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

Progress Report No. 2

F. G. Hammitt

E. M. Brower

Project Supervisor
F. G. Hammitt

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1.0 INTRODUCTION

1.1 Present Contract Objectives

The present contract runs from September 1, 1958 to September 1, 1959. It calls for the design and construction of a closed piping loop, powered by a centrifugal pump and including a cavitating venturi test section. This loop must be capable of obtaining realistic data relative to the effect of cavitation on turbomachinery performance and on material damage, with fluids of technical importance other than water. Of first interest in this respect are the liquid metals because of their present importance in nuclear technology and the wide divergence of applicable physical properties from water.

Initial operation of the loop with water to obtain a calibration and basis for comparison, and also a mechanical shakedown of the equipment, is anticipated within the present contract period. Initial liquid metal tests with mercury may also be possible. Mercury is chosen at this point because of its similarity in essential parameters to the other liquid metals of greater present technical application, because of its own potential and existing technical interest, and because of the greater ease of instrumentation.

1.2 Overall Project Objectives

The overall project objectives, encompassing a period of three to four years, include at least the items listed below (repeated for convenience from reference 1) for the following fluids which are of considerable technical interest: water, mercury, bismuth, sodium and various rocket propellants.

1) Determine those combinations of velocity, theoretical underpressure*, change of pressure with respect to time and axial distance, temperature, and container material which are permissible from the viewpoint of avoiding prohibitive wear with different liquid metals and other applicable fluids which are of interest. Such data will be suitable as a guide toward producing optimum pump designs.

2) Study the nature of wear or pitting as affected by temperature, material, fluid properties, underpressure*, rate of pressure change, and other applicable parameters which may become apparent. Fluid properties of interest include at least surface tension, density, viscosity, latent heat of vaporization, and freedom from impurities, solid and gaseous.

3) Develop methods for determining cavitation effects on pump impellers operating with liquid metals by water-testing of models.

4) Study basic mechanism of cavitation process with water, liquid metals, and other fluids. A wide range of physical properties is thereby afforded.

* Throat pressure which would exist in the absence of cavitation.

1.3 Present Position of Research Project

The present position of the research project is approximately as follows:

1) Except for minor details the design of the facility, with instrumentation suitable for the water and mercury phases of the program has been completed.

2) Procurement of all components of the above facility, with the exception of miscellaneous minor items, has been initiated and in most cases completed. All the major items of the facility will be suitable for high temperature liquid metals with the exception of certain portions of the instrumentation.

3) Fabrication and assembly of the tanks and piping of the loop proper is well underway.

4) A cavitating-venturi test section has been designed and fabricated from plexiglass along with a bracket assembly, so arranged that various test sections of plexiglass or steel, with various flow path configurations, may be easily inserted into the loop. Preliminary calibration of the initial test section, to determine pressure profiles, both axial and radial, as a function of Reynolds' Number and cavitation number using tap water, are presently underway. It is anticipated that these tests will be extended to include preliminary calibration of the sonic equipment. The test section includes 9 wall pressure tap locations as well as the socket for the sonic probe which is embedded in the wall.

1.4 Report Summarization

This report attempts to examine some of the parameters applicable to the cavitation phenomenon in a venturi test section from the viewpoint of both performance and wear effects, and to set up a test program capable of providing the information required to optimize fluid machinery component designs from the viewpoint of cavitation damage effects. In addition data relative to attaining an increased understanding of the basic nature of the cavitation phenomenon in the fluids tested will be obtained.

2.0 INTERRELATIONS OF APPLICABLE CAVITATION PARAMETERS

2.1 Characterization of Cavitation Phenomenon

In order to render observations taken in a test section of fixed geometry and specific fluid flow conditions applicable to cases differing in geometry and in fluid flow parameters, it is necessary to characterize the cavitation in some manner, and to recognize those parameters which may be expected to have a significant effect. It is further necessary to conduct an experimental program designed to determine quantitatively these effects, both upon performance and damage.

A convenient, but somewhat ill-defined sub-division of the various phenomena of interest is in terms of "degree" and "intensity" of cavitation. For the purposes of this report "degree of cavitation" will be understood to describe the geometrical factors involved such as the shape and extent of the cavitating region and of the individual voids if the overall region is so constituted. "Intensity of cavitation" will describe those factors related to the rate of damage of a standard material. Terms of this sort, which cannot be rigorously defined, have been used before to describe the cavitation phenomenon. It will be part of the purpose of this investigation to develop a more precise method of characterizing the phenomenon which can be applied usefully to fluid component designs. From the nature of these generalized terms it is to be expected that various intensities can be achieved at a fixed degree, for example, by suitably adjusting pressure and velocity; and also vice-versa.

2.1.1 Degree of Cavitation

Various independent approaches toward a measurement and characterization of the degree of cavitation are available. It is planned to use several of these so that as full a description as possible will be available.

The most obvious and commonly used method for the description of this phase of the phenomenon is simply visual observation in a transparent test section of the extent of the cavitating region and the apparent void fraction. The precision of this approach can be greatly increased by the use of fast photographic techniques, using either still or motion pictures. Great strides in this direction have been made by previous investigators as R. T. Knapp at California Institute of Technology (references 2 and 3) and it is planned to utilize to some extent the techniques which have been developed in the present investigation. However, the full utilization of the visual approach requires both a transparent test section and fluid. The initial phases of the investigation with water in a plexiglass test section will satisfy these requirements. However, due to the opacity of the fluid the method will be somewhat restricted in the tests which are planned utilizing mercury in plexiglass, and will be inapplicable to liquid metal tests in steel. Hence, it is necessary to develop other approaches which can be correlated with visual observations in water-glass systems and then carried on into systems utilizing liquid metals and metallic test sections.

An alternate approach to measure the extent of the cavitation voids, applicable to all fluids and test section materials, is the use of the different absorption capabilities for electromagnetic radiation of vapor and liquid spaces. Such techniques have been fairly widely used in the past for the measurement of void fractions in boiling heat transfer studies (references 4 - 10). To attain sufficient precision for the measurement of the relatively small void fractions to be encountered in cavitating flow, a rather soft radiation appears desirable, so that the choice lies between X and low-energy gamma radiation. It is planned to use this method of void fraction determination as a measure of degree of cavitation in a particular test section, and correlate the observation with the visual appearance of the phenomenon in a water-plexiglass system. It is planned to utilize photographic techniques to record and render more precise the visual observations.

In addition to the measurement of void fractions as described above, another independent method of observation, applicable to opaque and transparent systems is available. This is through the observation of the sound pattern generated by cavitation in a given geometrical system. The detection of cavitation through sonic techniques has been utilized considerably and with outstanding success in the past (references 11 - 16). It is hoped that a recording of the intensity versus frequency pattern generated (using a piezoelectric crystal feeding an oscillograph through suitable amplification) will be characteristic of the degree of cavitation (and perhaps also the intensity) at least in a given test geometry. It is planned to utilize and develop this technique to the fullest, since it is equally applicable to the water-plexiglass, mercury-plexiglass, or high-temperature liquid-metal-steel systems. Along with the use of electromagnetic radiation absorption, it will be used as a bridge between the tests which can be visually observed and those which cannot. Since the quantities measured by these two techniques (void fraction and sound pattern) are at first glance quite unrelated, it is hoped that the two techniques along with conventional pressure-velocity measurements will give a fairly comprehensive picture of the cavitation-degree in all cases.

In addition to all the above, there will be the conventional measurements of pressure and velocity. Thus, at least approximate knowledge of pressure and velocity at all points as a function of test section geometry, Reynolds' Number, and cavitation number will be available. From these measurements another independent characterization of degree of cavitation is gained in a given test geometry. The parameter in this connection, which might be expected to characterize the degree, is the cavitation number referred to the mean throat velocity and to the difference between the minimum throat pressure which would be attained under the given flow conditions in the absence of cavitation and the vapor pressure.

To summarize, it is hoped that the degree of cavitation can be characterized in terms of some or all of the following parameters, which will be measured and utilized in this respect:

1) Throat-velocity non-cavitating minimum suppression head cavitation number.

2) Void fraction as determined through radioactive absorption measurements.

3) Void fraction and shape and extent of void area as visually observed and photographed.

4) Sound pattern (intensity versus frequency) generated by cavitation.

With the exception of 3) above, they are applicable to all tests.

2.1.2 Intensity of Cavitation

As used in this report, intensity of cavitation refers to those characteristics of the phenomenon which affect the rate and nature of wear of a standard test specimen. It is strongly presumed, as a result of theoretical and experimental evidence (references 2 and 17 - 20) that these parameters include at least the following:

1) Fluid velocity field

2) Pressure field

3) Surface tension of fluid

4) Bulk modulus of fluid

5) Quantity of vapor released for a given pressure depression (reference 21 and 22)

6) Chemical reaction potential between fluid and standard test material

7) Viscosity of fluid

8) Purity of fluid with respect to solid and particularly entrained gaseous impurities.

It is believed that the above list covers the major parameters of interest. However, it is obvious from a consideration of the possible mechanisms of the phenomenon that almost all the physical fluid properties may be involved to some extent. It is also obvious that most or all of the above will also affect the size and shape of "voids" created, ie: the degree of cavitation.

The previous discussion has referred the intensity of cavitation to the wear of a standard sample so that the physical properties of the material are not involved. However, it is then necessary to consider a second term, as perhaps "cavitation damage index", which would describe the ratio of damage behavior between a cavitating fluid and any material of interest to that between the same fluid and a standard material. This ratio would be a function of the physical properties of the material including at least:

1) Strength, hardness, and ductility properties at the test temperature.

2) Chemical potentials between fluid and test material at test temperature.

If one adopts the operational definition of intensity of cavitation in terms of the wear of a standard sample, there is the problem of measuring and recording the wear in standard terms. Various possibilities could be considered as the following:

1) Removal of material per unit surface area per unit time.

2) Formation of pits per unit surface area per unit time.

3) Formation of pits of given mean volume per unit surface area per unit time.

Since typical cavitation wear is in the form of pits, the measurement of either the quantity of material removed alone or the number of pits alone would not suffice to characterize the wear from the viewpoint of incapacitating the component. Hence, it appears that the third approach listed above is required.

The measurement of wear, so defined, would be greatly facilitated if a non-destructive technique, such as the taking of some form of mold or cast of the inside of the cavitating-venturi test section could be devised. Also it may be that X-ray or photographic techniques (in the case of the plexiglass test sections) may be useful. The attempted development of such a technique is one of the project objectives.

Some assistance in the measurement of wear may be gained from the use of an irradiated test section with suitable counting instrumentation situated along the loop piping. Such a technique would clearly indicate the initiation of wear and would be most useful if, for example, a threshold in either time or fluid velocity were found in that many disassemblies would be avoided. However, such a method could not distinguish the type (depth of pits, etc.) of wear and hence could not adequately replace the pit measurement techniques described above. Initial studies to determine the feasibility of the irradiated test section approach have been undertaken although results are not yet forthcoming.

It is anticipated that for a given fluid and test sample material combination, with a given geometrical configuration and degree of cavitation, it should be possible to correlate the cavitation intensity, as defined in terms of wear, with the fluid-flow parameters. The most likely such correlation, based on obvious theoretical considerations and also on experimental evidence (references 2, 3, 20) is in terms of ρV^n. If cavitation damage is simply a function of local static pressure build-up, it would be expected that the exponent would be 2. However, the experimental results of reference 2 indicate an exponent of 6. It is hoped that the present research may indicate the possibility of describing cavitation intensity (or wear) in terms of such a parameter. Basically, most of the other fluid physical properties and test conditions must somehow influence the result and it may be that more comprehensive parameters can be evolved as a result of this study.

In addition to a correlation with the fluid flow parameters, it may be that cavitation intensity, defined in terms of wear, can be correlated with the sonic pattern generated by the particular intensity, assuming the degree of cavitation and the test geometry is fixed. It will be part of the basic objectives of this study to investigate this possibility. It might be expected, for example, that the sound intensity would be related to wear and that such a relation might carry-over for different fluids since the sound intensity and local pressure generated by bubble collapse are closely related.

2.2 Specific Anticipated Effects of Applicable Parameters On Degree Of Cavitation

2.2.1 Review of Ideal Cavitation Mechanism

According to the most simplified ideal concepts, if, at any point in a flowing system, the pressure is reduced to the vapor pressure of the liquid at the existing temperature, a vapor pocket will form at that point. The pressure within the vapor pocket will be the vapor pressure of the fluid. This vapor pocket will grow if carried into a region where, in the absence of vapor, the pressure would be still lower and will collapse (vapor condense) if carried into a region of higher pressure. Pressures lower than the vapor pressure cannot be attained because saturated vapor pockets will appear at this point.

In addition, the pressure differentials along a given test section with a given orientation are directly proportional to ρV^2 of the mean stream in the absence of cavitation. In other words, the non-cavitation pressure coefficient of a body is simply a function of the shape of the body and its orientation to the direction of the unperturbed velocity. Under the assumption that cavitation occurs instantly if the pressure is reduced at any point to the vapor pressure, the cavitation number of the body is also uniquely determined by body shape and orientation. The degree of cavitation would then be uniquely determined by these factors, the difference between static pressure and vapor pressure at any reference point.

If the assumptions discussed above were strictly realized, there would be no effect upon the degree of cavitation due to the influence of the physical size of the specimen, the fluid tested (other than through vapor pressure), the purity of the fluid, the magnitude of the velocity, or the fluid temperature (again, other than through the vapor pressure effect). However, a deeper consideration of the phenomenon and previous experimental measurements (references 3 and 23 - 25) indicate that such effects exist and may be significant.

2.2.2 Anticipated Deviations from the Ideal Case

Deviations from the ideal case seem likely because of the following considerations.

It is necessary to expose a finite portion of the fluid for a finite time to a pressure below the vapor pressure (in the absence of dissolved or entrained gases) to form a vapor pocket. If the time of exposure is long, the required underpressure to form a pocket increases very rapidly with the purity of the fluid, particularly with respect to dissolved gases, at least beyond a certain rather high degree of purity. (Reference 26). On the other hand, if there are dissolved or entrained gases in quantity, presumably the formation of macroscopic voids would be a function of the gas partial pressure rather than the vapor pressure. It is apparently the usual experience that cavitation in ordinary water occurs when the local pressure is reduced approximately to the vapor pressure. Our own experience in preliminary tests with a venturi test section using tap water (probably with high air content) has been that substantial cavitation occurred at pressures slightly in excess of the vapor pressure. Reference 27 and 28 cites measurements with de-aereated sea water where pressures significantly less than the vapor pressure were required to initiate cavitation. Reference 26 mentions the attainment of negative pressures of several hundred psi in thoroughly de-aereated water. In view of the above it seems likely that the initiation of a void is a function of magnitude of underpressure available and time of exposure to this underpressure. The required underpressure presumably depends upon the physical properties of the fluid, primarily surface tension and purity. In general, it is not expected that this dependence would be such that the degree of cavitation would be independent of velocity. Also density and viscosity should influence the rate of growth of bubbles beyond the microscopic stage. It then appears, since a fixed underpressure is required for given conditions, that the degree of cavitation will be a function of absolute velocity magnitude and physical size of sample, (references 3 and 23 - 25). These factors are usually characterized by the term "scale effect".

A second major variation from the simplified ideal model previously discussed lies in the fact that the fluid velocity across the test section is not uniform and hence all portions of the fluid are not exposed to the same pressure-time regime. Presuming that a finite boundary layer exists, some portions of the fluid must remain in the test section for appreciable periods of time regardless of the mean stream velocity and the formation of voids in substantial number should occur even at the highest mean stream velocities. The thickness of the boundary layer decreases as the throat diameter Reynolds' Number increases, increases with axial distance from the beginning of the throat, and is naturally influenced by the configuration of the nozzle leading into the throat. From the above considerations it would appear that an increase in mean stream velocity should decrease the mean "dwell time" of fluid in the low pressure region per se because the boundary layer thickness is decreased. Also, if the diameter of the test section throat is increased, the Reynolds' Number increases at constant mean stream velocity and the boundary layer thickness is reduced in proportion to the diameter. Then the mean "dwell time" (averaged between the boundary layer and free stream) is reduced. On the other hand, if the throat length is increased in proportion to the diameter to maintain constant L/D, the boundary layer thickness toward the end of the throat is increased because of the additional length. This tends to increase the mean "dwell time".

If a change in fluid is considered, even though mean velocity and dimensions are held constant, the Reynolds' Number is changed (increased by a factor of about 10 if the fluid is changed from water to mercury and other parameters are held constant) and hence the boundary layer thickness and mean "dwell time" are changed.

To summarize the previous discussion it appears that:

1) Increased velocity in the same test section motivates contradictory trends and its effect is uncertain.

2) Increase of size for a geometrically similar test section also motivates contradictory trends in that proportionate boundary layer thickness is reduced by increased diameter Reynolds' Number and increased by increased test section length.

3) Change to a fluid providing higher Reynolds' Number at a given velocity in a given test section should increase the cavitation number by decreasing boundary layer thickness and hence decreasing the mean (average for boundary layer and free stream) "dwell time" (assuming effect of different surface tension, viscosity, and other parameters is negligible).

From all the above considerations, a general delineation of all those effects associated with "scale effects" seems unlikely, although the maximum effort to measure the velocity and pressure profiles existing within the test section will be made. To obtain meaningful results it seems necessary to perform the experimental work over a range of physical dimensions and velocities which are typical of actual fluid machinery components with the fluids of interest. It may be demonstrated that within this range some or all of the various possible scale effect mechanisms previously discussed will be insignificant and that the degree of cavitation can adequately be described in terms of the cavitation number. However, at present this remains to be demonstrated.

2.3 Specific Anticipated Effects of Applicable Parameters on Intensity of Cavitation

The list of properties anticipated to have a significant effect upon cavitation intensity, defined in relation to wear has been previously given. These involve physical properties of both the fluid and the container as well as the flow parameters.

The most important of the fluid physical properties in this connection appear to be:

1) Density - the force developed on the container seems certainly a function of (probably proportional to) the density.

2) Bulk Modulus - an infinite bulk modulus would imply infinite forces from a collapsing bubble.

3) Surface Tension - appears to be the controlling parameter in the initiation of a microscopic bubble and in its final collapse.

4) Viscosity - significantly affects the rate of growth and collapse after a substantial size has been attained.

5) Purity of Fluid -

   a) Entrained gas either as microscopic bubbles in liquid or in crevices on container surface or on solid impurities must serve as nuclei for bubble formation. Otherwise cavitation at pressures in the vicinity of the vapor pressure could not occur in most fluids.

   b) Large quantities of gas, either entrained or in solution, can cause apparent cavitation at pressures above the vapor pressure. Also, the violence of collapse will be reduced by the presence of the non-condensibles.

6) Chemical potentials between fluid and solid or gaseous impurities and container.

In addition, it is presumed that the various factors discussed in relation to the influence of scale effect on degree of cavitation will also have application. For a given cavitation number based upon the non-cavitating minimum pressure and the vapor pressure, increased velocity means increased underpressure and hence driving force on the growth and collapse of bubbles. On the other hand, it also means decreased "dwell time" if the same test section is considered. Since the interrelations of the various parameters are not fully understood, whether or not these effects would in general cancel each other is not known.

3.0 REQUIRED TEST PROGRAM

As a result of the considerations developed in the previous section, it is possible to plan a test program to provide the information required to meet the overall project objectives (section 1.2). To the present the detailed planning encompasses only the water and mercury phases of the overall research program. It is expected that experience gained with this portion of the work will be most desirable in guiding the detailed planning of subsequent phases. The equipment, of course, has been designed to be of maximum utility in all phases. The anticipated overall scope of the experimental work has been discussed before.

3.1 Water Test Phases

Basically two test sections have been designed and the first fabricated of plexiglass. The first test section is shown in figure 1. They are designed as cavitating venturis with a cylindrical throat of length equal to approximately five times throat diameter. Nozzle and diffuser are essentially symmetrical with an included angle of approximately 6° in the vicinity of the throat. To reduce the required length and hence boundary layer thickness, the nozzle is not carried all the way to pipe diameter at this angle but is designed with a rounded approach in that region where the kinetic head is essentially insignificant. The test sections will be geometrically similar in the vicinity of the throat. The model which has been fabricated has a throat diameter of approximately 9/32 inches; the throat diameter of the second will be approximately 1/2 inch. As shown in figure 1, the present model has been equipped with 7 pressure taps: three evenly spaced along the throat length and two each in the adjacent sections of nozzle and diffuser, covering those regions where the kinetic head is significant. In addition, a traversing impact pressure probe can be fitted into any of the tap holes.

A socket for a 1/8 inch x 9 inch stainless steel rod is provided. This is to be attached to a barium-titenate crystal utilized as a sonic pick-up. The output will be fed through a linear amplifier into an oscilloscope. The extended rod construction is required to provide an apparatus suitable for high-temperature liquid metal testing since the temperature limitation of the crystal is restrictive.

It is planned to utilize the two test sections as a check on the existance and significance of scale effects with velocities and dimensions roughly in the range of interest. The centrifugal pump is sized to provide a maximum velocity of about 100 feet per second with water or sodium in the larger test section and somewhat more in the smaller test section. Maximum velocity with heavy liquid metals, such as mercury, in the large test section is approximately 50 feet per second. The smaller section was fabricated first to allow preliminary testing with tap water before the loop assembly should be complete.

In addition to the testing of the venturis it is planned to include a standard cavitation-performance test on the loop single-stage, centrifugal pump with water as a reference, and then with the various other test fluids. This will provide a reliable comparison at least of pump performance effects in an identical geometry at fixed suction specific speeds.

The basic sub-divisions of the water and mercury test programs as presently forseen follow, along with their anticipated results. The first sub-division has been substantially completed.

3.1.1 Calibration of Small Plexiglass Section with Tap Water

a) Detailed measurement of wall pressures as a function of flow rate (Reynolds' Number) in the absence of cavitation and with varying cavitation numbers (based on throat velocity and difference between minimum pressure and vapor pressure without cavitation).

b) Measurement of velocity profile across the tube in the throat area to determine the boundary layer thickness as a function of Reynolds' Number.

c) Measurement and record of sonic pattern of cavitation.

Anticipated Results

a) Knowledge of non-dimensional pressure and velocity as a function of axial and radial position for different mean velocities (ie: Reynolds' Number) at different cavitation numbers (previously defined). This will allow an estimate of the time-pressure regimes experienced by different portions of the fluid in this particular test section, and will assist in an understanding of future loop tests with different fluids wherin such comprehensive instrumentation will not be possible. Similar tests, prior to loop testing, are not possible for the larger test section due to the limitations on tap water supply. Consequently, it is presently planned to proceed through at least the initial phases of the test program with the smaller section since information so gained may alter the design to be used for the larger.

b) Sketch or photograph of sonic intensity versus frequency for the tests described above. It is not planned to carry these sonic measurements for the tap water tests beyond the stage necessary for the development of the technique since the high air content of the tap water may make results inapplicable. For the same reason the use of photographic techniques and gamma ray measurements will be postponed until the loop tests.

3.1.2 Calibration of Small Test Section in Pump Loop with Water

A method will be provided in the pump loop equipment for the de-aereation of the water so that the effect of this variable can be observed.

a) Using de-aereated water certain of the tap water tests will be repeated to ascertain that results are reliable. If significant variations are noted, the tests so involved will be repeated.

b) An attempt to estimate the void fraction obtained under various flow conditions using fast photographic and gamma ray or X-ray absorption techniques will be made.
c) The sonic pattern will be determined for the various flow conditions

Anticipated Results
a) Corroboration of tap water results in pump loop.
b) Indication of degree of cavitation through flow parameters, sonic pattern, and void fraction estimation.

3.1.3 Water Calibration of Loop Centrifugal Pump

Standard performance cavitation tests will be conducted on the centrifugal pump situated as it is in the loop. Runs will be made at constant speed and net positive suction head will be decreased until a decrease in the developed head is noted. In addition the sonic instrumentation will be used to determine whether an effect is noticeable in this manner before the performance change becomes evident. The effect of water de-aereation will also be noted. It is felt that the information so gathered will be of great interest when compared with effects with mercury and other test fluids under conditions of identical geometry, suppression head, pump speed, and flow rate. (ie: constant suction specific speed.)

3.1.4 Damage Tests - Water on Plexiglass, Small Test Section

At this point in the program several alternate courses are possible:

1) Preliminary tests with mercury to establish feasibility of operation.
2) Repeating of previous tests with large test section to investigate possible scale effects.
3) Water damage tests with small plexiglass test section for eventual comparison with mercury damage effects in same or identical test section.

To push as rapidly as possible toward the major project objectives it is felt that the last alternative, the conducting of damage tests in the water-plexiglass system, is the most desirable at this time. Testing with mercury, although desirable to establish the mechanical feasibility of the system, would involve considerable lost time since eventual water damage tests would be necessary, and hence a thorough purging of the system, to eliminate mercury vapor hazards, would be necessary to return to water testing. In addition, it is beleived that valuable techniques on wear testing methods can be developed most easily with water for eventual application with mercury and other fluids. The damage testing, rather than investigation of scale effects, is chosen for immediate application because it seems more in line with the basic program objectives. The decision as to whether to investigate scale effect with water prior to initiation of mercury testing, or to carry through into mercury with the small test section and then eventually repeat using the large test section with both fluids will be reserved until later when experience gained in the preceding phases can be used to influence the decision.

The procedure for the water-plexiglass wear tests as presently visualized will include the following steps:

1) Run various flow rates at a fixed degree of cavitation,

defined according to any of the methods previously discussed. This can be accomplished by suitable adjustment of the valves and/or the pump speed. Use of vacuums on the sump tank will be necessary to obtain values of head and flow similar to those to be obtained in the mercury tests.

2) Repeat for various degrees of cavitation. (Including zero cavitation where damage will be a result of erosion only).

3) Determine damage for each test by estimating the size and number of pits per unit area. It would be most desirable if a method which did not entail destruction of the test section could be used. Possibilities which come to mind include:

   a. Plaster or rubber mold impression of the inside of the test section.

   b. X-ray or gamma ray pictures.

   c. Use of irradiated test section. This possibility with a plexiglass test section has not been investigated as yet.

Anticipated Results

The anticipated results of these tests will be measurements of the quantity and character of wear versus cavitation degree and mean stream velocity in this particular plexiglass test section. Perhaps this data could form the basis for an intensity scale as previously discussed. In any case it will afford information on the effect of absolute velocity as a variable with a given fluid and also the effect of a change of fluid (from water to mercury) with all other variables held constant.

3.1.5 Mercury Performance Tests in Small Plexiglass Test Section

At this particular point it is conceivable that the program should repeat the water tests with the larger test section, or that it should commence mercury testing with the small test section (or an identical reproduction if substantial damage has been incurred). Tentatively, it appears at present that more valuable results would be attained if mercury testing were initiated at this point. As previously stated, the final decision in this matter will be reserved until more experience has been gained in the preliminary stages.

Assuming, for the present, that the decision is to proceed with mercury, the loop equipment used for the water tests will be fully applicable except that the manometer arrangement will require revision. It is presently planned to use a common manifold system equipped with individual valves in each line, and a calibrated pressure gage and also manometer attached to the manifold. (Figure 2). It will be possible to valve either out of the system. The manometer will be used to measure pressures of approximately plus or minus an atmosphere.

This will be sufficient to cover all pressures requiring high precision including those in the cavitating area. The Bourdon gage will be used to indicate the pressure before valving the manometer into the system to determine whether use of the manometer is safe for a particular measurement. The gage alone will be used for high pressures where its precision will be adequate. It is expected that the experience gained in the measurement of mercury pressures will be applicable to other fluids and that a substantial portion of the instrumentation equipment can be converted.

The tests to be conducted with mercury will parallel the the water tests which were previously described, with the exception that the detailed velocity and pressure profile measurements will be at least simplified. It will be assumed unless tests show contradictory evidence that these are only a function of Reynolds' Number, and that the Reynolds' Number is sufficiently high so that they are quite insensitive even to this parameter. The mercury tests will include cavitation performance tests on the pump as previously described for water so that a direct comparison will be afforded. They will also include damage tests on the plexiglass test section under flow conditions identical to those used with water. Hence a direct comparison of cavitation "intensity" or damage rate between water and mercury over a range of cavitation degrees will result.

After completion of the plexiglass-mercury tests, a steel test section of identical geometry will be substituted. This test section will be operated under flow conditions identical to those used with the plexiglass unit with both water and mercury so that a comparison between water and mercury on a material of structural interest will be gained as well as comparison with the original plexiglass section which may be a handy reference, in that significant damage should be created more rapidly. The use of plexiglass with mercury has the advantage in addition to affording a comparison between water and mercury of visualization of the interface between fluid and container where some voids may be detected and allow correlation with the sonic pattern and gamma ray void measurements which must be relied upon for measurement of degree of cavitation in opaque test sections.

3.1.6 Program Following Initial Mercury Damage Tests

The test program outlined in the preceding paragraphs carries through the presently forseen work with water and mercury within the scope of the major project objectives. This will result in the following broad groupings of significant data. Numerous significant detailed by-products will also result.

1) Cavitation intensity (or damage rates) caused by water and mercury at varying degrees of cavitation and varying mean stream velocity on a standard (plexiglass)

test section, wherein the pressure and velocity profiles are known in detail.

2) Cavitation intensity comparison with mercury on a standard material (plexiglass) and on structural materials of interest (stainless steel or steel) in the same test section as (1) above.

3) Comparison of effects upon head-flow relations of water and mercury in a centrifugal pump under identical conditions of geometry and flow parameters.

It is felt that data of the type listed above, where a fluid of interest replaces mercury, will serve to allow the optimum design of fluid machinery handling that fluid, from the viewpoint of cavitation damage and performance effects. Mercury was selected as a preliminary fluid since it is very similar in its characteristics to the liquid metals of more technical importance in the nuclear reactor field, particularly the lead and bismuth combinations, and can be handled and instrumented at low temperature with a minimum of difficulty.

If it can be ascertained as a result of the above data that a given fluid will cause prohibitive damage or a prohibitive decrease in performance under particular conditions of relative velocity, temperature, container material, and theoretical underpressure in the absence of cavitation, for example, but will be satisfactory at somewhat more moderate conditions of one or more of the above parameters, then it will be possible to design, with some confidence, a unit of more or less optimum size and weight. Such results will be applicable to turbomachines for example since the significant parameters can be approximated if the blading design is known. (Reference 29). The importance, cost-wise and weight-wise, of increased aggressiveness from the viewpoint of cavitation in turbomachinery was reviewed by one of the present authors in reference 30.

Consequently it is felt that following the initial water and mercury test program outlined, the research project should proceed to similar testing of fluids of technical interest at the temperatures of interest (because of the effect upon the strength and chemical characteristics of temperature on the container material). Such fluids include:

1) Bismuth or lead-bismuth alloy up to 1000 F.

2) Sodium or NaK up to 1200 F

3) Rocket propellants at ambient or low temperature as fuming nitric acid, oxygen, JP-4, etc.

4.0 CONCLUSIONS

The broad outlines of the research project which involve the determination of the damage and performance effects of cavitation in fluids of major technical interest other than water in a flowing system which can be readily related to fluid machinery components, indicate continued activity, at approximately present levels, over a period of three to four years. However, it is anticipated that the work to be completed within the initial project period of one year will include the construction of the facility, with the exception of some items of specialized instrumentation required for the various test fluids, and the completion of a considerable portion of the initial phases of the research program.

At present, design and fabrication of the major portions of the facility is nearing completion and initial testing of individual components has commenced. Assembly of the facility remains before loop tests can be initiated. This report includes a detailed description of the proposed research operation with water and mercury prior to the use of liquid metals of greater technical application and at high temperature. It is believed that most of the anticipated work with water can be completed within the present project period and perhaps a portion of the work with mercury.

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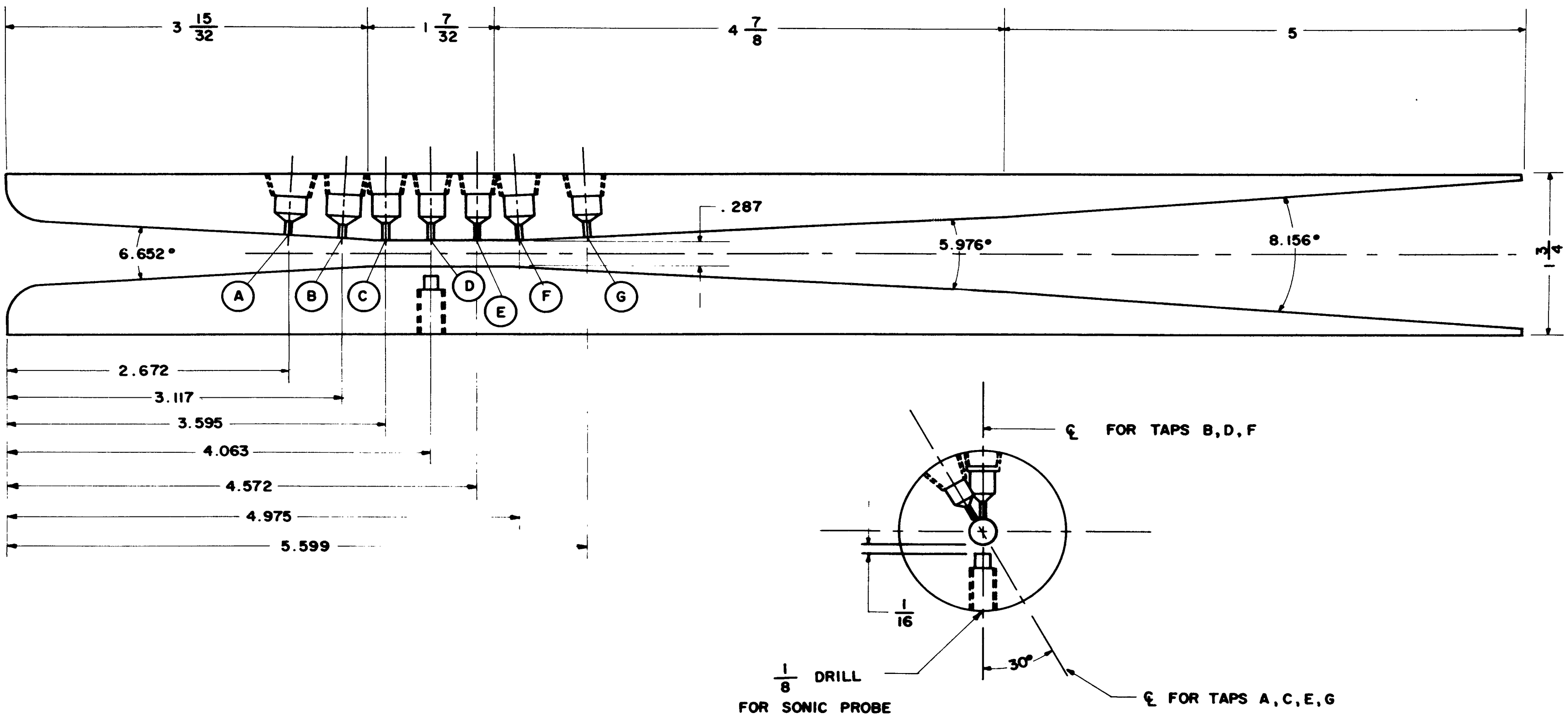

FIG. I CAVITATING VENTURI TEST SECTION NO. I

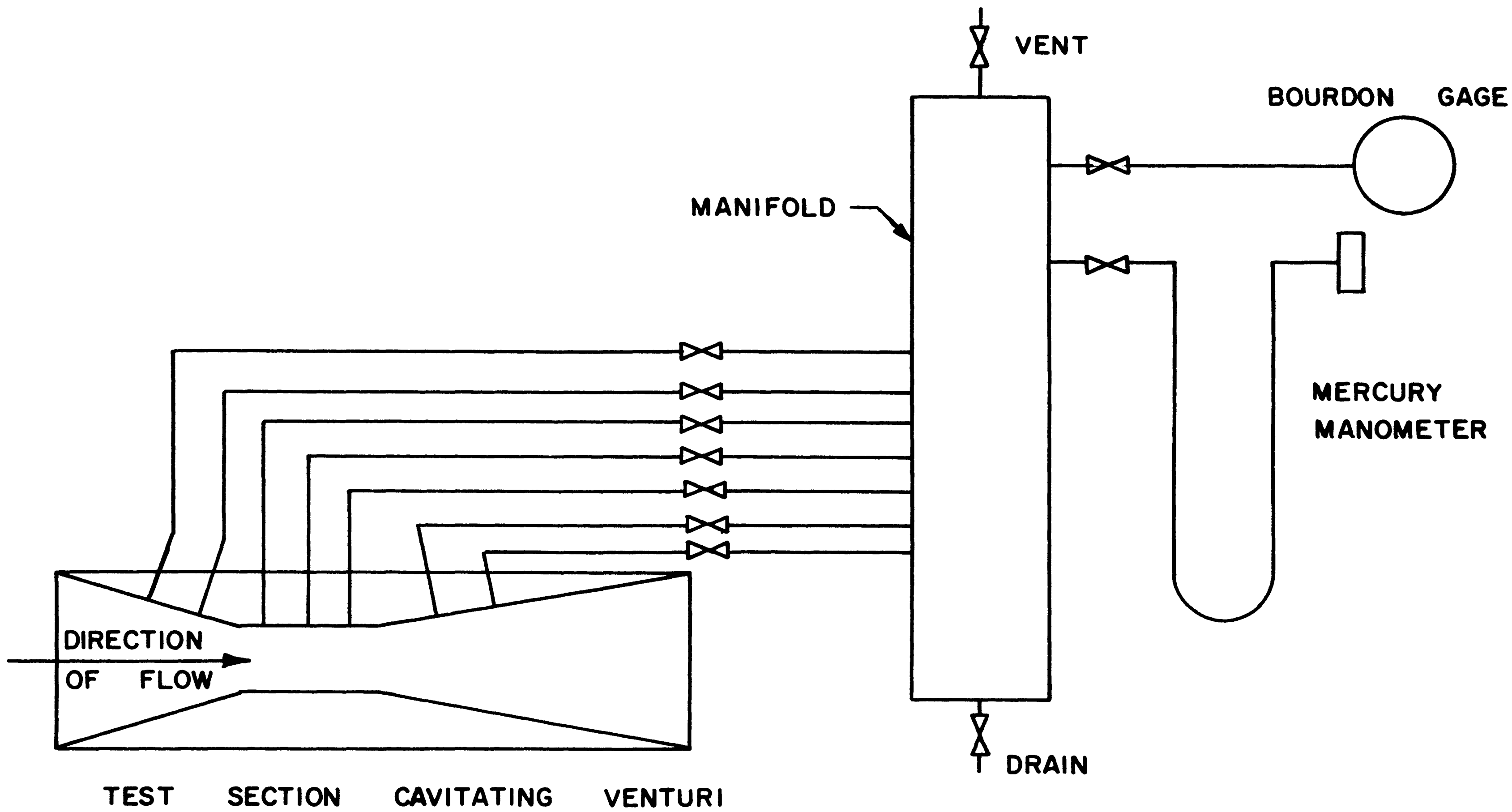

Figure 2. Schematic of Pressure Instrumentation for Water Flow.