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HYPERVELOCITY IMPACT DAMAGE INTO SPACE SHUTTLE SURFACES

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Summary —When Orbiter Vehicles (OV) are placed in low-Earth orbit (LEO) the exposed surface is subjected to hypervelocity collision with small particles of meteoroids and man-made orbital debris (M&OD). The external shell of the orbiter is specifically designed to provide thermal protection against the extreme temperatures during launch, space exposure, and reentry. Abrasion to these surfaces by impacting hypervelocity particles is detrimental to their thermal properties, and often requires repair after return to Earth. In an effort to better understand the source of particulates in LEO, and their effects on spacecraft hardware, the analysis of residues at collision sites by means of Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray analysis (EDX) was conducted to determine the nature of such particles. Based upon the bulk composition of these residues, we have made a preliminary discrimination between micrometeoroid and space debris-containing impact features. The data on projectile composition, source, and resulting target damage is useful in estimating impactor density, velocity, and size.

NOTATION

d Projectile diameter (cm)
Θ Impact angle from surface normal (degrees)
P Penetration depth (cm)
ρ Density (g/cm^3)
V Velocity speed (km/sec)
Subscripts: **p** projectile
t target

INTRODUCTION

We collected samples of meteoroid and orbital debris (M&OD) impact damage from Orbiter Vehicles (OV) upon completion of several Space Transportation System (STS) missions (STS-50, STS-55, STS-56). Samples were cored and/or removed from the OV as part of the normal procedures conducted after flight. Features include windshield impacts, Reinforced Carbon/Carbon (RCC) panel impacts, tile damage sites, radiator tape penetrations, and Ku-Band antenna damage (figure 1). Other samples collected at the Kennedy Space Center include impacts detected on SpaceLab and its connecting tunnel, which were located in the cargo bay during the STS-50 mission. The impact damage sites were typically less than 2-3 mm in diameter and in some cases penetrated several layers of protective shielding. Results from SEM/EDX analysis of the collected samples reveal the presence of natural cosmic dust components, and man-made debris, such as spacecraft paint (Zn, Ti, Si, Cl, Al) and metallic particles (Ti, and Fe, Ni, Cr). The source of damage to some samples could not be identified. The percentages of orbital debris, meteoroids, and unknowns was ~40%, 30%, and 30%, respectively.

In conjunction with the above analyses we used a computer based impact probability program, BUMPER-F, to calculate the impact frequency for orbital debris and micrometeoroids based on models designed for the Space Station Freedom (SSF) and other current models of the environment (ref 1). BUMPER-F was used to compare the various Orbiter flight attitudes on the basis of expected M&OD damage to exposed systems hardware.

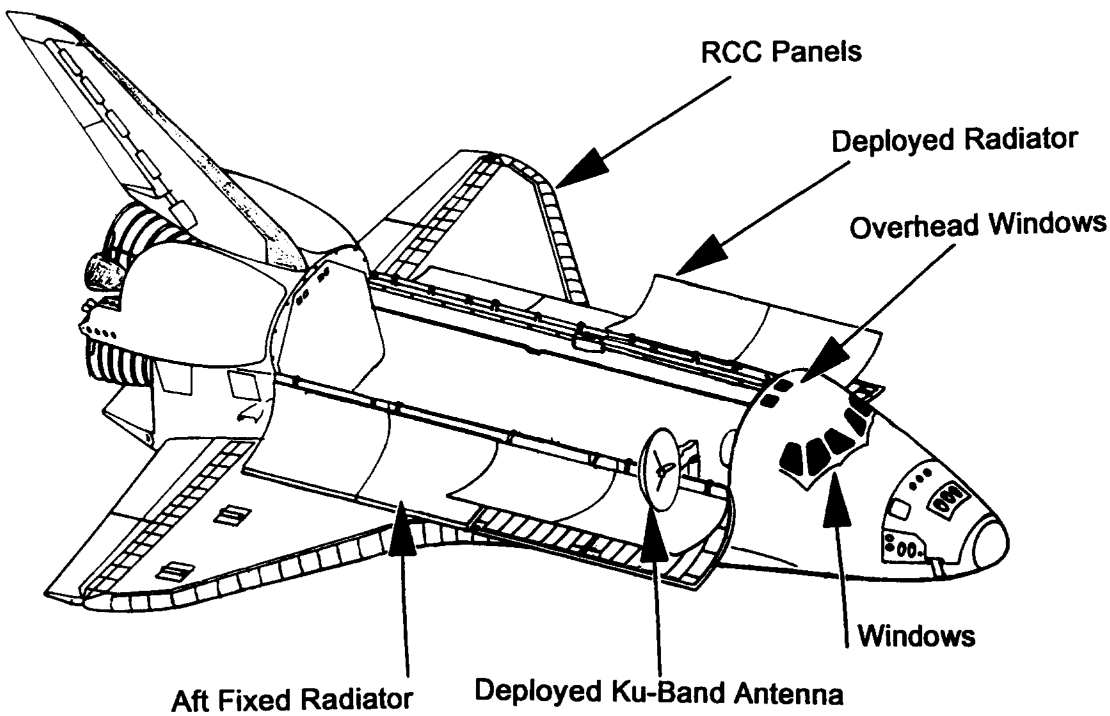


Figure 1. Regions of the Shuttle that contained impact features which were cored for Scanning Electron Microscope and Energy Dispersive X-ray analysis.

We also conducted hypervelocity impact tests at the JSC Hypervelocity Impact Test Facility (HIT-F) on similar orbiter materials to develop material response equations used in predicting the size of the impactor causing the observed damage. BUMPER-F relates the environmental M&OD impact fluxes to the expected damage using our material response data to derive predictions of expected damage severity. These efforts illustrate the measurement, interpretation, and prediction capabilities relative to the M & OD populations in LEO and the effects of M & OD impacts on spacecraft materials.

The primary source of impacts for this paper have come from OV-102 after STS-50, which flew in June of 1992. The mission lasted for over 13 days; approximately 9.7 days were flown with payload bay doors forward and in the open position. This attitude subjects the Orbiter upper surfaces to the ram velocity vector which significantly increases the apparent M&OD flux for the exposed radiator panels, overhead and forward windows, and cargo bay areas (ref 2,3). Samples of the STS-50 impact damage include 3 window impacts, 2 reinforced carbon-carbon (RCC) impacts and 16 radiator thermal tape penetrations. Other impacts presented in this paper include penetrations found on OV 102 after STS-55 and OV-103 from STS-56. During these missions elements of the deployed Ku-Band antenna were impacted by hypervelocity particles. Damage sites were on the graphite epoxy antenna reflector, and the Deployed Electronics Assembly (DEA) Box, which are Teflon coated 6061 aluminum cover and are both illustrated on the drawing in figure 2.

The samples were examined by SEM/EDX analysis to document the damage produced by collision and to determine the chemical composition of the residues associated with the impact sites which in turn categorize the damage as being either meteoritic or orbital debris in nature (ref. 3)

RESULTS

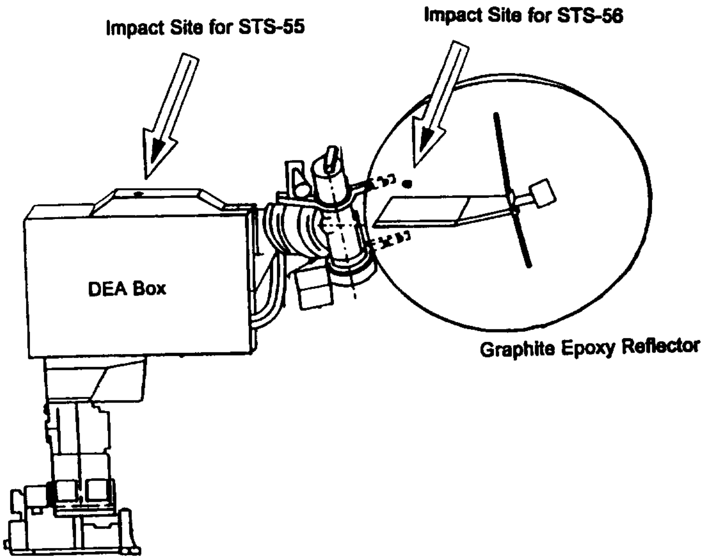


Figure 2. This drawing shows the locations of the two impact sites detected on the Ku-Band antenna structure.

STS-50

Post flight inspection of OV-103 (Discovery) after STS-56 was conducted to determine severity of impact damage caused to the exposed exterior surfaces. Examination of the Graphite Epoxy Reflector for the Ku-Band Antenna revealed a hypervelocity impact 1.4mm in diameter penetrating the 0.4mm thick graphite epoxy structure (figure 2).

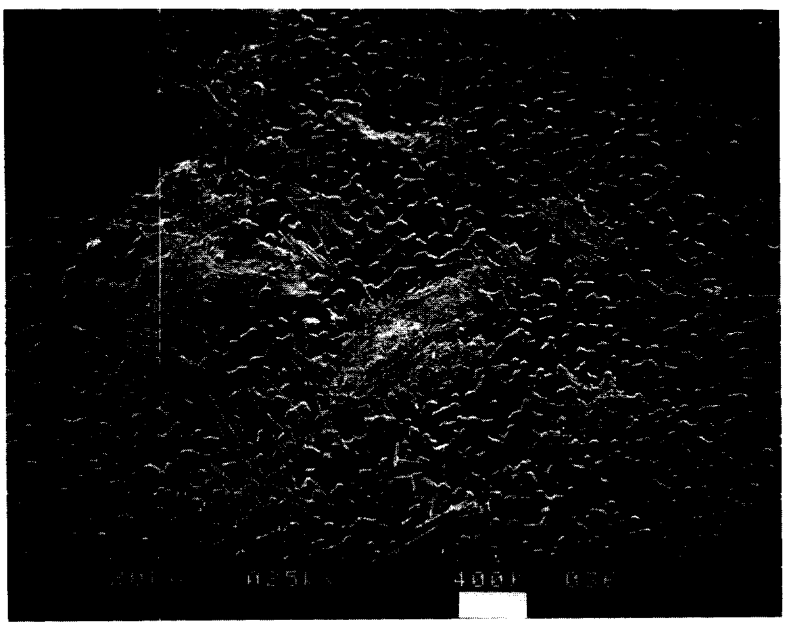


Figure 3. SEM image of the residue collected on a tape pull sample, large flakes and fibers from the graphite epoxy structure are clearly present

In an effort to determine the source of the impact, and because the impact feature on the antenna reflector could not be directly subjected to SEM examination, the analysis was conducted by a tape pull method. This technique was employed to extract remnants of projectile materials from the impact site by using an adhesive tape which was administered to the impact and pressed into the feature with a wooden probe. The residues on the tape were then analyzed by SEM/EDX. This method has shown favorable results with many samples in the past (ref. 4), and continues to be a reliable secondary source for collecting projectile remnants when first hand analysis is not possible. Analysis of contaminants from regions around the impact surface are carried out to establish background chemistry. By determining the projectile chemistry classification as being either micrometeoritic or man-made orbital debris one can estimate its relative impact velocity, the relative density, and calculate approximate particle diameter for every given impact detected.

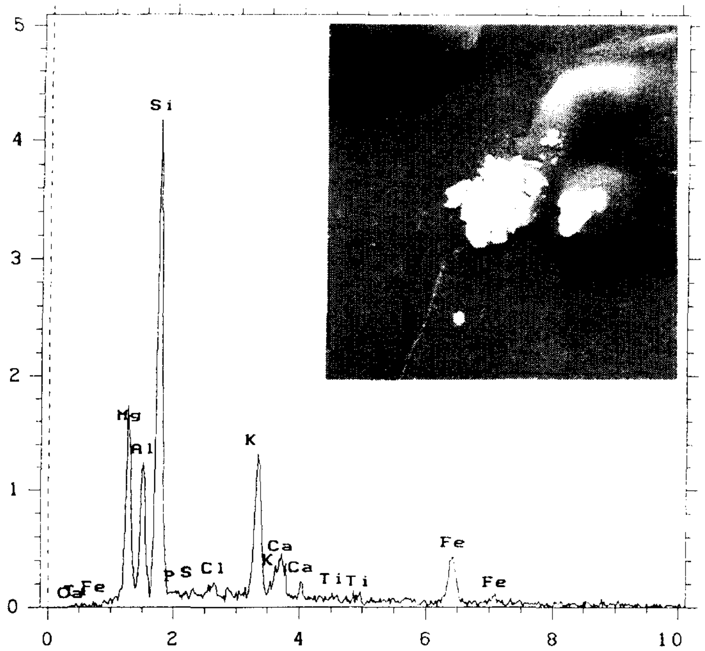


Figure 4. Energy Dispersive X-ray and SEM analysis of residues detected on the DEA antenna impact feature.

The tape pull analysis revealed that some large amounts of graphite (carbon) material fibers (figure 3), and globular mineral like grains were present at some of the tape sampling locations. The globular appearance of these small particles indicates that materials were exposed to high temperatures producing partial melts. The major elemental constituents in the mineral grains were silicon, magnesium, aluminum, iron, and also potassium which indicate the source of impact was meteoritic in origin (figure 4). In addition, many graphite fibers which may have originated from the impact debris cloud were detected on tape pull samples taken from the antenna rods on the front of the reflector dish, indicating the possible direction of the impact was back to front.

STS-55

After the STS-55 SpaceLab D-2 mission in May 1993, inspection of Space Shuttle Columbia (OV-102) determined that the Deployed Electronics Assembly (DEA) Box for the Ku-Band Antenna received a hypervelocity impact penetrating the Teflon coated top-cover (fig 2). Preliminary analysis was conducted by a tape pull method from samples taken from the front and back of the impact site as well as from cables on the interior of the electronics box. Figure 5 illustrates the morphology of residue particulates found during SEM examination of the tape pull samples.

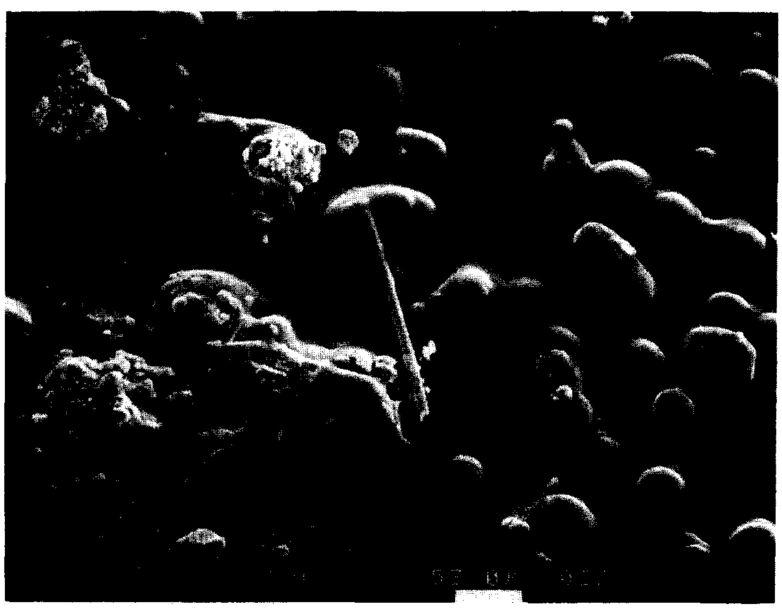


Figure 5. SEM image of residues recovered from a tape pull sample from the DEA Box Cover impact site.

The SEM tape examination revealed large amounts of silicon, and aluminum particles, silver flakes, and sulfur/nickel particles. The major elemental constituents of the remnants detected in EDX indicate that the likely source of these grains are from the DEA Box Cover materials. The components used in the manufacturing and assembling of the Box Cover can be seen in figure 6: the cross-sectional diagram of an impact which helps illustrate the source of such particles. Upon receiving the DEA Box Cover, the impact was optically photographed and documented. Measurement of impact features are as follows: Teflon delamination zone = 4.07mm; Edge of Teflon hole = 2.58mm; Aluminum crater diameter on front

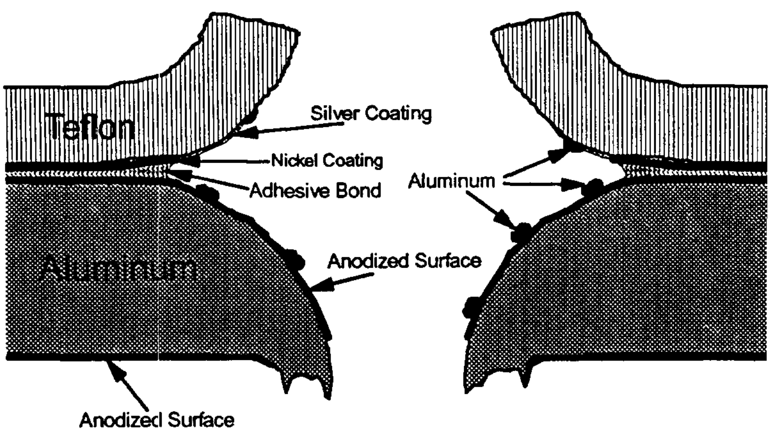


Figure 6. Cross-sectional view of the DEA Box structure at the area of impact.

facesheet = 1.76 x 1.18mm; Facesheet hole = 0.50 x 0.33mm; Back facesheet spall = 1.39 x 1.11mm. The impact was then cored by using the Long Duration Exposure Facility (LDEF) sample processing press. This provided a 0.50 inch diameter circular sample suitable for SEM/EDX analysis. Preliminary SEM and EDX examination has been conducted on the front and back of the impact (figs 7-8).

The morphology of the backside exit hole reveals that the penetration was very close to the ballistic limit for this laminated material. High magnification examination also reveals that the anodized layer of the 400 micron thick aluminum has a brittle mud-crack type structure and breaks from the surface when subjected to shock. This anodized surface of the 6061-T6 aluminum contains high levels of sulfur found on both the front and back sides of the aluminum structure. Covering the aluminum was a silverized Teflon blanket 125 microns thick. The silverized Teflon was flash coated with nickel for stabilization and held in place by a silicon adhesive and a Dow Corning primer. Many of the particles detected on and within the impact feature are target components. The Teflon coating was then removed to expose the penetration into the aluminum subsurface. Analysis of the back-side of the Teflon and the interior of the impact hole revealed that the anodized (sulfur) layer on the top-side of the aluminum had undergone only minor deformation, and that the sulfur remained intact. The back-side of the Teflon retained much of the silver coating and some particles found in this region are products of target material. Also detected in this area of the impact, both on the silver surface and the sulfur surface, were particles of aluminum alloy melt. Windowless EDX analysis of these melts show that they are not products from the aluminum target material, and that the morphological nature of the residues within the impact indicate that the aluminum melts are most likely remnants from the colliding projectile material. Application of the equations from reference number 12 indicates that if the relative impact occurred at at the calculated velocity of 10km/sec and at an angle of 45 degrees from normal (average orbital debris impact conditions), the estimated impactor size would be approximately 0.2mm in diameter.

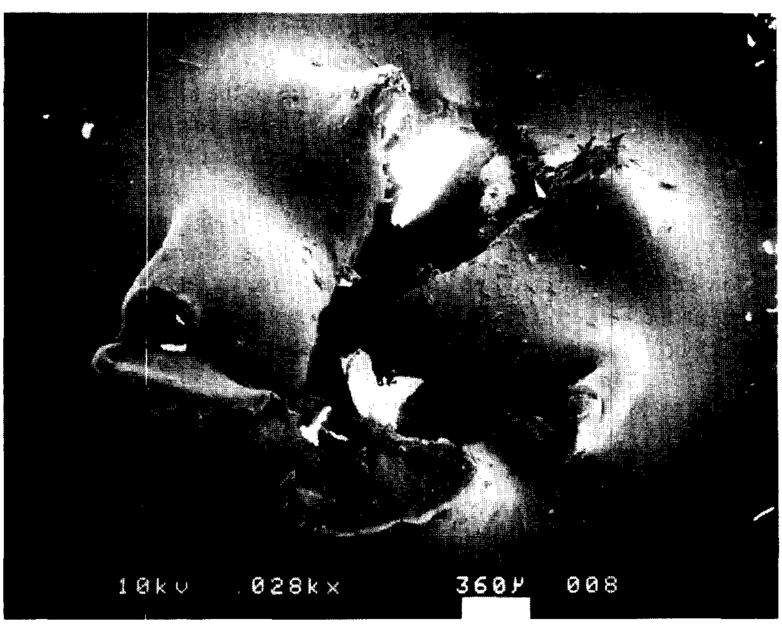


Figure 7. SEM micrograph of the front side (space exposed) DEA Box Cover showing the damaged Teflon and the 400μ diameter penetration.

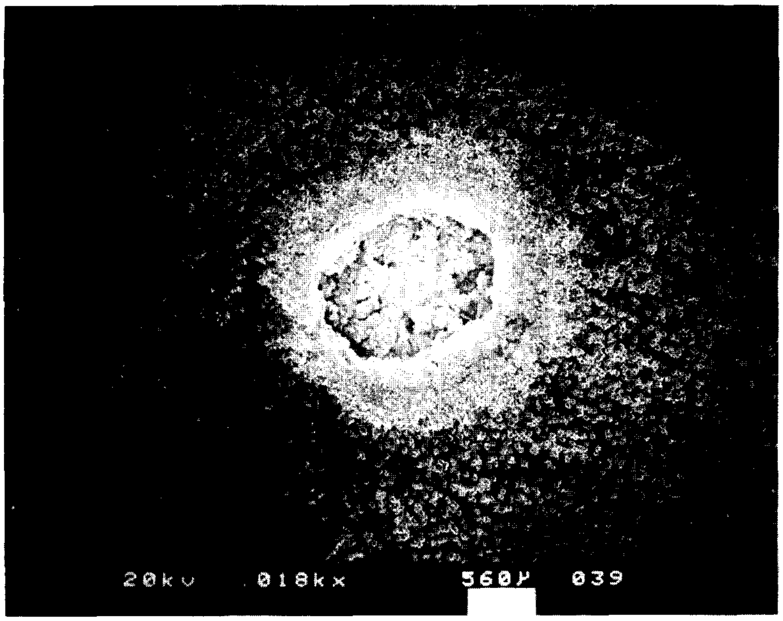


Figure 8. A view of the DEA Box cover penetration from the backside of the anodized aluminum. The spall zone damage is much larger than the hole damage, and the anodized surface has become pitted due to impact shock stresses.

STS-50

OV-102 has been optically inspected, and the impact damage sites were cored for repairs. Although small (0.8mm to 4mm in diameter) and not a safety hazard, these impacts resulted in over 20 repairs to the Orbiter. Samples collected from STS-50 included 3 window impacts, 2 reinforced carbon-carbon (RCC) impacts and 16 radiator thermal tape penetrations. Each feature was examined by SEM and EDX to determine the chemical composition of residues associated with the impact features and to categorize the projectile origin (i.e., meteoroid or debris) using criteria established at JSC (Ref. 3).

Analysis of the STS-50 data has provided useful information on the sources of high velocity impact damage to the Orbiter and has been beneficial in calibrating computer codes used to predict meteoroid and debris impact damage. These regions are relatively smooth and relatively clean, which makes impact detection possible, although these surfaces represent only ~10% of the total surface area of the vehicle and therefore receive only a fraction of the total M&OD hits on the vehicle. Most of the vehicle is covered by thermal protection system (TPS) tiles and blankets which would certainly also be impacted by M&OD. In fact, 50 to 200 TPS tile damage sites are normal after every mission, primarily due to low-speed impacts from ice and foreign object impacts during launch and landing (Ref. 5). Hypervelocity impact tests into TPS tile have been conducted and studies indicate that damage morphologies differ from that of low-velocity impacts (Ref. 6). However, due to the limited time and resources available in the processing period between OV-102 missions, it was not possible to inspect the tiles to differentiate the on-orbit tile impacts from the other tile damage.

Orbiter Radiator Impacts

The Orbiter radiators consist of 8 panels divided into starboard and port, forward (No. 1 and 2) and aft panels (No. 3 and 4). Each radiator panel is a 4.6m x 3.2m curved aluminum honeycomb structure from 1.3cm (aft) to 2.3cm thick (forward) with 0.028cm thick aluminum (2024-T81) face sheets. A silver-Teflon thermal control tape is bonded to the exterior, exposed side of the radiator panels (Figure 9). Freon is pumped through aluminum tubes that are mounted under the face sheets within the honeycomb at periodic intervals. The forward radiator panels are deployable (35.5° at the hinge line), but were not deployed during the STS-50 mission.

The Orbiter thermal control system radiator panels are a particularly good surface to observe the effects of on-orbit impacts. Their relatively smooth surface allows impacts as small as 0.5mm diameter to be detected by NASA Kennedy Space Center (KSC) inspection teams. Their large surface area of about $117m^2$ also increases the statistical significance of the data when collected. The "soft" silver-Teflon thermal control coating on the surface of the radiators acts as an effective particle collector, with many of the projectiles remaining somewhat intact for analysis. Because the radiators are only exposed to on-orbit impact damage while the Orbiter payload bay doors are open, damage from low-speed foreign object impact during launch and landing is not a factor in assessing radiator damage.

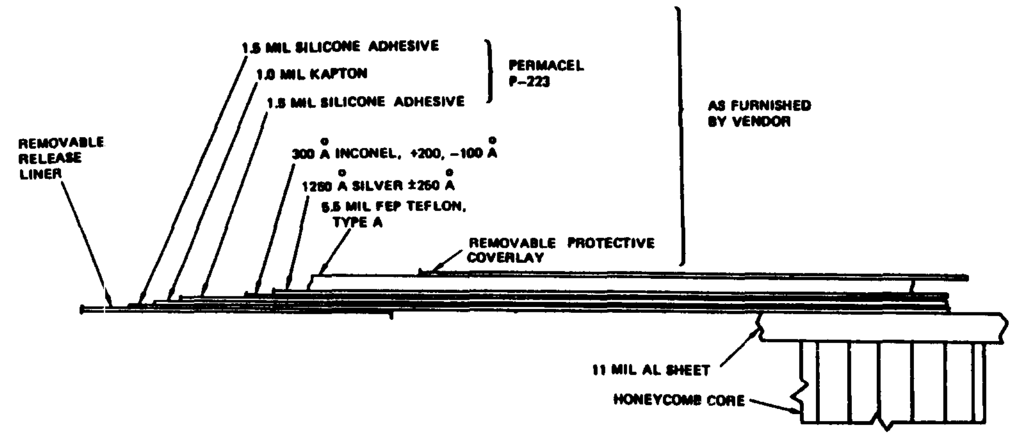


Figure 9. Radiator cross-section illustrating the multilayered structure of Teflon, Kapton, and aluminum, as well as the reflective coatings and binders.

There were 43 hypervelocity impacts found on Columbia's radiators after STS-50. In 17 instances, the impacts penetrated through the silver-Teflon thermal coating and damaged the facesheet of the radiator. In these cases, the silver-Teflon tape was removed by KSC to inspect and repair the radiator facesheet damage. Sixteen tape samples were provided to JSC for SEM/EDX analysis the extent of the damage to each was measured and the results are listed in Table 1. The largest impact on the radiators created a ~3.8mm diameter crater in the silver-Teflon tape and perforated the front facesheet. A total of 4 impacts perforated the front facesheet of the radiator panel. In the remaining 26 impacts, the silver-Teflon coating sustained crater damage but was not completely penetrated. In these cases, the damage was repaired or dispositioned without removing the tape and no sample was available for SEM/EDX analysis.

Table 1 also provides SEM/EDX results. In 6 of the 16 radiator tape samples (38%), the SEM/EDX spectrum indicated that orbital debris was the likely source of the impact damage: 4 with elemental constituents indicating impact by spacecraft paint, 1 by stainless steel, and 1 by a titanium-rich particle (possibly titanium metal). SEM image of the largest impact is shown in Figure 10. This was classified as an orbital debris impact from spacecraft paint because of the large amounts of titanium (paint pigment), silicon, chlorine, potassium, and calcium (inorganic binders) found in and around the impact site. Two of the 4 "paint" impacts had high levels of zinc as well as titanium. In 5 of the 16 samples (31%), material associated with the impact had detectable amounts of elements typically found in cosmic dust meteoroid particles (Si, Mg, Al, Ca, Na, Fe, Cl). In the remaining 5 samples (31%), no detectable remnant projectile material was found. This is due to vaporization of the projectile during impact, and/or ejecta of projectile material, resulting in insufficient mass within the impact to yield X-Ray counts (Ref. 7). Some of the unknowns had high aluminum content but it was not certain whether the aluminum detected resulted from the impacting projectile or damage to the aluminum facesheet of the radiator panel.

Figure 10. SEM image of the penetration through the radiator panel.

A series of hypervelocity impact (HVI) tests were performed at the JSC HIT-F on representative samples of the radiator (Ref. 4). Samples consisted of the silver-Teflon based thermal coating used on the Orbiters bonded to aluminum honeycomb. The results of an impact by a 0.4mm diameter aluminum sphere impacting at 7.59km/sec and 70° to the normal of the radiator panel (Shot 2331) had results very similar to impacts formed during LEO exposure. The silver-Teflon tape has a hole measuring 3.1mm x 2.2mm at the surface and a through-crack has formed at the bottom of the crater in the aluminum face-sheet (threshold perforation). Impact features from several other tests performed under laboratory conditions resemble impact damage found on the STS-50 radiators. These results were used to help determine projectile particle size from impact crater and penetration diameters measured on STS-50.

Table 1. STS-50 Radiator Impact Damage and SEM Results

		TAPE DAMAGE		FACE SHEET DAMAGE		
Location	Damage Comments	Hole Dia. (mm)	Lip Dia. (mm)	Crater Depth (mm)	Crater Dia. (mm)	SEM/EDX Results
RH#1, Item 5	Face-Sheet Cracked	1.4	1.8	0.28	0.9	Orbital Debris (Ti metal)
RH#2, Item 3	Tape Perforated	1.5	1.8	0.27	1.8	Orbital Debris (Paint:Ti,Si,Mg,Al,Cl,K)
RH#2, Item 4	Tape Perforated	0.9	1.3	0.13	0.6	Unknown
RH#2, Item 6	Tape Perforated	0.4	0.8	0.05	0.7	Meteoroid (Si,Mg,Al,Fe,K,Na)
RH#2, Item 19	Tape Perforated	0.6	1.2	0.10	1.2	Meteoroid (Si,Mg,Al,Fe,K)
RH#2, Item 20	Tape Perforated	1.1x0.6	2.4x1.8	0.11	1.9	Unknown
RH#3, Item 1	Tape Perforate	1.8	2.5	0.27	2.0	Orbital Debris (Paint:Ti,Zn,Si,Ca,Al,S,Fe)
RH#4, Item 3	Tape Perforated	1.9x1.6	2.8	0.27	3.3	Orbital Debris (Paint:Ti,Zn,Si,Ca,Al,S,Fe)
LH#1, Item 1	Face-Sheet Perforated	1.4	2.0	Perf.	1.7	Unknown
LH#1, Item 2	Face-Sheet Perforated	2.0x1.5	3.8	Perf.	1.1	Orbital Debris (Paint:Ti,Si,Al,Cl,K,Ca,Fe)
LH#1, Item 3	Tape Perforated	0.9	1.5	0.11	0.5	Orbital Debris (Steel:Fe,Ni,Cr)
LH#2, Item 5	Tape Perforated	1.1x1.0	3.0	0.14	0.6	Meteoroid (Si,Al,K,Na,Ca,Fe)
LH#2, Item 6	Tape Perforated	>1.0	NA	NA	NA	Unknown
LH#2, Item 8	Face-Sheet Perforated	0.9x0.7	1.6	Perf.	1.7	Meteoroid (Si,Mg,Ca,Fe,Cl)
LH#2, Item 15	Tape Perforated	0.7	1.1	0.09	1.3	Meteoroid (Si,Al,Mg,Ca)
LH#4, Item 4	Tape Perforated	NA	1.9	0.08	0.8	No Sample Available
LH#4, Item 5	Tape Perforated	1.2	1.9	0.16	0.6	Unknown

Note: RH = Right-Hand Panel, LH = Left-Hand Panel, NA - Not Available

Based on several HVI experiment results using aluminum and Nylon projectiles shot into samples of radiator panel material, a correlation factor was developed for hole diameter, Dhole (mm), in the tape:

$$D_{hole} = 1.028\, d\, \rho_p^{2/3}\, V^{2/3} \quad (1)$$

Another relation was developed to predict the projectile diameter, dperf (mm), resulting in perforation of the silver-Teflon tape and aluminum face-sheet of the radiator panel:

$$d_{perf} = 1.046\, \rho_p^{-1/3}\, (V \times \cos \Theta)^{-2/3} \quad (2)$$

The BUMPER computer program (Ref. 2) was used to predict the damage from M&OD impacts to the STS-50 radiator panels. Table 2 compares the number of holes found on the radiators at two different diameter thresholds: Dhole 0.8mm and Dhole 1.0mm, and the number of facesheet perforations. In addition, the relative quantity of orbital debris to meteoroid impacts measured by SEM/EDX for STS-50 is compared to the BUMPER prediction. Although the BUMPER predictions are fairly close in absolute numbers to the STS-50 actual damage, the relative amount of orbital debris damage is about 8 times higher for STS-50 than predicted using BUMPER. Even if all the "unknowns" were meteoroids, there are more STS-50 debris impacts than predicted using the current environment models in BUMPER. The current debris environment model predicts relatively little orbital debris at the altitude (300 km) and time of the STS-50 mission (1992) which was just after the period of peak solar activity. This data indicates that at the time of STS-50 the fluxes of particles in the size range less than ~0.2mm have a greater proportion of orbital debris particles than the current environment models predict.

Table 2. Comparison of BUMPER Predictions with STS-50 Radiator Damage

	STS-50 Actualize		BUMPER Prediction	
Criterion	**Total**	**Ratio M : OD : U***	**Total**	**Ratio M : OD***
Dhole 0.8mm	**13**	**15% : 46% : 38%**	**12.5**	**95% : 5%**
Dhole 1.0mm	**9**	**11% : 56% : 33%**	**6.7**	**[illegible]5% : 5%**
Face-Sheet Perfs.	**4**	**25% : 50% : 25%**	**6.[illegible]**	**[illegible]8% : 2%**

**M = Meteoroid, OD = Orbital Debris, U = Unknown*

Window Impacts

The Orbiter's crew module windows shown in F[illegible]clude pairs in the forward, middle, side, and overhead positions. The total exposed area of these 8 w[illegible]is 3.32m2. Each of these windows are sets of three glass panes, an outer thermal pane followed by [illegible]t pressure panes. The thermal panes are made of fused silica glass (Corning 7940). Details o[illegible]ace Shuttle Orbiter window system, operational and maintenance requirements are described else[illegible]Ref. 8).

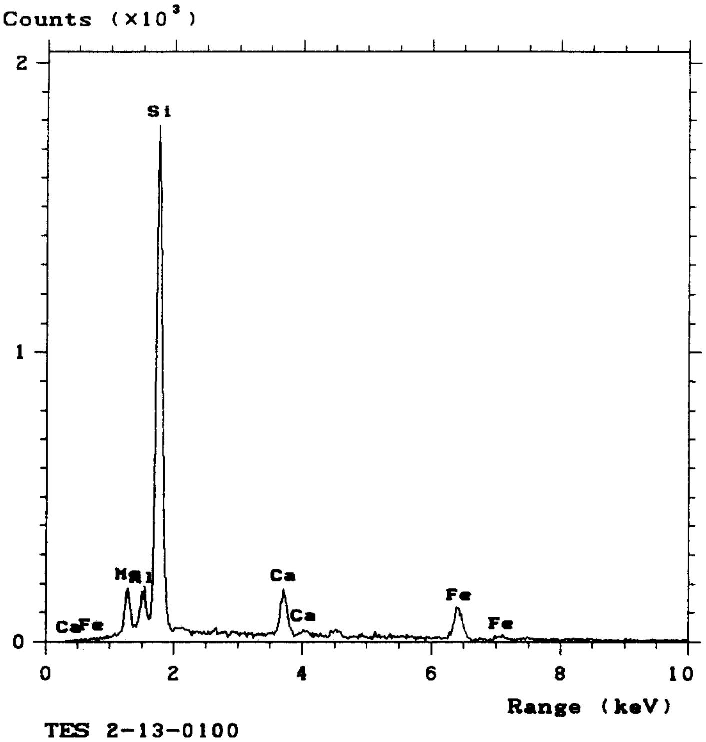
After each flight, the thermal panes are inspected [illegible]age that could propagate under the aerodynamic loads present during the next ascent. Table 3 lists six pits on five thermal panes found on *Columbia* after STS-50. The pit on the right-hand forward window (No. 4) was the deepest ever found on an Orbiter window and was found to be caused by a tita[illegible] orbital debris particle. Three of these windows were replaced after evaluation of the residual strength and remaining life of the windows by stress analysis.

Table 3. STS-50 Window Im[illegible]Damage

Window No. Location	Status	Pit Dia. (mm)	Pit Depth [illegible]	Crack [illegible]	SEM/EDX (mm) Results
#2, LH Middle	**Retained**	**1.8**	**[illegible].13**	[illegible]	**No Sample**
#3, LH Forward	**Retained**	**1.3**	**0.14**	[illegible]	**No Sample**
#3, LH Forward	**Retained**	**0.8**	**0.11**	**[illegible]0**	**No Sample**
#4, RH Forward	**Replaced**	**3.3 x 2.7**	**0.57**	**[illegible].2 x 6.8**	**Debris (Ti rich, Al)**
#6, RH Side	**Replaced**	**0.9 x 0.8**	**0.08**	**0.9 x .8**	**Unknown**
#8, LH Overhead	**Replaced**	**1.7 x 1.3**	**0.16**	**[illegible]7 X 1.3**	**Meteoroid (Mg,Al,Ca,Fe)**

Figure 11. Micrograph illustrating the spalled region of a shuttle window impact, small amounts of micrometeoritic residue was detected in the central pit region.

The damage sites on the three replaced windows were cored and analyzed by SEM/EDX to determine the chemical make up of the colliding projectile. Because of the brittle nature of the glass, relatively large amounts of glass are ejected during hypervelocity impact, which can easily result in remnant projectile material being lost along with the ejected glass (figure 11). Likewise the central pit (primary impact site) is often spalled away and the morphology of the region, which helps estimate impact velocities, is sometimes lost.



Figures 12. Energy dispersive X-ray spectra of micrometeoritic residues found in impact from figure 11.

Analysis of particles with melt-like morphology found in the largest STS-50 window impact revealed that the impactor was a particle of man-made origin. As shown in the spectrum in Figure 12, the impactor was a titanium rich particle. A small amount of aluminum was also found. Materials of meteoritic origin were found in another impact, while the source of the third impact pit is unknown. Traces of aluminum were found in the third impact site, but because of large amounts of contamination also present, it was not certain that the aluminum originated from the impacting particle. As shown in Table 4, BUMPER predictions compare reasonably well with the total number of hits found on the STS-50 windows, but over-predicts the ratio of meteoroid to orbital debris impacts compared to SEM/EDX results on residues detected within these impact features.

Table 4. BUMPER Predictions for STS-50 Windows

	STS-50 Actuals		BUMPER Predictions	
Criterion	**Total**	**Ratio M : OD : U**	**Total**	**Ratio M : OD**
P ≥ 0.08mm	**6**	**33% : 33% : 33%***	**5.6 : 96% : 4%**	
P ≥ 0.11mm	**5**	**0% : 50% : 50%****	**3.2 : 96% : 4%**	

** Based on 3 of 6 impacts analyzed* *** Based on 2 of 5 impacts analyzed*

BUMPER was used to calculate the number of craters with depths greater than 0.08mm and 0.11mm on the Orbiter windows using the Cour-Palais penetration equation for glass (Ref. 9):

$$P = 0.53\ \rho_p^{0.5}\ d^{1.06}\ (V \times \cos\Theta)^{2/3} \qquad (3)$$

Reinforced Carbon-Carbon Impacts

Reinforced Carbon-Carbon (RCC) is a structural composite used as the thermal protection system (TPS) for the high-temperature areas of the Space Shuttle Orbiter including the nose cap, wing leading edge, an area between the nose landing gear door and nose cap "chin panel", and a small area surrounding the forward attach fitting of the external tank to the Orbiter (Ref. 10). The majority of the RCC is in the wing leading edge panels (40.6m^2). The RCC has a typical overall thickness of 6.3mm, consisting of 4.3mm to 5.3mm thick all-carbon substrate (with a density of 1.44g/cm^3 to 1.6g/cm^3) that has been coated on either side with a dense 0.5 mm to 1.0 mm thick silicon-carbide (SiC) layer formed in a diffusion reaction process.

Table 5. STS-50 RCC Impacts

Location	Pit Dia. (mm)	Pit Depth (mm)	SEM/EDX Results
Upper Surface, LH #18	**2.5**	**0.3**	**Orbital Debris: Fe,Cr,Al,V (Steel)**
Lower Surface, RH #22	**2.5**	**0.4**	**Unknown**

Additional oxidation resistance and densification is provided by silicon dioxide, sodium silicate, and silicon carbide dispersed throughout the coating and carbon matrix to fill porosity and microcracks. In the two pits that were found on Columbia's wings leading edge RCC panel after STS-50 both possessed features resembling hypervelocity impact damage (Table 5). This damage was repaired without panel removal, but prior to repairing the damage, adhesive tape pull was administered across the pits in an attempt to sample possible projectile residues. The tape samples were analyzed by SEM/EDX. As shown in Table 5, evidence of the impacting particle was found in only one impact, but this was on the upper surface of the RCC which had a forward (ram) direction in the nominal bay forward attitude of STS-50. The material found consisted of several grains of metallic iron/chromium having a melt-like appearance. There were traces of aluminum and vanadium also present in the samples. A likely cause of the melted materials is a hypervelocity impact with an orbital debris particle: possibly a small piece of steel on the order of 0.09mm(from eqn. 4 using orbital debris impact conditions, i.e., 10km/sec, 45°).

Table 6. BUMPER RCC Predictions

	STS-50 Actuals		BUMPER Predictions	
Criteria	**Total**	**Ratio M : OD : U**	**Total**	**Ratio M : OD**
P _ 0.3mm	2	0% : 50% : 50%	1.4	97% : 3%

M = Meteoroid, OD = Orbital Debris, U = Unknown

Table 6 summarizes BUMPER predictions made using the following penetration equation (Ref. 11), a 3.2g/cm^3 SiC coating density, 2.8g/cm^3 orbital debris density, and 0.5g/cm^3 meteoroid density.

$$P = 0.61\, d\, (V \times \cos \Theta)^{2/3}\, (rp/rt)^{0.5} \qquad (4)$$

SUMMARY

There are several aspects of hypervelocity collision of particles on space exposed spacecraft hardware which have potentially serious and cumulative effects on a variety of materials. Ablation of the windows, penetration damage to the radiator panels, and surface damage to RCC panels by hypervelocity particles represents only about 10 percent of the shuttle surfaces We have documented over 50 (relatively small percentage of total impacts which occurred) impact damage sites after 3 different shuttle missions: STS-50, STS-55, and STS-56, the impact damages have been examined in the SEM/EDX to determine whether the colliding projectile was micrometeoritic or man-made orbital debris in nature. We have compared these findings to the predictions produced by using NASA meteoroid and orbital debris models and the BUMPER probability code. BUMPER calculations predicted 19.5 impacts greater than 0.8mm on the radiators, windows, and RCC panels while optical inspection detected 21 impact features between 0.8 and 4.0mm on these surfaces. Over half of the known impact sources were due to orbital debris. This percentage is significantly higher than that predicted using NASA environment models and the BUMPER probability code (by ~8 times). This evidence indicates that orbital debris population for this size range was greater than predicted using the orbital debris environment at low Shuttle operating altitudes (~300 km) during periods of 1992 We feel that the shuttle surfaces represent a constant source of impact information derived from LEO, and that much can be learned from the analysis of the residues detected as to develop models of particle flux, density and relative velocity. Because the post-mission inspections of the Orbiter vehicles exposed surfaces provide meteoroid and orbital debris data on a frequent and periodic basis, this investigation will continue in the future and will provide further data to define the dynamic nature of the small particulate environment in low Earth orbit.

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