Development of the Mariner Mars 1971 Meteoroid Shield

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A lightweight double-wall type meteoroid shield was developed for the enlarged propulsion system of Mariner Mars 1971. The outer sheet, composed of Teflon-impregnated glass fabric and multilayer thermal insulation, is much more effective than an aluminum sheet of the same weight. The increased effectiveness is due to a modification of the impact phenomena by the heterogeneous first sheet and the impact energy absorbtion of the thermal insulation. To obtain the effectiveness of this meteoroid shield under anticipated mission conditions, it was necessary to extrapolate the test data in both the impact velocity and meteoroid density parameters. The base for the extrapolation was a series of tests over a range of velocities using projectiles made of glass, nylon, and syntactic plastic. For this configuration, and for the the range of extrapolation involved, it was conservative to extrapolate these parameters linearly. The results indicate that the composite outer sheet is sufficient (no backup sheet is needed) for the specified meteoroid threat.

Spacecraft Configuration

ALTHOUGH all Mariner spacecraft have performed their missions without critical damage due to meteoroids, it appears that Mariner Mars 1971 will require a meteoroid shield to have a reasonable chance of successfully completing the mission. The spacecraft configuration is very similar to previous Mariner configurations except for the addition of the propulsion equipment above the bus.

At the beginning of this effort, the following ground rules were adopted:

1) Because passive thermal control is required around the propulsion system, it would be desirable to integrate the insulation into the meteoroid shield.

2) A double-wall type of shield would be the lightest type. Where the outer sheet of the shield must be close to the propellant tanks, a backup sheet would be provided so that the thickness of the tanks would not have to be increased to resist the meteoroid impact debris.

After a few tests, the configuration shown in Fig. 1 was adopted for a detailed evaluation. The outer surface of the meteoroid shield is a sheet of Teflon-impregnated glass fabric which is combined with multilayer thermal insulation into a "blanket." Around the upper portion of the propulsion tanks is a backup sheet of 0.016-in.-thick (0.041-cm) aluminum to resist the meteoroid impact debris.

The significant feature of this shield is its heterogeneous composition. In the glass fabric, each of the woven strands includes 1224 Beta glass filaments; there are 90 strands/in. in one direction and 65 strands/in. in the other. This fabric was used because it was relatively light, readily available, very tightly woven, and the tests indicated that it provides adequate protection. During this program, several industrial glass fabrics were also tested having filaments about twice the size of Beta filaments. Such fabrics would be effective components of shields for meteoroid threats of a different magnitude.

For convenience in fabrication and handling, a commercial variation of the fabric impregnated with Teflon was adopted. In tests in which the fabric was not impregnated, the damage to the backup sheet was slightly less than that experienced with the impregnated fabric. It was possible, however, to meet the mission requirements with the impregnated fabric.

The details of the multilayer insulation have not been specified for Mariner Mars 1971 at this time. However, tests of several multilayer configuration of about the same weight in this study showed very little difference in impact resistance. For most of the test, 25 layers of $\frac{1}{4}$-mil crinkled Mylar (aluminized on both sides) were next to the fabric. The inner surface was a 1-mil-Teflon sheet aluminized on the side next to the Mylar sheets.

The meteoroid environment was established by evaluating the data from satellites, Mariner II and Mariner IV, photographic and radar studies, and an interpretation of zodiacal light. The resulting flux applies primarily to cometary meteoroids and is similar to that published by Whipple,[1] Dohnanyi,[2] and Naumann.[3] The average cometary meteoroid density is assumed to be 0.5 g/cm^3. For a 99% probability of zero penetrations of the meteoroid shield,

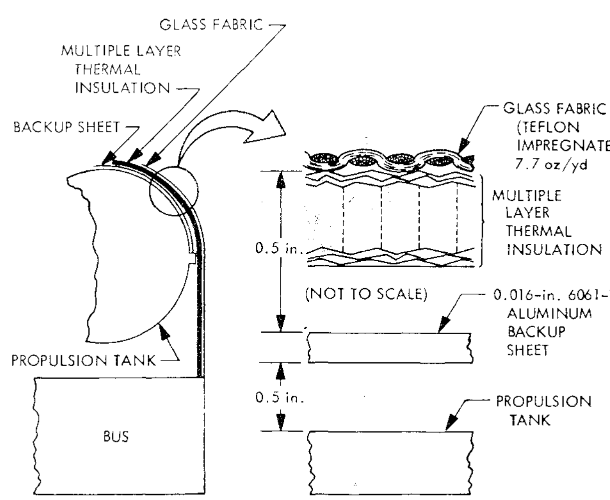

Fig. 1 Preliminary meteoroid shield design.

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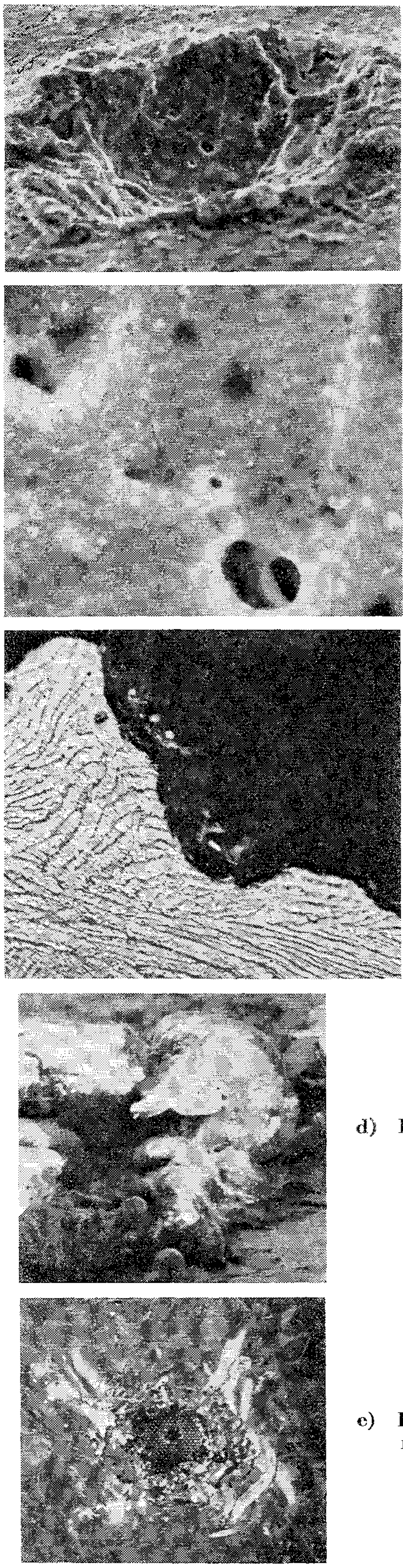


a) Backup sheet crater

b) Backup sheet crater wall

c) Crater cross section

d) Deposit on backup sheet

e) Hole through thermal insulation

Fig. 2 Magnified views of impact damage from 0.031-in.-diam glass sphere at 7.3 km/sec.

the most critical meteoroid diameter is about 0.0312 in. (0.0792 cm).

For this mission, it will take about 200 days to travel between earth and Mars in the cometary flux, and a briefer period will be spent in orbit around Mars in a combined cometary and asteroid flux. Because the exposure to the cometary flux is so much greater than the exposure to the asteroid flux, the cometary flux has the greater damage potential.

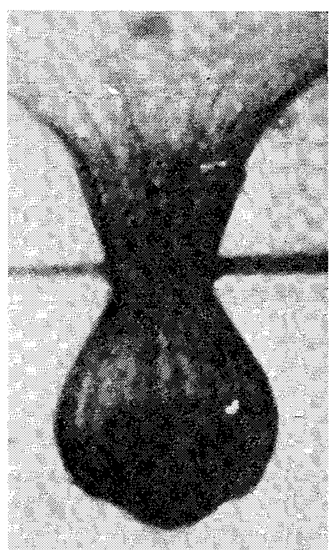
Discussion of Impact Phenomena

For most of the tests, a $\frac{1}{32}$-in.-diam solid glass sphere was used to simulate a meteoroid. These spheres were annealed after forming to remove any residual stresses. Figure 2 shows various characteristics of typical damage to this shield from an impact at 7.3 km/sec. The damage to the backup sheet is characterized by some small craters a few mils deep and some surface deposits. The cross section of a crater indicates that there has been no change in the microstructure of the metal. The surface deposits are a product of the interaction of the impact debris and the insulation. The hole through the thermal insulation is about 0.25 in. (0.635 cm). It is felt that a hole of this size will not significantly affect the thermal control characteristics of the insulation during the mission.

When the insulation is removed, the backup sheet is penetrated, which indicates that the insulation is effective in absorbing a significant part of the impact energy.

For reference purposes, a sheet of 0.004-in.-thick (0.010-cm) 2024-T4 aluminum was substituted for the fabric. This metal had about the same mass per unit area as the fabric. The

a) Glass fabric configuration



b) Thin sheet metal configuration

Fig. 3 Impact photogaphs showing the typically smaller backspray from a glass fabric configuration as compared to that from a metal sheet.

resulting backup sheet craters are about four times as deep as those resulting from the fabric configuration.

Figure 3a is a high-speed photograph of the impact on a similar shield at the Space Research Institute, Inc. Of particular interest is the amount of "backsplash" on the impact side of the shield. When compared with the typical backsplash from the impact on a solid thin metal shield (Fig. 3b), it is obvious that the backsplash from the impact on a fabric shield is significantly smaller. From the conservation of momentum, a decrease in the "negative momentum" of the backspray causes a decrease in the forward momentum of the debris cloud causing a less destructive spray. From the conservation of energy, a decrease in backspray energy results in a higher energy state of the impact debris.

No spalling of the backup sheet was observed in any of the tests, even when some of the pits almost penetrated the backup sheet.

Extrapolation of Test Data

Because of the limitations of hypervelocity test facilities, ground-test data must be extrapolated in velocity and density to cover the expected ranges of meteoroid values. However, it was not possible to correlate the test results with prior work on metal-on-metal impacts, as a basis for extrapolation. It was necessary to adapt the basic concept of hypervelocity impact phenomena to the observed test results and determine experimentally the coefficients necessary for extrapolation. Typical relationships between the backup sheet thickness t_b required to defeat a projectile and the impact velocity V are shown in Fig. 4 for three arbitrary configurations. The following description of these phenomena is based on information from Ref. 4–6 and the Mariner Mars 1971 tests.

At the lowest velocities in Fig. 4, the required t_b rises rapidly, because the projectile perforates the first sheet and impacts the backup sheet essentially as a single solid particle. But as V is increased, both the projectile and the material removed from the first sheet start to break up. A low-speed maximum thickness is shown where the fragmentation is sufficient to start distributing the debris energy over a significantly larger area of the backup sheet. As V is increased further, t_b diminishes because the fragmentation debris damage decreases more than the impulse increases.

Soon after fragmentation starts with increasing V, parts of the debris will be vaporized due to the extremely high localized impact stresses. With further increases in V and in fraction vaporized, a local minimum in t_b results from the trade-off between increasing momentum and more effective dispersion of the momentum. At still higher V's, the failure of the backup sheet is primarily due to pressure loading. Over a significant part of this velocity range, the pressure is due to a combination of debris vapor and very finely divided particles of molten debris. Under these conditions, the

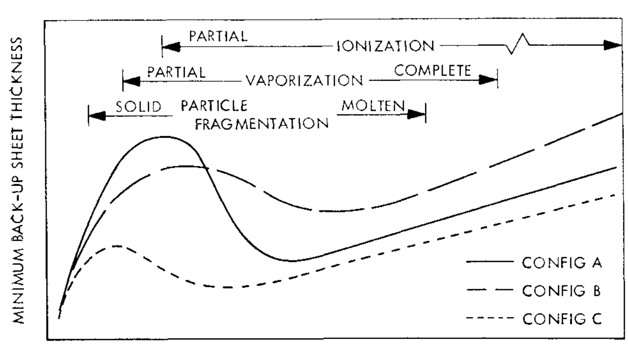


Fig. 4 Influence of impact phenomena variation with velocity.

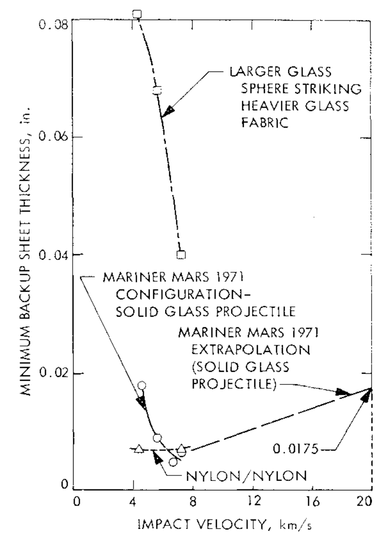


Fig. 5 Test data for minimum backup sheet thickness vs velocity.

minimum t_b varies linearly with V, as has been confirmed analytically for metal-on-metal impacts,[7] and experimentally for plastic-on-lead screen impacts.[8]

Although most of the debris is vaporized at meteoroid velocities, a few small particles will remain due to the relaxation of the impact phenomena around the edges of the hole in the first sheet. These small particles will cause relatively small pits on the backup sheet and slightly increase the thickness required.

Soon after the onset of the vaporization phenomenon, some of the debris are ionized. At the higher velocities, a significant amount of the debris particles is ionized and is classified as plasma. Until more information is available on the effects of ionization in this situation, the effects are assumed to be negligible.

It was not practical in the Mariner Mars 1971 study to conduct sufficient tests to determine the minimum t_b applicable to each test point. In most cases the damage to the backup sheet did not include a bulge or tension failure. This indicates that any backup sheet failure in the test velocity range would be due to particle penetration. On this basis, the depth of the deepest pit in the backup sheet was taken to be the thickness of the sheet that would have been penetrated at that test condition. In most cases each test point was repeated once.

The test data points for the Mariner Mars 1971 configuration are shown in Fig. 5 over the velocity range it was possible to obtain test data. Close examinations of the backup sheets for $V \gtrsim 7$ km/sec indicated very small pits which are typical of that to be expected near the minimum of the curve in Fig. 4. Therefore, it is reasonable to extrapolate linearly to higher velocities, as shown in Fig. 5. This extrapolation is felt to be conservative, because no allowance is made for the curved characteristic of the minimum thickness portion of the curve. Therefore, no provision is required for the minor pitting to be experienced at higher velocities. This linear extrapolation implies the assumption that pressure loading will be a major factor in the t_b requirements at mission impact velocity.

Figure 5 also presents test data for two similar configurations. The glass test configuration was similar to the Mariner Mars 1971 configuration with the glass projectile diameter increased by a factor of two and a heavier glass fabric, so that the ratio of the projectile mass to the mass of the impacted fabric remained approximately the same. The nylon/nylon test configuration was of the same dimensions as the glass test configuration but used a solid nylon projectile and nylon fabric. It appears that the lower-density nylon configuration is at the minimum thickness regime, whereas the glass test configuration is only approaching the

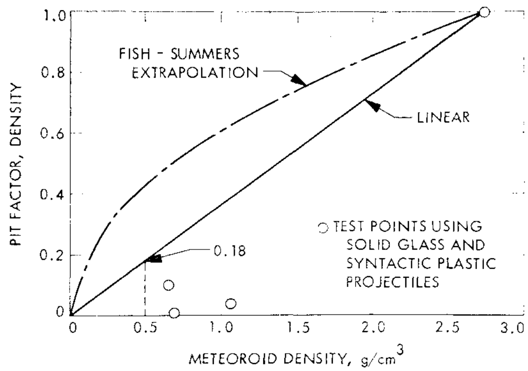


Fig. 6 Effect of projectile density on surface pitting.

minimum thickness regime. This difference is attributed to the fact that nylon requires considerably less energy to fracture, melt, and vaporize.

The assumed meteoroid density of 0.5 g/cm^3 is intended to be representative of cometary meteoroids. Studies of such meteoroids show them to be amorphous and to contain common elements such as iron, calcium, silicon, and sodium. For such a material to have a density of 0.5 g/cm^3, it must have an open structure or be a loose aggregate of small particles. Charters[9] suggests that the penetration by such a material would be less than that of a homogeneous solid having the same density.

In an attempt to simulate cometary meteoroids, some projectiles made of syntactic plastic were used. This material is a mixture of a plastic and extremely small hollow glass spheres. The density of the combination can be varied by changing the proportions of plastic and glass spheres, and by substituting solid spheres for the hollow spheres. Figure 6 shows the results of these tests, in terms of the "pit factor for density," defined as the ratio of the maximum pit depth on the backup sheet, at some projectile density of interest, to the maximum pit depth resulting from the impact of a solid glass sphere. Also shown in Fig. 6 is the curve that would result from applying the Fish-Summers equation over this density range. (It should be noted, however, that the Fish-Summers equation was developed from the impact of solid metal projectiles on solid metal thin sheets and applies to the *penetration of the first sheet* of a meteoroid shield.) To be conservative, it is assumed that the pit factor varies linearly with projectile density. Therefore, the pitting to be experienced from a cometary meteoroid would be 0.18 of that produced by the impact of a solid glass sphere, as shown in Fig. 6. Tests were made to determine the effect of meteoroid diameter d_p (or mass variation with a fixed density) with this configuration. For d_p's significantly smaller than the nominal value, the projectile was fragmented by the fabric, but the debris would not penetrate the thermal insulation. For larger d_p's, it was found that increasing d_p from 0.0312 to 0.0394 in. (0.0792 to 0.1000 cm) resulted in a ballistic limit test point for the 0.016-in.-thick, 6061-T6 aluminum backup sheet at 7.3 km/sec. The backup sheet failure was primarily due to pressure loading. These limited data suggest that the minimum t_b varies with d_p^3, or is directly proportional to the projectile mass, for this configuration.

The backup sheet spacing of the basic configuration was varied from 0.5 to 3.0 in. (1.27 to 7.62 cm) in tests with $V > 7$ km/sec. For each spacing, the damage to the backup sheet consisted of small pits of about the same depth. This finding indicates that the damage was caused by small particles whose energy was not affected (in a near vacuum) by this variation of spacing.

Mission Evaluation and Conclusions

The nominal mission impact criterion is a particle 0.0312 in. (0.0792 cm) in diameter, with a density of 0.5 g/cm^3 and an impact speed of 20 km/sec normal to the surface. As can be seen by the data in Figs. 5 and 6, the nominal backup sheet thickness required is t_{bN} = (0.0175) (0.18) = 0.0032 in. (or 0.0081 cm).

As the result of a design review subsequent to these tests, it was determined that the external surface of the propellent tanks can have a few pits 0.0032 in. (0.0081 cm) deep without changing their design. Therefore, the backup sheet is not necessary for the specified meteoroid threat, provided that the glass fabric surface of the insulation blanket is spaced a minimum of 0.5 in. (1.27 cm) from the tank surface.

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