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Experimental Determination of Cavitation Thresholds in Liquid Water and Mercury

by

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ABSTRACT

An overview is provided on cavitation threshold measurement experiments for water and mercury. Various aspects to be considered that affect onset determination are discussed along with design specifications developed for construction of appropriate apparatus types. Both static and transient-cavitation effects were studied using radically different apparatus designs. Preliminary data are presented for cavitation thresholds for water and mercury over a range of temperatures in static and high-frequency environments. Implications and issues related to spallation neutron source target designs and operation are discussed.

INTRODUCTION

For accelerator-driven neutron sources such as the Spallation Neutron Source (SNS)¹, powers in the 1 MW range (time-average) are close to present technology limits. The interaction of the energetic proton beam within a mercury target leads to very high heating rates. Although the resulting temperature rise is relatively small (a few °C), the rate of temperature rise is enormous ($\sim 10^7$ °C/s) during the very brief beam pulse (~ 0.5 μ s). The resulting compression of the mercury can lead to the production of large amplitude pressure waves in the mercury that interact with the walls of the mercury target and the bulk flow field. Safety-related operational concerns exist in two main areas, viz., (1) possible target enclosure failure from impact of thermal shocks on the wall due to its direct heating from the proton beam and the loads transferred from the mercury compression waves, and (2) impact of the compression-cum-rarefaction wave-induced effects such as fluid surging and potential cavitation. Understanding and predicting pressure pulse propagation-related issues concerning onset of cavitation are

considered critical for establishing the feasibility of constructing and safely operating such devices, as also for determining the potential for power upgrades to 5-MW type levels.

It is important to consider the cavitation of fluids in target systems for a variety of reasons. Its occurrence can possibly have a significant impact on heat transfer, pressure pulse generation, fluid jetting on to structures, surface erosion, and stresses induced in enclosures. Therefore, it is important to know the threshold pressure under which the fluid in tension will undergo cavitation. Another major aspect concerns the possible onset of cavitation in an oscillating pressure field. That is, one would need to know if fluids such as mercury and water will cavitate if the imposed tensile pressure in the fluid is of short duration (typically in the range of tens of microseconds).

Efforts were put in place early on to predict analytically what levels of pressure fluctuations would be expected in a 1-MW SNS mercury target, coupled with focussed experiments to determine what the "practical" cavitation onset thresholds would be. This paper presents a synopsis of analytical predictions of the magnitude and time history of fluid pressure fluctuations to be expected in a mercury target for the SNS, coupled with descriptions of experiments designed and executed so far for determination of cavitation onset thresholds.

ANALYTICAL PREDICTIONS

A detailed description of modeling and related analyses of wave propagation along with fluid-structural interactions in a 1-MW SNS target for selected cases has been reported elsewhere². These results indicated that pressure fluctuations in the mercury (in the absence of cavitation) can be

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$\sim \pm 30$ MPa in the bulk fluid regions, and $\sim \pm 10$ MPa at boundaries with structures. Another point relevant to cavitation onset concerns the duration of pressure pulses. Predictions indicate pulse widths lasting tens of microseconds to relatively small ~ 5 μ s. Questions naturally arise, "What is the influence of short-pulse durations on cavitation onset thresholds?, and, will cavitation onset be likely or possible under SNS conditions if the tensile state extends to ~ -30 MPa?"

DESIGNS FOR DERIVING SNS-RELEVANT INFORMATION ON CAVITATION ONSET

It is well-known that liquids (like solids) will break apart or form voids when put under sufficient tension^{3,6}. An exhaustive review of data obtained for various fluids and under different conditions over the past several decades clearly indicates that several factors can play a role (to varying extents) in affecting fluid cavitation. Some of the more important ones are, temperature, degree of impurity, amount of dissolved gases, geometry and surface conditions of surrounding structures, ionizing radiation and frequency. A review of past data for water and mercury indicate a wide range of estimates depending on the type of fluid state utilized and how the experiment was conducted. For example, Briggs obtained values ranging from -7 bars to -425 bars for cavitation onset in mercury depending on whether he utilized extreme measures such as setting his apparatus in a furnace at ~ 400 °C and torching the sides of containers.

DEVELOPING DESIGN CRITERIA

Lessons learned from past endeavors clearly indicate that cavitation onset is situation dependent. Therefore, efforts were placed on obtaining data which would be practically-significant for SNS design and analysis applications. Design criteria were developed to provide the ability to:

- determine cavitation thresholds in bulk fluid far away from vibrating walls,
- determine cavitation thresholds in fluid adjacent to vibrating walls,
- derive information on static and transient cavitation onset thresholds,
- vary frequency of imposed pressure fields in fluids, and,

to evaluate thresholds in mercury at various temperatures (ranging from room temperature to ~ 250 C), and varying degrees of gas content.

APPARATUS DESIGNS

Two different apparatus designs were utilized for studying onset of cavitation. The first design is an offshoot of the significant pioneering work done by Briggs^{3,4} and Hahn⁵ in which a spinner tube partially filled with fluid is spun about its axis. The combination of frequency and fluid arm length provides a desired tensile force in the fluid at the center of the spinning tube. An analogous apparatus (shown schematically in Figure 1) was used in the ORNL studies in which a diamond-shaped spinner tube made of Pyrex glass is used. The glass spinner is mounted on to a rubber base which is spun at variable frequencies ranging from 0 to 10,000 rpm. This design has the advantage of permitting cavitating gases to rise through the arms and to be expelled from the top. In our scoping studies, cavitation onset is defined at the rotation frequency at which a bubble of gas forms at the central bulb region and starts to grow rapidly with increase in frequency of rotation. Besides the elegant simplicity, another key benefit lies in the absence of any direct instrumentation required (besides knowing the frequency of spinning, which is all that is needed to determine the cavitation onset threshold directly). As has been mentioned previously by Briggs^{3,4}, such an apparatus does not clarify whether it is the loss of fluid-structure surface adhesion, or whether it is the nucleation of bubbles in the core of the fluid that leads to cavitation onset. However, under the assumption that surface effects are minimized via proper cleansing of the glass tubing, data obtained from the present setup should be useful for determining cavitation onset in fluids under a relatively static tensile pressure state. Additionally, in order to allow cavitation bubbles, to float upwards without getting stuck in a narrow capillary, and to minimize the surface area to volume ratio for the cavitating fluid (as would be the case for the SNS-type target design), the tubing chosen for ORNL studies was a relatively much larger readily available ~ 6 mm (0.25-in.) inner diameter (unlike much smaller ~ 0.1 mm diameters used by Briggs).

A second apparatus design was developed based on work done previously⁶ for which a ring-shaped magnetostrictive transducer is used to cause

volumetric cavitation in water. Acoustic energy is concentrated in the central fluid region and cavitation, if any, is induced far away from vibrating walls. Shakedown tests have confirmed that cavitation bubbles can indeed nucleate, grow and get transported under short-duration ($\sim 10\text{-}30\ \mu\text{s}$) tensile states. Key elements of this apparatus (enclosed in a large ventilated glove box type container - not shown) are depicted schematically in Figure 2. As seen it consists of a bias circuit, along with a wave generator coupled to a power amplifier which drives the transducer through two pathways. The transducer may either be placed directly in the fluid or fitted around an appropriately-sized container (for which the fluid in question is placed). Pressure and temperature variations are monitored using a calibrated pressure sensor with a $1\ \mu\text{s}$ rise time and a K-type thermocouple.

A third apparatus (currently being fabricated) is based on obtaining data on transient cavitation onset at fluid-structure interfaces along with provision of the ability to pressurize the system with desired gases such as air and helium, or to evacuate it. Details will be presented at a later time.

EXPERIMENTAL PROCEDURE & RESULTS

Experimental procedure

For the spinner apparatus, care was taken to clean the apparatus as thoroughly as possible. Prior to insertion of fluids into the pyrex glass test sections the glass internals were flushed with acetone and allowed to dry. Thereafter, distilled water was poured through a (pre-cleaned) funnel into the apparatus to obtain a desired arm-length separation between two ends of the fluid meniscus. Experiments were then conducted at various temperatures by preheating the entire glass-ware in a furnace and then mounted on the spinner to conduct the spinning operation and derivation of cavitation threshold data. A calibrated strobe light was also used in conjunction with the built-in tachometer to help identify and visualize / photograph the fluid fracture process. These experiments were done twice, once with and then without degassing the central bulb region (via use of a thermal treatment).

For the transient cavitation apparatus fluid was poured through a strainer and brought to a set level height. Ordinary tap water and triple distilled mercury was used. Distilled water was not used since the purpose of these tests with water were only to conduct shakedown tests for ensuring proper functioning of the entire electronics systems. A resistance heater element is used to heat the fluid contents to a desired temperature after which it is removed and the calibrated pressure probe is introduced to monitor dynamic pressure traces. The first resonance is established and the power level from the amplifier-wave generator system increased gradually until distinct evidence of cavitation is obtained. In the case of water, this is also possible to notice visually as small gas bubbles get released in a high-frequency stream. Significant efforts had to be undertaken to alleviate environmental safety and health (ES&H) concerns with mercury, especially at elevated temperatures. Despite precautions taken for exhausting the vapors continually, controlling the mercury vapor levels in the surrounding atmosphere below acceptable levels posed a challenge at elevated temperatures. This problem is being currently addressed. As of writing this paper it has not been possible to obtain and report relevant transient threshold cavitation data for mercury at elevated temperatures.

Preliminary Results

Salient results of tests conducted at various temperatures with water and mercury are summarized in Figures 3 through 6.

Figure 3 depicts data obtained from the spinner apparatus for water. Two sets of experiments were conducted. In the first case, there was no special treatment of the container to drive off entrapped gases from the surface between liquid and glass. For the second case the glass was subjected to heat to drive off as much of the interfacial gases as possible. As can be clearly seen from Figure 3, there was a distinct change in observed trends. Surface pre-treatment gave rise to significant variations in cavitation onset thresholds with temperature. However, no discernible change was seen without surface treatment.

Figure 4 shows variation of transient pressure profiles in ordinary tap water when subjected to high frequency ($\sim 17\ \text{kHz}$) pressure fluctuations. Two sets of curves are depicted, one indicating the traces close to the onset of cavitation and the other

under intense cavitation. As can be clearly seen, the threshold tensile pressure obtained with ordinary tap water (with no efforts at degassing) can be quite high (~ 0.8 bar). Upon increasing tensile states further in the bulk fluid the pressure profiles become quite erratic. The phenomenon is witnessed by the expulsion of a stream of small (~ 100 - 500 μm) bubbles. These data confirm that cavitation bubbles will indeed nucleate and grow under high (~ 17 kHz) frequency pressure oscillations. The fact that the onset is at ~ 0.8 bar rather than under sub-vacuum conditions (as seen from the spinner data) is ascribed to the absence of degassing and also due to large impurity contents in tap versus distilled water.

Figure 5a shows static cavitation data obtained for mercury (with and without surface treatment) over the temperature range of 25°C to 250°C . No efforts were made to go over 250°C since this is not of any practical interest to anticipated SNS conditions. The range of tensile pressures for cavitation onset without surface treatment is between -2 bar to -3.5 bar. With surface treatment the range is between -3.6 bar to -5 bar. As was seen before, surface treatment does tend to give higher tensile pressures. However, unlike that for water, no significant variation is noted with temperature, due likely to the absence of efforts at degassing of mercury (versus that done for water in the experiments with the spinner apparatus).

Figure 5b shows transient cavitation data taken for mercury at room temperature. As mentioned previously, it was not possible to obtain data at elevated temperatures in time for inclusion in this manuscript. However, the trace of pressure variations indicates onset of cavitation at ~ -1.5 bar, a value close to that seen at the low end of tensile pressures from the spinner experiments (see Figure 5a). This indicates that, under similar conditions transient cavitation onset thresholds under static and transient conditions will likely be close together. Due to significant turbulence it is likely that transient cavitation onset (in the absence of degassing) will occur earlier, a fact yet to be confirmed for mercury under various states of degassing and temperatures.

SUMMARY & CONCLUSIONS

To summarize, several different experimental apparatus types and methodologies were designed

and engineered for deriving SNS-significant data on cavitation onset thresholds. Data were obtained for static and transient environment conditions. It is expected that, from practical considerations mercury degassing will not be feasible, nor will it likely be practical to control the types and extent of possible nucleation sites in target internal structures. Data obtained so far indicate mercury cavitation onset at ~ -0.2 to -0.5 MPa. However, the estimated predictions indicate fluctuations of $\sim \pm 30$ MPa in the bulk fluid and $\sim \pm 10$ MPa in the fluid near structural walls of the target. Taken together, it appears that gaseous-type cavitation will be likely in the 1-MW SNS target. Such cavitation onset has pros and cons associated with it. Ability of the fluid to fracture and release gases provides the system with an air-bag-like cushion to "passively" absorb shocks during pulsation at the locations this is needed. Therefore, predicted stresses on to structures may be considerably lowered during repeated pulsed operation. On the other hand, gases released may migrate to undesirable locations and adversely affect wettability, and therefore heat transfer, between the mercury and steel.

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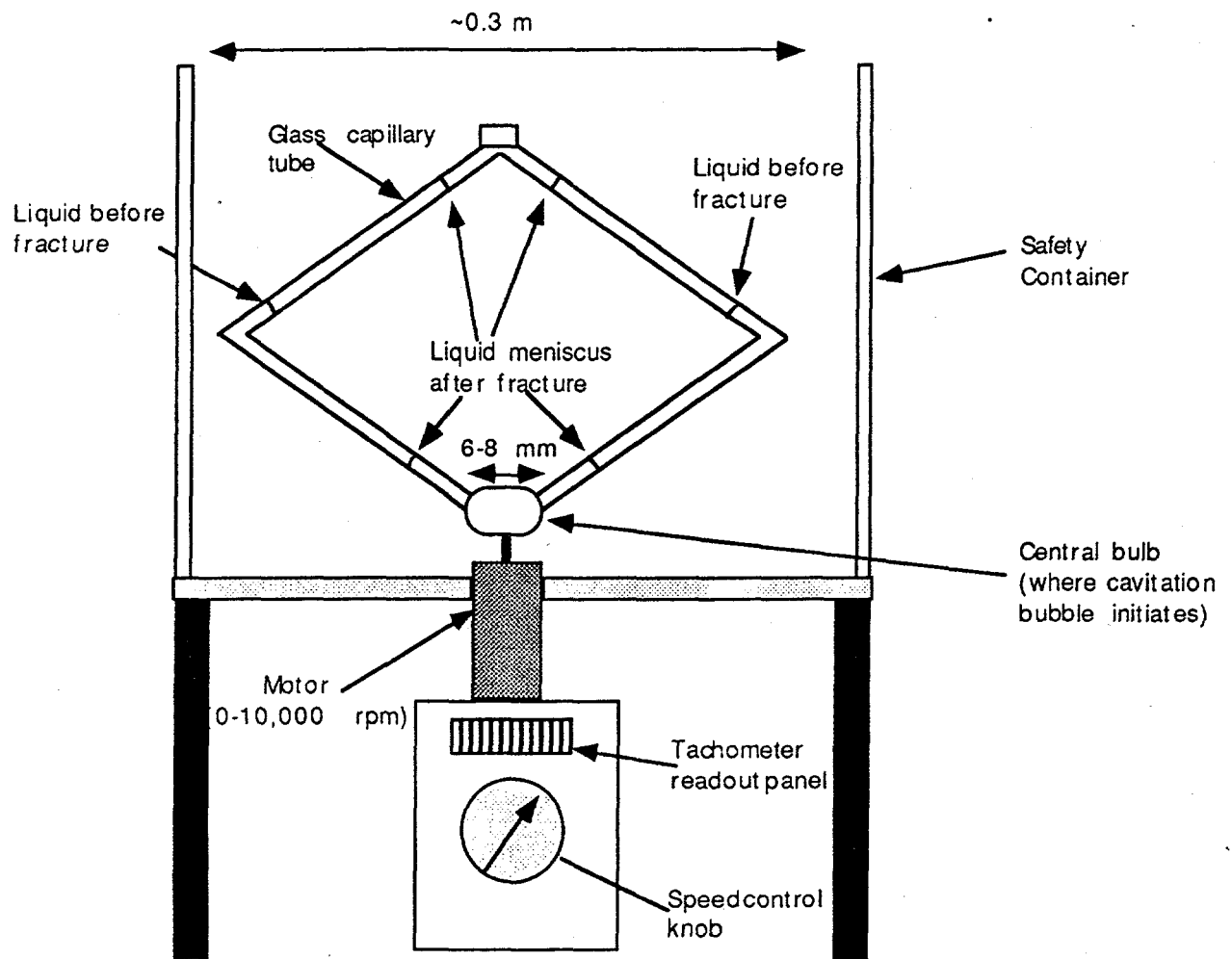


Figure 1: Schematic sketch of fluid cavitation threshold monitoring apparatus

Notes:

- 1) Mercury upon fracture can be noted via visual observation, break in photo-cell which trips the motor.
- 2) Upon fracture of Hg, the system is stopped automatically, the vapor bubble is allowed to collapse / escape so that the mercury drains back to the central bulb and the experiment is then repeated.

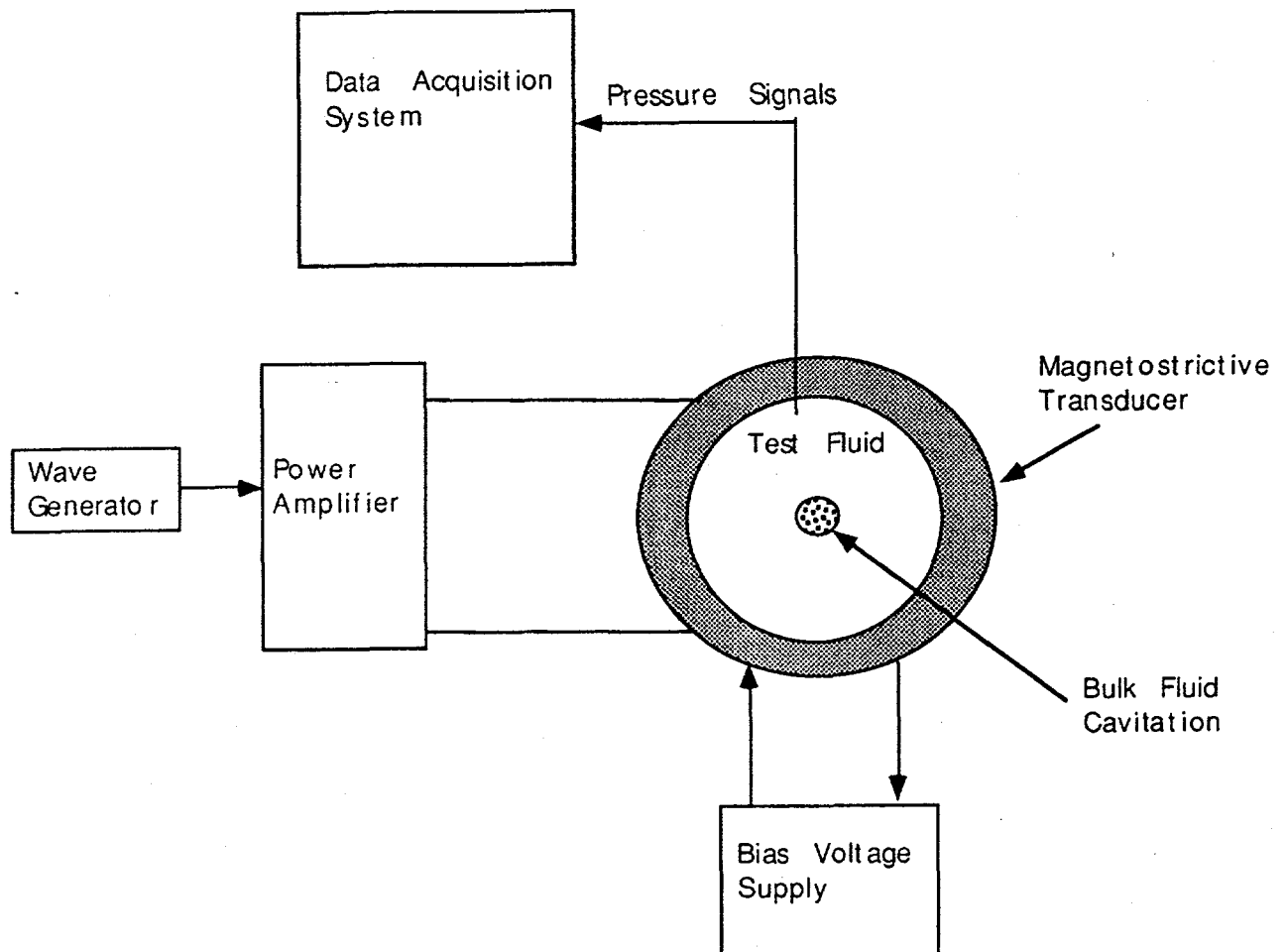


Figure 2. Schematic Representation of Magnetostrictive System for Determining Transient Cavitation Onset Threshold Pressures

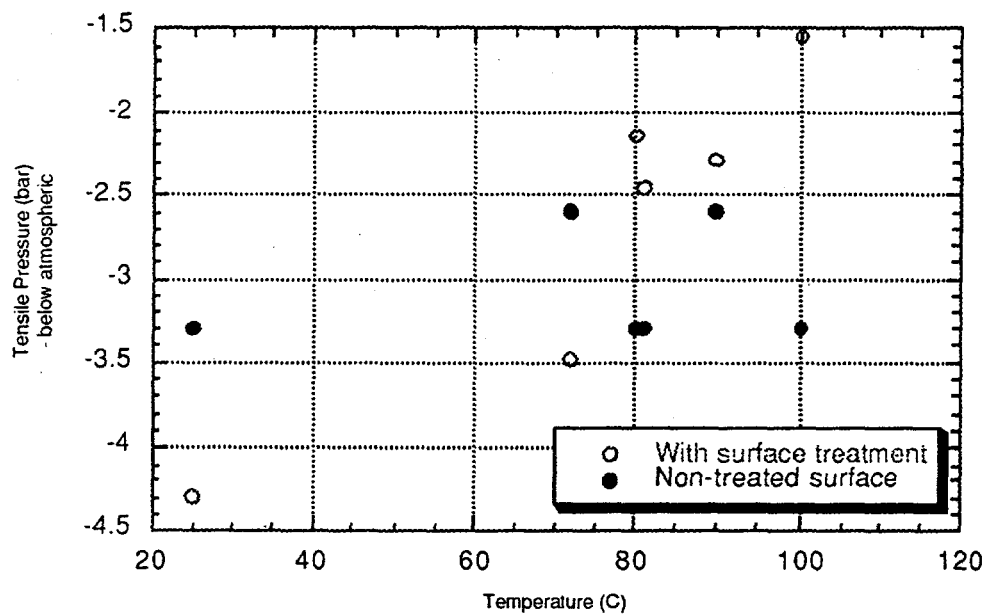


Figure 3. Cavitation Onset Threshold Tensile Pressures vs Temperature (Treated and untreated surfaces)

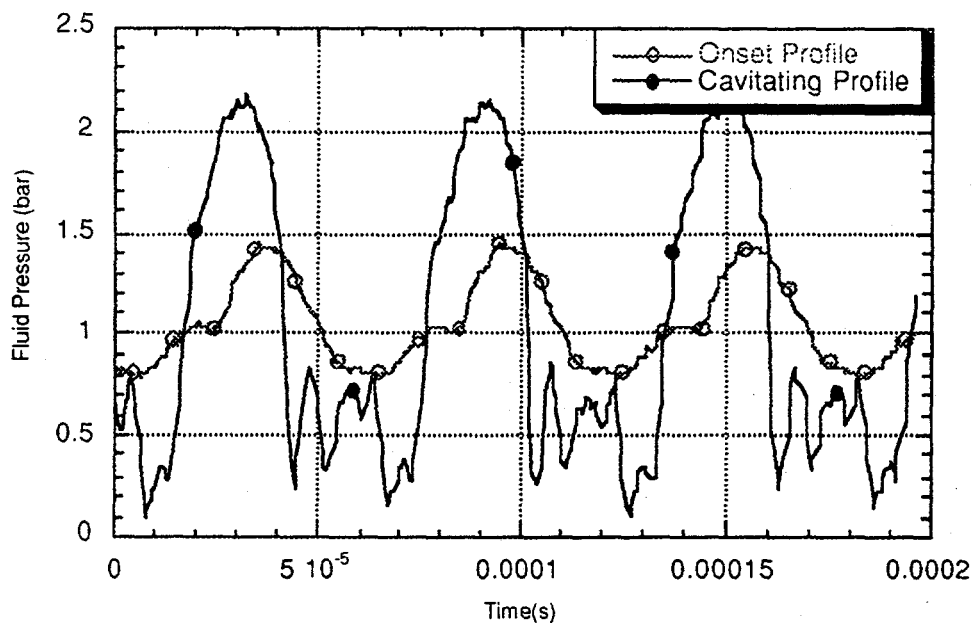


Figure 4. Transient Pressure Profiles for Onset and Cavitation Environment

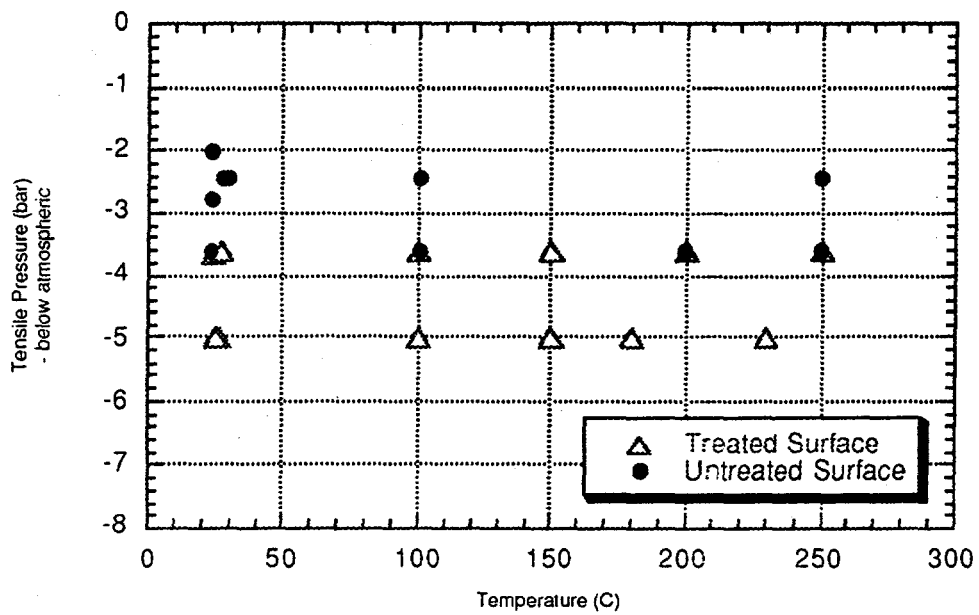


Figure 5a. Static Cavitation Onset Pressure Thresholds Vs Temperature (Treated and Untreated Surfaces)

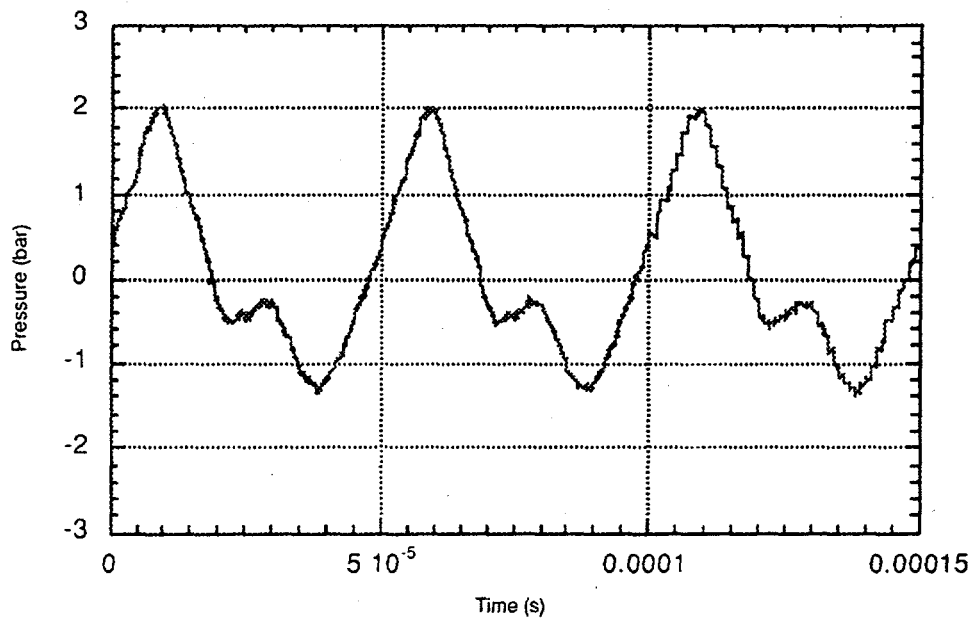


Figure 5b. Transient Pressure Variation at Cavitation Onset in Mercury