THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

ULTRASONIC-INDUCED CAVITATION STUDIES IN LEAD-BISMUTH ALLOY AT ELEVATED TEMPERATURES

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I. INTRODUCTION

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[1], 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 components handling predominantly gaseous two-phase flow), 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 demonstrated in the past, cavitation attack has occurred in bearings, close-clearance passages, etc., as well as pumps. In fact, recent studies[2] indicate that a form of microcavitation may well occur in many high-performance bearing applications and even in components such as gear teeth, so that the pitting found in such units may well be a form of cavitation. Liquid-metal cavitation is also important in the conventional nuclear power plant program which includes several existing and projected reactor systems using liquid metals as the coolant.

In the space application, particularly, the minimization of size and weight and the maximization of temperature are of over-riding importance. To approach these objectives, it is necessary that the fluid-handling equipment 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. It may not be possible or desirable to avoid the cavitating regime entirely by over-conservative design, as has been the previous practice.

Among the objectives of the present study are the measurement of 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, although the results presented here have been obtained in lead-bismuth alloy at 500°F and at 1500°F. 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.

Another objective of the present study is 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 applicable mechanical properties can be obtained. 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) could be used.

II. HIGH-TEMPERATURE ULTRASONIC CAVITATION VIBRATORY FACILITY.

The University of Michigan high-temperature ultrasonic cavitation vibratory facility has been described elsewhere[3]. 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 manner was first suggested by Mason[4]. 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. For studies at elevated temperatures the transducer-horn assembly is attached to the special cavitation vessel which is filled with the appropriate fluid. The accelerometer, oscilloscope, and frequency counter are utilized to monitor the amplitude and frequency of vibration of the transducer assembly.

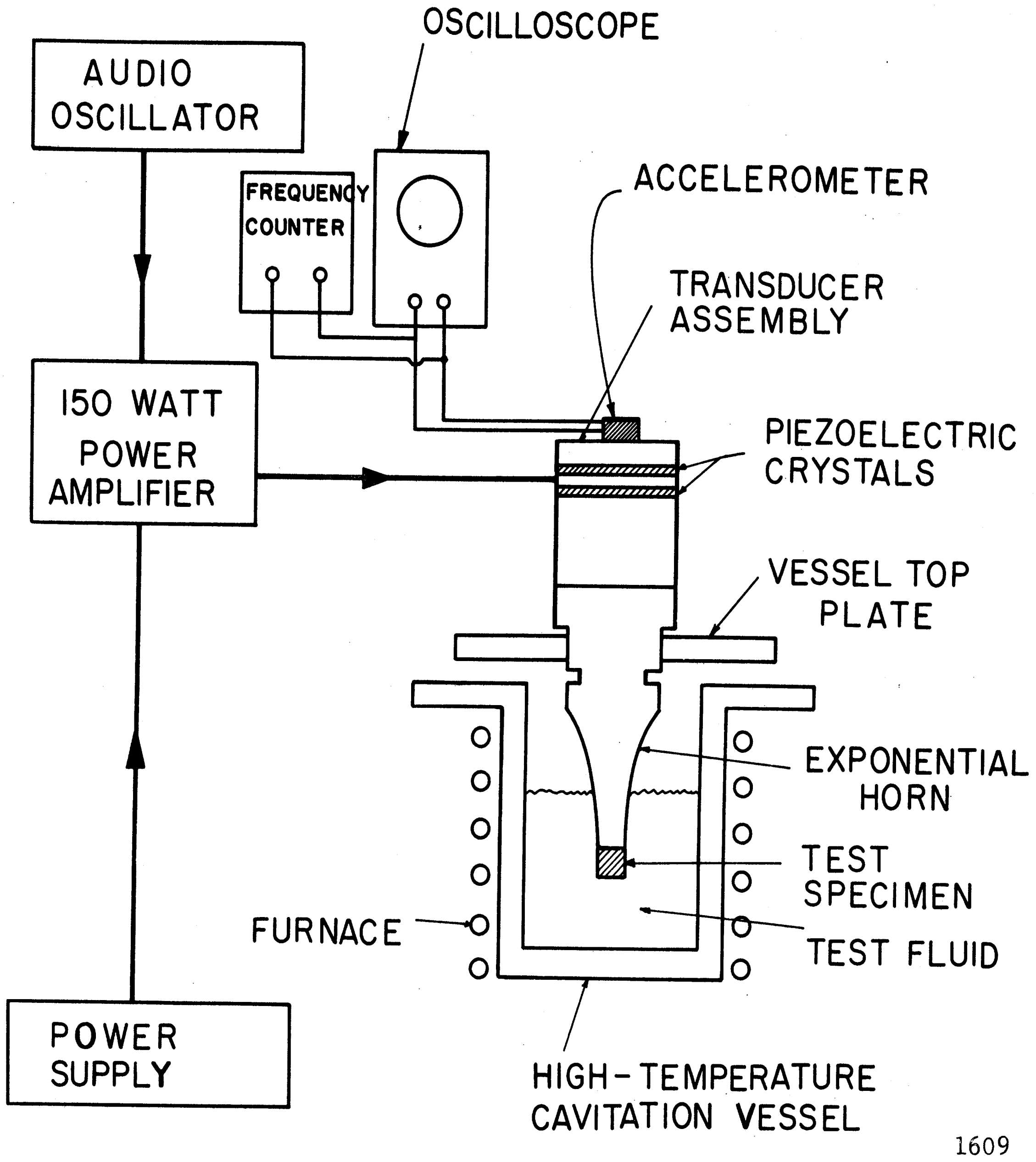

Figure 1. Block Diagram of the High-Temperature Ultrasonic Vibratory Facility

In this study lead-bismuth alloy (70% lead - 30% bismuth) was selected as the test fluid because of relative handling ease and similarity to mercury for which extensive cavitation results had already been obtained in this laboratory in venturi investigations. The materials tested at 500°F and 1500°F are shown in Table 1.

TABLE 1

MATERIALS TESTED IN LEAD-BISMUTH CAVITATION PROGRAM
AT 500°F AND 1500°F

304 Stainless Steel (U-M) *

316 Stainless Steel (U-M)

T-111 (Ta-8W-2Hf) (P & W)

T-222(A) (Ta-9.5W-2.5Hf-.05C) (P & W)

Mo-1/2Ti (P & W)

Cb-1Zr (P & W)

Cb-1Zr (A) (P & W)

* The designations (U-M) and (P & W) appearing after the materials indicate their origin, namely, The University of Michigan and Pratt & Whitney Aircraft (CANEL), respectively. The designation (A) appearing after the T-222 and the Cb-1Zr indicated that these materials were fully annealed, whereas the other samples were in a partially cold-worked condition.

The test specimens were oscillated at ~ 20 Kc./sec. with the horn tip immersed ~ 1 inch into the molten lead-bismuth alloy. The double amplitude at the specimen face was ~ 2 mils, being maintained constant for all tests, and the argon cover gas over the lead-bismuth was maintained at a slight overpressure of 0.5 psig throughout the investigations. Test durations varied for the different materials, ranging from 5 to 12 hours, depending on the amount of damage observed. However, intermittent monitoring of the surface and weighings were conducted until at least the complete face of the specimen was damaged, and an approximately uniform rate of damage obtained. Many of the specimens suffered severe damage during the prescribed time duration.

III. CAVITATION STUDIES AT 500°F

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 lead-bismuth alloy 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. 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 brazed to the top plate. In addition a fan in close proximity to the crystals provided additional cooling.

The specimens were subjected to the cavitation environment for a total test period of 12 hours with the exception of the Cb-1Zr(A) which showed gross erosion after 8 hours of testing. Previous tests in this laboratory had indicated that when this quantity of damage had been incurred, the damage rate begins to increase from a relatively constant value which had applied, once damage had become fairly uniform, up to this point. Hence, it is not desired to carry the test to very heavy damage conditions. At 2-hours intervals throughout the tests the specimens were visually examined, photographed, and carefully weighed.

The cavitation results obtained at 500°F can 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 face, is believed physically more 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., they do not distinguish isolated deep pits versus uniform wear, etc. However, the MDP calculation is sensitive to the density of the materials, which varies over a wide range in this study.

Figure 2 is a plot of accumulative MDP versus test duration for the 7 materials tested, while Table 2 presents average weight loss rate and average MDP rate.

On the basis of MDP it is clear that the alloy T-111 (P & W) has exhibited the greatest resistance to cavitation in this experiment, although T-222 (A) (P & W), Mo-1/2Ti (P & W), 304 SS (U-M), and 316 SS (U-M) are also quite cavitation resistant relative to the Cb-1Zr (P & W) and the Cb-1Zr (A) (P & W). The Cb-1Zr(A) suffered relatively gross damage after 8 hours of testing. It is clear from Figure 2 that the rate of erosion for each individual material was approximately constant throughout the test. It is significant that at 500°F the stainless steels tested fared almost as well as the best of the

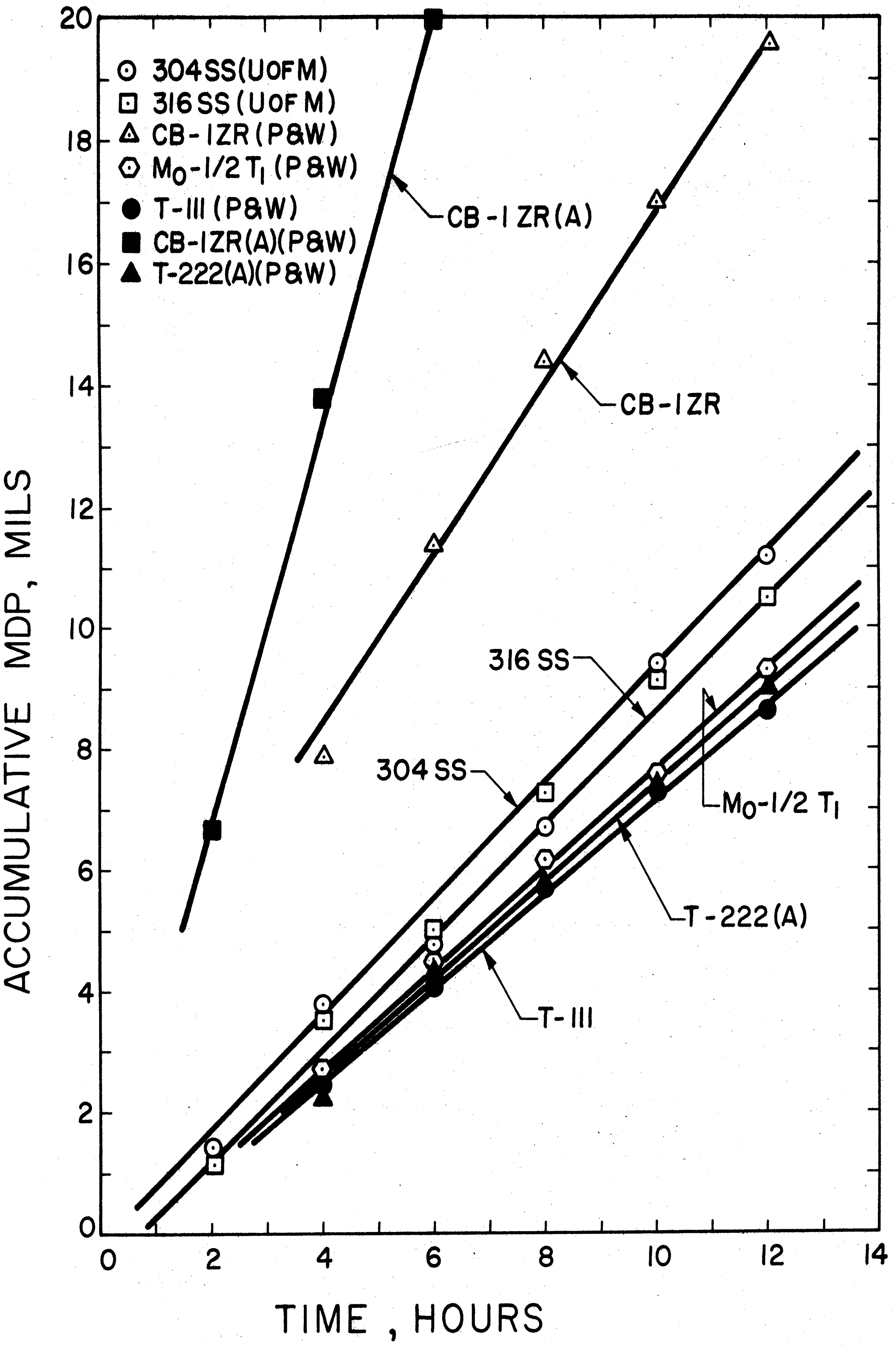

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Figure 2. Effect of Cavitation Test Duration on MDP at 500°F in Lead-Bismuth Alloy

TABLE 2

SUMMARY OF CAVITATION RESULTS AT 500°F

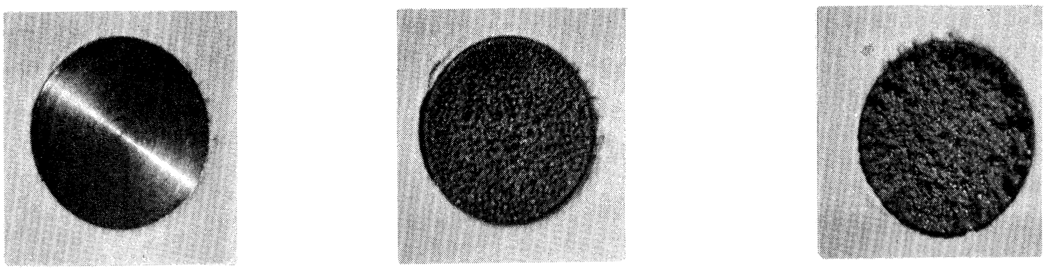
Material	Avg. Wt. Loss Rate	Average MDP Rate
T-111 (P & W)	49.1 mg./hr.	.72 mils/hr.
T-222(A) (P & W)	51.6	.76
Mo-1/2Ti (P & W)	30.7	.78
316 SS (U-M)	26.6	.88
304 SS (U-M)	28.2	.93
Cb-1Zr (P & W)	55.1	1.63
Cb-1Zr(A) (P & W)	119.5	3.54

refractory alloys, i.e., T-111, T-222(A), and Mo-1/2Ti, being relatively much more resistant than at the higher test temperature (1500°F).

Photographs of the test specimens before exposure and at the conclusion of the cavitation experiment are presented in Figure 3. The effect of the cavitation erosion action of the collapsing bubble field is quite apparent.

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 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. Typical specimens were also sectioned and metallurgically examined for signs of corrosion. No indication of corrosion was found. Hence, one might assume that the damage suffered by the test specimens was due almost completely to the mechanical aspects of the cavitation erosion process and not to chemical corrosion by the lead-bismuth alloy.

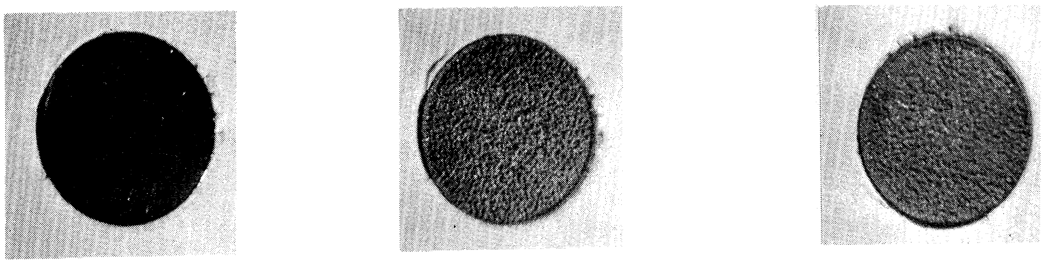
BEFORE EXPOSURE 500°F. 1500°F.



304 Stainless Steel (U-M)

304 Stainless Steel 12 Hour Exposure

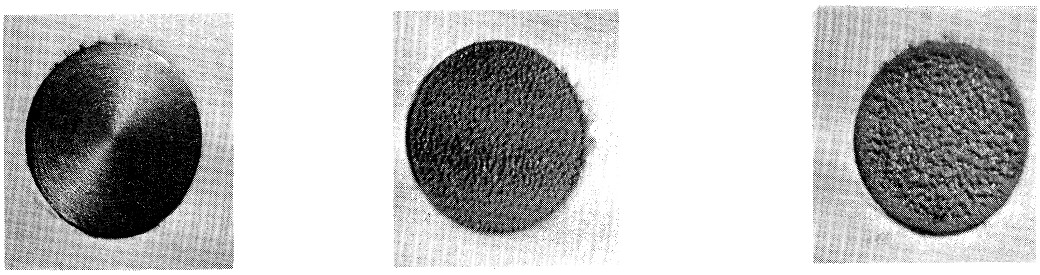
304 Stainless Steel 5 Hour Exposure



316 Stainless Steel (U-M)

316 Stainless Steel 12 Hour Exposure

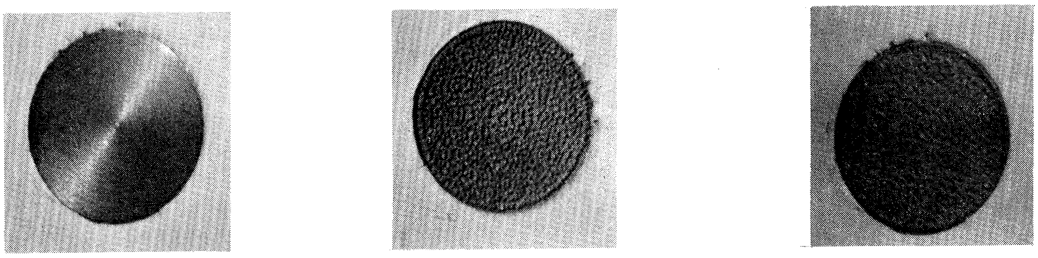
316 Stainless Steel 6 Hour Exposure



Mo-½Ti (P & W)

Mo-½Ti (P & W) 12 Hour Exposure

Mo-½Ti (P & W) 10 Hour Exposure



T-111 (P & W) (Ta-8W-2Hf)

T-111 (P & W) 12 Hour Exposure

T-111 (P & W) 10 Hour Exposure

Figure 3. Specimens Subjected to Cavitation Damage in Lead-Bismuth Alloy at 500°F & 1500°F

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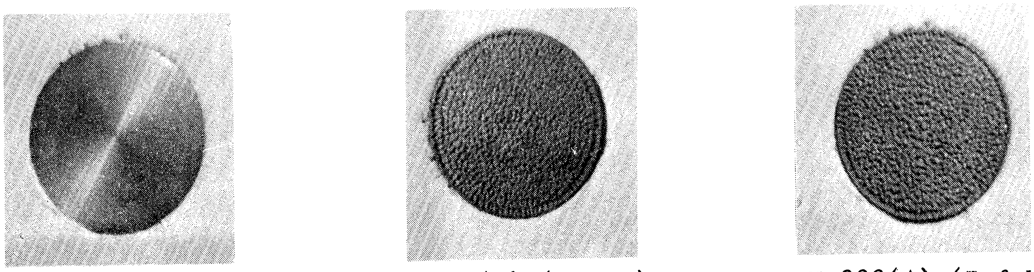
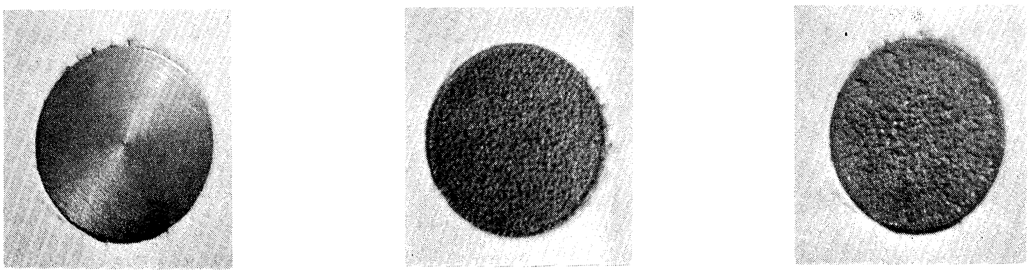
BEFORE EXPOSURE 500°F. 1500°F.



T-222(A) (P & W)
(Ta-9.5W-2.5Hf-.05C)

T-222(A) (P & W)
12 Hour Exposure

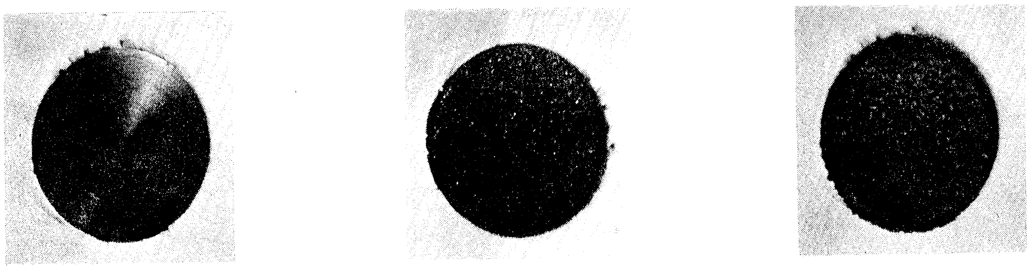
T-222(A) (P & W)
10 Hour Exposure



Cb-1Zr (P & W)

Cb-1Zr (P & W)
12 Hour Exposure

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



Cb-1Zr(A) (P & W)

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

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

Figure 3. Specimens Subjected to Cavitation Damage in Lead-Bismuth Alloy at 500°F & 1500°F

IV. CAVITATION STUDIES AT 1500°F

The materials tested at 1500°F were identical to those tested at 500°F and were listed in Table 1. Preliminary results obtained at 1500°F were previously reported[5]. The experimental procedure for the 1500°F tests was similar to that employed for the 500°F tests and only deviations from the 500°F procedure will be noted here. All transfers of the specimens to and from the high-temperature cavitation vessel were made at a temperature of 500°F. Hence, after securing the ultrasonic transducer assembly to the top plate of the cavitation vessel, the temperature of the lead-bismuth alloy was increased to 1500°F by means of the automatic temperature controller. Heating time from 500°F to 1500°F is approximately 1 1/2 hours. At the conclusion of the cavitation test the temperature was reduced to 500°F again so that the specimen could safely be removed from the end of the exponential horn and visually examined and weighed. Cooling time from 1500°F to 500°F is approximately 5 hours.

The 7 specimens tested for cavitation resistance at 1500°F were subjected to the cavitation environment for varying lengths of time, the stainless steel being exposed for 5-6 hours and the refractory alloys for a total of 10 hours. At appropriate intervals the specimens were visually examined, photographed, and weighed. Then the test was resumed. It was not possible to examine the refractory materials as frequently as the stainless steels because of numerous mechanical problems that were encountered.

The cavitation results obtained at 1500°F are displayed in Figure 4, which is a plot of accumulative MDP versus test duration for the 7 materials tested, while Table 3 summarizes the results as average weight loss rate and average MDP rate.

On the basis of MDP the refractory alloy T-111 exhibited the greatest resistance to cavitation damage in this experiment. This was also true at 500°F. The T-222(A) and the Mo-1/2Ti were also quite cavitation-resistant relative to the other materials tested. The Cb-1Zr and the 316 stainless steel rated behind the tantalum and molybdenum alloys, while both the Cb-1Zr(A) and the 304 stainless steel exhibited relatively poor resistance to cavitation erosion. Both were grossly damaged, expecially the 304 stainless steel after only 5 hours of testing. It is clear from Figure 4 that the rate of erosion for each individual material was approximately constant for all the materials tested during most of the test. This behavior was also noted at 500°F.

There is no question that the refractory alloys T-111, T-222(A), Mo-1/2Ti, and Cb-1Zr are far superior to the stainless steels with respect to resistance to cavitation erosion at 1500°F. Such materials are likely choices for components that are subject to cavitation damage in various types of turbomachinery, magnetohydrodynamic devices, etc., operating at elevated temperatures.

Photographs of the test specimens before exposure and at the conclusion of the cavitation experiment are presented in Figure 5. Differences in the damage suffered by the various materials at 500°F and 1500°F are apparent.

As was the case at 500°F and as confirmed by sectioning of typical samples there was no evidence of attack by corrosion at 1500°F.

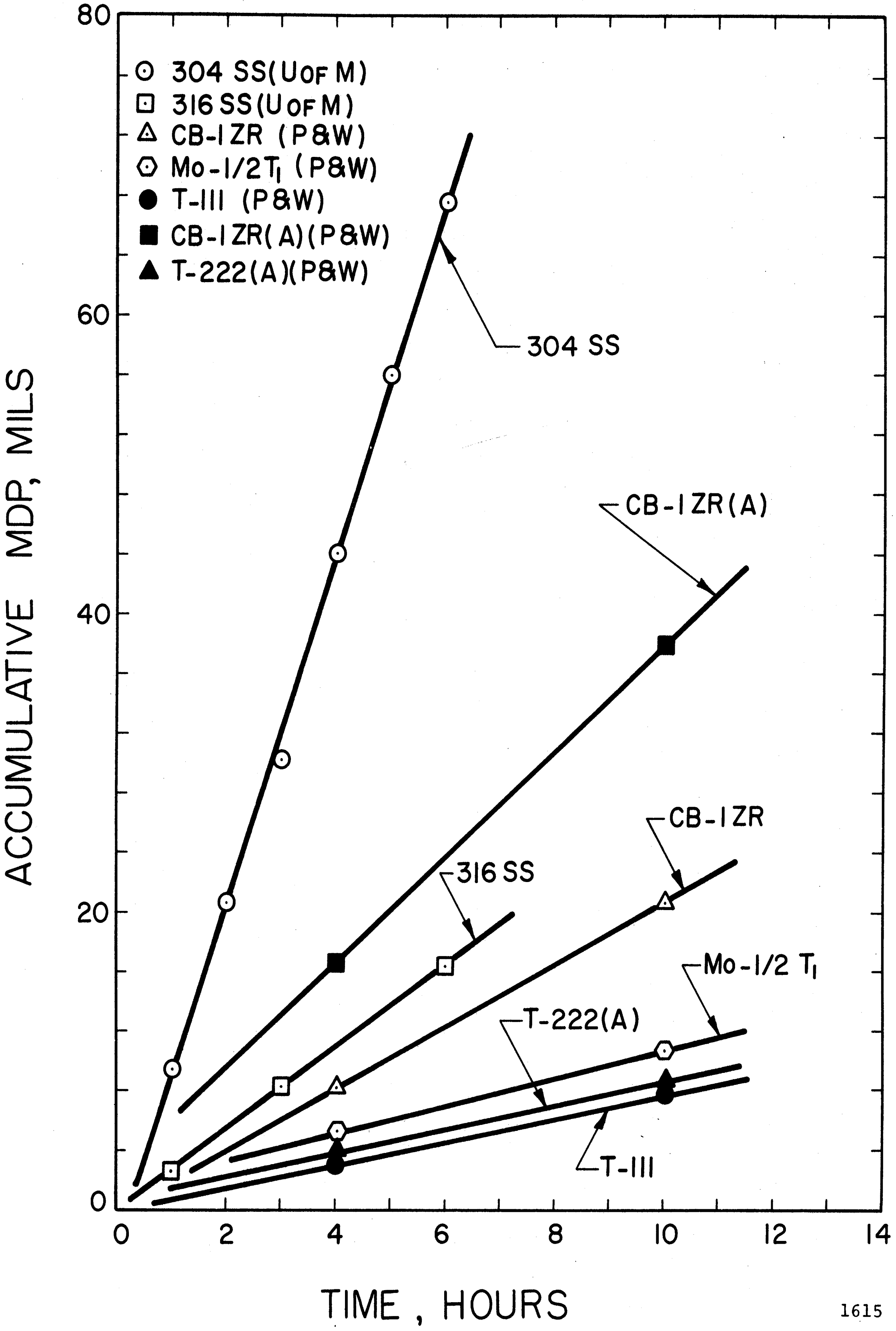


Figure 4. Effect of Cavitation Test Duration on MDP at 1500°F in Lead-Bismuth Alloy

TABLE 3

SUMMARY OF CAVITATION RESULTS AT 1500°F

Material	Avg. Wt. Loss Rate	Average MDP Rate
T-111 (P & W)	57.1 mg./hr.	.84 mils/hr.
T-222(A) (P & W)	59.9	.88
Mo-1/2Ti (P & W)	42.6	1.08
316 SS (U-M)	83.3	2.80
304 SS (U-M)	342.0	11.30
Cb-1Zr (P & W)	70.0	2.07
Cb-1Zr(A) (P & W)	128.4	3.80

TABLE 4

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

	500°F		1500°F	
Material	(Avg. MDP Rate)	Rating	(Avg. MDP Rate)	Rating
T-111	.72 mils/hr.	1	.84 mils/hr.	1
T-222(A)	.76	2	.88	2
Mo-1/2Ti	.78	3	1.08	3
316 SS	.88	4	2.80	5
304 SS	.93	5	11.30	7
Cb-1Zr	1.63	6	2.07	4
Cb-1Zr(A)	3.54	7	3.80	6

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

Table 4 summarizes the cavitation data obtained at 500°F and at 1500°F. The seven materials tested 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" would denote that material most susceptible to cavitation damage.

The tantalum alloys, T-111 and T-222(A), are the most resistant to cavitation at both 500°F and at 1500°F. The Mo-1/2Ti ranks third at both temperatures. It is significant to note the poor relative performance of the stainless steels at 1500°F after being only ~ 25% less resistant to cavitation than the T-111 and the T-222(A) at 500°F. The differences in the amount of erosion attack on the various specimens at the two test temperatures are apparent from an examination of Figure 3.

It is important to note that for each material tested the amount of damage sustained by the specimen at 1500°F was greater than that sustained at 500°F for the same test duration. However, the effect of temperature on the T-111, T-222(A), and Mo-1/2Ti is very small, while the effect on the stainless steels is substantial. As discussed shortly, this is due primarily to the fact that the mechanical properties of the stainless steels over the range tested are strong functions of temperature, as opposed to those of the refractories.

VI. MECHANICAL PROPERTIES DATA FOR THE TEST MATERIALS

In order to obtain a meaningful correlation between the cavitation resistance of the various materials tested and their mechanical properties, it is absolutely essential that the applicable properties such as tensile strength, yield strength, strain energy, hardness, elongation, reduction in cross-sectional area, etc., be measured at the test temperatures using tensile bars machined from the same bar stock as were the cavitation specimens. Otherwise the differences between material lots due to differences in heat-treat, cold-work, etc., are too large to allow useful results. Accordingly, all cavitation specimens, tensile bars, and special hardness specimens for each material were cut 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%.

The tensile specimens and hardness specimens supplied by this laboratory were tested at room temperature, 500°F, and 1500°F, at Pratt & Whitney Aircraft (CANEL). The results of the mechanical properties determination program were supplied to this laboratory by private communication[6] and have become an integral part of the cavitation analysis and correlation effort.

The data supplied by Pratt & Whitney Aircraft (CANEL) consisted of values of the ultimate tensile strength, 0.2% yield strength, elongation, reduction in cross-sectional area, hardness, and engineering strain energy at room temperature, 500°F, and 1500°F. All the mechanical properties data has been previously reported[7]. The following observations regarding these mechanical properties are noted here:

1. For 304 stainless steel the ultimate tensile strength and the 0.2% yield strength are nearly constant from room temperature to 500°F. Then they rapidly decrease as the temperature increases to 1500°F. The hardness decreases in a relatively uniform manner over the temperature range investigated.
2. For 316 stainless steel the ultimate tensile strength, 0.2% yield strength, and the hardness all decrease in a fairly uniform fashion as the temperature is increased. Thus for this material there is a substantial decrease between room temperature and 500°F.
3. For T-111 the ultimate tensile strength and the 0.2% yield strength decrease from room temperature to 500°F., but are relatively constant thereafter. The same comment applies to the variation of the hardness.
4. For T-222(A) the variation of the mechanical properties is similar to that of the T-111. The changes from 500°F to 1500°F are quite small.
5. For Mo-1/2Ti comments similar to (3) and (4) above apply.

6. For Cb-1Zr the variation of the mechanical properties is a very weak function of temperature.
7. For Cb-1Zr(A) there is a decrease in the ultimate tensile strength, 0.2% yield strength, and hardness as the temperature is increased from 70°F to 500°F. Thereafter, the properties are a very weak function of the temperature.
8. At room temperature the tensile strength and yield strength of the stainless steels are about 50% less than the corresponding properties for the T-111, T-222(A), and Mo-1/2Ti.
9. At 500°F the tensile strength and yield strength of the stainless steels are roughly comparable with the corresponding properties of the T-111, T-222(A), and Mo-1/2Ti.
10. At 1500°F the tensile strength and yield strength of the T-111, T-222(A), and Mo-1/2Ti are on the order of 4X greater than the corresponding properties of the stainless steels.
11. The strain energy of the stainless steels decreases rapidly with increasing temperature, while the strain energy of the T-111, T-222(A), and Mo-1/2Ti is not greatly affected by temperature.
12. The strain energy of the Cb-1Zr and the Cb-1Zr(A) is somewhat insensitive to temperature also, but the absolute magnitude of this quantity is much less than that of the other refractory alloys at any temperature.

Examination of the mechanical properties data indicates trends in its behavior which are very similar to some of the trends noted for the cavitation data. Hence, it should be possible to correlate the cavitation resistance of the materials tested with the applicable mechanical properties data.

VII. CORRELATIONS OF CAVITATION DATA WITH MECHANICAL PROPERTIES DATA

A complete correlation of the cavitation data with the mechanical properties data, of necessity, involves the use of a suitable digital computer program to arrive at a predicting equation of, say, Average MDP Rate as a function of the applicable mechanical properties. Those properties already mentioned that might apply include the ultimate tensile strength, yield strength, hardness, strain energy, percentage elongation, and percentage reduction of area. There may be other properties necessary for a complete correlation such as the elastic modulus, E; a coupling parameter between material and fluid as the ratio of the acoustic impedances of the specimen material and the test fluid; etc. A complete correlation presumably might be expressed as a sum of several of these properties each multiplied by an appropriate coefficient and raised to a suitable exponent. An attempt at a fairly complete correlation is presented later.

A qualitative feel for those mechanical properties that might best give some clue as to the cavitation resistance of a particular material can be obtained quite simply. The properties chosen for this purpose were the ultimate tensile strength, the 0.2% yield strength, the hardness, and the strain energy. On the basis of the mechanical properties values it is possible to arrive at several ratings of the materials tested. An ultimate tensile strength rating would be obtained by assigning that material with the greatest ultimate tensile strength a value of "1", while "7" (since 7 materials are involved) would denote that material with the smallest value of this property. In a similar manner the materials can be rated on the basis of the 0.2% yield strength, the hardness, and the strain energy. In each case a rating of "1" would be assigned to that material having the greatest value of the particular property involved, "7" denoting the material with the smallest value. It is intuitively obvious that those materials having greatest tensile strength, yield strength, hardness, and strain energy probably will be the most cavitation resistant also. Based on the 4 mechanical properties noted above, each material now has 4 ratings. If one now assumes a weighting factor of unity appropriate for each of these properties, it is possible to arrive at a final rating for each of the materials, namely, the sum of the 4 ratings already determined. Then the materials can be rated on the basis of the sum of the 4 individual ratings. The end result is an arrangement of the 7 materials tested with a rating of "1" denoting that material which will probably be most cavitation resistant, predicted on the basis of the mechanical properties listed above. The rating of "7" denotes that material which should be most susceptible to cavitation erosion. It is then possible to compare the final rating of the materials with the rating based on the actual cavitation data obtained in the experiment. The individual ratings of the materials based on mechanical properties, the final rating, and the rating based on the average MDP rate exhibited by the specimens are all summarized in Table 5. It is interesting to note that the experimental rating (based on MDP) agrees

TABLE 5

PRELIMINARY CORRELATION OF THE CAVITATION DATA WITH MECHANICAL PROPERTIES DATA AT 500°F

Material	UTS Rating	0.2% YS Rating	SE Rating	Hardness Rating	Total	Final Rating	MDP Rating
T-111 (P & W)	1	1	4	1	7	1	1
T-222(A) (P & W)	3	3	1	2	9	2	2
Mo-1/2Ti (P & W)	4	2	5	3	14	3	3
316 SS (U-M)	5	6	2	4	17	5	4
304 SS (U-M)	2	4	3	5	14	3	5
Cb-1Zr (P & W)	6	5	7	6	24	6	6
Cb-1Zr(A) (P & W)	7	7	6	7	27	7	7

almost exactly with the rating based on the mechanical properties data. So, incidentally, does a ranking of hardnesses (which has often been used as a basis for rating cavitation resistance). However, none of the other properties taken singly are successful in this regard. All these results are applicable at 500°F.

All of the comments made in the previous section apply equally at 1500°F. A qualitative correlation was also attempted at this temperature in the same manner as was indicated at 500°F. The results are summarized in Table 6. The experimental rating agrees very well with the final rating based on the mechanical properties data. Again, only hardness as a single property is reasonably successful in this regard.

The dependence of cavitation resistance on the mechanical properties of a material has been more quantitatively investigated by subjecting the experimentally-determined cavitation data and the appropriate mechanical properties data to a least mean squares fit by means of a digital computer program. For these studies the University of Michigan IBM 7090 digital computer facility was utilized along with a least mean squares stepwise regression program first proposed by Westervelt[8]. Utilizing 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:

$$Y = a + bX_1^{\alpha} + cX_2^{\beta} + dX_3^{\gamma} + eX_4^{\delta} + \ldots\ldots\ldots\ldots + qX_n^{\epsilon}$$

TABLE 6

PRELIMINARY CORRELATION OF THE CAVITATION DATA WITH MECHANICAL PROPERTIES DATA AT 1500°F

Material	UTS Rating	0.2% YS Rating	SE Rating	Hardness Rating	Total	Final Rating	MDP Rating
T-111 (P & W)	1	1	2	1	5	1	1
T-222(A) (P & W)	2	4	1	3	10	2	2
Mo-1/2Ti (P & W)	3	2	3	2	10	2	3
316 SS (U-M)	6	5	4	5	20	5	5
304 SS (U-M)	7	6	7	7	27	7	7
Cb-1Zr (P & W)	4	3	6	4	17	4	4
Cb-1Zr(A) (P & W)	5	7	5	6	23	6	6

where the X's are the independent variables, in this case the mechanical properties of the materials, and Y the dependent variable, (average MDP rate).

In the present analysis the allowed mechanical properties (independent variables) were taken to be the tensile strength, yield strength, hardness, strain energy,* percentage elongation, and percentage reduction of area. It is hoped that a minimum number of terms will provide a good statistical correlation so that the predicting equation can hopefully be more easily justified on physical grounds. This possibility would be unlikely if more than 5 or 6 terms were needed for the correlation.

The cavitation data obtained at 500°F and at 1500°F was all submitted to the program in an attempt to obtain a first-order interaction correlation that would be applicable at both temperatures and, hence, would have the greatest generality allowed by the present limited data. Initially, only tensile strength, yield strength, strain energy, and hardness were allowed as the independent variables, as it was felt on physical grounds and stated in previous papers from this laboratory[9], that properties both of the strength and energy type would be involved. Examination of correlating equations (1), (2), (3), and (4) below indicates that this is indeed the case. The best predicting equation (based on the greatest statistical accuracy possible)

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*"Engineering Strain Energy," i.e., proportional to the area under the load vs elongation diagram.

was then:

$$\text{Avg. MDP Rate} = K_1 + K_2(SE)^{-2} + K_3(SE)^{-3} + K_4(SE)^{-1} + K_5(H)^{-2} \qquad (1)$$

where:

Avg. MDP Rate is expressed in mils/hour

SE (denoting strain energy) is expressed in psi

H (denoting diamond pyramid hardness-1.1 Kg. load) is expressed in DPH units

$K_1 = -5.57$

$K_2 = -2.02 \times 10^9$

$K_3 = 6.37 \times 10^{12}$

$K_4 = 1.97 \times 10^5$

$K_5 = 1.68 \times 10^4$

Coefficient of Determination = .992

The inverse relationship indicates that materials with large strain energies would be the most cavitation resistant. The appearance of the hardness in an inverse relationship is also noted.

An alternate predicting equation obtained with almost as great statistical accuracy as equation (1) is:

$$\text{Avg. MDP Rate} = K_1 + K_2(SE)^{-2} + K_3(SE)^{-3} + K_4(TS)^{-3} \qquad (2)$$

where:

Avg. MDP Rate is expressed in mils/hour

SE (denoting strain energy) is expressed in psi

TS (denoting tensile strength) is expressed in psi

$K_1 = 1.52$

$K_2 = -3.14 \times 10^8$

$K_3 = 1.96 \times 10^{12}$

$K_4 = 4.42 \times 10^{13}$

Coefficient of Determination = .984

Once again strain energy along with a strength property is involved, each (as would be expected) in an inverse relationship to the average MDP rate.

When all six mechanical properties previously listed are used as independent variables, the best fit statistical correlation thus far obtained results:

$$\text{Avg. MDP Rate} = K_1 + K_2(\text{RA})^{-3} + K_3(\text{SE})^{-2} + K_4(\text{YS})^{-3} \qquad (3)$$

where:

Avg. MDP Rate is expressed in mils/hour

RA (denoting reduction in area) is expressed in percentage

SE (denoting strain energy) is expressed in psi

YS (denoting yield strength) is expressed in psi

$K_1 = .073$

$K_2 = 2.41 \times 10^5$

$K_3 = 4.90 \times 10^7$

$K_4 = 2.54 \times 10^{12}$

Coefficient of Determination = .994

It is seen here that the percentage reduction in area, strain energy, and yield strength are all indicated as inverse functions of the average

MDP rate. Since the product of a ductility term (as percentage reduction in area) and a strength term gives an energy term, the prominence of strain energy is reduced in this relation.

Since strain energy is not a readily available engineering property, its complete elimination would be desirable. Equation (4) results if the analysis is made without considering the strain energy as such. The highest coefficient of determination for all the equations (0.998) is then obtained, indicating extremely good agreement between the predicting equation and experimental data. Figure 5 shows the data scatter around the prediction line.

$$\text{Avg. MDP Rate} = K_1 + K_2(H)^{-2} + K_3(RA)^{-1} + K_4(RA)^{-3} \qquad (4)$$

where:

Avg. MDP Rate is expressed in mils/hour

H (denoting diamond pyramid hardness-1.1 Kg. load) is expressed in DPH units

RA (denoting reduction in area) is expressed in percentage

$K_1 = 4.02$

$K_2 = 1.39 \times 10^4$

$K_3 = -3.50 \times 10^2$

$K_4 = 4.42 \times 10^5$

Coefficient of Determination = .998

All of the correlations presented above indicate excellent agreement between the predicted values and the experimental points, but are, of course, limited to the rather narrow range of data used. It is obvious that further much more comprehensive results are required.

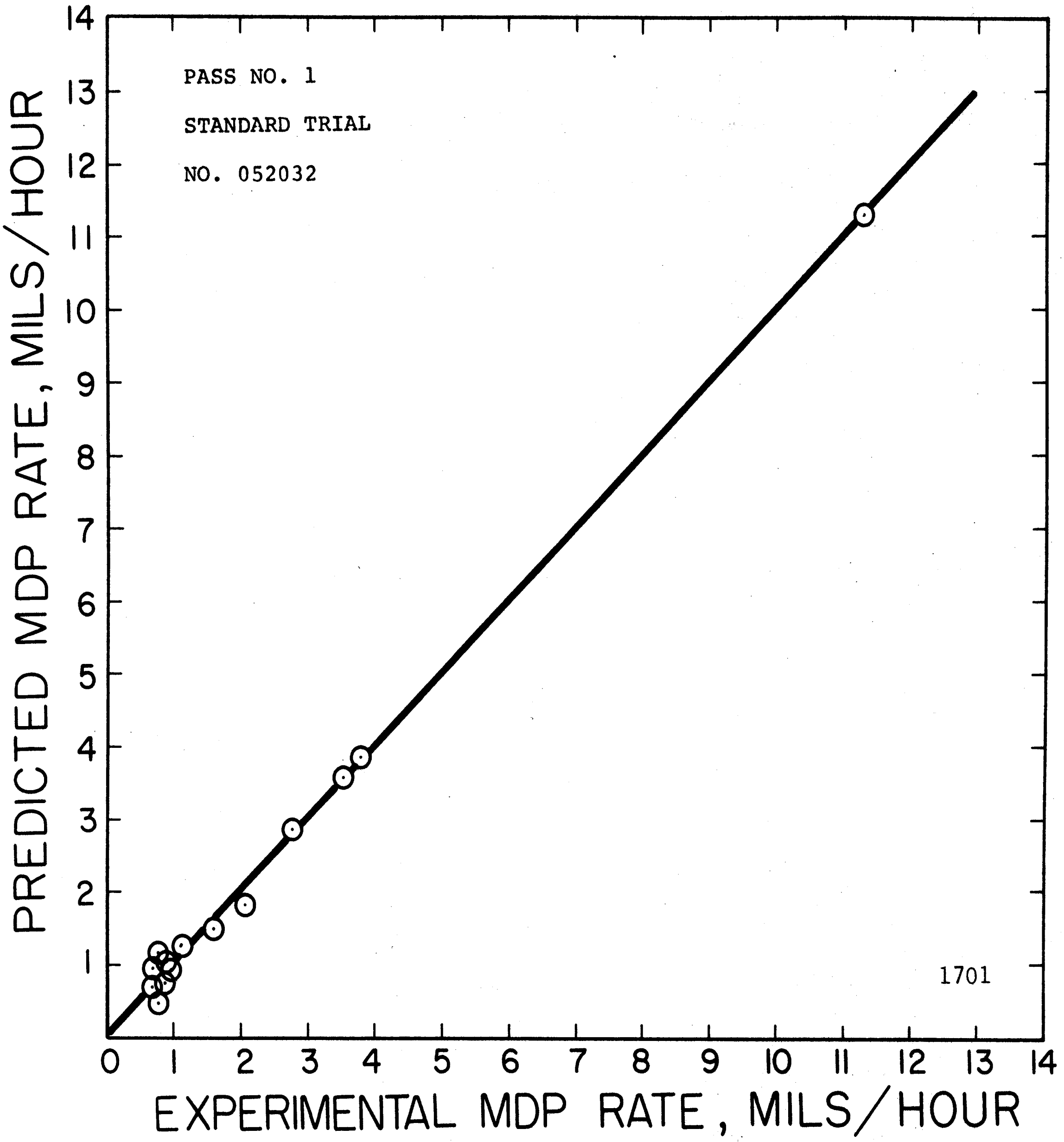

Figure 5. Comparison of Predicted MDP Rate and Experimental MDP Rate

VIII. SUMMARY AND CONCLUSIONS

The experimental investigations described in this report have shown the superiority of several of the refractory alloys in that they are very cavitation resistant at both 500°F and at 1500°F. At 500°F it was found that the T-111 was the most resistant followed closely be the T-222(A) and the Mo-1/2Ti. The 316 stainless steel and the 304 stainless steel rated fourth and fifth, but were only 25% less resistant than the tantalum and molybdenum samples. The Cb-1Zr and the Cb-1Zr(A) showed the greatest damage, the latter being substantially the worst.

At 1500°F it was found that the T-111 was still the most resistant to cavitation damage with the T-222(A) and the Mo-1/2Ti still being second and third choices. The stainless steels are no longer competitive with the refractories at this higher temperature. The 304 stainless steel ranked last at 1500°F and was quite grossly damaged after only 5 hours of testing.

It was noted immediately 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 cavitation. This was later confirmed by microsectioning the damaged specimens.

Good correlations of the cavitation data with the mechanical properties data were obtained in the form of any of several predicting equations relating the average MDP rate to various mechanical properties. However, in all cases a combination of terms involving both strength and energy properties was obtained. It will be necessary to obtain more comprehensive data before a final selection of an optimum predicting equation can be made.

BIBLIOGRAPHY

1. "Deformation of Solids by the Impact of Liquids," Program for Royal Society Meeting; London, England; May 27, 1965.

2. Hunt, J. B., "Cavitation in Thin Films of Lubricant," The Engineer, January 29, 1965, pp. 22-23

3. Garcia, R., and Hammitt, F. G., "Ultrasonic-Induced Cavitation Studies," ORA Technical Report No. 05031-1-T, Department of Nuclear Engineering, The University of Michigan, October, 1964.

4. Mason, W. P., "Internal Friction and Fatigue in Metals at Large Strain Amplitudes," Journal of the Acoustical Society of America, Vol. 28, No. 6, pp. 1207-1218, November, 1956.

5. Garcia, R., and Hammitt, F. G., "Ultrasonic-Induced Cavitation in Liquid Metals at 1500°F," Transactions of the American Nuclear Society, Vol. 8, No. 1, pp. 18-19, June, 1965.

6. Personal Communication from Henry P. Leeper, Project Metallurgist, Pratt & Whitney Aircraft (CANEL), to F. G. Hammitt; February 26, 1965, and May 13, 1965.

7. Garcia, R., and Hammitt, F. G., "Ultrasonic-Induced Cavitation Studies in Lead-Bismuth Alloy at Elevated Temperatures," ORA Technical Report No. 05031-2-T, Department of Nuclear Engineering, The University of Michigan, June, 1965.

8. Westervelt, Franklin H., "Automatic System Simulation Programming," Ph.D. Thesis. College of Engineering, the University of Michigan, November, 1960.

9. Hammitt, F. G., "Damage to Solids Caused by Cavitation," Internal Report 03424-26-I, Department of Nuclear Engineering, The University of Michigan, May, 1965. Paper presented before the Royal Society, Discussion on Deformation of Solids Due to Liquid Impact; London, England; May 27, 1965.