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CAVITATION AND DROPLET IMPINGEMENT DAMAGE OF AIRCRAFT RAIN EROSION MATERIALS

(Modified for Rain Erosion and Associated Phenomena, Third International Conference)

by

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Abstract

Tests using cavitation and liquid droplet impingement (Mach ~1.75[*]) facilities upon a variety of aircraft rain erosion materials including groups of ceramics, laminates, elastomers and plastics, and two metallic alloys are reported and compared with tests of the same materials at Mach 2 on the Holloman Air Force Base rocket sled. Correlations of maximum volume loss rates for the data sets show that good positive correlations exist between the rocket sled results and either the water gun or cavitation results, best with the water gun (liquid droplet impingement device), if the materials are grouped into the above general types. A negative correlation, however, was found between the rocket sled results and those of the two laboratory devices for the material group composed of elastomers and plastics, although the two laboratory devices for these materials show a positive correlation. The negative correlation is believed typical only of rubber-like materials. Past experience has shown such materials to be very resistant to cavitation or liquid impingement for low intensity, but very much less resistant, compared to conventional materials, to relatively high intensity attack. In general, a simple proportionality relation between results from the different types of tests is not as good as an exponential relation.

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[*] Based on sonic velocity at 60°F.

LIST OF ILLUSTRATIONS

Cavitation and Droplet Impingement Damage of Aircraft Rain Erosion Materials

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I. INTRODUCTION

The testing of materials for resistance to high-speed rain erosion or to other forms of liquid droplet impact is an important technological problem today. An entirely realistic test would involve the impact of spherical droplets of the desired diameter at the desired speed upon the target materials. Furthermore, the distribution of impact points, the number of impacts, and the angle of impact should be similar to those to be encountered in the actual field application. Such a degree of realism is necessary to obtain reliable results because of the present low level of understanding of the droplet impact failure mechanism as it applies to different materials. This is especially the case for the various non-metallic materials of interest for aicraft rain erosion resistance.

Since no reasonably economic and yet relatively realistic method exists for testing rain erosion materials, various less than perfect test procedures have been used to at least approximately evaluate the resistance of materials to rain erosion. The most realistic, and also most expensive of these, is probably the rocket sled upon which numerous materials have been tested.(1) However, the duration of exposure with this device is limited, and only terminal information is obtained though the impacts are indeed randomly distributed and occur with spherical droplets of approximate rain drop diameter distribution. Angles of impact and velocities can be adjusted to cover the desired range. Hence, data from these tests can be considered as being as realistic as any presently available.

Simpler laboratory tests with which the present report is concerned include a water "machine-gun" device and a cavitation test, both used and developed for this purpose in this laboratory. The water-gun device, previously described,(2) is capable of producing repeated liquid droplet impacts upon a target at velocities within the range of interest (up to about 600 m/s) as opposed to many of the rotating arm devices for which the maximum velocity is considerably lower, and at any desired angle. Its major lack of realism lies in the fact that the droplets, though of approximately desired diameter, are of only imperfect spherical shape. A leading roughly spherical droplet is followed by a long trail of relatively lower velocity liquid, which probably is not particularly damaging. However, little information is available allowing a comparison of damage effects to be expected for liquid particles of differing shapes.

There has been experimentation and postulation over the past 50 years(6) on the question of whether or not liquid impact and cavitation damage are sufficiently similar phenomena to allow data gathered in one field to be applied to the other. That this might be done is not an unreasonable hypothesis, since it has been emphasized by recent photographic studies (7, 8, 9) that at least an important contribution to cavitation damage is the impact of liquid "micro-jets" originating from asymmetrical bubble collapses upon material surfaces. However, no extensive data allowing a comparison between resistances of the same materials to cavitation and liquid impingement yet exist. It is the purpose of this report to partially fill this gap by comparing cavitation resistance to liquid impingement resistance, both for the rocket sled tests(1) and for our laboratory gun device,(2) of some materials applicable to the rain erosion application. These include groups of ceramics, laminates, and elastomers and plastics respectively, as well as two aluminum alloys.

II. EQUIPMENT ITEMS UTILIZED

The laboratory equipment items utilized include both our automated water gun device and a vibratory cavitation test adapted to the type of materials of interest in the aircraft rain erosion application.

The gun device patterned after a design originated by Kenyon,(3) provides approximately 30 liquid droplets per minute at velocities up to 600 m/s to be impacted against the target material. The droplet is in the form of an approximately spherical nose (Fig. 1) followed by a long trail of lower velocity liquid. For the present tests the droplet diameter was about 1.0 mm, which is within the range of interest of the rain erosion application. Since the extremely high pressure part of the impact exists only during its very initial portion, it is likely that the damage caused by the lower velocity trailing liquid jet is relatively negligible.

The cavitation tests were made using a nominal 20 kHz, 2 mil (0.050 mm) double amplitude vibrating horn to create a cavitating field. The test specimens were held stationary, parallel to and at close clearance (0.50 mm) from, the vibrating horn tip. They were not attached to and vibrated with the horn as in the usual arrangement because the necessarily firm attachment to the vibrating horn cannot be effected with some of the materials of interest in the rain erosion application. The arrangement has been previously described in detail.(10) Damage rates with this arrangement are the order of 1/2 those obtained with the conventional arrangement.

III. EXPERIMENTAL RESULTS

The entire experimental data from the cavitation and impingement tests have been presented elsewhere,(4) both in the form of photographs of damaged specimens of each type of material at the conclusion of the test and as curve sheets showing weight loss vs. time of exposure or number of impacts for each type of material. Typical photographs (Fig. 2) and curve sheets (Fig. 3) only, are also included here. The photographs of the specimens of a typical material at the conclusion of the tests are arranged (Fig. 2) so that a direct comparison between the water gun impingement test and the cavitation test can be made. A photograph of a specimen of the same material after the Mach 2 rocket sled test(1) is also included. In general, the damage from the cavitation test is of much "finer" texture than that from either of the impact tests.* This is to be expected since the cavitation attack consists of a very large number of "microjets" or micro-shock-wave impacts per unit area, while that from the impact tests is due to a much smaller number of impacts with much larger diameter liquid droplets. The jet velocities in all cases are probably of the same order of magnitude. The difference in form of attack between these three different types of tests is probably the principle reason for the differences in relative rankings of materials achieved.

A typical curve sheet for each material showing weight loss and MDP** vs. number of impacts for the water gun tests and time of exposure for the cavitation tests are shown in Fig. 3. No comparative curve can be shown for the rocket sled test since only overall weight loss can be measured. In the Mach 2 rocket sled run, a portion of the exposure area, 0.5 cm x 0.5 cm (about the damaged area in our gun tests) is exposed to ∼6 impacts on a passage through the rainfield(5) for the 60° impact angle specimens used.

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*This is not evident for the aluminum alloy selected for presentation here, since no volume loss was incurred in the rocket sled test for this material.

**MDP = Mean depth of penetration = volume loss/specimen area.

Ideally the gun and cavitation tests should result in "S-shaped" curves showing an intermediate maximum rate of weight loss. For numerical comparison of results, the maximum weight loss rates have in all cases been reduced to a "mean depth of penetration rate" = MDPR, i.e., volume loss rate/unit area. For simplicity these have been based in all cases on the exposed specimen area rather than upon the area of damage which differs somewhat depending upon the type of material, especially for the impingement tests. The density of the coating material, where this differs from the substrate, has been used to compute MDPR.

The cavitation specimens are approximately 0.6 inches square. However, the exposed area was considered to be only that part of the specimen directly under the vibrating horn tip, which is 0.547 inches in diameter. Two sizes of water gun specimens, 1-1/4 inches square and 0.6 inches square, were tested. However, MDP is based only on the smaller specimens, since the damaged area itself is considerably smaller than even the smaller specimen. The rocket sled specimens are 1-1/4 inches square, but the exposed area was only 1.0 square inches.(1)

The maximum computed MDPR values for our tests are listed in Table 1 for each material along with the rocket sled results. It is noted that the number of impacts in the rocket sled tests for an area approximating the area damaged in our gun tests (the same for all materials and depending only on the rate of rainfall and length of rain field(5)) is generally much less than that from our tests, which were continued until a relatively constant damage rate was achieved. Since the total damage in the rocket sled test was typically much greater, the damage per impact is much greater for those tests, probably due to the larger diameter of drop and its more nearly spherical shape, as well as to the somewhat higher impact velocity. This result also tends to confirm the relatively non-damaging nature of the trailing portion of the liquid cylinder in the gun tests.

IV. COMPARISON OF RESULTS FROM DIFFERENT FACILITIES

A. General

The maximum MDPR values for all specimens from the cavitation and water gun tests in this laboratory are listed in Table 1 along with overall MDPR values from the rocket sled tests for each material which we have tested either in the water gun or cavitation facility. The rocket sled data selected for comparison is that for the Mach 2 condition at 60° impact angle (648 m/s). The average impact velocity for the water gun tests is 598 m/s. However, a similar mismatch would be obtained if the Mach 1.5 rocket sled data were used, and due to the very small volume losses in some cases for the lower Mach number, the precision of the data is considerably less. Hence the Mach 2 condition was chosen for comparison. A 60° impact angle was chosen for the rocket sled data since the 90° volume loss is severely reduced by the action of the bow shock wave in breaking up the water drops before impact. 60° is thus the closest to perpendicular for which good data is available.

B. Detailed Comparison of Results

The water gun impact test or the cavitation test is valuable for evaluating the rain erosion resistance of materials only to the extent that their resistance in the actual application can be predicted from the results of these much simpler and more economical tests. Assuming that the rocket sled data represents the closest presently available approach to the actual application, a comparison of our water gun impact and our cavitation data for the same materials with the rocket sled data is extremely useful. However, any lack of agreement is not entirely due to the imperfections of our laboratory tests. The rocket sled data is much "cruder" in the sense that no volume loss vs. time curve is available (as it is for the laboratory tests), so that only an average MDPR for the entire test can be computed. This must then be compared with the maximum MDPR derived from the actual volume loss vs. time curves for the laboratory devices, since the selection of a fixed duration for these latter devices upon which a *mean* loss rate might be based is obviously indefensible. Thus a general similarity of results between rocket sled and the laboratory devices is all that could be expected even if the laboratory tests modelled the actual damage process perfectly. If a reasonable similarity of results if obtained between these different types of tests, it is quite probable that the laboratory devices are indeed closely modelling the actual phenomenon with reasonable success.

The actual comparisons between the data sets from the three types of tests here considered must be made on a statistical basis in terms of a correlation coefficient and standard error of estimate. Thus an algebraic relation must be assumed and the pertinent statistical parameters computed for this relation. A very good correlation could always be achieved between the different data sets if a complex relation such as a power series were assumed, and then best fit exponents found. However, the resulting relations would lack generality, and very probably would not be successful in correlating new data since they would have no physical basis. Thus we have limited this comparison to very simple forms of a hypothesized relationship between the different data sets. As a first approach we assume that a simple constant of proportionality relates MDPR for a given material from the cavitation tests with that from the water gun test, etc.; i.e.:

$$\begin{aligned} \mathrm{MDPR}_{\mathrm{gun}} &= C_{g-r}\,\mathrm{MDPR}_{\mathrm{rocket}} \\ \mathrm{MDPR}_{\mathrm{cav.}} &= C_{c-r}\,\mathrm{MDPR}_{\mathrm{rocket}} \qquad \text{---(1)} \\ \mathrm{MDPR}_{\mathrm{gun}} &= C_{g-c}\,\mathrm{MDPR}_{\mathrm{rocket}} \end{aligned}$$

Ideally, the value of each of the constants, C would apply for all materials. Actually, it will be sufficient if a single constant applies only for a well-defined type of material, e.g., ceramics, laminates, elastomers and plastics, and metal alloys, into which groups we have divided the available materials. Since the only metals tested were the aluminum alloys 2024-T-3 and 6061-T-6, no comprehensive metal alloy group could be formed. If such constants (eq. (1)) could be shown to apply reasonably well for such fairly comprehensive data sets, the laboratory test could be used to predict with some confidence actual application results for presently untested materials. Using these relations, all the available comparative data (Table 1) have been reduced by computer program to generate the constants, (C_{i-j}), correlation coefficients,* and the standard errors of estimate.* Table 2 shows these results.

A further calculation was then made assuming a slightly more general form of eq. (2); i. e.:

$$MDPR_i = C_{i-j} MDPR_j^b \qquad ---(2)$$

where b is a least mean square fit best exponent. The values of b and the constants C_{i-j} are also listed in Table 2. The correlation coefficient is unchanged by the form of data fitting relation assumed, i. e., eq. (1) or (2). However, the standard errors of estimate are improved with eq. (2) because of its greater generality. Fig. 4-15 are logarithmic plots of the data in the individual material groups and taken together, comparing rocket sled data with gun and cavitation data separately, and gun with cavitation data separately. On these plots, eq. (1) is represented by the best 45° straight line, and eq. (2) by a best slope straight line. These lines, as computed from the least mean square fit analyses, are shown along with the limits of the standard error of estimate* in all cases.

An examination of Table 2 and these figures shows the following salient points.

1. The correlation coefficient for the complete data set taken together is not sufficient for such a correlation to be useful.

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* Explained in Appendix.

2. The correlation coefficients are reasonably good for the ceramics and the laminates between all combinations of test devices. The correlation between the cavitation and water gun tests are best (0.885 and 0.981 for ceramics and laminates, respectively), perhaps indicating that these are both relatively low intensity tests compared to the rocket sled. The correlation coefficients between the cavitation test and the rocket sled is the worst, as might be expected, but those between the rocket sled and the water gun are quite good (0.674 and 0.871, respectively). Since the correlation of either laboratory device with the rocket sled is somewhat reduced by the imprecision of the rocket sled test itself,* it may be concluded that either laboratory test provides quite a useful correlation with actual rain erosion performance for these types of materials. The water gun test appears better in this respect than the cavitation test. Good results would probably also be achieved for either of these tests with metals, but no pertinent rocket sled data are available, zero volume loss being found for the metallic specimens tested. Also only two metallic alloys have been tested in our rain erosion laboratory devices.

3. The group of elastomers and plastics (plexiglas and teflon) show a negative correlation between rocket sled and either laboratory device (positive correlation between the laboratory devices). This may be indicative of the long recognized fact that such materials are often very resistant to low intensity attack either by cavitation or impact, but become relatively poor for very high intensity attack. Presumably, the more "rubber-like" their qualities, the more these trends may apply. Thus, negative correlations, 0.0 correlations being random, were found for these materials when comparing results from relatively low intensity

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*Aside from reasons already stated, the rocket sled test differs also in some cases from the others because its more intense attack wears completely through the coating and well into the substrate, whereas generally the laboratory tests do not.

with relatively high intensity tests. In the present tests, the cavitation attack is of extremely low intensity in terms of volume loss/impact, compared to the rocket sled or gun tests. There are perhaps 10^6 "impacts" (bubble collapses) per second in the cavitation test, compared to ~ 10 - 10^2 total impacts in the gun or rocket sled tests, and the total volume losses achieved in the cavitation test are also much less. The gun tests likewise are of considerably lower intensity than the rocket sled tests. Thus the elastomers and plastics are relatively most resistant in the gun test, and still less in the rocket sled test.

In the present tests the fact that there is a positive correlation for these materials between cavitation and water gun tests indicates that both are relatively of the same range of intensity.

4. Ideally a simple factor of proportionality should exist between damage rates achieved by the different test devices for the same material as postulated by eq. (1). If so, the best fit exponent, b in eq. (2), would be unity. Inspection of the logarithmic curve sheets (fig. 4-15) and Table II indicates that this is not the case. Actually b varies for the different material groups and test facility combinations between 0.521 and 1.53 for positive slopes, and shows a most negative value of -0.935 for the elastomer and plastics group. However, its closest approach to unity (1.016) is also for this group, when results for the water gun and cavitation test are compared. The reasons for the relative failure of the simple proportionality model, eq. (1), lie both in the differences in material reaction to different intensities of attack and in differences in the test other than simply intensity.

V. CONCLUSIONS

1. It can be concluded from this study that useful correlations of rain erosion damage resistance of materials exist between tests using either the water gun device or the vibratory cavitation device of this laboratory and true rain erosion exposure of materials. This conclusion is based upon a comparison of results for various rain erosion materials tested on the cavitation and water gun laboratory devices and on the Holloman AFB rocket sled. The correlation is best with the water gun device, but that with the cavitation device is also in a range to be useful.

2. The first conclusion applies either to materials of the ceramic type or to a grouping of laminates. It is believed that a similar correlation would be found to exist also for metallic alloys, but no evidence to substantiate this conclusion is yet available. The best-fit proportionality constant between damage rates achieved with these devices, however, is different for these two general types of materials.

3. A negative (i.e., inverse) correlation was found for elastomers and plastics between results from the rocket sled and those from either the water gun or cavitation test. A positive correlation for these materials was found between the cavitation and water gun. However, it is believed that the negative correlation is typical only of rubber-like materials which past experience has shown to be extremely resistant to cavitation or impingement erosion of low intensity, but very much less resistant, compared to conventional materials, to relatively high intensity attack.

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APPENDIX

A. Correlation Coefficient r:

The correlation coefficient is defined in the standard manner(11) as

$$r = \frac{\sum xy}{\sqrt{(\sum x^2)(\sum y^2)}} \qquad \text{---(1A)}$$

where $x = \ln X - \overline{\ln X}$

$y = \ln Y - \overline{\ln Y}$

It is necessary to use the natural logarithms rather than the original data because we fit the equation $Y = bX^{a}$ by transforming it into $\ln Y = \ln b + a \ln X$ and the equation $Y = bX$ by transforming it into $\ln Y = \ln b + \ln X$.

B. Standard Error of Estimate $s_{y,x}$:

The standard error of estimate is likewise determined in the standard manner using the logarithmic data. If $\ln Y_{pred}$ represents the value of $\ln Y$ corresponding to a given value of $\ln X$ as predicted by the least square regression line

$$\ln Y = \ln b + a \ln X \qquad \text{---(2A)}$$

then the scatter about the regression line is measured by the standard error of estimate of $\ln Y$ on $\ln X$,

$$s_{y,x} = \sqrt{\frac{\sum(\ln Y - \ln Y_{pred})^2}{N-1}} \qquad \text{---(3A)}$$

On a log-log plot, then, one would expect that 68.27% of the data points would lie within a band $\pm s_{y,x}$ from the least square regression line defined above (2A). Note that eq. (3A) for $s_{y,x}$ uses natural logarithms, and hence values of $s_{y,x}$ must be divided by 2.301 to give base 10 logarithms for use in Fig. 28-39.

TABLE I

MATERIAL AND EROSION RATE DATA

	Material Designation	Max. MDPR for Water Gun* (mils/impact)	Max. MDPR for Cavitation** (mils/hr)	Avg. MDPR for Rocket Sled*** (mils/sec)
Ceramics	A-1	--	0.488	1.67
	A-2	2.68×10^{-3}	0.613	37.6
	A-3	0.506×10^{-3}	0.198	0.488
	A-6	0.247×10^{-3}	0.286	3.76
	A-7	3.84×10^{-3}	7.37	2.37
	A-8	11.2×10^{-3}	18.5	64.0
	E-14	2.49×10^{-3}	5.29	6.76
Laminates	C-1	0.0712	10.0	22.8
	C-2	--	11.7	4.60
	C-3	0.0656	4.38	4.46
	C-6	--	10.0	19.7
	C-7	--	4.06	5.51
	C-8	--	20.8	104+
	D-1	0.481	92.9	98.6+
	D-2	0.673	274	71.1
Elastomers and Plastics	F-3	0.201	5.80	4.32
	F-5	0.0423	0.121	7.11
	F-7	0.0208	0.403	8.79
	F-16	0.0200	0.0865	5.51
	I-1	0.00387	0.129	0
	I-2	0.203	7.29	4.05
	I-3	0.183	0.448	20.6
	I-5	0.300	8.18	0.349
Metals	J-1	--	0.887	0
	J-2	0.636×10^{-3}	6.87	0

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*Water gun figures are based on the specimen face area of 0.36 in.^{2}, and not on actually damaged area.

**Cavitation data are based upon the exposed area of 0.235 in.^{2} directly under the vibrating horn tip.

***Rocket sled figures are based upon the MDP data in AFML-TR-67-164(1) and later supplements at Mach 2.0, a 60° impact angle, and the average exposure time of 2.82 seconds.

+No Mach 2.0 data are available: figures shown are extrapolated from Mach 1.5 data.

TABLE II-A

Statistical Correlations of Ceramics

Specimen No.*	Water Gun/Rocket Sled	Cavitation/Rocket Sled	Cavitation/Water Gun
	$C_{\text{gun-rocket}}$	$C_{\text{cav.-rocket}}$	$C_{\text{cav.-gun}}$
A-1	--	0.292	--
A-2	0.0713×10^{-3}	0.0163	227
A-3	1.07×10^{-3}	0.406	391
A-6	0.0657×10^{-3}	0.0761	1157
A-7	1.62×10^{-3}	3.11	1919
A-8	0.175×10^{-3}	0.289	1651
E-14	0.368×10^{-3}	0.783	2124
r	0.674	0.550	0.885
Linear Relation	$MDPR_g = .282 \times 10^{-3} \times (MDPR_r)$	$MDPR_c = .270 \times (MDPR_r)$	$MDPR_c = 942 \times (MDPR_g)$
S_{lin}	1.347	1.672	0.928
Exponential Relation	$MDPR_g = .689 \times 10^{-3} \times (MDPR_r)^{.521}$	$MDPR_c = .551 \times (MDPR_r)^{.572}$	$MDPR_c = 3380 \times (MDPR_g)^{1.20}$
S_{exp}	1.031	1.499	0.883

*See Table I for Material Description

TABLE II-B

Statistical Correlations of Laminates

Specimen No.*	Water Gun/Rocket Sled $C_{gun-rocket}$	Cavitation/Rocket Sled $C_{cav.-rocket}$	Cavitation/Water Gun $C_{cav.-gun}$
C-1	3.122×10^{-3}	0.438	140
C-2	--	2.543	--
C-3	14.708×10^{-3}	0.982	66
C-6	--	0.507	--
C-7	--	0.736	--
C-8	--	0.200	--
D-1	4.878×10^{-3}	0.942	193
D-2	9.465×10^{-3}	3.821	407
r	0.871	0.778	0.981
Linear Relation	$MDPR_g = .00679 \times (MDPR_r)$	$MDPR_c = .859 \times (MDPR_r)$	$MDPR_c = 165 \times (MDPR_g)$
S_{lin}	0.688	0.951	0.749
Exponential Relation	$MDPR_g = 0.0149 \times (MDPR_r)^{.767}$	$MDPR_c = 1.39 \times (MDPR_r)^{.843}$	$MDPR_c = 389 \times (MDPR_g)^{1.53}$
S_{exp}	0.606	0.927	0.370

See Table I for Material Description

TABLE II -C

Statistical Correlations of Elastomers and Plastics

Specimen No. *	Water Gun/Rocket Sled	Cavitation/Rocket Sled	Cavitation/Water Gun
	$C_{gun\text{-}rocket}$	$C_{cav.\text{-}rocket}$	$C_{cav.\text{-}gun}$
F-3	4.65×10^{-3}	1.342	28.9
F-5	5.50×10^{-3}	.0170	2.86
F-7	2.37×10^{-3}	.0458	19.4
F-16	3.63×10^{-3}	.0157	4.33
I-1	--	--	33.3
I-2	500×10^{-3}	1.80	3.59
I-3	8.88×10^{-3}	.0217	2.45
I-5	860×10^{-3}	23.44	27.3
r	- 0.422	-0.598	- 0.803
Linear Relation	$MDPR_g = .01904 \times (MDPR_r)$	$MDPR_c = .205 \times (MDPR_r)$	$MDPR_c = 12.39 \times (MDPR_g)$
S_{lin}	2.052	2.909	1.167
Exponential Relation	$MDPR_g = .159 \times (MDPR_r)^{-.392}$	$MDPR_c = 3.92 \times (MDPR_r)^{-.935}$	$MDPR_c = 12.95 \times (MDPR_g)^{1.016}$
S_{exp}	1.062	1.581	1.167

*See Table I for Material Description

TABLE II-D

Statistical Correlations of Metals

Specimen No.*	Water Gun/Rocket Sled $C_{gun-rocket}$	Cavitation/Rocket Sled $C_{cav.-rocket}$	Cavitation/Water Gun $C_{cav.-gun}$
J-1	--	--	--
J-2	--	--	10800

*See Table I for Material Description

TABLE II-E

Statistical Correlations of Combined Groups

	Water Gun/Rocket Sled	Cavitation/Rocket Sled	Cavitation/Water Gun
r	0.302	0.463	0.496
Linear Relation	$MDPR_g = .00338 \times (MDPR_r)$	$MDPR_c = .377 \times (MDPR_r)$	$MDPR_c = 119.8 \times (MDPR_g)$
S_{lin}	2.444	1.985	2.391
Exponential Relation	$MDPR_g = .0105 \times (MDPR_r)^{.453}$	$MDPR_c = .812 \times (MDPR_r)^{.638}$	$MDPR_c = 14.95 \times (MDPR_g)^{.468}$
S_{exp}	2.282	1.902	2.005

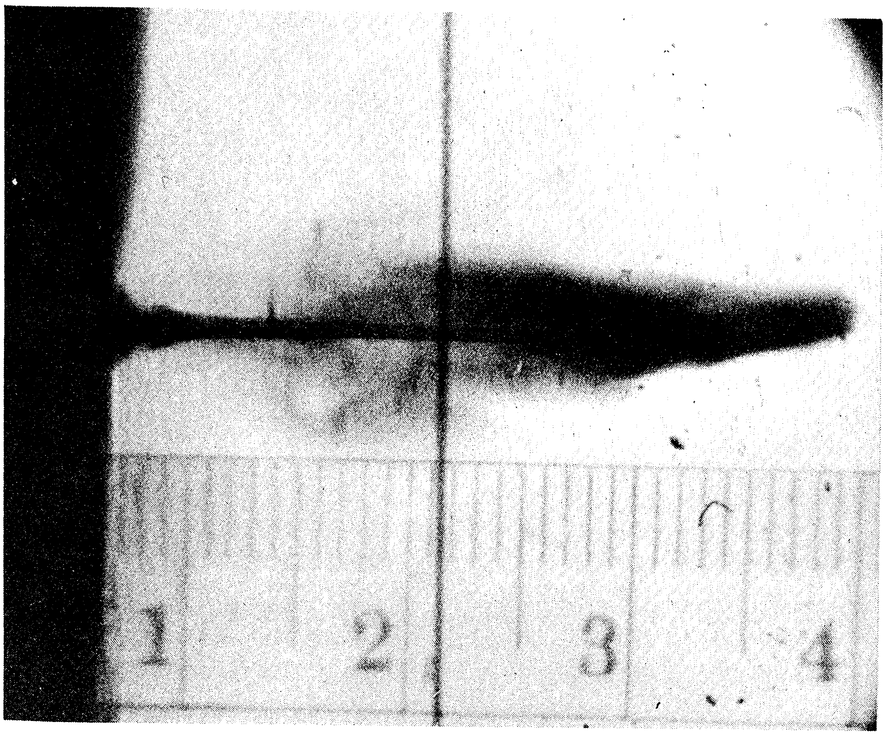

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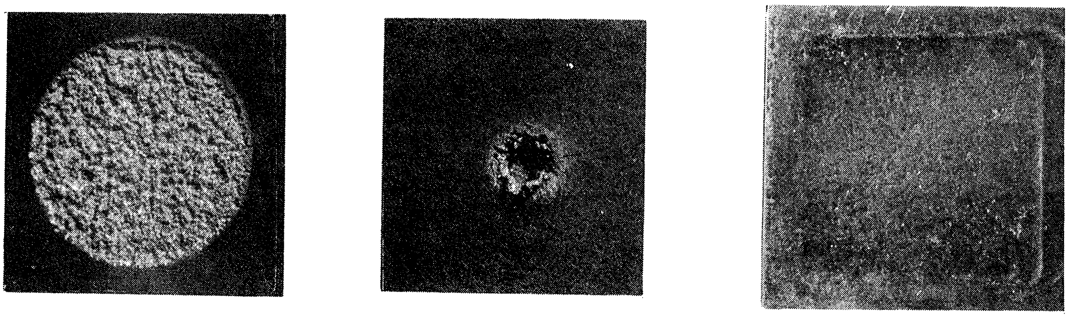
Figure 1. Droplet Ejected from the Water Gun at 550 m/s



6061-T-6 Aluminum

3023 i

Figure 2. Typical Photograph of a Material Damaged by Each of the Three Erosion Methods (Cavitation, Water Gun, Rocket Sled -- Left to Right)

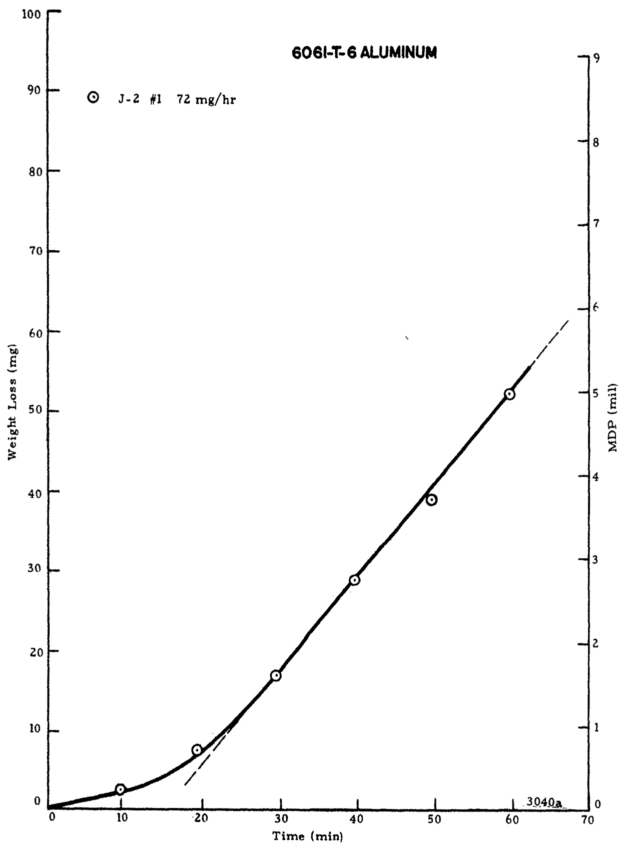


Figure 3a. Cavitation Damage Curve of Typical Material

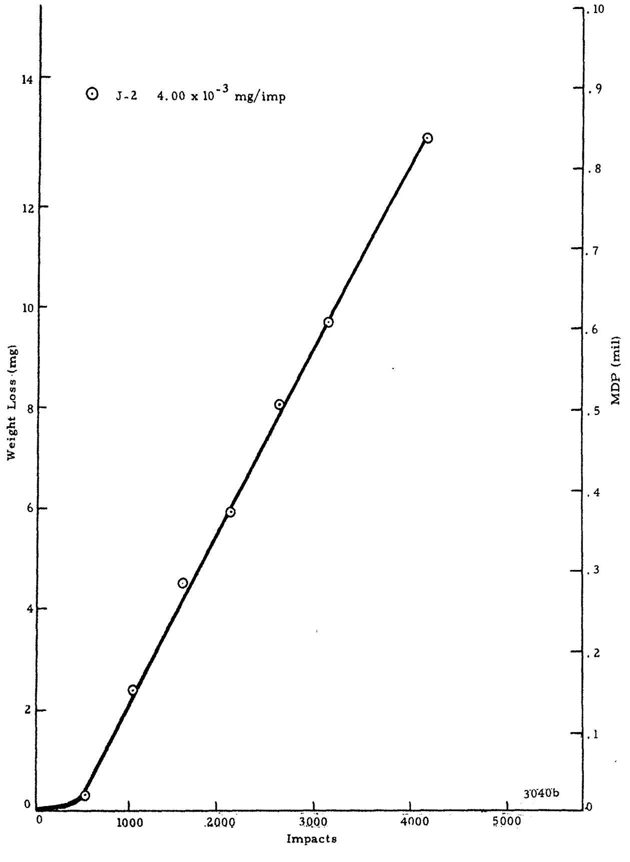


Figure 3b. Water Gun Damage Curve of Typical Material

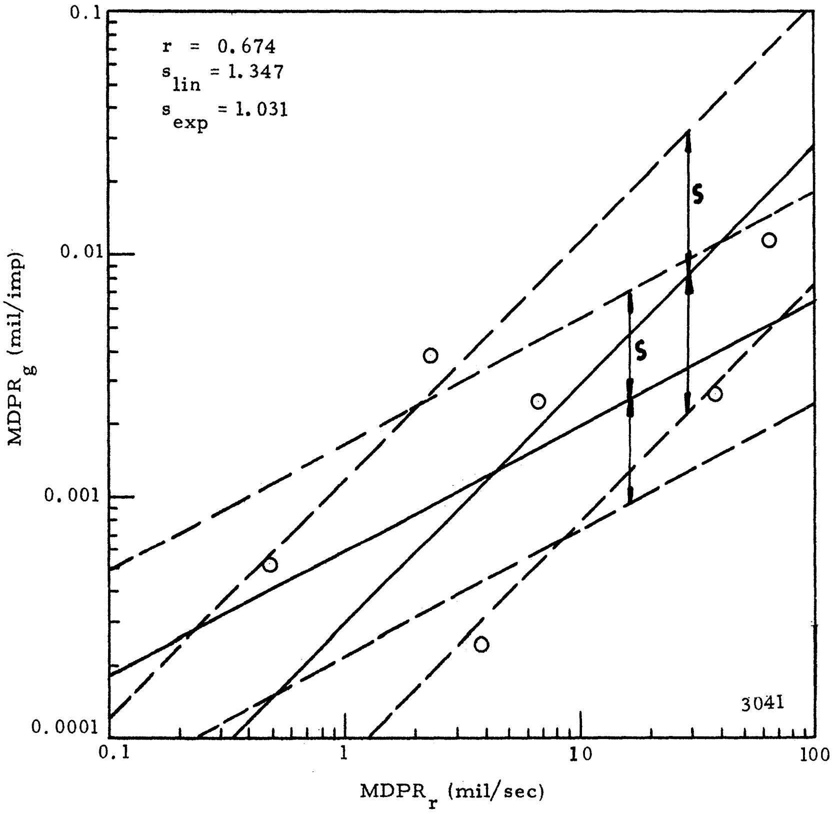


Figure 4. Correlations Between Water Gun and Rocket Sled Damage of Ceramics

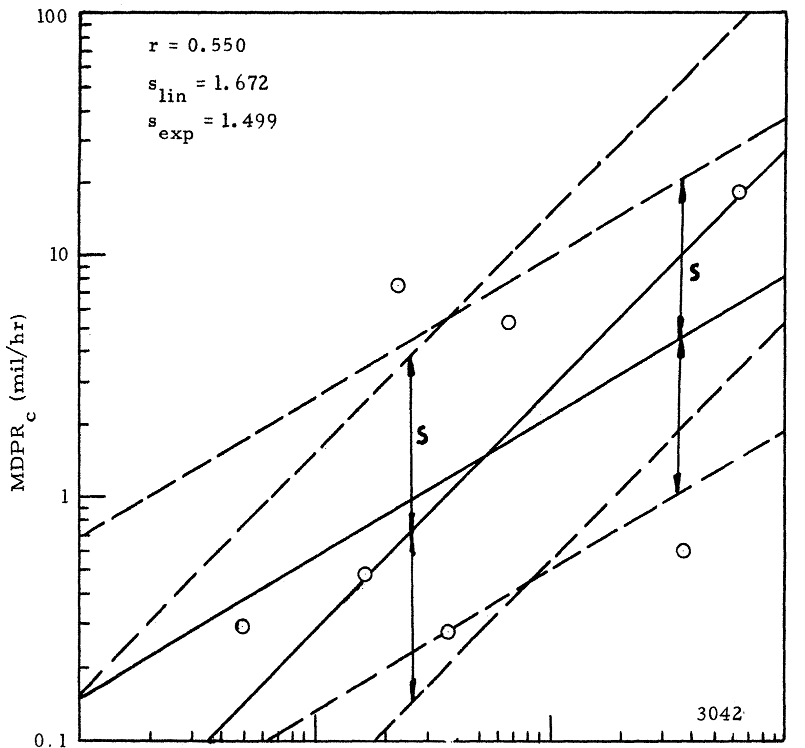


Figure 5. Correlations Between Cavitation and Rocket Sled Damage of Ceramics

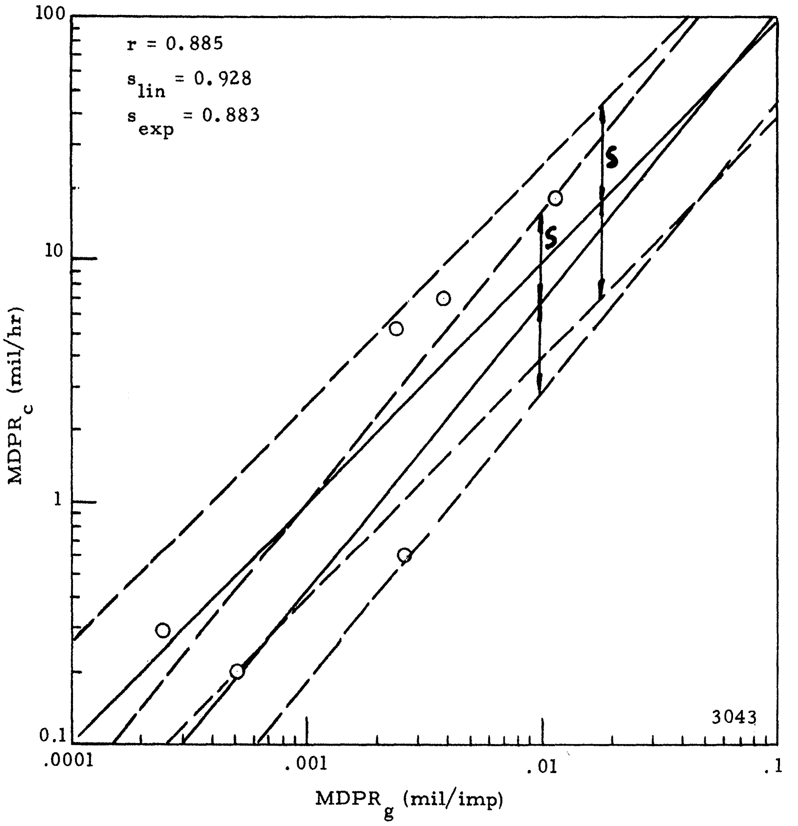


Figure 6. Correlations Between Cavitation and Water Gun Damage of Ceramics

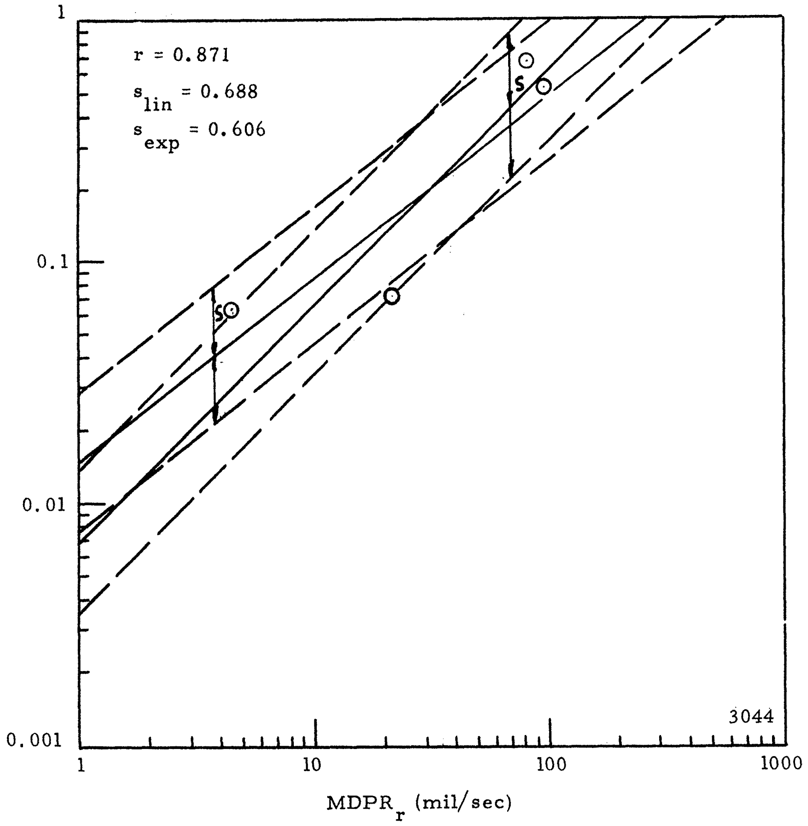


Figure 7. Correlations Between Water Gun and Rocket Sled Damage of Laminates

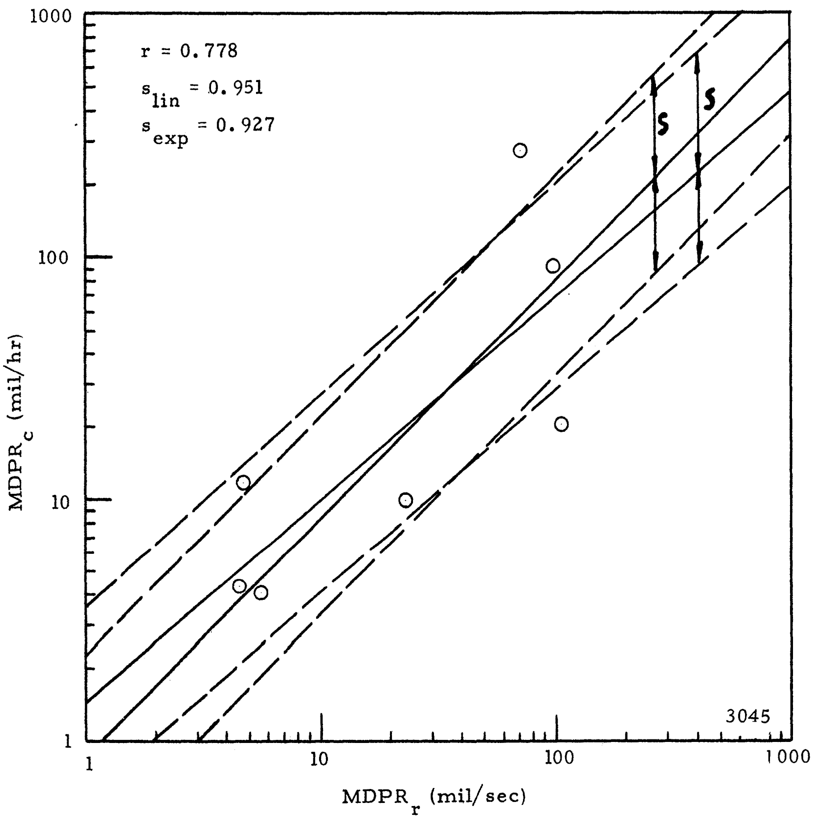


Figure 8. Correlations Between Cavitation and Rocket Sled Damage of Laminates

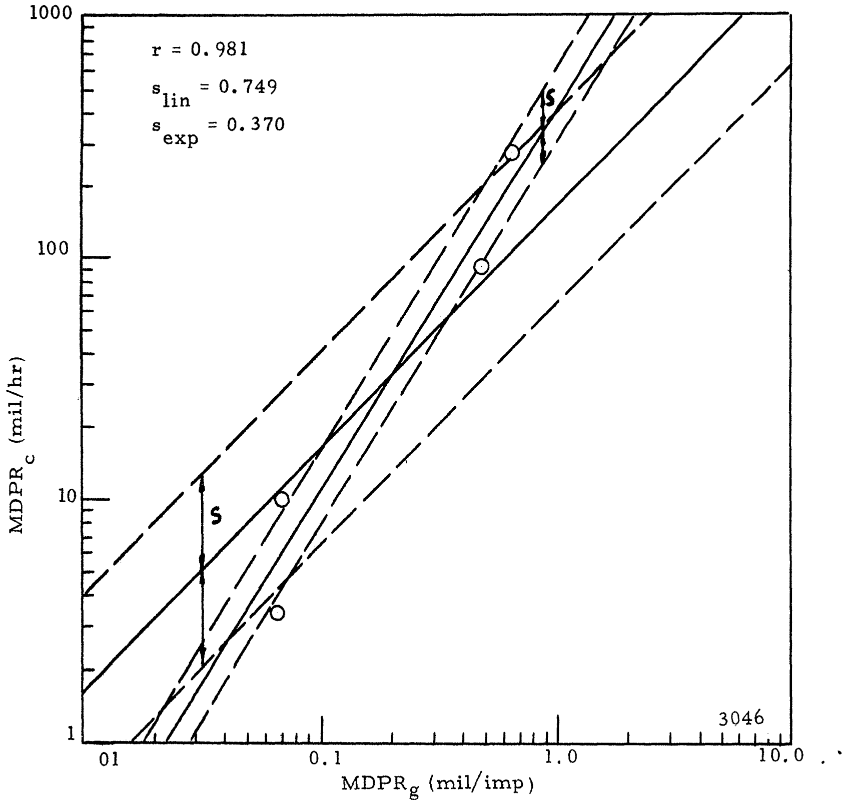


Figure 9. Correlations Between Cavitation and Water Gun Damage of Laminates

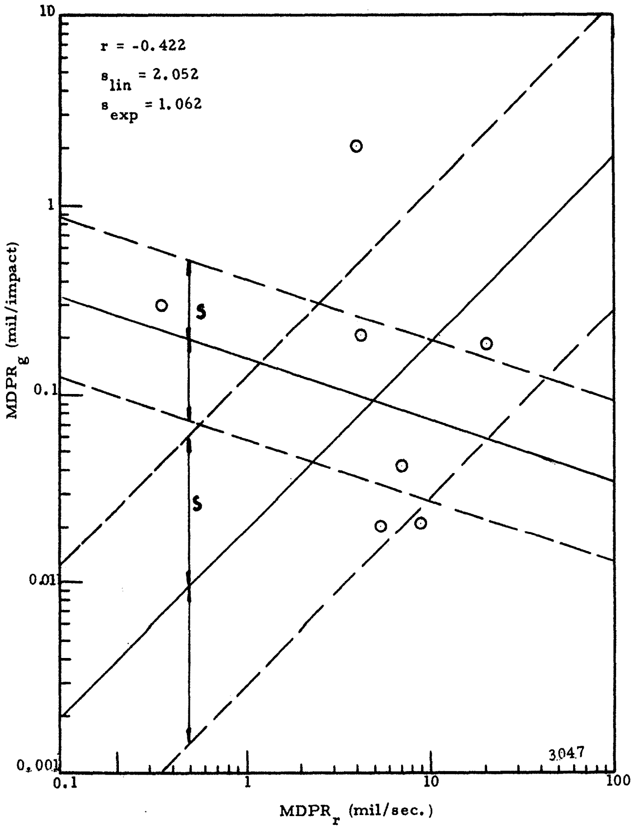


Figure 10. Correlations Between Water Gun and Rocket Sled Damage of Elastomers and Plastics

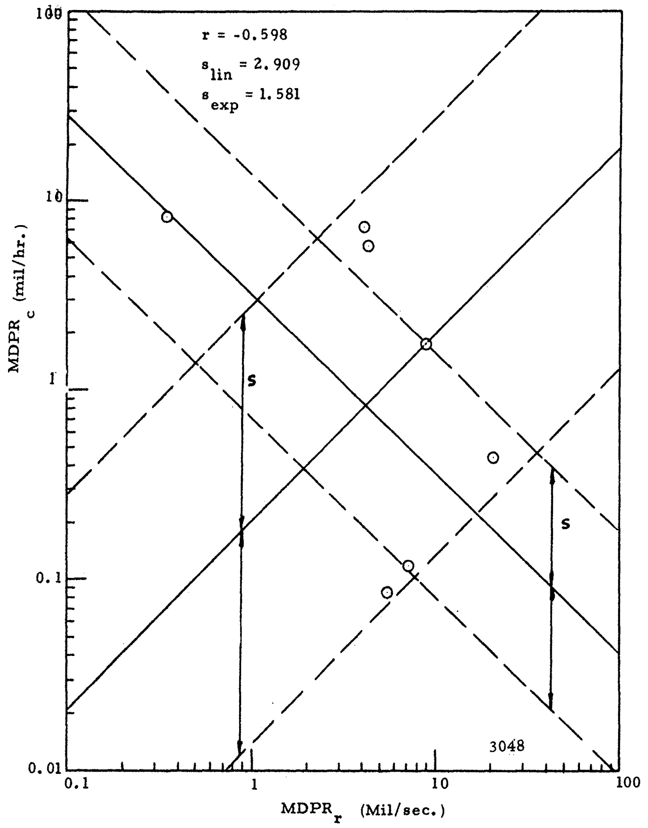


Figure 11. Correlations Between Cavitation and Rocket Sled Damage of Elastomers and Plastics

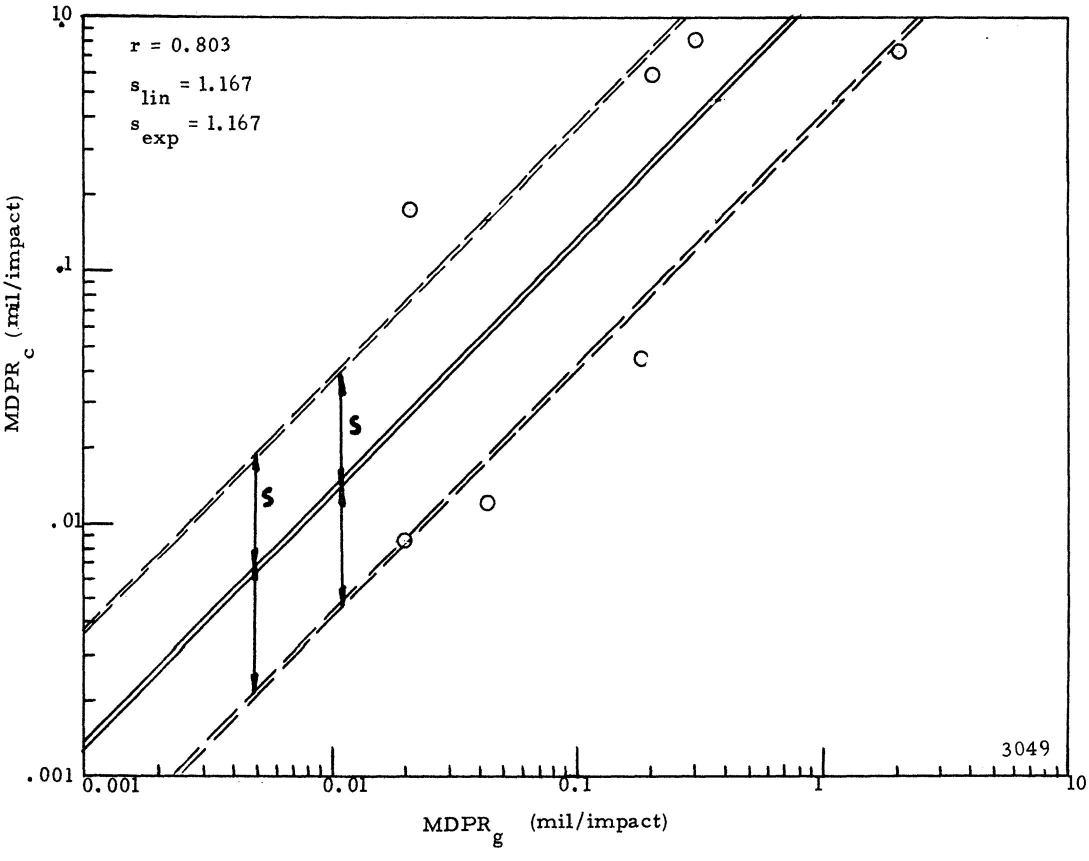


Figure 12. Correlations Between Cavitation and Water Gun Damage of Elastomers and Plastics

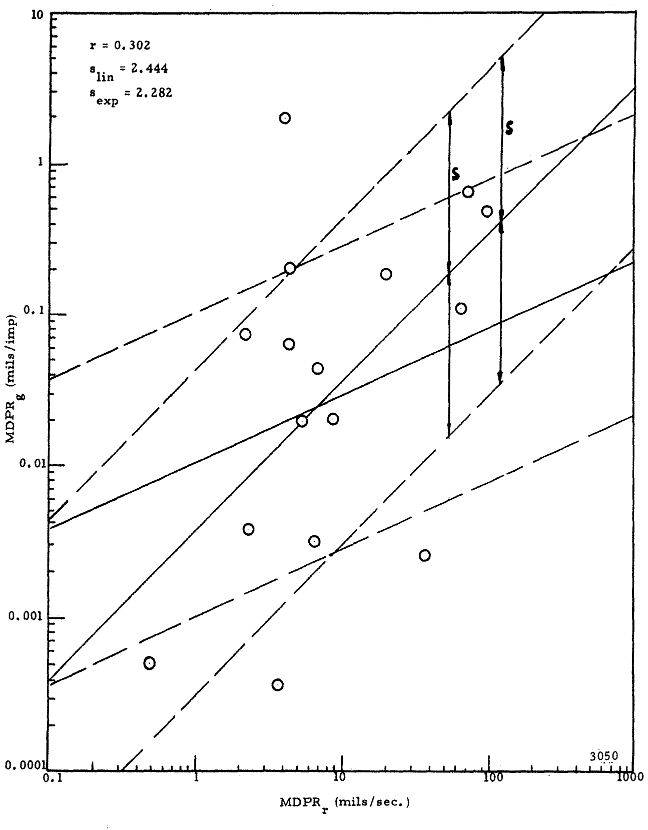


Figure 13. Correlations Between Water Gun and Rocket Sled Damage of All Materials

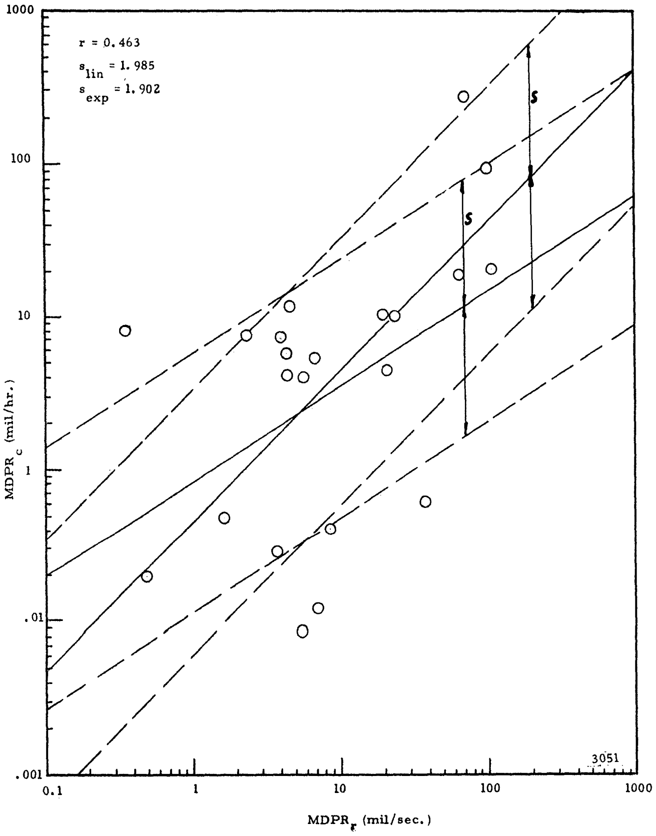


Figure 14. Correlations Between Cavitation and Rocket Sled Damage of All Materials

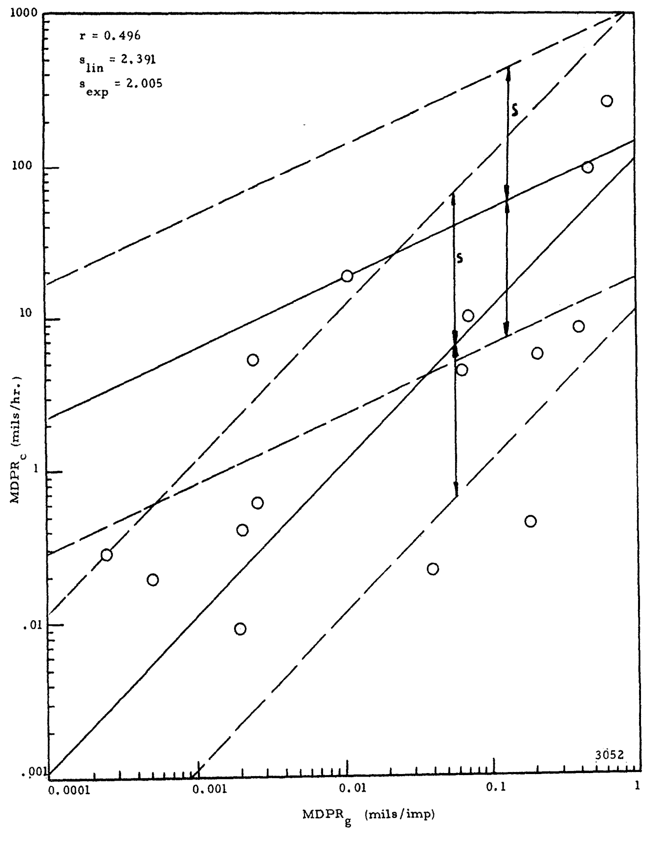


Figure 15. Correlations Between Cavitation and Water Gun Damage of All Materials