Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

ASSESSMENT OF HIGH VELOCITY IMPACTS ON EXPOSED SPACE SHUTTLE SURFACES

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ABSTRACT

A team of NASA and Lockheed engineers has identified 51 hypervelocity impact (HVI) damage sites on the Space Shuttle *Columbia* radiator panels, crew module window panes, and wing leading-edge carbon-carbon panels after the extended-duration STS-50 mission. Although small (0.8 mm to 4 mm in diameter) and not a safety hazard, these impacts resulted in over 20 repairs to the Orbiter. Scanning Electron Microscope (SEM) X-ray analysis indicated that approximately 35% of these were due to orbital debris impacts and 25% from meteoroids, while sources for the remainder are unknown. Predictions of STS-50 meteoroid/orbital debris damage were made using the BUMPER computer code, current NASA environment models, and the results of recent HVI tests on Orbiter components at the NASA Johnson Space Center Hypervelocity Impact Test Facility (HIT-F). BUMPER predicted a level of damage comparable to that observed on the STS-50 mission. However, more orbital debris and less meteoroid damage is observed on STS-50 than predicted by BUMPER.

NOMENCLATURE

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

1. INTRODUCTION

During STS-50, the Space Shuttle Orbiter *Columbia* (OV-102) sustained multiple, superficial meteoroid and orbital debris (M&OD) impacts to external surfaces. The impact damage sites were typically less than 4 mm in diameter. 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.

The STS-50 mission in June 1992 was an extended duration orbiter (EDO) mission conducted over 13 days 19 hours at 300 km altitude and 28.5° inclination. Approximately 9 days 17 hours were flown in a nose space, payload bay forward attitude (with a 12° starboard wing forward bias). This attitude directs the Orbiter upper surfaces, such as radiator panels and windows, into the forward direction which significantly increases the apparent M&OD flux. For orbiting spacecraft, the surfaces leading into the velocity direction are exposed to more M&OD impacts than surfaces facing in other directions (Refs. 1, 2).

Samples of the STS-50 impact damage were collected including 3 window impacts, 2 reinforced carbon-carbon (RCC) impacts and 16 radiator thermal tape penetrations. The samples were examined by Scanning Electron Microscope equipped with Energy Dispersive X-Ray Spectrometers (SEM/EDX) to determine the chemical composition of residues associated with the impact sites and to categorize the damage source (i.e., meteoroid or debris) using established criteria (Ref. 3).

The Hypervelocity Impact Test Facility (HIT-F) at the NASA Johnson Space Center (JSC) uses the BUMPER (version F) computer program to predict M&OD impact probabilities for various NASA programs (Refs. 2, 4). BUMPER impact probability calculations are based on the meteoroid and orbital debris environments defined for the Space Station *Freedom* (SSF) program (Ref. 1). HIT-F has used BUMPER to compare the various Orbiter flight attitudes on the basis of expected M&OD damage to the different systems and structures on the vehicle. This analysis indicates that the nominal STS-50 flight attitude (payload bay forward, nose toward space) is the worst attitude in terms of expected M&OD damage to windows and radiators. For the STS-50 mission, BUMPER was used to calculate M&OD damage to Orbiter windows, radiators and wing leading edge RCC panels (Figure 1). BUMPER relates the environmental M&OD impact fluxes to expected damage using predictor equations that were derived from HVI tests performed at the JSC HIT-F on Orbiter radiators, RCC, and windows.

The focus of this paper is the windows, radiators, and RCC which 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 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 impacts have been

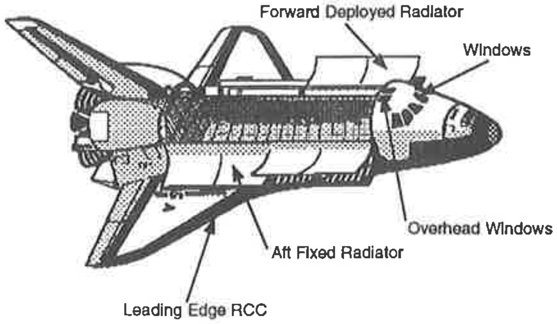
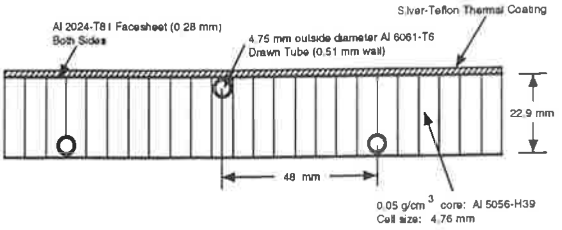
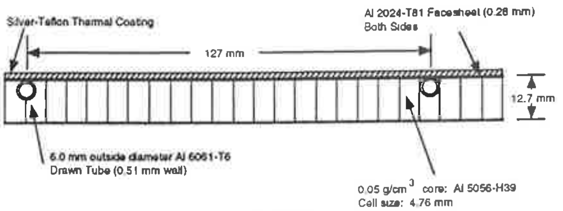


Figure 1. Orbiter Radiators, Windows, and Reinforced Carbon-Carbon (RCC)

studied and damage morphology differs from low-speed impacts (Ref. 6). However, due to the limited time and resources available in the processing period prior to the following OV-102 mission, it was not possible to differentiate the on-orbit tile impacts from the other tile damage.



Forward Panel



Aft Panel

Figure 2. Orbiter Radiator Cross-Section

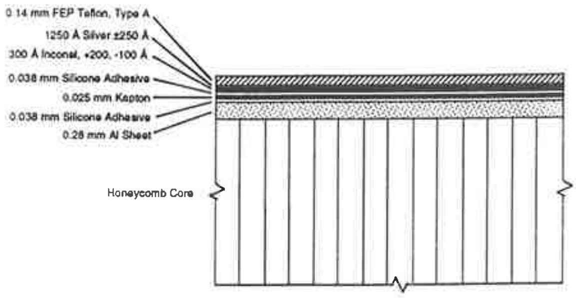


Figure 3. Silver-Teflon Radiator Coating

2. 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 4.6 m x 3.2 m curved aluminum honeycomb structure from 1.3 cm (aft) to 2.3 cm thick (forward) with 0.028 cm thick aluminum (2024-T81) facesheets (Figure 2). A silver-Teflon thermal control tape is bonded to the exterior, exposed side of the radiator panels (Figure 3). Freon is pumped through aluminum tubes that are mounted under the facesheets 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 radiators are a particularly good surface to observe the effects of on-orbit impacts. Their relatively smooth surface allows impacts as small as 0.5 mm diameter to be detected by NASA Kennedy Space Center (KSC) inspection teams. Their large area (117 m^2) increases the statistical significance of the data. The "soft" silver-Teflon thermal control coating on the surface of the radiators acts as an effective particle collector. Because the radiators are only exposed to on-orbit impact damage while the Orbiter payload bay doors are open, damage

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

		DAMAGE DIMENSIONS				DAMAGE ANALYSIS
		Tape Outer-Layer		Face-Sheet		
Location	Damage Comments	Hole Dia. (mm)	Crater Lip Dia. (mm)	Damage Depth (mm)	Damage Dia. (mm)	SEM/EDX Results
TAPE SAMPLES ACQUIRED						
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 Perforated	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

(Data on 26 impacts that resulted in cratering damage only to the thermal coating can be found in Ref.6)

Note: RH = Right-Hand Panel, LH = Left-Hand Panel, NA - Not Available from low-speed foreign object impact during launch and landing is not a factor in assessing radiator damage. In addition, because the bay doors are closed prior to returning, any impact damage to the radiators is protected from possible changes occurring during re-entry.

2.1. STS-50 Radiator Impacts

Table 1 lists 43 hypervelocity impacts found on Columbia's radiators after STS-50. In 17 cases, 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 and damage extent was measured. The largest impact on the radiators created a ~3.8 mm 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.

2.2. SEM Results

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). The SEM image and X-ray spectrum for the largest impact is shown in Figure 4. 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 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.

2.3. BUMPER Results

A series of hypervelocity impact (HVI) tests were performed at the JSC HIT-F on representative samples of the radiator (Ref. 8). Samples consisted of the silver-Teflon thermal coating used on the Orbiters bonded to aluminum honeycomb. Figure 5 shows the results of an impact by a 0.4 mm diameter aluminum sphere impacting at 7.59 km/sec and 70° to the normal of the radiator panel (Shot 2331). The silver-Teflon tape has a hole measuring 3.1 mm x 2.2 mm at the surface and a through-crack has formed at the bottom of the crater in the aluminum face-sheet (threshold perforation). This resembles impact damage found on the STS-50 radiators.

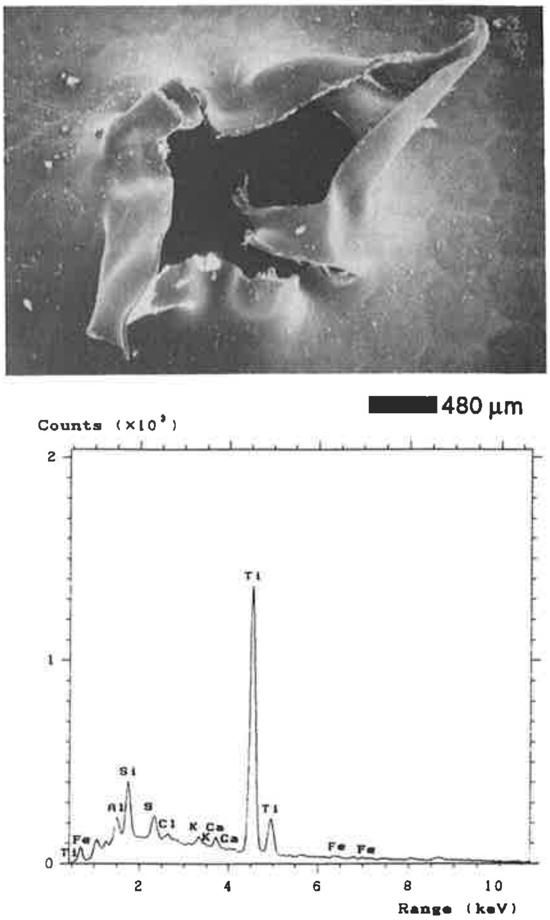


Figure 4. SEM Image and EDX Spectrum of Largest STS-50 Radiator Tape Impact

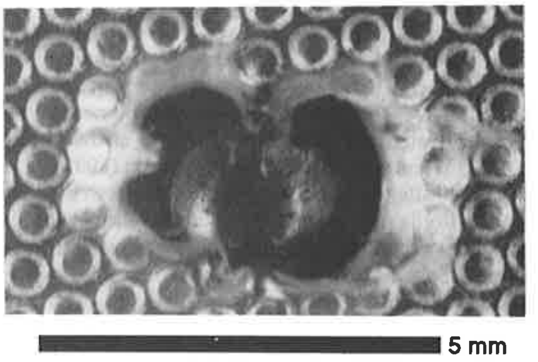


Figure 5. Results of HVI Test No. 2331 on Radiator Specimen (0.4 mm Aluminum projectile, 70° impact, 7.59 km/sec)

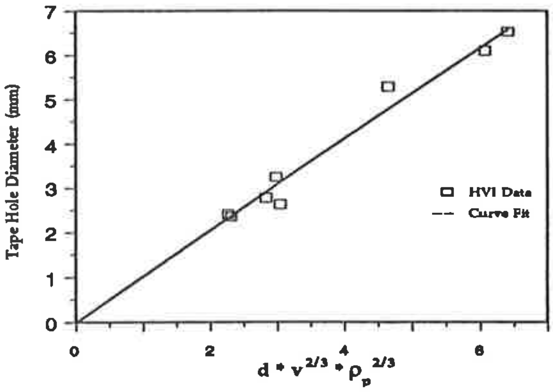


Figure 6. HVI Test Data and Radiator Tape Hole Size Correlation

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

Criterion	STS-50 Actuals Total	STS-50 Actuals Ratio M : OD : U*	BUMPER Prediction Total	BUMPER Prediction Ratio M : OD*
$D_{hole} \geq 0.8$ mm	13	15% : 46% : 38%	12.5	95% : 5%
$D_{hole} \geq 1.0$ mm	9	11% : 56% : 33%	6.7	95% : 5%
Face-Sheet Perfs.	4	25% : 50% : 25%	6.5	98% : 2%

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

Based on the HVI test results using aluminum and Nylon projectiles (Figure 6), a correlation was developed for hole diameter, D_{hole} (mm), in the tape:

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

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

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

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: $D_{hole} \geq 0.8$ mm and $D_{hole} \geq 1.0$ mm, 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 significantly 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. One possibility is that number fluxes of particles in the size range less than ~0.2 mm have a greater proportion of orbital debris particles than the current environment models predict.

3. WINDOW IMPACTS

The Orbiter's crew module windows shown in Figure 1 include pairs in the forward, middle, side, and overhead positions. The total exposed area of these 8 windows is 3.32 m^2. Each of these windows are sets of three glass panes, an outer thermal pane followed by redundant pressure panes. The thermal panes are made of fused silica glass (Corning 7940). Details of the Space Shuttle Orbiter window system, operational and maintenance requirements are described elsewhere (Ref. 9).

3.1. STS-50 Window Impacts

After each flight, the thermal panes are inspected for damage 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. Three of these windows were replaced after evaluation of the residual strength and remaining life of the windows by stress analysts.

3.2. SEM/EDX Analysis Results

The damage sites on the three replaced windows were cored and analyzed by SEM/EDX to determine (where possible) the chemical make-up of the impactor. Because of the brittle nature of 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.

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 7, 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.

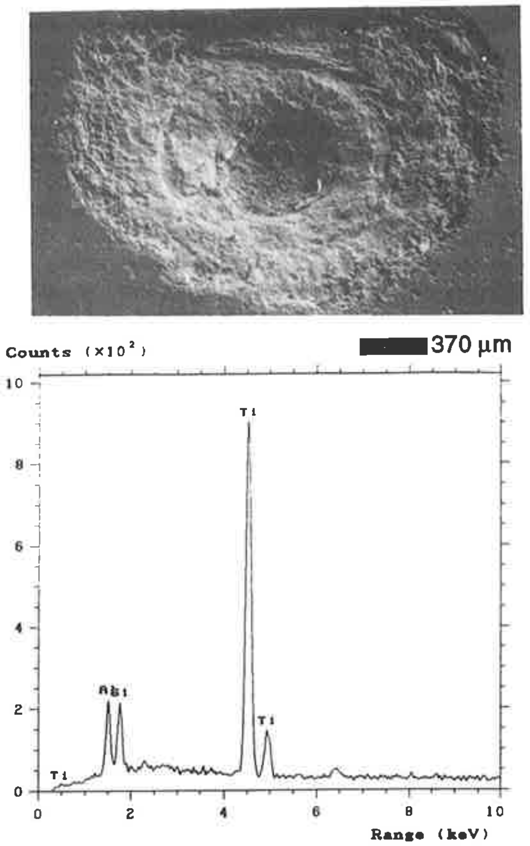


Figure 7. SEM Image and EDX Spectrum of Largest STS-50 Window Impact

3.3. BUMPER Results

BUMPER was used to calculate the numbers of craters with depths greater than 0.08 mm and 0.11 mm on the Orbiter windows using the Cour-Palais penetration equation for glass (Ref. 10):

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

As shown in Table 4, BUMPER compares 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.

4. 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. 11). The majority of the RCC is in the wing leading edge panels (40.6 m^2). The RCC has a typical overall thickness of 6.3 mm (Figure 8), consisting of 4.3 mm to 5.3 mm thick all-carbon substrate (with a density of 1.44 g/cm^3 to 1.6 g/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.

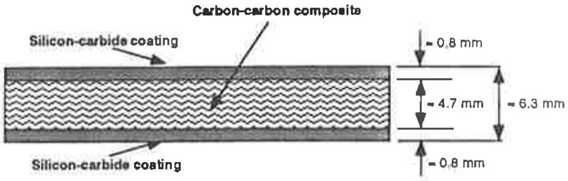


Figure 8. Reinforced Carbon-Carbon on Orbiter Wing Leading-Edge (Typical)

Table 3. STS-50 Window Impact Damage

Window No., Location	Status	Pit Dia. (mm)	Pit Depth (mm)	Crack Dia. (mm)	SEM/EDX Results
#2, LH Middle	Retained	1.8	0.13	1.9	No Sample
#3, LH Forward	Retained	1.3	0.14	1.4	No Sample
#3, LH Forward	Retained	0.8	0.11	1.0	No Sample
#4, RH Forward	Replaced	3.3 x 2.7	0.57	7.2 x 6.8	Debris (Ti rich, Al)
#6, RH Side	Replaced	0.87 x 0.79	0.08	0.87 x 0.79	Unknown
#8, LH Overhead	Replaced	1.7 x 1.3	0.16	1.7 x 1.3	Meteoroid (Mg,Al,Ca,Fe)

Table 4. BUMPER Predictions for STS-50 Windows

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

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

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

Table 6. BUMPER RCC Predictions

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

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

Additional oxidation resistance and densification is provided by silicon dioxide, sodium silicate, and SiC dispersed throughout the coating and carbon matrix to fill porosity and microcracks.

4.1. STS-50 RCC Impacts

Two pits were found on Columbia's RCC leading edge after STS-50 which had features resembling hypervelocity impact damage (Table 5). This damage was repaired in place, but prior to repairing the damage, adhesive tape was pulled 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 0.09 mm.

4.2. BUMPER Results

Table 6 summarizes BUMPER predictions made using the following penetration equation (Ref. 12), a 3.2 g/cm^3 SiC coating density, 2.8 g/cm^3 orbital debris density, and 0.5 g/cm^3 meteoroid density.

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

5. SUMMARY

Fifty-one meteoroid and orbital debris impacts were found on the radiators, windows, and wing leading edge RCC of the Orbiter *Columbia* after the STS-50 mission, which represents ~10% of the Orbiter's surface area. The radiators, windows, and RCC upper surfaces were oriented generally into the velocity direction for ~10 days during STS-50. The damage sites ranged in size from 0.8 mm to 4 mm in diameter, and did not represent a safety hazard to the crew. However, the impact damage resulted in replacement of 3 windows, 17 repairs to radiator surfaces, and 2 RCC repairs. Of these 22, SEM/EDX analysis indicates that 8 were due to orbital debris, 6 from meteoroids, and 8 from unknown sources. One of the STS-50 window pits was the deepest impact that has been recorded on an Orbiter window and it occurred from a titanium-rich orbital debris particle. Calculations using the NASA meteoroid and orbital debris environment models and the BUMPER probability analysis code predicted a similar level of damage as observed on STS-50 (BUMPER predicted 19.5 versus 21 impacts observed on windows, RCC, and radiators with holes at least 0.8 mm diameter). However, the predicted number of orbital debris impacts were ~1/8 of that observed. Small debris (0.05 mm to 0.2 mm) may be more numerous than predicted by the current orbital debris environment model.

6. ACKNOWLEDGEMENTS

The authors appreciate the efforts of the many NASA Kennedy Space Center personnel who assisted in acquiring the STS-50 impact data and samples for analysis including Rob Sommers, Rick Carrillo, Lyle Davis, Susan Cunningham, Jaime Palon, Frank Jones, John Fraley, and Charles Stevenson as well as Michelle Rucker of NASA White Sands Test Facility. The authors would also like to acknowledge the excellent HVI test support from the JSC HIT-F personnel including Lu Borrego, Earl Brownfield, Joe Falcon, Jay Laughman, Ken Oser, and Pat White, all of Lockheed Engineering and Sciences Company.

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