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Cavitation-Erosion Characteristics of Selected Materials in Mercury at 500°F.

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ABSTRACT

An experimental investigation of the cavitation resistance of three materials in mercury at 500°F is reported. The tests were conducted in the Ultrasonic Vibratory Facility in the Nuclear Engineering Department of the University of Michigan. The materials evaluated were: "pure" columbium, "pure" tantalum and 9M steel (9% chromium, 1% molybdenum, 0.1% carbon).

The pure columbium is by far the least resistant to cavitation attack, based on the mean depth of penetration (MDP) in mercury at 500°F. Pure tantalum is far better than columbium and the alloy 9M is the most damage resistant of the materials tested in this investigation.

A comparison of test data from this program is made with data obtained previously under the same conditions. This comparison indicates that alloys of both tantalum and columbium are more resistant to cavitation attack than are the pure materials. The alloy 9M is slightly more resistant to cavitation attack than 304 SS, but slightly less than 316 SS.

The mechanical properties of the materials are compared with predicting equations for average MDP rate and show that hardness and tensile strength are the most useful parameters for prediction of relative cavitation resistance of these materials. While the present tests were at 500°F, liquid temperatures in the SNAP boiler are expected to range up to 1100°F. Previous experience indicates that damage may be much less at the elevated temperature due to "thermodynamic effects".

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I. INTRODUCTION

Due to the possibility of using pure refractory metals, rather than alloys, as coatings in the mercury two-phase flow regime of one version of a mercury Rankine cycle SNAP boiler, it was desired to determine the cavitation resistance of such metals in mercury at 500°F. This temperature was chosen so that comparisons with previous tests conducted on other materials would be available. However, since the actual operating temperature may be as high as 1100° F, future tests at higher temperatures should be considered. It is quite likely that cavitation damage rates will be considerably reduced at the higher temperature where "thermodynamic" effects which moderate bubble collapse, are expected to be important[1,2,3].

The vibratory cavitation facility at the University of Michigan was used for this work since considerable damage testing of other materials in this facility had already been completed[1,2,3,etc.].

The materials tested were: columbium, tantulum and alloy 9M (9% chromium, 1% molybdenum, 0.1% carbon) which has been used as a reference material for some of the boiler work. The specimens were fabricated and supplied by NASA.

II. CAVITATION FACILITY

The University of Michigan Ultrasonic Cavitation Vibratory Facility is described in detail in reference 5. However, a short summary will be included here for completeness.

The facility consists of an audio-oscillator, power amplifier, piezoelectric crystal with coupled exponential horn, pressure vessel and high temperature furnace. Fig. 1 is a schematic block diagram of the vibratory facility and its associated auxiliary equipment.

The signal supplied by the variable frequency audio-oscillator is amplified and applied to a lead zirconate-titanate piezoelectric crystal. The application of the electric field to the piezoelectric crystal produces a mechanical strain, the magnitude of which is proportional to the square of the applied field strength. The resulting periodic variations in the axial extent of the crystal constitutes a standing wave generator. The crystal is attached to an exponential horn which amplifies the minute variations in crystal length to maximum displacements of the horn tip of approximately 3.5 mils at 20 kHz. However, a standard amplitude of 2 mils, which corresponds to previous tests, has been adopted.

The movement of the horn tip, to which the 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 specimen exposed to the collapsing bubble cloud. This facility has been operated successfully for extended periods at fluid temperatures in excess of $1500^{o}F$. Figures 2 and 3 show the facility with the transducer horn assembly both in and out of the high temperature cavitation vessel. The vessel is inserted in the furnace during high-temperature operation. Argon is used as a cover gas for the fluid. Fig. 4 shows the furnace and cavitation vessel with the transducer in place. The transducer components are shown disassembled in Fig. 5.

The specimen, detailed in Fig. 6, is screwed into the end of the exponential horn and tightened with a special wrench, which does not measurably damage the specimen. In previous investigations[5] it was found that the greatest amplitude could be obtained with specimens having a weight of 9.4 ± 0.1 grams. Since the density of the materials to be tested does vary, it is necessary to adjust dimension "A" of Fig. 6 so that the specimen under test will weigh the necessary 9.4 grams.

III. TEST PROGRAM

A. Experimental Procedure

The specimen to be tested was initially weighed, attached to the exponential horn tip and then immersed in mercury to a depth of 1-1/2 inches. An argon cover gas pressure of 2.4 psig was maintained in the test vessel. The mercury temperature was maintained at 500°F by suitable adjustment of the furnace.

All of the specimens were tested for a total of 12 hours in the cavitation environment. At intervals the specimens were removed from the test vessel, vacuum distilled to remove any trace of mercury, for a period of two hours at 500°F, visually examined and weighed. Weighing accuracy is ± 0.05 mg. The specimen surface was carefully inspected for signs of uneven damage or other blemishes, which would tend to disrupt the fluid in the area of the test specimen, before the test started.

B. Experimental Results

The experimental results are displayed as cumulative mean depth of penetration, MDP, versus test duration. The computation of MDP assumes that the damage is uniformly spread over the lower horizontal surface of the test specimen. Visual examination of the individual test specimens indicates that the cavitation damage does occur approximately uniformly over the exposed surface of the specimen for these tests (though not for tests with lower density fluids such as water). The MDP values are assumed to be more physically meaningful than weight loss since it is generally the total penetration of the 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 the material-fluid combination for a given test facility. A "figure of merit" such as MDP takes into account the large variation in density that may occur within a set of test materials.

In computing the MDP from weight loss, the following expression was used:

$$MDP = \frac{W}{\rho A}$$

where:

MDP = mean depth of penetration

W = weight loss

A = cross sectional area of test specimen

ρ = density of test specimen

The appropriate expressions for computing the MDP of the three test materials are presented in Table 1.

Table 1

Material	Density	Relationship
Columbium	8.58 gm/cc	MDP(mils) = 0.030 W/mg
Tantalum	17.12 gm/cc	MDP(mils) = 0.015 W/mg
9M	7.70 gm/cc	MDP(mils) = 0.034 W/mg

Fig. 7 is a plot of weight loss versus test duration of the three materials tested. Two specimens of each material were tested with excellent agreement between specimens except for the tantulum. As noted, the rate of weight loss in all cases is quite constant during the major portion of the test so that the materials can best be compared on the basis of the slope of the accumulated damage versus time curve.

Fig. 8 includes data previously obtained[3] on other materials in mercury at 500°F, along with the present weight loss data. It is seen that the weight loss rate of the pure refractories does not differ greatly from that of the corresponding alloys and that the 9M is quite comparable to 304 SS. Figs. 9 and 10 show the accumulated MDP in mils versus test duration. Fig. 9 is a plot of the data obtained in this study alone. On the basis of weight loss or MDP, 9M is the most resistant to cavitation erosion in these tests. However, on the basis of MDP, the tantalum is only slightly less resistant. The columbium is by far the least resistant to cavitation attack of the materials tested, but is comparable in this respect to the alloy, Cb-1Zr.

It is interesting to note that the weight loss curves for 9M and tantalum are quite linear, but slightly bowed downward for the columbium. Visual examination of the surface of the samples shows that the damage on all of the samples is approximately uniform out to the outer edge. However, the columbium, having the largest volume loss, has a substantial rim around the periphery which is relatively undamaged. This raised outer rim apparently perturbs the flow pattern on the surface of the sample so that the rate of damage decreases as the rim becomes more prominent. The surface of each of the specimens has been photographed and is shown in Fig. 11. The raised rim of the columbium sample is not noticeable in the photograph since the incident angle of the camera is normal to the sample surface.

The rates of damage, based on the uniform slope portion of the curves for each of the materials are listed in Table 2. Also tabulated for comparative purposes are the rates of the other materials[3] which are shown on the graphs.

C. Mechanical Properties

Stress-strain curves and hardness tests have been performed on the three materials investigated in this study. The stress-strain tests were performed at 500°F to correspond to the test temperature used in this experiment. From this data various mechanical properties have been calculated and are shown in Table 3.

In previous tests in this laboratory[1,3], a number of predicting equations were determined which relate the various mechanical properties to the average rate of material attrition. These correlating equations were obtained using a least mean squares stepwise regression analysis on The University of Michigan IBM 7090 computer.

From this work involving about 70 separate fluid-material-temperature combinations including water, mercury, lead-bismuth, alloy, and lithium, and covering temperature extremes between room temperature and 1500°F, it was found that the best overall single material property correlating equation was in terms of ultimate resilience[1,3]*. Even so, the average algebraic percent deviation was about 50%. However, for a single fluid such as mercury, better correlations were obtained (in terms of increased coefficient of determination and reduced percent deviation). The overall equation involving ultimate resilience and several other equations generated only for the previous mercury data, but which applied reasonably well also to the present data,

*All these properties are well defined in references 1 and 3.

are listed in Table 4. Properties involving true breaking strength are not useful with pure columbium, since it suffers almost 100% reduction of area before breaking. Hence "true strain energy" which correlated well for the mercury data alone (although not on an overall basis[1,3]) cannot be used for the present data. Also, the breaking strength for the calculation of ultimate resilience was assumed to be that existing at maximum load in the stress-strain relationship for this material, assuming no reduction of area.

Using these equations, a comparison of data from the present investigation with that of a previous study was made. Curves representing each of the four predicting equations have been plotted separately (Fig. 12, 13, 14 and 15) and compared with all the data obtained in 500°F mercury (present and past tests). For these tests, tensile strength and hardness agree best with the predicting equation.

IV. SUMMARY AND CONCLUSIONS

The experimental study which has been described in this report has resulted in a qualitative ranking of pure columbium, tantulum, and 9M steel according to their ability to resist cavitation erosion attack in mercury at 500°F in a 20kHz, 2 mil, vibratory facility at approximately one atmosphere overpressure.

The pure columbium was by far the least resistant to cavitation attack, being somewhat worse than a heat-treated Cb-1Zr alloy which has been tested and reported previously (although somewhat better than annealed Cb-1Zr)[3]. The slightly non-linear behavior of the rate curve for the columbium may be due to the change in the "flow pattern" of the cavitation cloud as the outer rim, which is formed by the loss of material, becomes more prominent.

The tantalum and 9M rank quite closely, with the 9M being only slightly better than the tantalum. The pure tantalum, like the pure columbium, is not as damage resistant as alloys of the same material seem to be.

Interesting observation can be made regarding the comparison of the 9M with the other steels which have been tested. The 9M is more resistant than 304 SS but not quite as resistant as 316 SS or as the cold rolled carbon steel.

Some pertinent mechanical properties of the present materials have been measured, and the damage data compared with previously generated predicting equations based on these properties. For this particular data, the best correlations with the predicting equation are obtained with tensile strength and hardness.

While the present tests were at $500^{o}F$, temperatures in the SNAP boiler are expected to range up to $1100^{o}F$. Previous experience indicates that damage may be much less at the elevated temperature due to "thermodynamic effects".

TABLE 2

Summary of Cavitation Results

in Mercury at 500°F

Material	Average Rate* mil/hr.	Material**	Average Rate mil/hr.
Columbium	2.56	Cb-1Zr	2.43
		T-111	0.43
Tantalum	.971	T-222	0.46
		304 SS	0.69
9M	.670	316 SS	0.63
		Hot rolled carbon steel	0.61
		Cb-1Zr (A)	3.73

* Present Tests

** Previous Tests

TABLE 3

Mechanical Properties Data for Columbium, Tantalum and 9M at 500°F

	Material		
	Columbium	Tantalum	9M
Tensile Strength, psi	27 000	47 600	75 000
Yield Strength, psi, 0.1%	9 900	14 900	42 800
Yield Strength, psi, 0.2%	11 250	15 800	45 500
Ultimate Resilience, psi	42.95	45.7	97.2
Engr. Strain Energy, psi	8 000	13 750	15 200
True Strain Energy (new), psi	421 000	65 000	43 200
DP Hardness, 1 kg	85.8	124.6	228.9
Elongation %	40.0	35.0	22.5
Area Reduction %	97.8	87.5	65.0
Elastic Modulus, psi	8.54×10^6	24.8×10^6	29.0×10^6

TABLE 4

Summary of Single Property Correlations - Mercury

Property	Predicting Equation	CD**
Ultimate Resilience, (UR):	*AMR = $0.142 + 8.918\ (ur)^{-1/2}$	0.780
Hardness, (H):	AMR = $0.242 + 1.76 \times 10^4\ (H)^{-2}$	0.921
Tensile Strength, (TS):	AMR = $-0.38S + 9.59 \times 10^4\ (TS)^{-1}$	0.909
Eng'r Strain Energy, (ESE)	AMR = $-0.179 + 1.58 \times 10^4\ (ESE)^{-1}$	0.752

* AMR = Average MDP rate

** Coefficient of Determination

Note: Correlating equation for Ultimate Resilience applies to many fluids and temperatures [1,3]. Others apply only to mercury[3].

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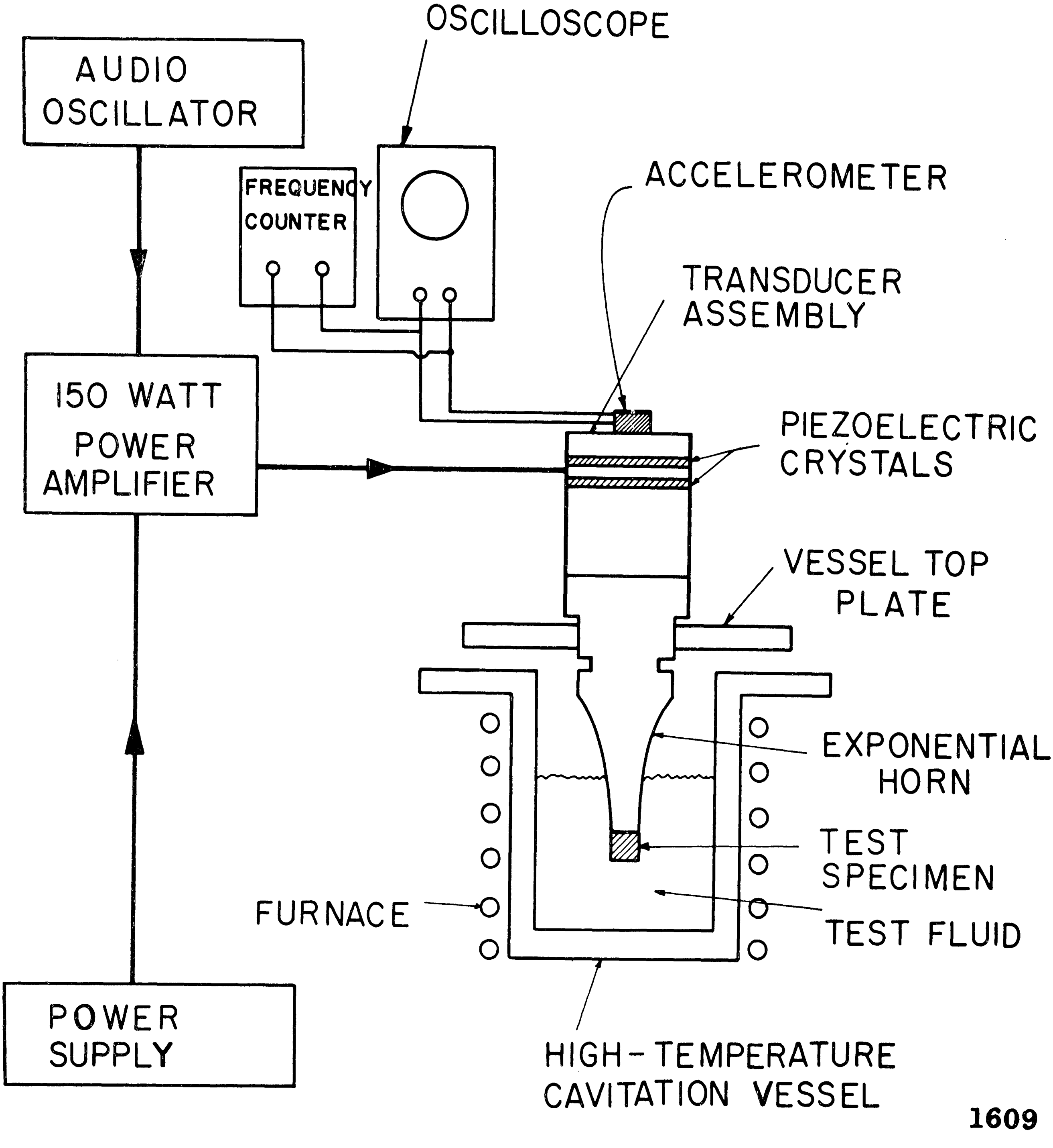


Fig. 1.--Block diagram of the high-temperature ultrasonic vibratory facility.

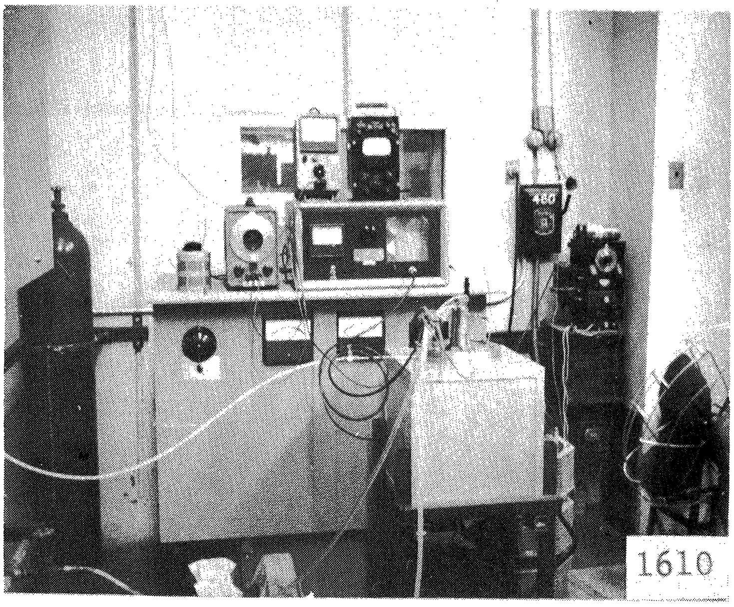


Fig. 2.--High-temperature cavitation facility with the ultrasonic transducer in place.

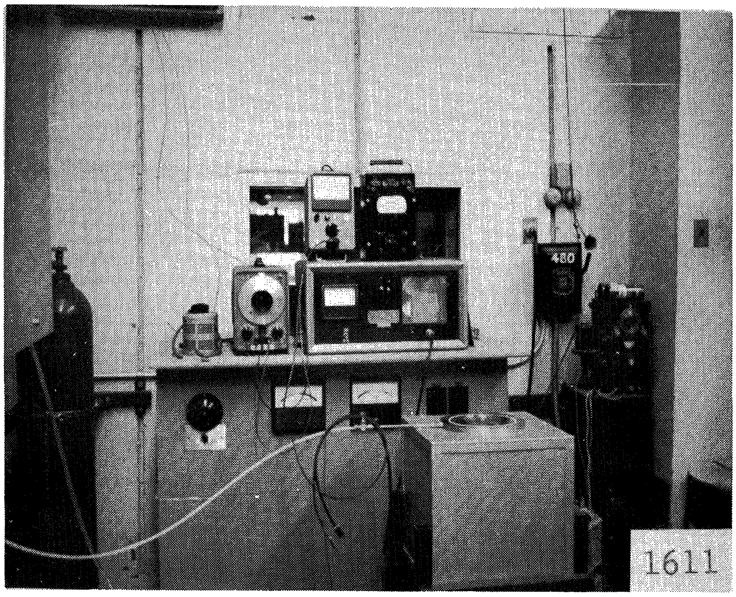


Fig. 3.--High-temperature cavitation facility with the ultrasonic transducer removed.

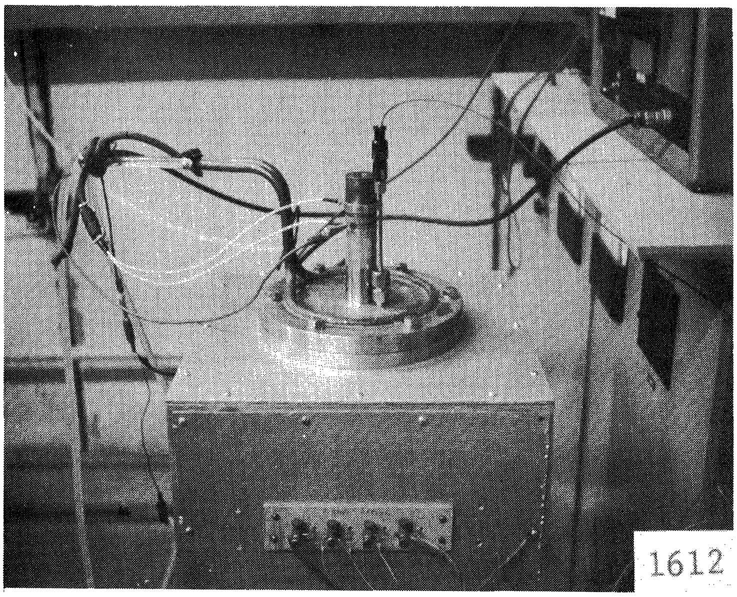


Fig. 4.--Close-up of the furnace and high-temperature cavitation vessel with the ultrasonic transducer in place.

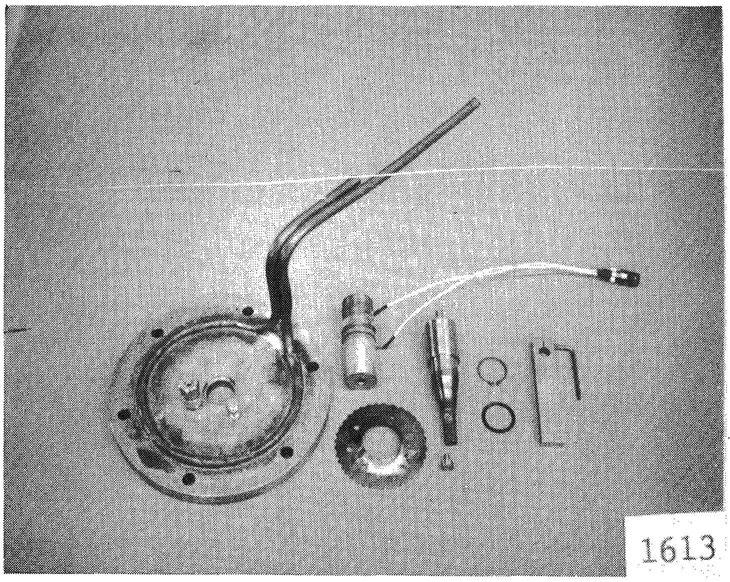
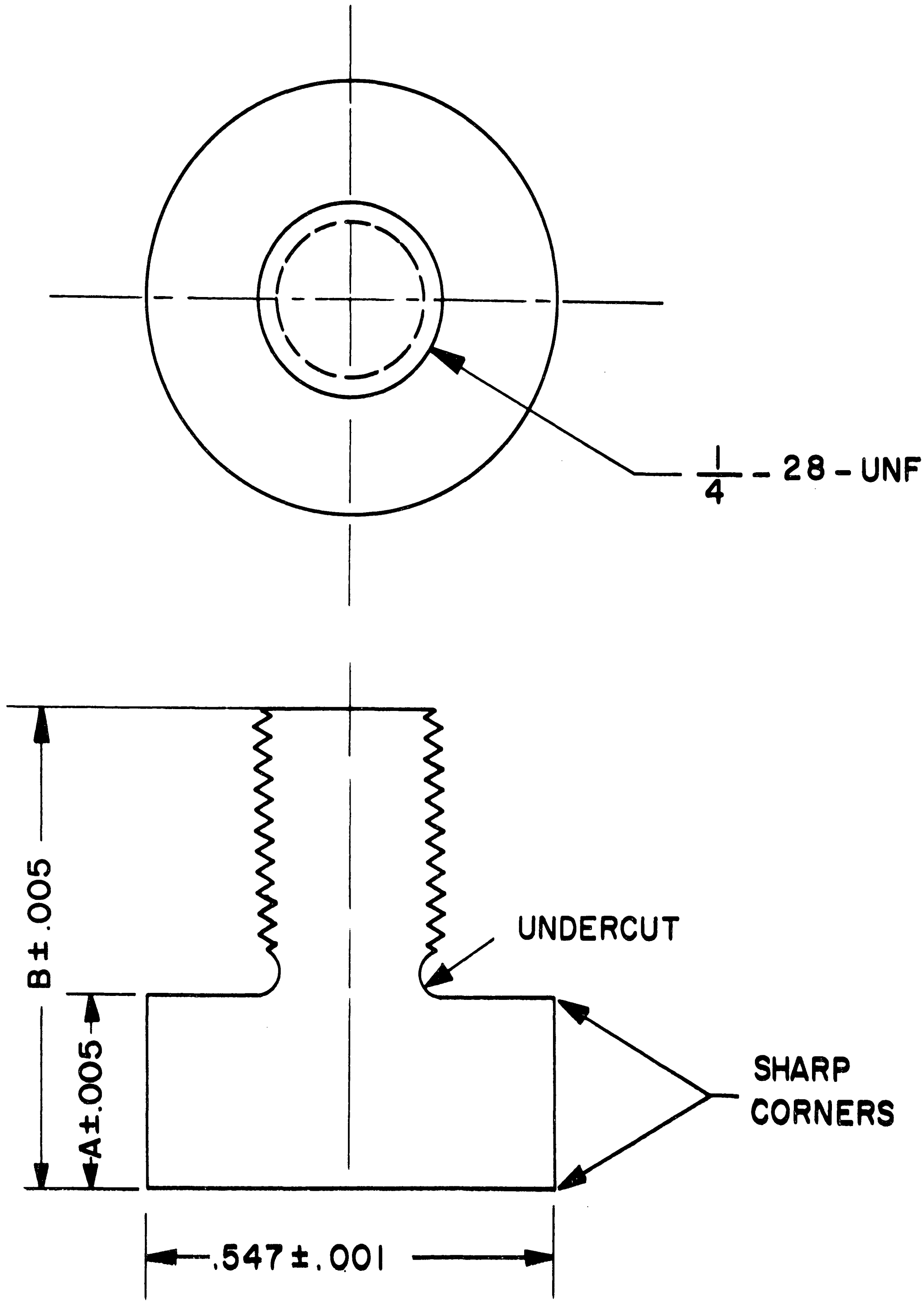


Fig. 5.--Various components of the ultrasonic facility.



NOTE :
DIMENSIONS "A" & "B"
VARY WITH SPECIMEN MATERIAL

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Fig. 6.--Cavitation test specimen.

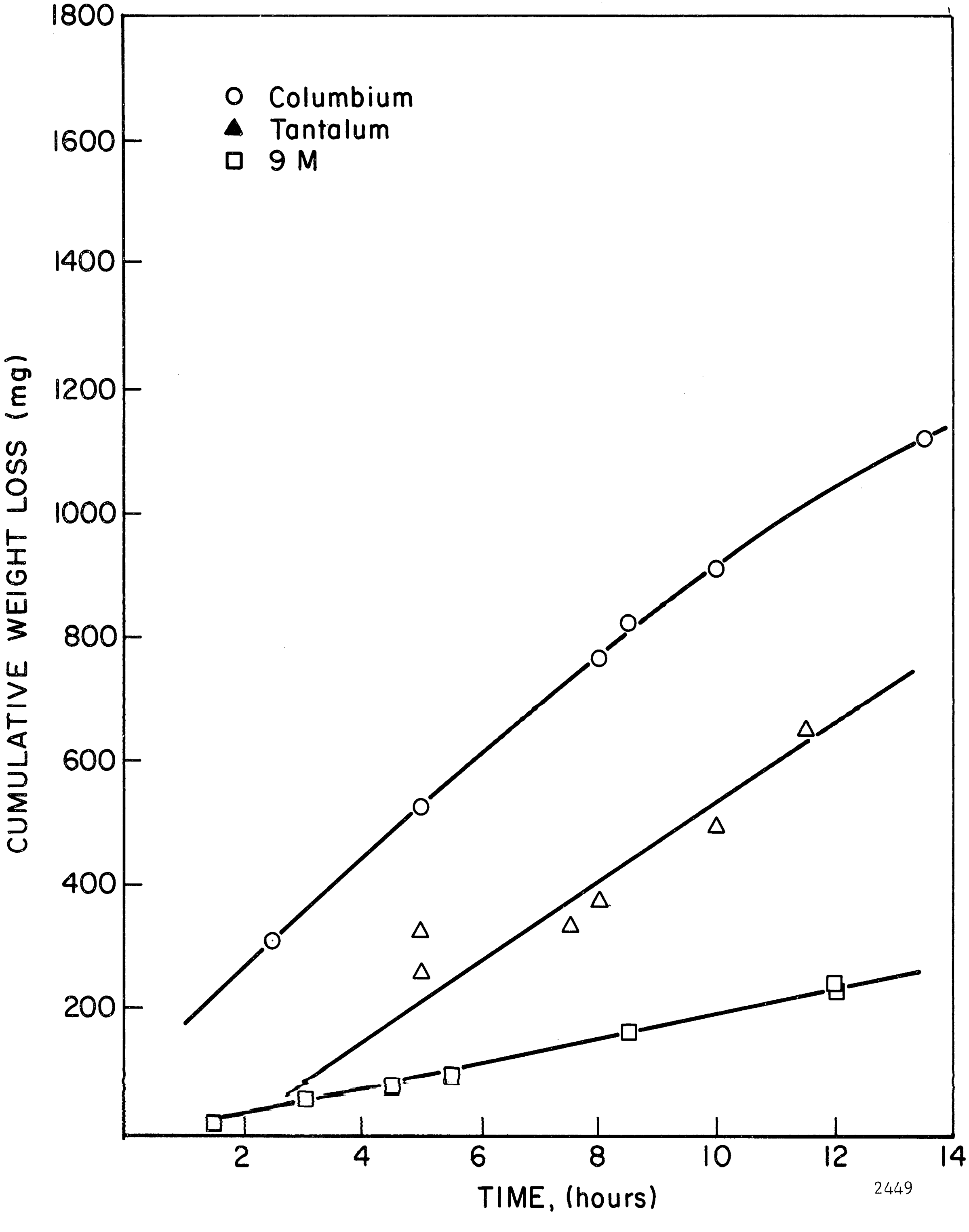


Fig. 7.--Accumulative weight loss versus duration for columbium, tantalum and 9M.

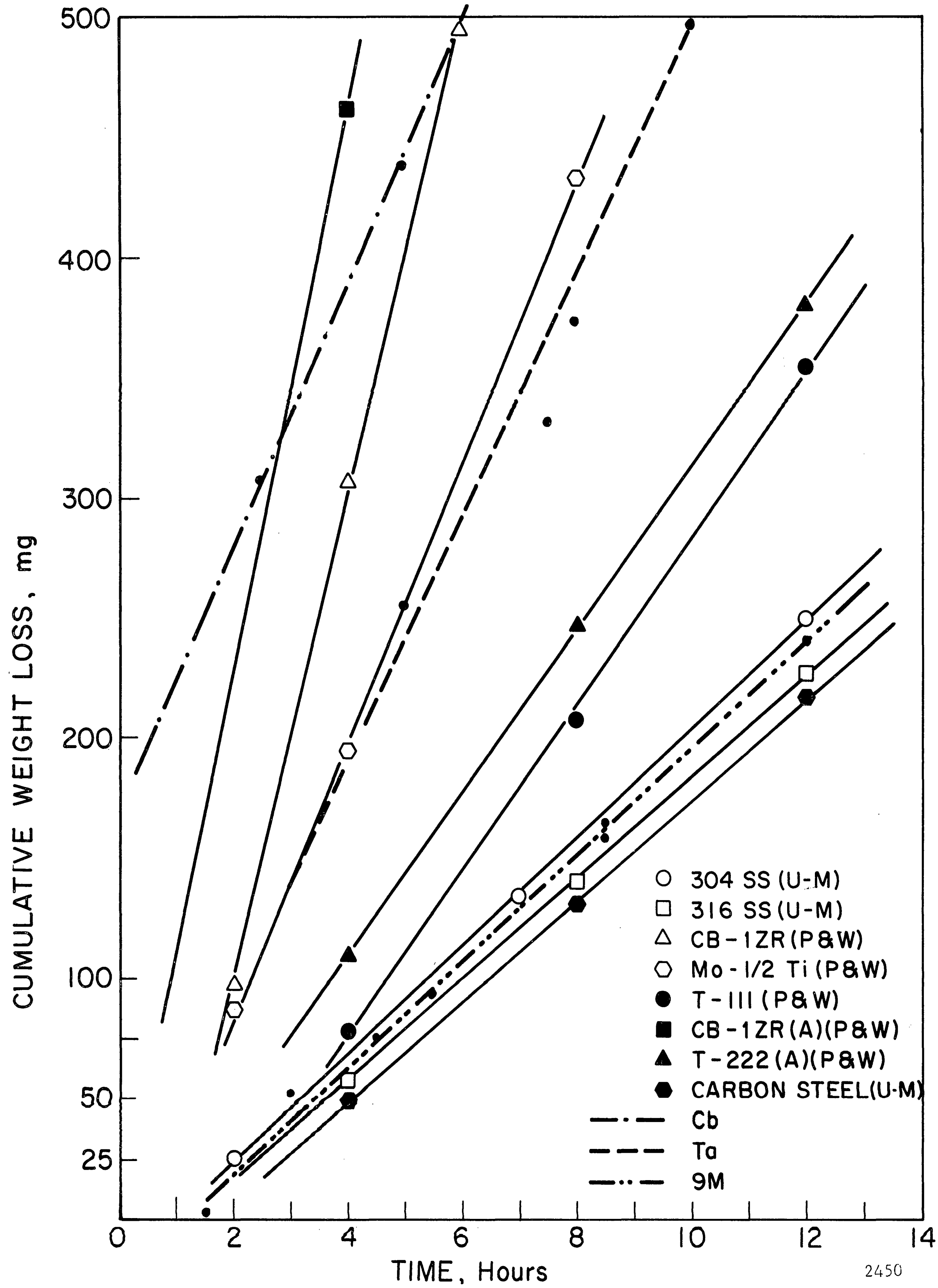


Fig. 8.--Accumulative weight loss versus duration, comparison of present results with materials previously tested in mercury at 500°F.

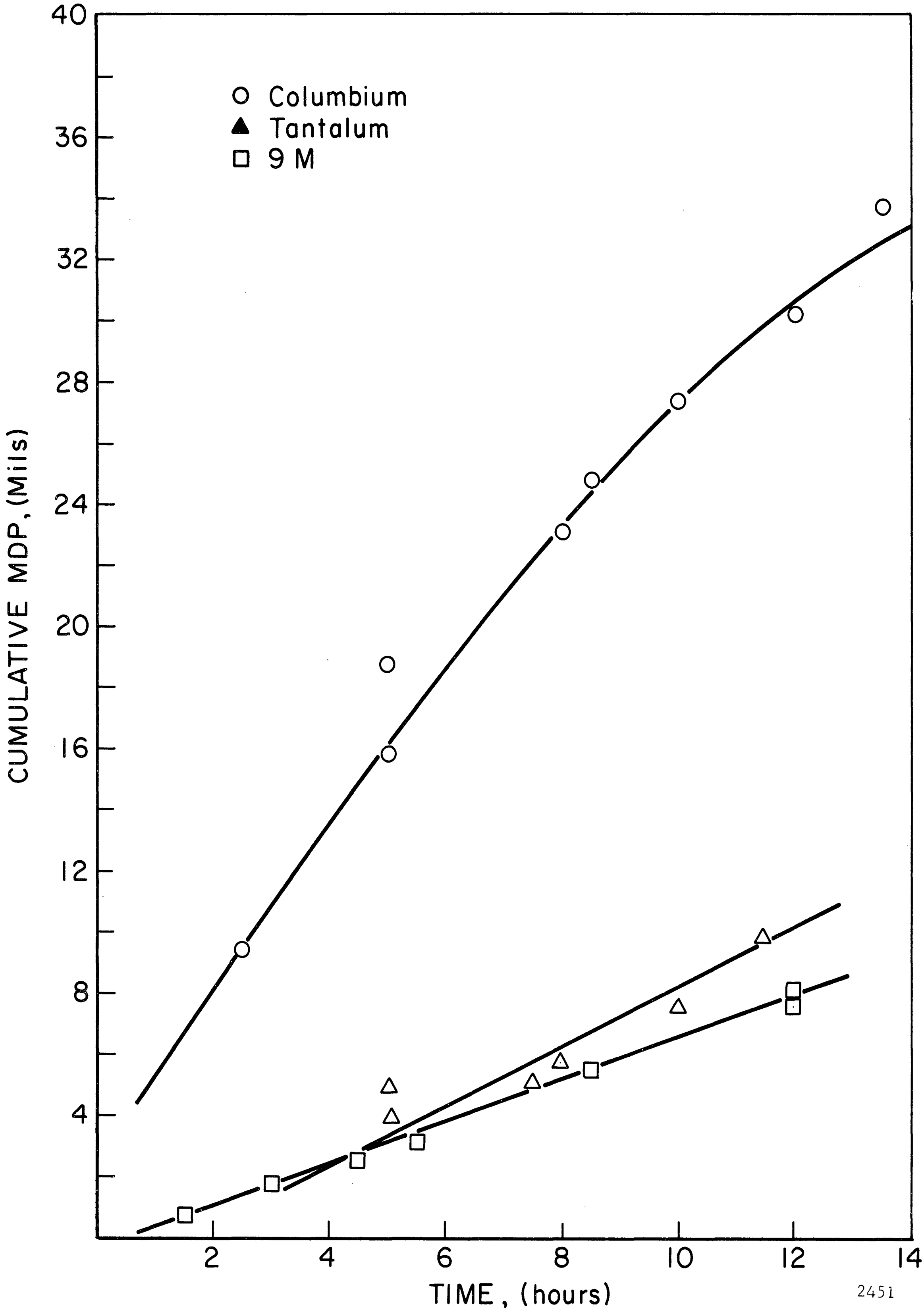


Fig. 9.--Accumulative MDP versus duration for columbium, tantalum and 9M.

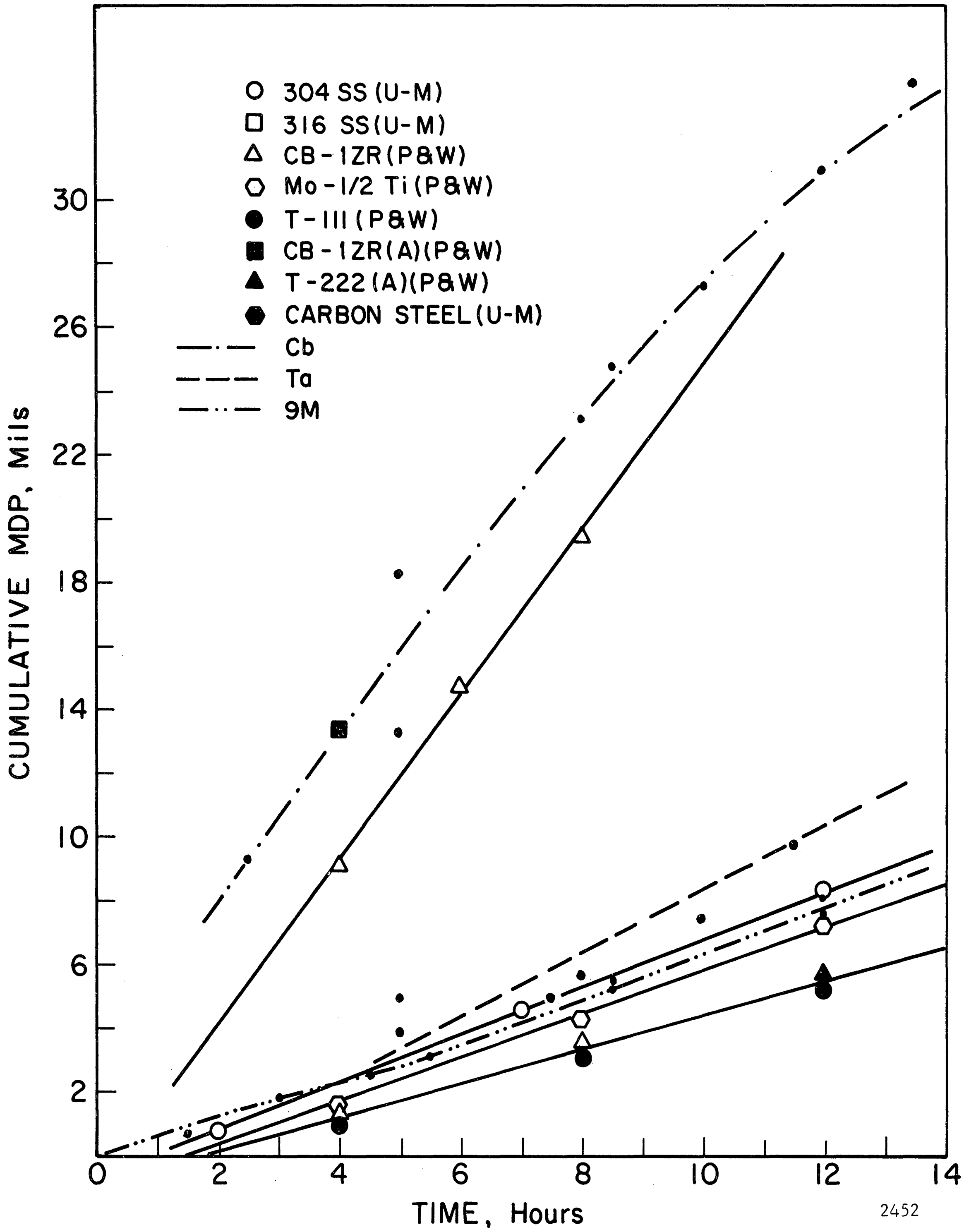
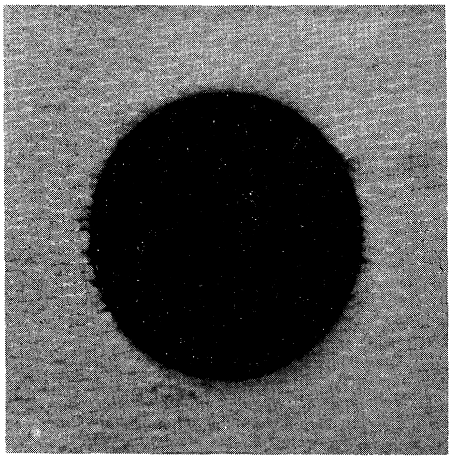
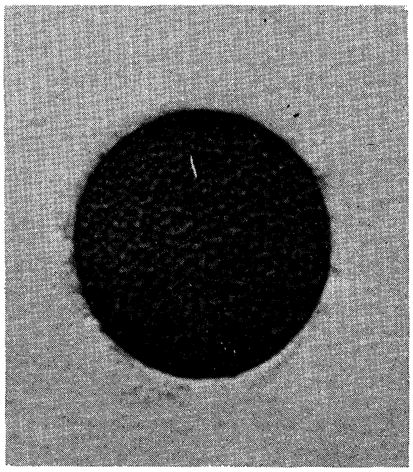


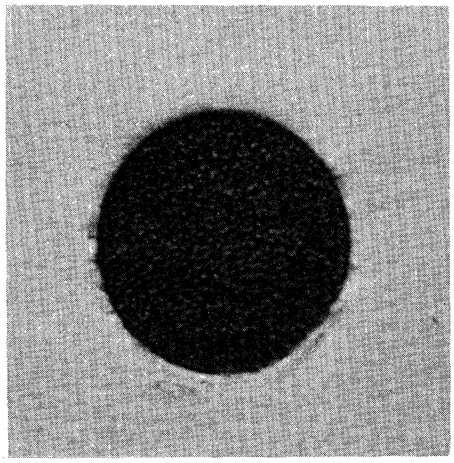
Fig. 10--Accumulative MDP versus duration, comparison of present results with materials tested previously in mercury at 500^{o}F.



COLUMBIUM



TANTALUM



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ALLOY 9-M

Fig. 11.--Specimen surface structure after completion of test in mercury at 500^{o}F.

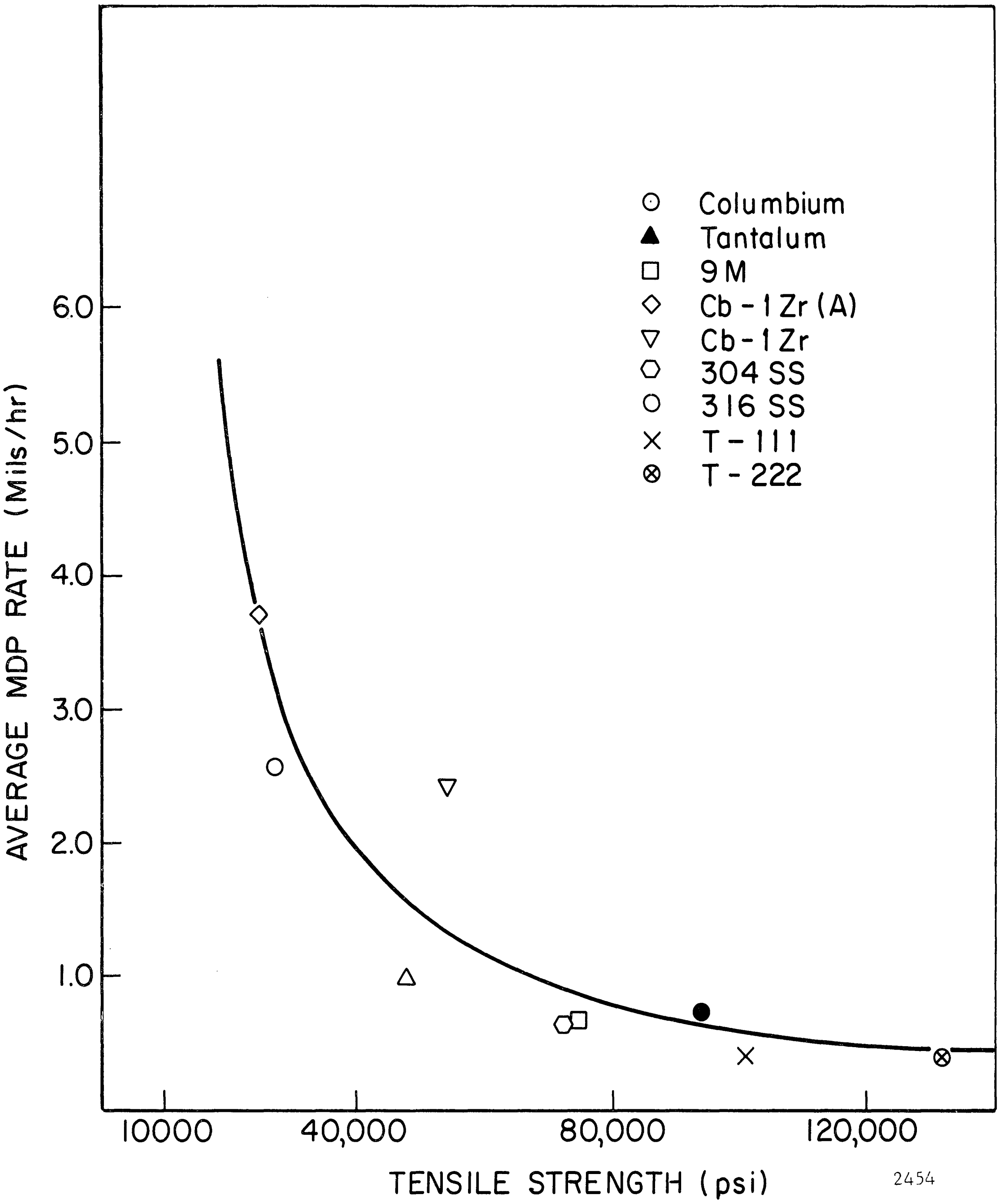

Fig. 12.--Comparison of predicted and experimental average MDP rate versus tensile strength.

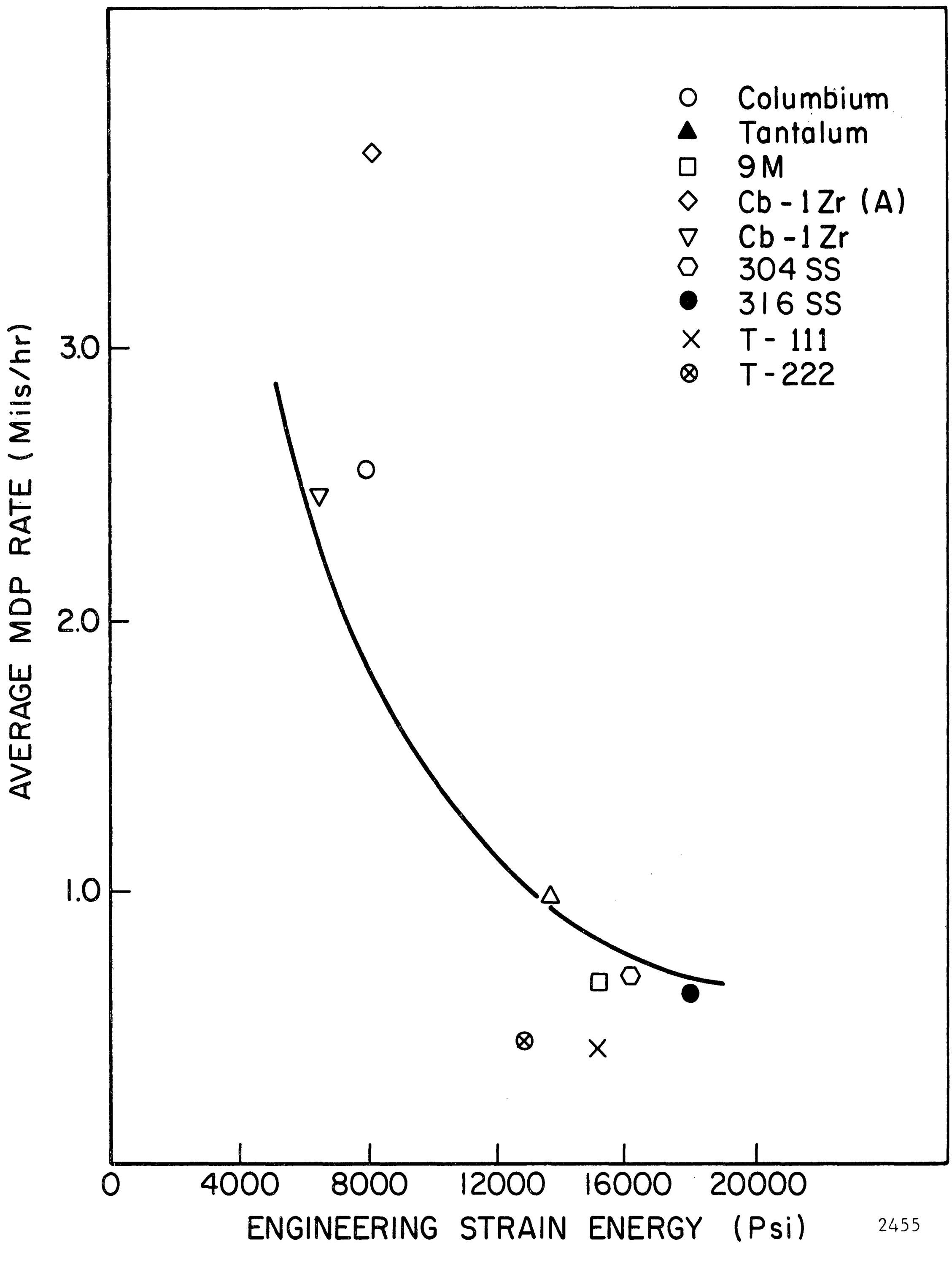

Fig. 13.--Comparison of predicted and experimental average MDP rate versus engineering strain energy

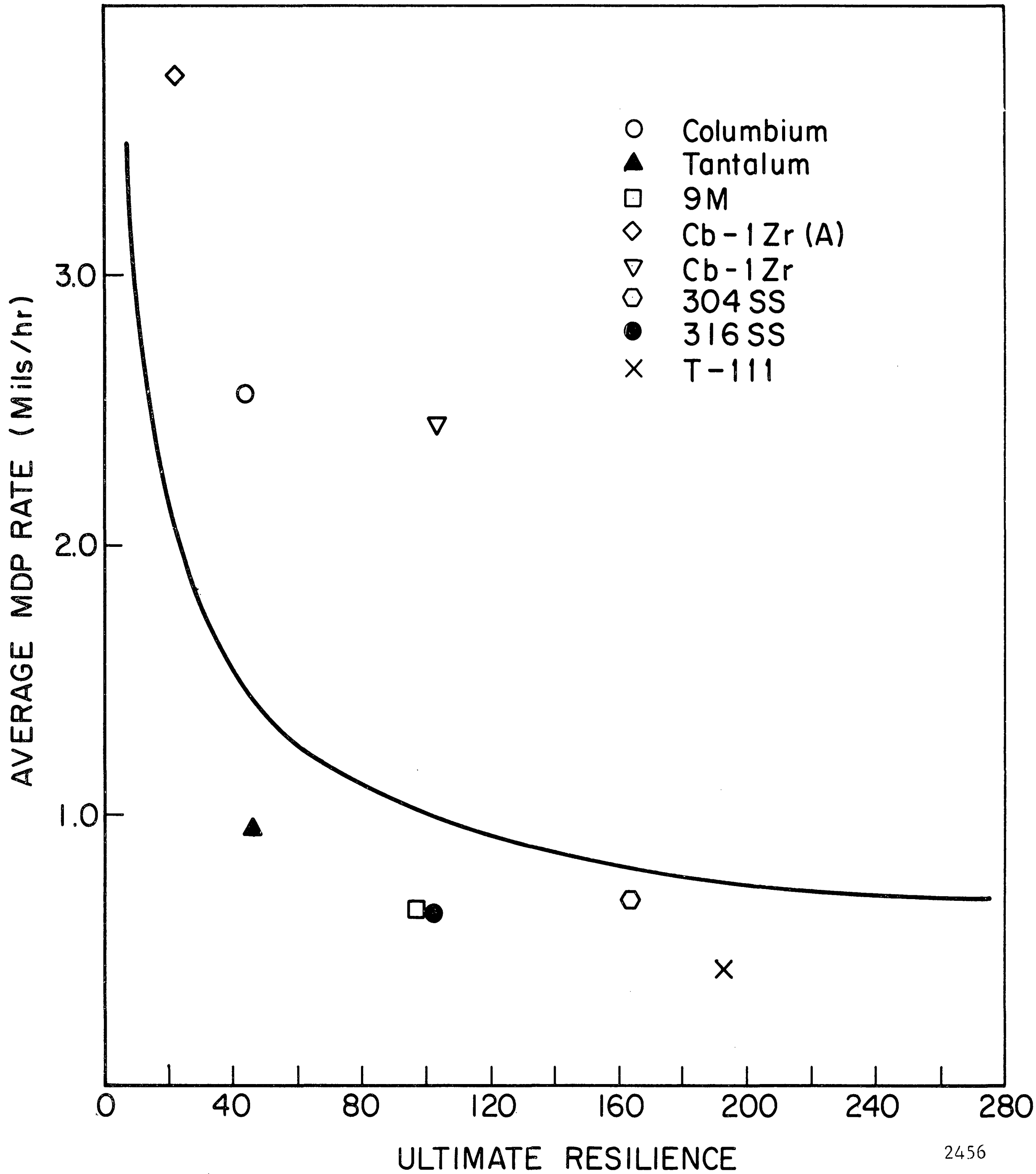

Fig. 14.--Comparison of predicted and experimental average MDP rate versus ultimate resilience.

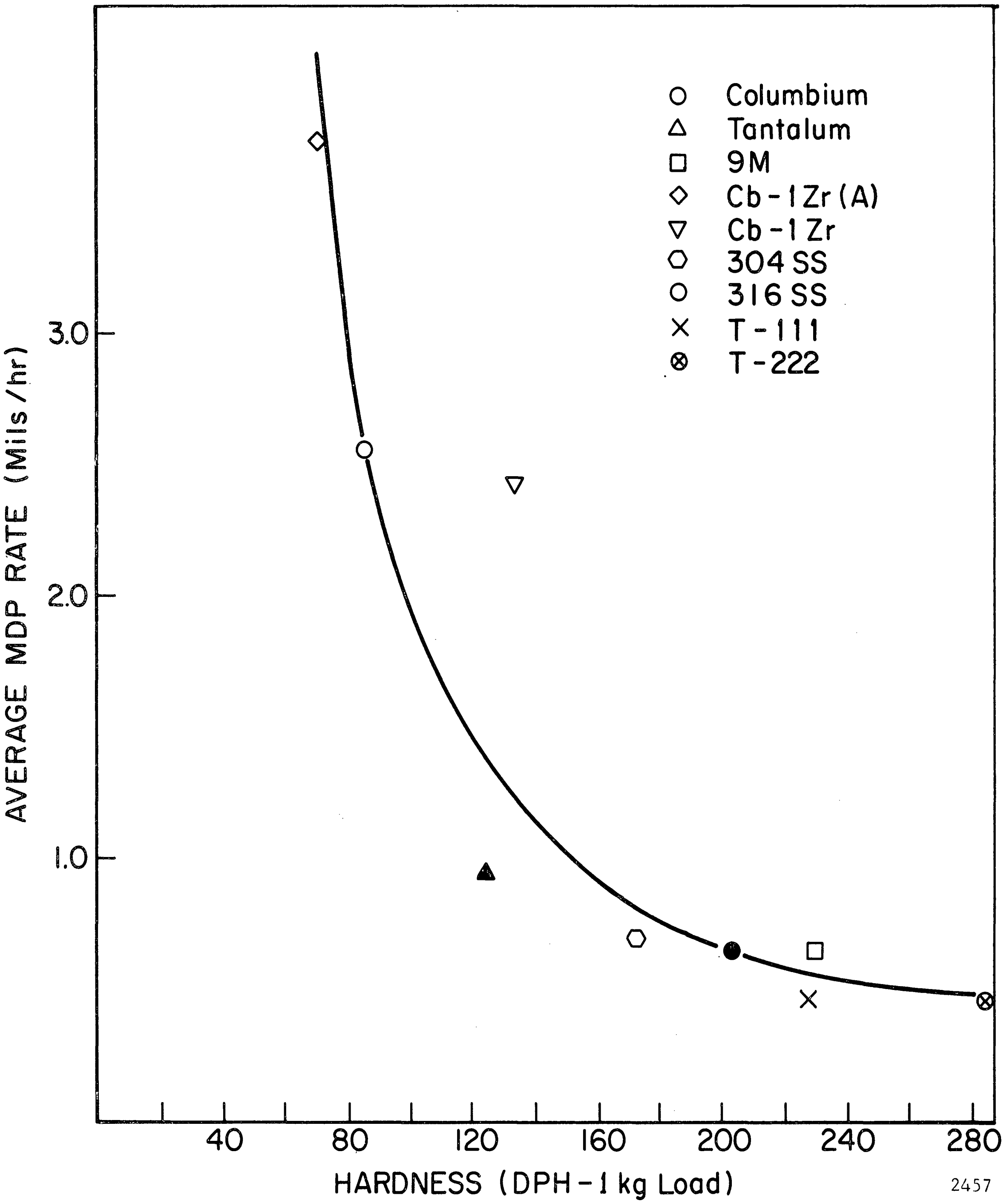

Fig. 15.--Comparison of predicted and experimental average MDP rate versus hardness.