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Technical Report No. 5

Ultrasonic-Induced Cavitation Studies in Lithium at Elevated Temperatures

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Financial Support Provided by:

National Science Foundation
(Grant G-22529)

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

May, 1966

ACKNOWLEDGMENTS

Financial support for this investigation was provided by a grant from the National Science Foundation. Mechanical properties data supplied by Pratt & Whitney Aircraft (CANEL) is also gratefully acknowledged.

Special thanks are also due Dr. Clarence A. Siebert, Professor of Chemical and Metallurgical Engineering, and Dr. M. John Robinson, Lecturer in Nuclear Engineering, for many helpful suggestions and continuing interest in this project; Mr. Richard L. Crandall, Research Assistant, Computing Center, for much assistance in the proper use of the Least Mean Squares Regression Program used for data correlation and the proper interpretation of results; Mr. Edward Rupke, Instrument Shop Supervisor, Mr. William Rekewitz, Instrument Shop Foreman, and Mr. John Love, Instrument Maker, for many helpful suggestions and prompt service in fabricating all of the test specimens and special hardware required; and Mr. Allen R. Schaedel, Research Assistant in the Department of Nuclear Engineering, for many helpful suggestions, stimulating conversation, and continuing interest in this project.

ABSTRACT

Ultrasonic-induced cavitation studies have been conducted in lithium at 500°F and 1500°F for seven materials including refractory alloys and stainless steels.

At 500°F the refractory alloys, T-111 and T-222(A), are the most resistant to cavitation damage among the materials tested, while the Cb-1Zr(A) is the least resistant. At 1500°F the refractory alloy, T-111, is the most resistant, while the stainless steels are the least resistant. The damage suffered by a material at 1500°F was less than that measured at 500°F. This indicates that "thermodynamic effects" are significant in lithium at 1500°F.

Computer correlations of the cavitation damage data at 500°F with applicable mechanical properties indicate that elongation, yield strength, true strain energy, hardness, and tensile strength are good individual indicators of cavitation resistance in these tests. Correlations of the combined set of lithium data at 500°F and 1500°F require that suitable fluid properties be included in the analysis.

TABLE OF CONTENTS

Chapter | Page

LIST OF FIGURES

LIST OF TABLES

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 a containing wall. The effects produced as a consequence of cavitation are twofold. First, for flow processes, it generally decreases the transferable energy and 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.

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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 has recently been formed to attempt to relate these various phenomena and form applicable test standards.

In the SNAP application the minimization of size and weight and the maximization of temperature are of over-riding importance, so that 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 often 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] Such studies have been most often 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 not until very recently have tests been conducted in high-temperature liquid metals as sodium,[3,12,13,32] lead-bismuth alloy,[14,15] mercury,[19,32] and, of course, the present tests in lithium.

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. Preliminary cavitation resistance ratings of materials tested in the venturi and vibratory facilities in both water and mercury show many similarities.[19] 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[20] 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 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. As discussed later, corrosion has apparently been quite negligible in the liquid metal tests in this laboratory.

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 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, elastic modulus, 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 have 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.[7,21] 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 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.[22] The movement of

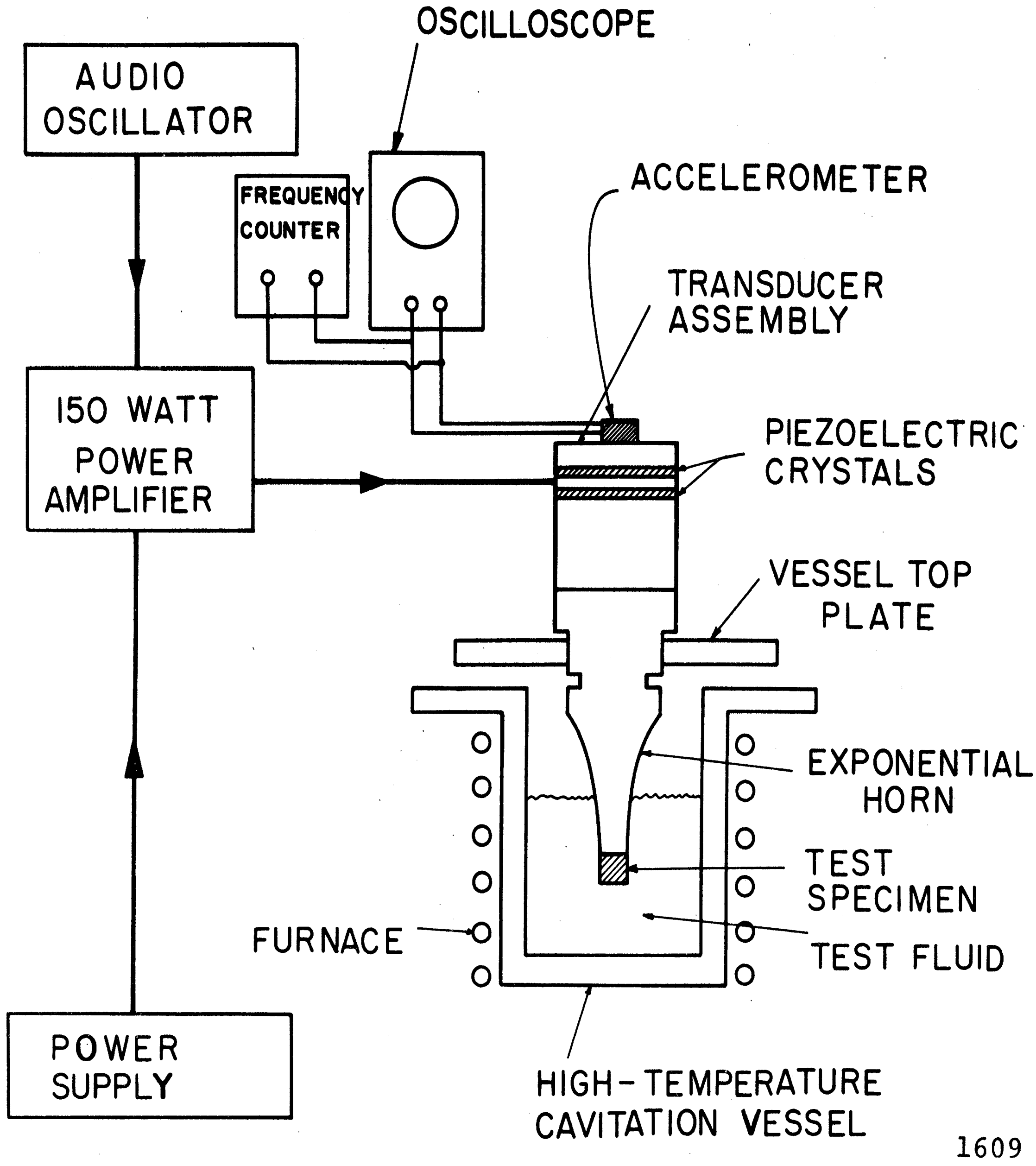

Figure 1. Block Diagram of the High-Temperature Ultrasonic Vibratory Facility

the horn tip, to which a test specimen is 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 installed in 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, voltmeter, oscilloscope, timer, temperature controller, furnace, 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

In a recent test series cavitation-erosion data have been obtained in lithium at 500°F and 1500°F for 304 stainless steel (U-M), 316 stainless steel (U-M), T-111 (P & W) (Ta-8W-2Hf), T-222(A) (P & W) (Ta-9.5W-2.5Hf-.05C), Mo-1/2Ti (P & W), Cb-1Zr (P & W), and Cb-1Zr(A) (P & W).* The choice of lithium as the primary reactor coolant in the

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*The notations (U-M) and (P & W) following the specimen materials indicate the source of the material, namely, The University of Michigan and Pratt & Whitney Aircraft (CANEL), respectively; whereas the notation (A) denotes an annealed condition of the material.

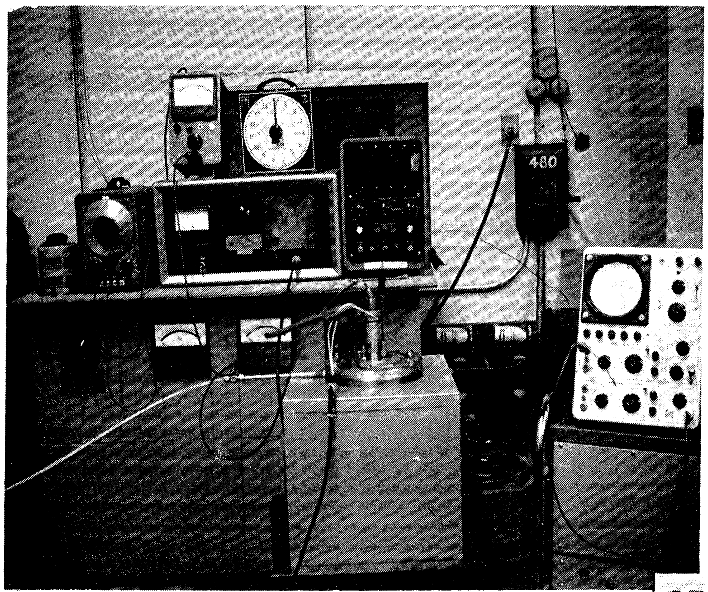

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Figure 2. High-Temperature Cavitation Facility

SNAP-50 nuclear auxiliary powerplant and a lack of high-temperature cavitation data in this fluid are the major reasons for the present studies. This investigation is part of a continuing effort whose objectives are the determination of materials showing the greatest cavitation resistance in water at room temperature and in liquid metals at elevated temperatures; the determination of material-fluid parameters to correlate damage and allow its à priori prediction; and the development of a relationship between the damage incurred in the venturi facilities operated by this laboratory and the damage noted in the present vibratory studies. Previously, cavitation-erosion results obtained in lead-bismuth alloy at 500°F and 1500°F,[23] in mercury at 70°F and 500°F,[19] and in water at 70°F[19] utilizing the vibratory facility were reported.

CHAPTER II

CAVITATION STUDIES IN LITHIUM AT 500°F

A. Experimental Procedure

The seven materials tested at 500°F were 304 stainless steel (U-M), 316 stainless steel (U-M), T-111 (P & W) (Ta-8W-2Hf), T-222(A) (P & W) (Ta-9.5W-2.5Hf-.05C), Mo-1/2Ti (P & W), Cb-1Zr (P & W), and Cb-1Zr(A) (P & W). 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 lithium test fluid is 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. Since the piezoelectric crystals must be maintained at a temperature below 150°F, the top plate of the cavitation vessel is cooled by circulating water through a copper cooling coil that is brazed to the top plate. In addition a fan in close proximity to the crystals provides additional cooling. 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 inch into the lithium. The double amplitude at the specimen was maintained at $\sim$ 2 mils for all the tests, as determined by a precision accelerometer,[24] previously calibrated by visual observation of the horn tip with a microscope. An argon cover gas was maintained over the molten lithium at an overpressure of 1.1 psig throughout the 500°F investigations. The value of argon cover gas pressure is chosen for a given fluid-temperature combination such that the suppression pressure, i.e., the difference between local pressure at the specimen and vapor pressure of the fluid, is approximately constant for all investigations involving a variety of fluid-temperature combinations. In addition it was desired that the argon cover gas pressure be positive so that in-leakage of oxygen would not occur. Test duration for each material was 10 hours with the exception of the Cb-1Zr(A) which showed gross erosion after 6 hours of testing. At frequent intervals the specimens were visually examined, photographed, and carefully weighed.

The lithium used in these investigations was obtained from the Lithium Corporation of America, Inc. (Bessemer City, North Carolina) in the form of individual 1/2 pound cylindrical ingots sized to fit into the cavitation vessel and fill it, upon melting, to the desired level. The ingots were shipped, hermetically sealed in individual tin cans, which were easily opened for charging the lithium into the experimental vessel. The solid ingot was first placed in a clean stainless steel beaker which fit snugly into the cavitation vessel and provided for easy removal and disposal at the conclusion of a test. The loading operation was carried out at room temperature (where oxidation would be at a minimum rate) in a glove box under an argon atmosphere. The sealed vessel was then removed from the glove box and placed in the furnace where the lithium was brought to the required test temperature of 500°F. Each test was conducted with a new, fresh lithium ingot. This procedure eliminated the need for transferring the molten lithium to and from the experimental vessel and eliminated trace heaters, hot traps, cold traps, valves, etc., from the system design. This procedure resulted in a very economical design and kept oxide contamination relatively uniform and at a minimum, since a fresh ingot was used for each test.

At the conclusion of each investigation the vessel was removed from the furnace and quickly air-cooled to a temperature of 375°F, which is slightly above the melting point of 362°F, and below the ignition temperature of 392°F. With the lithium at 375°F the vessel top plate was unbolted, and the ultrasonic transducer and specimen were quickly removed from the molten lithium while maintaining the argon cover gas over the test fluid. The vessel was then covered and the lithium allowed to solidify in the stainless steel beaker. The beaker and used ingot were then easily removed from the vessel and discarded. The next run made use of a new clean stainless steel beaker and a fresh lithium ingot.

After solidification, any excess lithium adhering to the test specimen and the exponential horn was easily removed by dipping the end of the transducer into a large container of cold water placed outdoors. The reaction of lithium with water under these conditions was not very vigorous and resulted in complete removal of the excess lithium metal in a few minutes. The test specimen was then removed from the tip of the transducer and weighed.

This complete procedure of ingot loading, unloading, and specimen retrieval was found to be completely safe and was carried out more than 50 times without incident. Personnel wore suitable protective clothing during the unloading and specimen retrieval operations.

B. Experimental Results

The cavitation results obtained at 500°F in lithium 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. However, 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 expression for computing the MDP of a given material is of the form:

$$MDP(mils) = C \cdot W$$

where W is the weight loss expressed in mg. and C is a constant for the given material. Values of the constant, C, for computing the MDP of all the materials tested, along with their densities, are presented in Table 1.

Table 2 summarizes the cavitation results obtained in lithium at 500°F. Figure 3 is a plot of accumulative weight loss versus test

TABLE 1

RELATION BETWEEN WEIGHT LOSS AND MDP
(MDP = C·W)

Material	Density	Constant, C*
304 Stainless Steel	7.85 g./cc.	.033
316 Stainless Steel	7.85	.033
T-111	17.66	.0147
T-222(A)	17.66	.0147
Mo-1/2Ti	10.22	.0253
Cb-1Zr	8.72	.0296
Cb-1Zr(A)	8.72	.0296

*Valid when MDP is expressed in mils and W is expressed in mg.

TABLE 2

SUMMARY OF CAVITATION RESULTS IN LITHIUM AT 500°F

Material	Avg. Wt. Loss Rate	Average MDP Rate
T-111 (P & W)	1.70 mg./hr.	0.03 mils/hr.
T-222(A) (P & W)	2.48	0.04
Mo-1/2Ti (P & W)	4.61	0.12
Cb-1Zr (P & W)	5.02	0.15
304 SS (U-M)	10.42	0.34
316 SS (U-M)	10.91	0.36
Cb-1Zr(A) (P & W)	33.70	1.00

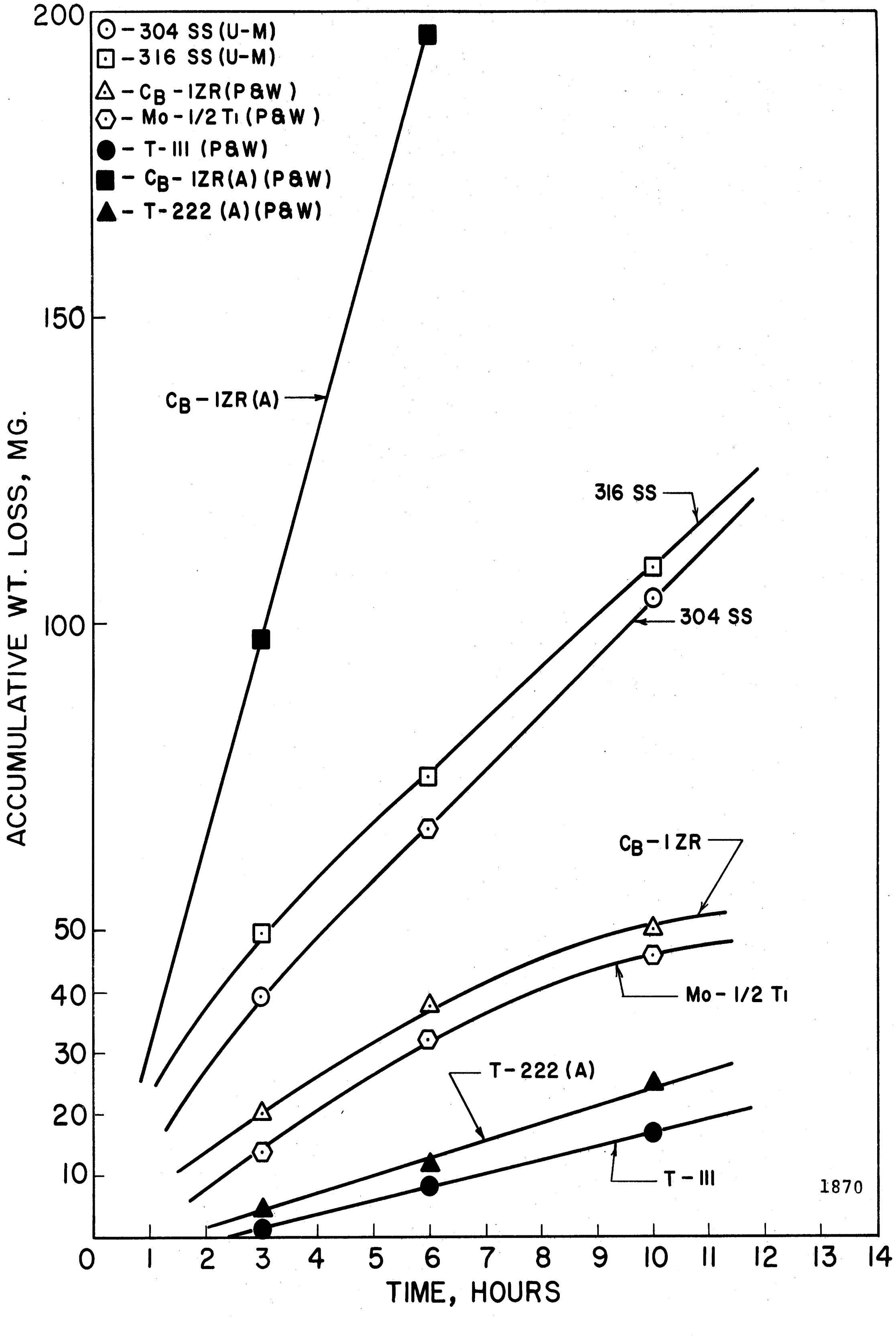


Figure 3. Effect of Cavitation Test Duration on Weight Loss at 500°F in Lithium

duration, while Figure 4 is the corresponding plot of accumulative MDP versus test duration for the seven materials tested.

On the basis of either average weight loss rate or average MDP rate it is clear that the T-111 is the most cavitation resistant of the materials tested, while the T-222(A) is about 30% less resistant. These materials exhibited average MDP rates of 0.03 mils/hour and 0.04 mils/hour, respectively. The refractory materials, Mo-1/2Ti and Cb-1Zr, rank third and fourth, respectively, with average MDP rates of 0.12 mils/hour and 0.15 mils/hour, respectively. The 304 stainless steel and 316 stainless steel were about equally resistant but suffered 11X to 12X the damage incurred by the T-111. The Cb-1Zr(A) was the least resistant to cavitation damage of the materials tested with an average MDP rate of 1.00 mils/hour, approximately 33X greater than the rate of damage exhibited by the T-111. It is clear from Figures 3 and 4 that the rate of erosion for each individual material is approximately constant for most of the test. In some cases the rate of damage is not constant in the early part of the test due to lack of temperature equilibrium of the ultrasonic transducer and the smooth surface of the specimen face which appears to prevent maintenance of a stable bubble cloud. In some cases the rate of damage decreases with increasing test duration. This is probably due to a decrease in the number of bubbles generated by some types of roughened surfaces.[33]

Photographs of the test specimens at the conclusion of the cavitation experiment are presented in Figure 5. The materials are arranged in order of decreasing resistance to cavitation damage. Note the very

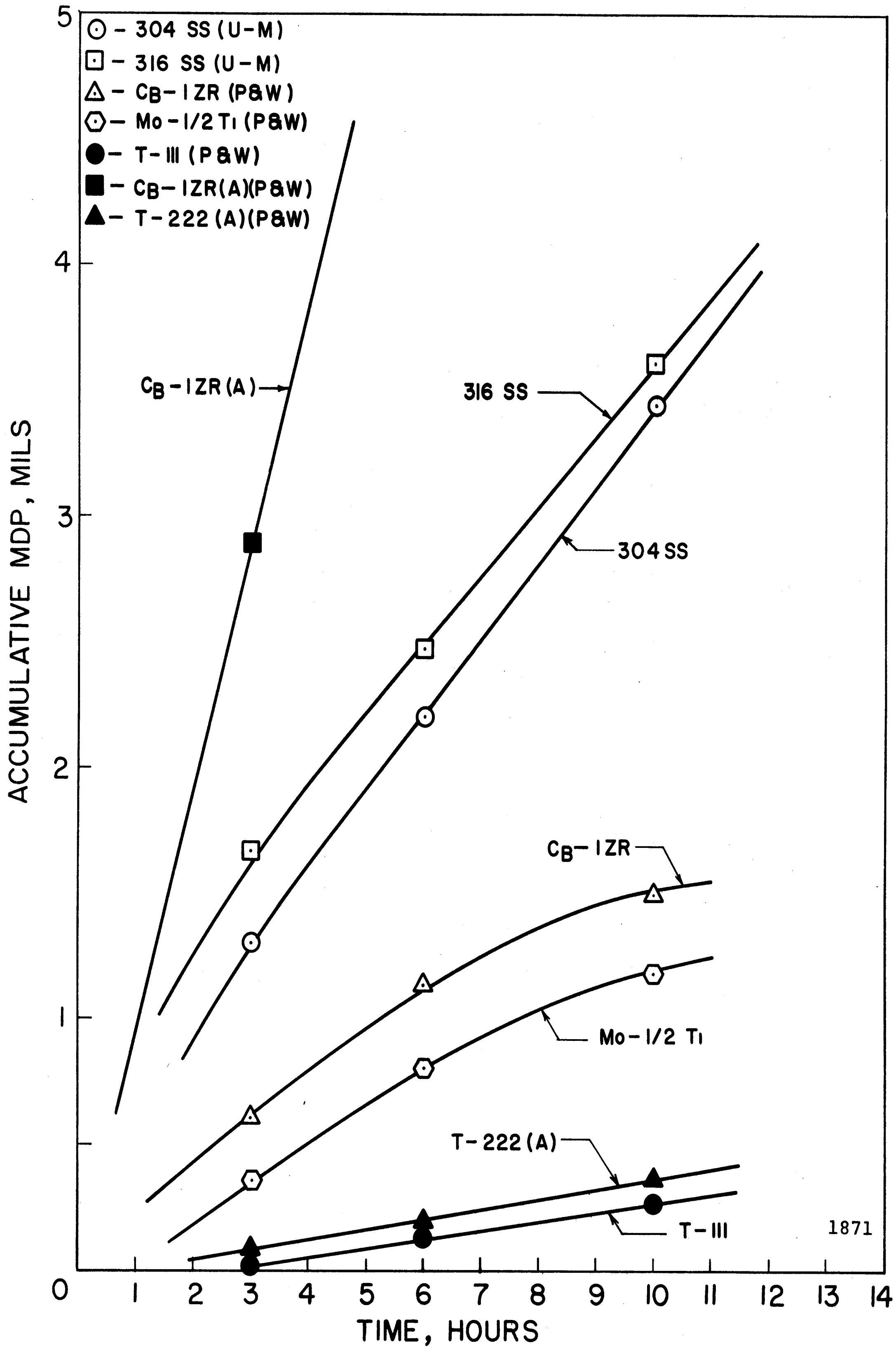
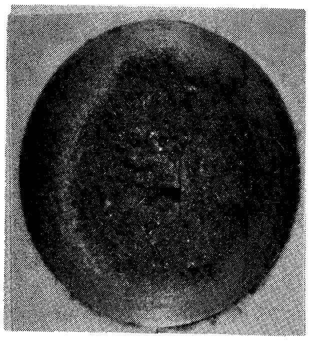
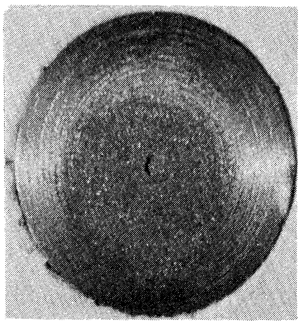


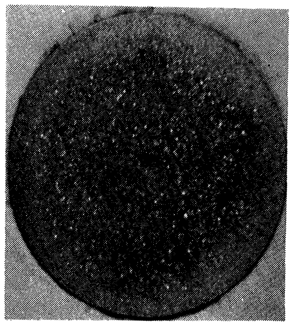
Figure 4. Effect of Cavitation Test Duration on MDP at 500°F in Lithium



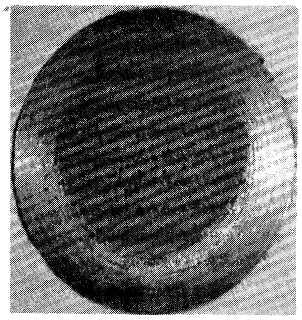
(1) T-111(P & W)
10 Hour Exposure



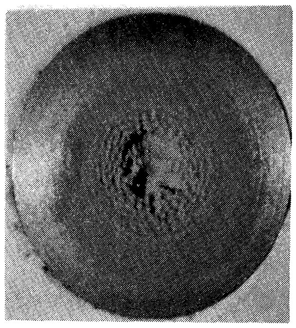
(2) T-222(A)(P & W)
10 Hour Exposure



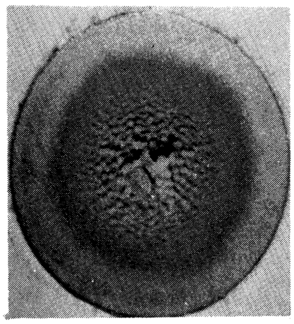
(3) Mo-1/2Ti(P & W)
10 Hour Exposure



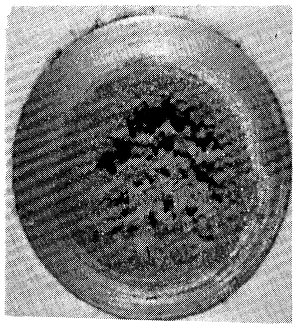
(4) Cb-1Zr(P & W)
10 Hour Exposure



(5) 304 SS(U-M)
10 Hour Exposure



(6) 316 SS(U-M)
10 Hour Exposure



(7) Cb-1Zr(A)(P & W)
6 Hour Exposure

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Figure 5. Specimens Subjected to Cavitation Damage in Lithium at 500°F

heavy pitting suffered by the Cb-1Zr(A), 304 stainless steel, and 316 stainless steel. The damage is concentrated at the central portion of the specimen with the outer rim nearly undamaged. It is thought that the lack of damage in the outer annular ring is due to vortex action[25,26] near the edge of the vibrating horn which results in higher pressures adjacent to the horn in this region and, hence, fewer bubbles. The damage suffered by the other specimens is somewhat more uniform with the exception of the T-111. However, the undamaged outer rim is present in all cases.

It has been noted in these tests with different fluids all conducted at a constant suppression pressure (lead-bismuth, mercury, water, and lithium) that the heavier fluids give quite a uniform damage pattern. The water patterns are intermediate between the heavy liquid metals and the lithium here observed, in that for the lighter fluids the damage tends to become concentrated toward the center and less pronounced on the outer edge. This may be due to the fact that NPSH is much greater for the light fluids than for the heavier, since suppression pressure was constant, i.e., the "flows" may not be properly modeled.

Detailed examination of the 303 stainless steel exponential horn, the 316 stainless steel beaker, and the sides of the various test specimens, all of which are not subject to cavitation, but are submerged in the test fluid, indicates that corrosion effects in the absence of cavitation in these investigations were negligible, as would be expected for the short durations involved.[34]

CHAPTER III

CAVITATION STUDIES IN LITHIUM AT 1500°F

A. Experimental Procedure

The materials tested at 1500°F were the 304 stainless steel, 316 stainless steel, T-111, and Cb-1Zr(A), which were also tested at 500°F. The experimental procedure for the 1500°F tests was similar to that employed for the 500°F tests discussed previously. However, for the 1500°F tests the argon cover gas pressure was raised to 1.2 psig since the vapor pressure at this temperature is approximately 0.1 psi. Total test duration was 10 hours in all cases with the exception of the T-111 which was cavitated for 30 hours. Frequent inspections and weighings were made. At the conclusion of a test the cavitation vessel remained in the furnace until it had cooled to 500°F. Then it was removed and air-cooled until the lithium temperature reached the required 375°F at which point the specimen was removed.

The cavitation tests at 1500°F were conducted at a frequency of $\sim$18 Kc./sec. and a double amplitude of $\sim$2 mils at the specimen. The submergence was maintained at $\sim$1 inch for all the tests.

B. Experimental Results

The data obtained in lithium at 1500°F will be displayed as accumulative weight loss versus test duration and also as accumulative mean depth of penetration (MDP) versus test duration. The expression and constants given previously for computation of MDP as a function of weight loss are applicable at 1500°F also.

Table 3 summarizes the cavitation results obtained in lithium at 1500°F. Figure 6 is a plot of accumulative weight loss versus test duration for the four materials tested, while Figure 7 is the corresponding plot of accumulative MDP versus test duration.

On the basis of either weight loss or MDP the refractory alloy T-111 exhibited the greatest resistance to cavitation damage at 1500°F. This was also true at 500°F. The refractory alloy Cb-1Zr(A) which suffered gross damage at 500°F and ranked last had an average MDP rate of only 0.017 mils/hour at 1500°F and ranked second. The two stainless steels were the least resistant of the four materials tested at 1500°F, as expected from mechanical properties considerations. The 316 stainless steel sustained 7X the damage rate of the T-111 whereas the 304 stainless steel exhibited 9X the damage rate. It is clear from Figures 6 and 7 that the rate of erosion for each individual material was approximately constant for all the materials tested during most of the test.

Photographs of the test specimens at the conclusion of the cavitation experiment are presented in Figure 8. The materials are arranged in order of decreasing resistance to cavitation damage. Very little damage is apparent on any of the specimens.

Corrosion effects on the non-cavitated surfaces in the tests at 1500°F were negligible, as was also the case for the 500°F tests.

TABLE 3

SUMMARY OF CAVITATION RESULTS IN LITHIUM AT 1500°F

Material	Avg. Wt. Loss Rate	Average MDP Rate
T-111 (P & W)	0.26 mg./hr.	0.004 mils/hr.
Cb-1Zr(A) (P & W)	0.58	0.017
316 SS (U-M)	0.81	0.027
304 SS (U-M)	1.04	0.034

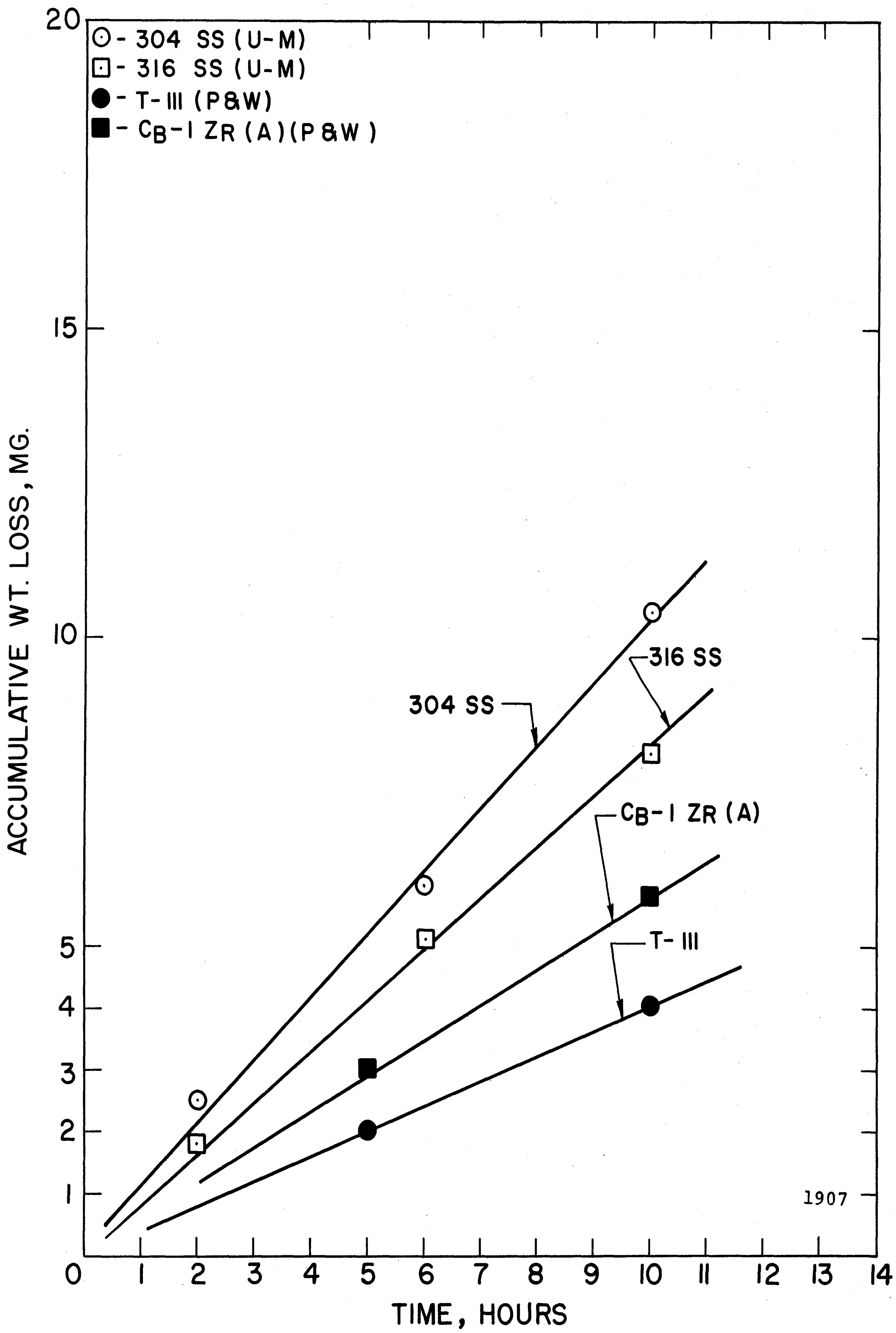


Figure 6. Effect of Cavitation Test Duration on Weight Loss at 1500°F in Lithium

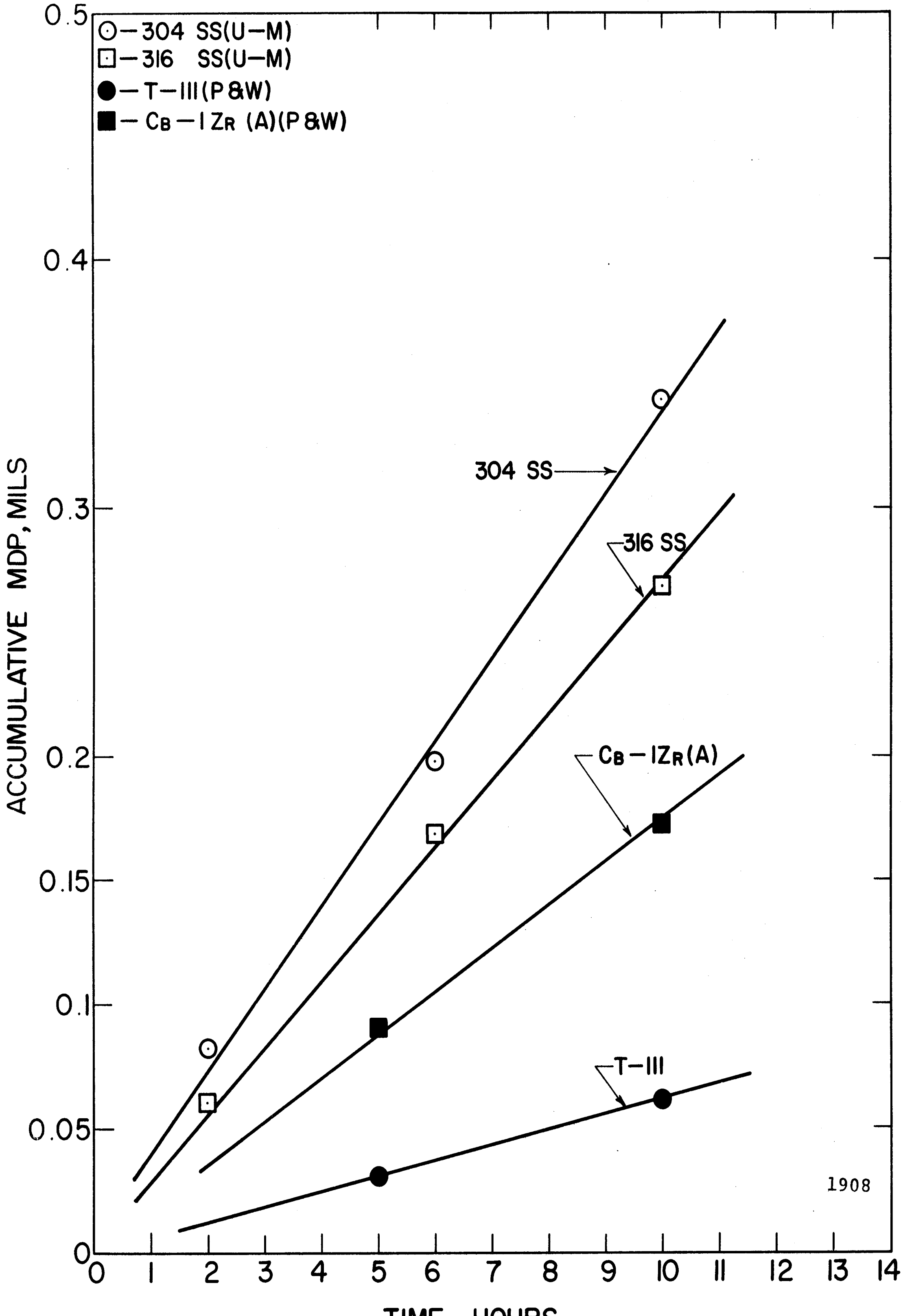
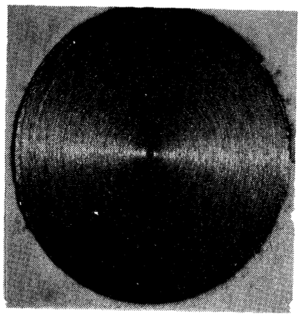
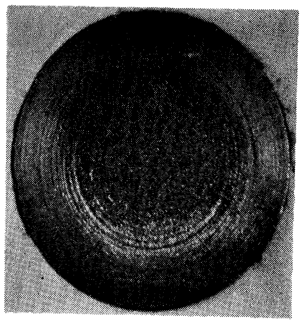


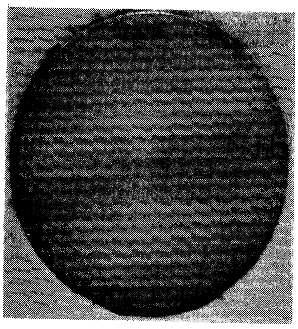
Figure 7. Effect of Cavitation Test Duration on MDP at 1500°F in Lithium



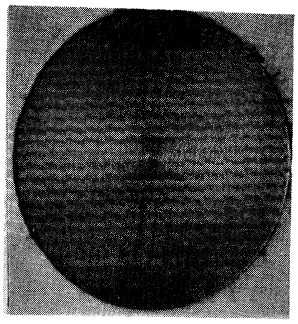
(1) T-111(P & W)
10 Hour Exposure



(2) Cb-1Zr(A)(P & W)
10 Hour Exposure



(3) 316 SS(U-M)
10 Hour Exposure



(4) 304 SS(U-M)
10 Hour Exposure

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Figure 8. Specimens Subjected to Cavitation Damage in Lithium at 1500°F

CHAPTER IV

COMPARISON OF CAVITATION RESULTS AT 500°F AND 1500°F

Table 4 summarizes the cavitation data obtained in lithium at 500°F and 1500°F. The seven materials tested at 500°F and four tested at 1500°F have been rated on the basis of cavitation resistance as determined by MDP, with a rating of "1" indicating the most cavitation resistant material, while a rating of "7" at 500°F and "4" at 1500°F would denote that material most susceptible to cavitation damage at each temperature.

The tantalum alloys, T-111 and T-222(A), are the most resistant to cavitation damage at 500°F, while the T-111 is the most resistant at 1500°F, T-222(A) not having been tested at this temperature. The Cb-1Zr(A) which had a rating of "7" at 500°F ranked second among the four materials tested at 1500°F. The 304 and 316 stainless steel were among the least resistant materials at 500°F (although superior to Cb-1Zr(A)), but ranked last at 1500°F. Thus, the expected superior performance of the refractories at the higher temperature, due to their less temperature dependent mechanical properties, was verified. At both temperatures the T-111 was approximately 10X more resistant than the stainless steels.

TABLE 4

COMPARISON OF CAVITATION RESULTS AT 500°F AND 1500°F

Material	500°F (Avg. MDP Rate)	500°F Rating	1500°F (Avg. MDP Rate)	1500°F Rating
T-111	0.03 mils/hr.	1	0.004 mils/hr.	1
T-222(A)	0.04	2	--	--
Mo-1/2Ti	0.12	3	--	--
Cb-1Zr	0.15	4	--	--
304 SS	0.34	5	0.034	4
316 SS	0.36	6	0.027	3
Cb-1Zr(A)	1.00	7	0.017	2

It is important to note that for each of the four materials tested at both temperatures the amount of damage sustained by the specimen at 1500°F was less than that sustained at 500°F for constant testing time. The exact opposite behavior was noted in the cavitation tests conducted earlier in lead-bismuth alloy[23] and mercury[19] where the damage sustained by a given material at the higher temperature was greater than that measured at the lower temperature. One might expect this latter behavior due to the reduced strength of the materials at the elevated temperature. However, the variation of the fluid properties with temperature is also important and must be considered. A recent paper by Leith[27] presents predictions of cavitation damage in a vibratory facility exposed to atmospheric pressure for liquid metals as a function of temperature for a material possessing constant mechanical properties, i.e., not a function of temperature. Leith's interpretation of the previously available data indicates that the specific gravity, vapor pressure, viscosity, and surface tension are important fluid properties which affect the amount of damage sustained as a function of temperature. In the case of NaK, potassium, lithium, rubidium, cesium, and sodium, Leith concludes that cavitation damage as a function of temperature reaches a maximum at a temperature 15% to 20% up the melting-boiling range, falling off below and above this maximum damage temperature. The mechanical properties of several refractory alloys, such as T-111, T-222(A), Mo-1/2Ti, and Cb-1Zr, tested in our investigations are very weak functions of temperature, and Leith's analysis would apply more closely to these than to the stainless steels.

It is our present feeling that the trend in the lithium results can be explained primarily on the basis of cavitation "thermodynamic effects,"[35] as follows. At 1500°F the vapor pressure of lithium is many times greater than at 500°F. When the cavitation bubbles collapse at the higher temperature, the heat of condensation from the condensing vapor trapped within the bubble must be conducted into the surrounding fluid. If this does not occur rapidly enough, then the uncondensed vapor serves to cushion the bubble collapse with a resultant decrease in collapse pressures and reduced damage to the test specimens. This effect was not operative in the lead-bismuth tests since the vapor pressure was essentially nil even at 1500°F. In the mercury tests the temperature range (70°F to 500°F) was not sufficient to make the effect important.

CHAPTER V

TEMPERATURE DEPENDENCE OF CAVITATION DAMAGE IN LITHIUM

As previously mentioned, the damage suffered by all materials tested at 1500°F in lithium was less than the corresponding damage measured at 500°F. To obtain further information on this somewhat surprising result, the temperature dependence of cavitation damage in our vibratory rig in lithium for a few selected materials over the range from 500°F to 1500°F was investigated. The 304 stainless steel, T-111, and Cb-1Zr(A) were chosen for this purpose. The mechanical properties of the 304 stainless steel vary greatly over this temperature range, and the predictions of Leith[27] would not be expected to apply without introducing corrections for this effect. The mechanical properties of the refractory materials, T-111 and Cb-1Zr(A), are weak functions of temperature, so that their behavior should more clearly illustrate the effects of fluid property changes over this temperature range.

Cavitation damage data for 304 stainless steel was obtained at 400°F, 500°F, 700°F, 900°F, 1100°F, 1300°F, and 1500°F using the experimental procedure previously discussed. Total test duration at each temperature was 10 hours. Table 5 summarizes the data obtained for 304 stainless steel in lithium at the various temperatures. Figure 9 is a plot of average weight loss rate versus test temperature, while Figure 10 is the corresponding plot of average MDP rate versus test temperature.

TABLE 5

EFFECT OF TEMPERATURE ON CAVITATION DAMAGE
304 STAINLESS STEEL

Temperature	Avg. Wt. Loss Rate	Avg. MDP Rate
400°F	7.23 mg./hr.	0.24 mils/hr.
500	10.42	0.34
700	5.39	0.18
900	2.88	0.10
1100	1.50	0.05
1300	1.21	0.04
1500	1.04	0.03

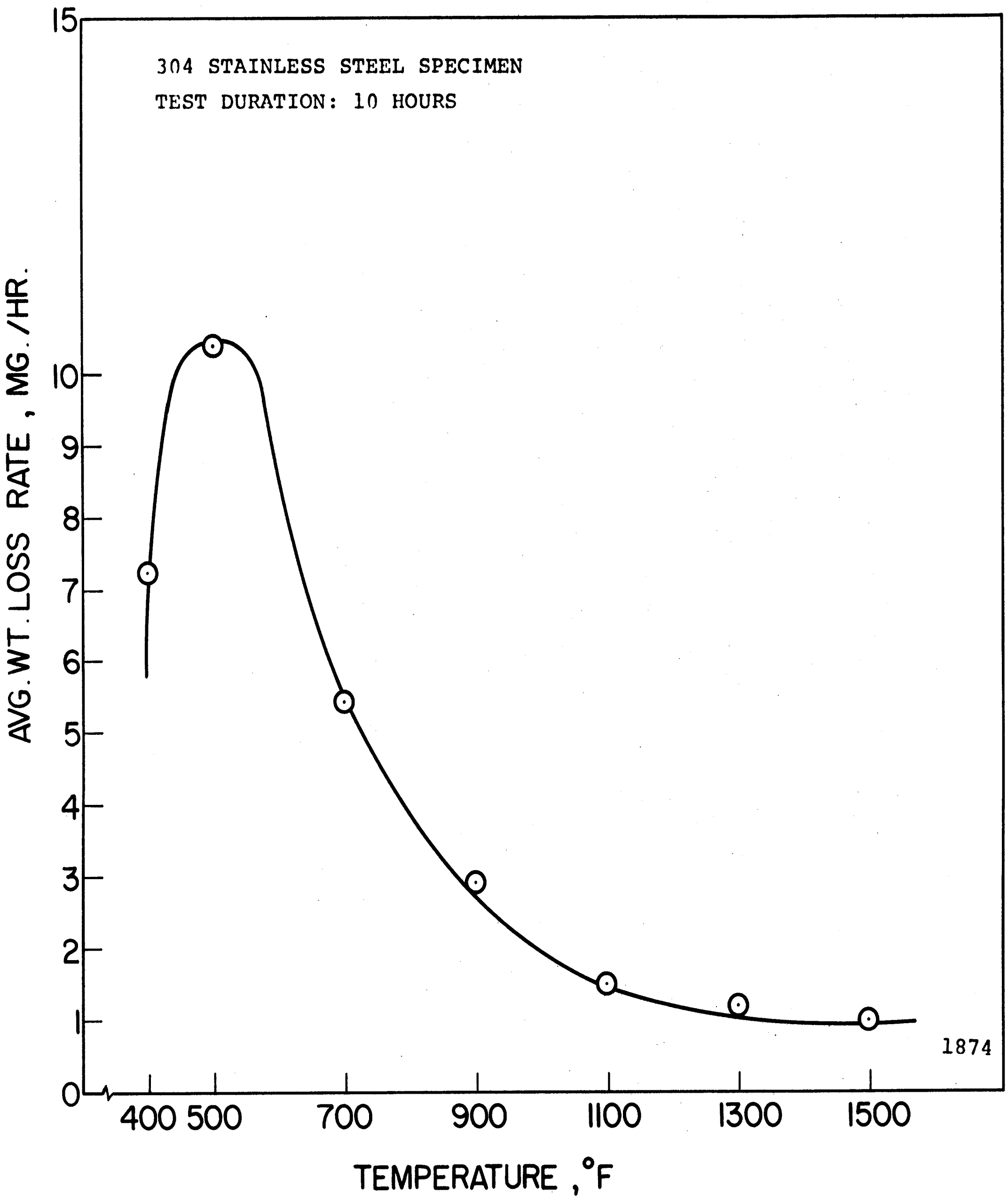

Figure 9. Effect of Temperature on Average Weight Loss Rate for 304 Stainless Steel

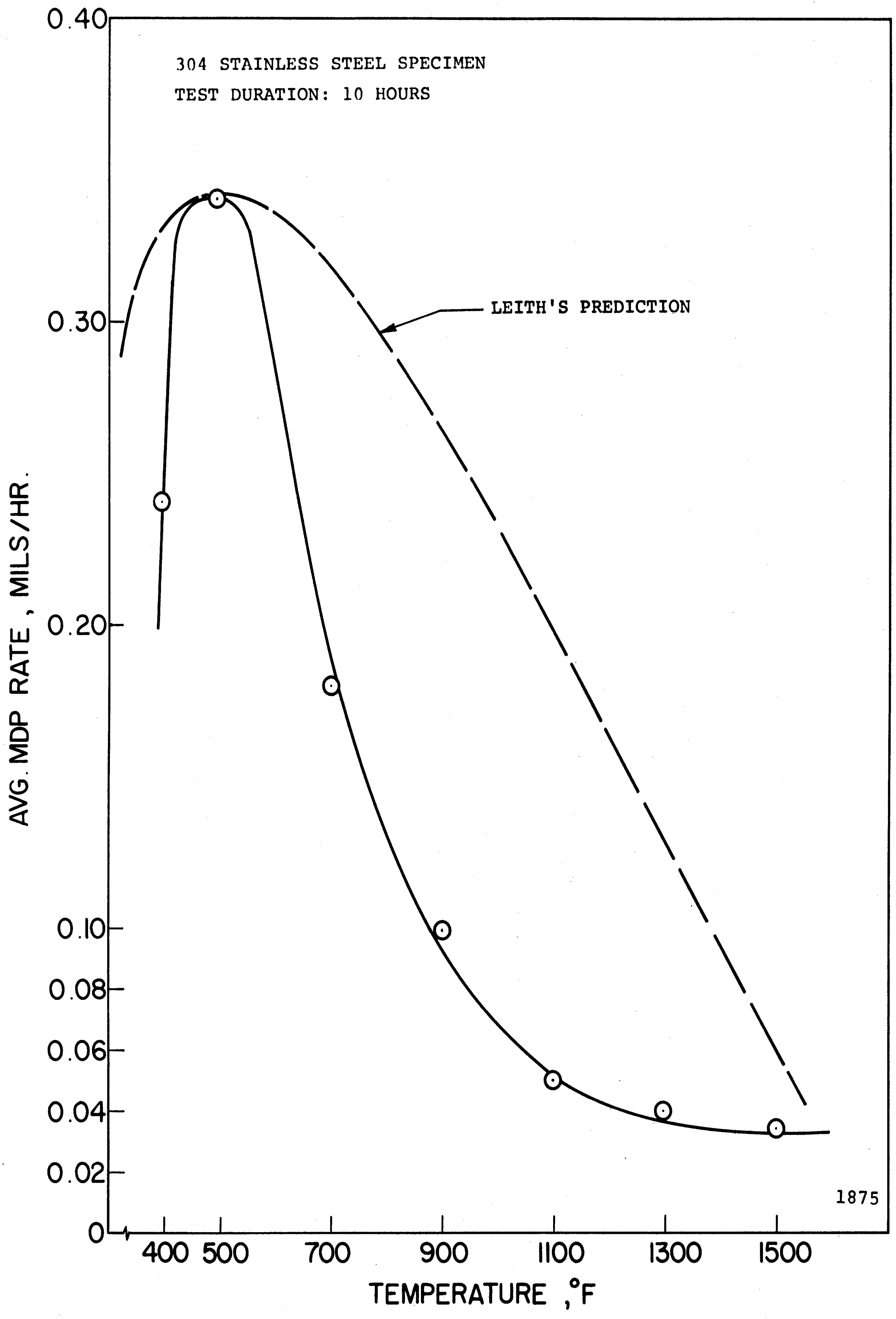

Figure 10. Effect of Temperature on Average MDP Rate for 304 Stainless Steel

The damage rate reaches a maximum at approximately 500°F and decreases thereafter, presumably due to the thermodynamic effects mentioned previously. The shape of the curve is similar to Leith's plot[27] of cavitation damage versus percentage of the melt-boil range for lithium. Leith's prediction for lithium is shown as a dashed curve in Figure 10.

Similar experimental data was obtained for T-111 and Cb-1Zr(A) at 500°F, 1000°F, and 1500°F. Total test duration at each temperature was 10 hours. Table 6 summarizes the data obtained, while Figures 11 and 12 are plots of average weight loss rate versus temperature and average MDP rate versus temperature, respectively, for the T-111 and Cb-1Zr(A). The T-111 damage rate decreases by a factor of 7 from 500°F to 1500°F while the Cb-1Zr(A) damage rate decreases by a factor of approximately 60 over the same temperature range. A very large decrease in damage in sodium tests in a similar facility over the same temperature range is reported by Hydronautics, Inc.,[13] although in their tests stainless steel appeared very much superior to the refractories at 1500°F. This is, of course, inconsistent with the mechanical properties of these materials (Tables 7 and 8).

TABLE 6

EFFECT OF TEMPERATURE ON CAVITATION DAMAGE
- T-111 AND Cb-1Zr(A)

Material	Temperature	Avg. Wt. Loss Rate	Avg. MDP Rate
T-111	500°F	1.70 mg./hr.	0.025 mils/hr.
	1000	0.61	0.009
	1500	0.26	0.004
Cb-1Zr(A)	500°F	33.70 mg./hr.	1.00 mils/hr.
	1000	8.10	0.24
	1500	0.58	0.02

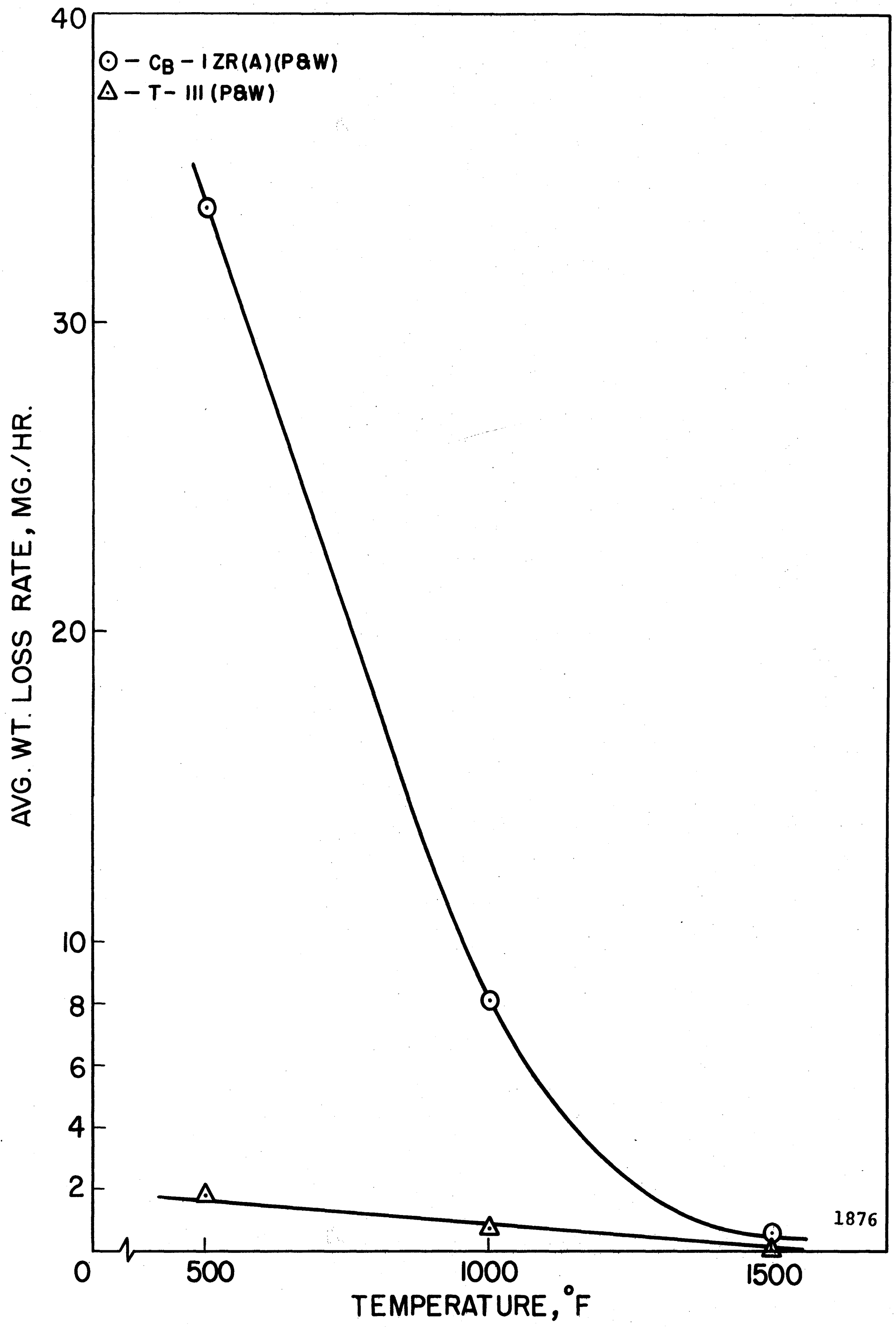

Figure 11. Effect of Temperature on Average Weight Loss Rate for T-111 and Cb-1Zr(A)

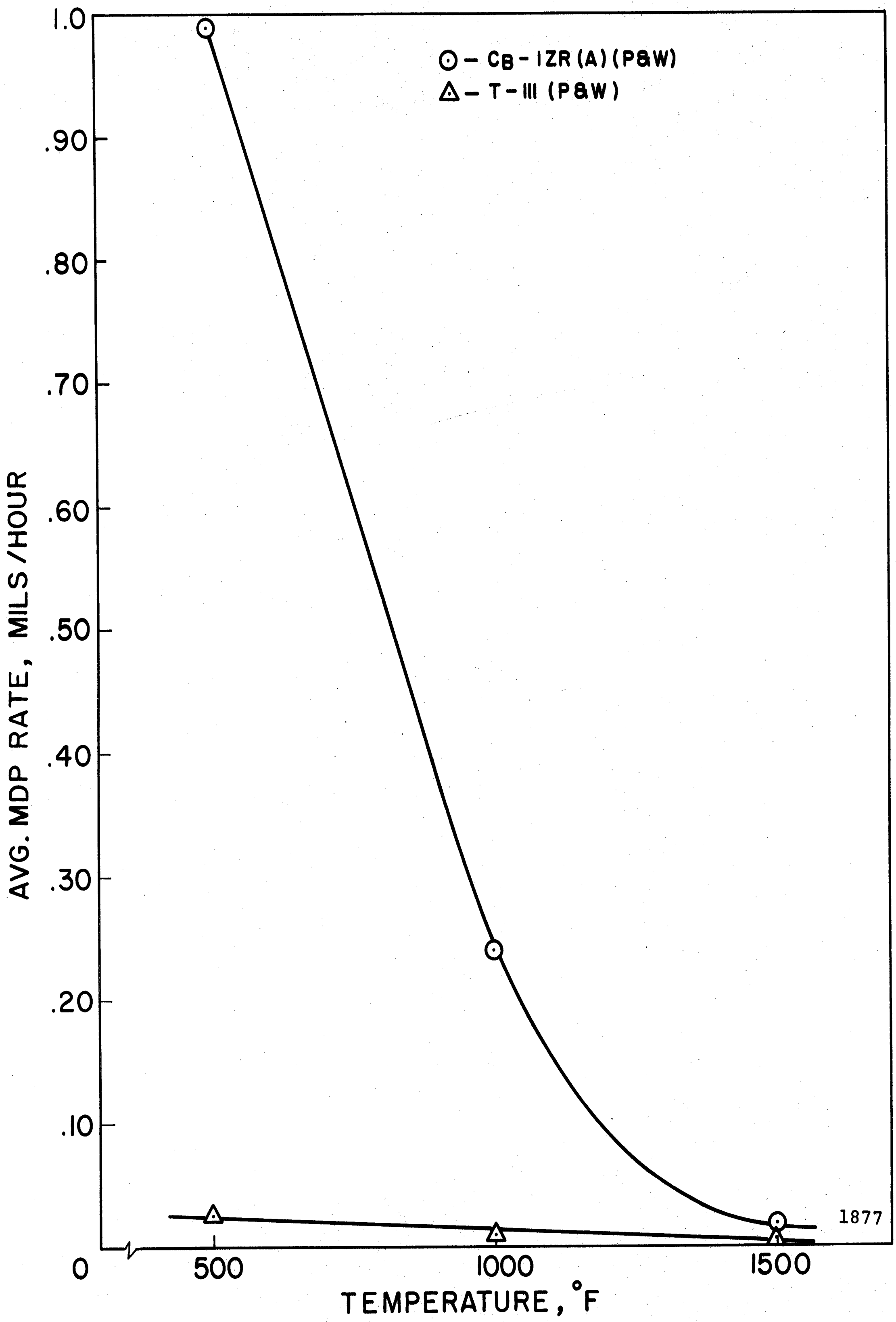

Figure 12. Effect of Temperature on Average MDP Rate for T-111 and Cb-1Zr(A)

CHAPTER VI

MECHANICAL PROPERTIES DATA FOR THE TEST MATERIALS

In order to obtain a meaningful correlation between the cavitation resistance of the various materials tested, their mechanical properties, and suitable fluid coupling parameters, it is absolutely essential that the applicable mechanical properties be measured at the test temperatures using tensile bars machined from the same bar stock as were the cavitation specimens. Otherwise the variations between material lots due to differences in heat-treat, cold work, etc., are too large to allow useful results. Accordingly, all cavitation test specimens, tensile bars, and special hot hardness specimens for each material were machined from the same piece of bar stock. It was found that handbook values or those supplied by vendors were not sufficiently accurate to be of use in this context even for relatively standard materials. It has been the experience of this laboratory that supposedly identical materials taken from different heats may have variations in applicable mechanical properties as great as 50%. Among the properties which appear important are tensile strength (TS), yield strength (YS), engineering strain energy (ESE), true strain energy (TSE), hardness (H), elongation (ELON), reduction in area (RA), and elastic modulus (E).

The mechanical properties data for the stainless steels and refractory materials were determined at 500°F and 1500°F at Pratt &

TABLE 7

MECHANICAL PROPERTIES DATA AT 500°F

Material	Tensile Strength psi	Yield Strength psi	Eng. Strain Energy psi	True Strain Energy psi		DPH Hardness 1.1 Kg.	Elongation %	Area Reduction %	Elastic Modulus psi
304 SS	92,500	56,700	16,150	18,200	37,200	154	30.8	72.9	26.0×10^6
316 SS	72,400	52,300	18,050	17,700	38,000	203	30.4	78.2	26.0×10^6
T-111	101,800	100,800	15,100	10,700	50,900	218	13.8	86.2	27.0×10^6
T-222	133,800	133,800	12,850	12,900	67,800	286	10.9	71.5	27.0×10^6
T-222(A)	92,300	63,400	20,650	33,800	42,200	209	23.6	66.9	27.0×10^6
Mo-1/2Ti	84,100	79,700	10,700	11,000	44,400	207	15.0	75.9	43.0×10^6
Cb-1Zr	54,700	54,700	6,450	5,185	27,700	133	12.7	88.7	14.5×10^6
Cb-1Zr(A)	25,000	11,600	8,100	3,780	7,890	71	35.9	92.2	14.5×10^6

TABLE 8

MECHANICAL PROPERTIES DATA AT 1500°F

Material	Tensile Strength psi	Yield Strength psi	Eng. Strain Energy psi	True Strain Energy psi		DPH Hardness 1.1 Kg.	Elongation %	Area Reduction %	Elastic Modulus psi
304 SS	21,900	18,400	4,600	1,640	2,410	66	19.7	30.5	18.0×10^6
316 SS	24,200	21,400	7,300	4,160	6,600	74	31.7	55.0	18.0×10^6
T-111	87,300	67,300	15,100	13,400	45,850	161	18.4	79.5	26.0×10^6
T-222	120,700	119,700	16,950	11,960	65,500	257	10.8	75.5	26.0×10^6
T-222(A)	85,500	41,800	16,950	14,030	38,500	140	22.1	72.9	26.0×10^6
Mo-1/2Ti	70,000	61,600	7,950	7,200	32,500	148	13.5	80.4	34.0×10^6
Cb-1Zr	47,600	47,100	5,650	3,460	19,500	106	11.6	84.1	13.5×10^6
Cb-1Zr(A)	28,000	9,700	6,700	2,200	7,050	67	26.5	91.1	13.5×10^6

rather than ductile failures are typical of cavitation damage. The remaining values listed in Tables 7 and 8 are rather commonly reported metallurgical properties and need no further explanatory remarks. The hardness values listed were measured with a diamond pyramid indenter and 1.1 Kg. load.

Examination of the mechanical properties data in Tables 7 and 8 strongly suggests that it will be difficult to correlate the combined lithium cavitation data at 500°F and 1500°F in terms of mechanical properties of the test materials only, although the experimental data and mechanical properties data at each temperature separately are consistent. As mentioned previously, the damage measured at 1500°F was less than that measured at 500°F even though all the strength and energy properties which have been considered of the test materials are reduced at the higher temperature. This again suggests the importance of the fluid properties and their role in determining cavitation damage. Further studies are presently being conducted in order to isolate the contribution of various fluid properties such as density, surface tension, net positive suction head, bulk modulus, kinematic viscosity, specific heat, thermal conductivity, heat of vaporization, thermal diffusivity, Prandtl Number, and vapor pressure. The present report discusses results only of correlations of the experimental data obtained at 500°F with applicable mechanical properties.

CHAPTER VII

CORRELATIONS OF CAVITATION DATA WITH MECHANICAL PROPERTIES DATA

A. Introduction

In order to fully investigate the dependence of cavitation resistance on the mechanical properties of the test materials and on the fluid properties, and to obtain a better understanding of the damage mechanisms involved, it is desirable to subject the experimentally-determined cavitation data and the appropriate mechanical and fluid properties data to a least mean squares fit by means of a suitable digital computer program. For these studies the University of Michigan IBM 7090 digital computer facility has been utilized along with a very sophisticated least mean squares stepwise regression program which was first proposed by Westervelt[30] and later revised by Crandall.[31] This program has been discussed in detail in previous reports.[19] However, for the sake of completeness in this report, the detailed explanation is included in the Appendix.

B. Single Property Correlations of Lithium Data at 500°F

As a first step in the analysis, an attempt was made to correlate the damage data obtained at 500°F with each mechanical property individually to determine the relative importance of each alone with respect to predicting the observed cavitation damage. Table 9 summarizes the results of this effort. The 10 properties considered, the statistically best predicting equations generated by the program for each property, the coefficient of determination (CD)* for the analysis, and the average absolute percent deviation (AAPD) for the analysis are noted. The predicting equations are arranged in order of decreasing statistical significance based on the coefficient of determination. It is seen that the elongation, yield strength, true strain energy based on reduction in area (TSER), hardness, and tensile strength are quite successful as single correlating parameters. The other mechanical properties listed do not suitably account for the experimental data on an individual basis.

It is further noted that the average MDP rate is inversely proportional to powers of yield strength, true strain energy based on reduction in area, hardness, and tensile strength. The dependence of average MDP rate on elongation is not as easily determined, since two terms in the predicting equation are functions of elongation, each contributing to the average MDP rate in an opposite manner. One might conclude that the cavitation resistance of a group of materials in lithium at 500°F could be at least qualitatively predicted on the basis of these five mechanical properties.

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*The coefficient of determination is a statistical quantity that can be interpreted as the proportion of the total variation in the dependent variable that is explained by the predicting equation. Its values range from 0 (no prediction) to 1.0 (perfect prediction).

TABLE 9

SUMMARY OF SINGLE PROPERTY CORRELATIONS--LITHIUM AT 500°F

Property	Predicting Equation	CD*	AAPD**
1. Elongation (ELON)	Avg. MDP Rate = $0.409 - 2.91\times10^{-3}(ELON)^2 + 9.34\times10^{-5}(ELON)^3$	0.992	14.1
2. Yield Strength (YS)	Avg. MDP Rate = $-0.899 + 43.40(YS)^{-1/3}$	0.959	3.2
3. True Strain Energy (TSER) (Based on Reduction in Area)	Avg. MDP Rate = $-0.494 + 1.32\times10^{2}(TSER)^{-1/2}$	0.929	31.7
4. Hardness (H) (DPH - 1.1 Kg. Load)	Avg. MDP Rate = $0.114 + 3.17\times10^{5}(H)^{-3}$	0.924	37.3
5. Tensile Strength (TS)	Avg. MDP Rate = $0.143 + 1.34\times10^{13}(TS)^{-3}$	0.920	40.3
6. True Strain Energy (TSEE) (Based on Elongation)	Avg. MDP Rate = $0.129 + 4.17\times10^{10}(TSEE)^{-3}$	0.839	44.2
7. Acoustic Impedance Ratio (AI)	Avg. MDP Rate = $0.028 + 6.36\times10^{2}(AI)^{2}$	0.705	33.1
8. Elastic Modulus (E)	Avg. MDP Rate = $0.035 + 1.139\times10^{14}(E)^{-2}$	0.647	73.9
9. Reduction in Area (RA)	Avg. MDP Rate = $-0.244 + 1.01\times10^{-6}(RA)^{3}$	0.612	25.1
10. Engineering Strain Energy (ESE)	Avg. MDP Rate = $0.055 + 2.74\times10^{3}(ESE)^{-1}$	0.520	87.3

*Coefficient of Determination

**Average Absolute % Deviation

C. Ten Property Correlations of Lithium Data at 500°F

Further attempts at complete correlations of the experimental data were conducted in which all ten mechanical properties noted previously, each raised to ten exponents, were possible terms in the predicting equation. Hence a total of 100 terms plus a pure constant were considered by the program. Table 10 summarizes the statistically best predicting equations obtained under these conditions. The coefficient of determination and average absolute percent deviation are noted for each of the correlations presented. Note that each equation contains only one mechanical property. In fact the equations containing the yield strength and the hardness are identical to those obtained in the single property correlations. The true strain energy based on reduction in area enters to the power (-1) in the ten property correlations, while it was present to the power (-1/2) in the single property correlations. Of course, the mechanical properties involved in the ten property correlations are those that were also quite successful in predicting cavitation damage individually, as expected.

D. Correlations of all Lithium Data

The combined lithium data obtained at 500°F and 1500°F was also submitted to the least mean squares regression analysis. As mentioned previously, one would not expect particularly good predicting equations in this case since only mechanical properties are allowed as independent variables. Thermodynamic effects are apparently quite important in lithium at 1500°F. Hence, a suitable correlation must involve fluid

TABLE 10

SUMMARY OF BEST CORRELATIONS WITH TEN PROPERTIES CONSIDERED--LITHIUM AT 500°F

(1)

Avg. MDP Rate = $-0.899 + 43.40(YS)^{-1/3}$

Coefficient of Determination = 0.959

Average Absolute % Deviation = 3.2%

(2)

Avg. MDP Rate = $-0.039 + 8.21\text{x}10^{3}(TSER)^{-1}$

Coefficient of Determination = 0.928

Average Absolute % Deviation = 40.6%

(3)

Avg. MDP Rate = $0.114 + 3.17\text{x}10^{5}(H)^{-3}$

Coefficient of Determination = 0.924

Average Absolute % Deviation = 37.3%

properties of lithium such as density, surface tension, net positive suction head, bulk modulus, kinematic viscosity, specific heat, thermal conductivity, heat of vaporization, thermal diffusivity, Prandtl Number, and vapor pressure. Such a correlation, involving both mechanical and fluid properties, is presently being undertaken. Nevertheless, single property correlations and full ten property correlations of the combined lithium data as a function of mechanical properties only were investigated. It was found in both cases that no suitable predicting equations existed for the combined data, as expected.

CHAPTER VIII

COMPARISON OF CAVITATION RESULTS IN LEAD-BISMUTH, MERCURY, AND LITHIUM

A. Experiments at 500°F

Previously, cavitation studies were carried out in this laboratory in lead-bismuth alloy[23] at 500°F and 1500°F, and in mercury[19] at 70°F and 500°F. It is interesting to compare the results obtained in lead-bismuth, mercury, and lithium at the same test temperature of 500°F in a further effort to determine fluid effects on cavitation damage.

Table 11 summarizes the cavitation results obtained at 500°F for the various materials tested in the three fluids in terms of average MDP rate. The following comments apply to the comparison:

1) The tantalum-base alloys, T-111 and T-222(A), are the most resistant in all the fluids, while the Cb-1Zr(A) is the least resistant. In fact, the order of ranking of the various materials based on ability to resist cavitation damage is quite similar for all three fluids, with only minor deviations being noted. Particularly, the stainless steels rank quite low in lithium after being only 20% to 45% less resistant than the best refractories tested in lead-bismuth and mercury.

TABLE 11

SUMMARY OF CAVITATION RESULTS IN LEAD-BISMUTH, MERCURY, AND LITHIUM AT 500°F

Material	Average MDP Rate		
	Lithium	Mercury	Lead-Bismuth
T-111	0.03 mils/hr.	0.43 mils/hr.	0.72 mils/hr.
T-222(A)	0.04	0.46	0.76
Mo-1/2Ti	0.12	1.09	0.78
Cb-1Zr	0.15	2.43	1.63
304 SS	0.34	0.69	0.93
316 SS	0.36	0.63	0.88
Cb-1Zr(A)	1.00	3.73	3.54
Carbon Steel	--	0.61	--

2) The damage suffered by a given material in lead-bismuth and mercury was of the same order of magnitude. This is not surprising considering the similarity of the fluid properties. However, the amount of damage sustained in lithium was less than that measured in mercury or lead-bismuth by a factor ranging from 2 to 30. The density of lead-bismuth and mercury is about 25 times that of lithium.

B. Experiments at 1500°F

The cavitation results obtained in lead-bismuth alloy and lithium at the same test temperature of 1500°F are summarized in Table 12 for purposes of comparison. Only four materials were tested in lithium at 1500°F. The following comments apply to the comparison:

1) The tantalum-base alloys, T-111 and T-222(A), are the most resistant in lead-bismuth alloy, while the T-111 is the most resistant in lithium (T-222(A) was not tested in lithium at 1500°F). The 304 stainless steel was the least resistant in both fluids.

2) The damage suffered by a given material in lead-bismuth alloy was 100 to 400 times more severe than the damage sustained in lithium. This is undoubtedly due not only to the much greater density of the lead-bismuth test fluid but also to thermodynamic effects which are very important in lithium at 1500°F, but negligible in lead-bismuth at this temperature.

In order to fullv determine the effect of various fluid properties on cavitation damage, it will be necessary to conduct computer

TABLE 12

SUMMARY OF CAVITATION RESULTS IN LEAD-BISMUTH AND LITHIUM AT 1500°F

Material	Average MDP Rate	
	Lithium	Lead-Bismuth
T-111	0.004 mils/hr.	0.84 mils/hr.
T-222(A)	--	0.88
Mo-1/2Ti	--	1.08
Cb-1Zr	--	2.07
304 SS	0.034	11.30
316 SS	0.027	2.80
Cb-1Zr(A)	0.017	3.80

correlations involving both mechanical properties of the test materials and fluid properties of the test liquid.

CHAPTER IX

SUMMARY AND CONCLUSIONS

Ultrasonic-induced cavitation studies have been conducted in lithium at 500°F and 1500°F for seven materials including refractory alloys and stainless steels. The detailed results are listed in the report. Various salient features include the following:

a) The ultrasonic cavitation facility is capable of operation at temperatures up to 1500°F in fluids including reactive liquid metals.

b) At 500°F the refractory alloys, T-111 and T-222(A), are the most resistant to cavitation damage among the materials tested, while the Cb-1Zr(A) is the least resistant.

c) At 1500°F the refractory alloy, T-111, is the most resistant, while the stainless steels are the least resistant among the 4 materials tested.

d) The damage suffered by a material at 1500°F was less than that at 500°F. This verifies the importance of thermodynamic effects in lithium at 1500°F.

e) The amount of damage sustained in lithium was less than that measured in mercury or lead-bismuth by a factor ranging from 2 to 30. The large variation in this ratio shows that coupling parameters between fluid and material are necessary to obtain a comprehensive correlation.

f) It was found that corrosion effects in these investigations were probably small since there was no observable attack in those areas which were submerged in the fluid but not subjected to cavitation.

Computer correlations of the cavitation damage data with applicable mechanical properties indicate the following conclusions:

a) At 500°F elongation, yield strength, true strain energy based on reduction in area, hardness, and tensile strength each individually predict the cavitation damage adequately. The ten property correlations also involve these mechanical properties.

b) In order to properly correlate the combined set of lithium data at 500°F and 1500°F, it is necessary to include applicable fluid properties in the analysis.

APPENDIX

COMPUTER REGRESSION ANALYSIS OF CAVITATION DATA

A least mean squares stepwise regression computer program was used to correlate the cavitation damage data with mechanical properties. Using the first-order interaction form of the program, the problem at hand can be simply stated as follows: it is required to determine the appropriate coefficients and exponents in a predicting equation of the form:

$$Y = C_0 + C_1X_1^a + C_2X_2^b + C_3X_3^c + C_4X_4^d + \ldots\ldots\ldots + C_nX_n^q$$

where C_0, C_1, C_2, C_3, C_4, ..., C_n are constant coefficients; a, b, c, d, ..., q are constant exponents; the X's are the independent variables, in this case the mechanical properties of the materials and the fluid properties; and Y is the dependent variable, the average MDP rate. The independent variables are allowed to appear in the predicting equation any number of times, each time raised to a different value of exponent and multiplied by an appropriate coefficient. The program allows great latitude on the possible exponents for the independent variables. The form of the program used in this investigation allows any or all of the independent variables to be raised to the following exponents: $\pm$ 1, $\pm$ 2, $\pm$ 1/2, $\pm$ 3, $\pm$ 1/3.

A predicting equation of the type noted above would be obtained by allowing only a "first-order interaction" of the possible terms, i.e., terms involving products of the independent variables would not be allowed. The program, however, does allow the option of a "second-order interaction," i.e., allows terms involving products of different independent variables. The choice must be made by the individual programmer.

In the present analysis (permitting only first-order interaction) the allowable mechanical properties (independent variables) were taken to be the tensile strength, yield strength, engineering strain energy,[29] true strain energy,[29] hardness, percentage elongation, percentage reduction in area, and modulus of elasticity. In addition, the ratio of acoustic impedances[19] of test fluid and specimen material was also included among the independent variables for all the correlations. Hence, in a given correlation, there were 10 independent variables and 10 possible exponents for each independent variable. As a result a total of 100 terms are possible candidates for inclusion in the predicting equation plus a pure constant. From a physical point of view, it is hoped that a good statistical correlation will be possible with a minimum number of terms so that the predicting equation may hopefully be justified on physical grounds. This possibility would be unlikely if more than 5 or 6 terms were needed for the correlation.

A brief outline will be given here of the mechanics of the program. The interested reader is referred to the literature previously cited for the details. The major features of the program are as follows:

1) of the 100 possible terms that are candidates for inclusion in the predicting equation, the program randomly selects a subset of 40 terms to be analyzed.
2) A correlation coefficient is computed for each of the 40 terms. The correlation coefficient is a measure of the ability of each

term to individually explain the experimental data, i.e., predict the average MDP rate.

3) The term with the greatest correlation coefficient is then included in the predicting equation, which at this point is of the form:

$$Y = C_0 + C_1 X_1^{a}$$

where C_0 and C_1 are constants to be determined.

4) The constants C_0 and C_1 are computed using the least mean squares criterion.

5) The initial 40 terms are then sorted into 2 subsets, those that are included in the predicting equation at this point, and those that are not.

6) An importance factor is computed for each term now in the equation. The importance factor is a measure of the total contribution made by each term in explaining the experimental data.

7) The importance factors of the terms in the equation are compared to a minimum level of importance set by the user. A typical range of values is 1% to 5%.

8) Terms having an importance factor less than the minimum level are deleted from the equation.

9) A potential importance factor is computed for each term not in the equation. The potential importance factor is a measure of the ability of each term not in the equation to explain the presently existing variance between the experimental data and the predicted data.

10) The potential importance factors of the terms not in the equation are compared to a minimum level of importance set by the user. A typical range of values is 1% to 5%.

11) Terms not in the equation having a potential importance factor greater than the minimum level are entered into the equation.

This procedure is used to examine the subset of 40 terms chosen randomly and is terminated either when all qualified terms have been entered into the equation or when certain statistical criteria (such as the coefficient of determination and standard error in the dependent variable) set by the user have been satisfied. Whenever a new term is entered into the equation, the least mean squares criterion is used to compute a new set of coefficients. For a given problem it is possible to analyze several subsets of 40 terms, each chosen randomly from the set of 100 possible terms available. Such a procedure is advisable in that it increases the probability that the most significant terms contained in the initial set of 100 terms will enter the predicting equation.

The output from the program includes the terms in the predicting equation along with the appropriate exponents and coefficients, predicted MDP rates based on the correlation, experimental MDP rates, percent deviations, standard error in the dependent variable, coefficient of determination for the analysis, average absolute percent deviation for the analysis, etc. As a result it is possible to show graphically the statistical accuracy of the predicting equation by plotting the predicted MDP values versus the experimental points and noting the deviation from a 45° line which would signify a perfect fit.

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