LIQUID-METAL CAVITATION-EROSION
RESEARCH INVESTIGATION FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Final Report

Period of September 1, 1958 to August 31, 1959

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LIST OF ILLUSTRATIONS

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ABSTRACT

This report summarizes the status of the project at the conclusion of the initial contract and continues to consider the anticipated research under the renewal grant. Under the first heading, the primary theoretical considerations are reviewed; the facility itself is described in detail; and the results of preliminary operations and tests of components discussed. Under the second heading, anticipated initial research under the grant is reviewed; and the various problems, which, in many cases, have become more apparent through preliminary testing, are described.

1. INTRODUCTION

1.1. OBJECTIVES OF CONTRACT

The contract, for which this document is the final report, covered the period September 1, 1958 to August 31, 1959. This contract has been superceded by a grant covering the period September 30, 1959 to September 30, 1961. The initial contract called for the design and construction of a closed piping loop, powered by a centrifugal pump, and including a cavitating venturi test section. This loop was to be capable of obtaining realistic data on the effects of cavitation on turbomachinery, including both performance and damage effects, with fluids of technical importance other than water. The initial emphasis was to be upon the liquid metals because of their importance in nuclear technology and their wide divergence of applicable physical properties from water. Initial operation of the loop with water to obtain a calibration as a basis for future comparison and an understanding of the phenomenon with water in the particular configuration of interest was to be included within the initial contract. After completion of water tests, mercury was to be substituted. Mercury was chosen as the first liquid metal to be investigated because of its greater ease of handling and instrumentation, its similarity in applicable physical parameters to other liquid metals of interest, and its own inherent potential in various technical applications. It was hoped initially that some testing with mercury might be accomplished within the initial contract period. However, a more thorough investigation with water than was initially contemplated has seemed desirable, with the results that the initiation of mercury testing has been postponed for several months, and water testing has continued into the grant phase of the project.

1.2. OVER-ALL PROJECT OBJECTIVES

The over-all project objectives, encompassing a period of at least three to four years, were listed in detail in Refs. 1 and 2. These are summarized here for convenience. The items apply to water, mercury, sodium, perhaps one or more additional liquid metals if it appears desirable, and perhaps various other fluids of technical interest; for example, certain rocket propellants.

(1) Determination of those combinations of fluid dynamic parameters and fluid and container material properties which are permissible from the viewpoint of avoiding prohibitive wear and/or performance deterioration with the various fluids. Such data should be suitable as a guide toward producing optimum pump designs.

(2) Study the nature of wear or pitting as affected by the various fluid-dynamic and physical properties.

(3) Develop methods for determining cavitation effects on pump impellers operating with various fluids from water testing.

(4) Study basic mechanism of cavitation phenomena with water and other fluids utilized. A wide range of physical properties is thereby afforded.

2. STATUS OF PROJECT AT COMPLETION OF INITIAL CONTRACT

The status of the project at the end of the initial contract period is reviewed in this section. To aid in the understanding of the facility design and the program of initial testing, a brief review of the applicable theoretical considerations will be given first.

2.1. APPLICABLE THEORETICAL CONSIDERATIONS

The theoretical considerations applying to cavitation in a venturi, as they are presently understood, were reviewed in some detail in Ref. 2. The following material will be largely a summarization.

2.1.1. CHARACTERIZATION OF PHENOMENON

The terms "degree of cavitation" and "intensity of cavitation" will be used to characterize the geometrical configuration of the cavitating region and the rate of wear of a standard sample respectively. It has been convenient to standardize the "degree" to the conditions of sonic initiation, visible initiation, and cavitation extending to various marks in the test section (as, 1 inch, 2 inches and 3 inches from the start of the diverging section in the initial test section). Standardization of "intensity" might be in terms of wear of a standard sample, or perhaps in terms of a grouping involving various of the physical and fluid-dynamic parameters (as density, velocity, surface tension, pressure gradients, container and fluid properties, etc.), or alternatively in terms of acoustic pressure and container and fluid properties. This problem is as yet unresolved and no wear tests have yet been made.

If degree is understood to encompass only the macroscopic configuration of the cavitating region, it is obvious (and has been demonstrated in the facility) that a given degree can be obtained under various conditions of pressure, flow, and temperature, and presumably fluid. It is presumed that various intensities can also be obtained for each of the standardized degrees, depending upon the various applicable fluid-dynamic and physical properties.

2.1.2. MEASUREMENT OF PHENOMENON

2.1.2.1. Degree

As it has been defined, the macroscopic degree of cavitation can be measured visually in a water-glass system. However, it is necessary to measure this characteristic also in opaque systems, and it is desirable to obtain more detailed information even in the water system. To accomplish these goals, it is proposed to use several techniques:

(1) Void fraction measurement by differential absorption of electromagnetic radiation

(2) Analysis of acoustic pattern

(3) Measurement of venturi loss coefficient

(4) Measurement of cavitation number

(5) High-speed photography

Void fraction measurement, if it were sufficiently precise, should characterize in detail the cavitating zone for any of the fluids. Sonic instrumentation to record and amplify the acoustic pattern produced is certainly useful in determining the initiation of cavitation. It may also be useful in determining the degree for cases of more fully-developed cavitation. Measurement of the loss coefficient (ratio of over-all pressure loss to pressure loss between venturi inlet and throat) is useful in determining the extent of the cavitating zone. Presumably, cavitation number also will be useful in this determination. High-speed photography can be extremely useful in obtaining an understanding (using the water-glass system) of the void fraction and acoustic measurements. It may also be of use with a mercury-glass system in observing activity along the interface; but it is of no application to metallic test sections.

2.1.2.2. Intensity

Measurement of the intensity of cavitation, as previously defined, involves basically measuring the rate of wear or erosion of samples under given fluid-dynamic and physical property conditions. It would be a great advantage if this could be correlated with a grouping of more readily measured properties or conditions. This may be possible in terms of various of the fluid-dynamic and physical property conditions or in terms of the acoustic pressure. The discovery of such a correlation is one of the primary objectives of the project.

The direct measurement of wear involves both quantity of material removed and distribution (i.e., pitting, even wear, etc.). This must involve either an examination of the sample through X- or gamma-ray picture, the obtaining of an impression in plaster, rubber, etc. without disassembly, or by disassembly and direct examination. A test section wherein wear samples can be readily placed and also from which they can be removed is most desirable, since direct examination will certainly be required eventually. However, development of the other techniques is also desirable. In addition, the use of a radioactive tracer in the test material which can be monitored downstream by a suitable counter may be of great assistance in that the initiation of wear can be determined to high accuracy and without disassembly. However, such a technique cannot replace visual examination, since it will tell nothing of the character or distribution of wear.

2.1.3. DEVIATIONS OF PHENOMENON FROM IDEALIZED MODEL

It is to be expected that the phenomenon in both the venturi and the powering centrifugal pump will differ somewhat from that predicted by the usual idealized model wherein cavitation always occurs when the vapor pressure is reached locally, pressures below the vapor pressure cannot exist; and the instantaneous pressures in the venturi are the mean pressures read by static wall taps. Under the assumptions of this model, cavitation number would uniquely describe the degree of cavitation in the venturi regardless of other conditions, for tests at the design point, and suction specific speed the degree of cavitation in the pump.* A significant portion of the test program has been designed to determine the degree and significance of variation from this ideal model in the particular configuration, both with water and with the other fluids.

Possible mechanisms of deviation were described in detail in Ref. 2. These are associated with the concepts of liquid tensile strength, scale effects and thermodynamic and heat transfer effects. In testing with a single fluid, they may be made manifest in the facility with respect to cavitation number by variation, at a fixed cavitation degree, of:

(1) Test section size

(2) Absolute fluid velocity

(3) Fluid temperature

(4) Impurity content, primarily entrained gases

It is certainly to be expected that all of these will also affect intensity of cavitation. For example, the intensity should certainly increase strongly with velocity (see Ref. 2 for extensive bibliography of previous work on these various effects) and decrease with increased gas content (cushioning effect). The possible effects of temperature are numerous, involving at least a change in "void" content with vapor pressure, in container strength and in chemical reaction potentials.

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*It seems desirable to compare the effects of cavitation upon pump performance with the different fluids (as well as venturi tests), since this information may be gained with little additional effort.

Boundary layer thickness, degree of turbulence and location of bubble collapse are functions of test section size and may influence intensity. All of the above considerations apply if a given degree of cavitation is obtained and do not include the interrelations between degree of cavitation and the various parameters discussed in the previous paragraph.

2.2. CAVITATION-EROSION FACILITY

In consideration of the various factors discussed in the preceding section, a cavitation-erosion facility has been designed and constructed. As far as practicable, the design has been such as to allow the use of water, mercury and high-temperature liquid metals in turn in the same facility with a minimum of component substitutions. Essentially, the facility is a closed-loop circuit powered by an overhung, sump-type centrifugal pump, and including a cavitating-venturi test section, upstream and down stream throttling valves, a set of calibrated venturi and orifices as required for flow measurement, heating and cooling sections, a sump tank for fluid storage and degassing if required, variable speed pump drive, instrumentation for acoustic pattern and void fraction measurement, systems for pressure and temperature measurement, instrumentation for measurement of gas content.

2.2.1. MAJOR COMPONENT SPECIFICATIONS

The sizing of the major components was described in some detail in Ref. 1. To summarize briefly, it was desired to obtain a velocity in the cavitating venturi test section of about 50 feet/second for the heavy liquid metals (as mercury, lead or bismuth), and about 100 feet/second with the lighter fluids (as sodium, sodium-potassium alloy or water). Operation up to at least 1000° F. should be possible. This choice of operating conditions was believed adequate to approximate as closely as necessary the expected range of operation of full scale equipment, based upon previous studies reported in Refs. 3 and 4. It is also necessary that a test section diameter large enough for suitable instrumentation and visualization and also suitable for the obtaining of realistically large Reynolds' Numbers be used. It was felt that a minimum test section diameter for the obtaining of the required flow conditions was 1/4 inch, while a 1/2-inch section for the major part of the testing would be desirable.

It was further felt that only a sump-type centrifugal pump could provide the required conditions over the wide range of fluids to be tested at permissible cost. To minimize leakage through the shaft seal for such a pump, it is necessary that the sump be maintained at approximately atmospheric pressure. This condition, along with the fluid-dynamic requirements of the preceding paragraph, fix the pump requirements. Approximately, these are the production of a 45-foot head at 40 GPM for the heavy liquid metals, and four times the head at twice the flow for the lighter fluids. The fluid-dynamic design of the loop is reported in detail in Ref. 1. Subsequent testing has approximately confirmed these design calculations.

2.2.2. PUMPING LOOP PROPER

2.2.2.1. Over-All Assembly

The over-all loop layout is shown in Fig. 1, while Fig. 2 is a photograph of the actual equipment. Selection of piping diameters and section lengths is described in Ref. 1. An 18-8 stainless steel has been used throughout to maximize adaptability. The use of throttling valves on either side of the test section is necessary to control the pressure level in the test section, since the pump inlet pressure is roughly fixed to atmospheric pressure by the seal requirements. The cooler shown in the lower return leg is sized to remove sufficient pump work to allow full flow operation with low temperature mercury (150° F. maximum). The electric heater in the vertical leg downstream from the test section is sized to allow operation with water at low flow rates at temperatures close to the boiling point (limit is imposed by plexiglas test section). For higher temperature liquid metals, a spray-type cooler is to be substituted for the water cooler shown. In these cases, preheating will also be required to attain a molten fluid. The detailed design and specifications of these components is given in Ref. 1.

2.2.2.2. Centrifugal Pump

The centrifugal pump, manufactured by the Berkeley Pump Company, is of the overhung, sump type. Its characteristics are described in detail in Ref. 1. The cross-section is approximately sketched in Fig. 3. Fig. 4 is a photograph of the pump assembly. To summarize briefly, the design conditions are 45-foot head at 40 GPM at 1800 RPM. It was anticipated that it would be possible to operate at speeds approaching 3600 RPM with water or light liquid metals so that the desired test section velocity and flow rate would be attained. As the result of preliminary tests, this has proved possible with water; although some cooling of the shaft in the vicinity of the bearings and of the stuffing box has been desirable under these operating conditions.

The wetted portions of the pump and sump tank are of an 18-8 stainless steel as are all wetted sections of the loop. It was felt that this material offered the best adaptability to the various fluids which it was expected to use.

2.2.2.3. Valves

The main loop throttling valves are 1-1/2-inch Y-pattern valves of the bellows-sealed type, 18-8 stainless steel, manufactured by the William Powell Company. Smaller bellows-sealed stainless steel valves have also been used in the charging and dumping lines. These are 1/2-inch globe valves manufactured by the Associated Valve and Engineering Company. In the preliminary loop water tests, all valves have performed satisfactorily.

2.2.2.4. Flow Meters

Flow meters of maximum precision must be provided to measure a wide range of flow rates with water and with liquid metals. It was decided that pressure-drop type instruments (i.e., orifices or venturi) should be used. At maximum flow rate, it is necessary that loop losses be minimized if the desired performance is to be obtained. For this reason, a venturi was selected as the most desirable type and designed to produce a reasonable head differential for measurement in the applicable flow range. A drawing of the meter is included as Fig. 5. Calibration of this meter against a weigh tank disclosed that, while the discharge coefficient was quite constant with Reynolds' Number in the design flow range, it was not suitable for the lower flows required with small-bore (1/4 inch) test sections both because there was considerable variation of discharge coefficient with Reynolds' Number and because the differential heads were inconveniently small for precise measurement. Consequently, an orifice meter was designed, constructed and calibrated for the lower flow range. The comparatively large head loss of the orifice is acceptable at low flow since the available pump head is greater for this condition.

It is expected that these two meters will be used for both the water and mercury phases of the program. In either case, the differential pressures can be measured by height of liquid column in a simple manometer. Since the discharge coefficients are practically constant for high Reynolds' Number, no new calibration with mercury or other liquid metals will be required. Measurement of the differential pressures with high-temperature liquid metals will require special instrumentation but is believed feasible. No attempt to specify in detail the required instrumentation has as yet been made.

2.2.2.5. Test Sections

The general principles guiding the design of the venturi test section assembly and the resultant design features, are the following:

(1) Cavitation is to be obtained under conditions where velocity and pressure regimes can be easily measured and also accurately predicted. Hence, a conical diffuser with gradual convergence, constant diameter throat section and gradual divergence was chosen. (Good diffusion is required to obtain desired velocities.) To avoid an unduly thick boundary layer, a rapid

convergence (rounded approach nozzle) was used in the inlet section with gradual convergence only adjacent to the actual throat. A cross-section drawing of the initial test section is reproduced for convenience from Ref. 2 (Fig. 6a of this report). Pressure taps to determine the axial pressure profile are spaced as shown. Fig. 6b shows the larger test section (1/2" nominal throat). It is geometrically similar to the smaller in those regions where significant kinetic heads exist.

(2) Test sections must be reasonably inexpensive and possible to replace without undue effort. Consequently, the test section has been designed as an insert into a flanged* bracket for insertion into the loop. The cross-sectional drawing is shown in Fig. 6a,6b, and Fig. 7 is a photograph of the complete assembly as presently installed in the loop. The assembly as shown is only intended for service with water and mercury; and for this reason, it is possible to use an "O" ring end seal as shown in the drawing. Preliminary design studies for high-temperature test sections have been made. It is believed that the flanged assembly and connecting pipe must be integral for these cases with perhaps a removable insert within the pressure shell as an actual test section.

(3) For water and mercury, the maximum visibility must exist. For this reason, Plexiglas has been used. For wear tests, it is expected that removable wear inserts can be inserted into the Plexiglas holders. If necessary, a stronger, transparent plastic may be substituted for the mercury tests.

The test program for all fluids is divided into two major portions. First, the conditions governing the initiation and degree of cavitation must be established for each fluid, and then the wear condition which will result. As explained in the discussion of theoretical factors, it seems necessary to establish the effect of the following upon

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*Corrugated, asbestos-filled, stainless steel gaskets have been specified for all flanged joints for the water and mercury phases. It is hoped that these will also be successful for high-temperature liquid metals. They are a product of the Goetzke Gasket Division of Johns-Manville.

initiation and degree of cavitation in this particular test facility.

(a) Test section size
(b) Fluid Velocity
(c) Entrained gas content

(4) Thermodynamic Parameters: To accomplish these objectives, it is presently planned to utilize throughout geometrically similar test sections; but in at least two basic sizes: nominal 1/4-inch and 1/2-inch throat diameter (it may also be desirable to include a 3/4-inch throat for certain tests). The effect of gas content can be investigated with water by utilizing water with various degrees of aeration. Hence, equipment for deaerating and measuring air content is required. This will be described in the next section. It may also be possible to control and measure gas content with mercury and perhaps high-temperature liquid metals. However, some slight modifications of the sump tank may be required to prevent gas entrainment with the liquid metals. The required methods and devices will be first tested with water.

The effect of the thermodynamic parameters can be investigated with water quite easily by using cold and moderately heated water, since the quantity of vapor formed per unit mass of water per unit head depression varies greatly between these conditions. To obtain hot water, a heater section is required. This is described in the next section.

2.2.2.6. Deaerating Equipment and Heaters

Deaerated water can be produced by prolonged boiling at atmospheric pressure requiring a heat source, by boiling under vacuum at approximately room temperature, or by a combination of these methods. A stainless steel dump and storage tank was designed and fabricated for storage of the test fluid outside the loop in case disassembly or repairs were required. This is shown in Fig. 4, standing beside the pump. It was subsequently wound with an electric resistance heater and used as a deaerator.

Since it was desired to run tests with hot water as well as cold, a second electric resistance heater was wound on the vertical leg and a portion of the upper horizontal leg of the loop as shown in Fig. 2.

The measurement of dissolved gases can be performed in various ways. The first objective of the tests with deaerated water was to determine whether gas content would cause an appreciable effect in this particular facility; and hence, whether control of this variable was necessary. For this purpose, the simplest and least expensive method of gas content estimation seemed adequate. The method used was the chemical Winkler test for dissolved oxygen. From this, the total gas content can be inferred, assuming a constant proportion between oxygen, nitrogen and carbon dioxide. As noted by other investigators (Ref. 5) and our own preliminary tests, this method allows only a rough estimate at best because of the possibility of chemical reactions involving the oxygen. A better determination can be made using the Van Slyke apparatus for the extraction of all dissolved gases under vacuum. This allows no differentiation between gases. However, such differentiation does not appear essential. It is intended to obtain one of these instruments in the near future. A far more exact determination of entrained gas (which is the portion of the total gas considered to be significant from the cavitation viewpoint) can be made sonically using methods described in Ref. 6. If it becomes of importance to measure entrained gas in liquid metals (dissolved gas is almost nil), it may be necessary to consider such a method.

2.2.2.7. Pump Drive

The pump drive is effected through four V-belts in parallel as shown in Fig. 2 from a variable speed fluid coupling which is driven by a 20-horsepower, 1760-rpm induction motor. The fluid coupling allows continuous speed adjustment between approximately 500 and 1800 rpm of the drive pulley. Two pulleys of different diameters are available for the pump, allowing maximum speeds of either 1800 or approximately 3200 rpm. The fluid coupling allows continuous downward adjustment in either case.

2.2.2.8. Test Cell

The facility is located in a cell of the Automotive Laboratory of The University of Michigan. The cell is equipped with a continuously-operating exhaust system which changes air approximately every two minutes and isolates the cell from the remainder of the building in the event of the escape of noxious vapors. This is an especially desirable location for a facility utilizing mercury or other fluids whose leakage might be hazardous. The cell has been equipped with adequate electric power, cooling water and compressed air for the operation of the facility.

2.2.3. SPECIAL INSTRUMENTATION

2.2.3.1. Pressure Instrumentation

It is necessary to measure individual pressures up to approximately 150 feet of fluid (pump discharge and test section inlet) and down to approximately zero absolute (venturi throat) as well as the rather moderate differential pressures across the flow-meter. With water, most of these pressures can be measured conveniently with water or mercury manometers (at least up to perhaps 50 feet of water). The higher pressures can be measured conveniently with a calibrated Bourdon gage. Measurement of pressures slightly above or below vapor pressure, which may be encountered in the vicinity of the test section throat, requires that the instrument lines not rise appreciably above the level of the test section. To assist in such measurements, it has also been found desirable to operate with test fluid somewhat above room temperature so that boiling in the instrument lines will not be caused by heat flow from the ambient air.

Although a mercury manometer bank was used initially in the water tests, it was found to be not suitable because of the great range of pressures required and the necessity for keeping lines and instruments below test section level. Also, a manometer bank would be entirely unsuited to mercury tests, since the reduction in column height due to the ratio of mercury to water density, essential for the water tests, would not be available.

It was decided to develop a system suited to both water and mercury tests and of maximum possible application to high-temperature liquid metal tests. It would then be possible to obtain operating experience with this system with water, easing greatly the transition to mercury. The system which seemed best to meet these requirements utilizes a stainless steel manifold into which all pressure points are valved and to which suitable pressure instrumentation can be attached. In the case of water tests, a calibrated Bourdon gage is supplied for the highest pressures in parallel with a 60-inch mercury manometer, and a 30-inch mercury manometer mounted below test section level for vacuums and moderate pressures. A calibrated vacuum Bourdon gage is mounted in parallel with the manometer. Suitable venting lines are provided with the effluent water returned to the system through a glass surge vessel mounted above the pump tank. Avoiding make-up requirements in this way is highly desirable for the deaerated or high-temperature water tests and absolutely essential for mercury or other liquid metal tests. The manifold, manometers, etc. can be seen in Fig. 2. The additional manometers shown are for measuring the flow-meter differential heads. These also could be used directly in a mercury system.

The measurement of test section or pump pressures with a mercury system requires either a pressure transducer capable of handling mercury or a Bourdon gage. Of course, no brass or copper-wetted parts are permissible.

In the preliminary water tests, the manifold system appears workable and satisfactory.

2.2.3.2. Velocity Profile Measurements

It was desired to determine the approximate boundary layer thickness in the test section. A device was designed and fabricated consisting of a 0.063-inch hypodermic needle with a small hole drilled normal to the axis, which traverses the test section in a radial direction. A dial indicator, spring-loaded against the tube holder, was used to measure position. The needle was extended into the opposite wall at all times to avoid end effects. It could be rotated to obtain a maximum reading which was taken to indicate its proper orientation. An adaptor was provided to allow its insertion through any of the pressure tap holes (a hole in the opposite wall to receive the end of the tube was provided for those positions where traverses were to be taken). Knowing the exact diameter of the test section and the exact movement of the probe, it was possible to accurately position the resulting profiles assuming axial symmetry. The results obtained are discussed in a later section.

2.2.3.3. Sonic Instrumentation

As previously discussed in Refs. 1 and 2 and in this report, it is desired to use the sonic pattern from cavitation to indicate its incipience and perhaps delineate the degree and intensity. A preliminary arrangement to test these possibilities has been designed, assembled and tested. Some of the major principles considered in the selection of this particular arrangement and their consequences are:

(1) Piezoelectric crystals of adequate sensitivity are highly temperature sensitive and cannot be used above rather moderate temperatures. Also, the design should if possible be applicable to all fluids to be tested. It seemed evident that an arrangement suitable for high-temperature liquid metals must isolate the crystal sufficiently from the system to allow the maintenance of low, and perhaps, controlled temperature. Also, it should not penetrate the pressure shell because of possible sealing problems. Hence, it was decided to attach the crystal to the end of a stainless steel rod, approximately 9 inches in length and 3/16 inches in diameter. This rod would screw into the wall of the test section, penetrating to about 1/16 of an inch from the fluid. Calculations indicated that heat loss to ambient air along its length would be sufficient to maintain low temperature at the end. If not, forced cooling could be used. A barium-titanate wafer, approximately 3/16 inches in diameter and 0.020 inches thick was spring-loaded against the rod-end (or glued, in one version). Barium-titanate was selected in spite of its severe

temperature limitations because of its high sensitivity. Of course, if the system is to be used only with water or low temperature mercury, closer proximity between the crystal and the fluid could be considered. In that case, a wetted probe might be used, since mechanical sealing should not be difficult with these fluids.

(2) Since cavitation noise is more or less white noise, extending into very high frequencies, a high-pass filter is required to exclude machinery noise (ball-bearings in pumps and motors, etc.).

(3) No consideration of individual bubble collapses is feasible within the over-all project objectives; only of the total effect of many bubbles.

The system is shown schematically in Fig. 8. The output of the crystal is fed through a preamplifier with a gain of either 100 or 1000, depending upon setting, into an adjustable filter, thence into an oscilloscope, a scalar and an RMS voltmeter (last three components mentioned being in parallel). The probe was shielded to minimize 60-cycle pick-up which initially appeared to be a problem. Generally, the signal amplitude was found to be very sensitive to cavitation degree and also to test section velocity. The preliminary tests will be discussed in further detail in a later section.

2.2.3.4. Void Fraction Instrumentation

Determination of the void fraction (vapor-volume fraction) at various positions along the test section axis would delineate the cavitating zone, and thus serve as a method for determining the degree of cavitation within opaque containers. This would provide a parallel but independent determination from that of the acoustic pattern (if the latter could be used in this connection). In addition, determination of the void fraction in various cavitation patterns would be very useful basic data, not presently available, in assisting the understanding of the cavitation phenomenon itself.

To attain these objectives, an analytical and experimental investigation, using the differential absorption between vapor (or gas) and liquid for X- or gamma-radiation was initiated. Since the void fractions to be measured were not known even approximately, and it was suspected that they were probably very small, it was felt that a determination precise to about 2 per cent void was necessary. Preliminary investigation indicated that a very soft radiation would be necessary for water, although a more common gamma would suffice for mercury (since mercury is a much better absorber). While X-rays would be optimum, a conventional X-ray generator of suitable specifications was prohibitively expensive.

It was eventually determined that a promethium-tungsten ($Pm_2^{147}(WO_4)_3$) source, emitting K-capture X-rays from the tungsten with intensity peak at about 67 Kev would be adequate. A model Plexiglas test section, in which the void fraction could be statically determined by filling to given depth, was fabricated. Using the chosen source and a scintillation "well" counter, calibration runs were initiated to determine the precision which might be attained. The results will be discussed further in a later section.

2.2.3.5. Radioactive Tracer Damage Detection Instrumentation

To enable a precise determination of the start of wear, and to avoid costly and time-consuming disassemblies, particularly with liquid metals, use of irradiated wear samples and downstream monitoring for radiation would be most useful. A preliminary analytical investigation into the required specifications for instrumentation, feasible wear materials, reactor time, etc. was initiated. While it appears that the use of a method of this type will be eventually useful, it does not appear at present to be of great urgency for the water testing phase, and no detailed studies along this line have been made as yet.

2.2.3.6. Temperature Instrumentation

A sealed-in iron-constantan thermocouple probe is inserted through a pressure-tight fitting into the pump casing.

2.2.4. ADAPTABILITY OF EQUIPMENT TO HIGH-TEMPERATURE LIQUID METALS

It is believed that all the major loop components are suited to liquid metals such as sodium, sodium-potassium alloy, bismuth, lead-bismuth or lead up to perhaps 1200° F. Items requiring modification for such service are principally the following:

(1) Pressure measuring instrumentation

(2) Test section assembly sealing arrangement

(3) Heaters and coolers

(4) Gas pressurization: Inert gas must be substituted for air.

(5) Pump: Methods for cooling pump shaft, bearings and stuffing-box may be necessary. Forced-circulation oil-cooling of bearings and air- or water-cooling of inside of hollow shaft may be suitable.

2.3. PRELIMINARY OPERATION AND TESTS

2.3.1. TEST SECTIONS

2.3.1.1. Pressure and Velocity Profiles

A. Degree of Cavitation

Tap water tests (pumping loop was not yet available) to determine axial pressure profiles in the test section as a function of degree of cavitation were made. The small (1/4" bore) test section was used because of the limited volume flow-rate of the tap water system. It was felt that detailed knowledge of this sort was necessary to obtain an understanding of the pressure-time regimes experienced by the fluid. It was also desired to make preliminary runs on the test section at as early a date as possible to be sure that cavitation of the desired degree could be obtained within the flow and head characteristics of the pump.

It was found that slight cavitation could be obtained for flow rates as low as 10 GPM when the test section discharged to atmosphere (as is approximately the case in the pumping loop). Also, the measured minimum pressure, using tap water which was presumably somewhat super-saturated with air and containing undoubtedly numerous undissolved air nuclei, was slightly above the vapor pressure. For convenience, the degrees of cavitation to be considered were standardized to the following:

(1) Sonic initiation: First audible indication or first appearance of noticeable disturbance on scope beyond that due to machinery noise and turbulence.

(2) Visible initiation: Very fine, relatively symmetrical ring of vapor around throat discharge appears. Visible localized cavitation on pressure taps was not considered sufficient.

(3) One-inch: Cavitation zone covers the region from throat discharge one inch into the diffuser.

(4) Two-inch and three-inch: This is defined in an analogous manner to one-inch cavitation. Obviously, all the above definitions of cavitation condition are somewhat open to personal interpretation. However, as a result of direct observations, it can be stated that the possible variations are not very large, so that these definitions can be assumed to define approximately unique states of flow. It is hoped that they can be used throughout

the investigation. The degree will be determined in those cases where visualization is not possible by void fraction measurement and/or sonic pattern.

As mentioned, only sonic and visible initiation could be obtained with 10 GPM. However, all the modes mentioned above could be obtained at about 15 GPM (maximum capability of the tap water system--maximum pump capability with this test section is about 20 GPM). All but three-inch cavitation could be obtained at about 13 GPM.

The general shape of the axial pressure profiles is shown in Fig. 9 for the various degrees of cavitation. The significant features are the following:

(1) Friction pressure drop in throat is quite significant so that cavitation starts quite near throat discharge.

(2) Pressure remains near minimum over range of cavitating region and then rises rapidly over a short axial distance almost like a normal shock.

(3) Venturi loss coefficient (ratio of head loss between inlet and discharge to throat kinetic energy) is very sensitive to degrees of cavitation beyond initiation conditions.

The detailed results will not be reported herein because the tests are continuing in the loop facility, and all data from previous tests has not as yet been reduced. It appears more desirable to report this data later, when sufficient runs will be available to estimate the validity of the data and delineate the significant trends.

B. Radial Velocity Profiles

Velocity traverses in the radial direction were made in the throat section of the 1/4-inch test section using the tap water system. The purpose of these runs was to determine the approximate boundary layer thickness, and thus obtain some idea of the possible time intervals which bubbles of various sizes might spend in the low pressure region within the boundary layer. The traversing probe used for these tests has been previously described. Figs. 10 and 11 show the velocity profiles obtained at several flow rates and upstream and downstream ends of the throat. Fig. 12 shows the boundary layer thickness as a function of flow-rate. As expected, it decreases as flow-rate increases. In any case, it is only a few mils in thickness. The thickness values shown are believed to be larger than actual values because of the finite diameter of the impact hole used. Since the readings were taken near the throat discharge, they represent boundary layer thickness maxima, presuming it grows in thickness downstream from the throat inlet as might be expected.

The absolute velocity magnitudes measured with this type of impact tube are not expected to be precise. Instead, the curve is fitted around the mean velocity (known from flow and diameter), so that the total integrated flow equals the measured flow. (No true static reading was available at the probe position; instead, probe readings with the impact tube well immersed into the wall were taken to be approximate static pressure. Since the probe occupied a significant portion of the flow area, static pressure readings taken in the absence of the probe are not applicable.) Although the absolute velocities computed from the impact readings are not very accurate, the point of rapid velocity decrease indicating the edge of the boundary layer should be reasonably precise within the precision allowed by the finite hole size. If it seems desirable, these tests will be repeated at a later date with the larger test section.

2.3.1.2. Sonic Tests

The apparatus to observe the acoustic patterns from cavitation in the test section has been previously described. Preliminary tests were conducted on both tap water and loop systems using the 1/4-inch test section to ascertain the suitability of the equipment and to obtain an approximate idea of the results to be expected. No quantitative results will be given at this time. These will be detailed in a future report when more results are available and when an opportunity to compare results with those from improved equipment is afforded. However, the most significant points resulting from the preliminary tests are the following:

(1) Cavitation causes a strong increase in signal even in the initiation stage. Hence, the sonic apparatus should be very useful in determining cavitation initiation. The electronic indication corresponds closely to that obtained by ear. However, a close approach to the test section will not be possible when the fluid is at high temperature. Also, machinery and other background noises tend to reduce the sensitivity of perception by ear. Finally, it is believed that the use of the electronic instrumentation will allow greater precision and repeatability in defining the point of sonic initiation.

(2) There is a great increase in signal strength as measured by RMS Voltmeter as the degree of cavitation is increased, or as the velocity is increased at a given degree. The increase at fixed velocity between visible initiation

and cavitation to the 2-inch mark appears to be by a factor of the order of 2, whereas the increase from sonic initiation as it was defined is of the order of 5. The increase due to a velocity increase from about 55 to 70 feet/second throat velocity is the order of 1.5 (proportional to velocity to the 1.7 power).

(3) The energy per collapse appeared to be greatest when cavitation was in the range of visible initiation. It was possible to obtain a count rate measurement with an electronic scalar. It is assumed that the pips which were counted correlate to some extent with individual bubble collapses. Because of the complicated nature of the sound path between fluid and crystal, the nature of such a correlation is difficult to predict, and any definite conclusions to be drawn from this set of experiments must await further analysis and repeated tests with improved equipment.

The energy per pip (which may or may not correspond to an individual collapse) was definitely greatest for cavitation in the range of visible initiation. It was possible to set the threshold voltage for the scalar at different levels. It was noted that there were considerable numbers of pips above a given voltage at visible initiation, but virtually none for either more (or less) fully developed cavitation. However, the number of low energy pips increased rapidly beyond the range of the scalar as the degree of cavitation was increased beyond visible initiation. This large increase in number accounts for the increase of RMS voltage previously mentioned in spite of the decrease of energy per pip.

If substantiated by future experiments, these results are of considerable significance from the viewpoint of damage, implying that maximum damage would probably result from only slight degrees of cavitation. The writer believes that this is substantially the case with hydraulic machinery based on the observations of operating engineers in this field.

2.3.1.3. Void Fraction Mock-Up Tests

As mentioned in the description of special instrumentation, a promethium-tungsten source was procured to measure void fractions due to cavitation. The strength of the source was 0.5 curies. A dummy Plexiglas test section was fabricated and arranged so that it could be filled to varying depths with water.

The source and a well-type scintillation counter were mounted on opposite sides of the test section, and the resultant impulses from the well counter fed to an electronic scalar. As expected on theoretical grounds (because the product $\mu x \ll 1$), the relation between water depth and count rate was approximately linear, whether the beam was well collimated or not. If such a relationship is correct, it is possible to calculate void fraction in the actual test section as a function of count rate, if it is assumed that the voids are concentrated around the periphery. Of course, suitable corrections for the change to circular geometry must be made. Also, as pointed out in Ref. 6, it must be assumed that the alternate layers of liquid and gas are normal to the direction of the beam (or are well homogenized). If the voids are concentrated around the periphery, the condition of normality is substantially met. Also, although there is theoretically a difference if the fluid layers are parallel to the beam direction, the difference is not great in the particular case under investigation where the difference between full and empty count rates is not large. It is not possible with a circular test section to ascertain the radial location of the cavitation from visual observation. However, studies of cavitation in two-dimensional venturis (e.g., Ref. 7) indicate that the voids are along the walls. There seems to be no reason to believe that the circular section should differ in this respect. This conclusion may be verified in future tests by impact tube measurements.

With the source strength used, the count rates were sufficient to obtain statistically precise results in a conveniently short counting period. Also, the differences obtained between full and empty conditions were sufficient to allow a precision of approximately ±2% in the void fraction determination. Hence, it is felt that this arrangement will allow precise measurements of the cavitation void fractions. The next step will be to test it on the actual facility.

2.3.1.4. Test Section Wear

No tests to determine wear have been made as yet. However, it is a somewhat surprising fact that no wear or erosion of any kind has been observed on the Plexiglas test section, although it has been operated under various degrees of cavitation a total of perhaps five to ten hours. Throat velocities under which cavitation has been obtained were, on the average, approximately 70 feet/second.

2.3.2. PUMP

2.3.2.1. NPSH and Suction Specific Speed Tests

Since the centrifugal pump is an integral part of the loop, it is desirable and relatively easy to determine its performance with respect to cavitation both with water and liquid metals. Thus, a direct comparison will be afforded in a condition of fixed geometry. First, it is necessary to determine the effects upon cavitation performance in water of gas content, temperature, pump speed, and proximity of operating point to design point. For these reasons, tests to determine the net positive suction head (NPSH) for inception of cavitation under various conditions of the above independent variables were undertaken. An arbitrary definition was adopted that cavitation inception would be the point where the pump head had decreased by 5 per cent from the non-cavitating condition at constant RPM and flow-rate. From these values, the corresponding suction specific speeds can of course be calculated.

The test is difficult to run with the present facility because of difficulties with the stuffing-box. Quite a substantial vacuum is required in the pump tank to cause cavitation with the combination of flow-rate and rpm which can be obtained. The required low pressures in the tank were produced with a pair of vacuum pumps in parallel equipped with an adjustable vent valve. It is difficult to maintain steady-state because of the uncertain and substantial leak of the stuffing-box. The situation is somewhat alleviated with hot water, since required vacuum is less because the vapor pressure is greater. However, since the NPSH is computed from the difference between two relatively large numbers (the vapor pressure and the absolute tank pressure), a small error in either makes a substantial difference in NPSH. Since the vapor pressure is very sensitive to temperature, great exactness in temperature measurement is required. An iron-constantan thermocouple, sealed within a thin-walled stainless steel probe, was inserted into the pump tank to a point slightly above the top of the pump casing proper. Because of the strong turbulence in this area, which has been observed through a view-port, it would seem that the temperature so measured would be closely equal to that seen by the pump impeller.

No quantitative data will be submitted in this report, since additional testing is contemplated. To overcome the difficulty of obtaining accurate pressure readings where a good steady-state is not obtainable, it may be desirable to use a recording pressure-transducer set-up in the future runs. In general, it was found that cavitation could be obtained for pump speeds of approximately 1800 rpm and higher with either room temperature or heated water for the pump design flow or higher flows. The break in the pump head curve as NPSH was reduced was generally sharp and well defined.

2.3.2.2. Allowable Pump Speed

The pump is designed for operation at a maximum speed of 1800 RPM with high-temperature lead-bismuth alloy according to the vendor's specifications. However, it was desired to operate at approximately twice this speed with the light fluids to obtain the desired test section velocity. Because of the difference in density between water, NaK, etc., and mercury, bismuth or lead-bismuth, the power required for the lighter fluids at twice design speed is only roughly half that required for the heavy fluids at the design speed. Also, the loads on bearings, pressure stresses, torques, etc., are less. From manufacturer's specifications on the shaft bearings, it appeared that the higher speed with the lighter fluids would not result in too rapid bearing failure. A check of the shaft critical speed indicated it was probably somewhat above 1800 rpm but well below the desired high-operating speed. For these reasons, it was felt that high-speed operation would be satisfactory.

Initial operation has tended to confirm this supposition. It was found that prolonged operation at approximately 3100 rpm (maximum attainable speed with motor, fluid-coupling, pulley combination) resulted in over-heating of the bearing housing. This was controlled by water-cooling of the hollow shaft, simply placing a small quantity of water in the shaft and using the cooling effect of the resultant evaporation. So far this method has been highly successful.

Initial runs have also indicated that the stuffing-box readily over-heats either at design speed or high speed if reasonable tightness is maintained, unless a small stream of cooling water is applied, either by leakage or by an external stream. It is expected that continued operation will iron out these minor mechanical difficulties. They will be discussed in considerably more detail in future reports when more experimental information is available.

2.3.2.3. Test Section Velocities

A detailed analysis of the fluid dynamics of the system was given in Ref. 1 for NaK. It was predicted that cavitation could be obtained for test section velocities ranging between approximately 45 feet per second and 80 feet per second. Since NaK is quite similar in fluid properties to water, the same approximate limits should apply. The lower limit is occasioned by the fact that the pump suction must necessarily be at approximately atmospheric pressure, at least for liquid metal tests to avoid stuffing-box leakage, so that sufficient velocity is necessary to allow diffusion from cavitating pressure to atmospheric. The corresponding limits for mercury are approximately 4 to 40 feet per second (1800 rpm maximum). Because of the higher density, an atmosphere corresponds to many less feet of fluid, and the minimum limit is substantially reduced. The upper limit is reduced approximately in proportion to the pump speed.

Actual test results with water show that cavitation can be produced for throat velocities ranging between about 50 and 95 feet per second with the pump operating at 3100 rpm for the upper limit. The agreement with the prediction is reasonably good, and the limits seem suitable for attaining all required flow conditions.

2.3.2.4. Characteristics of Pump

Pump characteristic curves were run at several speeds and found to match quite closely the manufacturer's specification at 1800 rpm if scaled according to the affinity laws. Fig. 13 shows these results.

2.3.2.5. Deaeration Tests

The deaeration tank and possible methods for producing deaerated water were previously described. It was found that production of deaerated water in the tank was moderately successful, requiring perhaps a full day of boiling to reduce the gas content to fifty per cent below saturation under ambient conditions. The difficulty is probably due to the proportionately small free surface. It was found that the process was somewhat accelerated if a vacuum were produced in the tank, rather than allowing boiling under atmospheric pressure. A practical difficulty aside from large time requirements is the maintenance of under-saturated conditions in the tank, unless it is completely filled, in which case boiling would not be possible.

An alternative method of producing deaerated water, which has been used successfully in several water tunnel facilities, is to draw off by vacuum pump a portion of the mixture of vapor, liquid and gas in the cavitating region. This method would have the advantage of producing the deaerated water directly in the facility where deaeration would not be lost during transfer. Perhaps it would also be more rapid. It will be tried in the near future.

A further difficulty that was experienced initially was the maintenance during a test of the loop water in a deaerated condition. Water level in the pump sump was held at a point a few inches above the pump casing (see Fig. 3 for arrangement). It was felt that such a mode of operation would be a necessity if tests were to be run with high-temperature liquid metal, since it would be necessary to maintain a substantial gas blanket between liquid metal and stuffing-box both to prevent liquid metal leakage and also extensive heating of stuffing-box and bearings. However, it was found that under these conditions the water rapidly entrained air, since there was considerable turbulence in the area above the pump casing. It has been since demonstrated that the problem can be overcome for water by simply allowing the water to rise to the stuffing-box and allowing a slight outward leak to prevent over-heating of the packing. While such a solution might be feasible with mercury, it does not seem possible with high-temperature liquid metals.

3. ANTICIPATED INITIAL RESEARCH UNDER RENEWAL GRANT

3.1. RESEARCH PROGRAM

The anticipated initial phases of research under the renewal grant are listed and discussed primarily as a guide rather than as an attempt to lay down a rigid program. Past experience with research programs of this type indicates the likelihood of major changes as the information from preceding phases becomes available.

3.1.1. COMPLETION OF WATER FLUID-DYNAMIC TESTING

A careful completion of the investigation of the fluid-dynamic behavior of the facility with water is indicated as a first step. Since preliminary testing and existing literature indicate that the degree of cavitation and its initiation may be substantially affected by the parameters, test section size, fluid velocity, vapor pressure and gas content, to mention those apparently most important, it is necessary to ascertain these effects in this particular facility with water before any valid comparisons can be made with other fluids. Because of the practical difficulties of changing fluids in the facility, it is felt that all the water testing, as far as can be foreseen, should be completed before the shift to mercury is initiated. The alternative possibility of an intermediate shift to mercury had been indicated in Ref. 2.

3.1.2. WEAR TESTING WITH WATER

It is necessary that wear testing, as well as fluid-dynamic testing, be completed in water before a change to mercury is made. As presently planned, this will involve a redesign of the test section to include easily removable wear samples. The flow-path design will of course not be changed so that all pressure and velocity measurements will be applicable. It is hoped that an arrangement can be used which will allow visual observation of the progress of wear in the water tests and will also allow the easy substitution of wear samples of different materials. It is hoped that the wear test section can also be used in mercury, and that a wear material can be found that will be usable in mercury and yet will show reasonably rapid wear in water, so that a direct comparison will be afforded.

3.1.3. FLUID-DYNAMIC TESTING WITH MERCURY

After the completion of all water testing, the facility will be adapted for use with mercury. This will involve various modifications of pressure instrumentation, venting arrangements, perhaps baffling in the pump tank, vapor detection instrumentation, substitution of stainless steel for copper and tygon tubing, etc. The required modifications will be described in detail in a future report after actual experience with a suitable arrangement has been gained.

When reliable operation has been attained, a program of fluid-dynamic testing similar to that conducted for water will be initiated. The general objective will be to discover whether cavitation is obtained under parameter values similar to those of the water tests, and, if not, to delineate those parameters responsible for significant variation. The cavitation degree and description will be observed visually and with the aid of void fraction measurements, acoustic pattern and fluid-dynamic parameters. Special care may be necessary to measure and control air or inert gas entrainment.

3.1.4. WEAR TESTING WITH MERCURY

A wear test program similar to that described for water will be initiated at the conclusion of the fluid-dynamic tests. The design of test section, choice of materials, etc., will be largely guided by experience gained in the water tests, and hence cannot be discussed in detail at this time.

3.1.5. OVER-ALL MERCURY PHASE

As a deeper understanding of the phenomena of interest and further detailed operating experience and test results are developed, it may appear that a greater degree of the over-all project objectives can be realized with low-temperature mercury than had been originally anticipated. If this is the case, fewer tests with high-temperature liquid metals may be desirable than originally thought, and the length of the mercury phase may be somewhat expanded. Realistic decisions regarding the optimum attainment of project objectives must, however, await further operating experience in the initial phases of the program.

3.2. ANTICIPATED PROBLEMS

3.2.1. WEAR IN PRESENT CONFIGURATION

Although numerous reports can be found in the literature concerning cavitation-wear testing with water, previous observations of wear on a conical venturi diffuser have not as yet been found. Most fairly recent damage investigations concern themselves with "accelerated cavitation" produced acoustically. For those cases where a flowing system is used, it is common to place a wear sample in the throat of a water tunnel in such a manner that the cavitation is induced upon the obstruction rather than the walls of the tunnel. The motivation for this arrangement is obvious in that it is not desired to damage the tunnel walls. An investigation of this sort involving wear on soft aluminum is reported by Knapp (Ref. 8). Here, pitting was produced quite rapidly (several pits per second per square inch) with stream velocities ranging between 60 and 100 feet/second. Ref. 9 reports a damage investigation on a severely modified two-dimensional venturi wherein severe pitting was obtained in a few hours on various steel alloys but with water velocities of approximately 250 feet/second. These results show that the rate of wear is proportional to velocity to the 8.4 power while Knapp's results showed a dependence to the 6th power. Ref. 10 includes damage observations in a two-dimensional water venturi on lead and glass wear samples for throat velocities of about 75 feet/second. It was noted that a diffuser divergence of about 10° was most effective in producing damage. This is approximately comparable in cone angle to the 6° divergence of the conical venturi of the present test sections. However, it is noted that the major portion of the damage occurred on the flat side plates rather than on the diverging portions.

In view of the above, it appears likely that damage can be induced rather quickly with water on soft materials such as annealed aluminum or lead with the present facility (maximum velocity of about 95 feet/second), and more slowly on stronger materials. This is also pointed out in Ref. 11 where studies of the conditions of intensive cavitation erosion are taking place beyond the model of a circular profile. It would also seem likely that much more rapid damage would results with a higher density fluid such as mercury or with a high-temperature fluid if similar velocities and wear samples are used. However, it cannot be shown definitely from the literature survey that wall damage will be produced at all in the three-dimensional venturi, since it is not certain that the cavitating regions are actually adjacent to the walls. Since this is the case in a two-dimensional venturi, however, it seems likely to be so also for the three-dimensional. Also, in the two-dimensional venturi (Ref. 10), the damage was predominantly on the side plates. Finally, as previously mentioned, no damage has as yet been noted on the Plexiglas test section. It is believed that this latter observation may be the results of the very low hardness and elastic modulus of the Plexiglas or of the long-chained molecule structure of the material. The applicable physical properties are compared with lead and aluminum in Table I. That Plexiglas does not damage readily may be analogous to the fact that rubber-coating of steel members prevents cavitation damage.

On the other hand, it may be that the test section design is not suitable for the rapid production of damage and that considerable modifications will be necessary. However, from a consideration of the literature it does appear that the velocities are adequate in water for at least relatively susceptible materials, and presumably more than adequate for liquid metals.

TABLE I

Material	Elastic Modulus (psi)	Hardness (Brinell) (500 Kg Load)	Tensile Strength (psi)	Yield Strength
Plexiglas	3.5-5 x 10^5[a]	56.8[e]	8,000-14,300[a]	---
Lead	2.47 x 10^6[b]	4.2[c]	3,000[c]	1,000-4,000[b]
Aluminum 3S	10 x 10^6[d]	27.0[e]	16,000[d]	6,000[d]

[a] "Table of Properties," Cadillac Plastic and Chemical Company, Detroit, Michigan.

[b] *Kent's Mechanical Engineers' Handbook*, 12th Edition, 1941, John Wiley & Sons.

[c] *Handbook of Chemistry and Physics*, 36th Edition, 1954-55, Chemical Rubber Publishing Company.

[d] *Alcoa Aluminum and Its Alloys*, 1950, Alcoa Aluminum.

[e] Tests conducted by The University of Michigan Research Institute.

As previously mentioned, the use of an irradiated test section with downstream monitoring of radiation appears to offer a method for very rapid and precise determination of wear rates. This may prove doubly attractive if it happens that substantial wear for visual observation cannot be produced in reasonable time intervals.

The choice of suitable materials for providing a comparison between the effects of water and mercury is difficult if it should appear that ferrous alloys cannot be worn appreciably with water in feasible time intervals. Due to amalgamation effects, it appears that an aluminum alloy would not be usable in mercury. However, it is possible that anodized aluminum might be suitable if cavitation did not penetrate the anodized surface. Other possibilities are various plastics; perhaps glass, perhaps relatively pure iron. These possibilities can best be investigated when actual wear tests have been conducted.

3.2.2. ENTRAINED AND DISSOLVED GAS

Based on theoretical considerations and the observations of other observers, it seems likely that the presence of undissolved gas in the fluid will significantly influence the initiation of cavitation. Also, the presence of dissolved gas may affect the rate of bubble growth and collapse, and hence both degree and intensity of cavitation. As mentioned in earlier sections of this report, equipment for controlling and measuring total gas content in water has been included in the facility and tests to determine the significance of this parameter are included in the program.

The problems of both control and measurement will be somewhat more difficult in mercury than in water and still more troublesome with high-temperature liquid metals. Also, inherent theoretical differences are involved. Since the solubility of liquid metals for gases is practically zero, it is expected that dissolved gas will be of no significance. In water it has been assumed that if the total gas would be maintained well below saturation for a considerable period, the entrained gas would be diminished by an order of magnitude over that found in ordinary running water. The total gas can be easily measured. However, it is apparent from the literature that entrained gas does not entirely disappear and various mechanisms to explain this phenomenon have been suggested. Nevertheless, there may be a significant difference in cavitation-initiation behavior between ordinary water and water which has been held under sub-saturated conditions over an appreciable period. With liquid metals, since there is virtually no dissolved gas, the only possible methods for measurement of gas content must deal with the very small quantity of entrained gas. It could be established, by use of the Van Slyke type of apparatus, that this content was below a certain fixed limit. However, it is not known whether the measurement would be sufficiently precise to be of significance. As an alternative, the sonic methods proposed in Ref. 5 could be tried.

The problem of control of gas content is also difficult with the liquid metals. Except possibly with mercury, it appears certain that an inert gas blanket must be maintained between the metal surface and the stuffing-box. It may be difficult to prevent entrainment at this point. However, a suitable baffling arrangement to provide a quiet surface may be satisfactory. With mercury, it is conceivable that the mercury surface could be allowed into the stuffing-box as with water, and that a small leak (if it occurs) could be collected and returned to the system. Another possibility is to float water or oil on the mercury in the pump tank and allow a slight leak through the stuffing-box. If oil were used, it could be returned to the system. The water could be replenished continually through a connection into the pump tank above the mercury level. Again, suitable baffling would probably be necessary to prevent entrainment of the sealing fluid into the mercury at the interface.

In general, these problems can best be solved as operating experience is gained.

3.2.3. PUMP CAPABILITIES

It is possible that difficulties may be experienced with the pump bearings and/or stuffing-box with high-speed water operation, with heavy-fluid operation, or with high-temperature operation with either fluid. As mentioned in an earlier section, preliminary tests have indicated that the high-speed water operation is feasible, although some assistance from shaft and stuffing-box cooling may be desirable. It is believed that low-temperature operation with mercury will present no problems of stuffing-box over-heating. However, the bearing load may be such that cooling of that portion of the housing or shaft will be required. It is likely that some form of shaft cooling will be necessary for high-temperature operation. Conceivably, this could take the following forms (or a suitable combination thereof):

(1) Air cooling of inside of shaft.

(2) Water-evaporation cooling of inside of shaft (preliminary calculations indicate that the quantity of heat to be removed is low enough to allow this expedient without prohibitive quantity steam formation).

(3) Forced circulation oil flow in bearing housing to remove heat.

It is believed that pump performance can be considerably improved by such methods.

3.2.4. ACOUSTIC INSTRUMENTATION PROBLEMS

The preliminary arrangement of the sonic instrumentation has been previously described as well as some of the preliminary test results. While this arrangement is sufficient to indicate the initiation of cavitation and provide some information relative to the degree and intensity, it is not ideal in many respects. The effects of the length probe in distorting the frequency pattern, the effects of the cavitation chamber itself, and of the transmission through a portion of the chamber wall before entering the probe are all unknown and tend to distort any relations which might be surmised between cavitation intensity and acoustic signal. In addition, there is the effect of extraneous noise introduced through machinery vibrations, turbulence and possible cavitation in other parts of the circuit (e.g., the valves or pump). It is hoped that more refined designs may be evolved, perhaps actually wetting the piezoelectric crystal with the working fluid. These will be discussed in further detail in future reports.

3.2.5. INSTRUMENTATION AND HANDLING OF LIQUID METALS

It is obvious that many special problems are involved in the instrumentation and handling of liquid metals in the facility. These have been previously discussed to some extent in this report and also in Refs. 1 and 2. While it is believed that these problems are considerably less difficult of solution with mercury than with the other liquid metals, certain modifications of existing equipment will still be required, and special precautions will be necessary to prevent and detect the build-up of dangerous concentrations of mercury vapor. These questions will be discussed in greater detail in later reports when some actual experience has been gained.

3.3. PROBABLE SCHEDULE OF OPERATIONS FOR COMING YEAR

Possible schedule of operations have been discussed in Ref. 12, written approximately six months ago. However, since that time some changes in emphasis have become desirable, and also it is possible to assess more realistically the probable rate of progress. For these reasons, the presently anticipated schedule of operation for the coming year is presented as a guide. It is of course realized that as work progresses, changes in objectives and scheduling may be necessary.

	Item	Time Period
(1)	Completion of water fluid-dynamic tests on test section and pump	September 1, 1959 to February 1, 1960
(2)	Wear tests with water	February 1 to April 1, 1960
(3)	Conversion to mercury and initial operation with mercury	April 1 to June 1, 1960
(4)	Fluid-dynamic tests with mercury	June 1 to September 1, 1960

4. CONCLUSIONS

A facility capable of providing cavitation in a venturi test section or in a centrifugal pump with water and with liquid metals has been designed, constructed and tested with water. Preliminary research data has been obtained with water. Various modifications, mostly to instrumentation, are required before introducing mercury, and eventually high-temperature liquid metals, as the working fluid. Minor problems involved in the operation of the facility with water have been largely overcome and no prohibitive difficulties with liquid metals operation are presently evident.

REFERENCES

1. F. G. Hammitt, "Liquid-Metal Cavitation-Erosion Research Investigation for National Advisory Committee for Aeronautics," Progress Report No. 1, November 1, 1958, Report No. 2824-1-P, The University of Michigan Research Institute.

2. F. G. Hammitt, "Liquid-Metal Cavitation-Erosion Research Investigation for National Aeronautics and Space Administration," Progress Report No. 2, March 1, 1959, Report No. 2824-2-P, The University of Michigan Research Institute.

3. F. G. Hammitt, "Continuous Flow Fluid Tunnel Cavitation-Erosion Facility, Engineering Research Institute, University of Michigan 461, Report No. 1117-3-P, May 1957.

4. F. G. Hammitt, "Considerations for Selection of Liquid Metal Pumps," Chemical Engineering Progress," May 1957.

5. L. G. Straub and R. M. Olson, "Cavitation Testing in Water Tunnels," University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Project Report No. 42, December 1954.

6. M. Petrick, "Two-Phase Air-Water Flow Phenomena," ANL-5787, March 1958.

7. H. Novotny, "Werkstoffzerstorung durch Kavitation," 1942, VDI-Verlag GmbH, Berlin (Published by Edward Brothers, Inc., Ann Arbor, Michigan, 1946), page 2.

8. R. T. Knapp, "Recent Investigations of the Mechanics of Cavitation and Cavitation Damage," ASME Trans., October, 1955.

9. J. M. Mosson, "Pitting Resistance of Metals under Cavitation Conditions," ASME Trans., 59, 1937.

10. J. C. Hunsaker, "Cavitation Research - A Progress Report on Work at MIT," Mech. Engr., April 1935.

11. K. K. Shalnev, "Experimental Study of the Intensity of Erosion Due to Cavitation," Chapter 22, Cavitation in Hydrodynamics, National Physical Laboratory (1956).

12. "Proposal to National Aeronautics and Space Administration, Research Investigation on Cavitation-Erosion Phenomena," The University of Michigan Research Institute, Ann Arbor, Michigan, May 1959.

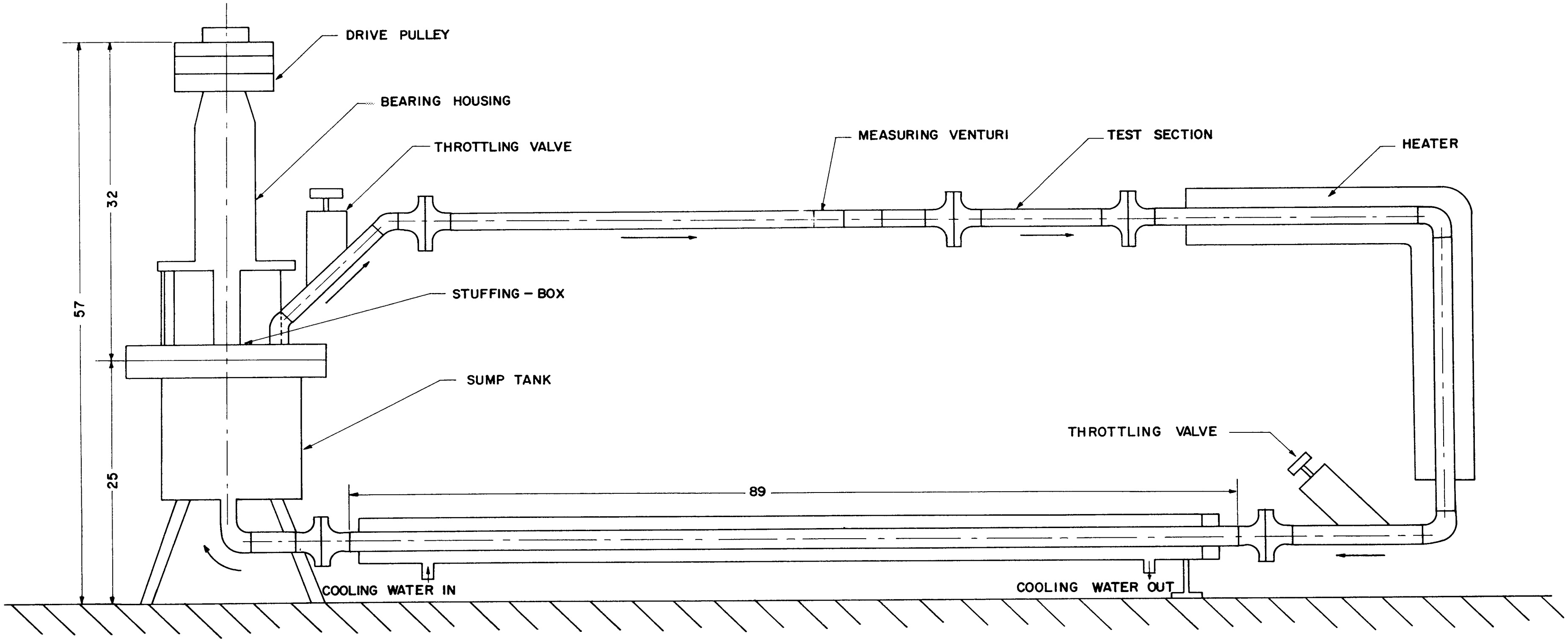

Figure 1. Sketch of Over-All Loop Layout

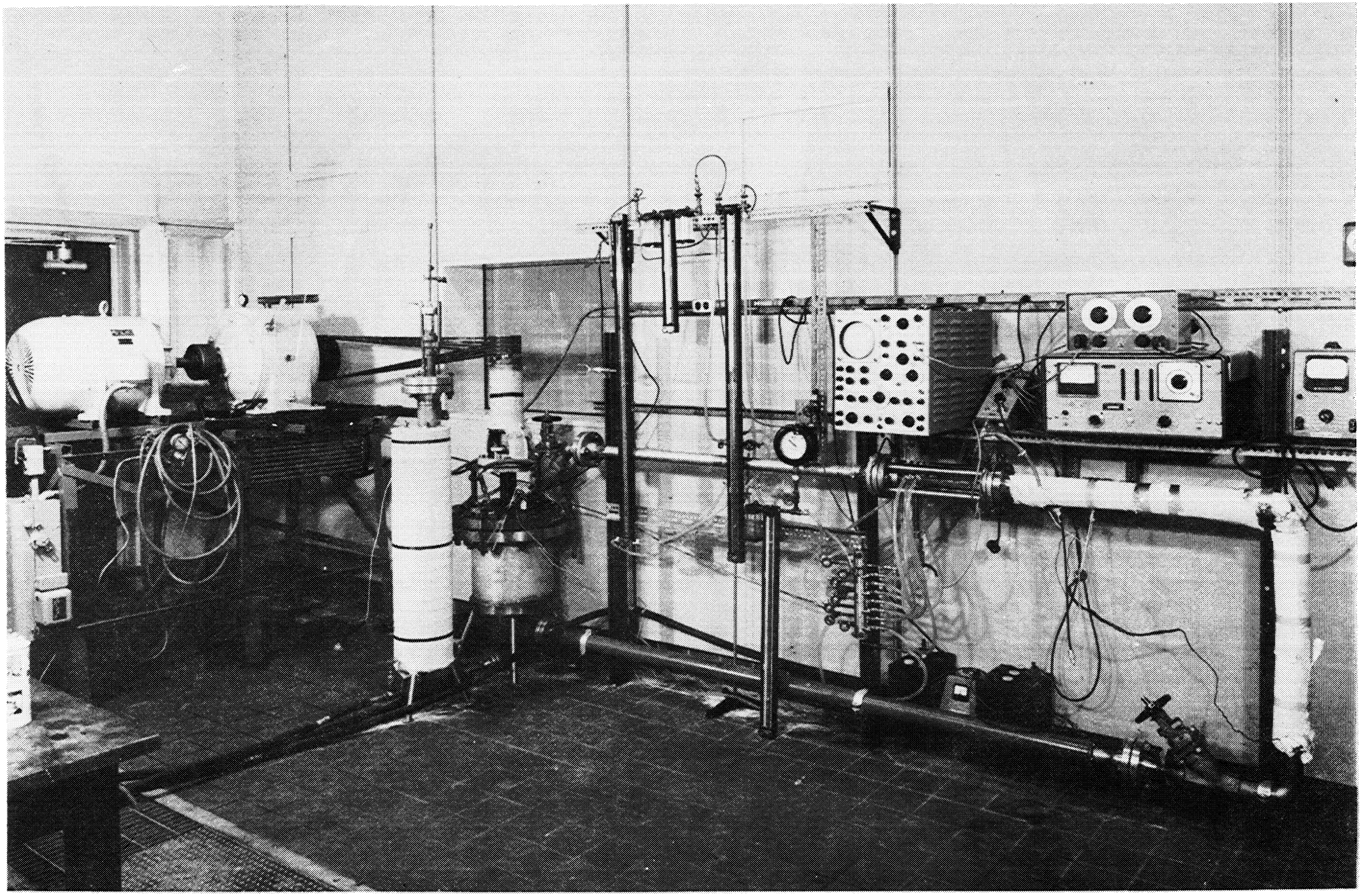

Figure 2. Photograph of Over-All Loop Layout

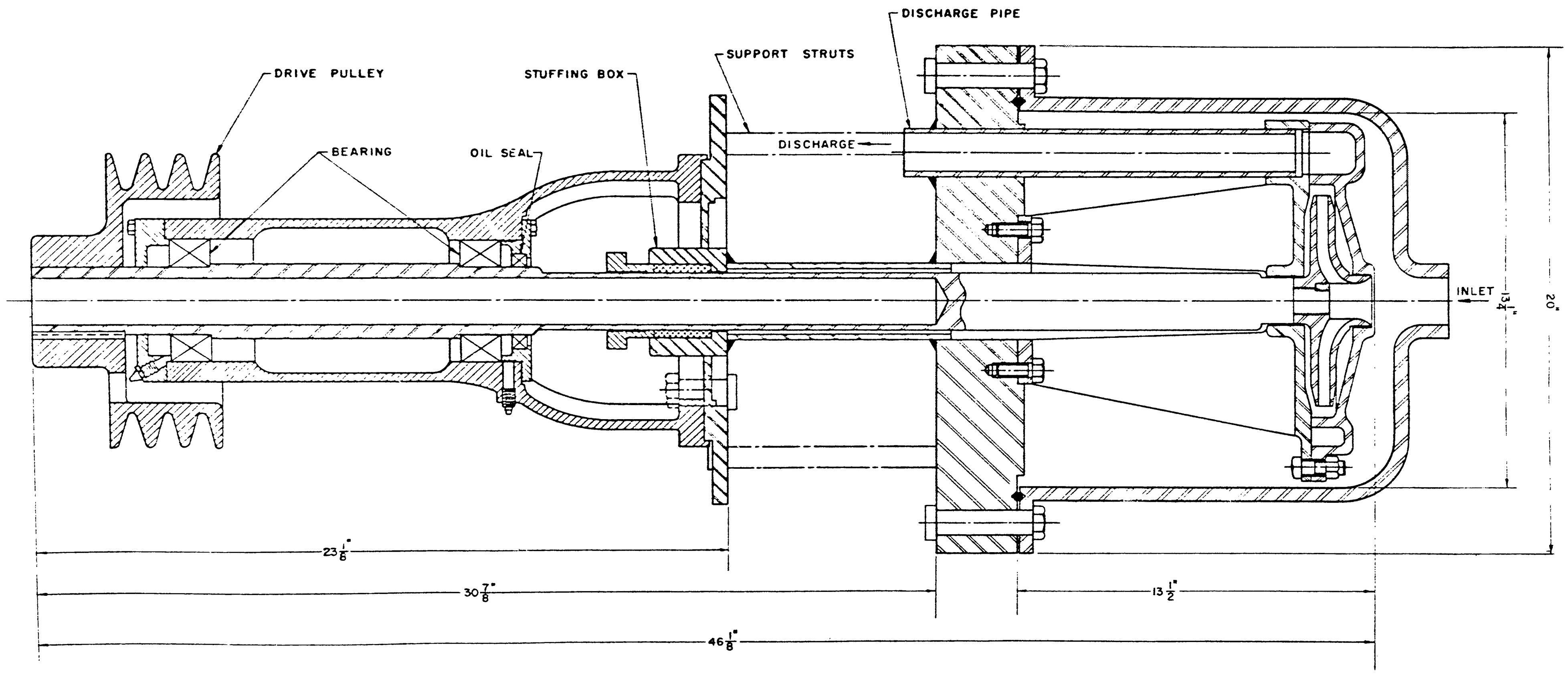

Figure 3. Sketch of Pump Cross-Section

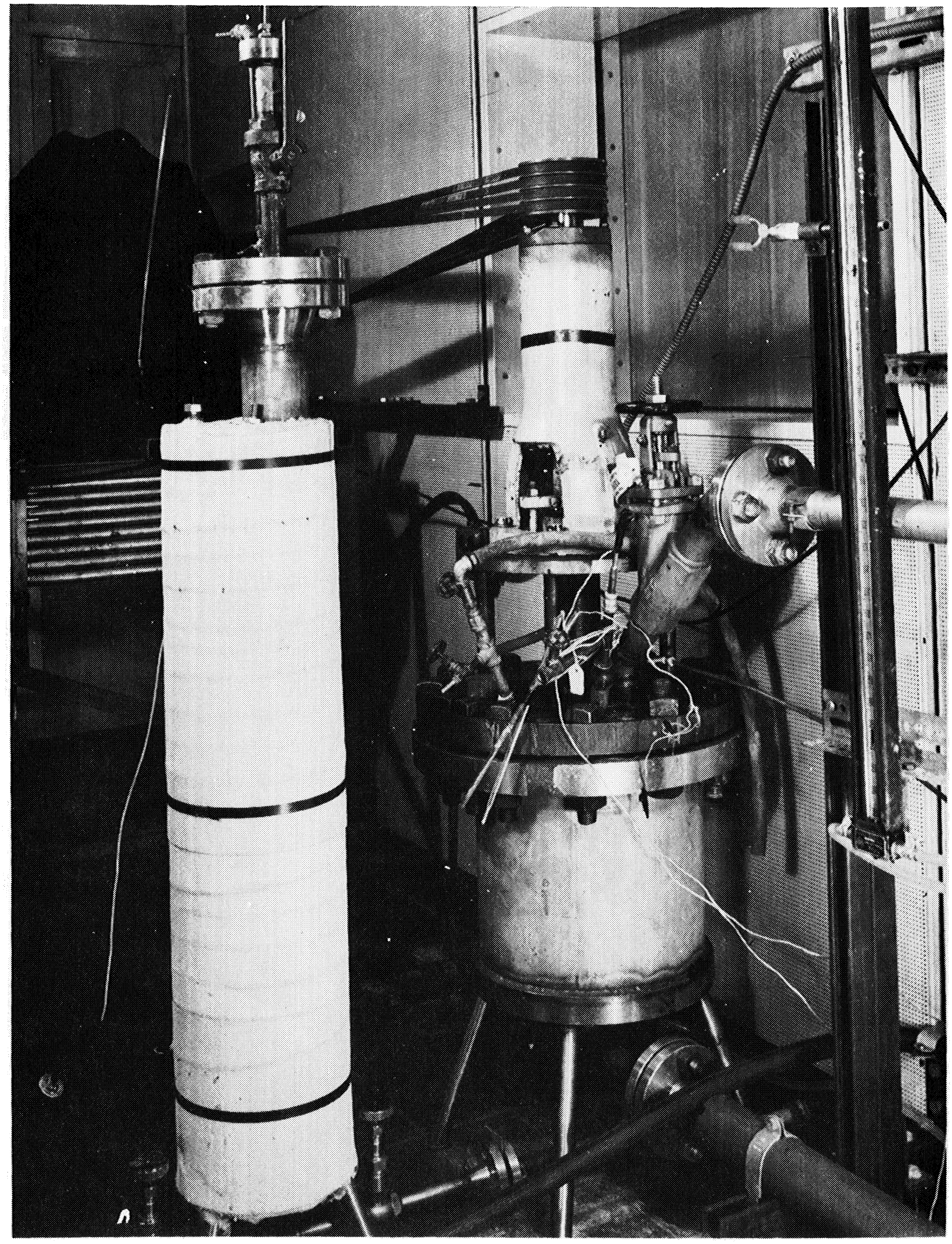

Figure 4. Photograph of Pump Assembly

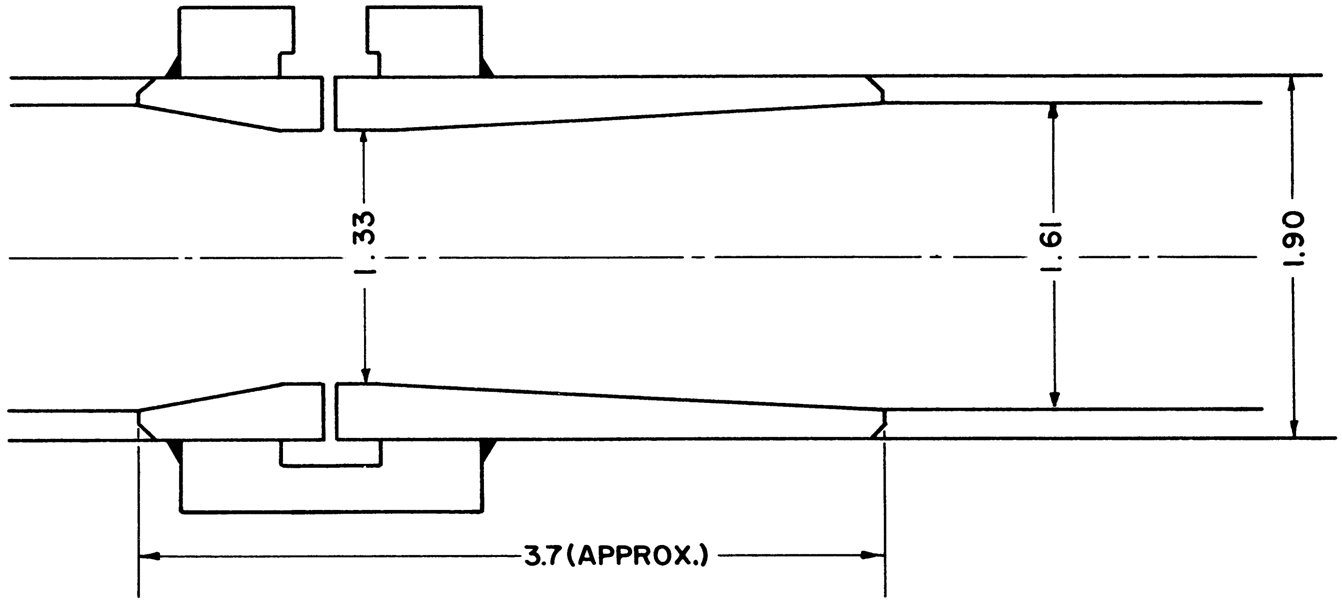

Figure 5. Sketch of Venturi Flow Meter

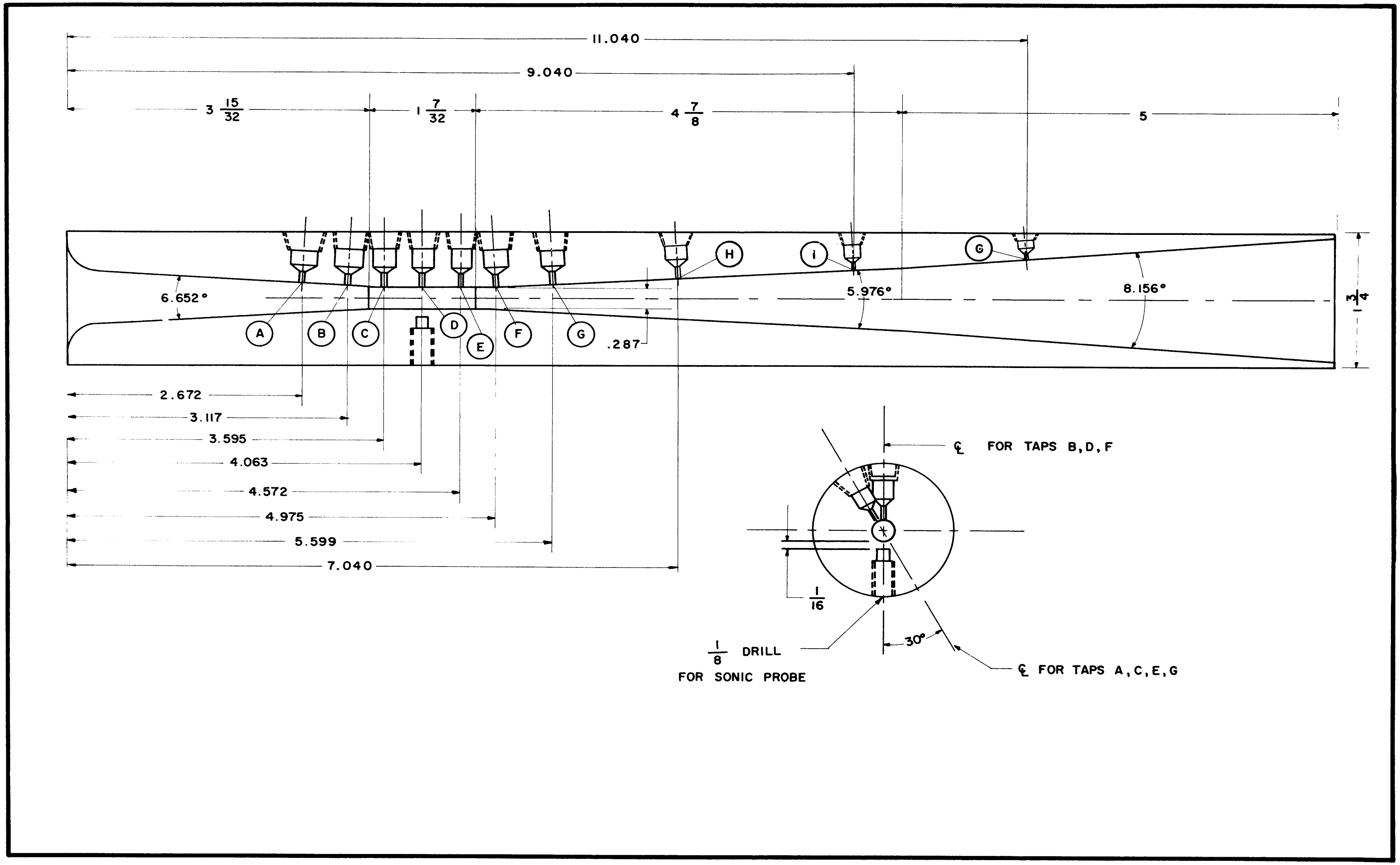

Figure 6a. 1/4" Cavitating Venturi Test Section

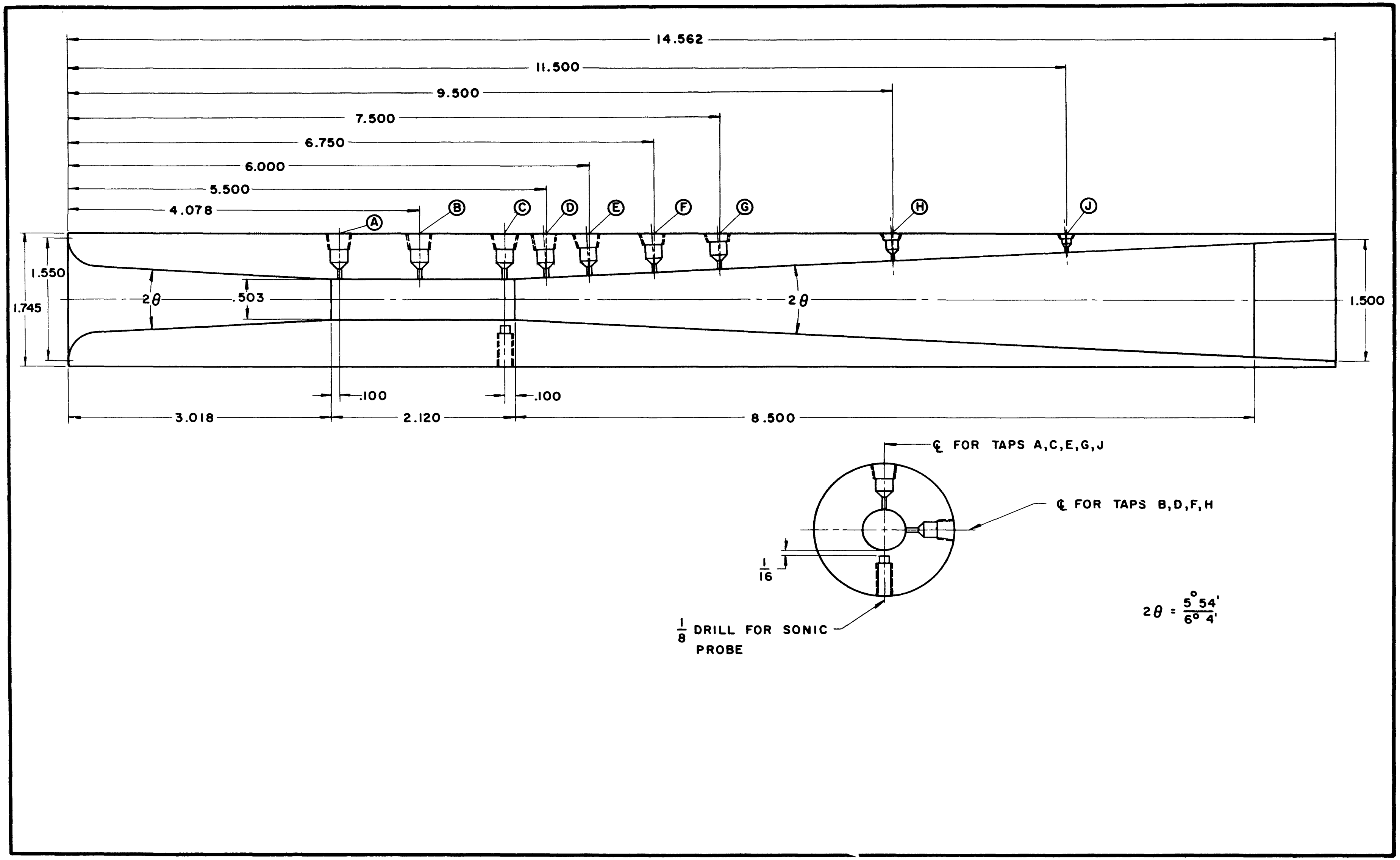

Figure 6b. 1/2" Cavitating Venturi Test Section

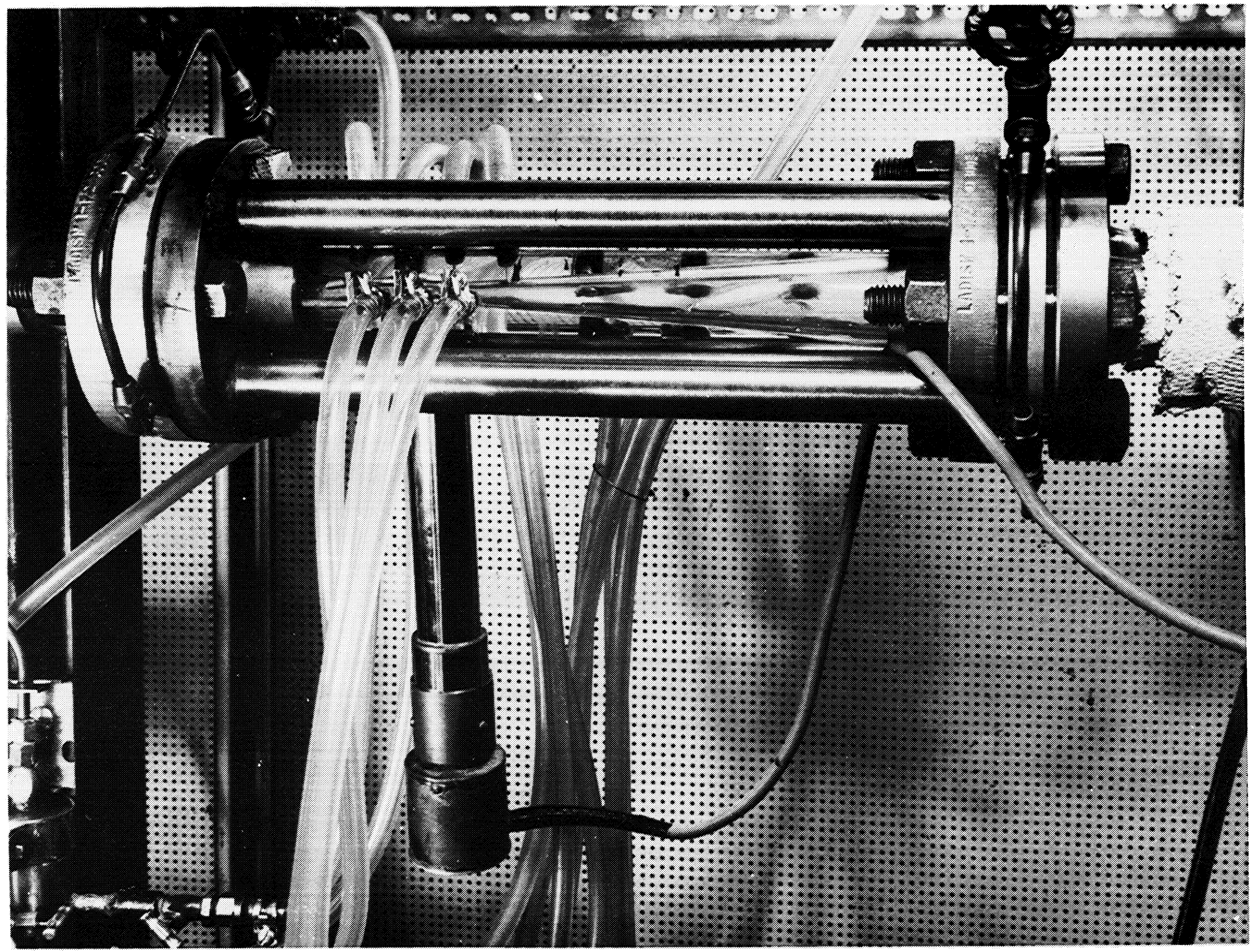

Figure 7. Photograph of Cavitating Venturi Test Section

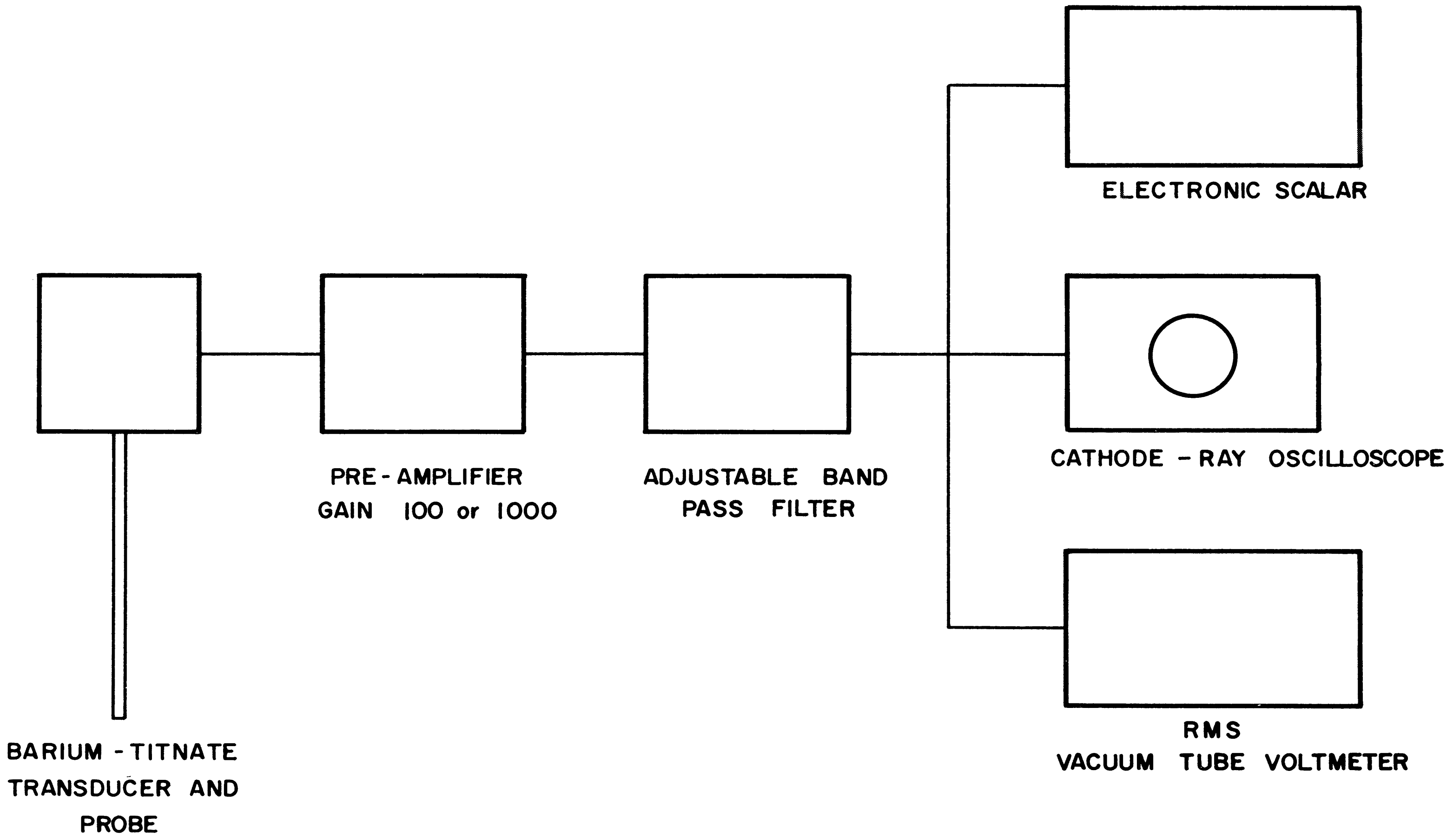

Figure 8. Schematic of Sonic Circuitry

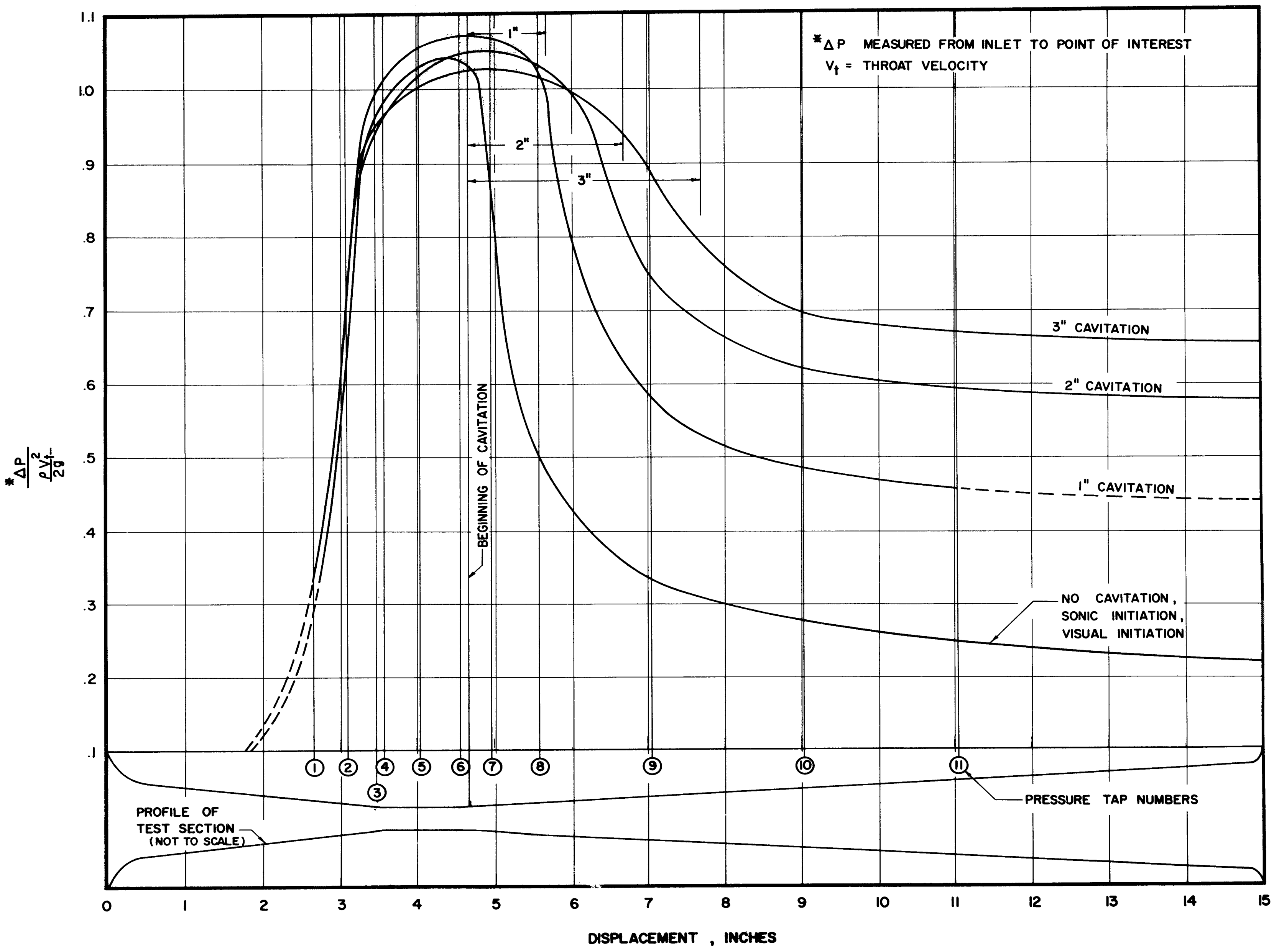

Figure 9. Axial Pressure Profiles vs. Cavitation Degree

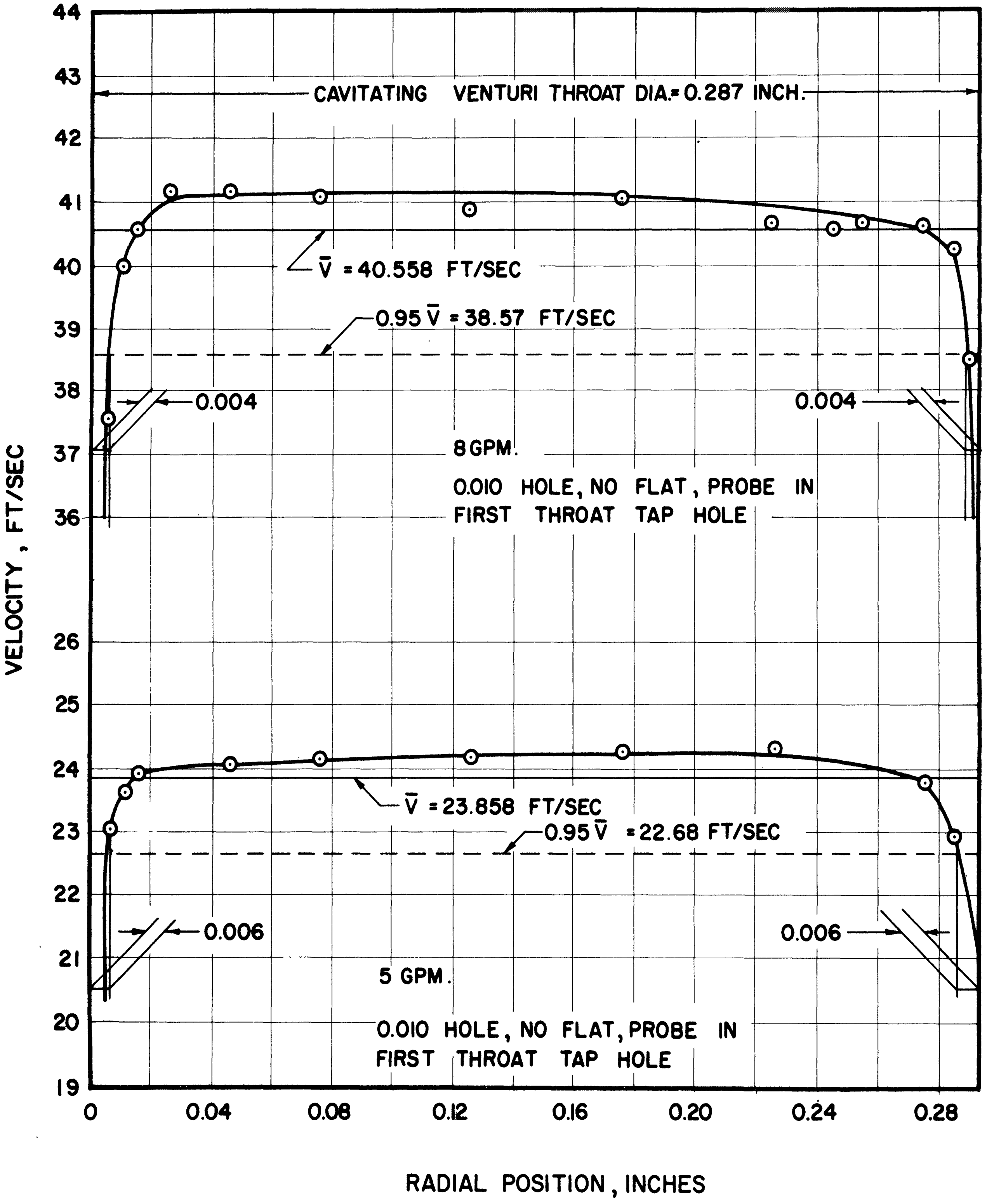

Figure 10. Inlet Throat Velocity Profiles in the Radial Direction

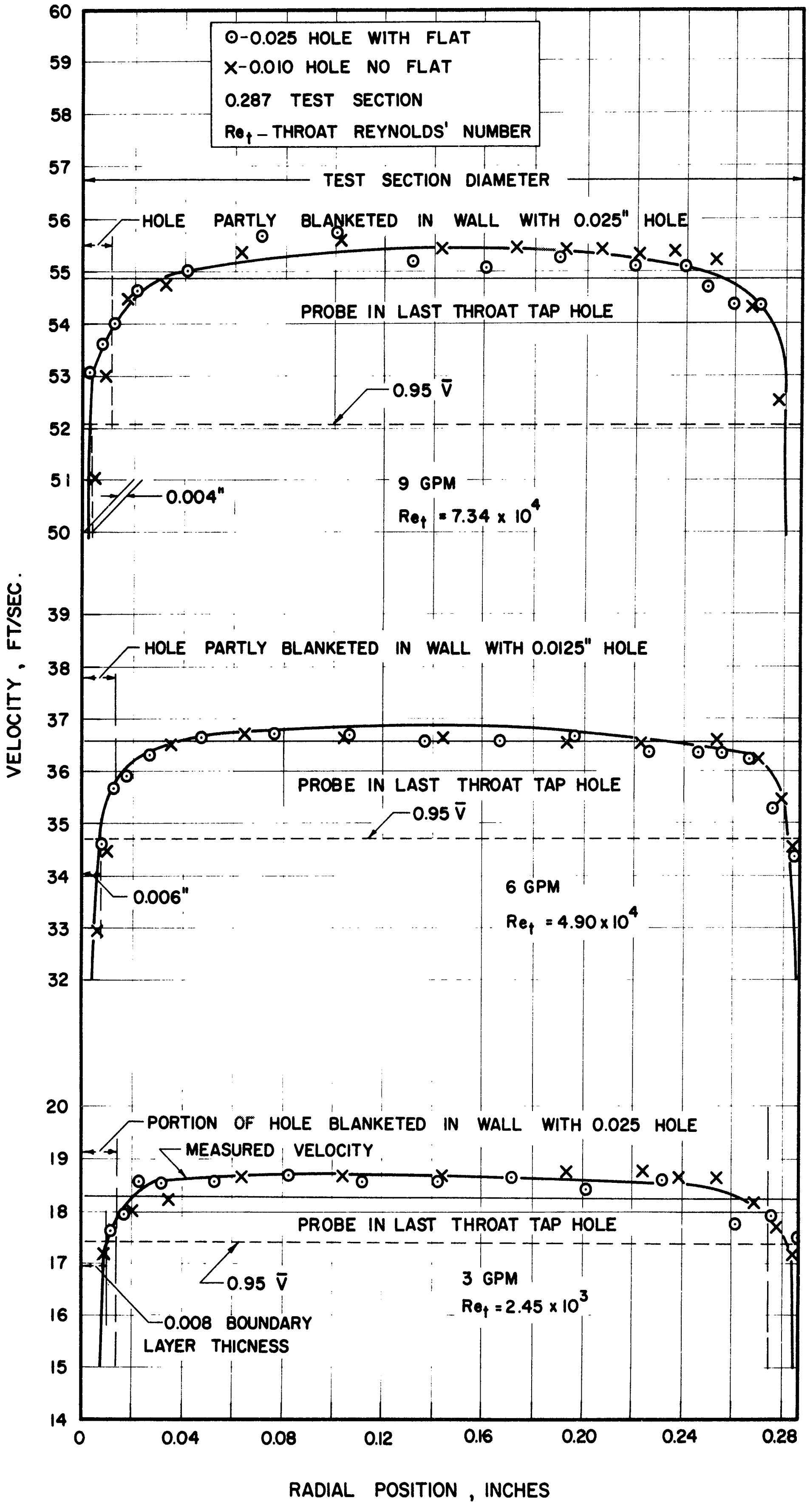

Figure 11. Exit Throat Velocity Profiles in the Radial Direction

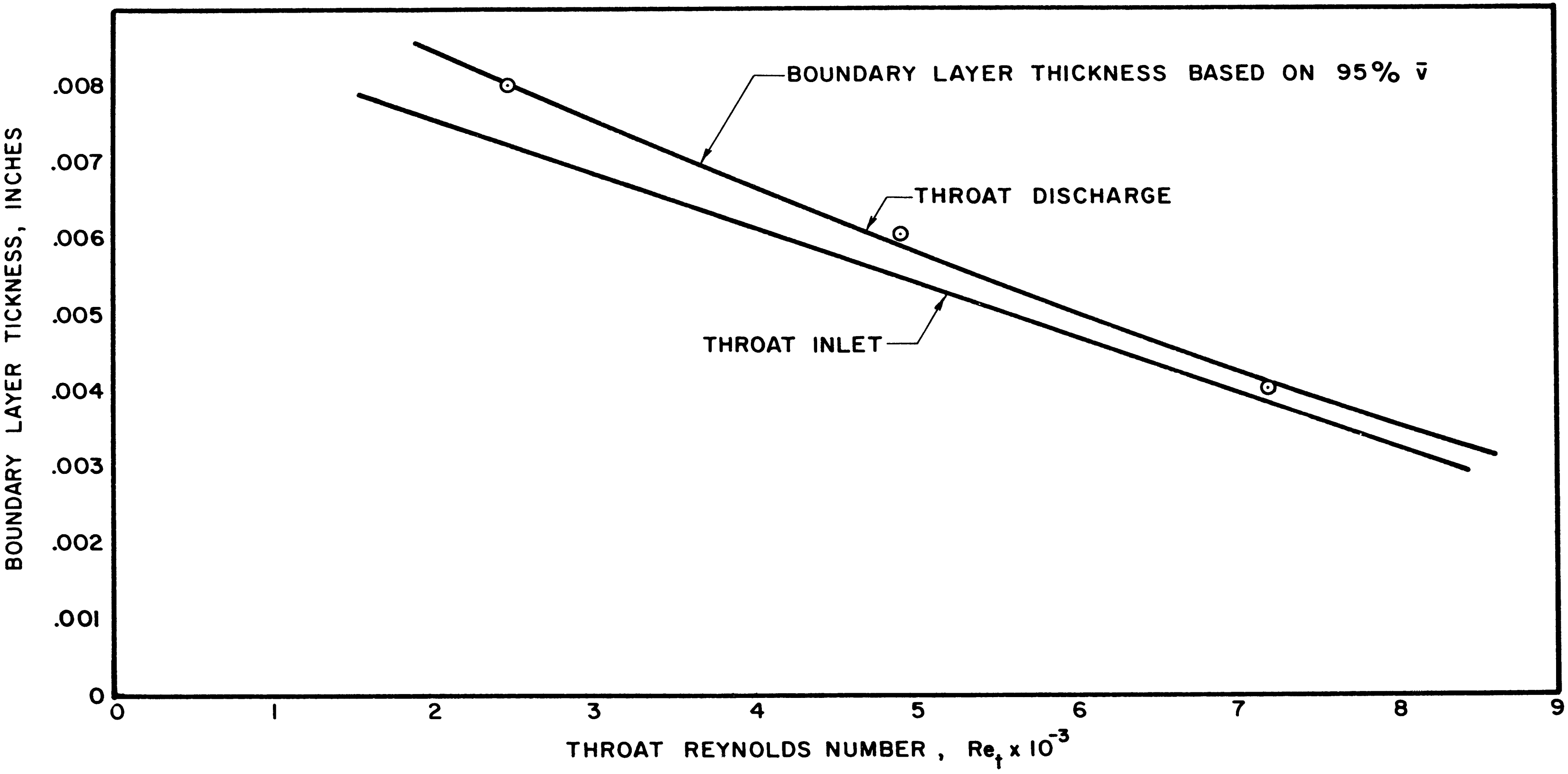

Figure 12. Boundary Layer Thickness vs. (Flow Rate) Throat Reynolds Number

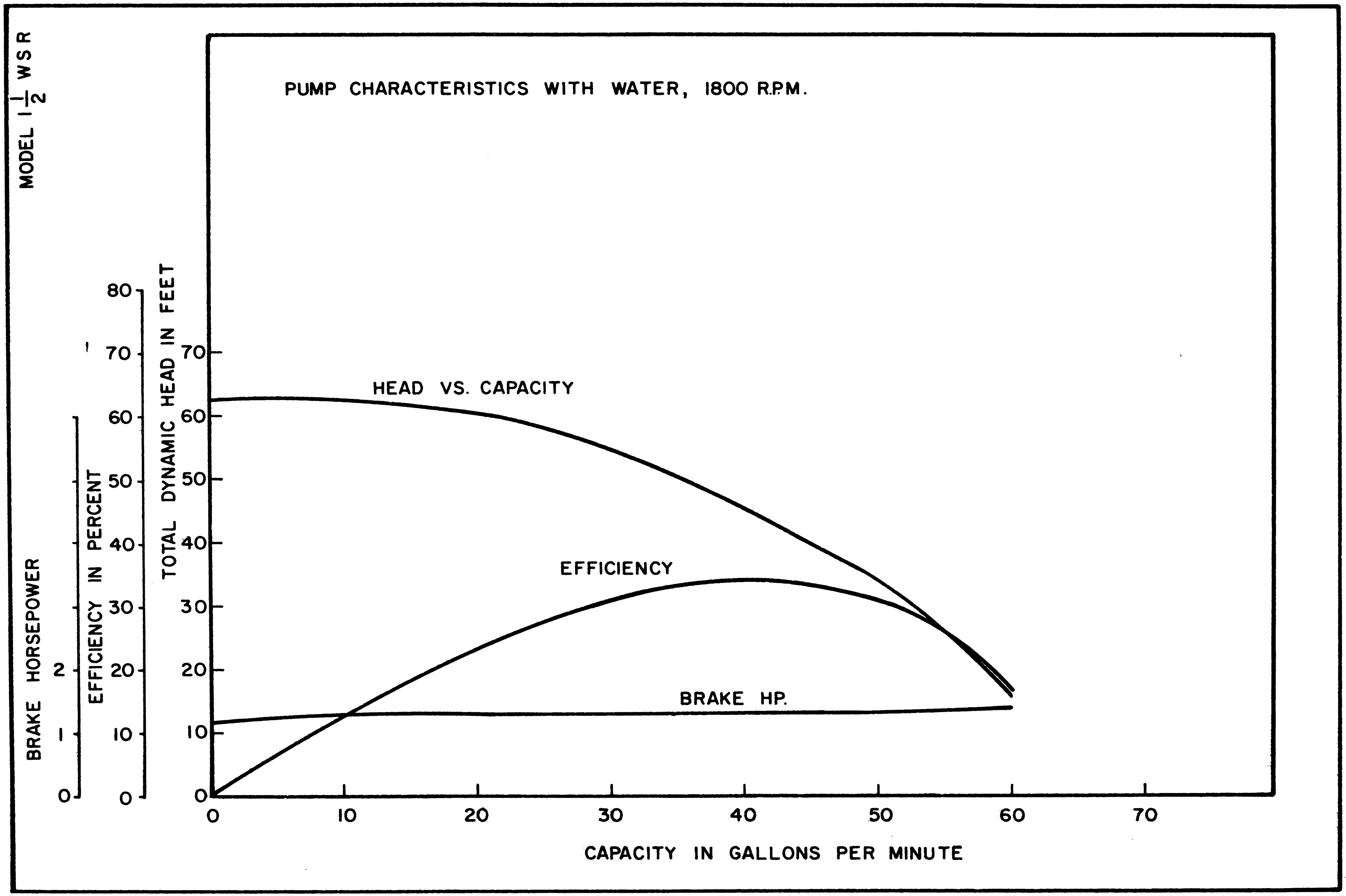

Figure 13. Pump Characteristic with Water, 1800 RPM