THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

# CAVITATION DAMAGE AND PERFORMANCE RESEARCH FACILITIES

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Those University of Michigan research personnel chiefly responsible for the development of the facilities and techniques described are Messrs. L. Barinka, V. Cramer, R. Garcia, R. Ivany, J. Robinson, and W. Smith. The writer is also indebted to Messrs. Ivany and Robinson for assistance in the preparation of this paper.

TABLE OF CONTENTS

LIST OF FIGURES

## I. INTRODUCTION

The cavitation research facilities which have been developed in recent years in the Nuclear Engineering Department of The University of Michigan are designed especially for research on cavitation damage over a broad range of fluid-material combinations and temperatures. They are also useful for cavitation scale-effects investigations, and have been so used;[1] in fact, it soon becomes obvious that cavitation performance (or scale effects) must, in many cases, be investigated along with damage effects, even though an investigation of the latter is the major objective. In addition to modified versions of various relatively standard types of devices, certain special techniques have also been developed in connection with the present research investigations.

Historically, cavitation research facilities have ranged from large systems providing relative flow, such as water tunnels and towing tanks, to small static fluid devices such as ultrasonic vibratory units. Intermediate have been various specialized devices such as small tunnel-type units, rotating discs, jet impactors, etc., some of which will no doubt be described at this meeting. Generally, the facilities can be functionally classified according to several criteria as, e.g.:

i) Production of true cavitation as opposed to the impact of liquid drops, or of stream segments, or other phenomena which simulate cavitation damage,

ii) cavitation in a flowing stream as opposed to an ultrasonic vibratory system using a static liquid,

iii) cavitation under fluid and ambient conditions approximating prototype conditions of interest, as opposed to units departing to differing degrees from this goal.

From the viewpoint of cavitation damage investigations related to the phenomenon as it affects fluid-flow machinery, it is most desirable if the cavitation occurs under conditions approximating as closely as possible those of prototype units. Except for cavitation damage tests in full-scale machines, usually prohibitive for reasons of both cost and elapsed time, none of the various cavitation research devices are ideal from this standpoint. However, all apparently have a place, in that it is generally true that a trade-off exists between degree of realism, and cost and elapsed time. It is in consideration of all the above that the University of Michigan facilities were selected and developed.

## II. DESCRIPTION OF UNIVERSITY OF MICHIGAN, NUCLEAR ENGINEERING DEPARTMENT FACILITIES

### A. General Objectives and Facilities

The cavitation facilities, which are the subject of this paper, were developed for the investigation of cavitation damage, particularly as it might apply to the fluid-flow components to be utilized in space power devices, involving liquid-metal fluids and extremely high temperatures. As the best possible compromise between the somewhat contradictory requirements, a cavitating venturi was selected for the basic test vehicle. Such a device combines the realism of a flowing system, wherein the pressures and velocities are somewhat comparable to anticipated prototype conditions and the flow regime reasonably non-complex, with mechanical simplicity and low cost, at least as compared to prototype testing. Due to the requirement for special fluids, and also for the control of purity and gas content of all fluids, closed-loop systems become mandatory. The capabilities of such tunnel systems in terms of velocity, temperature, and test section diameter, within a reasonable budgetary and time requirement, are then primarily controlled by the requisite pumping units.

To date, there are two University of Michigan cavitating-venturi tunnel facilities, both employing basically the same venturi design.

i) A single-venturi loop[1,2] designed for use with water as well as various fluids at temperatures up to about 1000°F. Tests with lead-bismuth alloy to approximately this temperature, and with mercury at intermediate temperatures, are scheduled. At the time of writing approximately 6450 specimen-hours of mercury tests at room temperature have been completed as well as 900 specimen-hours of water tests. The maximum throat velocity attainable with water is about 100 feet per second, and that with the heavy liquid metals about 65 feet per second. Figure 1 is a schematic drawing of this loop, and Figure 2 a photograph showing the loop and the heater construction.

ii) A multiple-venturi system(3) (4 loops in parallel), for use only with water, but including deaereating and purifying facilities considerably advanced over those of the single-venturi loop, designed for operation with a minimum of attention, and producing throat velocities considerably in excess of those of the single venturi loop (up to 200 feet per second). Figure 3 is a schematic drawing of this facility, and Figures 4 and 5 photographs of the test venturi and the completed assembly. At the time of writing approximately 7875 specimen-hours of tests had been completed.

The cavitating venturi systems listed above are able to obtain damage data for a wide variety of fluid-material combinations, with good control over fluid purity and gas content, and, in some cases, up to relatively elevated temperatures. Also, the data so obtained can be almost directly applied to fluid-flow prototype components operating over the same fluid-material, velocity, and temperature ranges. The rate of damage obtained, though comparable to that observed in prototype units, is relatively low when compared to various other cavitation-damage research devices,

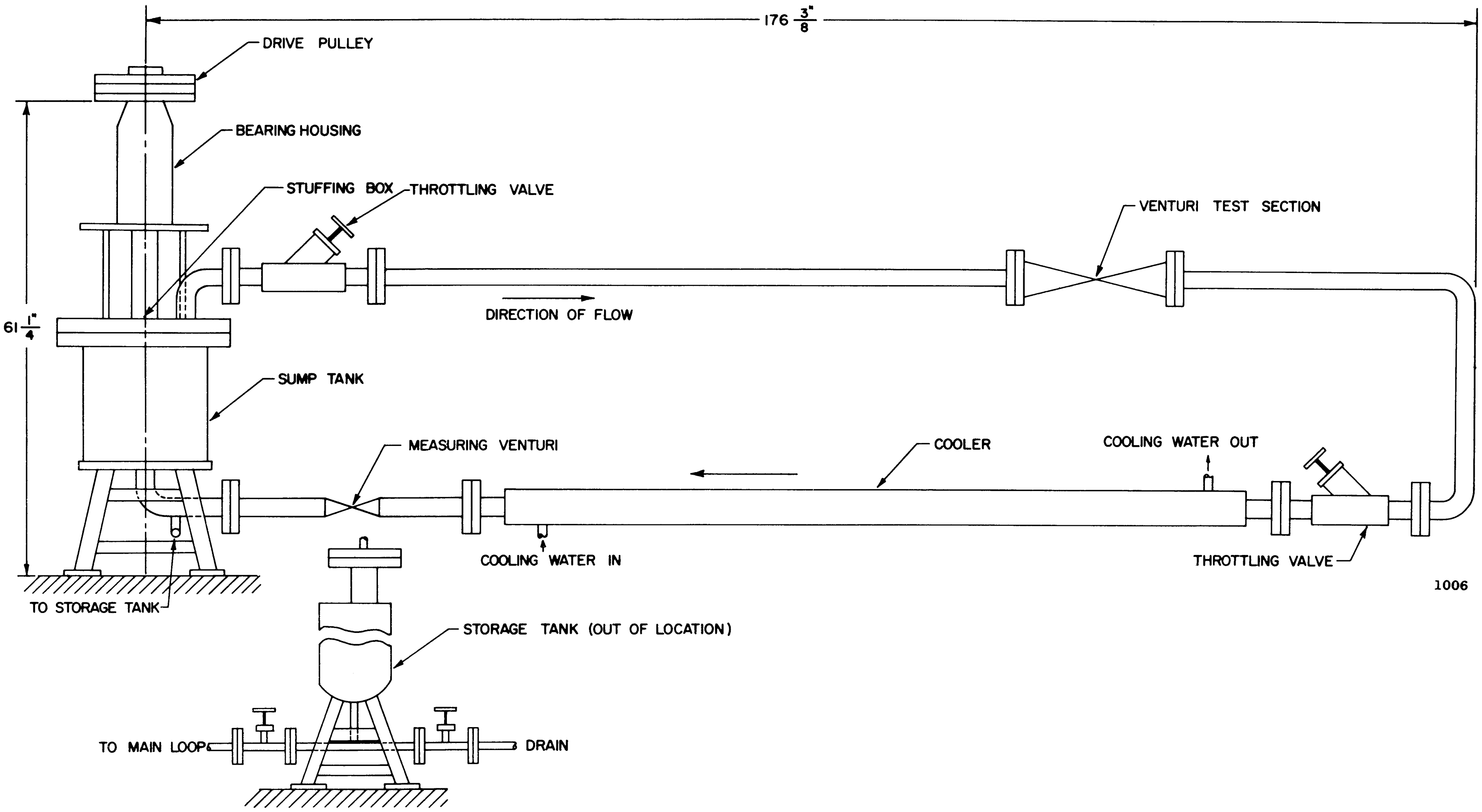


Figure 1. Sketch of Overall Liquid Metal Loop.

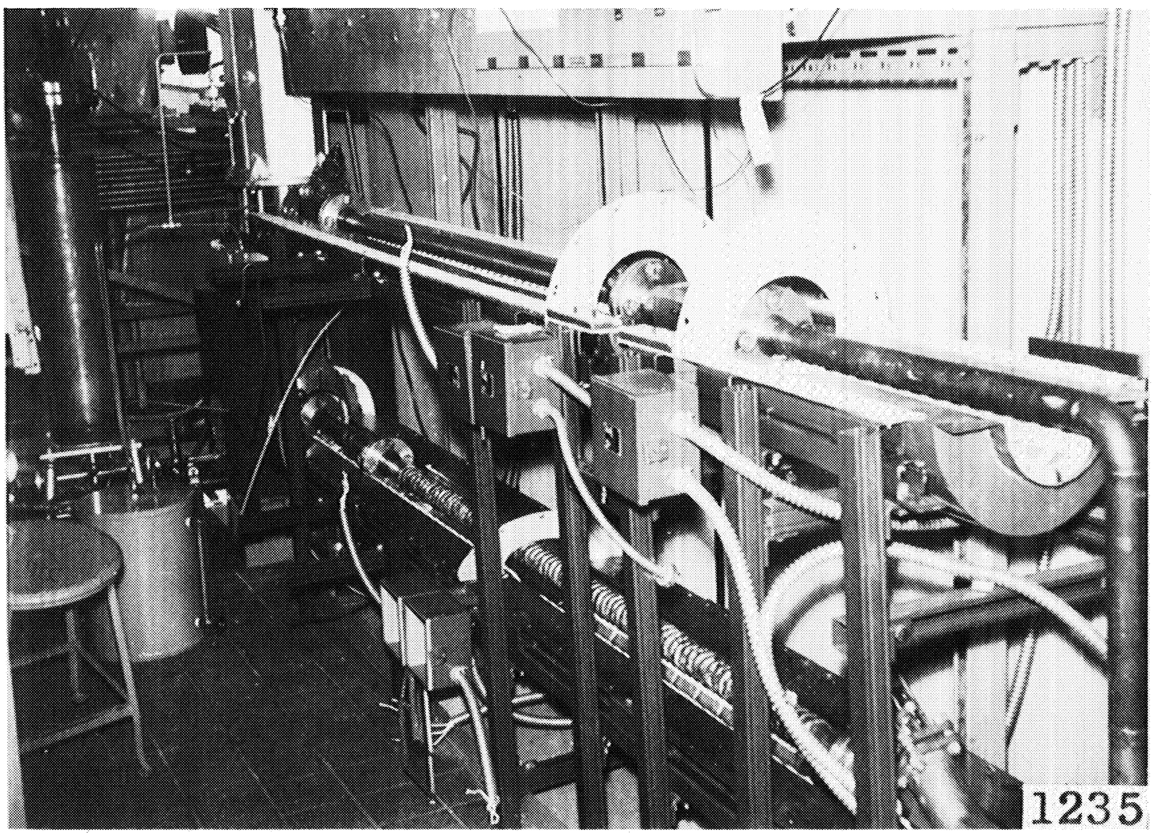


Figure 2. Liquid Metal Loop with Top Half of Heater Sections Removed.

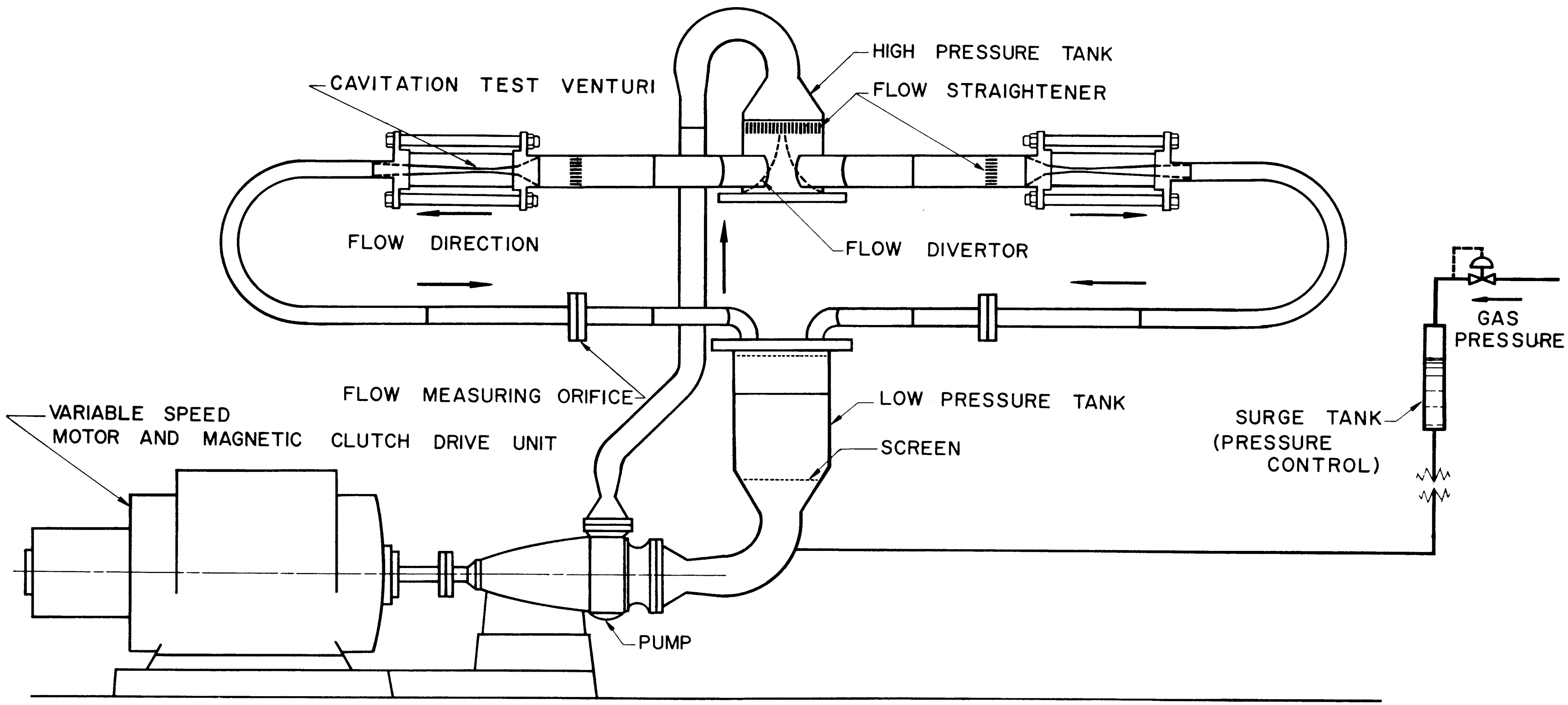


Figure 3. Schematic of Water Cavitation Damage Facility (Only two of the Four Loops are Shown)

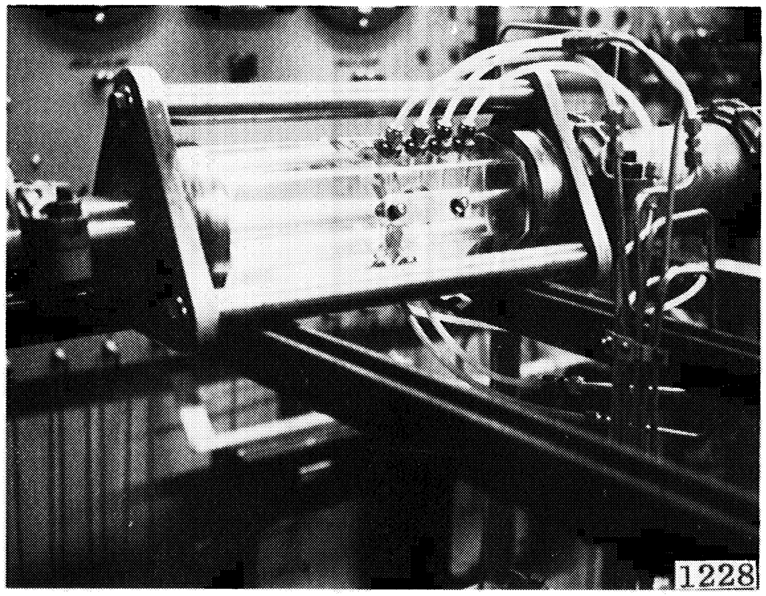


Figure 4. Plexiglass Test Venturi in the Water Cavitation Damage Facility.

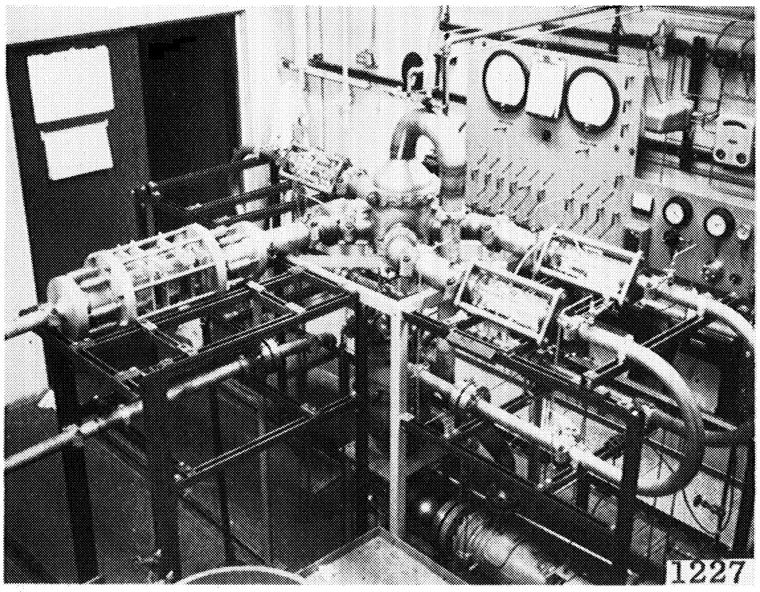


Figure 5. Water Cavitation Damage Facility.

e.g., ultra-sonic vibratory units, rotating disc units, etc. However, the damage observed in some of the latter may not be so directly applicable to prototype units.

One of the primary objectives in the development of the U-M cavitation damage research facilities was the study of the phenomenon in liquid metals under temperature conditions applicable to the advanced SNAP-type units. It would certainly be possible to design and construct a cavitating-venturi closed-loop tunnel facility for operation under such conditions, although the technological problems involved, particularly with the driving pump and the instrumentation, are considerable. However, the cost would be at least an order of magnitude greater than so far involved in the loops constructed for more moderate conditions. Consequently, to obtain data under these very difficult technological conditions, it was decided to rely upon an ultrasonic vibratory unit, wherein tests parallel to those conducted in the tunnel facilities could be performed, and compared and correlated with tests under fluid and temperature conditions of direct prototype applicability. Such a unit, driven by a lead-zirconate transducer at frequencies up to 20 kc, has been constructed for operation with various fluids including liquid metals at temperatures up to 2000°F. At the time of writing, the design of the periphery equipment is complete, and fabrication about to commence. Figure 6 is a photograph of the transducer-horn unit with electronic driver and Figure 7 a drawing of the overall mechanical assembly. The design is such as to provide the necessary thermal barrier and cooling capacity to prevent overheating of the transducer and of the sealing components.

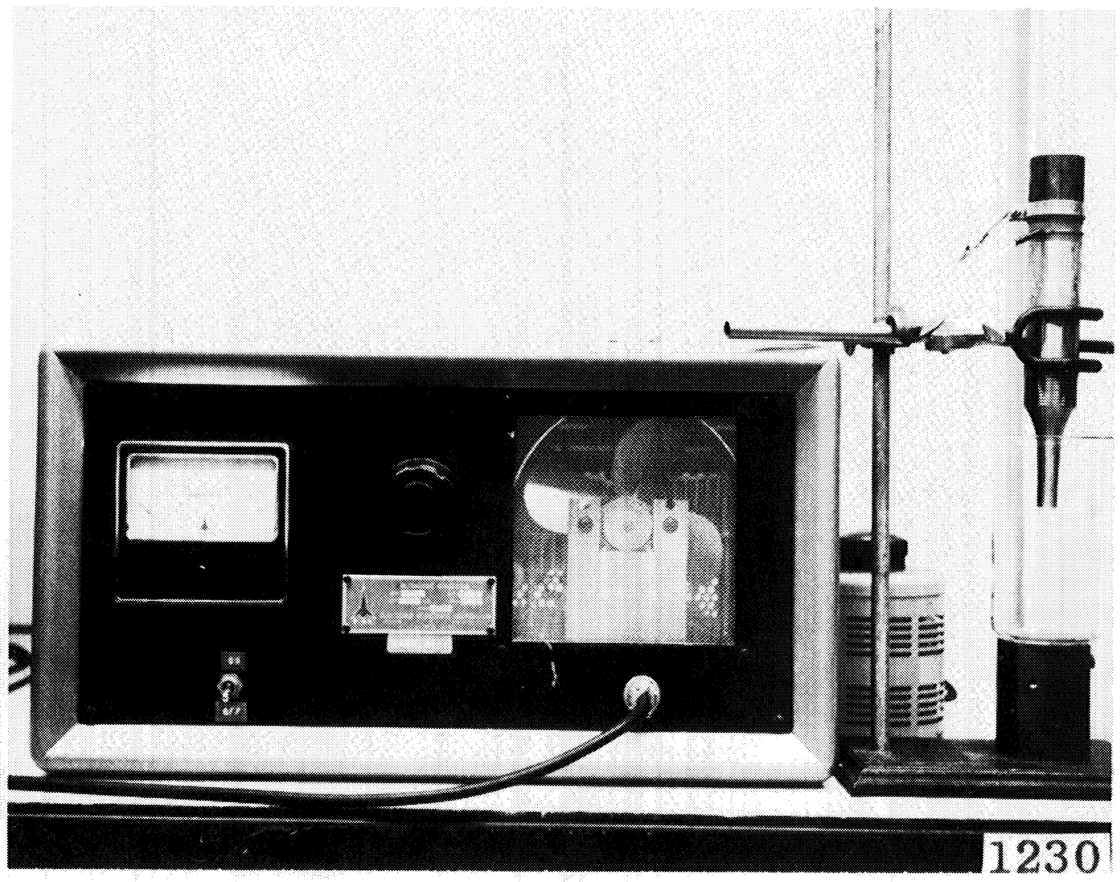


Figure 6. Piezoelectric Crystal Transducer-Horn Unit and Electronic Driver.

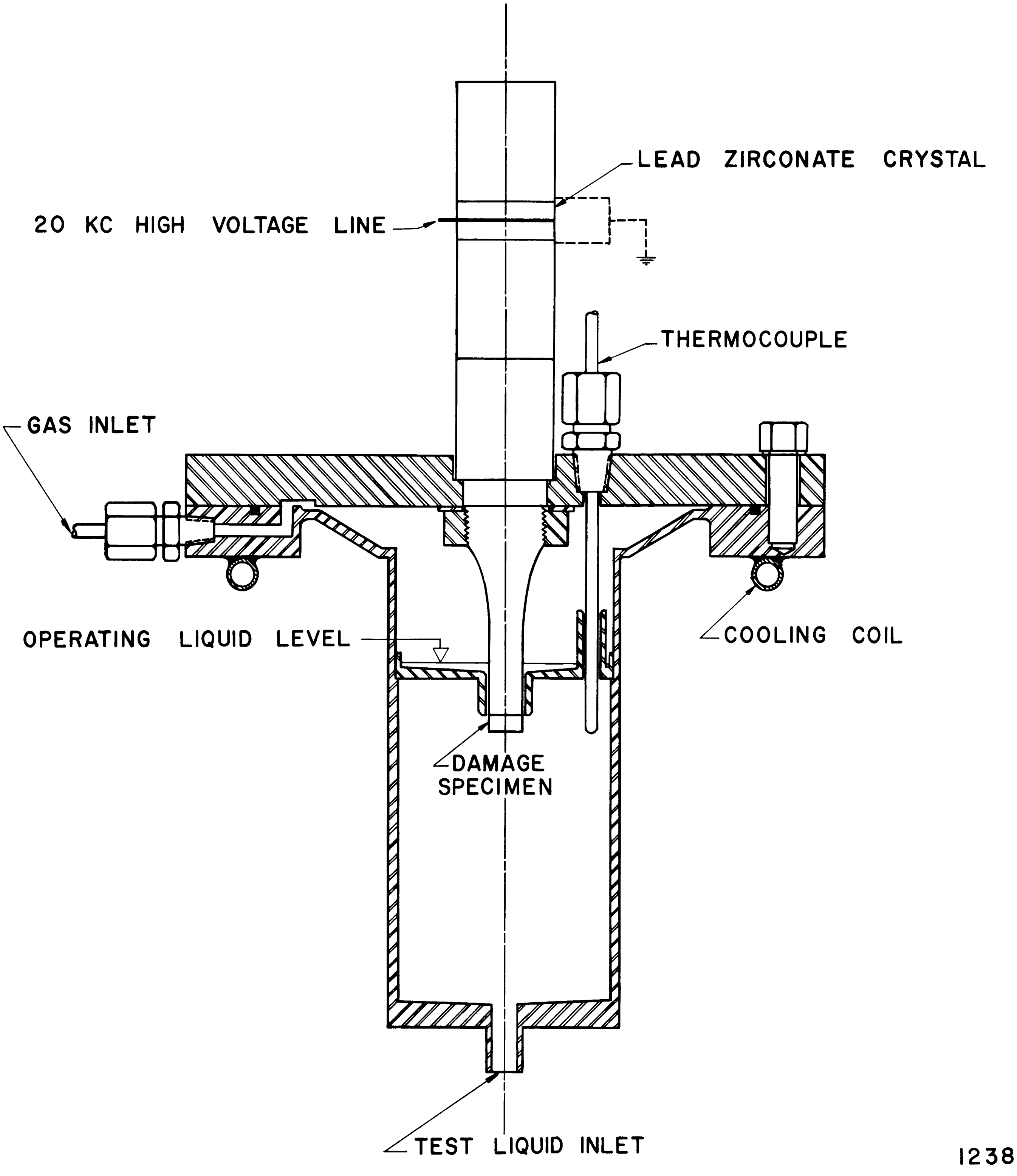


Figure 7. Schematic of High Temperature Vibratory Cavitation Damage Assembly.

## B. Cavitating Venturi Details(2)

### 1. Damage Test Venturis

All the cavitation damage tests to the time of writing have been conducted in venturis with identical flow-paths. The basic flow-path design (Figure 8) includes a nominal 1/2 inch cylindrical throat of 2.35 inches length. The flow-path is symmetrical about the throat with a nominal 6° straight cone included angle, extending for 3 inches in the upstream direction to form the nozzle (but preceded by a rounded entrance from the full pipe diameter). The conical diffuser extends with the same angle almost out to the full pipe diameter. The damage specimens, thin flat plates, nominally 1/16" x 5/8" x 1/2", and with tapered ends (Figures 9 and 10), are inserted in suitable holders through the walls of the venturi to a submergence of about 3/16", so that they are parallel to the stream direction, with the smallest dimension normal to the flow. The venturis used in the single-loop facility have provision for two specimens, inserted from the top with a 90° separation, thus being symmetrical with respect to elevation. However, venturis with three specimens, symmetrically located, are used in the multi-loop facility.* It was found that the two-specimen arrangement utilized resulted in non-symmetrical flow, and, on the other hand, that the kinetic heads were sufficiently large so that the effect of elevation was negligible.

A third type of venturi-specimen assembly has been used for testing specimens under stress. In this arrangement an external clamp

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* Three of the four parallel loops have generally been used in the damage tests, so that nine specimens are tested simultaneously.

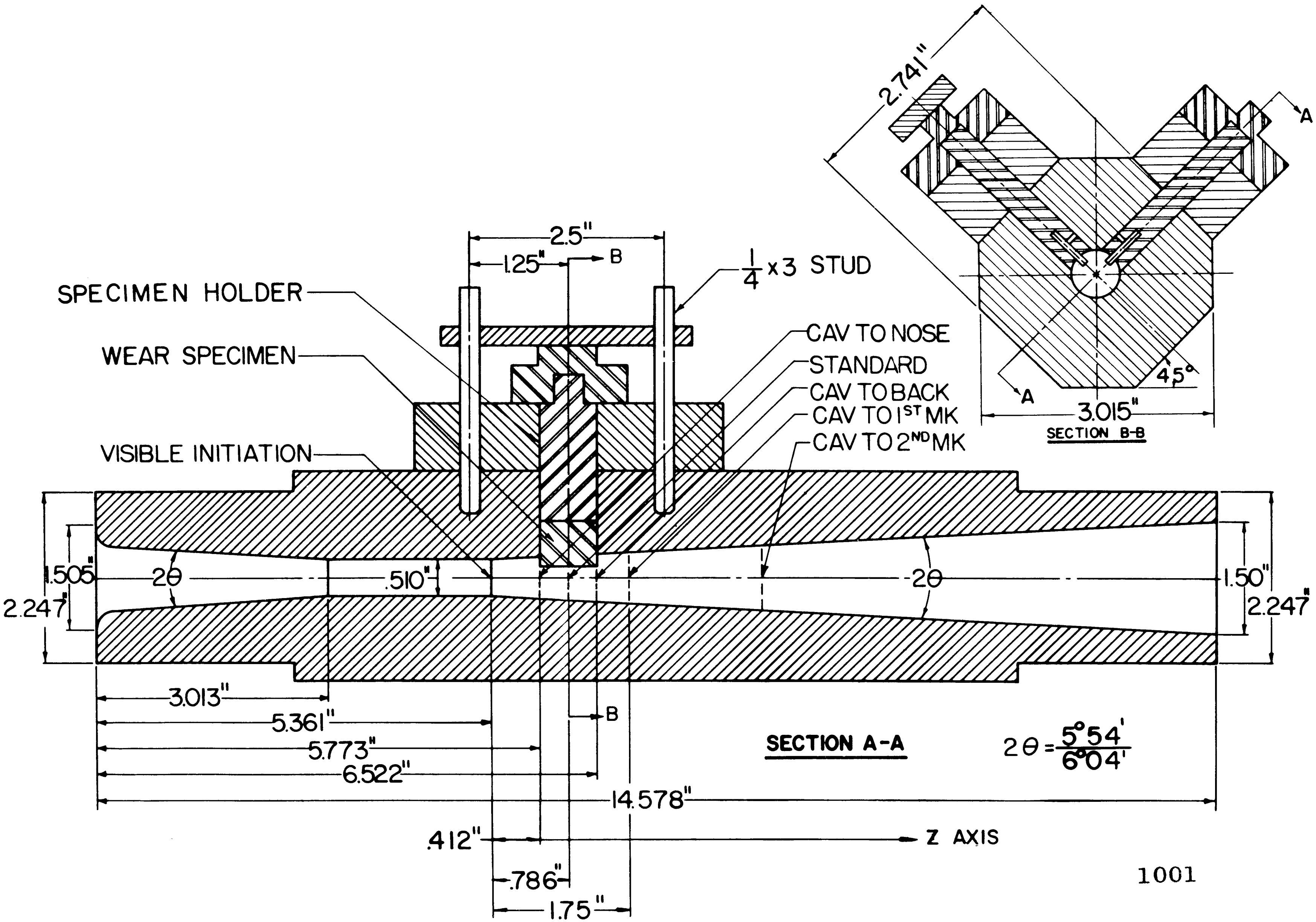


Figure 8. Damage Test Venturi.

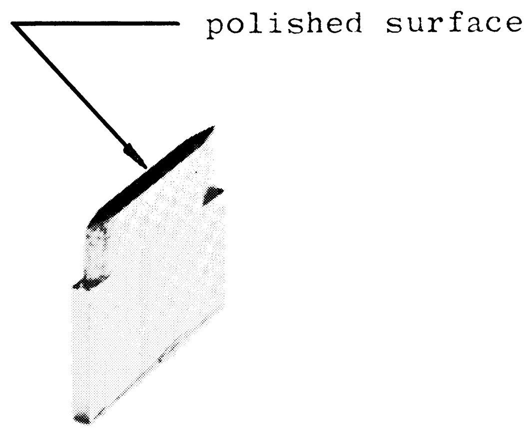


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Figure 9. Photograph of Test Specimen.

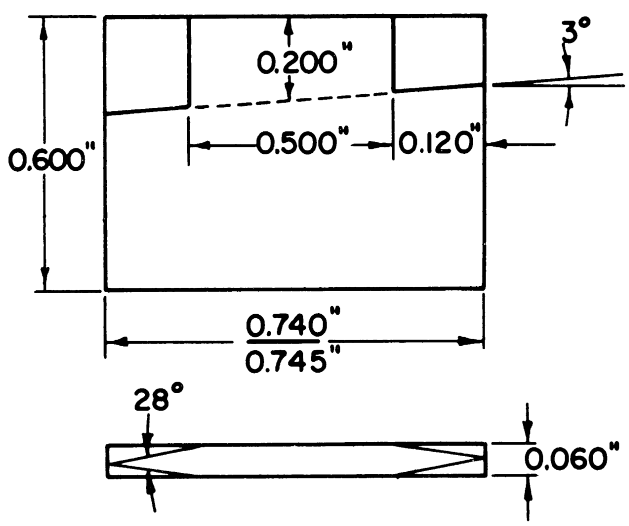


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Figure 10. Drawing of Test Specimen.

is used to stress a specimen which extends entirely across the venturi (Figure 11). The flow-path design of these venturis is the same as that already discussed.

The venturis used in the water and mercury tests so far have all been of plexiglass, so that the degree of cavitation could be determined visually as well as by flow and pressure measurements. A venturi of identical flow-path and test specimen arrangement, but of stainless steel, has fabricated for high-temperature tests. It is expected to use flow and pressure indications in conjunction with void fraction measurements (discussed latter) for setting of cavitation conditions in such an opaque venturi.

2. Scale-Effect Test Venturis

In order to obtain significant damage data and apply them in a meaningful manner, it is first necessary to know when cavitation will occur, and what form it will take. Hence, performance (or scale effects) tests, in the system in which damage is to be studied, become mandatory. In the present system, e.g., it immediately became obvious that strong scale effects existed.[1]

To investigate these effects over as wide a range of parameters as possible, a geometrically similar venturi, but with throat diameter and length reduced by a nominal factor of two, was used along with the type previously described. A geometrically similar venturi with scale increased by a factor of about two is also feasible with the available head and flow.

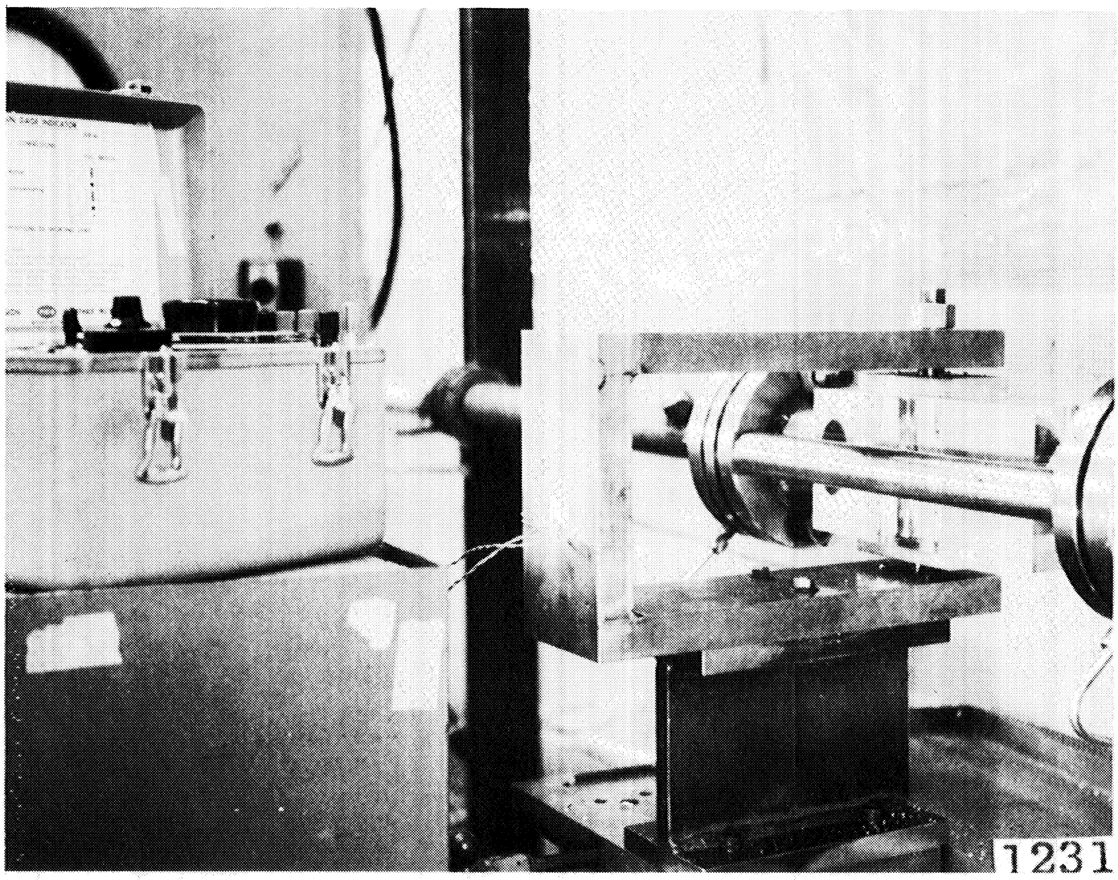


Figure 11. Cavitation Damage Test Arrangement of Specimen Under Tension.

For the further study of scale effects, a two-dimensional plexiglass venturi, so arranged that the throat height can be varied from 1/8 inch to 3/4 inch has been designed and fabricated (Figures 12 and 13). It presently occupies the fourth loop of the multi-loop facility. The two-dimensional design has been used to obtain improved visualization of the flow. It is planned to study the effects of velocity, size, temperature, gas content and purity, divergence angle, and turbulence level (as controlled by the upstream honeycomb arrangements) on the cavitation number corresponding to various degrees of cavitation, as well as on the flow regime (observed through high-speed photography), and on the pressure profiles.

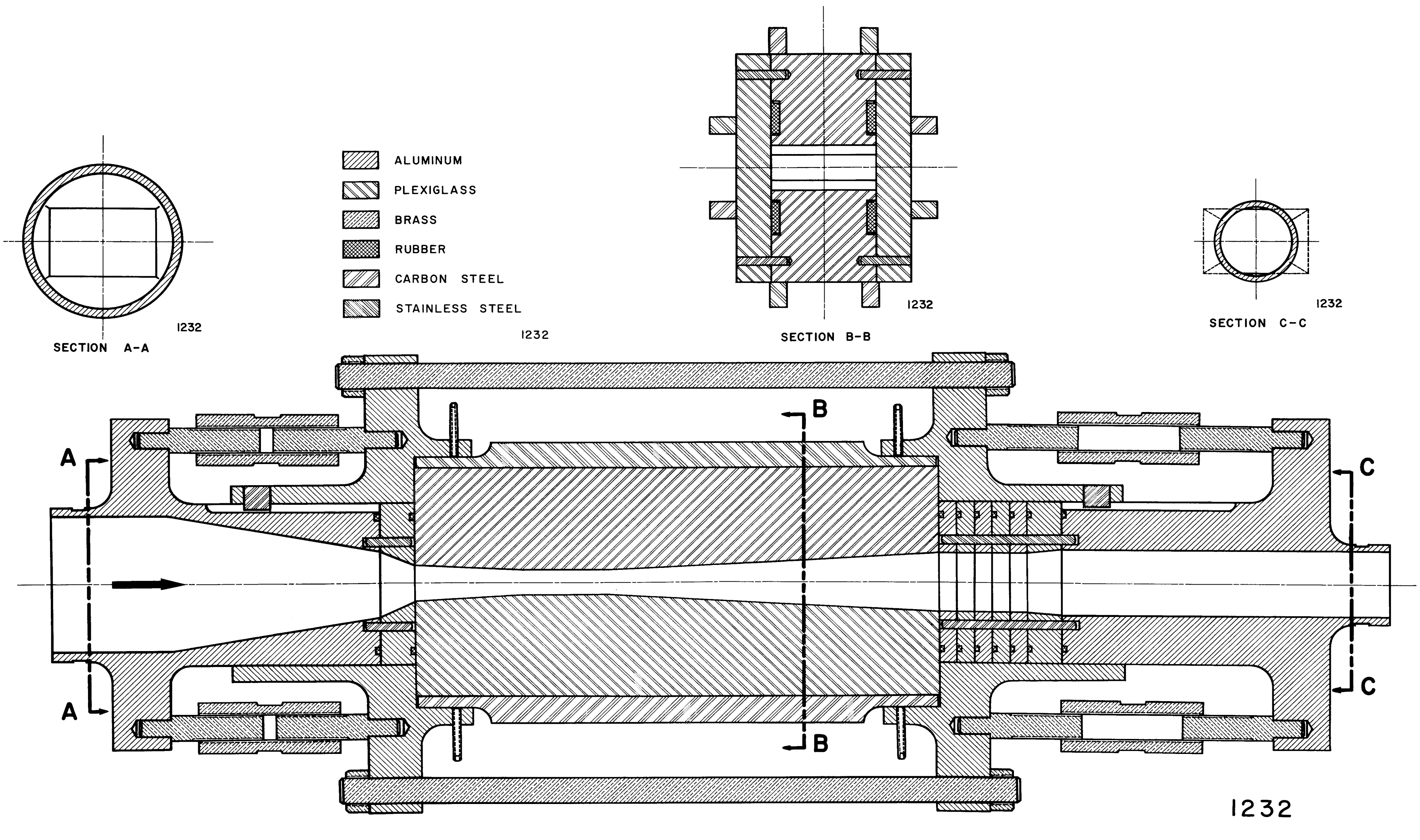


Figure 12. Drawing of Two-Dimensional Transparent Venturi.

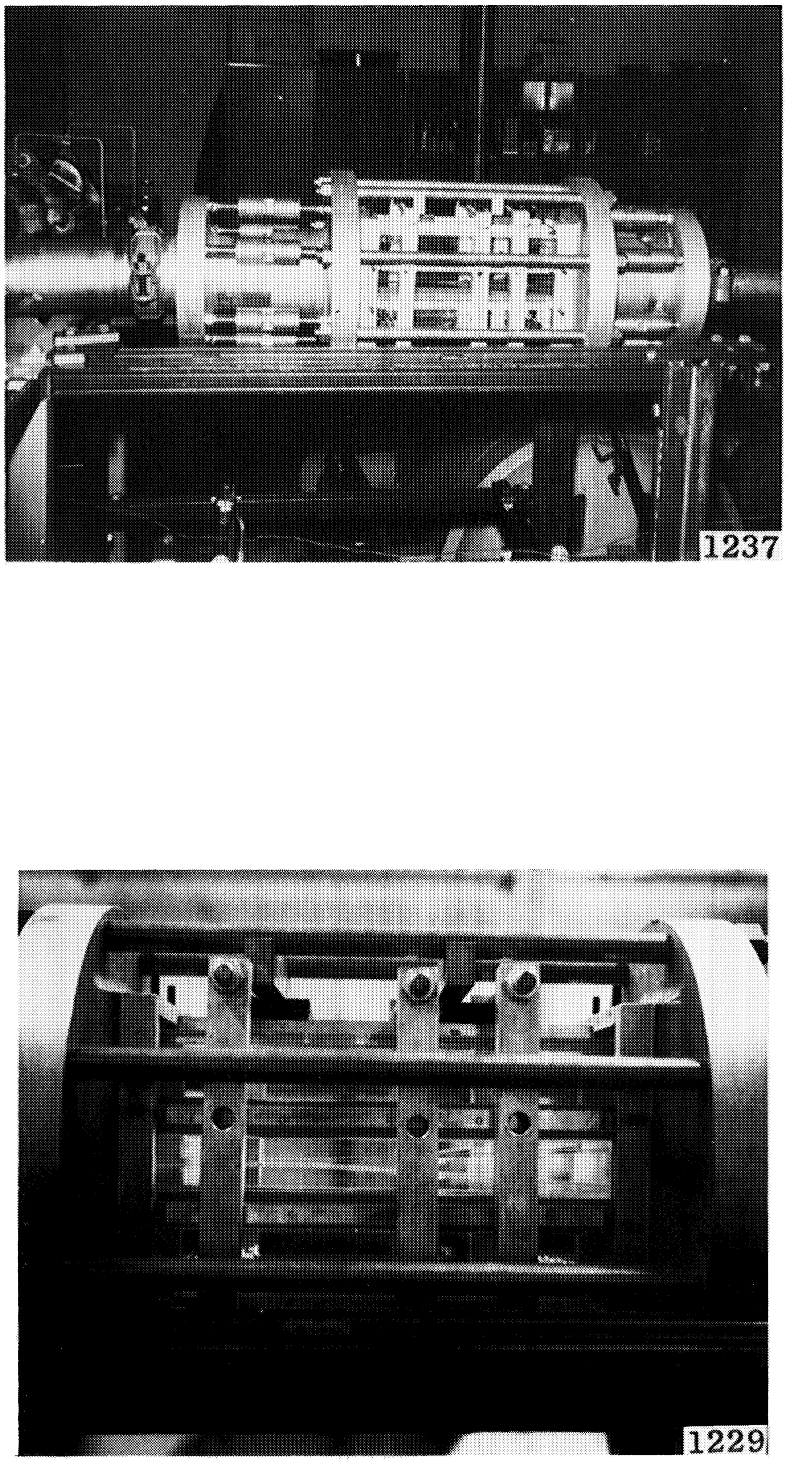


Figure 13. Two Dimensional Transparent Venturi.

## III. TECHNIQUE DEVELOPMENT

In connection with the overall research program it has been necessary to perfect and utilize certain specialized techniques which are of interest, in that they can be applied to other similar investigations. The most significant of these will be described.

### A. Test Specimen Examination

#### 1. Direct Weight Loss Measurement

The observation and recording in a meaningful manner of cavitation damage presents difficulties. Weight loss, or mean depth of penetration of the exposed area, has been utilized, as in many other investigations, as one of the quantities of primary interest. Obviously, in itself, this is not a sufficient description of the phenomenon, since character and distribution of the attack is not thus delineated, nor is its seriousness from the viewpoint either of deterioration of structure, or pollution of the system. However, weight loss can easily be obtained by direct measurements, providing the damage is sufficient, and hence it has been used as at least one important data parameter in the present investigation.

Special techniques for the determination of weight loss in those cases were direct measurement is not feasible and/or significant have been developed. These provide in addition to weight loss, other significant information on the damage phenomenon, and hence may be useful even when direct weight measurements are used.

2. Pit Count and Tabulation

Pitting density, i.e., the number of pits formed per unit time and exposed area in various size categories, has been used by previous investigators, notably Knapp,[4,5] as a measure of cavitation damage. This approach has been amplified in the present investigation by developing a technique for the computation of weight loss from tabulated pit counts, using very detailed measurements of typical pit surface and depth profiles in the various size categories.[2,3,6] The technique is useful in allowing an estimate of weight loss in cases where a direct measurement is not possible. However, the data obtained in applying the technique, i.e., the observations of pit size and location distribution, shape and other facets of general appearance, and finally depth, are of very great interest themselves in a basic investigation. The methods for observing and recording some of these data items are described in the following sections.

a. Depth Profile Determination

Depth profiles of individual pits, ranging in size from 1 to 10 mils, have been determined with considerable precision using a profilometer-type insturment,* which is sensitive to vertical displacements of a few microns (pit depths range generally from about 10 to 1000 microns). It is also capable of tracing parallel paths, spaced by 1 mil or less, across a pit. Thus, on the larger pits, a detailed mapping of the crater can be obtained. In this way, repeated observations of the depth profile of a given pit after differing durations of exposure have been made.[2,3,7] The accuracy of such profiles has been verified by

* Linear Proficorder, Micrometrical Mfg. Co. of Ann Arbor, Michigan.

sectioning the material through the pit, and comparing the resultant photo-micrographs with the proficorder traces.

Proficorder traces can also, of course, be used to measure surface roughness (rms) before and after exposure. This grosser measurement, while not involved in the pit count technique, is also to some extent a measure of cavitation damage.

As mentioned above, sectioning of the material through damaged regions can also be used to measure pit depth profiles. It also provides general information on depth of attack, and effects upon the material microstructure in the damaged region. This technique has been used by various previous researchers as well as in the present investigation.[2,3]

Molding of the damaged region with a material capable of penetrating the extremely small openings and then being withdrawn, while still maintaining an accurate representation of the individual pits, provides another possible method for obtaining both depth and surface profile data. If feasible, this has the advantage, compared with the sectioning technique, of being non-destructive, and much faster and more economical. However, it obviously does not provide the same degree of precision. A material is being used in the writer's laboratory for this purpose at present and seems quite promising.*

b. Surface Attack Recording and Observation

The observation of pit shapes and sizes is performed using low-power metallographic microscopes, while recording of this data

* RTV-60, General Electric Co., Silicone Products Dept, Waterford, N.Y., and suggesged to writer by personnel of Aerojet-General Corp., Sacremento, Calif.

is accomplished by tabulation and photomicrographs. In the present investigation, use has been made of composite photomicrographs of the entire surface to show distribution (as a function of degree of cavitation, e.g.,) and general characteristics* of pitting.[3] Individual photomicrographs[2,3,] have been used to show greater detail of individual pits, as well as to follow a given pit through successive exposures to cavitation. A general difficulty with the use of photography to record cavitation damage, at least in its relatively initial stages, is the fact that if high enough magnification is used to assure the damage will be visible, the area covered per photomicrograph is extremely small, so that a very large number of pictures may become necessary.

B. Irradiated Test Specimen for Damage Studies

Irradiated test specimens have been used in the present investigation[8,9] to develop a technique for obtaining a relatively continuous weight loss record without removing the specimens from the facility, and so interrupting the test. Such a technique would be extremely valuable for tests where disassembly was especially difficult, as e.g., with high temperature liquid metals. In addition to weight loss, it was found that valuable data on the size distribution of particles removed from the test specimens, could be obtained using precision filtration techniques.[8,9]

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* E.g., a surface has been etched prior to testing, and then possible correlation between pit location and grain boundaries observed.[3]

It is concluded from the irradiated specimen tests already completed that the technique can be extremely useful and convenient, providing at least the following conditions are met:

i) Particles removed are "wet" by the test fluid;

ii) Loop geometry is such that the particles are not readily trapped or segregated from the main stream, so that a relatively homogeneous slurry is maintained;

iii) Specimen material is such that suitable isotopes for irradiation exist.*

In the case of tests with steel in water,[8] all the above conditions were well met. The tests were very successful, and were performed with a minimum of difficulty. However, considerable trouble was later experienced with steel in mercury,[9] primarily because of the lack of good wetting of the steel particles by the mercury. This led to difficulties with filtering, and also to the trapping of the debris particles out of the process stream into the pump sump.

C. Flow Regime Examination Techniques

Flow regime examination and measurement in the present studies has been accomplished using many standard techniques which it is not necessary to mention here. Only those techniques which appear of special interest will be discussed.

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* (This is generally the case for other than high-purity, single-component materials.) Otherwise, considerable development may be required to achieve successful results.

1. "Void Fraction" Measurements by Gamma-Ray Densitometer

Void fraction (or local density) is a parameter of importance in any two-phase flow regime. In the case of the cavitating venturi, it is a bit of significant physical data which, together with various other independent items, will hopefully allow a complete and detailed description of the flow regime.

Void fraction has been measured in many flow situations (reference 10, e.g.,) using the fact that the attenuation of a gamma-ray beam is a function of the density of the material through which it passes. The work of various previous investigators has been modified and adapted to the case of a cavitating venturi in the course of the present investigagions, and used successfully both with water[11] and mercury.[12] The facility, consisting of a source-holder, axially-aligned slit collimators both above and below the venturi, and a shielded scintillation counter is shown in Figures 14 and 15. The assembly is mounted on a planning table so that it can be moved with precision normal to the venturi centerline.

If the flow is axially-symmetric, as assumed for the venturi, it is apparent that all available information, applicable to a given axial position, will have been gained by a single traverse across the flow, since there is no preferred direction in a plane normal to the centerline. Consequently from the data so obtained it is possible to compute the local fluid density.[11,12]

The procedure to be employed is essentially the same for any fluid, unless high temperature requires certain modifications of the equipment. However, the choice of source and source strength is determined by the fluid,

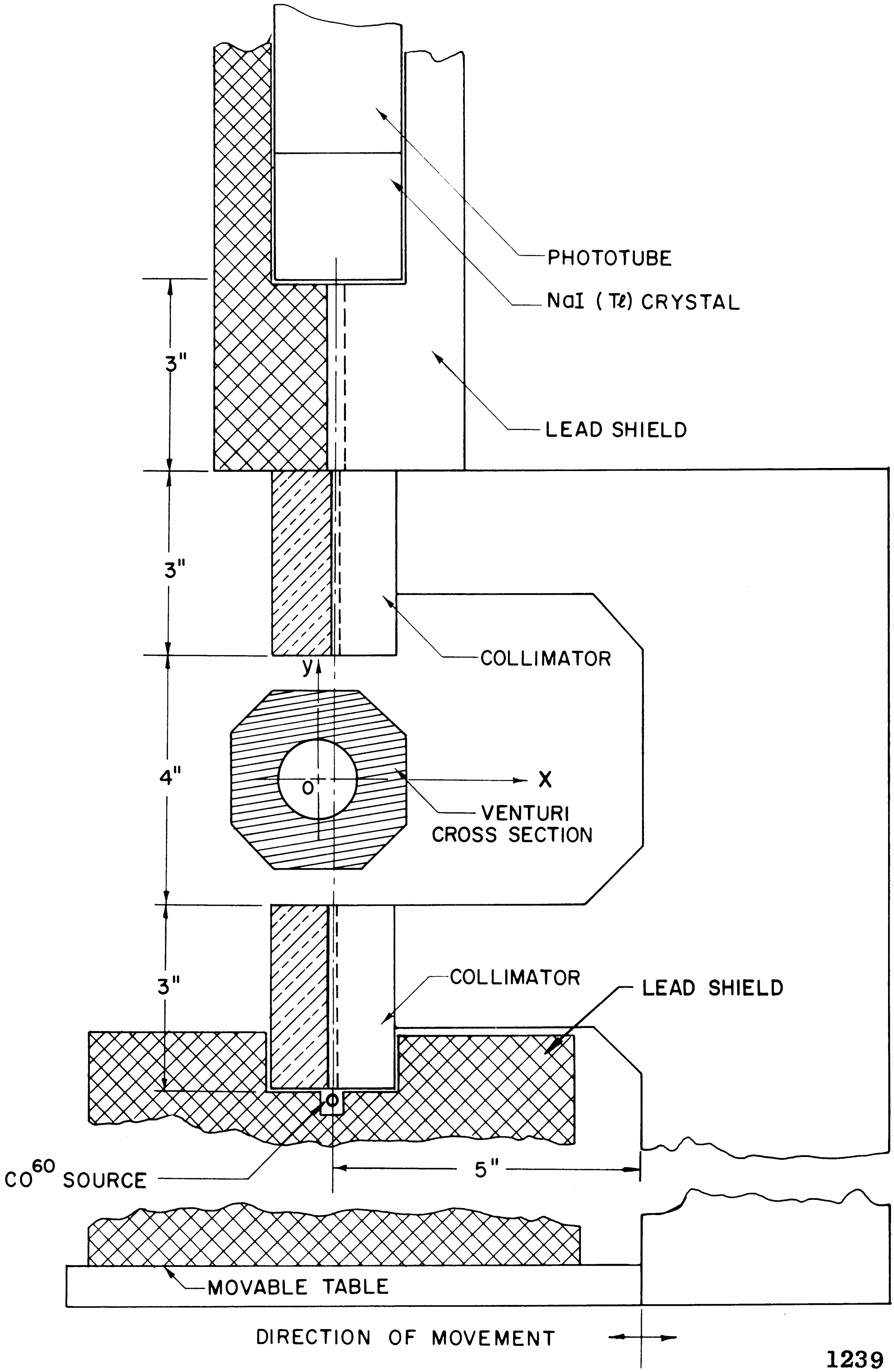
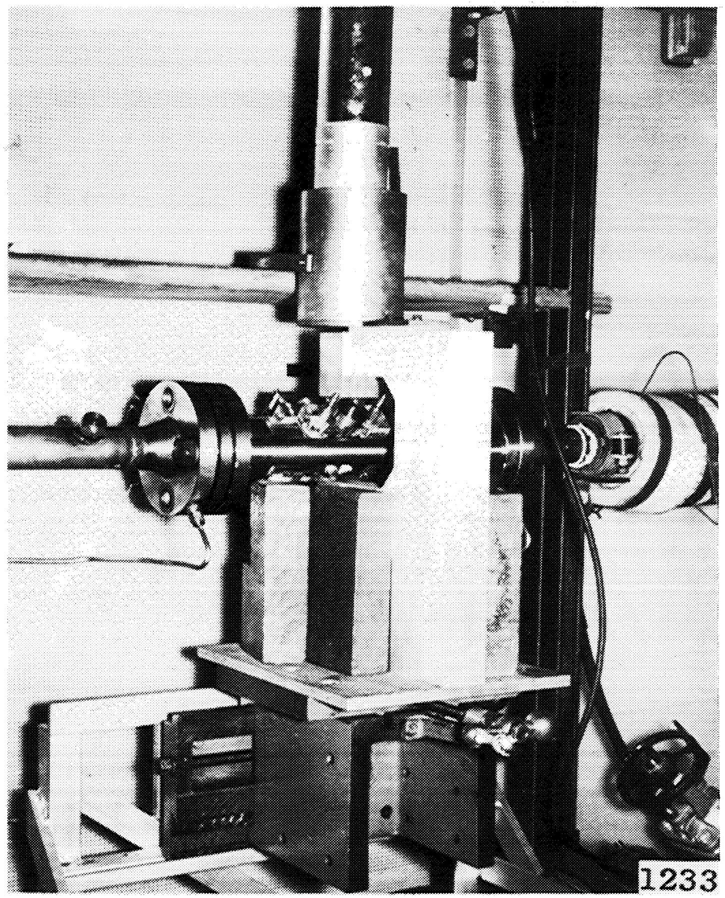



Figure 14. Arrangement of Gamma-Ray Densitometer.



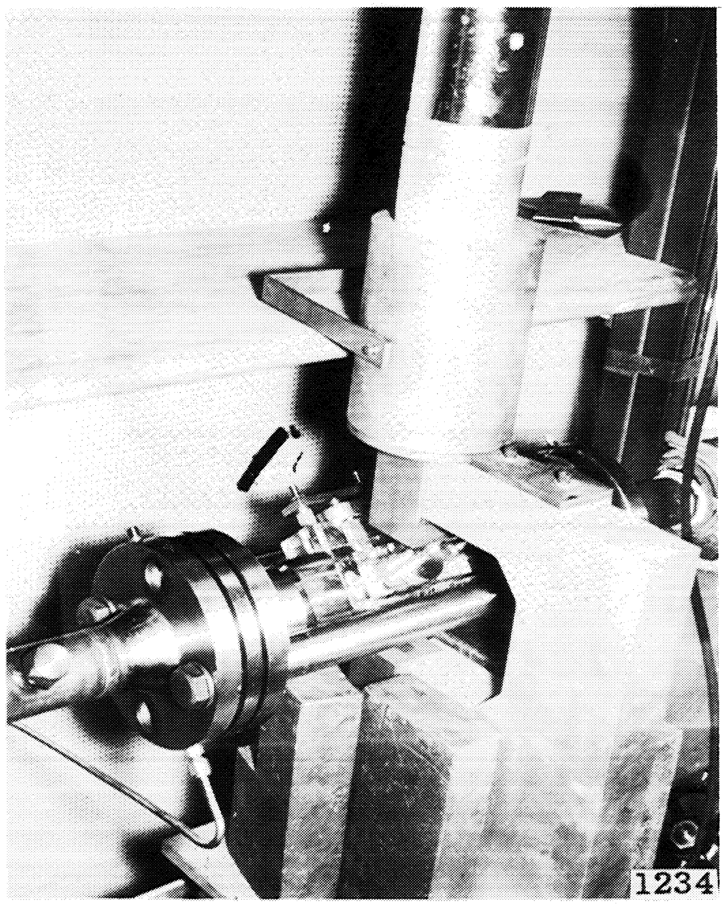




Figure 15. Gamma-Ray Densitometer Mounted at Venturi.

the path length in the fluid, and the degree of precision desired. To obtain sufficient discrimination with a limited path length in a low density fluid such as water (as in one of the present cases), it is necessary to use a source producing very low energy gammas, X-rays, or even Betas. Thus, a source of promethium-tungstate was selected for this case, producing 60 kev X-rays. Once the type of source has been selected, it is necessary to provide a sufficient number of milli curies of the material (opposite the collimation apperature),* so that for the degree of collimation required, and for reasonable counting intervals, the statistics acheived will be adequate for the minimum increment of void fraction which it is desired to measure.

For the measurements in mercury, in which the attenuation per unit path length is much greater than for water, it is necessary to select a source of higher energy. In this particular case, $Co^{60}$ was used, providing two gammas of the order of 1 mev. Again the selection of a suitable source strength (mc), consistent with the factors mentioned above, and also with safety for this higher energy isotope, must be made.

## 2. Flow Visualization Using High-Speed Photography

Conventional flow measurements, including the void fraction measurement just discussed, are essentially time-mean measurements. However, the attaining of an understanding of two-phase flow regimes often requires data related to the instantaneous behavior. Significant information of this type can be obtained for the present cavitating venturis, both in

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* Thus the mc per unit volume of the source may become a factor.

water and mercury,* using either still or motion pictures with a resolving time of the order of 100 microseconds. If motion pictures are to provide a meaningful continuous record, the framing speed must be at least of the order of 5000 frames per second. These conditions fortunately can be obtained with relatively inexpensive commercially available equipment, and considerable useful information on the characteristics of the flow regime has been obtained.(1)

The axially-symmetric venturis used for most of the tests in the present investigation are undesirable for flow visualization studies with transparent fluids in that the precise location of an observed happening is not known in a meaningful way, i.e., in terms of distance from wall, e.g. Partly for this reason a two-dimensional transparent venturi has been constructed. This unit was described previously in this paper.

D. Special Purpose Fluids

It may be desirable in some cases to use special purpose fluids for the study of cavitation performance or damage effects, perhaps to accelerate or intensify the phenomenon, or perhaps to study some special aspect, to which a given fluid is especially adapted (corrosion vs. mechanical effects, e.g.,). For this reason, i.e., to explore the effects of high fluid density and low vapor pressure, and also because it is a fluid of considerable present technological importance, mercury has been used in the present investigations. In the near future, to investigate the effects

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* A very useful observation of bubble behavior in the boundary layer has been obtained using an opaque fluid (mercury), and a transparent venturi.

of high temperature with a similar fluid, it is planned to use lead-bismuth alloy. These points are mentioned to suggest the possible desirability of tests in special fluids.

In addition to providing a broad coverage of various fluid parameters of basic interest, the use of mercury has been highly successful in that it has provided a substantially "accelerated" (or intensified, since there is not a one-to-one correspondence in damage characteristics between water and mercury) cavitation damage test. The factor of acceleration in terms of weight loss is estimated[3] to be the order of 100.

## IV CONCLUSIONS

Facilities for the investigation of cavitation damage and also performance (or scale) effects using a variety of fluids including high temperature liquid metals having been developed at the University of Michigan. These include two tunnel-type closed-loop facilities using cavitating venturis as the test vehicles; one designed primarily for water, and one capable of handling various fluids including moderate temperature liquid metals. In addition an ultrasonic vibratory facility has been constructed, and is being modified for use with fluids including liquid metals under extremely high temperatures.

Various special techniques have been adapted or developed for use with these facilities and these are described in the paper. It is felt that in some cases they may be useful in similar or related research investigations.

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