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College of Engineering

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Cavitation and Multiphase Flow Laboratory

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CAVITATION THRESHOLD OBSERVATIONS

IN WATER AT 14.5 kHz

by; Y. C. Huang
     F. G. Hammitt
     L. P. Solomon
     C. L. Kling

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ABSTRACT

Measurements of cavitation incidence and desinence threshold pressure have been made at 14.5 kHz in a vibratory horn facility in water over the temperature range between melting and boiling points at one atmosphere. These are compared with similar results previously obtained with liquid sodium over its comparable temperature range, and relatively close agreement in terms of pressure magnitudes as a function of a reduced temperature is found.

Additional interesting visual observations on the cavitation field are reported.

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I.   INTRODUCTION

Recently, investigations have been made in this laboratory on the onset and cessation of cavitation in liquid sodium.[1]   These tests were motivated by concern over "superheat effects" for highly transient temperature or pressure pulses upon void fraction and hence nuclear reactivity in sodium cooled fast reactors; thus the studies were conducted over a temperature range including temperatures close to the saturation temperature of the liquid sodium at the ambient pressure, i. e., ~1500°F. These studies pointed out that certain physical properties of the liquid are important to the results obtained.

Most flowing systems in use today throughout the broad spectrum of engineering employ water as a coolant fluid. It should be noted that room temperature water has physical properties fairly similar to those of high temperature liquid sodium, and thus certain effects connected with the nucleation and superheat in liquid sodium will no doubt occur in water. Therefore, it was determined that tests similar to the sodium tests would be performed using water as the test fluid, and employing identical procedures under correspondingly identical conditions employed by Nystrom[1].

II.   CAVITATION EXPERIMENTS USING WATER

A.   TEST EQUIPMENT

Garcia and Hammitt[2],[3] developed an ultrasonic facility for use in performing cavitation tests in high temperature liquid metals and other fluids. Their equipment was later modified by Nystrom[1] to measure the onset of cavitation in liquid sodium. A block diagram of this ultrasonic vibratory facility is presented in Fig. 1. One of the transducer assemblies employed by Nystrom, as well as that used in the tests reported here, has a resonant frequency of 14.5 khz. In

order to avoid possible effects due to surface roughness, the transducer tip employed by Nystom was replaced by a new, smooth stainless steel tip. The use of the Nystom assembly for the water tests insured that the water tests would be performed with a frequency identical to one of the Nystrom tests on liquid sodium.

A photograph of the general assembly is given in Figure 2; Figure 3 shows the high temperature cavitation vessel and ultrasonic transducer. Figure 4 shows the details of the 14.5 kHz ultrasonic transducer assembly.

The vibration amplitude of the tip of the ultrasonic horn was measured using a Fotonic Sensor.* This enabled a calibration curve to be established between the voltage supplied to the counterweight crystal affixed to the top of the horn and the vibration amplitude of the horn tip. A detailed description of the calibration procedure as well as the Fotonic Sensor itself is given by Nystrom[1].

B.   TEST FLUID AND ITS TREATMENT

It is well known that solid impurities in water may significantly affect the onset and cessation of cavitation. In order to attempt to eliminate these undesirable effects, distilled water was employed as a test fluid.

Another very important parameter which affects cavitation onset is air content of the water. Since this study was not concerned with this particular effect, air content was minimized. This was accomplished by degassing the distilled water for about two hours, or until bubbles were generated only spasmodically. The degassing process was performed using a vacuum pump and agitating the water in a glass container. Due to the loss of latent heat during the degassing process, the initial temperature (at the start of the cavitation test) was about $10^{\circ}F$ below the ambient temperature. A VanSlyke apparatus (Figure 5) determined the gas content of the "degassed" distilled water. Since the degassed distilled water is not in equilibrium with its surroundings, its air content will obviously increase with time. Therefore, the cavitation tests were begun immediately upon conclusion of the degassing operation.

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* Model KD-38 MTI Fotonic Sensor

C.   TEST PROCEDURE

The vibrational motion of the tip of the test specimen, immersed in the test fluid, produces pressure waves which are transmitted through the test fluid. As the input power to the ultrasonic transducer is increased, the amplitude of the horn and therefore the amplitude of these pressure waves increases. In general, if the local pressure at some point in the liquid falls below the vapor pressure of the test fluid, cavitation may occur, resulting in bubbles which grow and collapse in the acoustic field. Furthermore, as a result of the unsteady bubble motion, both in translation and dilatation, noise is produced. The onset and the cessation of cavitation is defined to be when the associated noise appears and disappears.

After the proper preparation of the water, the system was connected as shown in Figure 1. The output of a thermocouple used to measure the water temperature was connected to a Brown potentiometer pyrometer. The counterweight of the vibratory horn was connected to a dual-beam oscilloscope and a volt-meter.

Cavitation was assured to occur when the noise signal appeared on the oscilloscope. By increasing the power to the transducer horn assembly, sound power levels and thus the pressure levels, had minima which were conducive to the formation of cavitation bubbles. The radiated field of these bubbles was then sensed by the crystal mounted on the counterweight, rather than by the special sonic probe used by Nystrom[1] in sodium.

After cavitation was fully established, power was decreased and at some point, cavitation ceased. The power was then reduced to zero; this completed one test cycle. This process was repeated 10 times in order to give average values of input power at which cavitation began and ended. It should be noted that due to hysteresis effects, these powers will not be the same. It requires more power to begin cavitation than to sustain it, leading to the not unexpected result that power to start

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cavitation is less than the power at which it stops.

As a base point, the cyclic process was done with water at room temperature. The water temperature was then raised in steps of 10 (or 20) degrees with consistent results until 160°F. Above that point, the readings are not repeatable. It is felt that this uncertainty is due to the convective thermal current within the liquid.

D. TEST RESULTS

(Counterweight Crystal Voltages at the Onset* and Cessation* of cavitation in water at 14.5 kHz.)

According to linearized acoustic theory, the pressure perturbation is the product of acoustic impedance, frequency, and displacement ($p' = \rho c \omega \xi$). Both pressure and displacement amplitudes at the horn tip can be calculated by knowing the counterweight crystal voltage which has been calibrated using the Fotonic Sensor. Test results are listed in Table I, and plotted in Figs. 6 and 7. The data listed in Table I are actual values of measurements, while each data point plotted in Fig. 6 represents an average value at the temperature of measurement. According to the relation used by Nystrom[1] to convert rms voltages to pressures, 10 rms volts is equivalent to 50 psi for the present case.

The above result of onset of cavitation of water was obtained using the acoustical detection method, which has been used by several investigators. The results were extended by Esche[4] and summarized by Flynn[5]. Our present measurements fall about midway in terms of ratio within the very broad range of Esche's limiting values (150 psi to 6 psi at 14.5 kHz).

The cavitation inception and desinence of both liquid sodium[1] and water were plotted against a reduced temperature defined as $(T - T_{M.P.})/(T_{B.p.} - T_{M.P.})$ over the interval of melting point temperature, $T_{M.P.}$ and boiling point temperature, $T_{B.p.}$ at the static pressure used in the test (Fig. 7). The required

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*"Incidence" and "desinence" according to the cavitation literature.

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oscillating pressure amplitude for either inception or desinence decreases approximately linearly with temperature for both liquids and in fact has quite similar values, perhaps indicating a similar gas nuclei size and population distribution in both fluids. The slope of the curve with reduced temperature is greater for liquid sodium perhaps indicating a greater temperature dependence over the reduced temperature range of both nuclei distribution and other pertinent properties. This would not be surprising since the actual temperature range in sodium is much greater than in water.

Nystrom [1] converted his pressure oscillation magnitude measurements to the equivalent temperature magnitudes which would be required to cause nucleation under the same circumstances, i.e., "superheats", using the Clausius-Clapyron relation in the same manner as Ellion [6] in developing his superheat equation. This is not possible with the present water data since the pressure oscillations to cause nucleation are such that actual negative pressures exist in the water in the vicinity of bubbles (i.e., tensions). In such cases, the thermodynamic equilibrium Clausius-Clapyron relation is of course not applicable. The same difficulty was encountered in some of Nystrom's data which then could not be interpreted in terms of superheat. It is clear that with ordinary water, tension is not required to cause boiling, so that the present requirement of tension must be due to the highly transient nature of the applied pressure field. Thus lower and higher frequency experiments are desirable with water to clarify the effect of frequency and wave-form on required pressure amplitude (and "superheat").

III. OBSERVATIONS AND DISCUSSIONS

A. AIR CONTENT

The air content is an extremely vital factor in the problem of onset of cavitation. It is clear that liquids with higher gas content will require reduced pressure oscillations to cause cavitation in a test of this type. Furthermore the cavitation "jump and drop off" (explained below) will decrease in strength with high air content, until eventually they no longer appear. These terms ("jump" and "drop off") are rather difficult to define. However, consider the following: at some voltage, which will correspond to some minimum pressure level, cavitation will just begin for a fluid with some particular gas content. As the voltage is slightly increased, the level of cavitation (or bubble population) will suddenly drastically increase from a few bubbles which occur at onset to myriads of bubbles suggesting fully developed cavitation. We have called this observed phenomenon, "cavitation jump". The corresponding sudden drop in cavitation activity for a slight decrease in voltage from a fully cavitating condition to a barely cavitating condition we have called "drop off". As the air content increases in the test fluid, these effects became much less pronounced until for high gas contents, they disappear entirely.

The quantitative data, Fig. 6 and 7 and Table I were all taken at about 20% saturation air content.

B. NOISE SIGNAL AND DATA SCATTER

As already emphasized, the onset of cavitation and the associated noise signal depend very much on the air content, and, therefore, on the unknown spatial and size spectra of nucleation sites. The scatter of data which was also encountered by Nystrom[1] may be connected with redistribution of nucleation sites after each cycle of external disturbance.

In the cases when air content is high or temperature is high, the noise signals are less clear-cut and cavitation jumps are not distinguishable.

C. TEMPERATURE

The effect of temperature, and its interpretation in terms of reduced temperature have already been discussed in relation to Fig. 7. However, additional remarks are pertinent to the present experiment.

The boundary condition at the bubble wall is $P_v + P_g + P_s - P_a = \dfrac{2\sigma}{R}$ where P_v, P_g, P_a, and P_s are the pressures of water vapor, air in the bubble, atmosphere, and applied sinusoidal pressure field respectively. σ is the surface tension of water. R is the radius of the bubble. As the temperature increases, the surface tension decreases as does the difference between ambient pressure and vapor pressure in this test. Hence, on both accounts, the amplitude of pressure oscillation required for cavitation is decreased.

However, when the temperature is high enough, i.e., near the boiling point, the convective thermal currents in the water appears to be strong enough to affect the nucleation phenomena. Under these conditions, the rms voltage of the counter weight crystal, instead of remaining stationary, begins to oscillate randomly around a mean value of 4.0 — 4.5 volts. It appears that at higher temperature, the intensity of cavitation becomes a continuous function of vibratory amplitude (as opposed to the "jumps" observed at lower temperature).

D. FREQUENCY SHIFT

The resonant frequency of the vibratory horn is not entirely invariant, due no doubt to the thermal expansion of the horn and the change in horn elasticity and hence resonant frequency if length is constant. In one case, the resonant frequency shifted from 14,530 cps at 70°F to 14,370 cps at 190°F.

E. DEFINITION OF ONSET OF CAVITATION

In general, the noise signal associated with cavitation is a good indication of its onset. However, this is naturally dependent to some extent upon the sensitivity of the transducer, and also upon the gas content of the test fluid. Extremely degassed test fluids, such as the liquid sodium, exhibited a sharp delineation between the existence and non-existence of cavitation. Unfortunately, this is not the case for water, even distilled water. In liquid sodium the micro-bubble spectra may be discontinuous; so that for a slight increase in voltage and corresponding decrease in pressure level, large numbers of full-scale cavitation bubbles suddenly appear. In water, such a slight pressure change gives rise to only a few bubbles which in general can not be detected by the instrumentation at hand. Thus cavitation onset, though well defined using acoustic techniques for liquid sodium[1], appears to be somewhat ambiguous for water, particularly water with high gas content.

F. DETECTING METHODS

The pressure at which the first bubble can be visually detected is less than or equal to that at which the noise signal may be sensed. The pressure at which the first bubble disappears also is less than or equal to that at which the noise signal may be sensed. Thus the visual observation method, though inapplicable to fluids such as sodium, is believed to be more consistent and accurate than the noise signal method, which is still the only feasible alternative for opaque fluids.

IV. CONCLUSIONS

It has been shown that the required sinusoidal pressure amplitude at a single frequency (14, 5 kHz) to cause cavitation nucleation and desinence in partially degassed water as a function of temperature

over the range between nelting and freezing points at one atmosphere is quite similar to that of liquid sodium over its comparable temperature range.

It has also been found that tensions of considerable magnitude are required to nucleate this water at this frequency even though no special care was taken to obtain high purity or thorough degassification. The frequency effect must therefore be important, so that it is desirable to explore both lower and higher frequencies. A facility modification for more careful air content and impurity control is desirable for further tests.

Additional interesting visual observation of bubble behavior around the vibrating horn have been made.
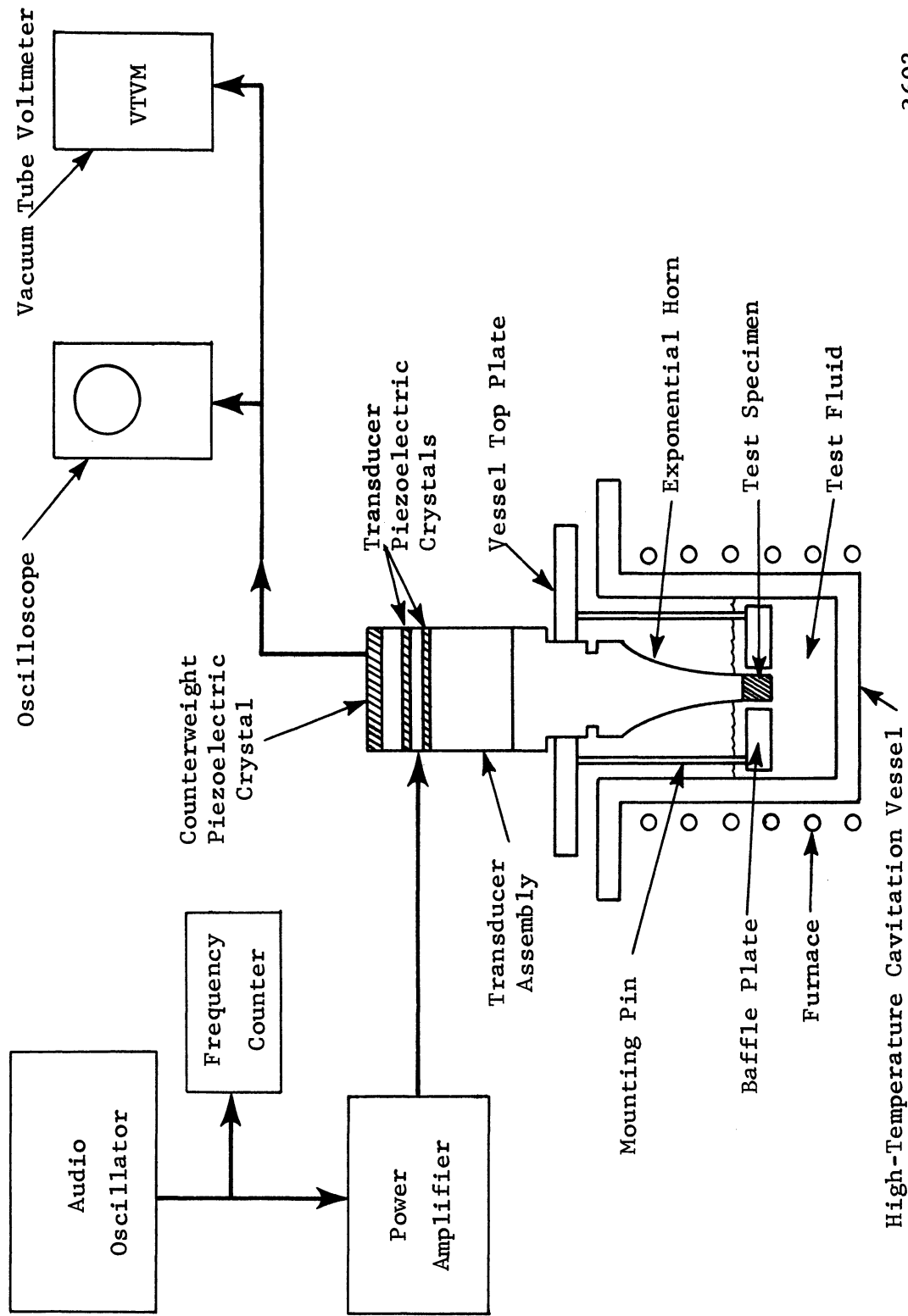
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TABLE I - AIR CONTENT OF WATER: 0.33% AIR BY VOLUME

AT STP = 20% SATURATED

(Saturation air content of water = 1.67% at STP)

Temperature °F	Cavitation Onset (rms volts)	Cavitation Cessation (rms volts)
70	11.0	8.0
	11.0	6.5
	9.5	6.5
	10.5	6.5
	10.5	8.0
	12.0	6.5
	12.5	6.5
	11.5	7.0
	12.0	6.5
	12.5	6.5
80	12.0	6.5
	12.0	6.5
	10.0	7.0
	11.0	6.5
	11.0	6.5
90	11.5	6.5
	11.0	6.5
	10.5	6.5
	11.0	6.0
	11.0	6.0

Temperature °F	Cavitation Onset (rms volts)	Cavitation Cessation (rms volts)
100	10.5	6.5
	11.0	6.5
	10.5	6.5
	11.0	6.0
	10.0	6.0
120	11.5	5.5
	9.0	5.0
	10.0	4.5
	9.0	7.0
	9.5	5.0
140	9.0	6.0
	9.0	6.0
	9.0	6.5
	8.0	6.0
	8.0	6.0
160	8.0	6.0
	8.0	5.5
	8.0	6.0
	8.0	5.5
	8.0	5.5

Fig. 1. Block Diagram of High Temperature Ultrasonic Facility

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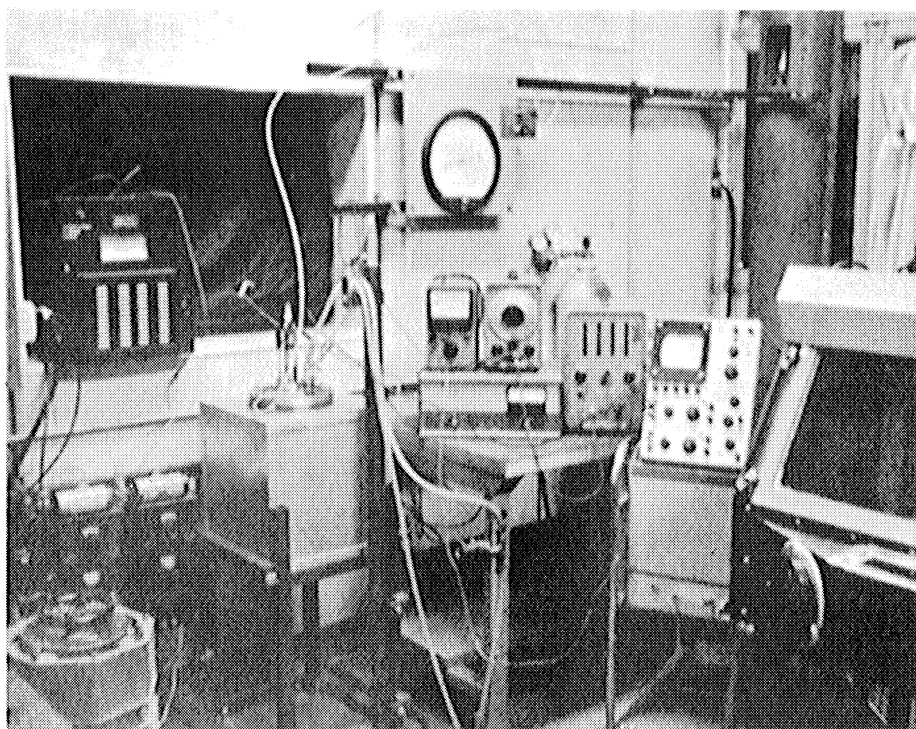
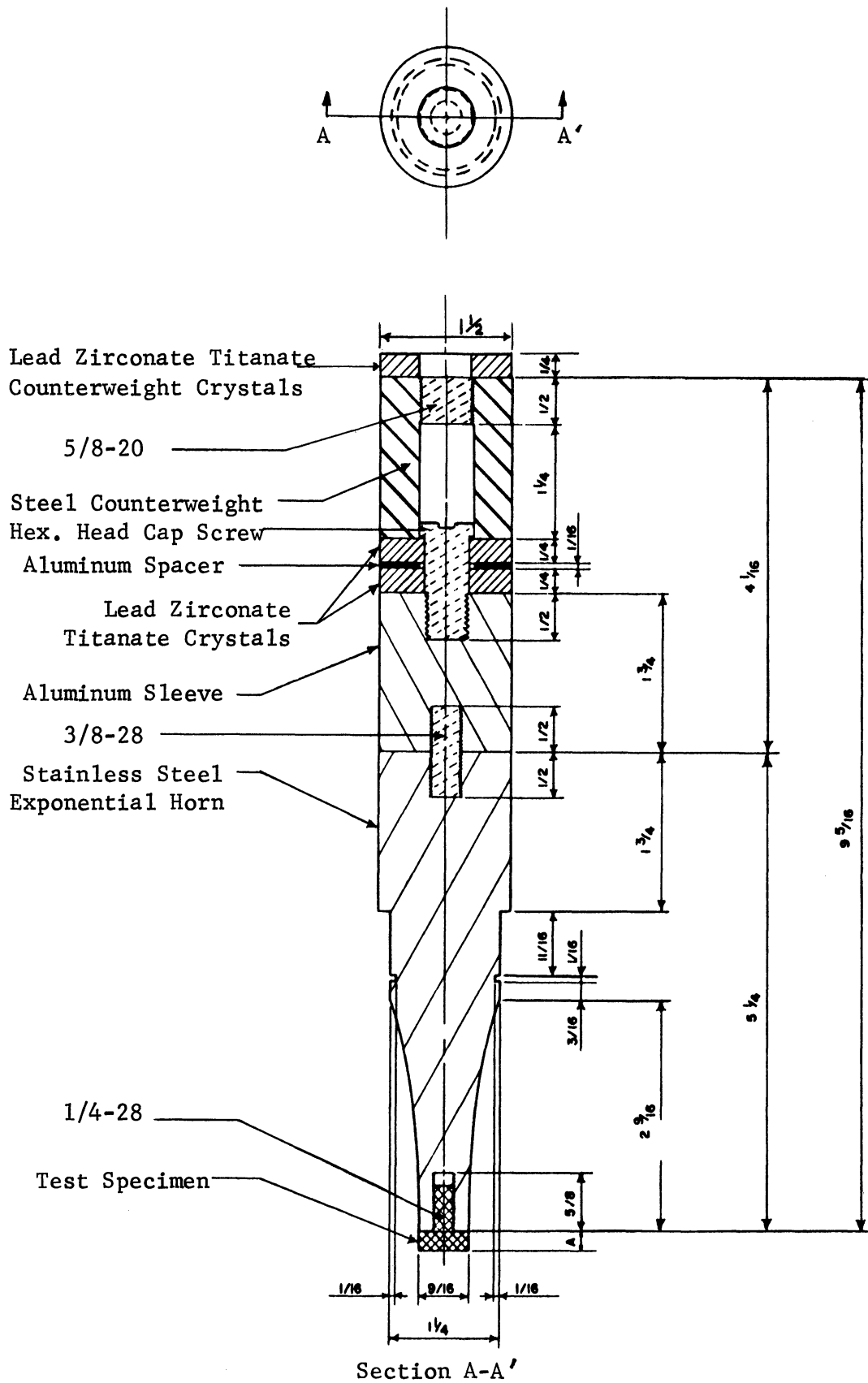2604

Fig. 2. Photo of Ultrasonic Facility
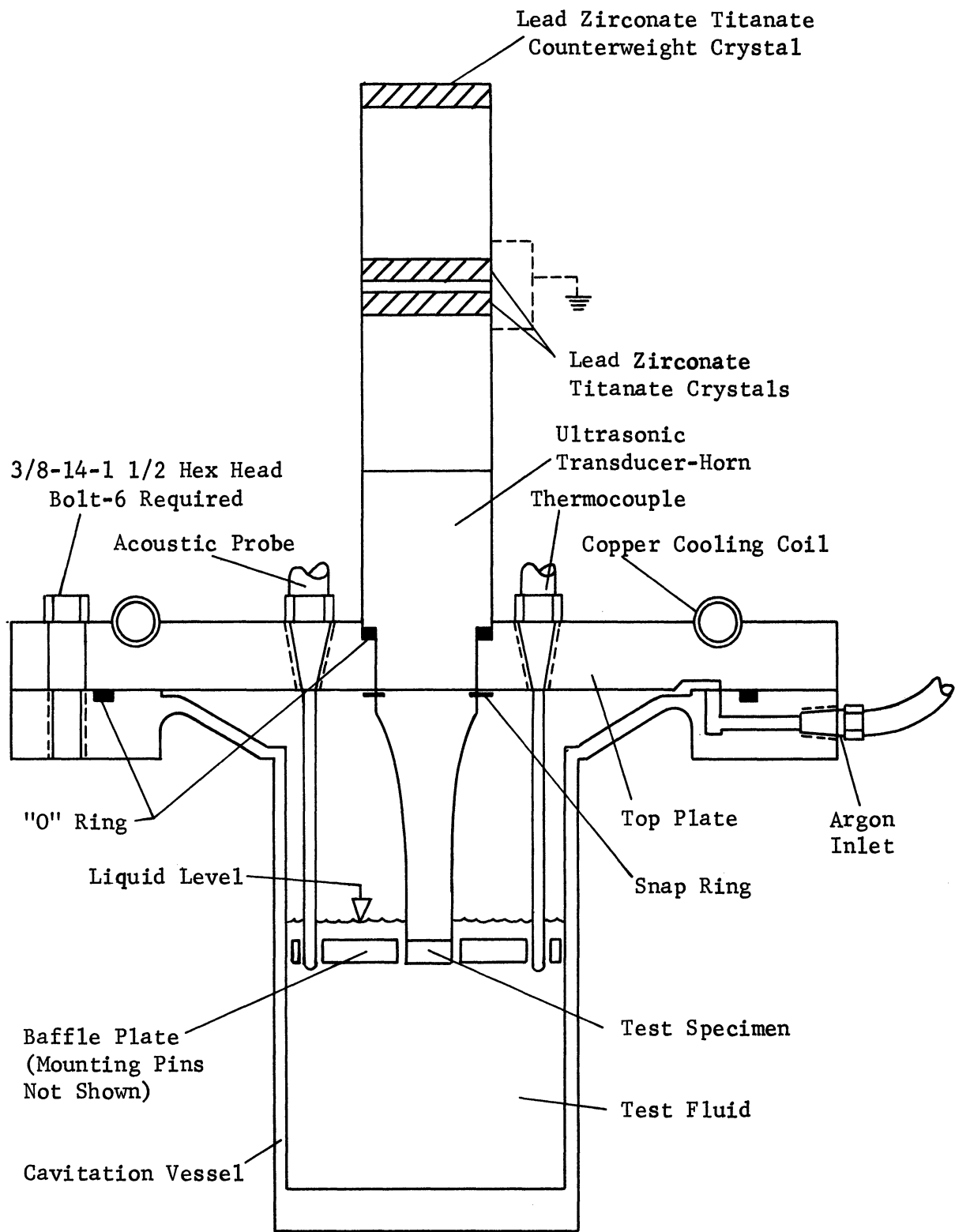
Fig. 3. High temperature cavitation vessel
and ultrasonic transducer
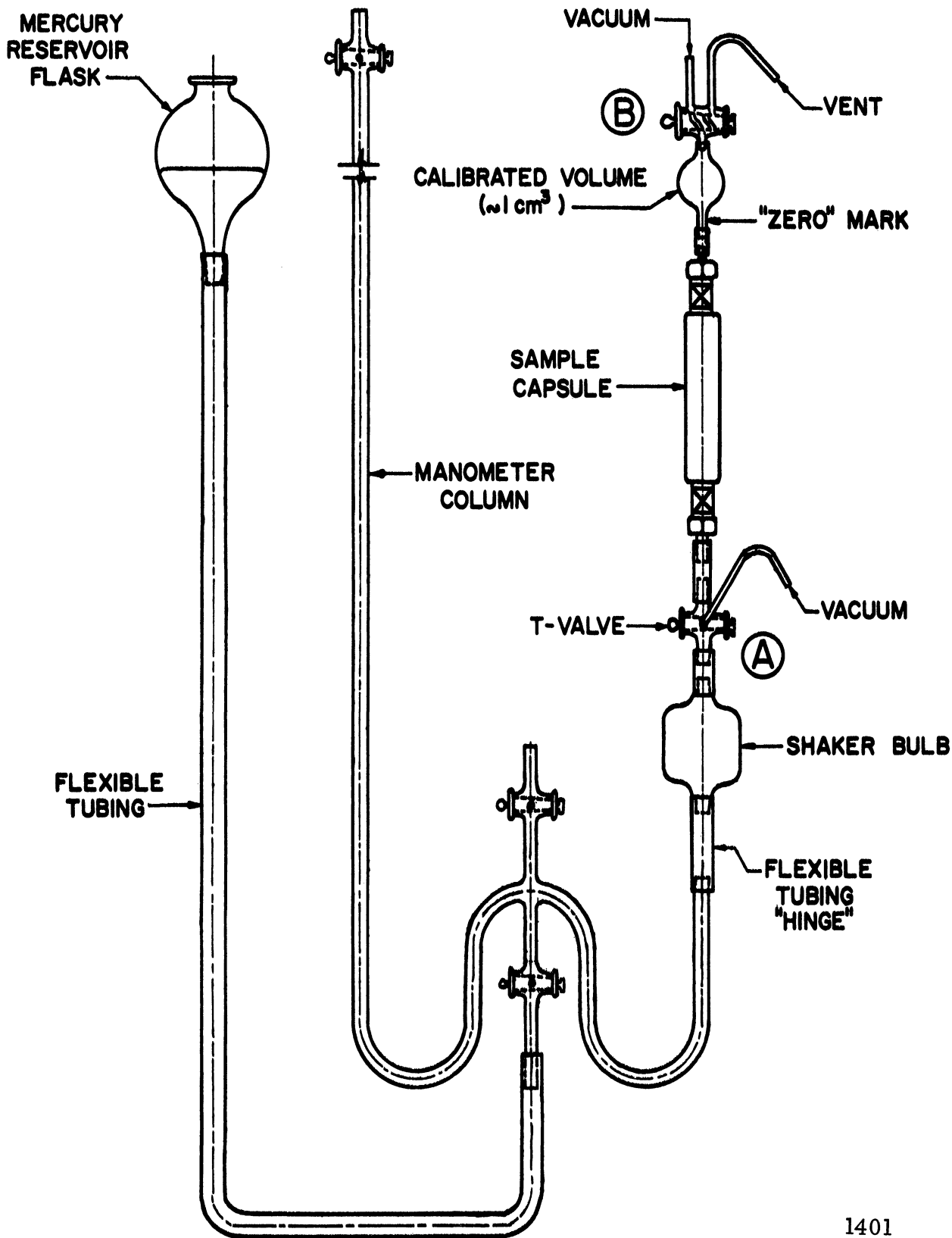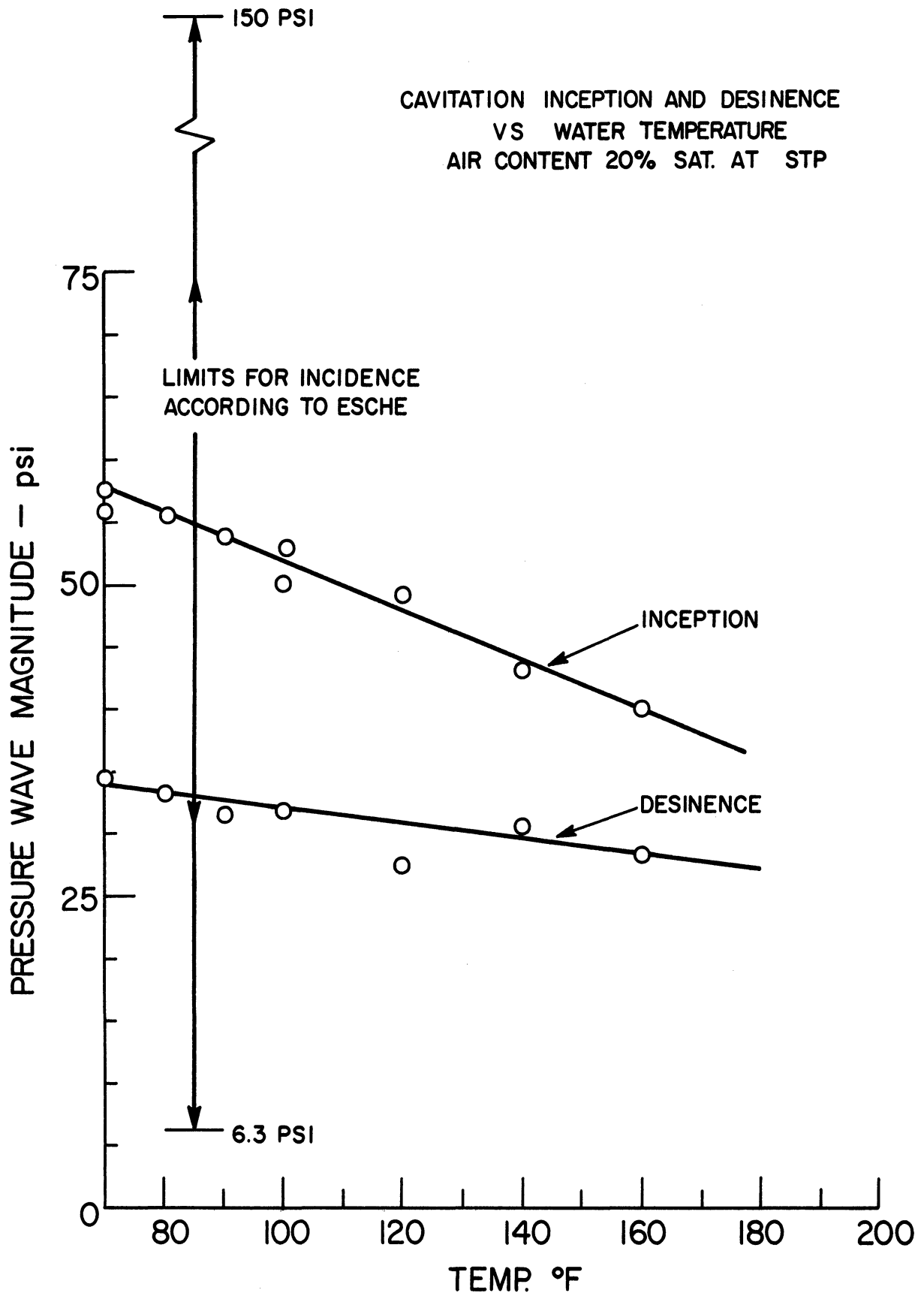
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Fig. 4. Details of Ultrasonic Transducer
Assembly
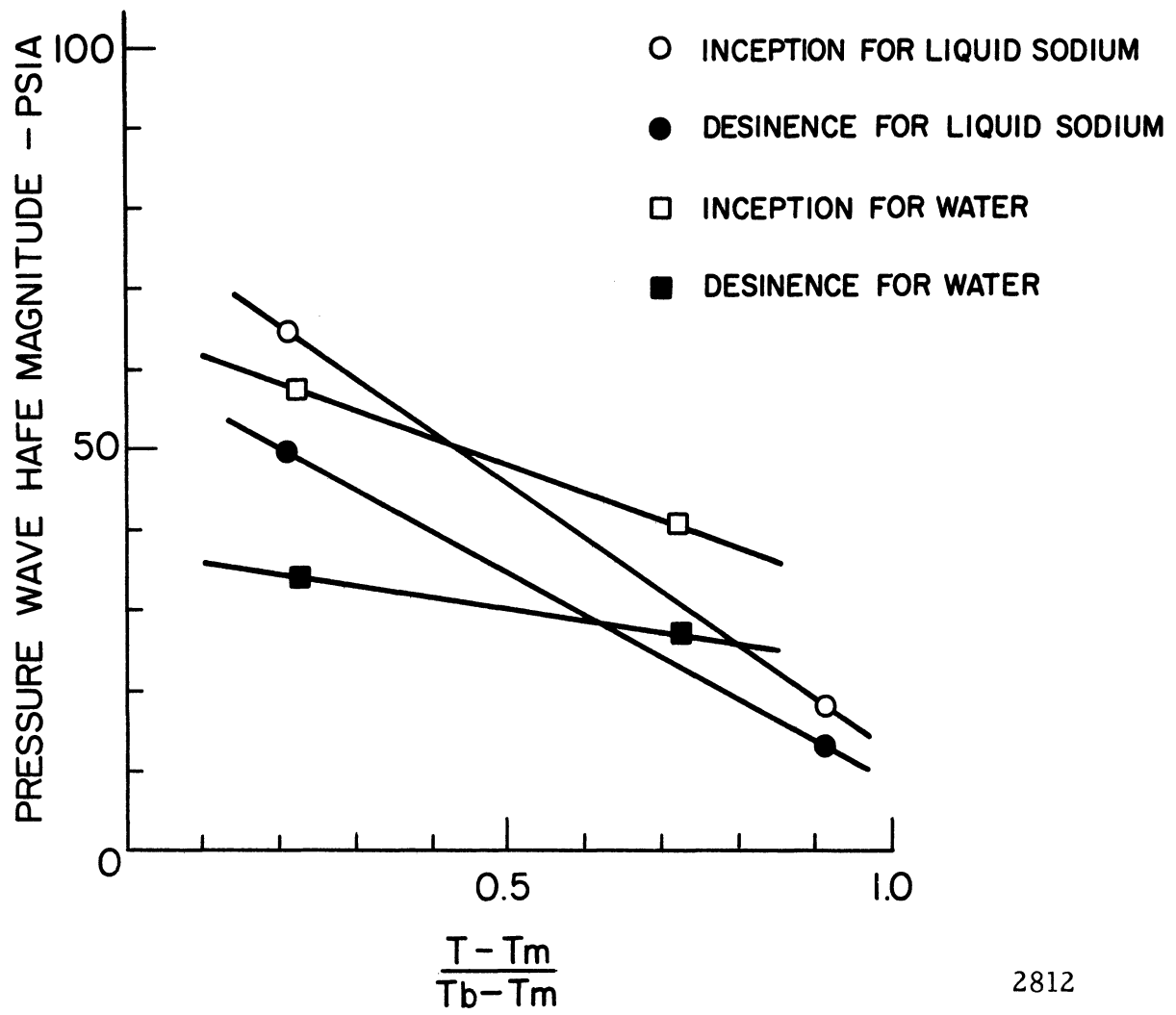
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MERCURY RESERVOIR FLASK

VACUUM

VENT

Ⓑ

CALIBRATED VOLUME (~1 cm³)

"ZERO" MARK

SAMPLE CAPSULE

MANOMETER COLUMN

T-VALVE

VACUUM

Ⓐ

SHAKER BULB

FLEXIBLE TUBING

FLEXIBLE TUBING "HINGE"

1401

Fig. 5. Schematic of Van Slyke Apparatus

Fig. 6. Cavitation Inception and Desinence for
Water as a Function of Temperature

Fig. 7. Cavitation Inception and Desinence for
Water and Sodium as a Function of
Normalized Temperature

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