THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING

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Technical Report No. 1

# CAVITATION-EROSION CHARACTERISTICS OF SELECTED BEARING MATERIALS IN MERCURY

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# ABSTRACT

Cavitation studies of selected bearing materials have been conducted in mercury at 500°F and 70°F and in water at 70°F utilizing an ultrasonic vibratory unit and high-temperature cavitation facility. Test specimens of various materials were attached to the ultrasonic transducer and vibrated at a frequency of $\sim$20 Kc./sec. with a double amplitude of $\sim$ 2 mils. The test materials that were subjected to the cavitation environment were tool steels BG-42 ($R_c$[*] = 64), BG-42 ($R_c$ = 53), BG-42 ($R_c$ = 47), and Blue Chip Tool Steel. In addition refractory alloys Mo-1/2Ti and Cb-1Zr(A) and also single-crystal tungsten and two grades of graphitar were tested. The effectiveness of teflon as a protective coating against cavitation-erosion attack was also investigated.

The BG-42 ($R_c$ = 64) and Blue Chip Tool Steel were the most resistant in this cavitation test on the basis of mean depth of penetration (MDP)[**] in mercury at 500°F. The average MDP rate (MDPR) for both of these materials was 0.04 mils/hour. The single-crystal tungsten, BG-42 ($R_c$ = 53), and BG-42 ($R_c$ = 47) ranked third, fourth, and fifth, respectively, with average MDPR = 0.08, 0.10, and 0.19 mils/hour, respectively. The remaining materials tested (Mo-1/2Ti, Cb-1Zr(A), and

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[*] $R_c$ indicates the hardness value on the Rockwell-C scale.

[**] Volume loss per unit area of cavitated surface.

two grades of graphitar) were very much less resistant with the refractories exhibiting average MDPR on the order of 10X that of the three BG-42 specimens, Blue Chip Tool Steel, and single-crystal tungsten. The graphitars were on the order of 100X less resistant than the tool steels and single-crystal tungsten.

The use of teflon as a protective coating against cavitation-erosion attack in mercury at 350°F was not successful in that it was very quickly removed from the specimen face by the cavitation.

Preliminary qualitative correlations of the cavitation data with the hardness data indicate that for these studies hardness alone is a good indicator of cavitation resistance.

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# CHAPTER I

# INTRODUCTION

## A. Importance of Cavitation Studies

Cavitation can be described as a hydrodynamic phenomenon which relates to the formation and collapse of vapor bubbles in a liquid. In general terms, these bubbles form in regions where the local pressure is reduced below the vapor pressure at that temperature and start to collapse as soon as the local pressure exceeds the vapor pressure. The bubble collapse can be considered as giving rise either to a shock wave which is propagated through the fluid, or to a small high-velocity liquid jet, in either case terminating at the wall of the fluid container. The effects produced as a consequence of cavitation are two-fold. First, for flow processes, it generally decreases the transferable energy, and hence causes a loss in efficiency. Secondly, destruction (damage) of the material may take place at the point at which the shock wave or liquid jet terminates. Thus, it becomes necessary to investigate carefully those conditions resulting in cavitation and the damage suffered by various materials.

Since the cavitation damage process is apparently very closely related to damage from droplet or particle impingement or conventional erosion,* the damage data so obtained for various structural materials is also to some extent applicable to the resistance of these materials to these other forms of attack, so that the fields of droplet erosion in wet vapor streams (as in turbines or other two-phase flow passages), rain erosion of high-speed aircraft, micrometeorite bombardment of space vehicles, etc., are involved.

The successful pumping and handling of high-temperature liquid metals, wherein cavitation itself is a problem, is of considerable importance in the present and future space program, particularly from the viewpoint of power generation using nuclear heat sources and liquid-metal Rankine cycle power-conversion equipment. As has been recently demonstrated, damaging cavitation attack can occur in bearings,[2] close-clearance passages,[3] etc., as well as pumps.[4,5] Recent theoretical studies[6] emphasize, in addition, a form of microcavitation that may also occur in many high-performance bearing applications and even in components such as gear teeth, so that the pitting which is often found in such units may well be a result of a form of cavitation. The same problems are, of course, also important in the conventional nuclear power plant program,[3] which includes several existing and projected reactor systems using liquid metals as the coolant.

In the SNAP application the minimization of size and weight and the maximization of temperature are of over-riding importance, so that

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*Reference 1 includes many papers on the relations between these various forms of attack including one by one of the present authors. Also ASTM Committee G-2, of which one of the authors is the present vice-chairman, has recently been formed to attempt to relate these various phenomena and form applicable test standards.

the fluid-handling equipment must be designed to operate under conditions approaching cavitation or actually in a cavitating regime. Hence, it becomes necessary to know realistically under what conditions cavitation can be anticipated, and the quantity and quality of damage to be expected for a given degree of cavitation, since it may not be possible or desirable to avoid the cavitating regime entirely by over-conservative design, as has been the practice for conventional applications.

## B. Importance and Significance of Accelerated Cavitation Studies

In a prototype system, the damage due to cavitation appears usually only after fairly lengthy operation under design conditions. Hence, it is clear that if a systematic study is to be made, involving a variety of materials and numerous plant conditions, it will be necessary to expend large amounts of time and money. An alternate approach, sacrificing direct applicability to some extent in the interests of economy, is to accelerate the cavitation losses by employing any one of several laboratory techniques which have been developed for this purpose. One commonly-used method which is also employed in our own laboratory is a flowing tunnel system utilizing a venturi test section and a centrifugal pump to circulate the test fluid around a closed loop. This system has been described elsewhere.[7] The venturi is reasonably similar to actual flow systems, but at the same time damage occurs only rather slowly. As an alternative to a flowing system, various acoustic techniques have been used by researchers in the past to bring about accelerated cavitation.[8,9,10,11] Presently, accelerated cavitation studies are conventionally conducted through the use of polarized magnetostrictive or polycrystalline piezoelectric materials. Various materials exhibit either the piezoelectric effect or the phenomenon of magnetostriction. Both effects are reversible. The utilization of such acoustic techniques appears to allow economical screening of a wide variety of materials in various fluids under ambient and elevated temperatures. The method has been widely used in the past for cavitation studies in water and other ambient temperature fluids, but only until very recently have tests been conducted in high-temperature liquid metals as sodium[3,12,13] and lead-bismuth alloy[14,15] and, of course, the present tests in mercury.

In the past, the utility of acoustic cavitation damage results has been limited because no direct correlation with cavitation in a flowing system has been available. However, if such a correlation could be formulated, it might be possible to substitute relatively economical acoustic testing for tests in a tunnel facility. Our own laboratory has conducted cavitation tests in both water and mercury in venturi facilities[16,17,18] for the past several years and has accumulated much useful data over this period of time. It is expected that the accelerated cavitation data obtained with the acoustic facility can be compared with the tunnel results, so that a correlation can be obtained, allowing a more direct application of the accelerated test results. In the meanwhile, it is our belief that the accelerated device provides a useful and economical screening test, but that final check tests of a few selected materials should be made in a flowing system such as the venturi facility.

It has been demonstrated[19] that a pulsing technique, whereby a short period of cavitation is followed by a longer non-cavitating interval, produces more meaningful results in cases where corrosion is important. The accumulated non-cavitating time allows a more realistic opportunity for any corrosion mechanism to manifest itself on the test specimen. In a purely cavitating experiment of the accelerated type, the test time involved might be so short that the corrosion contribution to the total damage mechanism would be negligible as compared to field conditions, and hence the results obtained misleading. Such pulsing apparatus can be used for both steady and pulsed cavitation studies. Hence, the effect of corrosion damage can be quantitatively determined. Although the present facility has this capability, it has not been used in this fashion thus far since, as discussed later, corrosion has apparently been quite negligible.

It is possible to measure the relative cavitation resistance to high-temperature liquid metals of numerous potentially useful alloys in a simple and economical test using the vibratory facility which has been developed by this laboratory. Almost any liquid metal of interest could be accommodated in the present facility. This initial screening of materials under relatively realistic fluid and temperature conditions would be of great value in choosing materials for those components susceptible to cavitation-erosion attack or, as previously mentioned, droplet-impingement or pure erosion.

In addition to the cavitation testing program, it is essential to determine the applicable mechanical properties of the materials tested at the test temperatures so that a correlation between resistance to this form of two-phase liquid-metal attack and some combination of the mechanical properties can be obtained. Applicable mechanical properties certainly might include the ultimate tensile strength, yield strength, hardness, strain energy to failure, elongation, reduction in area, impact resistance, etc. If such a correlation were available, it would be possible not only to choose intelligently materials for these various purposes, but also to specify the most desirable heat-treat program, surface treatment, etc. Such a procedure would eliminate the necessity for costly materials-screening programs such as has been necessary many times in the past after the construction of a particular facility. Further, it would be possible to specify materials in critical locations in advance so that more aggressive designs (and hence more economical designs, as for liquid metal pumps, etc.) could be used.

## C. The University of Michigan High-Temperature Ultrasonic Cavitation Vibratory Facility

The University of Michigan high-temperature ultrasonic cavitation vibratory facility has been described elsewhere.[7,20] However, the major features of the facility will be reviewed here. Figure 1 is a schematic block diagram of the high-temperature ultrasonic vibratory facility showing the audio-oscillator, power-amplifier, transducer-horn assembly, test specimen, oscilloscope, frequency counter, high-temperature furnace and cavitation vessel, and accelerometer. The signal supplied by the variable-frequency audio-oscillator is amplified and applied to the piezoelectric crystals. The resultant periodic motion of

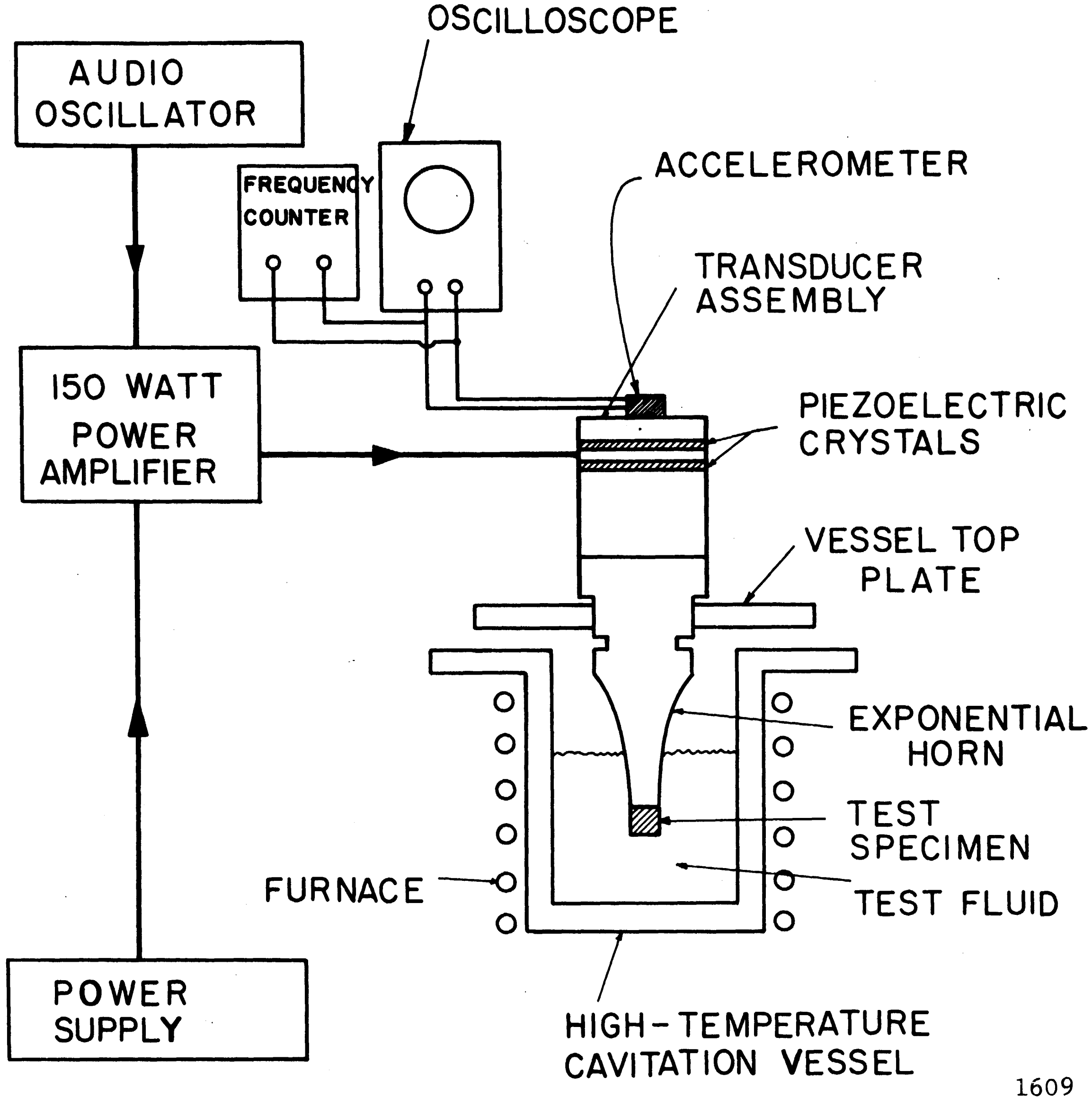

Fig. 1.--Block Diagram of the High Temperature Ultrasonic Vibratory Facility.

the crystals effectively constitutes a standing wave generator with the amplitude of the standing wave being increased as it traverses the exponential horn assembly. The use of exponential horns as velocity transformers in this fashion was first suggested by Mason.[21] The movement of the horn tip, to which a test specimen has been attached, results in a rapid variation in local pressure, causing the periodic formation and collapse of an intense cavitation cloud. The final result is an accelerated erosion of the test specimens subjected to the collapsing bubble cloud. The materials of interest can be tested in a variety of fluids over a wide temperature range. For studies at elevated temperatures the transducer-horn assembly is attached to the special cavitation vessel which is filled with the appropriate fluid. Figure 2 is a photograph of the facility showing the audio-oscillator, power-amplifier, voltmeters, oscilloscope, timer, temperature controller, and the transducer-horn assembly installed in the high-temperature cavitation vessel. The vessel is inserted in the furnace. The line running to the vessel supplies argon as a cover gas for the fluid.

The cavitation facility has been completely calibrated and operated at fluid temperatures in excess of 1500°F at a frequency of $\sim$ 20 Kc./sec. and double amplitude of $\sim$ 2 mils. It is capable of operation with a variety of fluids.

## D. Present Investigation

As mentioned previously, it has been shown both experimentally[2] and theoretically[2,6] that damaging cavitation may well occur in many

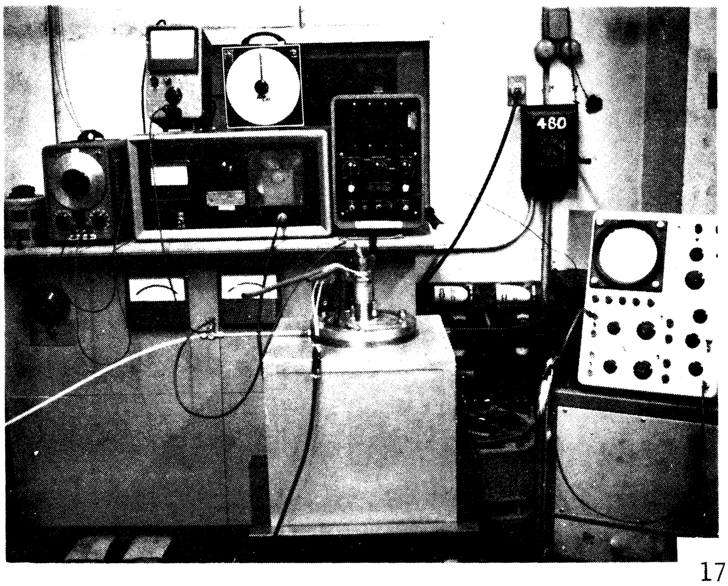

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Figure 2. High-Temperature Cavitation Facility

high-performance bearing applications. This problem is at present of considerable importance to the designers of the mercury space powerplant components.[2] The objective of the present study is the determination of the cavitation-erosion characteristics of several selected bearing materials in mercury at 500°F. It was necessary to conduct some of the investigations at reduced temperature, and in one case to utilize water as the test fluid, due to various mechanical and compatibility considerations which are discussed fully later. The materials examined in this study include three heat-treated specimens of the tool steel alloy BG-42 (a modified 440-C stainless steel), Blue Chip Tool Steel (18-4-1 tool steel), Mo-1/2Ti, Cb-1Zr(A), two grades of graphitar, single-crystal tungsten, and teflon-coated type 304 stainless steel. Table 1 summarizes the material-fluid-temperature combinations which were studied in this investigation.

TABLE 1

MATERIALS TESTED IN BEARING PROGRAM

| 70°F Mercury | 350°F Mercury | 500°F Mercury |
|---|---|---|
| Graphitar-Grade 50(U-M) | Teflon-Coated 304 SS(U-M) | BG-42 ($R_c$ = 47)(TRW) |
| Graphitar-Grade 80(U-M) | | BG-42 ($R_c$ = 53)(TRW) |
| | | BG-42 ($R_c$ = 64)(TRW) |
| | | Blue Chip Tool Steel (TRW) |
| 70°F Water | | |
| | | Mo-1/2Ti(P & W) |
| Single Crystal Tungsten(U-M) | | Cb-1Zr(A)(P & W) |

NOTE:

The notations (TRW), (P & W), and (U-M) following the specimen materials indicate the source of the material, namely, Thompson-Ramo-Wooldridge, Pratt & Whitney Aircraft (CANEL), and The University of Michigan, respectively; whereas the notation (A) denotes an annealed condition of the material. The grades of graphitar are designations of the United States Graphite Company.

# CHAPTER II

## CAVITATION STUDIES IN MERCURY AT 500°F

### A. Experimental Procedure

The six materials tested in mercury at 500°F were BG-42(TRW) in three heat-treated conditions, Blue Chip Tool Steel(TRW), Mo-1/2Ti (P & W), and Cb-1Zr(A)(P & W). The BG-42 in the "as-received" condition was subjected to the heat treat schedule specified in Table 2 so as to obtain specimens of three distinct hardness ranges, as noted. In Table 3 the heat treat schedule for the "as-received" Blue Chip Tool Steel is specified. This results in specimens with a hardness of approximately 64 $R_c$. Prior to any heat treating, standard cavitation test specimens, as shown in Figure 3, were machined from available bar stock. The required dimensions "A" and "B" for the six materials tested are listed in Table 4.

TABLE 4

SPECIMEN DIMENSIONS

| Material | "A" | "B" |
|---|---|---|
| BG-42 (all heat-treats) | .250" | .625" |
| Mo-1/2Ti | .175" | .550" |
| Cb-1Zr(A) | .220" | .595" |
| Blue Chip Tool Steel | .220" | .595" |

## TABLE 2

## HEAT TREATMENT FOR BG-42 CAVITATION EROSION SPECIMENS

The following process shall be performed:

1. In a salt bath preheat the part thoroughly at 1400°F to 1450°F.
2. Transfer the part to a salt bath at 2075 to 2100°F. Soak at temperature for 1/2 hour per inch of thickness (20 minutes minimum).
3. Oil quench to room temperature.
4. Temper at 300 to 400°F for one hour.
5. Refrigerate at minus 100°F ± 10°F for 1/2 hour.
6. After allowing the specimen to warm to room temperature, double temper in a neutral salt bath (preferably chloride) for 2 + 2 hours at one of the following temperatures:

| Desired Final Hardness, $R_c$ | Temper Temperature, °F |
|---|---|
| 44-46 | 1150-1180 |
| 53-55 | 1060-1090 |
| 62-64 | 975-1000 |

7. Air cool to room temperature in still air after each temper.

## TABLE 3

## HEAT TREATMENT FOR BLUE CHIP TOOL STEEL
## (AMS 5626, T-1, 18-4-1)

For a hardness level of Rockwell C 61-64:

1. In a protective compound, salt, or atmosphere, preheat the specimen slowly over a two hour period to 1500°F - 1600°F.
2. Soak at 1500°F - 1600°F for one hour and then transfer the part to a controlled atmosphere furnace or salt bath at 2325°F - 2350°F.
3. Soak at 2325°F - 2350°F for 2 - 5 minutes, the exact time being dependent on the size of the part. This soaking time should never be overdone.
4. Remove and cool in still air to room temperature.
5. Draw at 1025°F - 1050°F for 2 1/2 hours, then allow to cool slowly to room temperature.
6. Re-draw at 700°F - 750°F for two hours, then allow to cool slowly to room temperature.

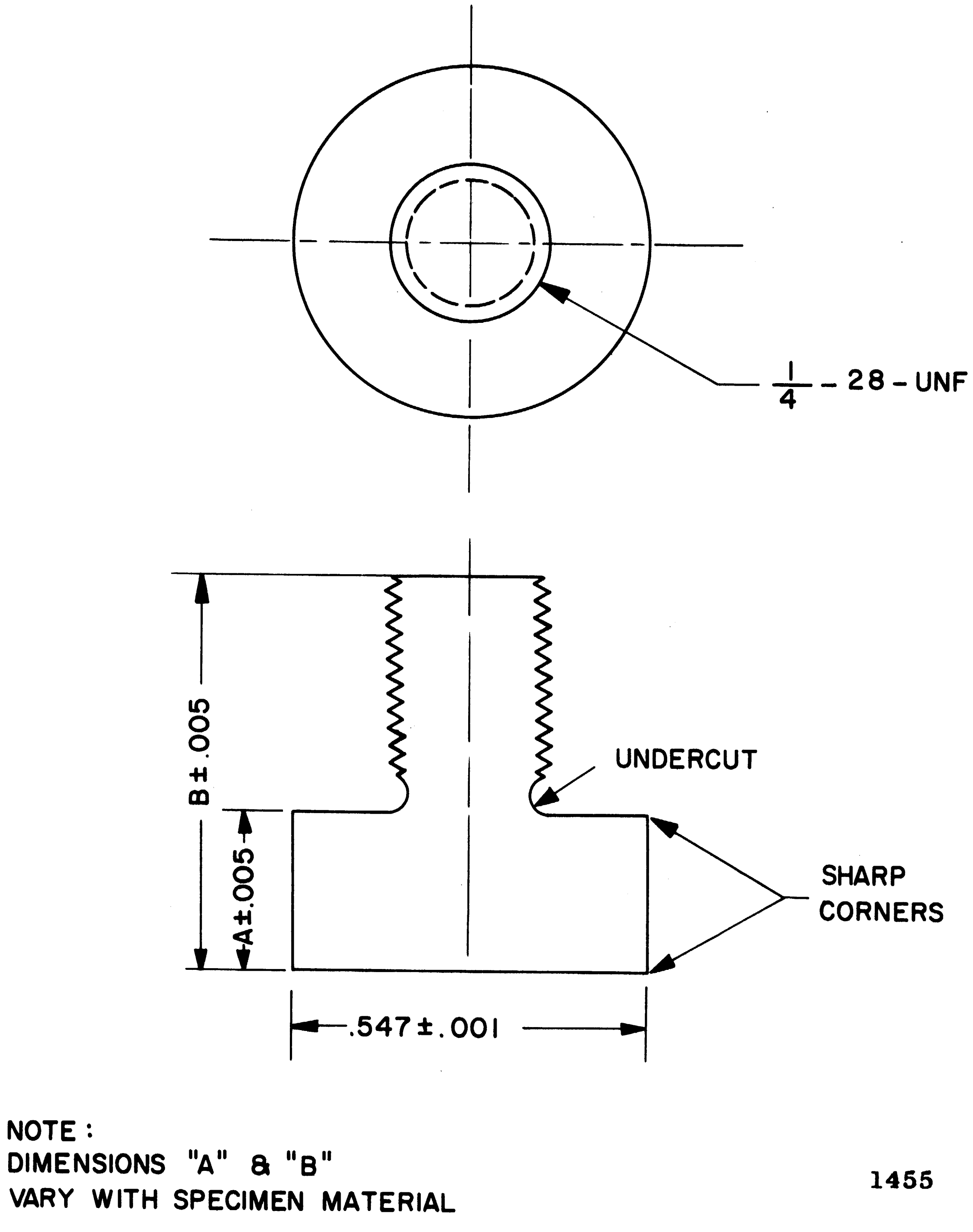

Figure 3. Cavitation Test Specimen

These dimensions provide a standard specimen weight of 9.4 ± .1 g. Initially, each of the specimens was weighed on a precision balance to an accuracy of 0.01 mg., and then attached to the tip of the stainless steel exponential horn, whereupon the unit was assembled. The mercury test fluid was maintained at the required test temperature of 500°F throughout the test with a suitable temperature controller. Variations in temperature during the test amounted to less than 5°F. The test specimens are oscillated by a pair of lead-zirconate-titanate piezoelectric crystals at $\sim$20 Kc./sec. with the horn tip immersed $\sim$1 1/2 inches into the mercury. The double amplitude at the specimen was $\sim$ 2 mils and the argon cover gas over the mercury was maintained at 2.4 psig throughout the 500°F investigations. The value of argon cover gas pressure is chosen for a given fluid-temperature combination such that the difference between local pressure at the specimen and vapor pressure of the fluid is approximately constant for all the investigations involving a variety of fluid-temperature combinations. Total test duration varied for the different materials, ranging from 8 to 12 hours, with frequent inspections and weighings monitoring the specimen surface. Some specimens were not inspected and weighed as frequently as others due to their brittle nature and the possibility of damaging or breaking the test button during assembly and disassembly. Prior to each weighing any excess mercury adhering to the specimen surface was removed by heating in a vacuum furnace so as to eliminate oxidation of the specimen.

## B. Experimental Results

The cavitation results obtained at 500°F in mercury will be displayed as accumulative weight loss versus test duration, and also as accumulative mean depth of penetration (MDP) versus test duration. The mean depth of penetration, computed assuming that the weight loss is smeared uniformly over the cavitated specimen surface, is felt to be more physically meaningful than weight loss, since it is generally the total penetration of a particular component by cavitation erosion that would render it unfit for service. Of course, neither weight loss nor MDP is sensitive to damage distribution and form, i.e., damage may vary from isolated deep pits to relatively uniform wear, depending on material-fluid combination. Obviously, a "figure of merit" such as MDP takes into account the large variation in density that may occur within a set of test materials.

The appropriate expressions for computing the MDP of all the materials tested are presented in Table 5.

Table 6 summarizes the cavitation results obtained in mercury at 500°F. Figure 4 is a plot of accumulative weight loss versus test duration, while Figure 5 is the corresponding plot of accumulative MDP versus test duration for the six materials tested.

On the basis of either average weight loss rate or average MDP rate it is clear that the three BG-42 materials and the Blue Chip Tool Steel are far superior to the Mo-1/2Ti and the Cb-1Zr(A). The BG-42 with a hardness of 64 $R_c$ is the most resistant to cavitation based on average weight loss rate while the Blue Chip Tool Steel with identical

## TABLE 5

## RELATION BETWEEN WEIGHT LOSS AND MDP

| Material | Density | Relationship |
|---|---|---|
| BG-42 (all heat treats) | 7.85 g/cc. | MDP(mils) = .033W* |
| Blue Chip Tool Steel | 8.70 | MDP(mils) = .0296W |
| Mo-1/2Ti | 10.22 | MDP(mils) = .0253W |
| Cb-1Zr(A) | 8.72 | MDP(mils) = .0296W |
| Graphitar-Grade 50 | 1.70 | MDP(mils) = .152W |
| Graphitar-Grade 80 | 1.80 | MDP(mils) = .144W |
| Single-Crystal Tungsten | 19.30 | MDP(mils) = .0161W |

*W is the weight loss expressed in mg.

## TABLE 6

## SUMMARY OF CAVITATION RESULTS AT 500°F

| Material | Avg. Wt. Loss Rate | Avg. MDP Rate |
|---|---|---|
| BG-42 ($R_c$ = 64) (TRW) | 1.20 mg./hr. | .04 mils/hr. |
| Blue Chip Tool Steel (TRW) | 1.43 | .04 |
| BG-42 ($R_c$ = 53) (TRW) | 3.08 | .10 |
| BG-42 ($R_c$ = 47) (TRW) | 5.88 | .19 |
| Mo-1/2Ti (P & W) | 43.16 | 1.09 |
| Cb-1Zr(A) (P & W) | 125.78 | 3.73 |

hardness is about 15% less resistant. Based on average MDP rate these materials exhibit identical resistance to cavitation damage. The BG-42 specimens with hardnesses of 53 $R_c$ and 47 $R_c$ ranked third and fourth, respectively, among the six materials tested. The Mo-1/2Ti and Cb-1Zr(A) specimens were both much more severely damaged, and exhibited average weight loss rates of 43.16 mg./hour and 125.78 mg./hour, respectively. It is interesting to note that the hardest of the BG-42 specimens exhibited the greatest resistance to cavitation damage, while the softest showed least resistance. It is clear from Figures 4 and 5 that the rate of erosion for each individual material is approximately constant for all the materials tested for the duration of the test.

Photographs of the test specimens at the conclusion of the cavitation experiment are presented in Figure 6. Note the severe pitting of the Mo-1/2Ti and the Cb-1Zr(A) surfaces. Very little damage is noted in the case of the BG-42 ($R_c$ = 64) and the Blue Chip Tool Steel. A photograph of the Cb-1Zr(A) specimen before exposure indicates a representative surface condition for all the specimens tested.

Detailed examination of the 303 stainless steel exponential horn, the 316 stainless steel container vessel, and the sides of the various test specimens, all of which are <u>not</u> subject to cavitation, but <u>are</u> submerged in the test fluid, indicates that corrosion effects in the absence of cavitation in these investigations were negligible. Hence, it seems most probable that the damage suffered by the test specimens was due almost completely to the cavitation erosion process and not to chemical corrosion by the mercury test fluid.

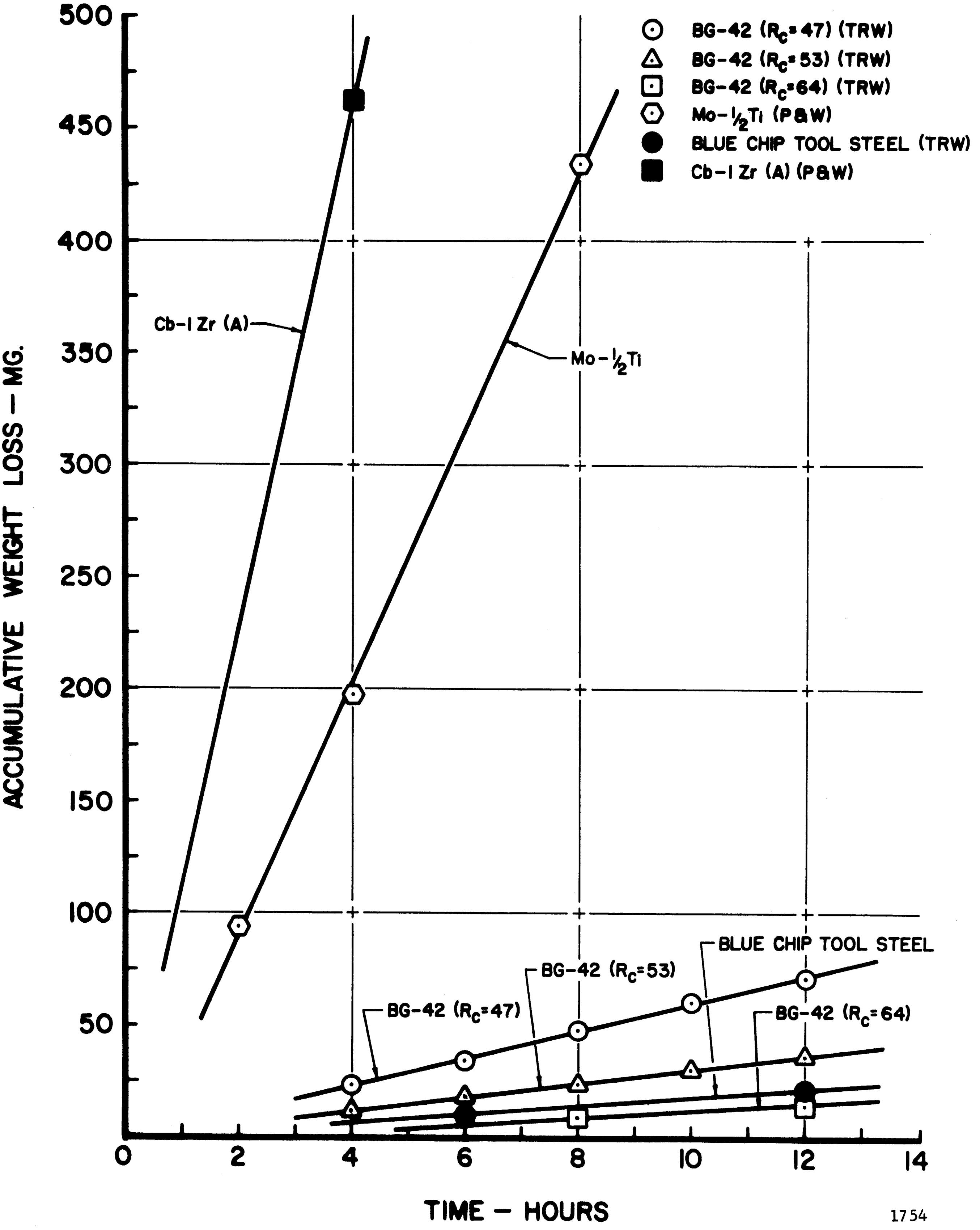

Fig. 4.--Effect of Cavitation Test Duration on Weight Loss at 500°F in Mercury.

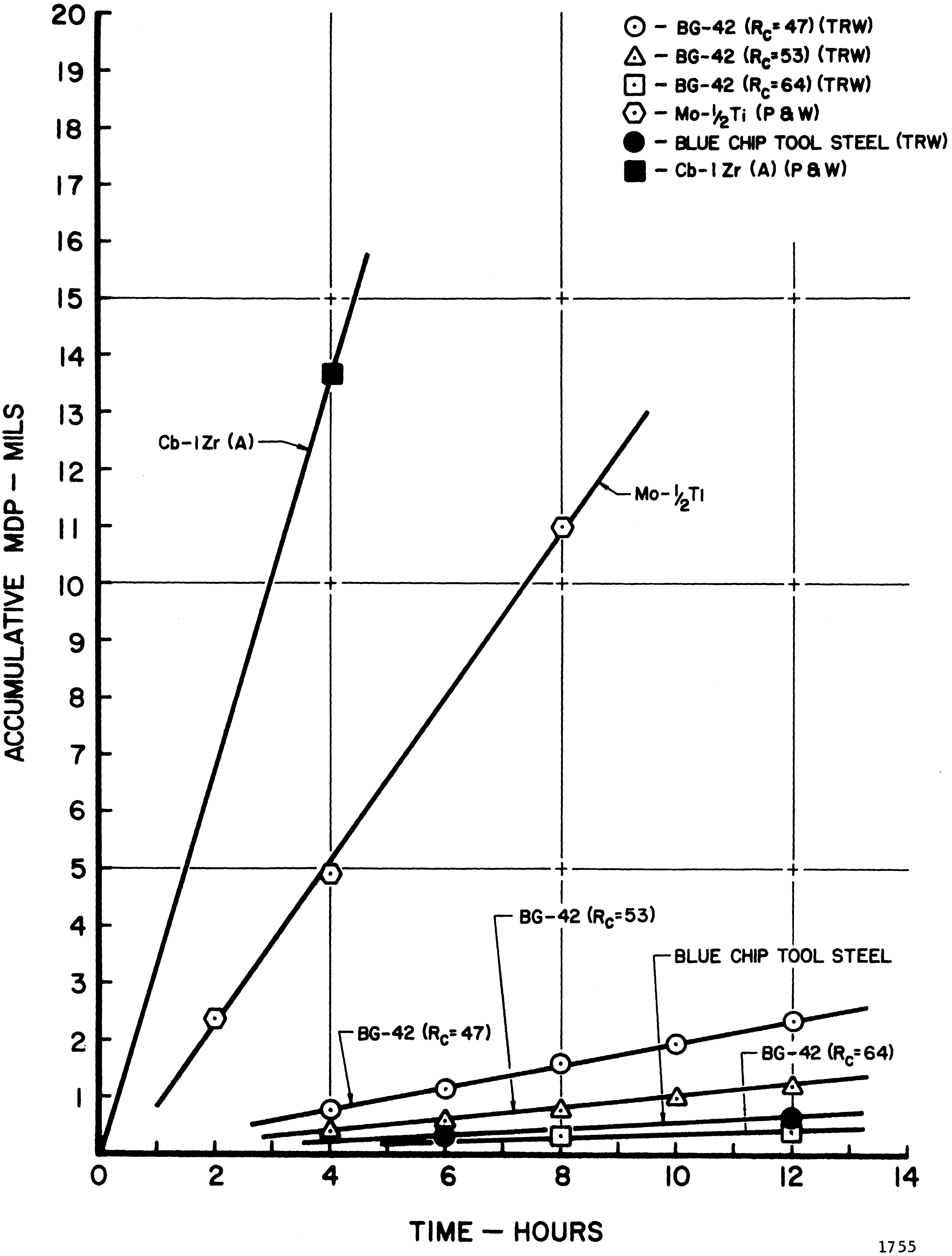

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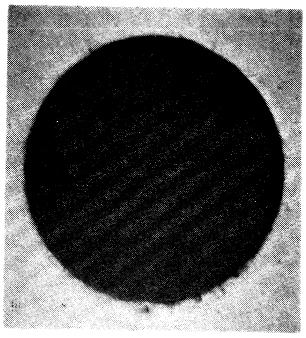
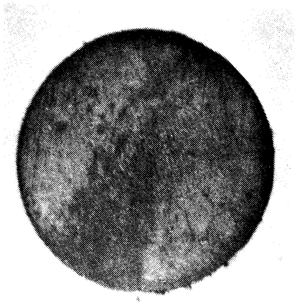
Fig. 5.--Effect of Cavitation Test Duration on MDP at 500°F in Mercury.



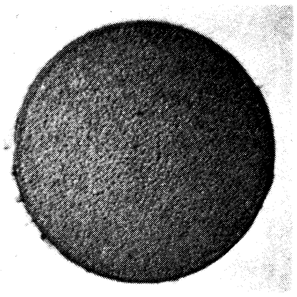
(1) BG-42($R_c$ = 64)

12 Hour Exposure



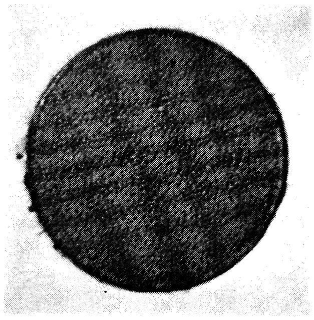
(2) Blue Chip Tool Steel($R_c$ = 64)

12 Hour Exposure



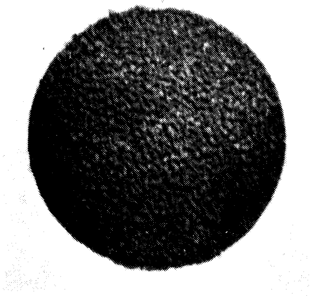
(3) BG-42($R_c$ = 53)

12 Hour Exposure



(4) BG-42($R_c$ = 47)

12 Hour Exposure

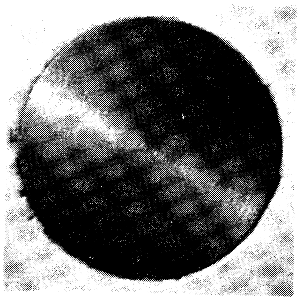


(5) Mo-1/2Ti

12 Hour Exposure

(6) Cb-1Zr(A)

8 Hour Exposure



Cb-1Zr(A)

Prior to Exposure

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Figure 6. Specimens Subjected to Cavitation Damage in Mercury at 500°F

# CHAPTER III

## CAVITATION STUDIES IN MERCURY AT 70°F

## (GRAPHITAR)

### A. Experimental Procedure

The initial intention was to conduct all of the cavitation-erosion tests at 500°F in mercury, but a variety of mechanical and compatibility problems made this impossible in the case of the graphitar and the single-crystal tungsten. The graphitar materials conceivably could have been tested at 500°F, but it was felt that the changes in mechanical properties from 70°F to 500°F were negligible. Further, testing at 70°F would enable a direct comparison (from a temperature standpoint) with the single-crystal tungsten which had to be tested in water at 70°F, as discussed below.

Graphitar is formed from carbon and graphite powders which are compacted under high unit pressures and then furnaced at temperatures up to 4500°F. A variety of grades are available from The United States Graphite Company and differ in hardness, density, compressive strength, and other mechanical properties. The two grades investigated here are denoted as grades 50 and 80 and were chosen to provide a reasonable variation in mechanical properties. Applicable mechanical properties are presented in Chapter VII.

Due to the low density of the graphitar (compared to the other materials tested) and its brittle, porous nature, it was completely impractical to fabricate standard cavitation test specimens as shown in Figure 3. The low density would result in an unusually large "A" dimension to obtain the required weight, while the brittle, porous nature of the material made it impossible to firmly affix a specimen to the ultrasonic horn without damage to the threaded stud. It is necessary that the specimen be firmly and tightly attached to the horn tip so that the ultrasonic energy is properly transmitted across the interface for efficient operation. Hence the design shown in Figure 7 consisting of a graphitar test specimen with internal thread and a separate stainless steel mounting stud was adopted and proved to be satisfactory. The mounting stud results in a firm attachment of the graphitar cylinder to the horn tip without damage to the graphitar internal threads. This design overcomes all of the problems encountered with the standard cavitation test specimen.

The experimental procedure employed for the testing of the graphitar specimens in mercury at 70°F closely parallels that used for the 500°F tests discussed previously. However, for the 70°F tests the argon cover gas pressure was maintained at 0.5 psig throughout the investigations to again provide the same pressure above vapor pressure at the specimen surface. Total test duration for both grades of graphitar was 10 hours, with two specimens of each being run. Frequent inspections and weighings were conducted to monitor the specimen surface. Since the graphitar is very porous and absorbs mercury during the

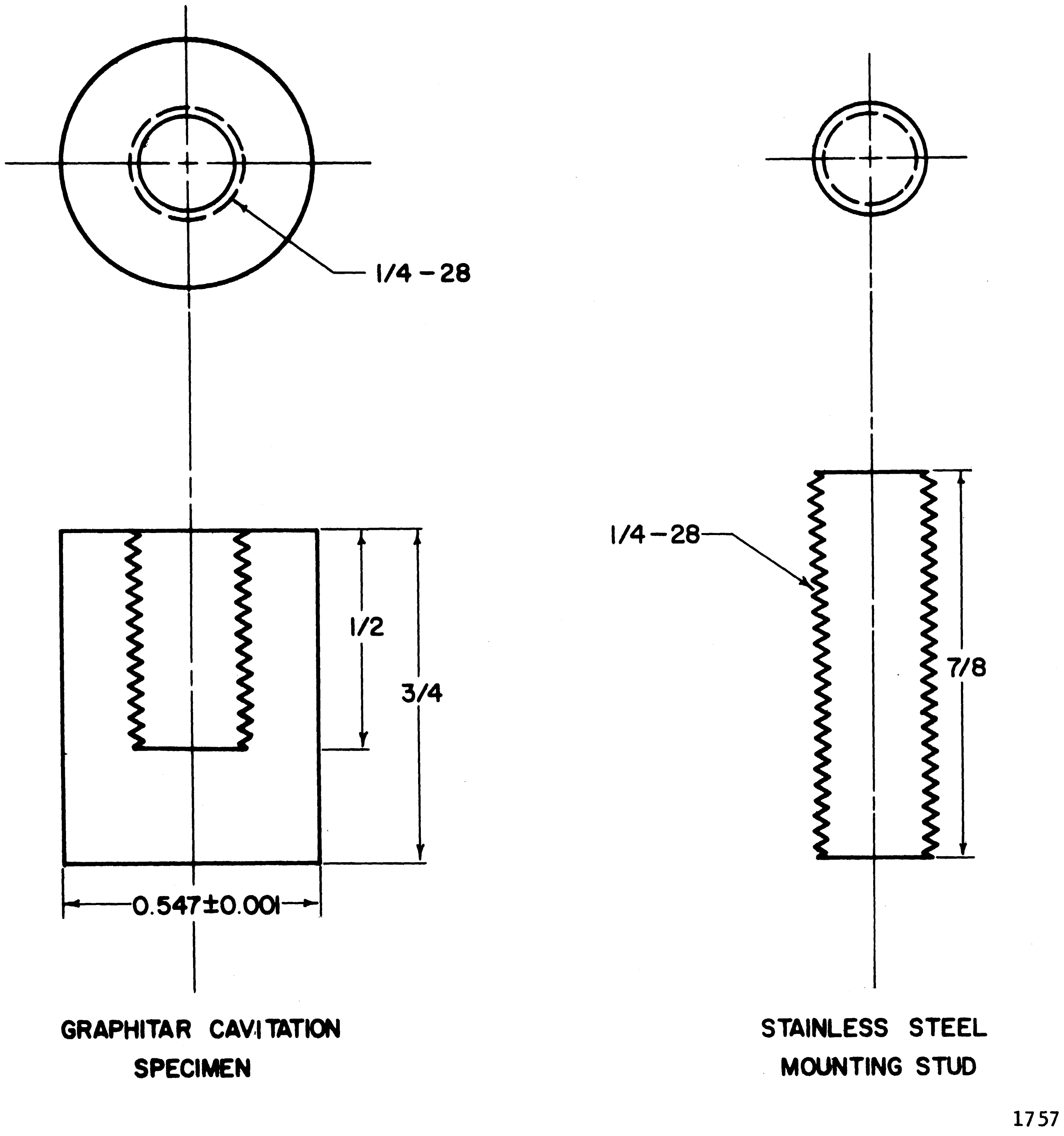

Fig. 7.--Graphitar Cavitation Test Specimen and Mounting Stud.

cavitation test, it was necessary to drive off the absorbed mercury by heating in a vacuum furnace before weighing. The vacuum is necessary to eliminate oxidation of the specimen material.

## B. Experimental Results

The cavitation results obtained at 70°F for graphitar will be displayed as accumulative weight loss versus test duration, and also as accumulative mean depth of penetration (MDP) versus test duration.

Table 7 summarizes the cavitation results obtained in mercury at 70°F. Figure 8 is a plot of accumulative weight loss versus test duration, while Figure 9 is the corresponding plot of accumulative MDP versus test duration for the two grades of graphitar tested. The response of the graphitar to cavitation-erosion was non-linear for the duration of the test, as opposed to all the other materials tested.*

On the basis of either average weight loss rate or average MDP rate the Grade 80 variety of graphitar appears to be superior to the Grade 50. However, both grades suffered a total MDP which was on the order of 100X as great as that of the Blue Chip Tool Steel and BG-42 specimens tested at 500°F. In fact the maximum penetration, as opposed to mean penetration, of both grades of graphitar was approximately 1/4" (250 mils).

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*It has been found in our facility that damage rates are relatively constant with time as long as the very early, somewhat erratic, portion of the test is neglected, and the total MDP does not exceed the order of 10-20 mils. This behavior is in agreement with that recently reported by Plesset and Devine,[22] although in disagreement with that of another investigator.[23]

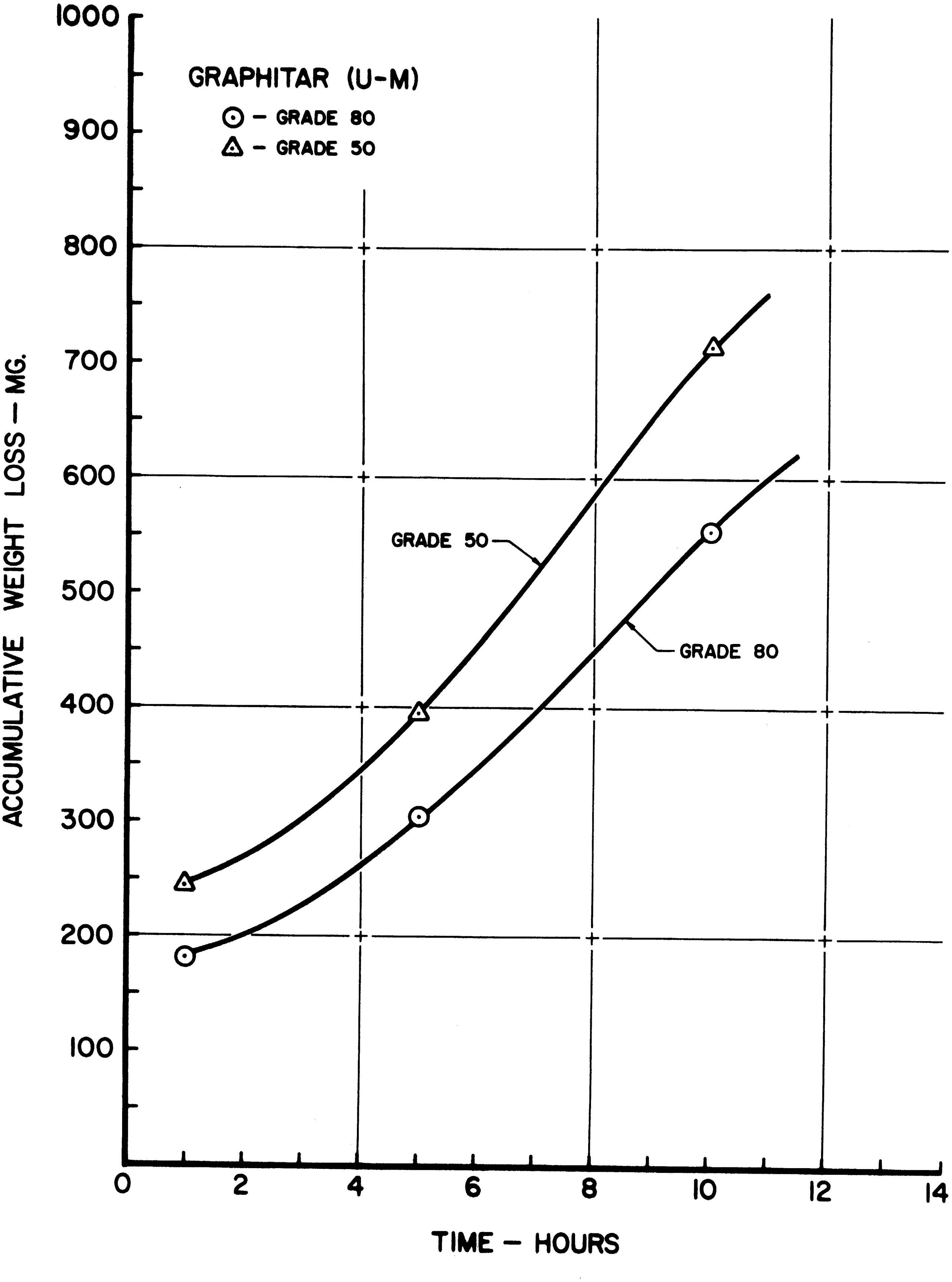

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Fig. 8.--Effect of Cavitation Test Duration on Weight Loss of Graphitar at 70°F in Mercury.

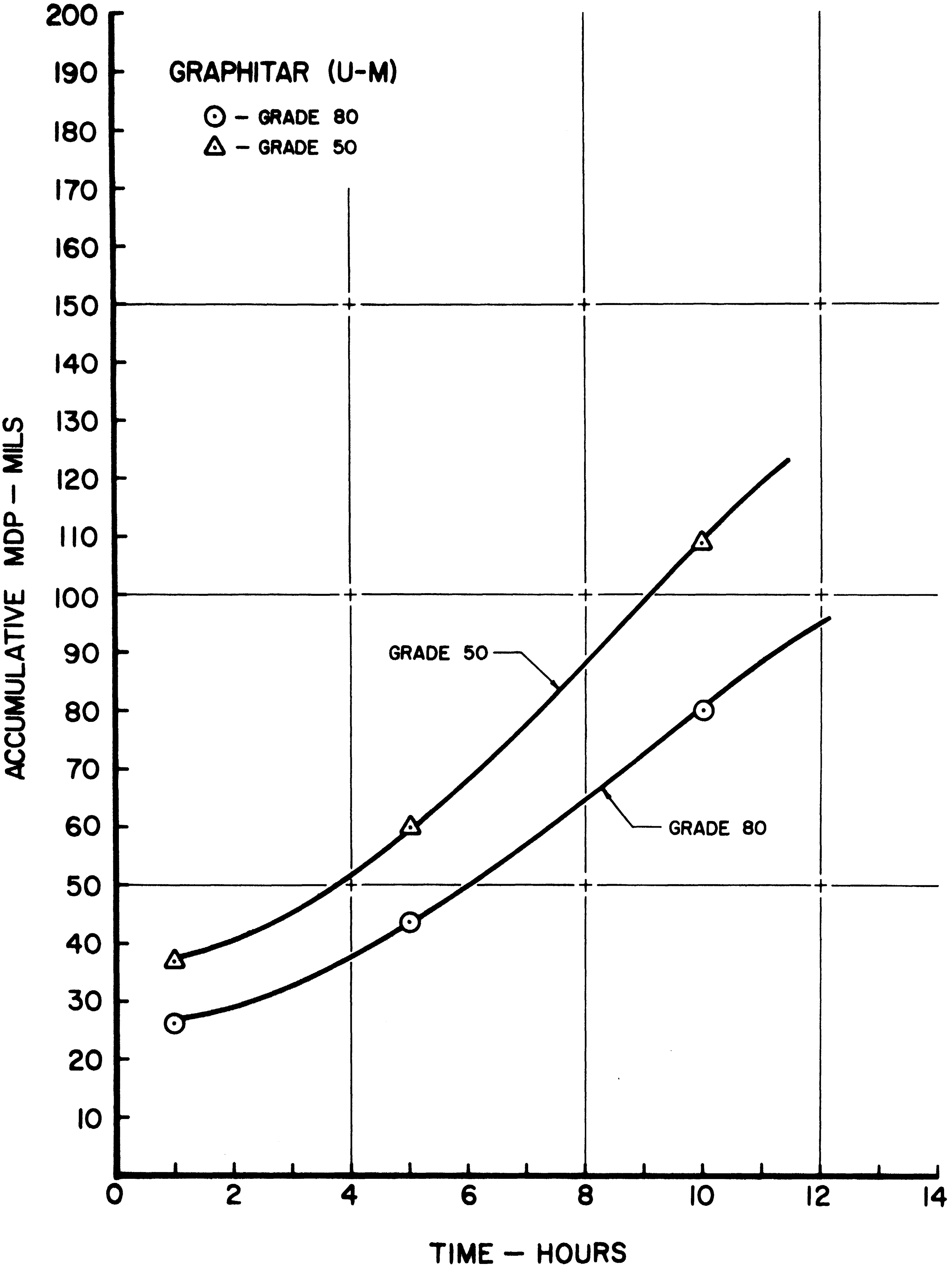

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Fig. 9.--Effect of Cavitation Test Duration on MDP of Graphitar at 70°F in Mercury.

TABLE 7

SUMMARY OF CAVITATION RESULTS AT 70°F

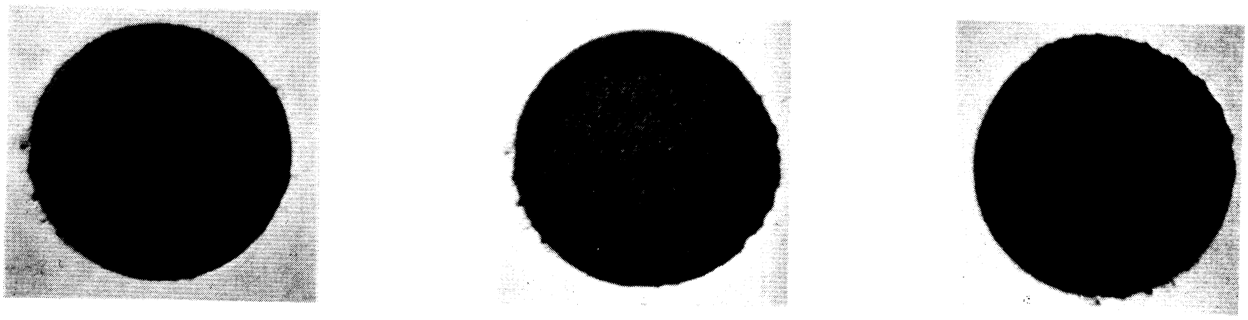
| Material | Avg. Wt. Loss Rate | Avg. MDP Rate |
|---|---|---|
| *Graphitar-Grade 50(U-M) | 71.60 mg./hr. | 10.90 mils/hr. |
| *Graphitar-Grade 80(U-M) | 55.30 | 7.95 |
| **Single Crystal Tungsten(U-M) | 1.55 | .025 |

*Tested in Mercury.

**Tested in Water.

Since the graphitar does not melt at any temperature and begins to sublime at approximately 6000°F, it is felt that the mechanical properties of the two grades tested here would not be significantly affected had the tests been conducted at 500°F. Hence it is assumed that the data presented in Table 7 for graphitar is approximately applicable at 500°F also.

Photographs of the test specimens at the conclusion of the cavitation experiment (10 hours duration) are presented in Figure 10. A photograph of a typical graphitar cylinder before exposure is included for comparison. Note the very severe damage suffered by both grades of graphitar.

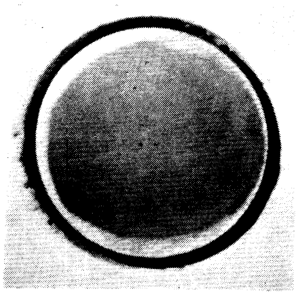


Graphitar

Before Exposure

Graphitar
Grade 80
10 Hour Exposure

Graphitar
Grade 50
10 Hour Exposure



Single Crystal Tungsten

50 Hour Exposure

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Figure 10. Graphitar and Single Crystal Tungsten Specimens Subjected to Cavitation Damage at 70°F

# CHAPTER IV

## CAVITATION STUDIES IN WATER AT 70°F

## (SINGLE-CRYSTAL TUNGSTEN)

### A. Experimental Procedure

It was intended to test the single-crystal tungsten in mercury at 500°F. However, because of the very great difficulty encountered in machining a standard cavitation test specimen from this material, and due to the lack of a suitable grinder for forming the threaded stud portion of the specimen as well as the general lack of time and funds, alternate designs were considered. It was found feasible to produce a simple disc of single-crystal tungsten by grinding, but it was still necessary to affix the disc firmly to the ultrasonic horn. Initially, an attempt was made to use epoxy resin to attach the tungsten disc to a stainless steel adaptor. However, the epoxy has little elasticity and very low strength in shock. As a result the epoxy bond was immediately fractured at the start of the test. Various other cements provided similar results. Finally, the design shown in Figure 11 was found to be satisfactory. Here a simple disc of single crystal tungsten has been attached to a stainless steel adaptor with silver solder. The silver solder was found to form a very suitable bond between the tungsten and

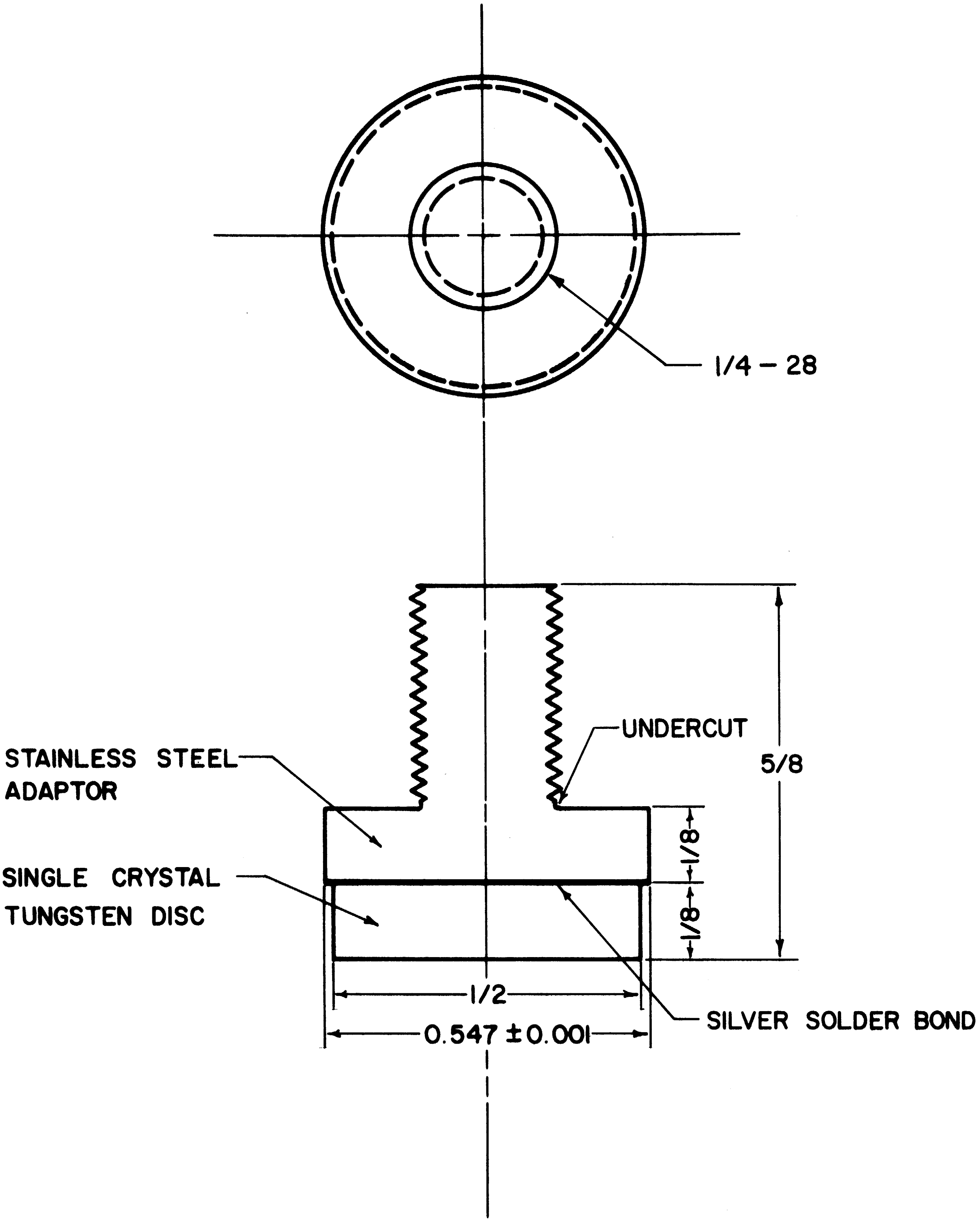

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Fig. 11.--Special Single Crystal Tungsten Cavitation Test Specimen.

stainless steel and resulted in satisfactory transmission of the ultrasonic energy across the interface. The diameter of the tungsten disc (1/2") was slightly smaller than the diameter of the stainless steel adaptor (.547") due to unavailability of tungsten in a larger size at the time of the tests.

The silver solder proved to be satisfactory in all respects with the exception of its compatibility with mercury. Even during a relatively short test in mercury and in spite of the small surface exposed, the bond was destroyed. Hence it was necessary to test the tungsten in water. Due to pressure limitations of the equipment, 500°F in water was not possible. Since the properties of tungsten are not significantly temperature-dependent in this range, it was decided that 70°F water would suffice to at least obtain some realistic idea of the cavitation resistance of the material. The single-crystal tungsten used in these investigations was obtained from Cleveland Tungsten, Inc.

Due to the previously-mentioned fabrication difficulties and lack of time, only one specimen of tungsten was tested. The tests were conducted at the same frequency, amplitude, and submergence used in the other tests. The argon cover gas pressure was maintained at 1.1 psig to obtain the same pressure above vapor pressure at the specimen surface. The total test duration was 50 hours, with inspections and weighings being conducted at 10 hour intervals.

## B. Experimental Results

Table 7 summarizes the results obtained with the single-crystal tungsten. Figure 12 is a plot of accumulative weight loss versus test

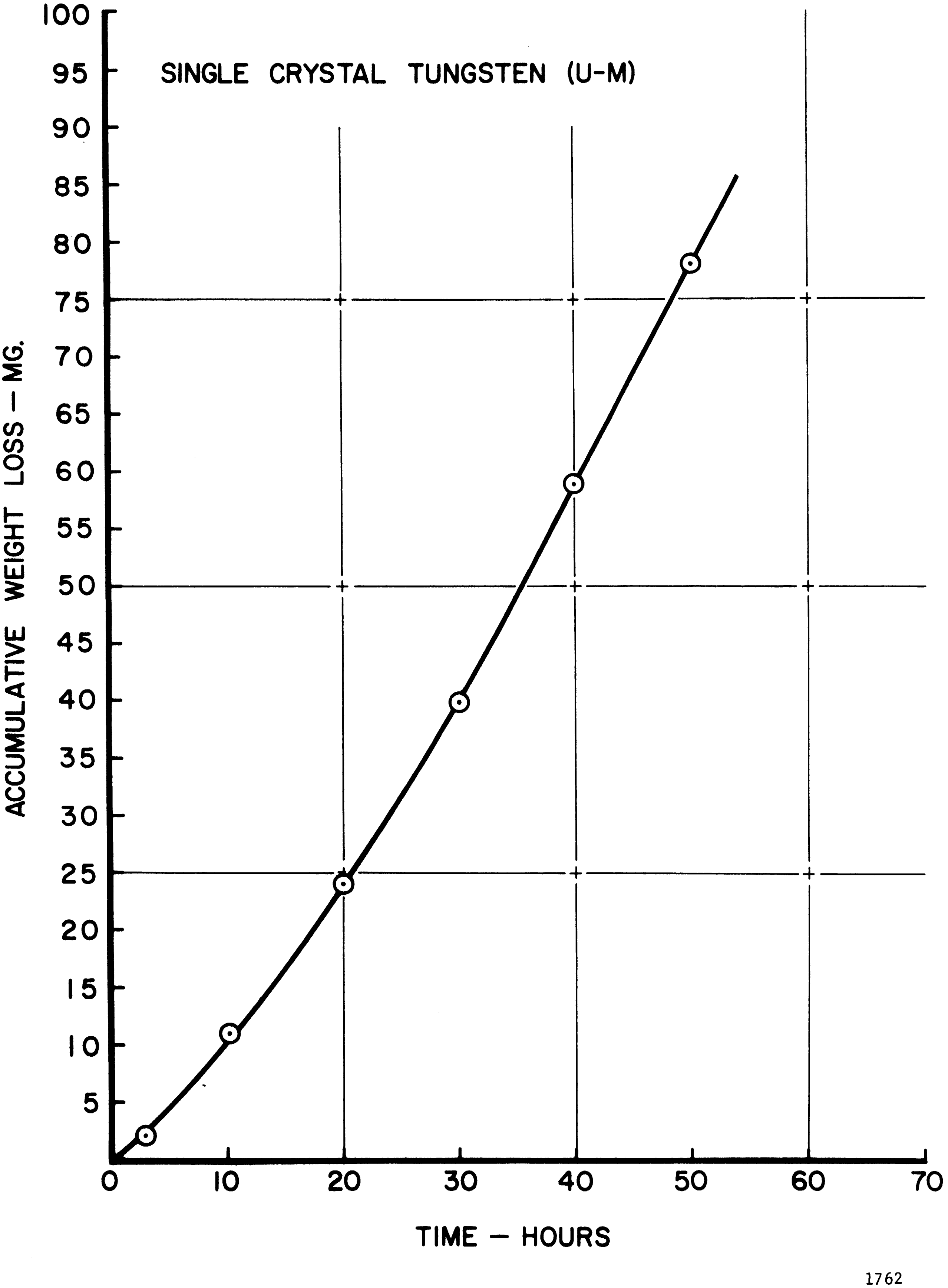

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Fig. 12.--Effect of Cavitation Test Duration on Weight Loss of Single-Crystal Tungsten at 70°F in Water.

duration, while Figure 13 is the corresponding plot of accumulative MDP versus test duration for the single-crystal tungsten tested. The response of the single-crystal tungsten to cavitation-erosion attack is nearly linear for the duration of the test.

Clearly, the tungsten tested in water was damaged only slightly compared to the graphitar tested in mercury at the same temperature. In fact, the amount of damage incurred by the tungsten is on the order of that suffered by the Blue Chip Tool Steel and the three BG-42 specimens tested in mercury at 500°F. Before any true comparison can be made between these materials, it is necessary to correct the tungsten results obtained in water at 70°F in an appropriate manner so as to reflect the expected additional damage that the tungsten would have suffered in mercury at 70°F and 500°F. Cavitation-erosion data was recently obtained[24] for type 304 stainless steel in water at 70°F and in mercury at 70°F and 500°F. Hence, if one assumes that the tungsten and the stainless steel both suffer the same % increase in damage when changing the test fluid from water to mercury at 70°F, and when increasing the mercury temperature from 70°F to 500°F, then it is possible to compute projected damage rates for the single-crystal tungsten on the basis of the 304 stainless steel data available. Hence, one might compute the expected rate of damage for single-crystal tungsten in mercury at 70°F as follows:

$$W_{70^\circ\mathrm{F}\ \mathrm{Hg}} = W_{70^\circ\mathrm{F}\ \mathrm{H_2O}} \times \frac{304\mathrm{SS}_{70^\circ\mathrm{F}\ \mathrm{Hg}}}{304\mathrm{SS}_{70^\circ\mathrm{F}\ \mathrm{H_2O}}}$$

$$W_{70^\circ\mathrm{F}\ \mathrm{Hg}} = (.025\ \text{mils/hr.}) \times \frac{.32\ \text{mils/hr.}}{.10\ \text{mils/hr.}} = 0.08\ \text{mils/hr.}$$

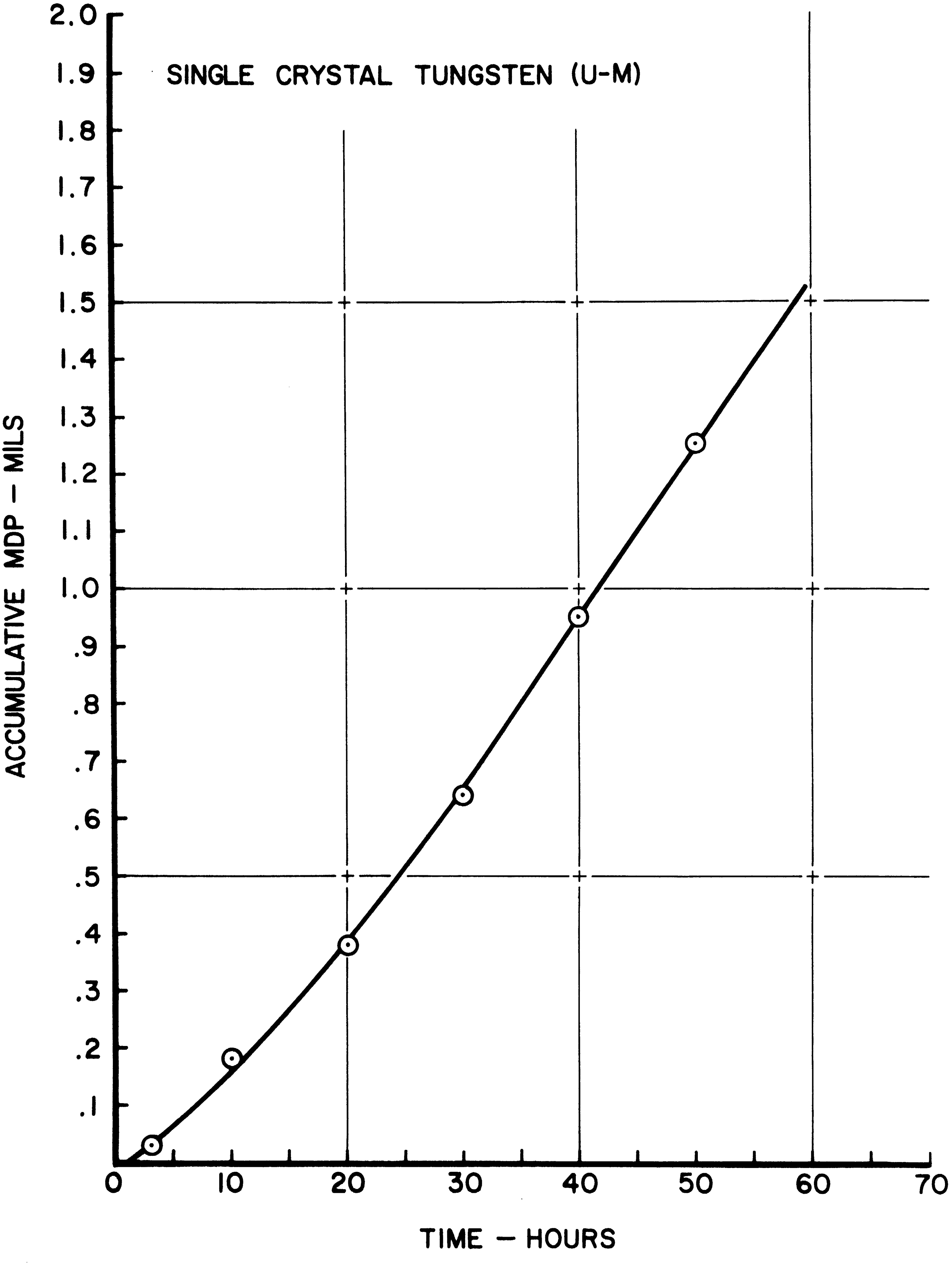

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Fig. 13.--Effect of Cavitation Test Duration on MDP of Single-Crystal Tungsten at 70°F in Water.

where W and 304SS denote the corresponding MDP rates of these materials. In a similar manner one can estimate the expected rate of damage for the single-crystal tungsten in mercury at 500°F as follows:

$$W_{500^\circ F\ Hg} = W_{70^\circ F\ H_2O} \times \frac{304SS_{500^\circ F\ Hg}}{304SS_{70^\circ F\ H_2O}}$$

$$W_{500^\circ F\ Hg} = (.025\ \text{mils/hr.}) \times \frac{.69\ \text{mils/hr.}}{.10\ \text{mils/hr.}} = 0.173\ \text{mils/hr.}$$

It is felt that the estimate at 500°F is probably conservative, since the mechanical properties of the single-crystal tungsten are only slightly affected by the increase in temperature from 70°F to 500°F as compared with the stainless steel.* Then the MDP rate of 0.08 mils/hour may be more applicable for a test in 500°F mercury. Presently mechanical properties data for the single-crystal tungsten at the two temperatures in question are not available, and this matter will remain in some doubt until such data is obtained.

A photograph of the single-crystal tungsten cavitation specimen at the conclusion of the 50 hour test is included in Figure 10 (previously cited). Very little damage is apparent. The outer ring noted in the photograph is not part of the tungsten specimen, but represents a space between the edge of the specimen and the cardboard holder used for photography.

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*It is believed that the effects of the change in mercury properties between 70°F and 500°F are probably small.

# CHAPTER V

## EFFECT OF TEFLON COATING ON CAVITATION-EROSION CHARACTERISTICS

### A. Experimental Procedure

Several type 304 stainless steel standard cavitation test specimens were coated with liquid teflon obtained from DuPont, Inc. in an attempt to determine its effectiveness as a protective coating against cavitation-erosion attack, since various coatings of this type have sometimes proven effective in water tests. The stainless steel specimens were sand-blasted so as to roughen the surface, and then the liquid teflon was applied with an insecticide sprayer to a thickness of 2.5 mils. The cavitation tests were conducted in mercury at a temperature of 350°F, which was believed to be about the upper limit of applicability for teflon, at a frequency of $\sim$ 20 Kc./sec. and double amplitude of $\sim$ 2 mils.

### B. Experimental Results

Initially, a teflon-coated 304 stainless steel specimen was soaked in mercury at 350°F for 15 hours with no cavitation present to determine whether the teflon coating would adhere to the stainless steel surface in this environment. Visual examination indicated no damage or loss of teflon, and precision weighing confirmed this conclusion.

Several teflon-coated 304 stainless steel specimens were then subjected to cavitation in mercury at 350°F. The rate of weight loss was essentially the same as that obtained with uncoated 304 stainless steel tested at 500°F in mercury (agreement within ± 2%). In fact, after only 5 minutes of testing, it was found that the teflon coating had been completely removed. Since the teflon coating remained intact upon exposure to the 350°F non-cavitation environment (i.e., did not "soak off"), it appears that the teflon coating was ineffective as a protective measure in the presence of cavitation in mercury at 350°F.

# CHAPTER VI

## COMPARISON OF CAVITATION RESULTS

Although it was not possible to test all of the materials in mercury at 500°F, it is possible to compare all of the results as corrected to 500°F mercury, as previously discussed. Table 8 summarizes all the cavitation data obtained in this investigation. The values given for graphitar and single-crystal tungsten are projected values based on assumptions previously discussed. All of the values for the other specimens were actually obtained in mercury at 500°F and previously presented in Table 6.

It is clear from Table 8 that the BG-42 ($R_c$ = 64) and the Blue Chip Tool Steel are the most resistant to cavitation in mercury at 500°F. The single-crystal tungsten with the estimated MDP rate of .08 mils/hour ranks third and the BG-42 ($R_c$ = 53) fourth. The BG-42 ($R_c$ = 47) is about 90% less resistant than the BG-42 ($R_c$ = 53). The Mo-1/2Ti and Cb-1Zr(A) were both much more heavily damaged and suffered average MDP rates of 1.09 mils/hour and 3.73 mils/hour, respectively. The graphitars were both very grossly damaged, exhibiting by far the least resistance to cavitation attack of the materials tested.

Presumably, Table 8 could serve as a materials guide for the designer of bearings, serving to indicate those materials which exhibit

## TABLE 8

## COMPARISON OF CAVITATION RESULTS
## (BASED ON 500°F MERCURY OPERATION)

| Material | Avg. Wt. Loss Rate | Avg. MDP Rate |
|---|---|---|
| BG-42 ($R_c$ = 64)(TRW) | 1.20 mg./hr. | .04 mils/hr. |
| Blue Chip Tool Steel(TRW) | 1.43 | .04 |
| *Single Crystal Tungsten(U-M) | 4.96 | .08 |
| BG-42 ($R_c$ = 53)(TRW) | 3.08 | .10 |
| BG-42 ($R_c$ = 47)(TRW) | 5.88 | .19 |
| Mo-1/2Ti(P & W) | 43.16 | 1.09 |
| Cb-1Zr(A)(P & W) | 125.78 | 3.73 |
| *Graphitar-Grade 80(U-M) | 55.30 | 7.95 |
| *Graphitar-Grade 50(U-M) | 71.60 | 10.90 |

*These values estimated from data obtained at 70°F.

the greatest resistance to cavitation-erosion attack among those tested in mercury at 500°F. However, it is believed that final check tests in a flowing facility similar to the University of Michigan mercury tunnel would be desirable.

Although it has been indicated that considerable difficulty was encountered in fabricating the single-crystal tungsten, it is believed that these difficulties could be overcome if time and funds for further experimentation were available so that a test in 500°F mercury could be accomplished. Since the only specimen tested ranked among the best materials, such a continued effort would be desirable to obtain the performance of other closely related materials.

While the teflon coating was unsuccessful, it may be that other coating materials and perhaps more suitable bonding procedures would provide useful materials in this context. Again, additional time and funding are required.

# CHAPTER VII

## MECHANICAL PROPERTIES DATA FOR THE TEST MATERIALS AND PRELIMINARY CORRELATIONS

Presently, the only mechanical properties data available for all of the materials tested in this investigation consists of values for the hardness. In addition, fairly complete properties are available for both grades of graphitar tested.

It is useful to attempt to obtain a qualitative correlation between the cavitation data and the corresponding hardness data. In Table 9 the materials tested in this study are rated according to their cavitation resistance based on average MDP rate, with the BG-42 ($R_c$ = 64) and the Blue Chip Tool Steel being the most resistant and each having a rating of "1". The Graphitar-Grade 50 was damaged the most and has a rating of "9". The hardness values for all the materials are also listed along with a rating based on hardness. The material with the greatest value of hardness is given a rating of "1", while the softest is given a rating of "9". There is quite good agreement between the MDP rating and the hardness rating. Only in minor instances is there disagreement. It appears that the cavitation resistance of these materials correlates quite well with hardness on a qualitative basis. Of course,

## TABLE 9

## HARDNESS DATA AND PRELIMINARY CORRELATIONS

| Material | MDP Rating | Hardness | Hardness Rating |
|---|---|---|---|
| BG-42 ($R_c$ = 64)(TRW) | 1 | 64 $R_c$ | 1 |
| Blue Chip Tool Steel(TRW) | 1 | 64 $R_c$ | 1 |
| BG-42 ($R_c$ = 53)(TRW) | 4 | 53 $R_c$ | 3 |
| Single Crystal Tungsten(U-M) | 3 | 32 $R_c$ | 5 |
| BG-42 ($R_c$ = 47)(TRW) | 5 | 47 $R_c$ | 4 |
| Mo-1/2Ti(P & W) | 6 | 7 $R_c$ | 6 |
| Cb-1Zr(A)(P & W) | 7 | 81 $R_f$ | 7 |
| Graphitar-Grade 80(U-M) | 8 | 80* | 9 |
| Graphitar-Grade 50(U-M) | 9 | 100* | 8 |

*Average Scleroscope Hardness.

hardness has been selected by many past investigators as the best measure of the ability of a material to resist cavitation-erosion attack.

The graphitar-grade 50 and graphitar-grade 80 have average compressive strengths of 35,000 psi and 20,000 psi, respectively. However, the grade 80 appears to be the most cavitation resistant of the two, despite having the lower compressive strength, and also the lower hardness.

Obviously, a complete correlation of cavitation data with the applicable mechanical properties data demands full knowledge of the appropriate properties and a suitable digital computer program for analysis. Such a study has been undertaken by this laboratory,[24,25] for materials tested under an NSF grant.

# CHAPTER VIII

## SUMMARY AND CONCLUSIONS

The experimental investigations described in this report have resulted in a qualitative rating of the materials tested based on ability to resist cavitation-erosion attack in mercury at 500°F. It was found that the BG-42 ($R_c$ = 64) and the Blue Chip Tool Steel were the most resistant, while the single-crystal tungsten, BG-42 ($R_c$ = 53), and BG-42 ($R_c$ = 47) ranked third, fourth, and fifth, respectively. The Mo-1/2Ti, Cb-1Zr(A), and the two grades of graphitar tested all suffered much more severe damage. Presumably, qualitative rankings such as these could serve as a materials guide for the designer of bearings, serving to indicate those materials which exhibit the greatest resistance to cavitation-erosion attack among those tested in mercury at 500°F.

It is believed that corrosion effects in these investigations were negligible since there was essentially no observable attack in those areas which were submerged in the fluid but not subjected to the cavitation action.

The use of teflon as a protective coating against cavitation-erosion attack in mercury at 350°F apparently does not offer much promise based on the tests conducted in this laboratory.

Preliminary qualitative correlations of the cavitation data with hardness indicate that in these studies hardness alone is a good indicator of the ability of a material to withstand cavitation-erosion attack.

Further tests on single-crystal tungsten in the vibratory facility and of all the promising materials in a flowing system would be highly desirable. In addition, tests of other coating materials would be useful.

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