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THE LONG-TERM EFFECTS OF THE MICROMETEOROID AND ORBITAL
DEBRIS ENVIRONMENTS ON MATERIALS USED IN SPACE

Burton G. Cour-Palais
NASA Lyndon B. Johnson Space Center
Houston, Texas

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Introduction

The purpose of this report is to discuss the long-term effects of the orbital debris and micrometeoroid environments on materials that are current candidates for use on space vehicles. In addition, the limits of laboratory testing to determine these effects are defined and the need for space-based data is delineated. The impact effects discussed are divided into primary and secondary surfaces. Primary surfaces are those that are subject to erosion, pitting, the degradation and delamination of optical coatings, perforation of atomic oxygen erosion barriers, vapor coating of optics and the production of secondary ejecta particles. Secondary surfaces are those that are affected by the result of the perforation of primary surfaces, for example, vapor deposition on electronic components and other sensitive equipment, and the production of fragments with damage potential to internal pressurized elements. The report defines the material properties and applications that are required to prevent or lessen the effects described.

Encounter Dynamics and Typical Damage

In dealing with the long-term effects of the micrometeoroid and orbital debris environments on materials used in space, we have to know something about these solid particles that pack so much energy. Kessler, (Reference 1), presented a detailed look at these environments, but let us look at what an encounter with a micrometeoroid or an orbital debris particle means.

Micrometeoroids, as most of you know, can have Earth encounter velocities of 11 to 73 km/sec. However, the most probable encounter velocity for a spacecraft in Earth orbit is about 17 km/sec. For modeling purposes, the meteoroid cumulative flux-mass curve given for NASA use (SP 8013) is tied to an average velocity of 20 km/sec. Similarly, the average mass density of meteoroids given by the same model is 0.5 gm/cc. The flux of these particles is altitude dependent, and they are omni-directional.

Orbital debris particles by definition, have a relative encounter velocity of 0 to 16km/sec for a spacecraft in Earth orbit. In fact, there is a velocity distribution and the average encounter velocity is 11 km/sec. Most orbital debris particles are postulated to be aluminum fragments from explosions in space, and therefore have a mass density of 2.8 gm/cc. What do these velocities and mass densities mean for the surface of an object in space that encounters a micrometeoroid or an orbital debris particle? First, these particulates are very energetic. The specific kinetic energy for a micrometeoroid at 20km/sec is 2×10^5 joules/gm, and for orbital debris at 10 km/sec, 6×10^4 . So micrometeoroids are several times more energetic than orbital debris particles, but we must also be concerned with the relative number of particles of each that are encountered.

Table 1 lists the number of micrometeoroids and orbital debris particles encountered per square meter of surface area in 10 years. For the particle sizes of interest in this study, the fluxes of the two environments cross over to make one or the other dominant. However, we are concerned with the total number of impacts.

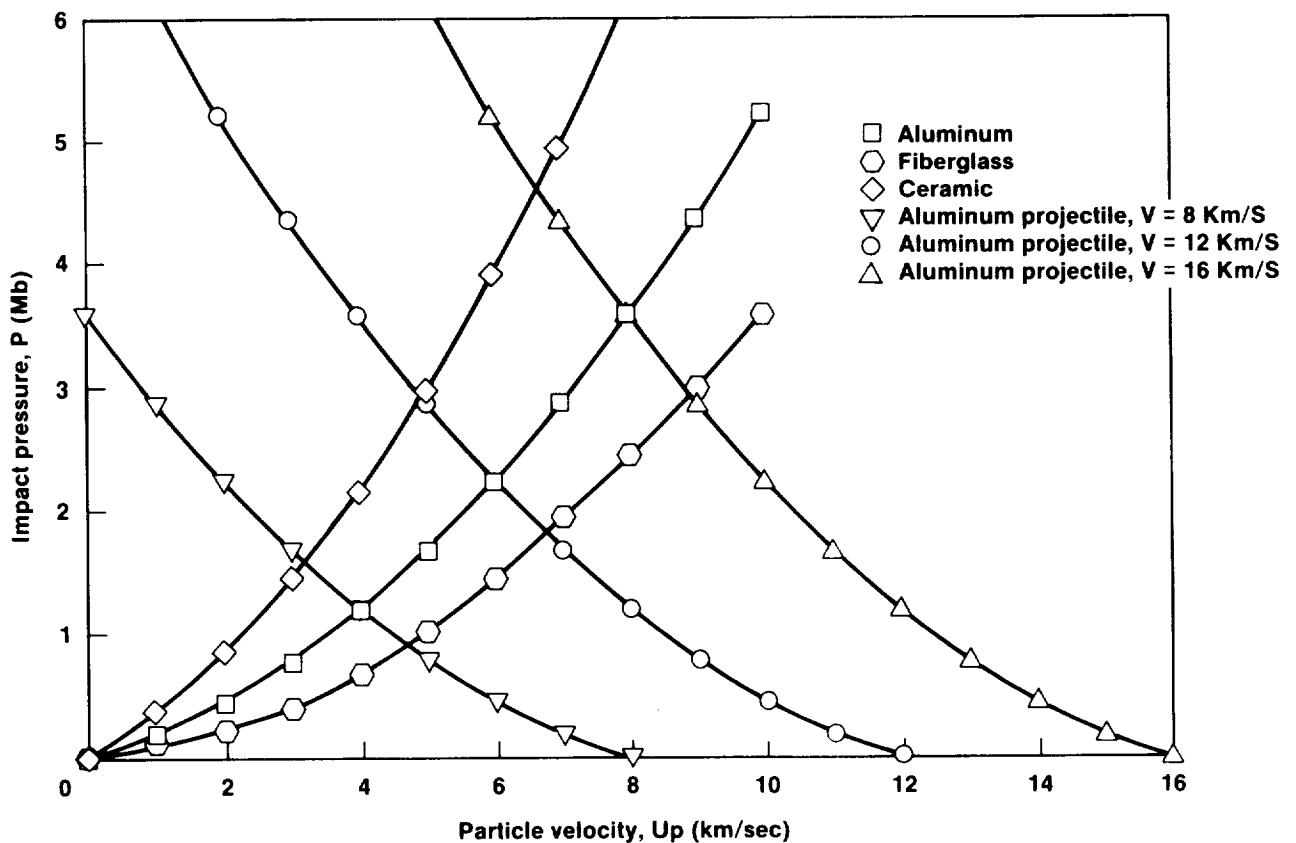
Table 1

NUMBER OF MICROMETEORIDS AND ORBITAL DEBRIS PARTICLES ENCOUNTERED IN 10 YEARS (1996 - 2005).

DIAMETER (cm)	ORBITAL DEBRIS (number/sq.meter)		MICROMETEORIDS (number/sq.meter)	
	385-475km	800km	385-475km	800km
0.001	5100	12000	2400	2600
0.01	16	37	49	53
0.10	0.051	0.120	0.019	0

Secondly, a characteristic of an encounter with these particles is the very high impact pressures and shocks associated with them. For a micrometeoroid, the average impact pressure is 2.5 megabars and for the orbital debris, 1.9 megabars, a megabar being equal to 14.5×10^6 psi. Figure 1 shows a graphical means of determining the initial impact pressure as a function of the particle or shocked material velocity. The intersections of the left-running projectile curves and the right-running target curves denote the impact pressure. Three aluminum projectiles are shown at 8, 12 and 16 km/sec, and the target materials are graphite-epoxy, aluminum and a ceramic.

Initial Shock Pressure Effect of Shield Material Density



Graphical Solution for the Initial Impact Pressure.

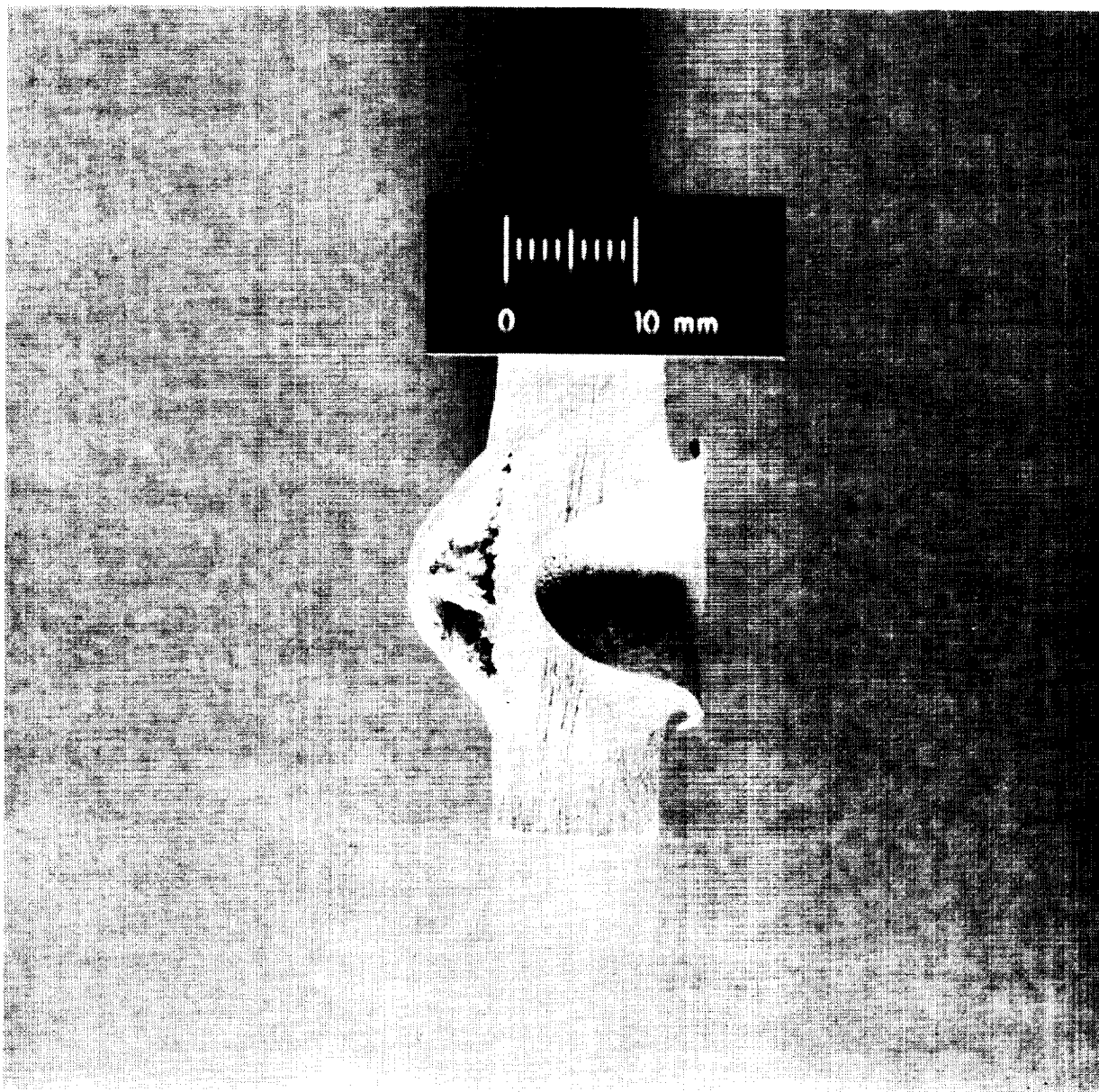
Figure 1

These very high pressures decay rapidly but remain well above the material strength so that the elements close to the impact point flow like a liquid. In addition, the impact process of instantaneous compression followed by slower release of pressure causes the projectile and target material to be locally heated due to an increase of entropy. The temperatures generated are always high enough to melt the materials in contact, and quite often to vaporize them. Table 2 shows some metallic materials of interest with their melting and vaporization temperatures, and the impact pressures and velocities required to achieve these states, (Reference 2).

Table 2
IMPACT SHOCK HEATING

MATERIAL	TEMPERATURE		INCIP. Mbar	MELT Km/s	COMP. Mbar	MELT Km/s	INCIP. Mbar	VAPOR Km/s
	Melt _o C	Vap _o C						
Aluminum	660	2057	0.65	5.6	0.90	6.6	1.67	10.2
Cadmium	321	767	0.40	3.0	0.60	3.9	0.88	5.2
Steel	1535	3000	1.80	7.9	2.10	8.8		>>9
Lead	327	1620	0.30	2.0	0.35	2.6	0.90	4.8
Titanium	1800	>3000	1.30	7.6		>>8		

Figure 2 shows a cross-section of a laboratory impact crater formed in an aluminum 1100-0 alloy plate by a 45 milligram aluminum projectile at just over 6 km/sec. The near hemispherical shape and raised lip is characteristic of a hydrodynamic impact crater. In this case, the impact shock pressure is 0.8 megabars, and from Table 2 one would expect the material to have been melted. Another feature illustrated in Figure 2 is the near spallation of the rear surface. A thin segment of the aluminum plate has separated due to the tensile stress induced by the shock after reflection. The rarefaction or release stress wave reflected off the rear surface was still high enough to cause this alloy to fail in tension. Incidentally, the specific KE was about 2×10^4 joule/gm.

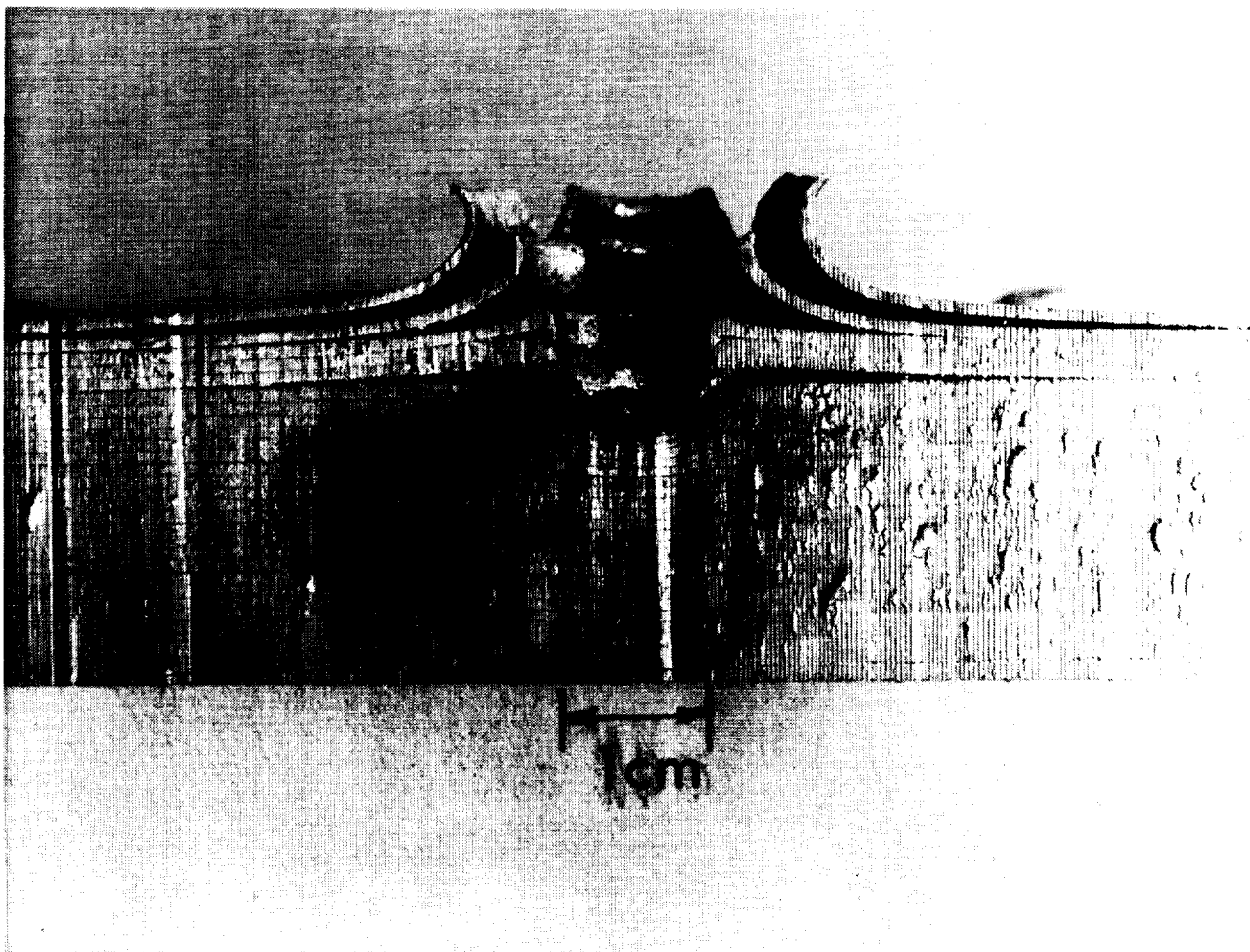


Hypervelocity Impact Cross-section: 1100-F Aluminum Alloy Plate.

Figure 2

In Figure 3, we see a cross-section of an impact into laminated aluminum plates held together mechanically. It is a useful illustration of the impact forces that cause the problems seen in hypervelocity encounters with the first surface of a spacecraft. We see delamination of the upper layers, peeling under the influence of shearing forces at edges of the crater, shock compression in the layers and the rebound of a significant proportion of the target.

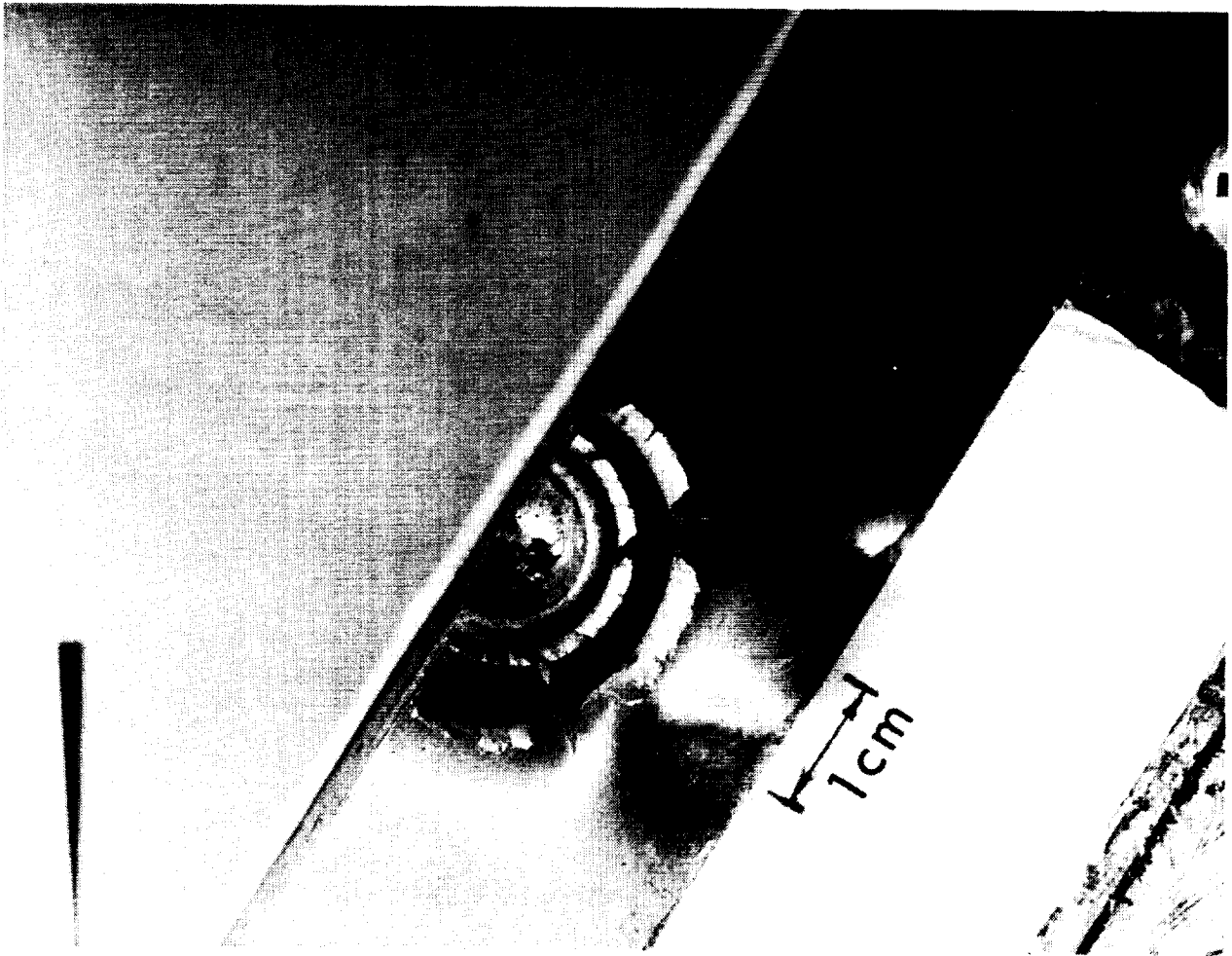
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Side View Sectioned Hypervelocity Impact into an Aluminum Alloy Laminate.

Figure 3

In Figure 4, the top view, we see the splitting of the material in the process of peeling back of the upper layers. These two views are important in understanding the basic processes taking place in delamination and ejection of surface materials, such as coatings and atomic oxygen barriers, etc., examples of which will be shown shortly. This impact occurred at 7 km/sec using a Pyrex glass projectile so the impact pressure was over 1 megabar and the specific KE, 2.5×10^4 joules/gm.



Top View of Figure 3.

Figure 4

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The target described previously is a reasonable analogue of the front surface of a glass or similar brittle material that has been impacted by a hypervelocity projectile. In this aluminum target there is a residual crater as is usually seen in glass targets, (Figure 5) and there are two levels of ejected spall rings, also seen in the glass target. Also the deeper layer of the aluminum stack separated from the main body is analogous to the sub-surface fracture zone present in most glass targets at laboratory impact velocities. The glass target was impacted by a 0.16 cm glass (2.3 gm/cc) projectile at 7.3 km/sec. This is approximately the same impact pressure as for the aluminum laminated target.

This completes our quick look at the dynamic characteristics of hypervelocity impacts and some of the typical effects on the spacecraft first surface.

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Damage to a 2 cm thick Glass Target by a 0.15 cm Projectile at 7.3 km/sec.

Figure 5

Long-term Damage Effects

Let us now discuss the long-term effects of the micrometeoroid and orbital debris environments on typical materials used in space. Impact effects will be divided into those that could cause a problem to the first or outer surface of a spacecraft, and those that can also affect the surface or region behind it.

First surfaces are primarily affected by the smaller particles in both environments, and Table 3 lists the penetration depths and diameters that can be expected for orbital debris in aluminum and glass. The equations used were developed during the Apollo program, (Reference 3), and the spall diameters are consistent with the target shown in Figure 5. For typical large spacecraft that have aluminum first surface thicknesses of 0.16 to 0.25 cm as bumper shields, particles under 1 mm would not penetrate.

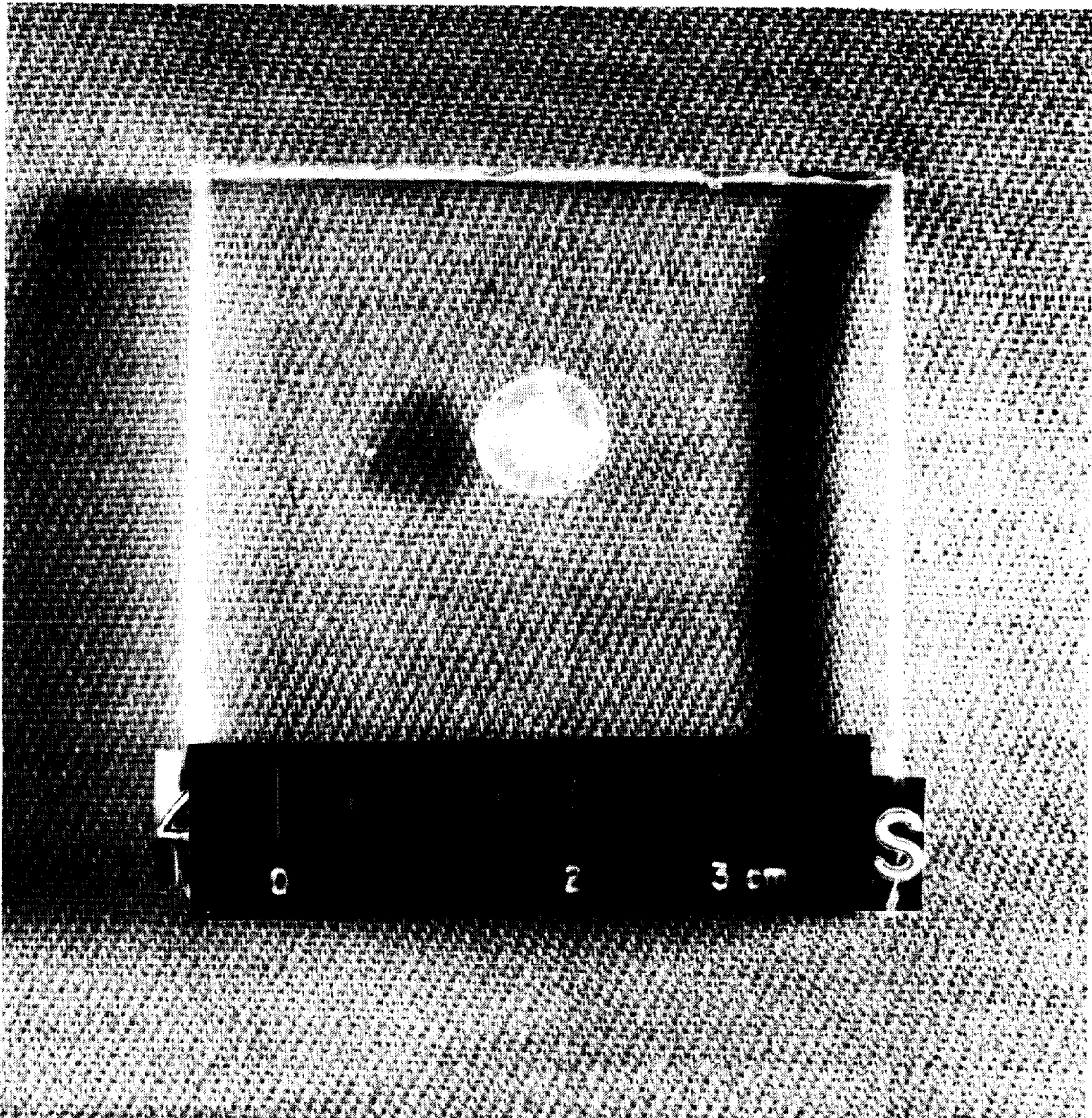
PENETRATION DEPTHS AND CRATER DIAMETERS
IN ALUMINUM AND GLASS SURFACES.

MATERIAL	PROJECTILE DIAMETER (cm)	CRATER DEPTH (cm)	INNER SPALL DIAMETER (cm)	OUTER SPALL DIAMETER (cm)	CRATER DIAMETER (cm)
Aluminum (2024T3)	0.001	0.0017	-----	-----	0.0034
	0.010	0.0194	-----	-----	0.0390
	0.100	0.2210	-----	-----	0.4420
Aluminum (1100-F)	0.001	0.0025	-----	-----	0.0050
	0.010	0.0287	-----	-----	0.0570
	0.100	0.3271	-----	-----	0.6540
Glass (7940)	0.001	0.0012	0.012	0.024	-----
	0.010	0.0138	0.138	0.276	-----
	0.100	0.3615	3.620	7.230	-----

Table 3

The types of impact problems to be expected on first, or for that matter any single surface such as solar panel or radiator paddles, are discussed next.

Erosion, pitting and degradation of optical transmissibility as shown in Figure 6. This impact damage resulted from a 0.4 mm glass projectile (2.3 gm/cc) at 7.4 km/sec. The shock damage diameter is 7 mm which gives an obscured diameter of about 0.4 sq.cm. Although there would only be between 2 and 3 impacts of this size per square meter in ten years for the combined environments, the summation of the crater areas for this size and all smaller sizes could present a problem.



Impact Damage Area caused by a 0.04 cm Projectile at 7.4 km/sec.

Figure 6

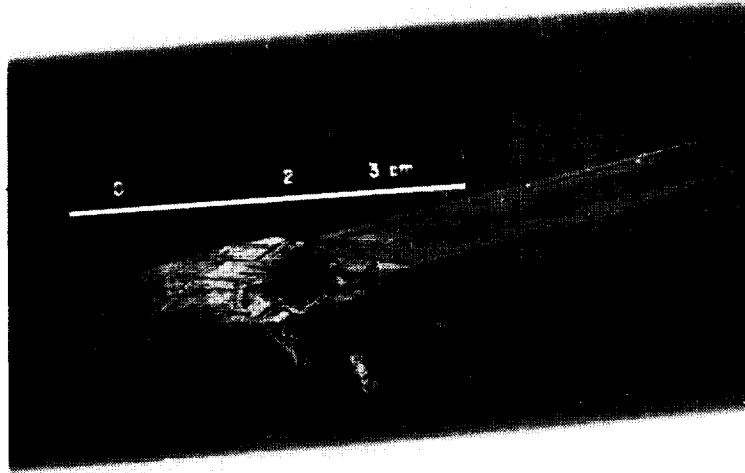
Ejection of mirror surfaces and optical coatings by impact spallation is shown in Figure 7. The particular target shown resulted from a double impact of 0.17 mm tungsten-carbide projectiles at over 6 km/sec and it is illustrative of the effect of impacts on mirrored surfaces. The actual damage areas will be similar to the values quoted for pitting discussed previously.



Impact Damage to a Mirrored Glass Surface by Hypervelocity Impact.

Figure 7

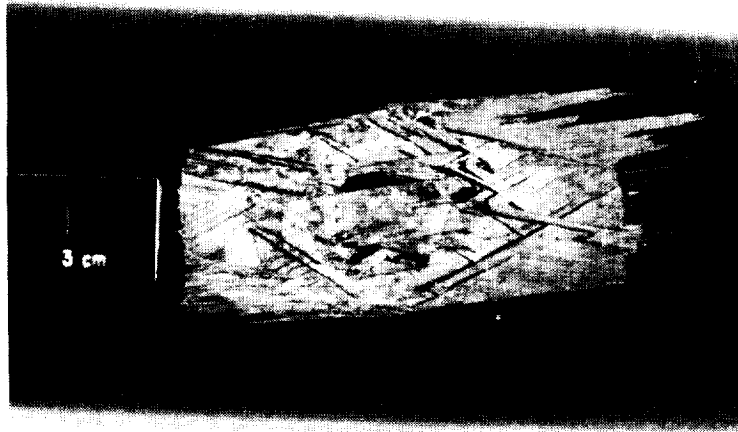
Delamination of composite materials by shock effects. Figures 8a (entry) and 8b (exit) show the results of a 2.4 mm aluminum projectile impacting a graphite-epoxy tube at 7.48 km/sec. The entry side breaks up the projectile like a bumper and the impact of the debris plume causes the extensive damage seen on the exit side. This size of impact has a 70% chance of occurring at least once in 10 years for a tubular structure area the size of the Phase 1 Space Station Freedom.



Graphite-Epoxy Tubular Strut: Hypervelocity Impact Entry.

Figure 8a

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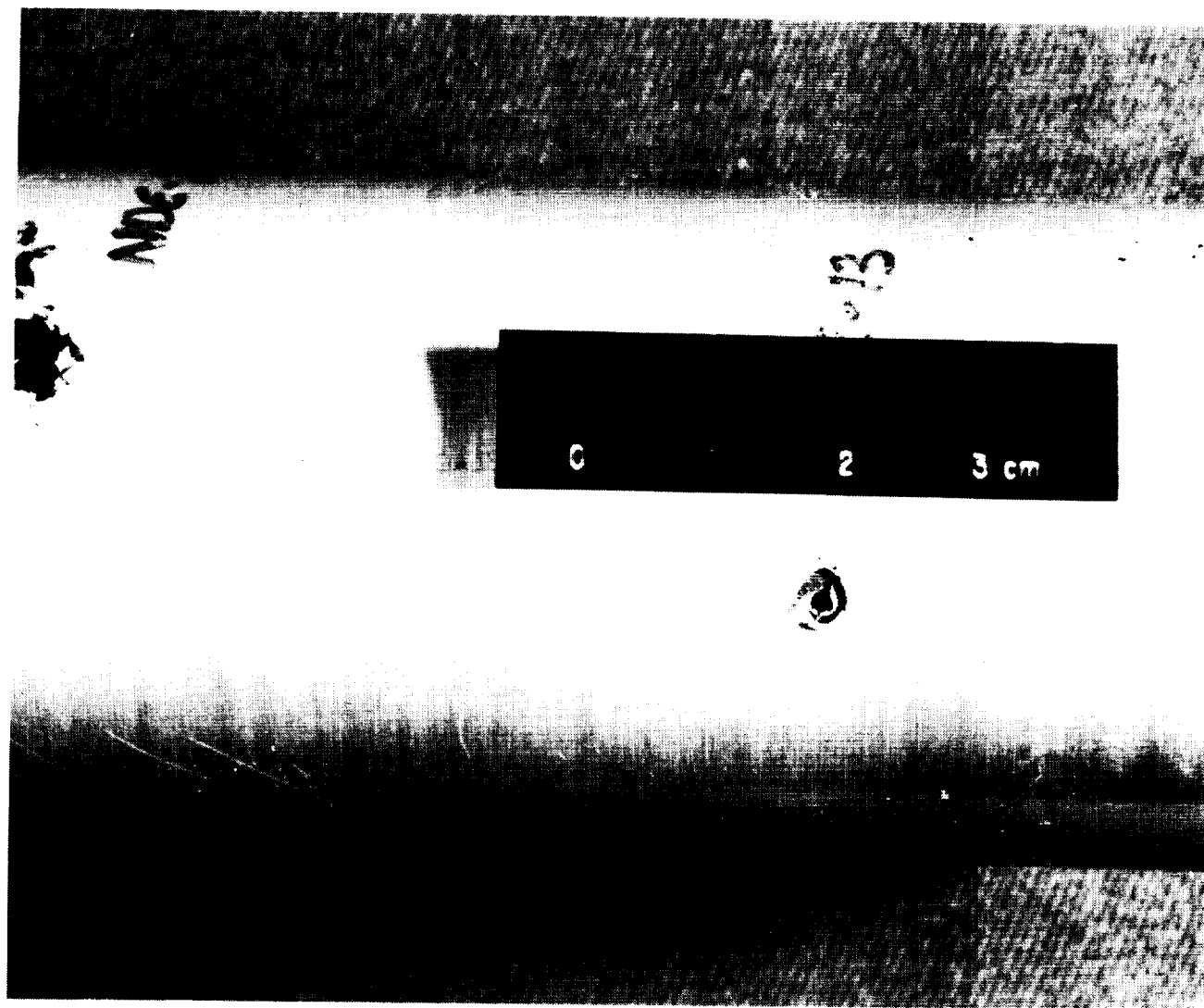


Graphite-Epoxy Tubular Strut: Hypervelocity Impact Exit.

Figure 8b

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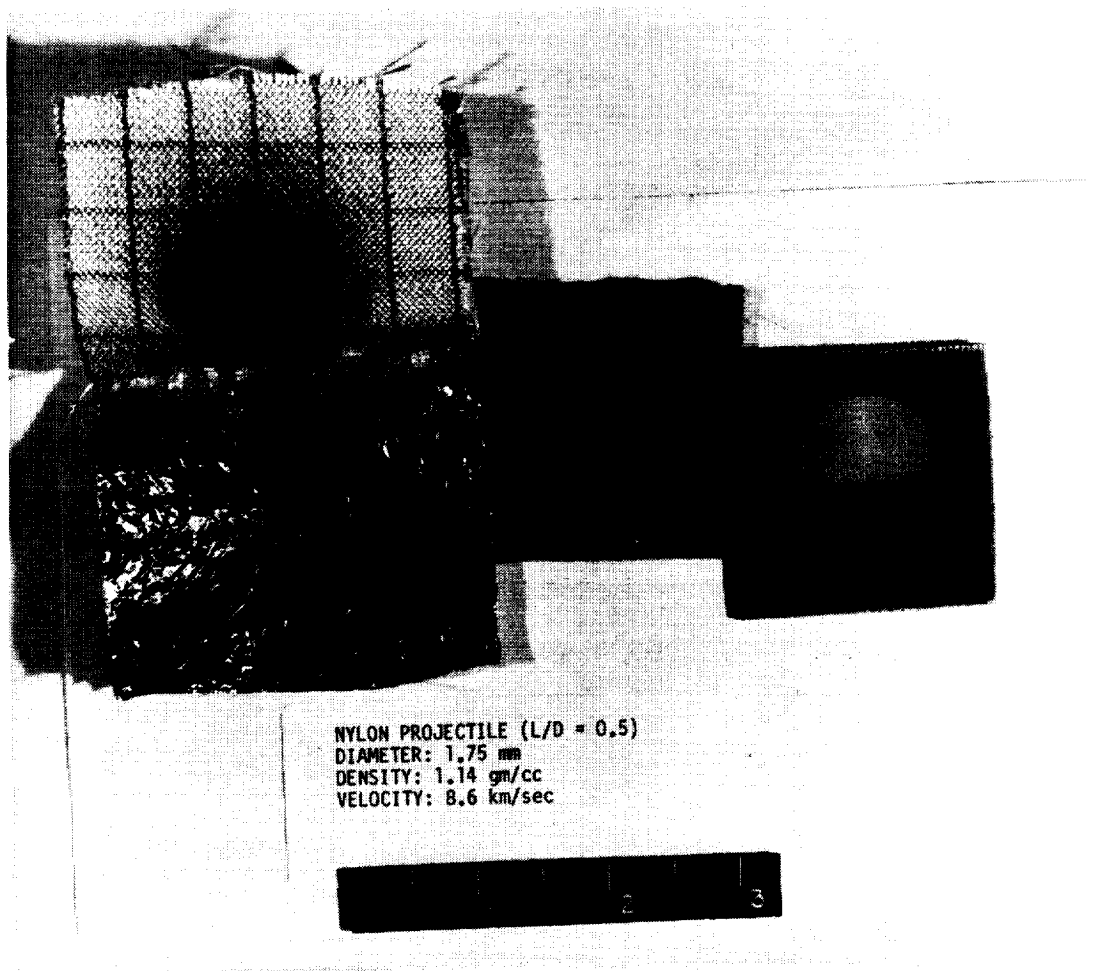
Perforation and peeling of barrier layers used to protect materials subject to atomic oxygen erosion. These impact effects are shown in Figure 9. The smaller one is the result of a 0.77 mm glass projectile impact at 4.7 km/sec, and the larger one is due to a 1.5 mm aluminum projectile at 6.7 km/sec. The barrier layer was a 0.05 mm thick aluminum 2024-T3 bonded sleeve on a 35×10^6 modulus tube. Orbital debris particles equivalent to these sizes can be expected to impact the Phase 1 Space Station Freedom several times in a 10 year period.



Aluminum-coated Graphite-Epoxy Strut: Impact Damage to Coating.

Figure 9

Flammability, vapor deposition and toxicity. Figure 10 is a view of a space-suit element with the outer thermal barrier material folded back to reveal the large hole in the aluminized mylar insulation layer, the hole and blackening of a kapton felt layer and the delamination of a fiberglass laminate. The projectile in this test was a 1.75 mm nylon projectile that impacted at 8.6 km/sec.

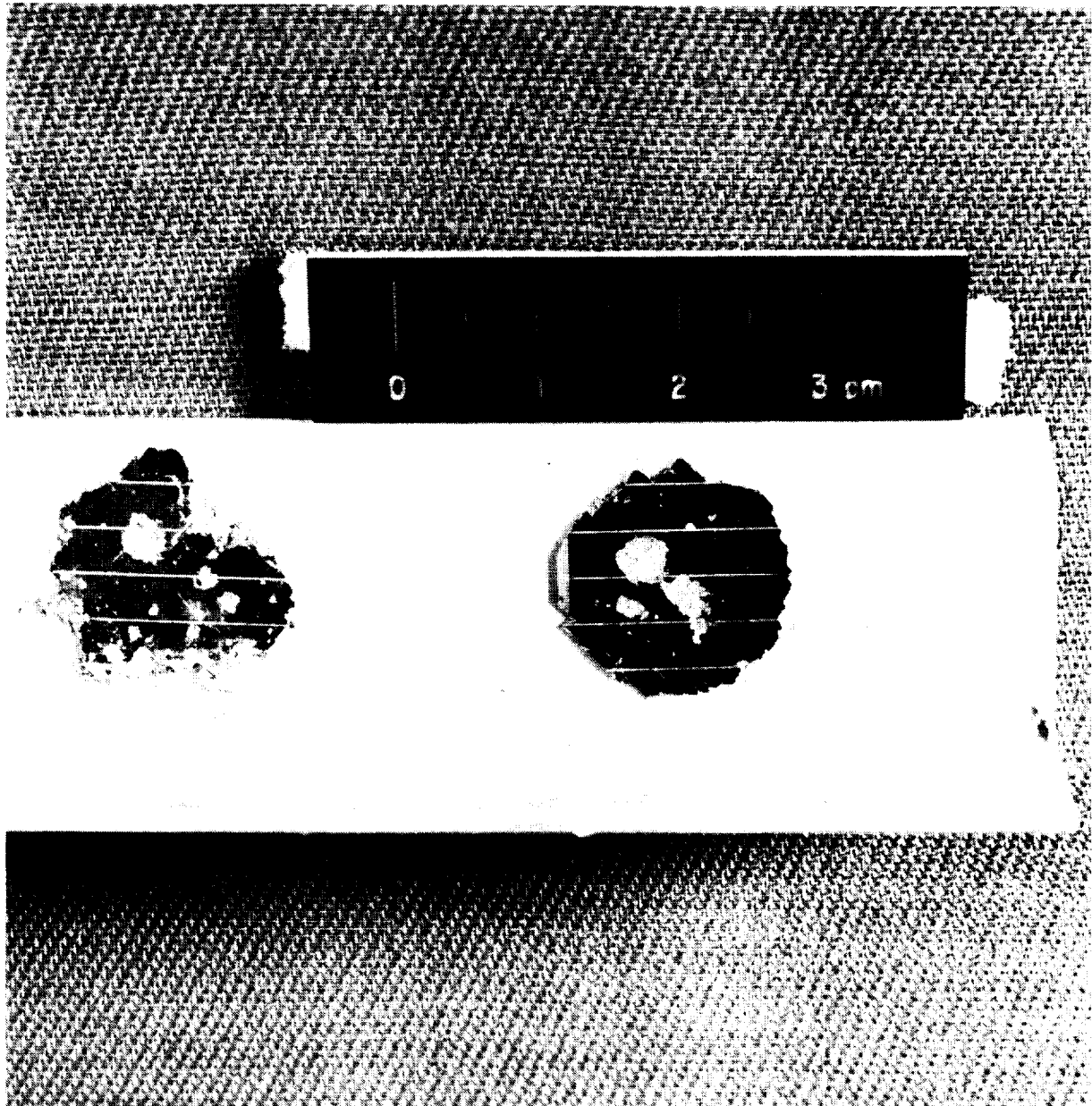


Space-suit Element showing Damage to Materials in the Layup.

Figure 10

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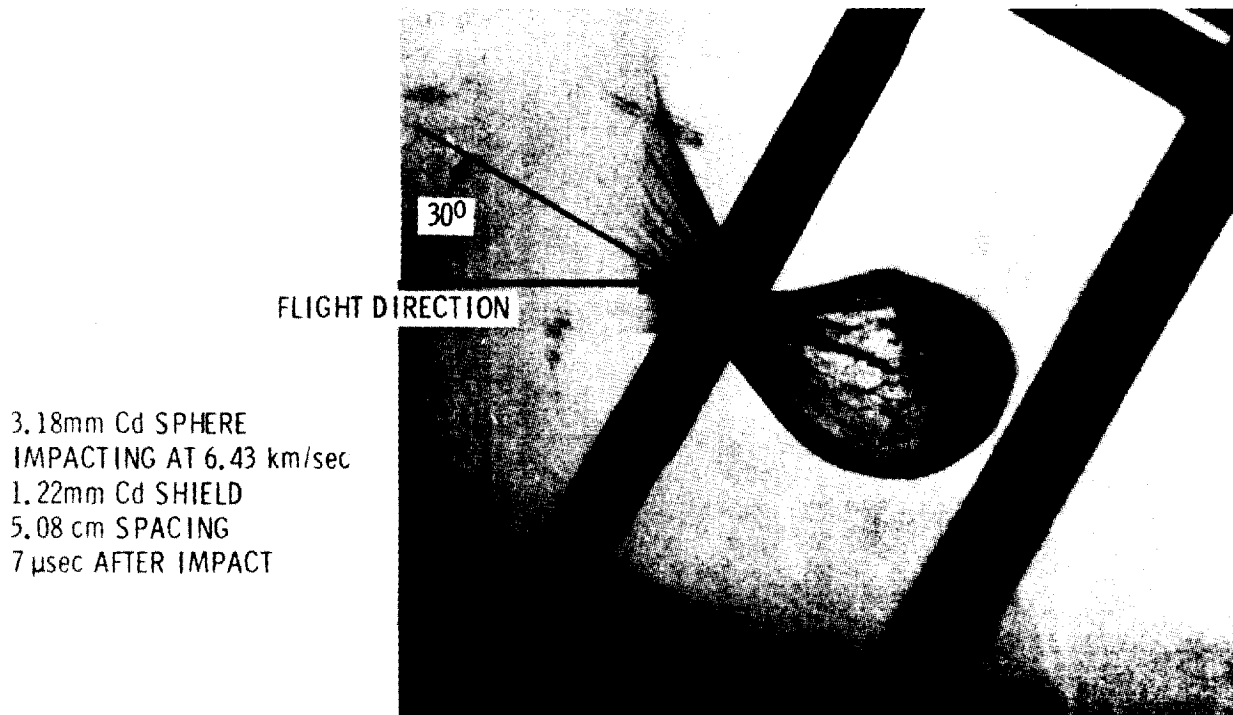
Impacts, molten splatter and vapor deposition result from an impact on a first surface. Oblique impacts are the norm and there will be ejecta from the impact site that will affect other spacecraft components or sensors in the line of flight. Figure 11 is an illustration of secondary impacts on solar cell elements bonded to an aluminum L-section. The damage to the cells is extensive, and the magnification factor for brittle materials can be seen by comparison with the impacts on the aluminum substrate. One impact by a micrometeoroid or an orbital debris particle can result in thousands of secondary impacts on another surface in the way.



Effect of Impact Ejecta on Solar-cell Bonded to Aluminum Substrate.

Figure 11

Second or subsequent surfaces are those that are exposed to the results of perforation of the first surface. The high-speed photograph, Figure 12, from Reference 4. It shows a projectile debris plume generated by an impact on the first sheet of a dual-sheet target and illustrates how the second sheet and the void between can be affected. The plume can be a vapor, molten droplets or even solid fragments. Generally, the second surface is the component that is being protected, but in some instances it could be vulnerable system components.



Flash X-Ray Showing Effect of Oblique Impact

Oblique Impact in Two-sheet Target showing Debris Plume.

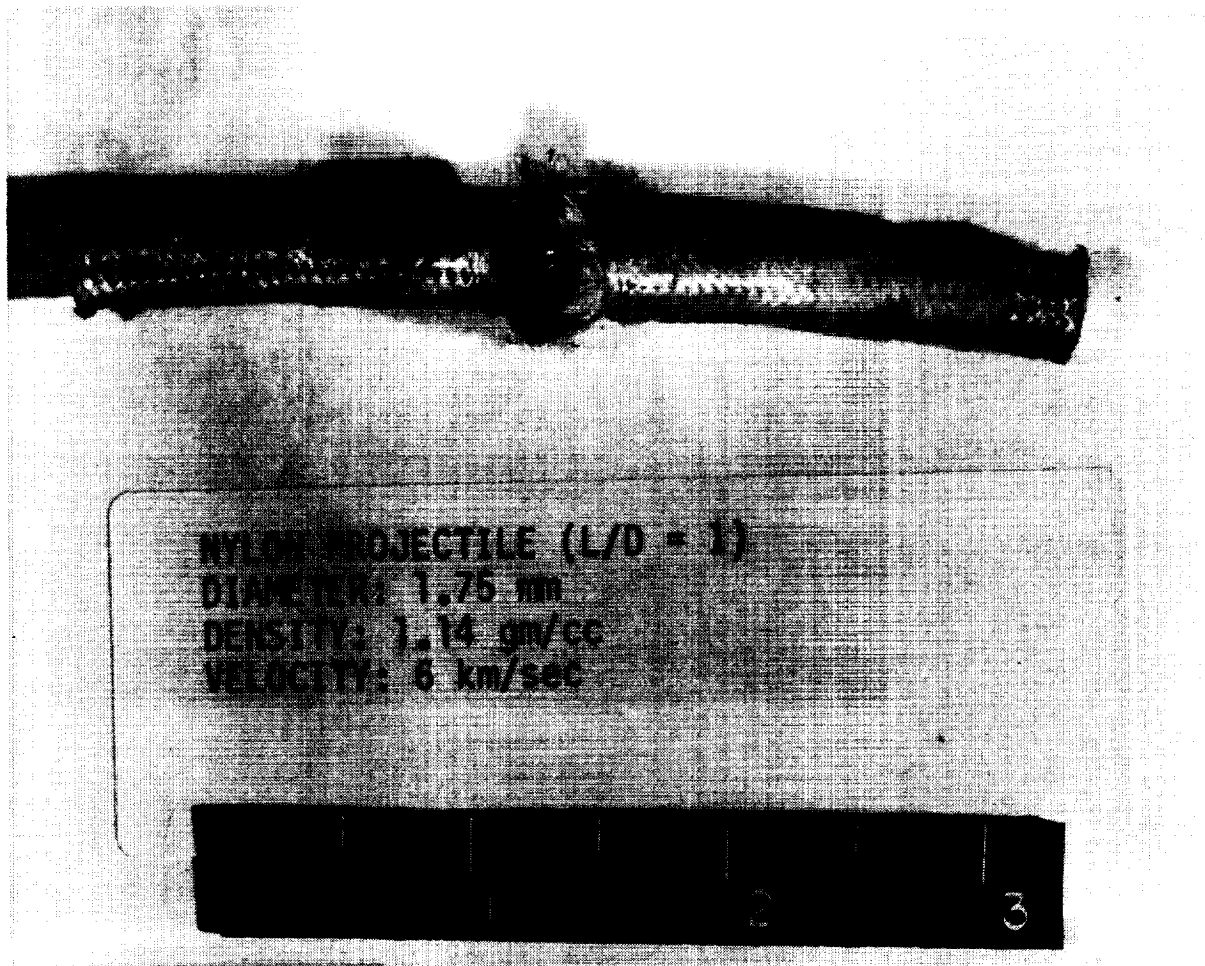
Figure 12

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Some of the effects of impacts by micrometeoroids or orbital debris particles are as follows:

a. Shield and projectile fragment damage to pressure vessels, wire bundles and sensitive electronic packages.

In Figure 13, a wire cable has been impacted by a large fragment from a debris plume resulting in significant damage.



Electrical Cable Impacted by a Hypervelocity Projectile.

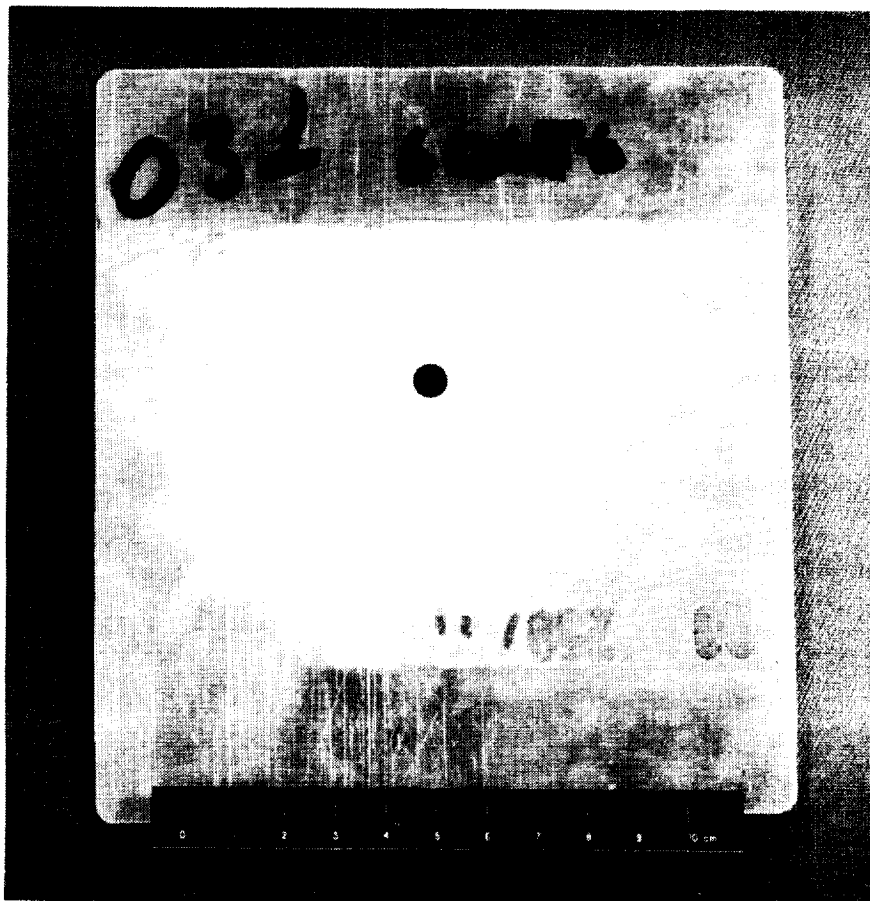
Figure 13

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b. Molten droplet and vapor deposition on electronic components could cause shorts.

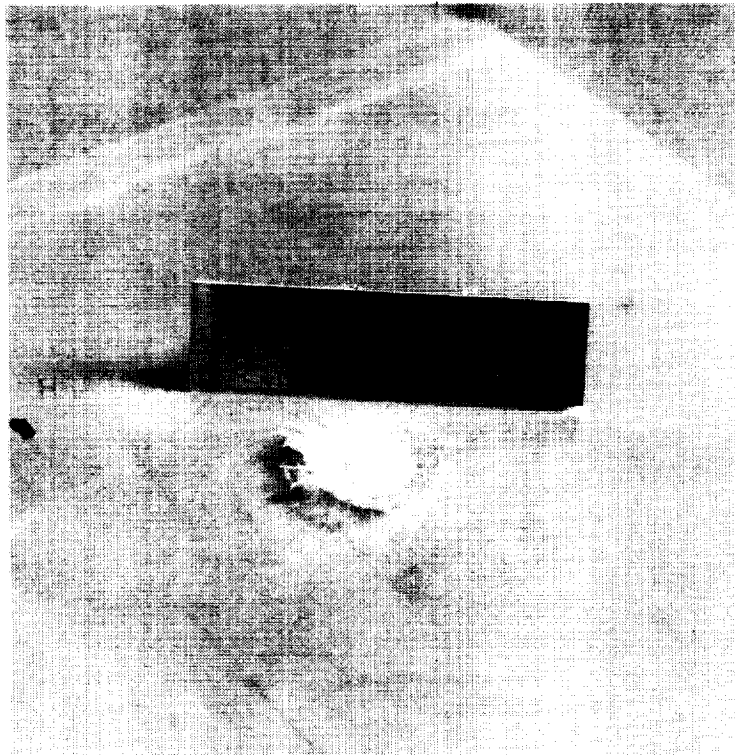
Examples of these can be seen in the next three figures. Figure 14 shows vapor deposited on the rear surface of the first sheet. A molten aluminium droplet adhering to an aluminum second sheet surface is shown in Figure 15. In Figure 16, a molten aluminum splash and vapor deposit is shown coating a copper second sheet surface.

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Rear View of First Sheet Impacted showing Vapor Deposited.

Figure 14



Molten Aluminum Droplet on Aluminum Second Sheet Surface.

Figure 15



Molten Aluminum Splash and Vapor Deposit on Copper Second Sheet Surface.

Figure 16

c. Destruction of a large area of multi-layer thermal insulation (MLI) barriers often placed in the void behind the first surface to protect the second surface.

This effect can be seen in Figure 10, where the aluminized MLI is part of the thermal protection in a space suit.

d. Thermal effects such as burning, charring and toxic by-products.

These effects are also visible in Figure 10.

Material Properties and Practices for Space Durability

The information presented above should lead to a better understanding of how some of the material properties and environmental shielding practices can be improved upon or avoided for long-term space applications. However, the following list of avoidable materials is offered as a starting point:

- a). Brittle materials such as glass for mirrors and uncovered windows or lenses, and monolithic ceramic shields. Tough, transparent, optically acceptable synthetic materials respond very well to laboratory hypervelocity impacts.
- b). Deposited optical coatings will be easily delaminated and ejected over an area 20 to 30 times the size of the impacting particle. The use of tinting in conjunction with the suggested materials in (a) above would be a solution.
- c). Laminated materials can be used provided that impact-caused delaminations do not present a problem. The nonmetallic laminates would be beneficial first surfaces from the secondary impact effects standpoint.
- d). Low vaporization temperature materials to avoid vapor coating components that would malfunction.
- e). Glass mirrors. Metal mirrors should be the rule as far as possible.
- f). Laminated first surfaces with oriented fibers dictated by strength requirements should have an external layer of basket-woven fibers bonded to it. This prevents the peeling along the oriented fibers that results from a hypervelocity impact.
- g). Electronic and electrical components should be protected by a double shield to prevent short circuits due to molten droplets or vapor from a first surface impact debris plume.

Spaceflight Experiment Requirements

There is a definite need for in-situ experiments to determine the long-term effects of micrometeoroid and orbital debris impacts on materials used in space. As is indicated by the numbers of impacts as a function of size given in Table 1, test panels required to obtain data on particles 1 mm and larger would be prohibitively large. For instance, a 100 sq. meter test panel exposed for 10 years would collect between 7 and 14 total impacts of this size, depending on orbital altitude. It is however, reasonable to consider flight testing materials subjected to the smaller particles. A 10 sq. meter panel would collect a total of 630 to 900 impacts of the 0.1 mm particle size, and probably 1 or 2 of the 1 mm size, in 10 years of exposure. Obviously, shorter durations of 2 or 3 years would still yield useful data for the 0.1 mm and all smaller sizes. Laboratory hypervelocity impact facilities cannot launch projectiles in the range of sizes between 0.1 mm and 0.01 mm at velocities greater than 6 km/sec.

Although it is not reasonable to expect dedicated flight experiments for micrometeoroid and orbital debris impacts for sizes larger than 2 mm, it should be possible to use reserved areas of the Space Station Freedom truss structure to attach test panels requiring a long exposure.

Laboratory hypervelocity impact facilities have successfully launched 0.2 mm projectiles when required, although normal testing calls for 0.8 to 3.2 mm. The velocity ranges most readily obtained for all these sizes are between 5.5 and 7.5 km/sec. As a result, ground-based hypervelocity testing of new materials for space use could be a part of an overall plan to develop space durability for the impact environments.

Conclusion

The long-term effects of the micrometeoroid and orbital debris environments on materials that are commonly used in space are dominated by the particles smaller than 1 mm in size. These particles are numerous enough to cause erosion of surface layers, optical degradation by pitting and vapor deposition, the destruction of coated and mirrored glass surfaces, the delamination and penetration of anti-atomic oxygen coatings and impact ejecta effects on surrounding structure. If a penetration of an outer layer of a spacecraft occurs, the impact debris plume can cause damage to electrical and electronic elements by solid particulate matter, molten droplets, and vapor deposition. Some materials are more susceptible to be damaged than others, and some are worse from the standpoint of secondary effects. This report presents information that could lead to enhanced long-term performance of current materials and the development of new materials designed to mitigate the effects described.

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