frequency spectrum. Some very limited but successful experimentation with methods similar to those here suggested has been reported (8-10, eg), using primarily vibratory cavitation damage facilities, as we have also in our work to date (11, 12, eg).

2. Sub-Question No. 1 - Correlation between "Spectrum" of Cavitation Noise and Rate of Erosion

At present there is no general meaningful correlation, existing or published, between cavitation "noise" and the rate of erosion, to my knowledge. As mentioned in the foregoing, previous attempts (1-7, eg) to provide such a correlation between total cavitation "noise" and erosion rate (expressible, eg, as MDPR = mean depth of penetration rate) provide results perhaps useful for specific types of machines, geometries, etc., but in my opinion cannot be adequately generalized. In perhaps over-simplified terms, this can be ascribed to the fact that the same overall "noise" can be produced by various combinations of numbers of collapsing bubbles, mean "intensity" of bubble collapse (related to cavitation "sigma"), distance of bubble collapse from probe, attenuation of noise signal in intervening liquid-vapor mixture, and also other possible complicating factors. Also little is gained, other than for purposes of general research (13, eg), by examining the frequency spectrum of the noise, other than through the elimination of relative lower frequency noise due perhaps to extraneous causes such as general flow noise, machinery noise, etc.

For the reasons discussed above, it is my opinion that correlations between noise spectrum and erosion rate, to be of general utility, must contain information in addition to that of the amplitude-frequency spectrum. At a minimum, the number of "blows", along with their amplitude, is required. As already mentioned, this is the approach which we have been developing at Michigan during the past 2-3 years. Some success has been obtained (11,12, eg.), and this will be elucidated somewhat in the following material. However, it certainly cannot be stated at this point that a generally applicable correlation between bubble collapse pulse number and amplitude spectra and erosion rate has yet been attained. This work continues in this lab with Office of Naval Research (ONR) support, and it is our hope that such correlations will be attained using flow tests in a venturi, as well as vibratory facility results, in the not too distant future. While some initial vibratory tests were previously conducted here in sodium under ERDA sponsorship, we do not expect to continue work in sodium for ONR. Hence, further support from CEA/Cadarache for this purpose would be extremely useful.

In addition to our own work in the development of this type of correlating capability, previous related work has also been reported from Japan (8,9, eg) and USSR (10). Both groups (8-10) state that positive correlations between such pulse-count spectra and MDPR were obtained. Further details of our preliminary results follow.

Experiments here have included cavitation damage rate measurements in both water and molten sodium over a range of temperatures and suppression pressures in our 20 kHz, 1.5 mil (38 μm) vibratory horn cavitation damage facility. Detailed results are found elsewhere (11,12), but Fig. 1 illustrates the type of correlation obtained between measured bubble collapse pressure spectrum area and measured damage rate (MDPR). The best-fit relation is described by Eq. 1.

$$\text{MDPR} = C(\text{Spectrum Area})^{n} \qquad \text{-------} \qquad (1)$$

where C is a constant obtained empirically. The average value obtained for the exponent n is ~5 for high intensity tests, and ~1 for low intensity. The standard percent error for these correlations is only ~20%, which is surprisingly small for relatively rough experiments* of this kind. It is planned to continue this type of experiment in a venturi facility with water, and eventually also in field devices.

Though the evidence yet available is relatively sparse, in my opinion this à priori erosion rate prediction technique, which can eventually be developed for application to many field devices, seems almost "in hand". If so, it would then be possible to predict, from rapid and easy acoustic measurements, eventual erosion rates which might be experienced in many field devices. Eventual application to rotating components also seems feasible, but obviously involves geometric considerations pertinent to specific applications. Such capabilities, within even the very approximate limits of possible engineering utility, are unfortunately virtually non-existent today.

In direct reply to Sub-Question #1, it is my opinion that no usuable correlation between any form of cavitation noise spectrum and cavitation erosion rate exists at the present time. However, in my opinion, the research program (described above) in which we are now engaged at the University of Michigan, may well lead to such a meaningful correlation in a few years, and thus to the possibility of determining à priori eventual cavitation damage rates in field devices (eventually including rotating machines) from external acoustic measurements. In my opinion, only the approach (which we are now using) of determining both number and strength of bubble collapse pulses at the point to be eroded, is

*Or erosion experiments of any sort.

capable of producing such an à priori predicting capability, along with necessary correlations.

Since this work at Michigan is supported now by Office of Naval Research (rather than ERDA), it is unlikely that further sodium tests will be included. Hence, additional modest support from CEA/Cadarache for the inclusion of sodium tests in the overall program would be most useful to verify the resultant correlations for use by CEA in sodium.

2. Sub-Question No. 2 - How Differentiate Acoustically between Eroding Flows and Those which are Not Eroding

a. Acoustic Spectral Method

In general this sub-question is answered in the above discussion relating particularly to Sub-question No. 1; ie, in my opinion, this differentiation can only be made through the use of bubble collapse pulse spectra, which provide both number and strength of pulses at the wall to be eroded. Information is also required of course relating the spectrum "areas" so obtained, and the measured MDPR of the material in question. This latter information can only be obtained by damage tests. These can most easily and economically be performed using a vibratory type facility, but perhaps with more realism, and certainly with much more expense, in a flowing tunnel system. As previously stated, our present work at Michigan has relied upon a vibratory-type facility to obtain the necessary damage data in both sodium and water, but confirming data in water is expected from a flowing venturi system.

b. Use of Erosion Noise

In conversations last May at Cadarache, the possibility of using the noise of erosion itself to determine, and perhaps measure, the occurrence of cavitation erosion was discussed. My stated belief at that time was that it was probably not a feasible technique, since the bubble collapse noise would probably mask any noise due to erosion itself.

I have since discussed this possibility with various colleagues, particularly Prof. Julian Frederick, who is a world-recognized authority on the question of "acoustic emission" from material deformation, as well as author of the book "Ultrasonic Engineering" (14). Prof. Frederick had heard of some similar attempts to detect the formation of "surface micro-cracks" primarily from liquid corrosion-erosion (not cavitation) for ERDA several years ago. The "acoustic emissions" from micro-crack formation was not sufficient to be detectable in the presence of ordinary flow noise. Since cavitation noise is much louder than flow noise in its absence, Prof. Frederick agreed with my original thought that it would be probably impossible to detect erosion through its acoustic emission in the presence of a cavitating flow. While neither of us know of any published references to support this position, it is possible that some can be found in the future, in which case I will pass these along to you. In summary, it is our present belief* that the noise of "acoustic emission" is orders of magnitude less than that of cavitation and hence probably not detectable in its presence. Since cavitation noise, as well as acoustic emission, both extend into the very high frequency range, it is improbable that selected frequency filtering would help in detecting acoustically micro-crack formation, or other aspects of erosion due to cavitation. Incidentally, Prof. Frederick believes that acoustic emission research is now being conducted at Battelle Institute in Frankford, Germany. Perhaps pertinent information could be had by inquiring there.

Somewhat pertinent to the question of acoustic emission from erosion, is knowledge concerning the size of particles and their mode of departure from the eroded surface. There have been only a few studies to my knowledge concerning

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*As well as that of numerous "acoustitians" with whom I discussed this question at the very recent 7th Int'l Sym. for Non-Linear Acoustics (ISNA), Blacksburg, Va., Aug. 1976. I was told there that an international acoustics emission conference would take place in Japan this year, but I have no further details.

the size of cavitation-eroded particles. However, one such study was done in our laboratory (15) some years ago, where neutron irradiated steel specimens were used so that the cavitation debris could be isolated and sieved. It was found that particle diameters ranged up to $\sim$ 0.1 mm. I believe that any other such studies which may have been conducted elsewhere tend to confirm the result that particle sizes are certainly not uniform, that no minimum diameter can be specified, and that the maximum is at least of the order of a fraction of a millimeter.

We have recently obtained some very fragmentary information concerning the mode of particle departure from an eroded surface of aluminum from a high-speed motion picture sequence concerning the collapse of electric-spark generated cavitation bubbles in our water venturi system. In these 10^6 frame/second pictures of asymmetric cavitation bubble collapse and microjet formation adjacent to a soft aluminum wall, the departure of an apparent erosion particle from the surface at $\sim$ 100 m/s normal to the surface was observed. The particle observed had an elongated shape with length of $\sim$ 1 mm. If departing eroded particles have typically such large ejection velocity, it is conceivable that the associated acoustic emission could be detected even in the presence of a collapsing bubble, since the transmission loss associated with the particle ejection would probably be much less than for the bubble collapse, which occurs in the liquid and must be transmitted to the solid material in which the probe could be installed. However, to my knowledge, no detection of such direct erosion noise has yet been reported. What information does exist, as previously mentioned, indicates that its detection is improbable in the present state of the art.

B. Erosion Potential and Level of Nucleation

1. General

Presumably the "level of nucleation" in the present context refers essentially to cavitation "sigma", i.e., the cavitation "number" at which cavitation occurs, as compared to "inception sigma", rather than to the presence of "nuclei" (germes), which are of course necessary for cavitation inception. Of course some relationship must exist between the spectrum of such "nuclei" and cavitation damage, since cavitation (and damage) would not exist at all for a given "cavitation sigma" unless sufficient numbers of such nuclei were present. However, I assume that this is not the aspect of interest in the present case.

I assume then that the question of present interest is the relationship between the externally-measurable parameter of "cavitation sigma" and cavitation damage. In a specific case (venturi, pump or other given device) such a dependence certainly exists, as will be discussed in the following. However, whether or not a useful general relationship can be found may be more questionable. However, in general, it can be assumed that a curve of damage rate (MDPR) vs. sigma for almost any type of device will show a maximum MDPR for moderate sigma with damage rate decreasing for higher or lower sigma. For very high sigma, i.e., high suppression pressure or low velocity, it it is obvious that the cavitation erosion rate will go to zero, since cavitation will then be completely suppressed. However, in some cases, it is possible that simple liquid erosion or corrosion might still cause some material removal.

On the other hand, for very low sigma* the relative suppression pressure necessary to drive the bubble collapse process would become too small to cause damage, even though in many cases many large bubbles in the collapse region would still exist. For such low sigma, in some cases, bubble collapse occurs only

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*Almost similar to "saturated boiling" where damage is not a factor.

behind the cavitating component, as, eg., in "super-cavitating" propellors, "inducer" impellers, or hydrofoils. For these cases, the damage rate at very low sigma would be virtually zero. However, for components such as cavitating elbows, it is likely that even at very low sigma there would still be some damage as bubble collapse adjacent to material surfaces would still occur.

Presumably the same type of damage vs. sigma curve is to be expected for the vibratory facility test. However, such tests as are reported (16, eg.) are at relatively low sigma, ie, suppression pressure, so that damage increases for increased pressure. If the pressure were increased sufficiently, it is clear that damage rate would pass through a maximum and then again decrease, since cavitation would be suppressed entirely for sufficiently high pressure. However, no such high pressure vibratory tests are as yet reported.

2. Pressure and Velocity Effects and Sigma

Systematic cavitation damage tests in which damage was studied as a function of sigma in specific flow systems are few. One of the best documented cases may be that of the vibratory horn (16, eg.), but unfortunately this case is not readily applicable to flow devices, since no characteristic velocity, which is necessary for the calculation of sigma, exists in the vibratory device. Obviously then, the vibratory horn does exhibit a "pure" pressure effect, since no "velocity effect"is involved. This point indicates a principle difficulty, which must be inherent in any correlation between sigma itself and damage rate. At fixed sigma, there is certainly a strong dependence in many cases of damage rate upon velocity. This has been well-documented for years in the cavitation literature (17, eg.). In fact it has been reported under these conditions that damage rate in many cases is roughly proportional to the 6th power of velocity (17,18,eg.). At constant sigma no doubt there is also a strong effect of variation of either suppression pressure or temperature upon damage rate. While these are not yet well documented in the literature for flowing systems, both pressure and temperature effects are clearly delineated concerning the vibratory horn device (16, eg.). No doubt they are also important for most flowing systems. While the temperature effect does not enter strongly into a calculation of sigma (except through its effect upon vapor pressure), the suppression pressure does directly affect sigma. Thus there is the difficulty of separating individual pressure, velocity and temperature effects, if sigma alone were to be used as a correlating parameter for MDPR, eg. Such a sigma correlation would then presumably necessarily be limited to given velocity and temperature, with sigma variation achieved only through variation of suppression pressure, if it were to be meaningful. Variations in the correlation would then apply to different velocities, temperatures, and of course also fluids and test materials.

Adding to the complexity of delineating a sigma effect upon damage rate is the observed variability of the velocity effect as reported in the literature. The velocity "exponent", while usually reported to be ~6 (17,18, eg.) has been noted in some cases to vary between negative values* (19, eg.) to ~10 (20, eg.). In my opinion, this large variability of the "velocity exponent" is primarily a result of the differences in suppression pressure variation accompanying the velocity variation in these cases; ie., if sigma is maintained constant, suppression pressure increases with velocity squared, whereas if sigma is sufficiently decreased for increasing velocity, suppression pressure may remain constant or even decrease. In this latter case, a negative, or only slightly positive, velocity exponent may occur. For the case of constant or increasing sigma with increasing velocity, very high "velocity exponents" would be expected. Thus the "sigma effect" and the "velocity effect" are intimately related, ignoring for the moment the added influence of possible "thermodynamic effects". Unless this

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*Figure 2 is typical

complexity is recognized, no meaningful correlation between damage and sigma, or the other parameters already discussed, becomes possible.

3. Specific Results

While various relatively scattered tests are reported in the literature (17-20, eg., and others by other investigators), to my knowledge there exists insufficient data at present to resolve the questions regarding the effects of sigma, and other possible independent parameters, upon erosion rate. Some relatively pertinent work, previously not reported in a way related to the present question, was conducted here in a venturi system (21, 22, eg). Figure 3 shows the venturi used, and Fig. 4 shows typical measured wall axial pressure profiles. From these, sigma values based on the minimum wall pressure measured, can be computed. Figure 5 shows resultant plots (previously unpublished) of normalized MDPR vs. sigma. As previously stated, these show a maximum MDPR corresponding to an intermediate sigma, with damage rate falling for higher and lower sigmas. However, the maximum damage sigma differs depending upon the material tested, liquid used (mercury and water), test velocity, and minor changes in test section geometry (2 vs. 3 test specimens inserted, see Fig. 3). It is thus confirmed that a correlation between MDPR and sigma must depend upon these various test parameters at least, even for cases of nearly identical geometry.

4. Conclusions on Sigma-Damage Correlation Possibility

It seems desirable at this point to briefly summarize my opinion concerning the possibility of developing useful correlations between sigma and cavitation damage. Firstly, it seems unlikely that a simple and reasonably general correlation between damage rate and cavitation sigma can be found, primarily because of the different influences upon damage rate of various factors such as "velocity effect" , "suppression pressure effect", and "temperature" (or thermodynamic) effects, the parameters of which all influence directly cavitation sigma.

Very recent and current pertinent acoustic-damage correlation work has been reported from the group of Prof. S. P. Hutton at the University of Southampton (23-26, eg.). This has involved water tests in a two-dimensional venturi, wherein the test section flow path is composed of a divergent-convergent 8-deg. wedge located parallel to a flat plate which is the opposite wall of the test section. Damage is observed on the soft aluminum wall of the divergent portion of the wedge, and acoustic measurements are made closely downstream of the wedge. Throat opening is 20 mm; throat velocity ranges from 15-45 m/s. Gas content is in the range 0.6-0.9 saturation at standard temperature and pressure.

Total RMS sound pressure is measured by the probe mounted flush with the wall immediately downstream of the wedge, over the range 30 Hz to 30 kHz. No pulse count studies, such as our own, have been made.

Total RMS sound pressure is then compared with measured pit count rate in soft aluminum (either thin film or plate) as a function of cavitation sigma. Tests at both constant sigma and constant velocity were made. Sigma is here referred to throat pressure (as in our own test previously discussed) rather than upstream pressure, which is used in many applications.

Pertinent significant results from these tests are the following:

1. RMS sound pressure and pitting rate curves are of similar shape.
2. At constant sigma, both RMS sound and pitting rate vary approximately as V^4.
3. At constant velocity, both vary approximately as σ^{-2}.

The trend of pitting rate variation with sigma is consistent with the previous discussion in this report and with our own results, in showing a trend of decreasing damage rate with increasing sigma. Although the Hutton data (22, eg) does not show a corresponding fall-off at very low sigma, since tests were not carried into that range, it too must exist since the driving pressure for bubble collapse would there disappear, as previously discussed.

On the other hand, the general shape of a sigma vs. MDPR curve for given velocity, temperature, test liquid, test material, and test geometry is already known, i.e., very large or very small sigma will produce very little damage, with maximum damage corresponding to an intermediate sigma value, such as is shown in Fig. 5. However, the value of the maximum damage sigma and the detailed shape of the curve will depend on the various related parameters mentioned above.

Thus my final conclusion is that cavitation sigma is certainly a very important parameter to be considered in developing an overall correlation between externally measurable parameters and eventual damage rate, but that it is not alone a sufficient correlating parameter. Most importantly, it must be considered along with related separate velocity and suppression pressure effects, as well of course as thermodynamic, material, liquid, and flow geometry effects. I believe, then, that cavitation sigma is perhaps the most logical externally-measurable parameter with which to start in the formulation of damage rate correlations and the planning of logical test programs. However, it is not a sufficient parameter for the eventual development of generally applicable cavitstion damage correlations.

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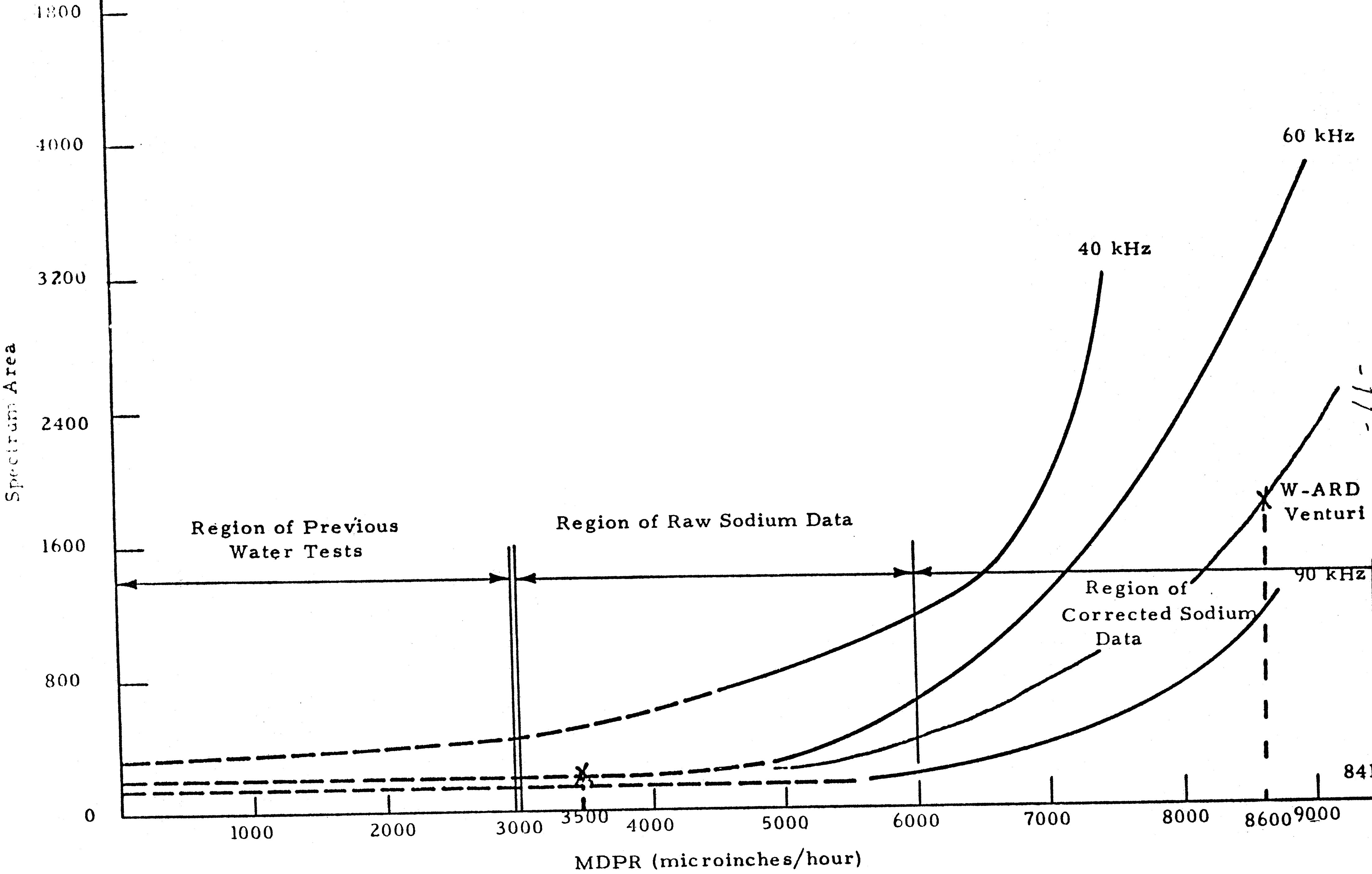
List of Figures

Fig. 1 Correlation of Pulse Pressure Spectrum Area and MDPR



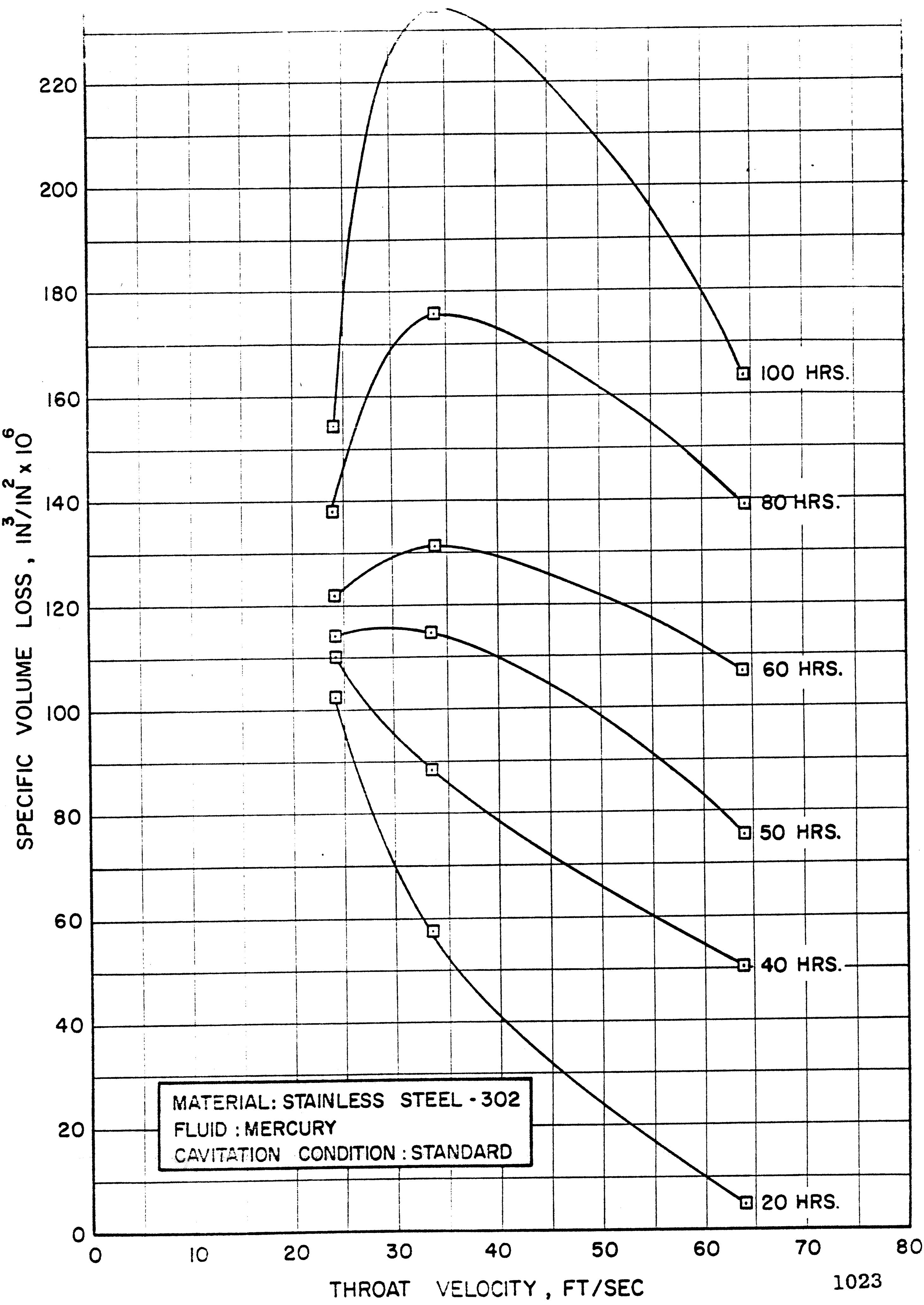


Fig. 2 - Venturi Velocity Damage Effect.

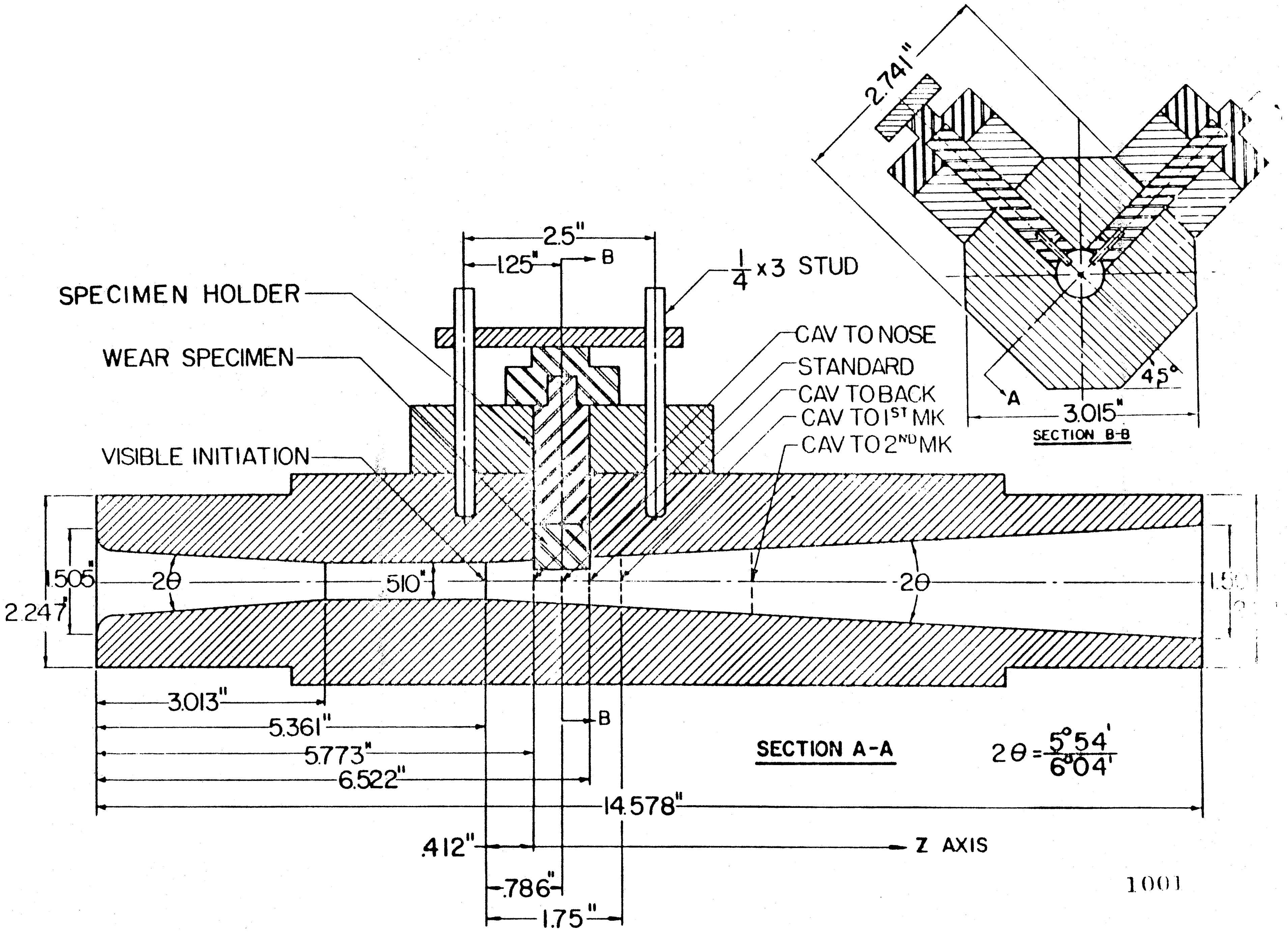


Fig. 3 - U-M Damage Venturi Schematic.

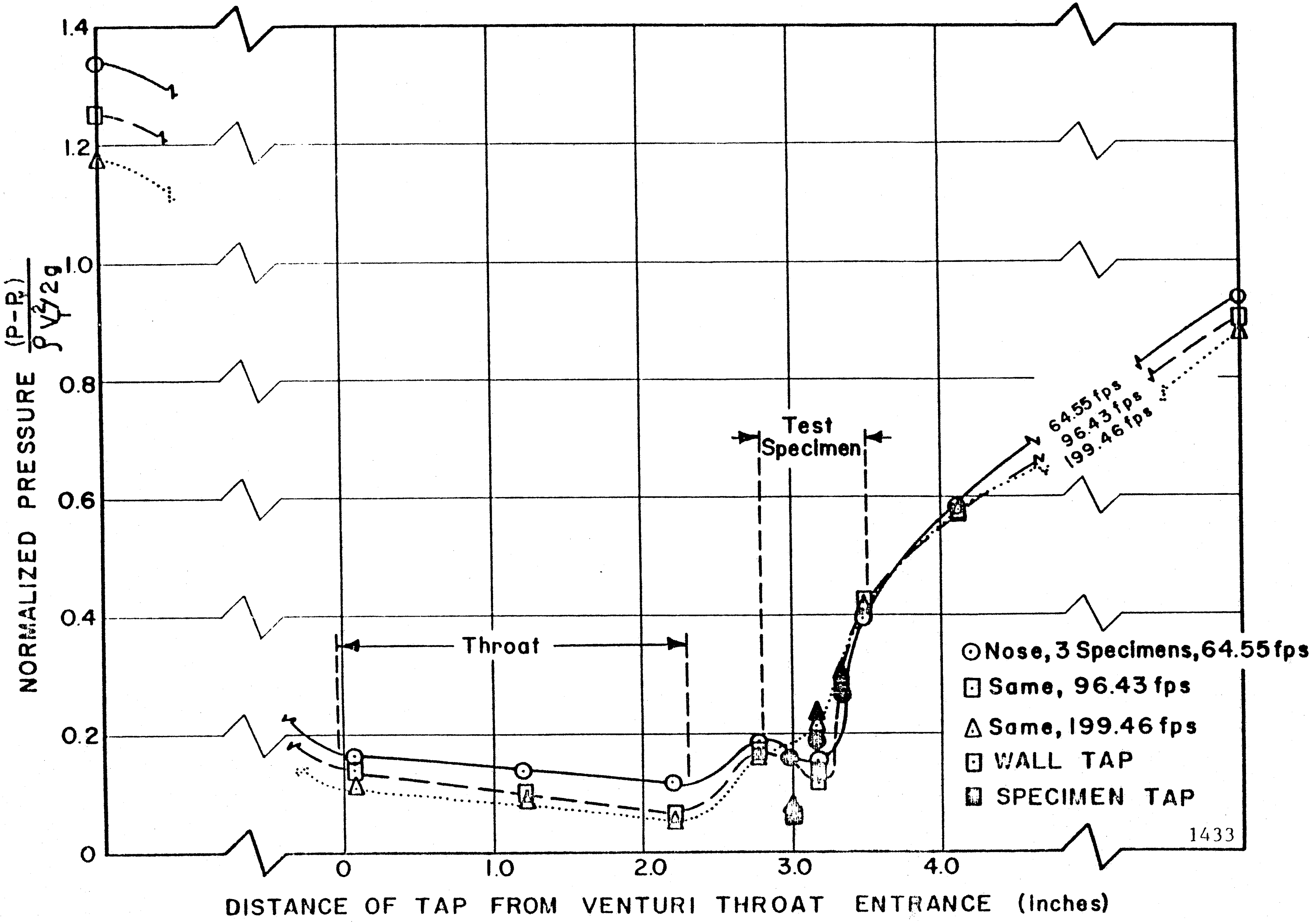


Fig. 4.--Normalized pressure profile for "cavitation to nose" with three specimens in water at various velocities.

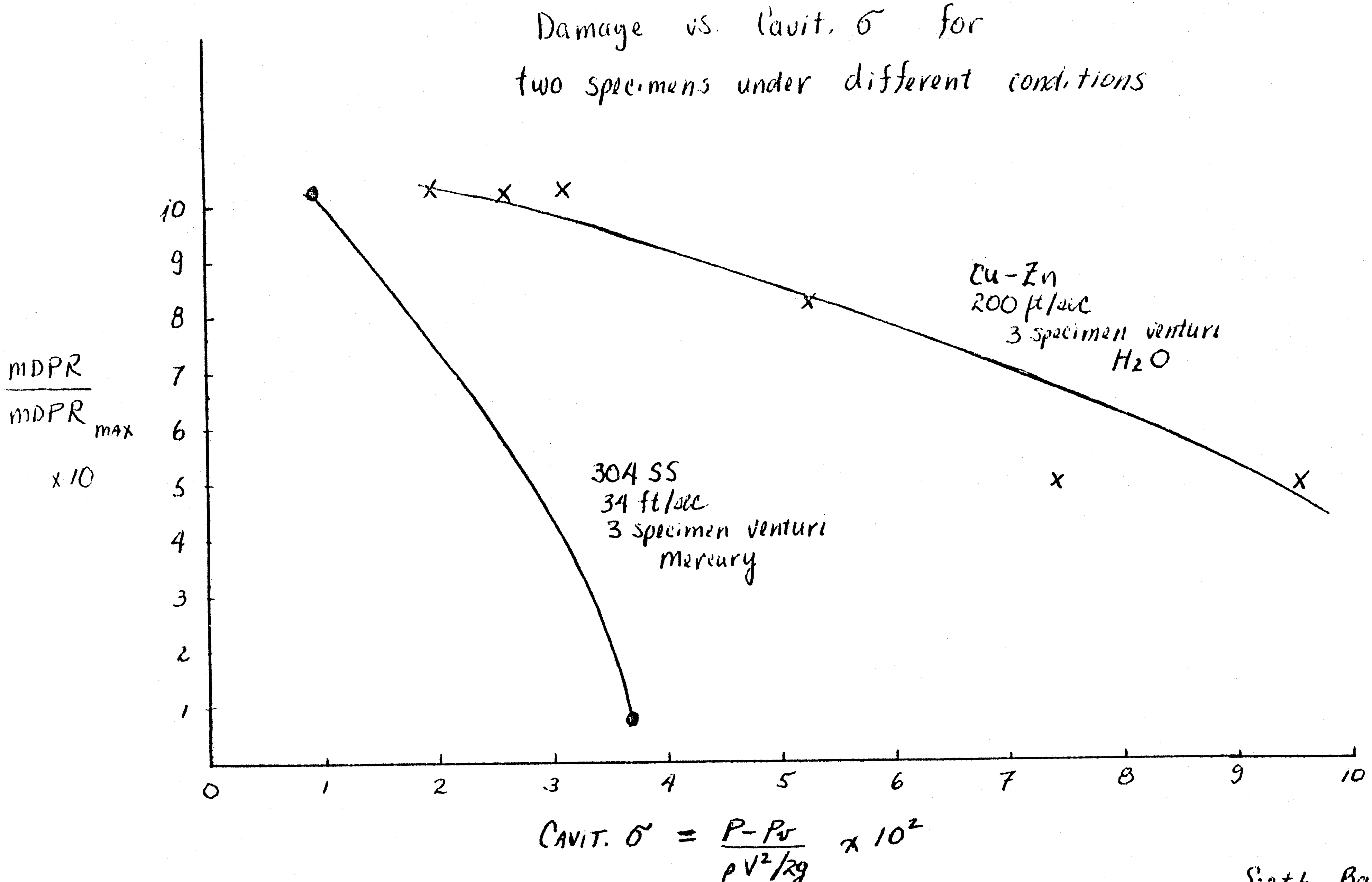


Fig. 5 - Normalized MDPR vs. Sigma

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