NASA/TP-2006-213716

STS-111 (OV-105 Flight 18) Meteoroid/Orbital Debris Postflight Assessment

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April 2006

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Acronyms

ATL	attitude timeline
EDX	energy dispersive X-ray
FRR	Flight Readiness Review
FRSI	flexible reusable surface insulation
HITF	Hypervelocity Impact Technology Facility
HVI	hypervelocity impact
JSC	Johnson Space Center
KSC	Kennedy Space Center
LH	left hand
LV	local vertical
LVLH	local vertical local horizontal
M/OD	meteoroid and orbital debris
ODRC	Orbiter Data Reduction Center
PR	problem report
RH	right hand
RCC	reinforced carbon-carbon
SEM	scanning electron microscope
SSC	Stennis Spacecraft Center
SSME	Space Shuttle main engine
TPS	thermal protection system
VV	velocity vector

EXECUTIVE SUMMARY

Thirty-two hypervelocity impact sites were observed on Space Shuttle OV-105 surfaces after the STS-111 mission. The largest impact, which occurred on payload bay door radiator panel R3, was caused by a meteoroid particle with an estimated diameter of 0.4 mm. This impact produced a 3.2-mm-diameter hole in the thermal tape and a 0.2-mm-diameter hole in the facesheet. The estimated diameter of the meteoroid impactor that perforated the radiator face-sheet approaches the 0.5-mm critical particle diameter of the wing leading edge reinforced carbon-carbon (RCC) panel high-temperature regions (Zone 3, figure E1) that was established during Return to Flight (STS-114) testing of the RCC panels.

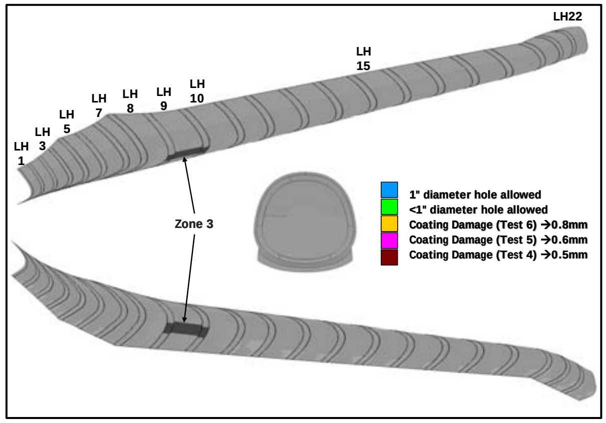


Figure E1. RCC M/OD failure criteria map.

A perforation, approximately 3 in. forward of the aft manifold (figure E2), was detected in tube 358 of the SSME-3 [Space Shuttle main engine-3] nozzle hot wall. Impact site features were consistent with the morphology of a hypervelocity impact. The crater lip had a diameter of 0.58 mm, and the bottom of the crater revealed a 0.10-mm pinhole in the stainless-steel material. Although no sample was taken at the impact site, a stainless-steel impactor with an estimated diameter of 0.2 mm would be a reasonable assumption. The engine nozzle was repaired and returned to service for the STS-114 mission.

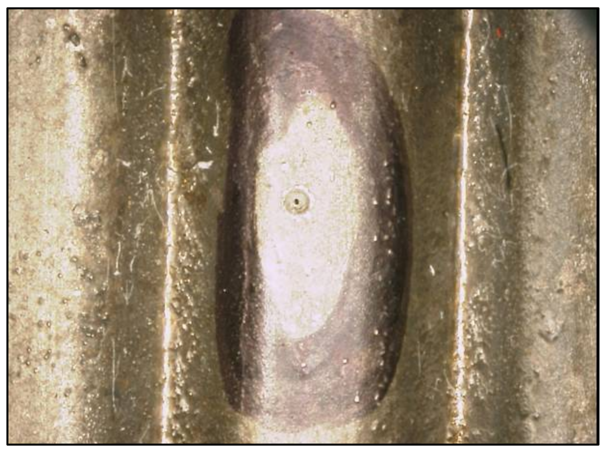


Figure E2. SSME-3 nozzle, tube 358.

Results from the as-flown meteoroid and orbital debris (M/OD) threat assessment compared reasonably well to observations. Although the analysis predicted one crew module window replacement, two replacements due to hypervelocity impact were required following the mission. Payload bay door radiator facesheet perforations were over predicted, with one observed perforation compared to an estimation of about two.

The STS-111 radiator facesheet perforation rate of 0.073 per mission day was about 21 percent less than the program average of 0.092 per mission day (STS-50 through STS-111). The window replacement rate of 0.144 per mission day was very close to the program average of 0.145 (based on STS-1 through STS-111).

ABSTRACT

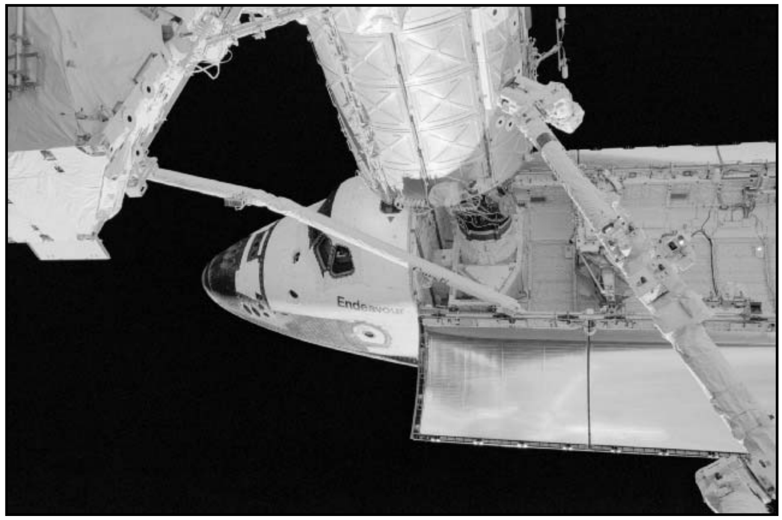


Figure A1. The Space Shuttle *Endeavour* is pictured docked to the Pressurized Mating Adapter-2 at the forward end of the Destiny laboratory on the ISS. Source: http://spaceflight.nasa.gov

STS-111 was the eighteenth flight for the Space Shuttle *Endeavour*. This UF-2 mission to the International Space Station (ISS) involved a crew rotation and the delivery of new supplies and experiments in the multi-purpose logistics module (figure A1). The mission, which took place between June 5 and June 19, 2002, had an orbital inclination of 51.6 deg and an altitude of about 389 km (210 n. mi.).

This report on the meteoroid/orbital debris (M/OD) experienced during the mission of STS-111 is divided into two sections: The "As-Flown Assessment" section compares the results of a risk analysis using postflight attitude data with postflight damage observations and preflight risk predictions; and the "Postflight Damage Inspection" section documents the M/OD that was observed during inspections at Kennedy Space Center following the mission.

Preflight and postflight assessments were performed using BUMPER-II code with the ORDEM 2000 orbital debris environment [Liou, 2002] and the SSP-30425 meteoroid environment [NASA, 1993]. At Shuttle/ISS altitudes, the new environment predicts a higher number of particles in the 0.01-mm-to-4-mm-diameter range and a fewer number of particles in the 4-mm-to-10-cm-diameter range [Lear, 2001].

CHAPTER 1 – POSTFLIGHT DAMAGE INSPECTION

Introduction

This section details the inspection and analysis conducted in the months following the STS-111 mission. The outer surfaces of OV-105 (the Space Shuttle *Endeavour*) were examined, and samples were collected from sites of potential hypervelocity impact (HVI) damage from meteoroid and orbital debris (M/OD). The surfaces include the Orbiter radiators, windows, payload bay door flexible reusable surface insulation (FRSI), and wing leading edge reinforced carbon-carbon (RCC).

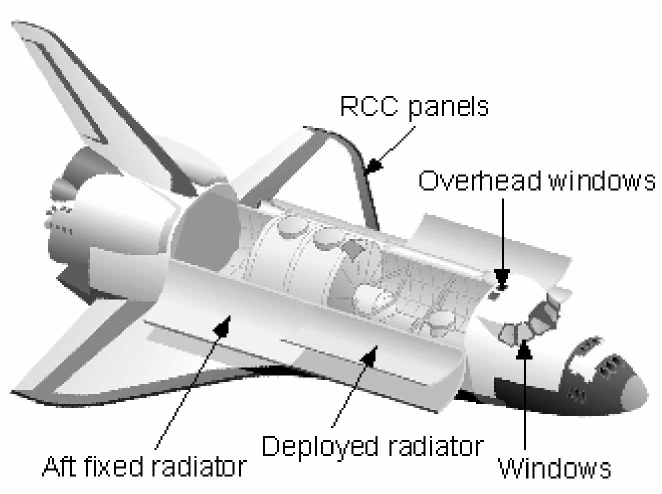


Figure 1. Orbiter radiators, windows, and RCC.

Figure 1 illustrates the location of these surfaces. In total, approximately 10 percent of the OV-105 vehicle exterior surface was surveyed during the post-mission M/OD inspection. Kennedy Space Center (KSC) and Johnson Space Center (JSC) personnel documented damage that exceeded the threshold size for each Orbiter surface as noted in table 1. The areas reported in table 1 are the total exposed area for each surface. Although the total payload bay door FRSI area is 64 m^2, the Orbiter shadows ~24 m^2 of the surface area. This leaves a total ~40 m^2 of FRSI exposed to M/OD impactors. The reader is encouraged to consult Appendix C of this document for a history of the post-mission M/OD survey campaign and for further details on impactor collection, analysis, and size/velocity estimation.

Table 1. Threshold for Reporting Damage and Inspected Surface Area for Orbiter Regions

Orbiter Region	Damage Size Threshold (mm)	Area (m^2)
Windows	0.25	3.6
Radiator Panels	1.0	117
RCC	1.0	41
FRSI	1.0	40

Thirty-one samples were collected from OV-105 by tape pull, dental mold, or wooden probe extraction techniques. Impact site dimensions ranged from 3.2 to 0.27 mm in equivalent diameter. Samples were examined with a scanning electron microscope (SEM) and evaluated with energy dispersive X-ray (EDX) analysis. This report serves to document the HVI damage accumulated during the STS-111 mission.

Meteoroid/Orbital Debris Impacts on Crew Module Windows

The Orbiter crew module windows include left and right (port and starboard) pairs in the forward, middle, side, and overhead positions. The total exposed area of these eight windows is 3.32 m^2. The crew module windows are composed of sets of three glass panes: an outer thermal pane followed by redundant pressure panes. In addition, a pair of windows overlooks the payload bay and a small circular window on the port side hatch. Figure 2 shows the locations of the windows (the thermal panes are made of fused silica glass (Corning 7940)); figure 3 shows the distribution of M/OD and unknown impactors on the windows; and figure 4 provides a breakdown of the distribution of orbital debris materials recovered from the materials postflight. Space Shuttle Orbiter window systems, operational, and maintenance requirements are described elsewhere [Edelstein, 1992].

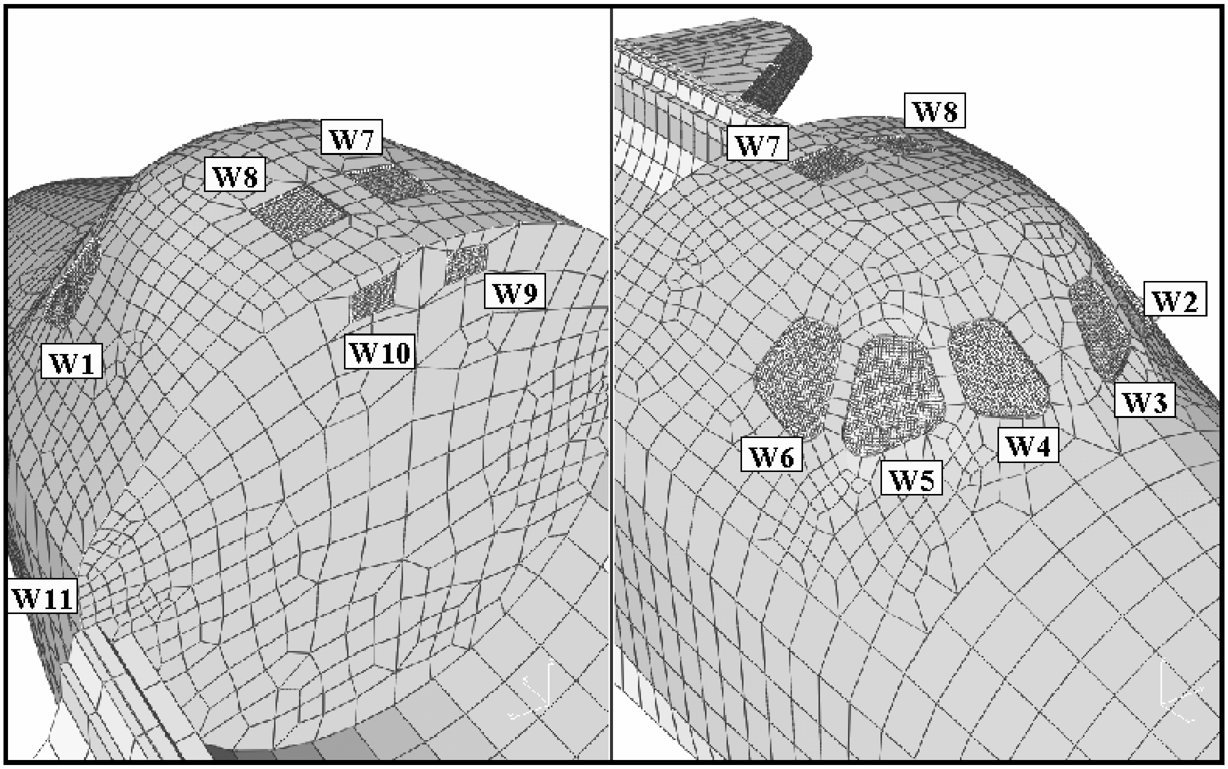


Figure 2. Orbiter crew module window locations.

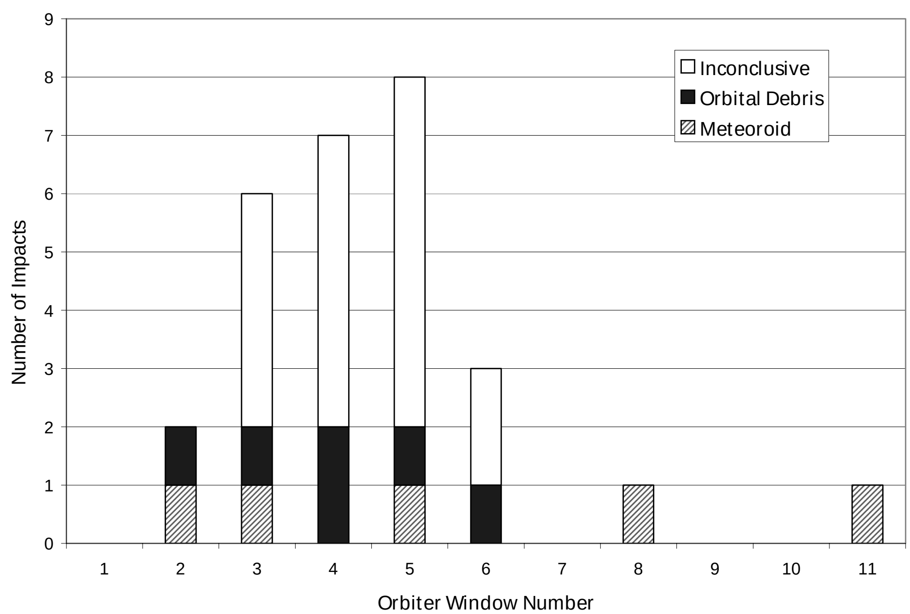


Figure 3. Distribution of orbital debris, meteoroids, and unknown impactors on STS-111 windows.

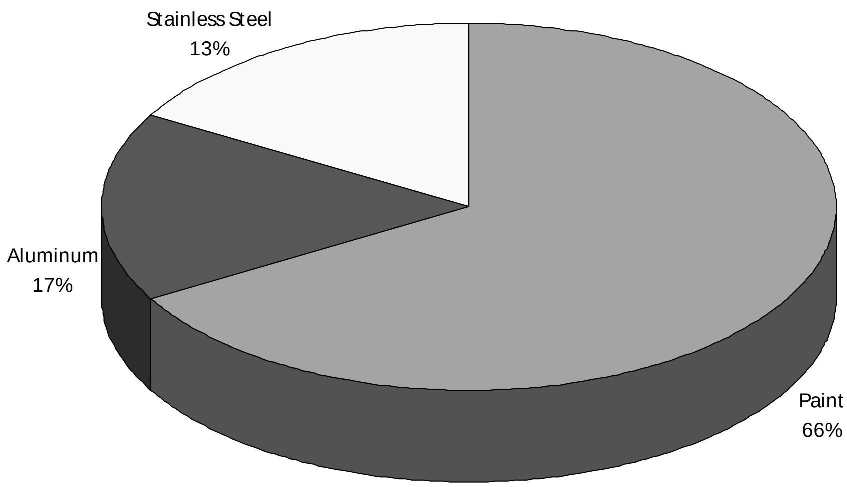


Figure 4. Percentage distribution of orbital debris materials recovered from STS-111 windows.

The M/OD damage sustained by the windows on STS-111 is shown in an SEM image taken from a dental mold impression of the damage as well as from EDX spectra in figures 5 through 16. Specifically, figures 5 and 6 provide views of strike damage from a meteorite particle to window 2, problem report (PR) 30. Figures 7 and 8 show damage to window 2, PR 36, caused by an aluminum orbital debris particle. An orbital debris particle of spacecraft paint produced the damage to window 4, PR 144 (figures 9 and 10). Window 5, PR 41, was damaged by a meteorite particle (figures 11 and 12). The damage caused by a particle of spacecraft paint to window 6, PR 2 (figures 13 and 14), was sufficiently severe that it caused the window to be scrapped. Finally, window 8, PR 1, was damaged by a meteorite particle, as in figures 15 and 16; this window, like window 6, also needed to be replaced.

Table 2 itemizes the impact damage found on the Orbiter windows after STS-111. KSC inspectors reported 28 new impacts that were greater than 250 microns in diameter. Windows 6 (right-hand side) and 8 (left-hand overhead) were scrapped after the STS-111 mission due to impacts sustained during the flight. Despite this, the largest impact feature was observed at window 3, which sustained a central pit 0.076 mm deep and a 0.840-mm-diameter crater. Analysis results indicated that the impactor was a meteoroid particle.

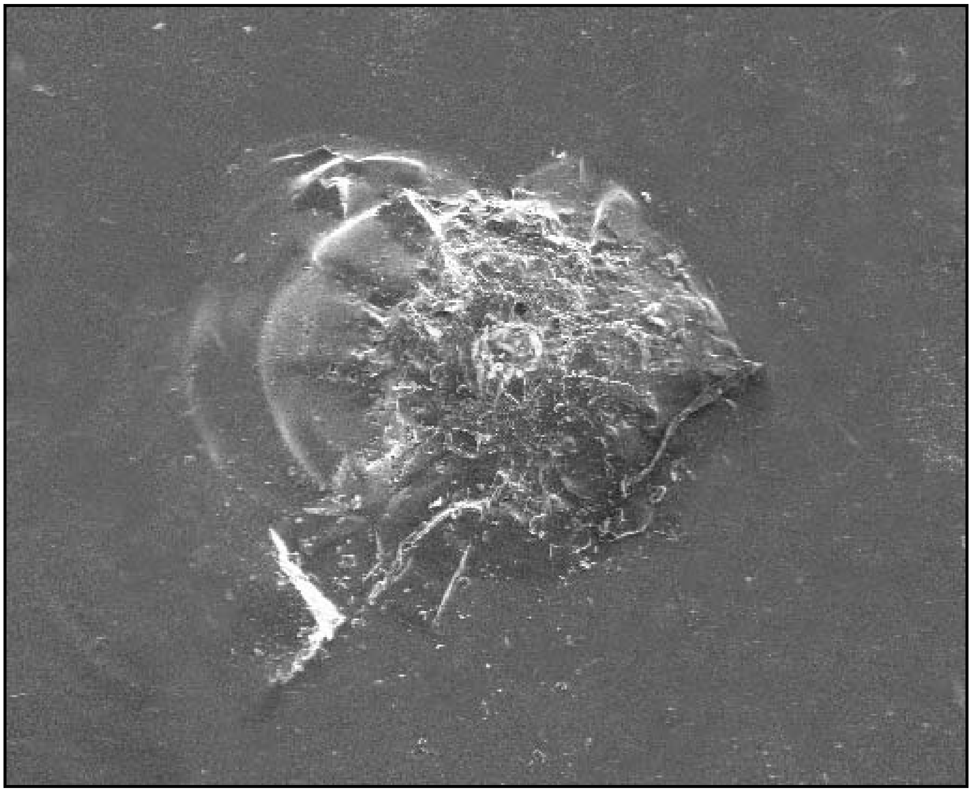


Figure 5. SEM image from the dental mold sample taken at window 2, PR 30.

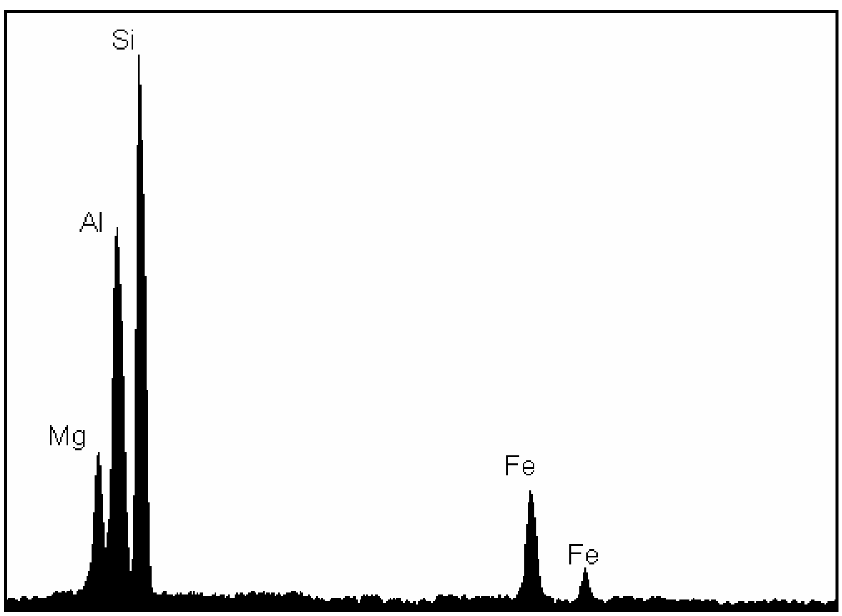


Figure 6. EDX spectra from the dental mold sample taken at window 2, PR 30. This impact was caused by a meteoroid particle.

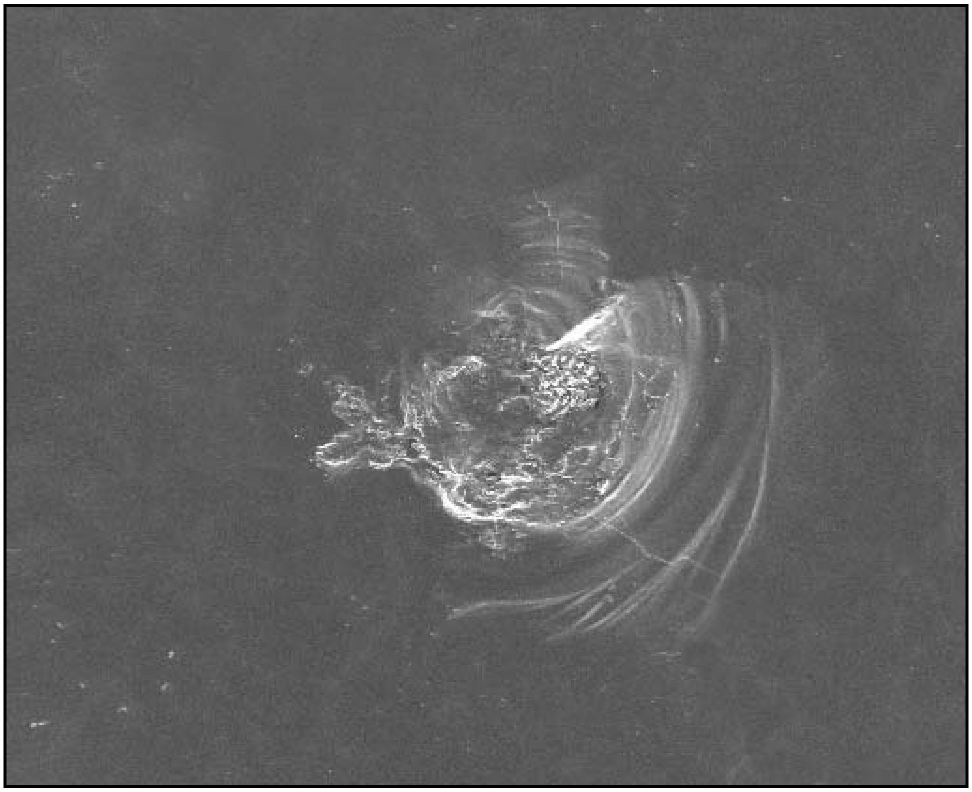


Figure 7. SEM image from the dental mold sample taken at window 2, PR 36.

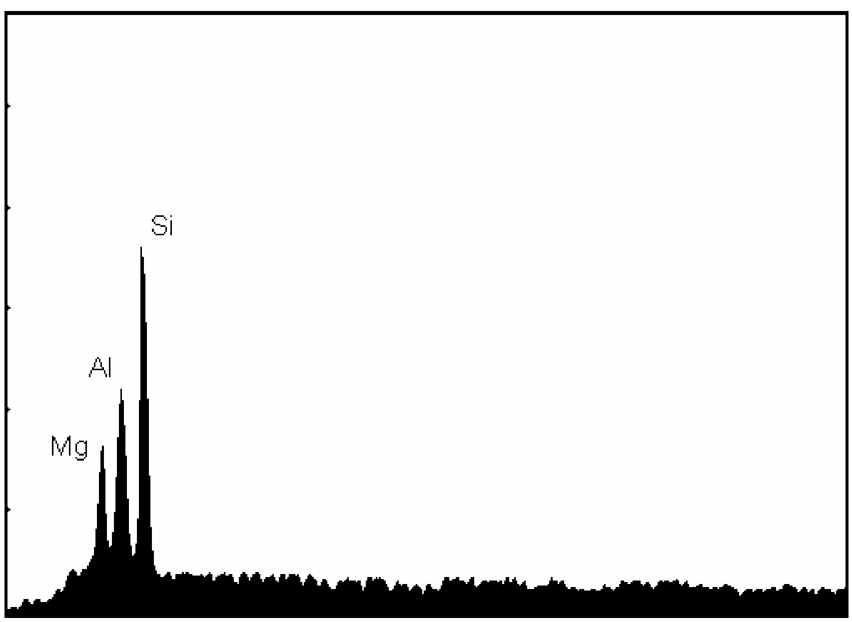


Figure 8. EDX spectra from the dental mold sample taken at window 2, PR 36. This impact was caused by an aluminum orbital debris particle.

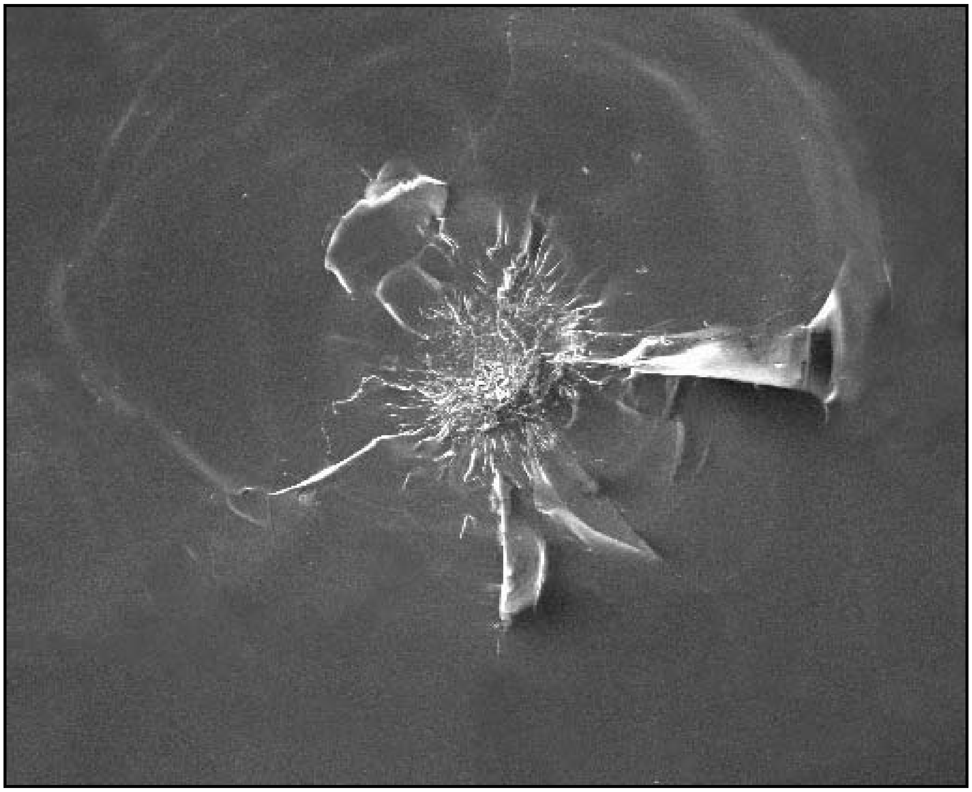


Figure 9. SEM image from the dental mold sample taken at window 4, PR 144.

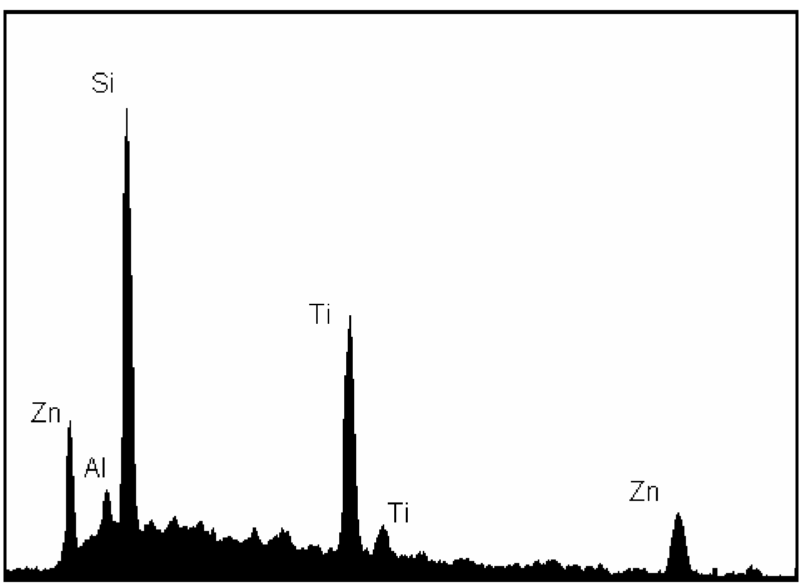


Figure 10. EDX spectra from the dental mold sample taken at window 4, PR 144. This impact was produced by an orbital debris particle of spacecraft paint.

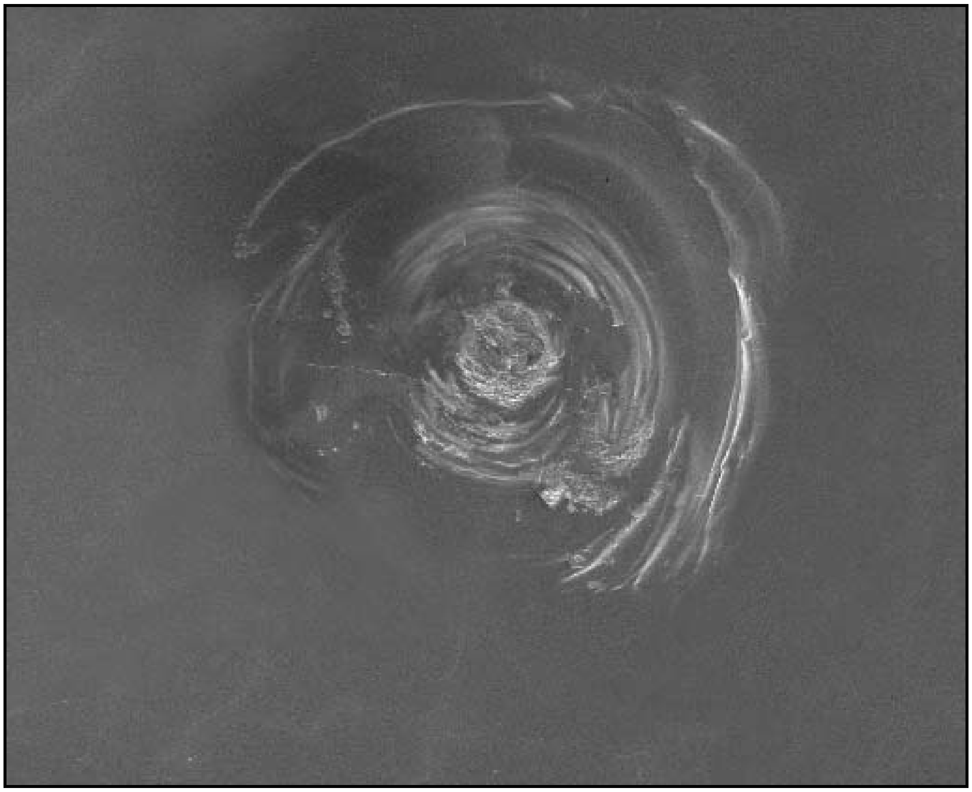


Figure 11. SEM image from the dental mold sample taken at window 5, PR 41.

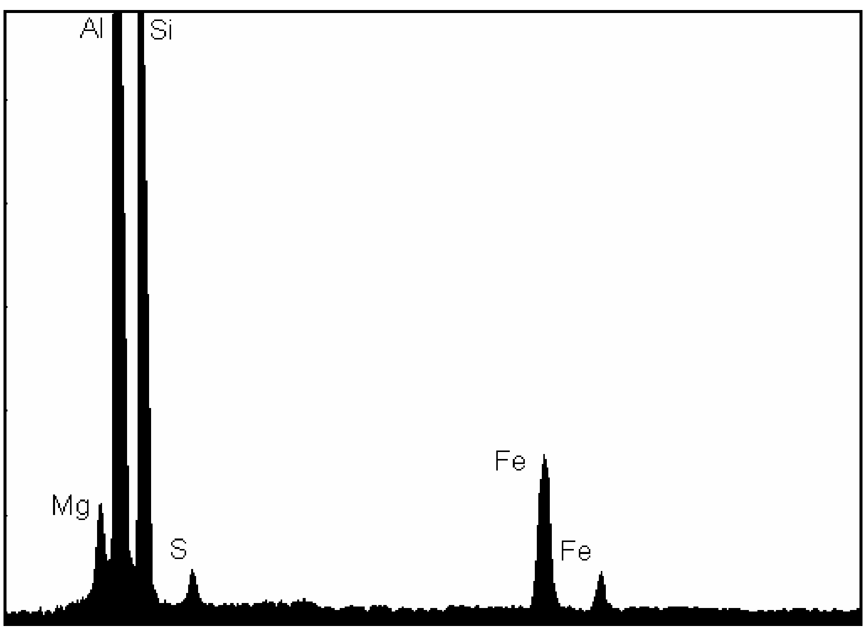


Figure 12. EDX spectra from the dental mold sample taken at window 5, PR 41. This impact was caused by a meteoroid particle.

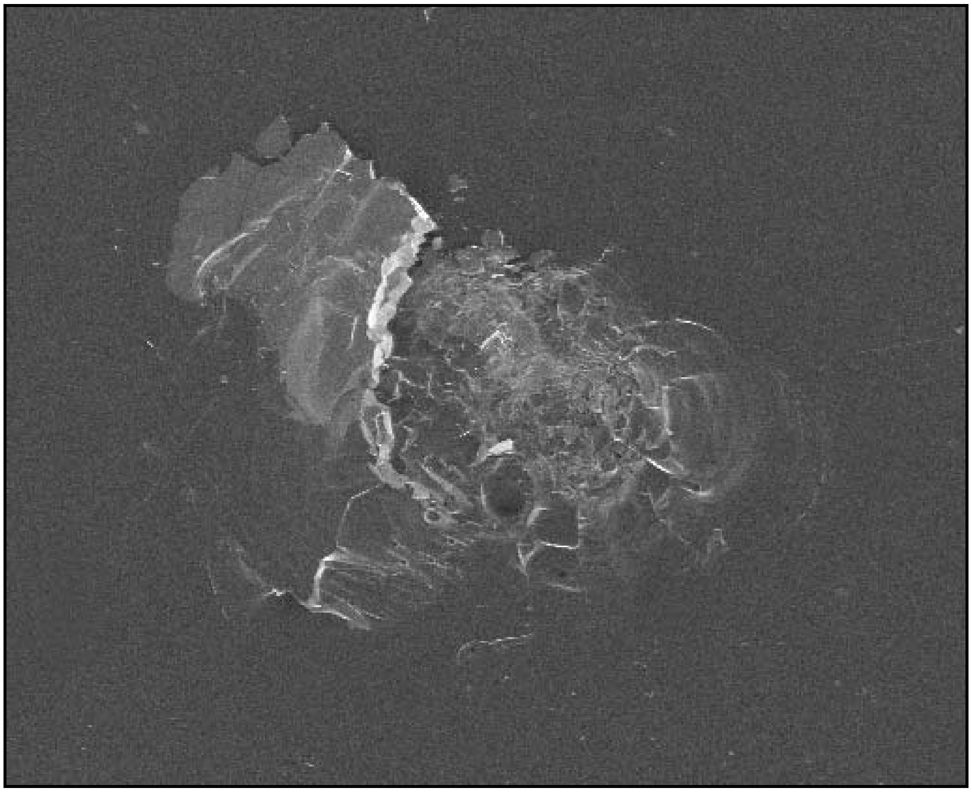


Figure 13. SEM image from the dental mold sample taken at window 6, PR 2.

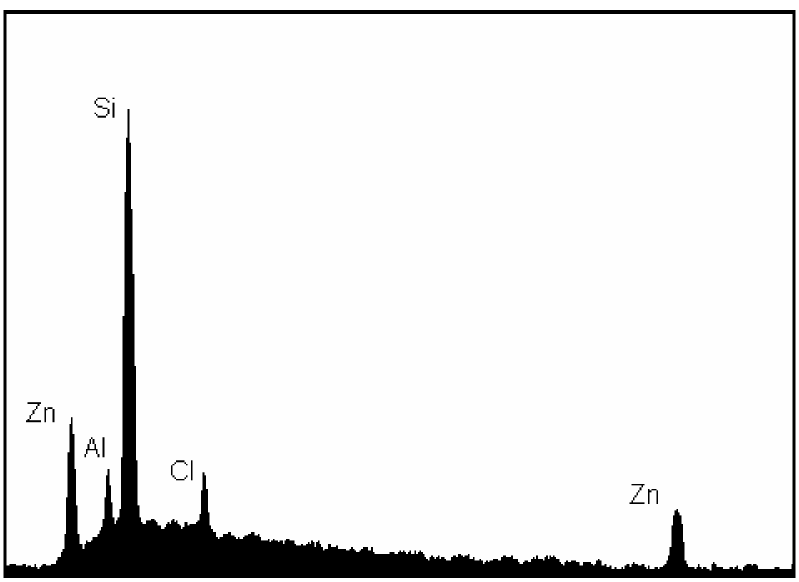


Figure 14. EDX spectra from the dental mold sample taken at window 6, PR 2. This impact, from a particle of spacecraft paint, caused the window to be scrapped.

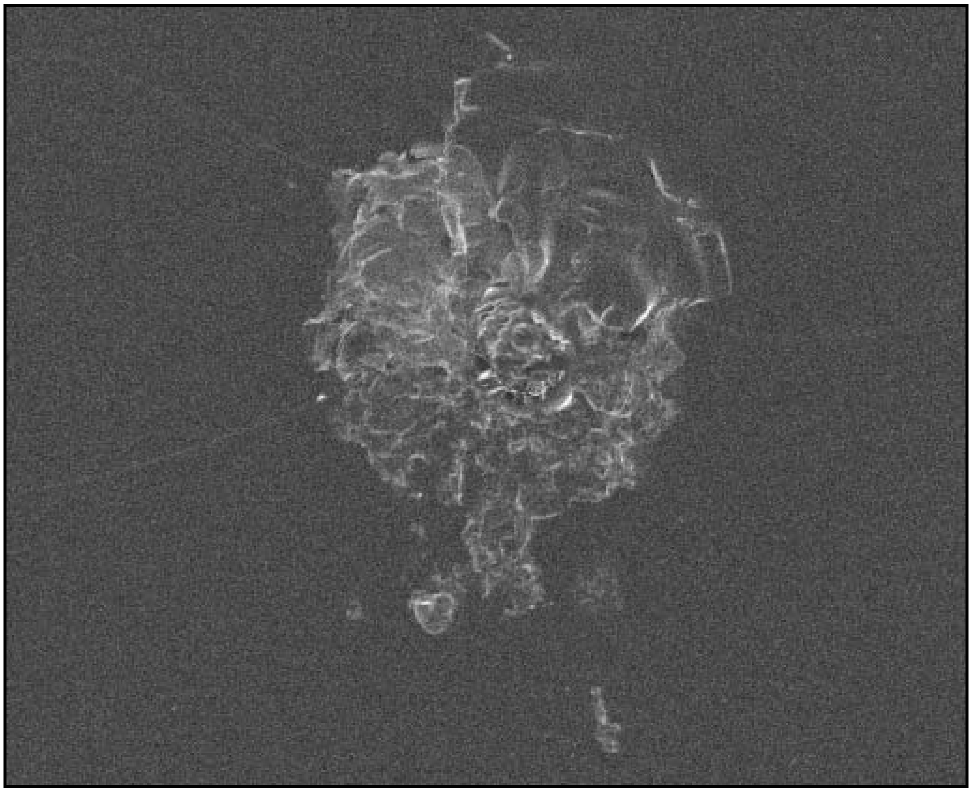


Figure 15. SEM image from the dental mold sample taken at window 8, PR 1.

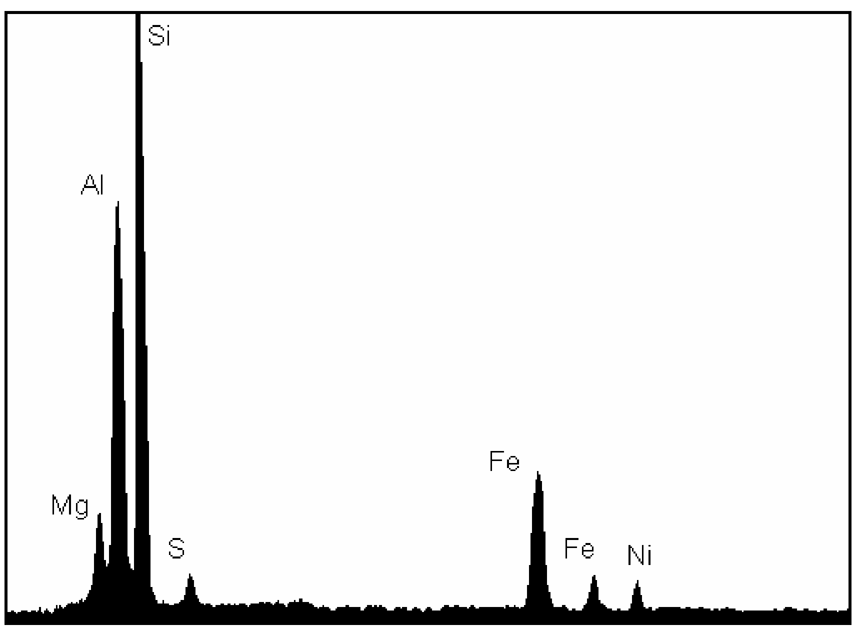


Figure 16. EDX spectra from the dental mold sample taken at window 8, PR 1. A meteoroid particle was the cause of this window replacement.

Table 2. STS-111 Window Damage

Window	PR#	Crater Dimensions (LxWxD) (mm)					Estimated Impactor Diameter (mm)	Estimated Impactor Length (mm)	SEM/EDXA Results
1									No PR's[1]
2	30	0.335	x	0.330	x	0.038	0.025	0.019	Meteoritic: (Al, Si, Mg, Fe)
2	36	0.350	x	0.350	x	0.062	0.025	0.033	Orbital Debris: Alum (Al, Mg)
3	5	0.310	x	0.300	x	0.043	0.024	0.021	Unknown[2]
3	7	0.840	x	0.840	x	0.076	0.050	0.036	Meteoritic: (Si, Al, Mg, Fe)
3	9	0.360	x	0.350	x	0.044	0.026	0.022	Unknown[2]
3	10	0.300	x	0.300	x	0.037	0.023	0.018	Unknown[2]
3	12	0.380	x	0.370	x	0.043	0.027	0.021	Unknown[2]
3	13	0.440	x	0.420	x	0.055	0.021	0.018	Orbital Debris: Stainless Steel (Fe, Ni, Cr)
4	144	0.300	x	0.300	x	0.043	0.022	0.023	Orbital Debris: Paint (Ti, Zn, Al, K)
4	145	0.380	x	0.380	x	0.056	0.028	0.027	Unknown[2]
4	150	0.420	x	0.410	x	0.051	0.030	0.025	Unknown[2]
4	160	0.480	x	0.480	x	0.048	0.032	0.026	Orbital Debris: Paint (Zn, Ti, Na, Cl)
4	169	0.280	x	0.280	x	0.040	0.022	0.020	Unknown[2]
4	178	0.290	x	0.285	x	0.043	0.023	0.021	Unknown[2]
4	193	0.510	x	0.500	x	0.069	0.034	0.033	Unknown[2]
5	41	0.430	x	0.430	x	0.056	0.030	0.027	Meteoritic: (Al, Mg, Fe, S)
5	44	0.280	x	0.280	x	0.028	0.022	0.014	Unknown[2]
5	46	0.355	x	0.350	x	0.041	0.026	0.020	Unknown[2]
5	47	0.330	x	0.330	x	0.040	0.025	0.020	Unknown[2]
5	52	0.400	x	0.400	x	0.048	0.027	0.025	Orbital Debris: Paint (Ti, Zn, Cl)
5	64	0.330	x	0.330	x	0.064	0.025	0.031	Unknown[2]
5	69	0.320	x	0.320	x	0.038	0.024	0.019	Unknown[2]
5	74	0.350	x	0.350	x	0.046	0.026	0.023	Unknown[2]
6*	**2**	**0.635**	**x**	**0.600**	**x**	**0.028**	**0.037**	**0.014**	**Orbital Debris: Paint (Zn, Al, Cl)**
6	3	0.330	x	0.330	x	0.037	0.025	0.018	Unknown[2]
6	4	0.350	x	0.350	x	0.035	0.026	0.018	Unknown[2]
7									No PR's
8*	**1**	**0.275**	**x**	**0.270**	**x**	**0.025**	**0.022**	**0.013**	**Meteoritic: (Al, Mg, Fe, Ni, S)**
9									No PR's[1]
10									No PR's[1]
11	1	0.320	x	0.320	x	0.031	0.024	0.016	Meteoritic: (Fe, Ni, S)

NOTE:
1. Window inspected. No impact features > 250 microns
2. SEM/EDXA performed. No detectable projectile residue.
* Window replaced

M/OD Impacts on Payload Bay Door Radiators

Orbiter payload bay door radiators consist of eight panels divided into port and starboard, forward (1 and 2), and aft panels (3 and 4). Each radiator panel is a 4.6-m-by-3.2-m curved aluminum honeycomb structure 2.3-cm-(forward) and 1.3-cm-(aft)-thick with 0.028-cm-thick aluminum (2024-T81) facesheets. Silver-Teflon thermal control tape is bonded to the facesheet of the radiator panels. During the mission, Freon is pumped through aluminum tubes under the facesheet. The forward half of each radiator can be rotated to expose the lower surface (35.5 deg at the hinge line), although, in practice, thermal requirements seldom cause them to be deployed.

The relatively smooth surface of the radiator thermal tape allows the detection of holes as small as 1 mm in diameter to be detected by the KSC inspection teams. The large area (117 m^2) of exposed surface increases the likelihood of experiencing an impact event, and the relatively soft silver-Teflon thermal control coating of the radiators acts as an effective particle collector. Because the radiators are exposed to the on-orbit environment only while the Orbiter payload bay doors are open, damage from low-speed foreign objects impacting during launch and landing is not a factor in assessing radiator damage (figure 17). In addition, since the payload bay doors are closed prior to the Shuttle returning to Earth, existing impact damage to the radiators is protected from possible changes occurring during entry.

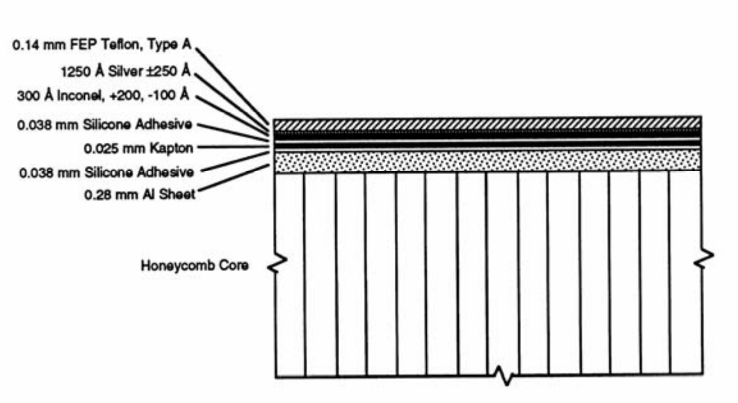


Figure 17. Cross section of the radiator panel and silver-Teflon thermal tape [Christiansen et al., 1998].

Aluminum orbital debris impactors are difficult to detect on the Orbiter radiators due to the strong aluminum "background" signature in the SEM/EDXA spectrum from the aluminum radiator facesheet; therefore, some of the "unknowns" are likely to be aluminum orbital debris particles.

The OV-105 vehicle (*Endeavour*) was flown with the payload bay door radiator M/OD upgrade installed for the STS-111 mission. Typically, the loss of a radiator coolant loop would cause a mission abort. This modification significantly mitigates the risk of a coolant tube penetration by attaching "doubler" plates to the radiator panel facesheets over each tube. This lowers the probability of an orbital debris or meteoroid penetration by presenting a thicker surface to the flux in the vulnerable area. Figure 18 illustrates the radiator doubler installation.

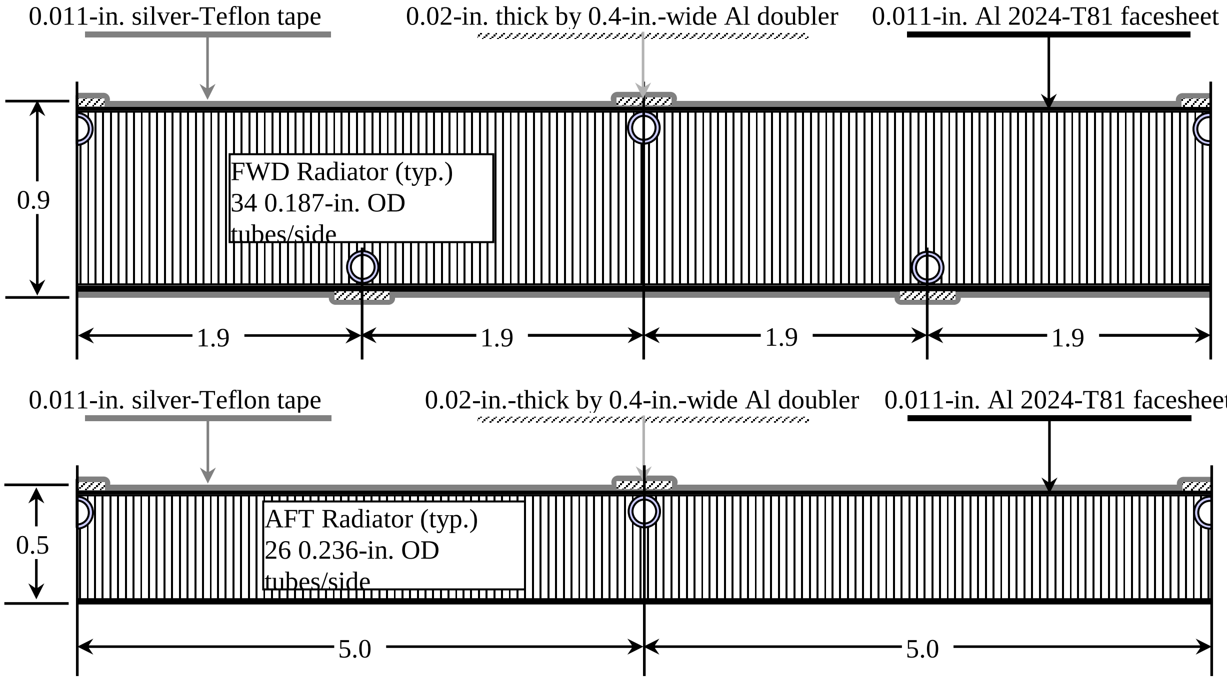


Figure 18. Payload bay door radiator M/OD upgrade.

The Shuttle Radiator Damage Database, which is found at http://hitf.jsc.nasa.gov [Hyde, 2002], can be used to extract details about each impact. The application can also be used to create damage maps of each radiator panel. Table 3 shows the "Damage Report" output from the site.

Table 3 also shows all 10 defects reported on OV-105 radiators after STS-111. The figure, which is shown below table 3, indicates the relative location of the single hypervelocity impact that was observed—a perforation of the facesheet in panel R3. The size of the damaged areas was determined initially by KSC inspection personnel and documented in a radiator PR. These damaged areas were confirmed by later measurement when actual samples of the damage became available (either radiator tape or mold impressions). The radiator inspection did not record the distance of the facesheet perforation to the closest doubler.

Table 3. Sample Output from Radiator Damage Database STS-111 (OV-105, Flow 19)

DAMAGE REPORT - All Damage Types — Number of Records: 10

Orbiter: OV-105 — Date: 08/19/03 — Time: 09:38 AM CST

Panel	Flow	Detected	ID No.	Defect Type	Surface	Location				Defect Dimensions X	Y	Diam	PR Number	Description	Date
5L1	19	V31-14195	5	1	T	A	5.0	C	54.0	0.5	0.75	0.0	2978061	Enter comments	05-Jul-02
5L3	19	V31-14195	6	1	T	A	12.0	H	43.0	0.0	0.0	0.05	2978061	Enter comments	05-Jul-02
5L3	19	V31-14195	7	1	T	A	13.0	H	42.0	0.0	0.0	0.05	2978061	Enter comments	05-Jul-02
5R1	19	V00-10072	4	2	T	F	74.0	C	30.0	0.0	0.0	0.01	MEQ-5-19-0793	Wiped with DI water and applied dot of MBO125-055 to area.	23-Sep-02
5R2	19	V31-14195	13	1	T	F	36.5	C	18.5	0.481	0.093	0.0	N/A	Smooth bottom dent, tape intact, not over freon tubeline. Depth=.004inch.	03-Jul-02
5R3	19	V31-14195	6	2	T	F	12.0	C	23.5	0.0	0.0	0.004	2978061	Enter comments	05-Jul-02
5R3	19	V31-14195	7	2	T	F	43.5	C	33.5	0.0	0.0	0.002	2978061	Enter comments	05-Jul-02
5R3	19	V31-14195	8	7	T	F	17.0	H	33.0	0.0	0.0	0.06	MEQ-5-19-0770		05-Aug-02
5R4	19	V31-14195	17	2	T	F	9.125	C	30.875	0.0	0.0	0.01	2978061	Enter comments	05-Jul-02
5R4	19	V31-14195	18	2	T	A	27.625	C	40.5	0.0	0.0	0.008	2978061	Enter comments	05-Jul-02

DEFECT TYPES: 1-Dent, 2-Tape Damage, 3-M/OD (legacy), 4-Stain, 5-M/OD (tape hole), 6-M/OD (facesheet crater), 7-M/OD (facesheet hole)

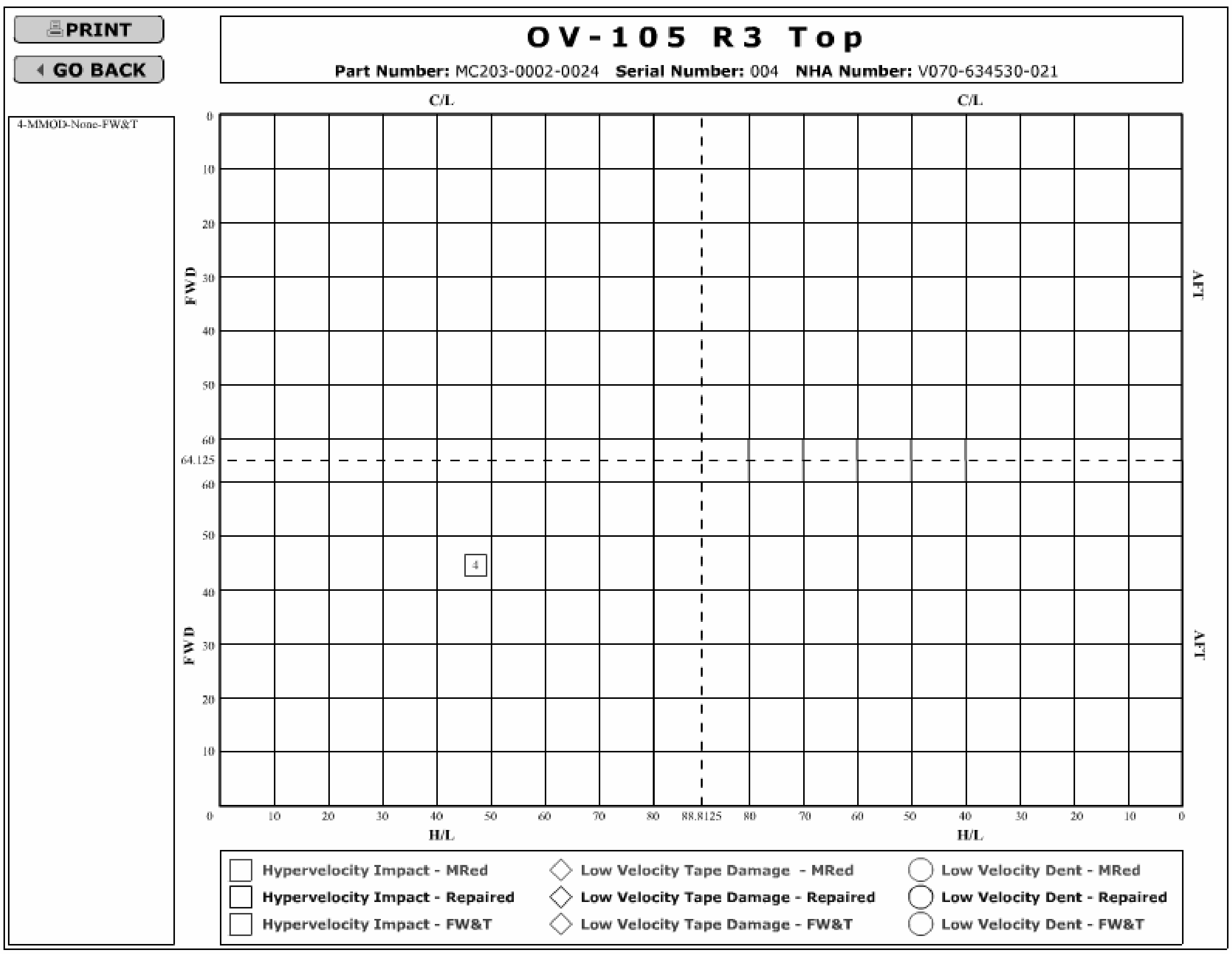


Table 4. STS-111 Radiator Silver-Teflon Tape and Facesheet Damage

Panel #	Sample #	Tape Hole Diameter (LxW) (mm)	Facesheet Damage (LxWxDepth) (mm)	Estimated Impactor Diameter (mm)	Impact into Doubler ?	Impact Thru Facesheet ?	SEM/EDXA Results
RH3	RH3-5	3.2 x 3.2	0.16 x 0.16 x hole	0.4	☐	☑	Meteoritic (Si, Fe, S, Ni)

M/OD Impacts on Payload Bay Door FRSI

Approximately 70 percent of the exterior of the payload bay doors are covered with FRSI, which consists of a Nomex felt pad and white rubberized coating. Figure 19 provides an idealized cross section of the payload bay door FRSI lay-up.

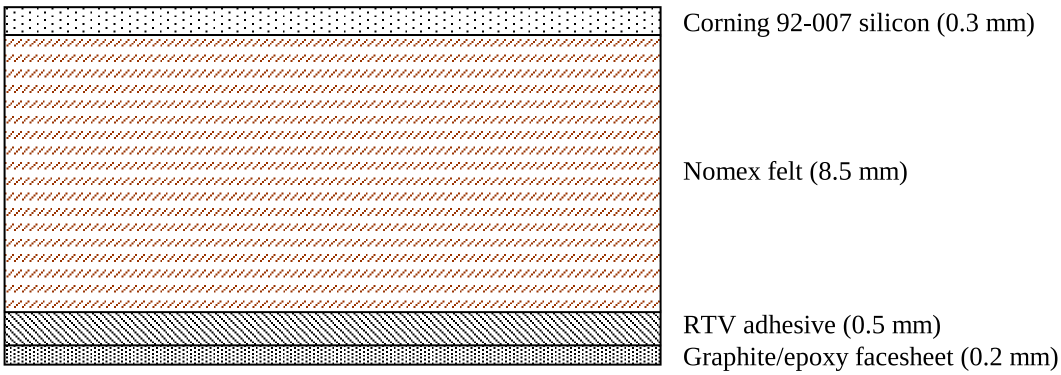


Figure 19. Payload bay door FRSI cross section.

Table 5 details the two impacts greater than 1 mm in diameter that were detected on the exterior of the payload bay doors. Samples were obtained at both locations. One sample yielded evidence of an aluminum impactor on the site, while analysis on the other site revealed no conclusive evidence of foreign object.

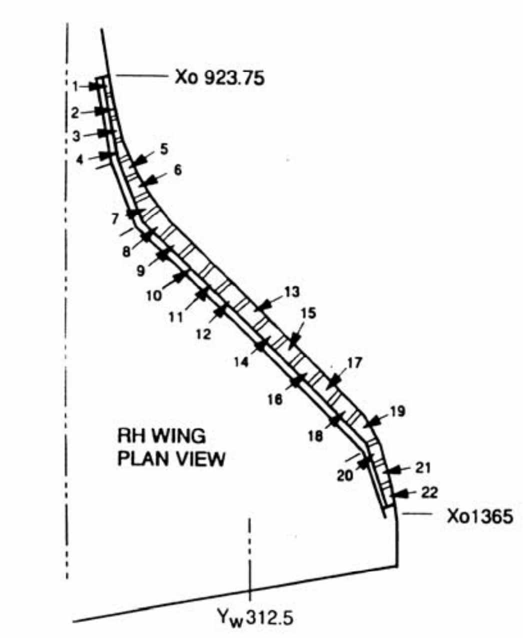
Table 5. STS-111 Payload Bay Door FRSI Damage

Location	Damage (LxWxDepth) (mm)	Estimated Impactor Diameter (mm)	SEM/EDXA Results
LH panel 1	1.3 x 1.1 x 1.5	0.2	Orbital Debris (Al)
RH panel 2	1.1 x 1.3 x 1.8	-	Unknown

M/OD Impacts on Wing Leading Edge Reinforced Carbon-Carbon

The Orbiter RCC consists of a carbon substrate coated on both sides with silicon-carbide. Figure 20 shows the location convention for the panels. A schematic of the wing leading edge RCC is presented in figure 21. Because the RCC panels experience intense aero-heating during entry, impact crater geometry can be altered and impact deposition products lost. No RCC impacts were recorded after the STS-111 mission.

RCC is a structural composite used as the thermal protection system (TPS) for high-temperature areas of the Orbiter. These areas include the wing leading edge (shown here), the nose cap, an area between the nose landing gear door and nose cap “chin panel,” and a small area surrounding the forward attach fitting of the Orbiter external tank. Most of the RCC is in the wing leading edge panels (40.6 m^2). Each panel is numbered as shown here, with an LH (port) or RH (starboard) to designate left or right wing, respectively. RCC typical overall thickness is 6.3 mm, consisting of 4.3-mm-thick to 5.3-mm-thick all-carbon substrate (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-thick to 1.0-mm-thick silicon-carbide layer formed in a diffusion reaction process [Christiansen, et al., 1998].



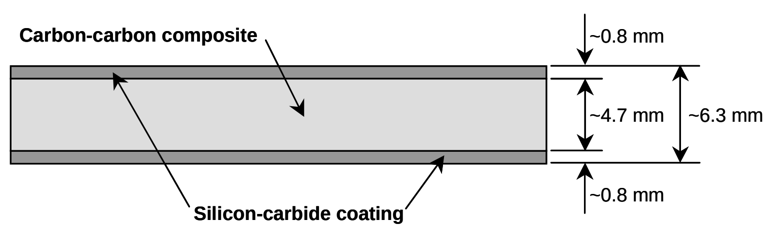


Figure 20. Orbiter wing RCC.

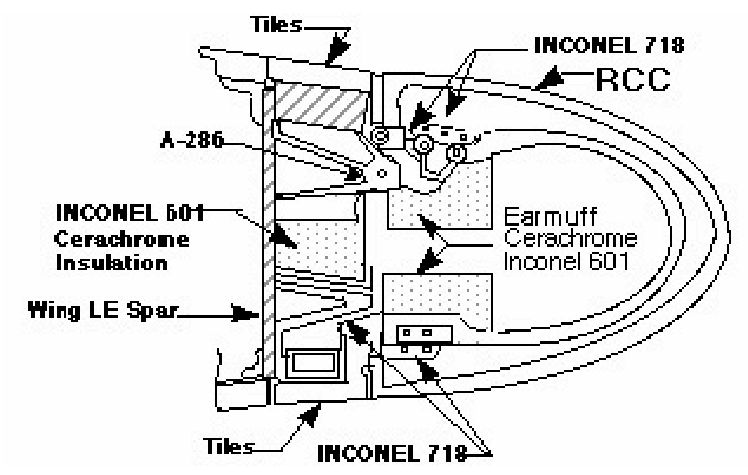


Figure 21. Wing leading edge RCC M/OD upgrade.

The STS-111 mission (OV-105) was flown with the wing leading edge RCC M/OD upgrade. The modification addressed the potential vulnerability of the wing leading edge attachment structure to entry heating due to an M/OD perforation of an RCC panel. It involves the installation of a layer of Nextel fabric to the Cerachrome insulation at the four locations where each RCC panel mounts to the wing leading edge spar structure. The modification permits the Space Shuttle Program to accept a larger diameter hole in the RCC panels, resulting in reduced critical penetration risk.

M/OD Impacts on Space Shuttle Main Engine Nozzle

During postflight processing at Stennis Spaceflight Center (SSC), a small hole was observed on Space Shuttle main engine-3 (SSME-3) nozzle 2030 tube 358 (SSC MR #700-3585). Figures 22 and 23 describe the general location of the impact site. The coolant tubes are constructed of nickel-plated A286 stainless-steel material, and have a wall thickness range of 0.010 in. to 0.012 in. in the area where the impact occurred. The crater displayed the distinctive morphology of a hypervelocity impact event, with a raised lip and a smooth bottom. It was located approximately 3 in. forward of the aft manifold. The impact crater measured 0.58 mm (0.023 in.) in diameter, and there was a 0.076-by-0.127-mm (0.003-by-0.005-in.) hole in the bottom of the crater. Figures 24 and 25 provide views of the impact crater.

Since there were no samples obtained from the impact site, the origin of impact is unknown, but the fact that a perforation occurred in the high-density nozzle tube material suggests that the impactor was not a low-density meteoroid. If the projectile was stainless steel (density = 8 g/cc), impacting with a velocity of 9 km/s and an impact angle of 45 deg, it would have had an estimated equivalent diameter on the order of 0.2 mm. A lower density aluminum particle (2.8 g/cc) at the same impact velocity and angle would have an estimated equivalent diameter on the order of 0.3 mm [Christiansen et al., 1998, equation (13), page 62].

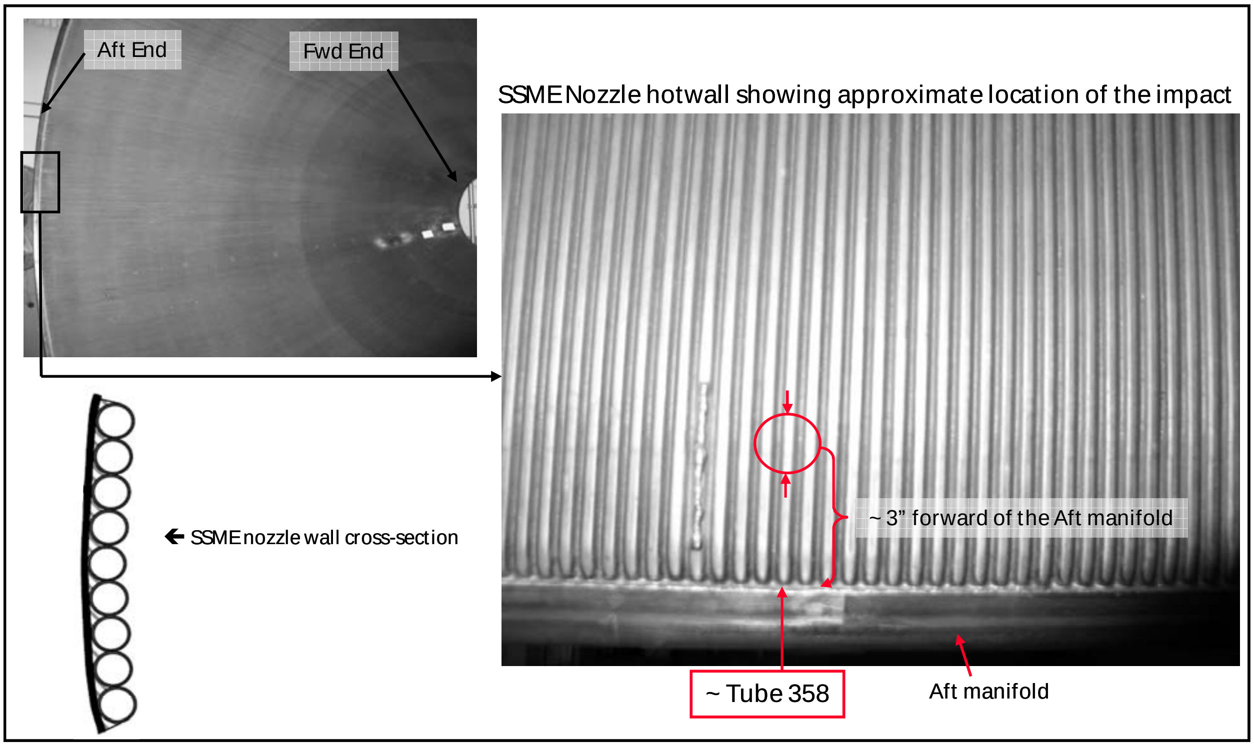


Figure 22. SSME nozzle impact location.

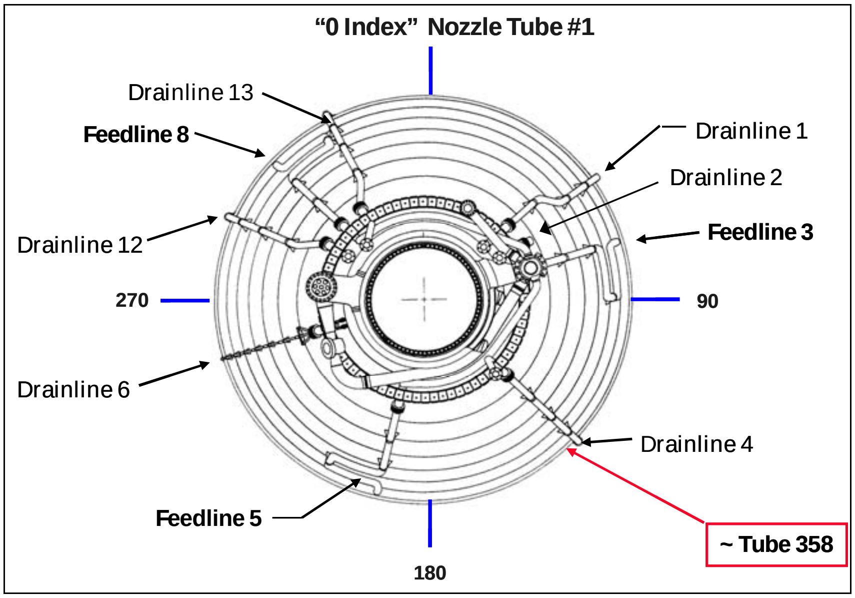


Figure 23. SSME nozzle tube 358 location.

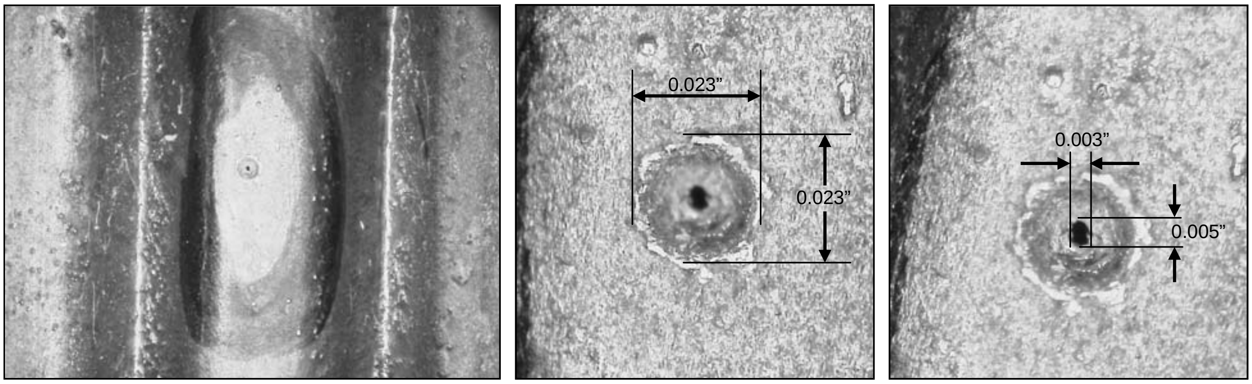


Figure 24. SSME nozzle tube 358 impact details.

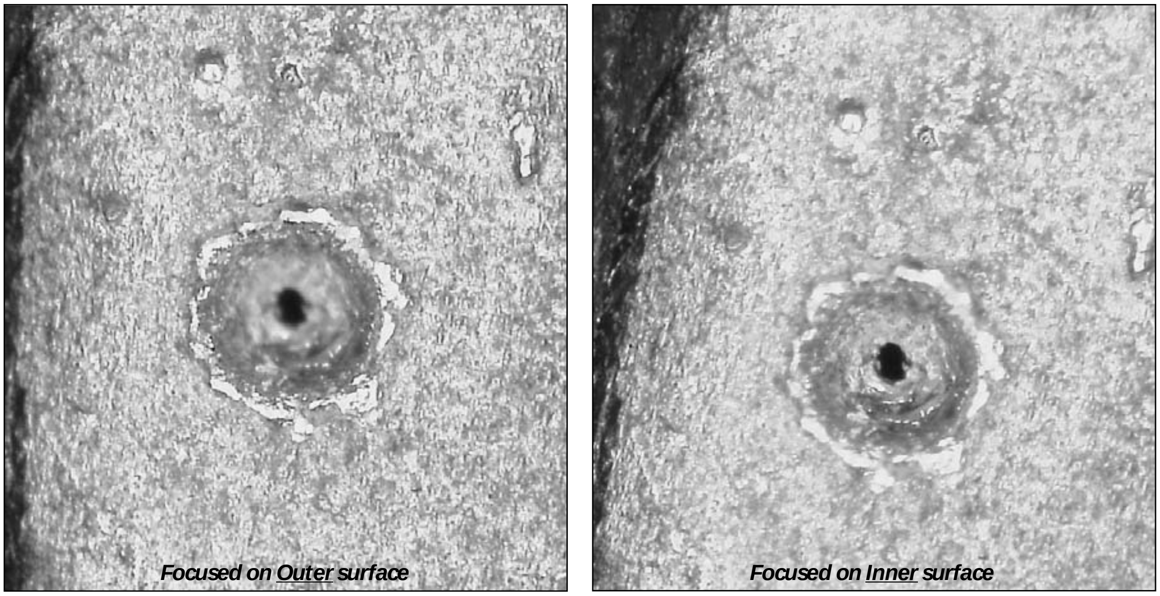


Figure 25. SSME nozzle tube 358 impact details.

STS-111 Postflight Summary

A survey of the Orbiter *Endeavour* (OV-105) exterior surfaces was conducted following the STS-111 mission. Table 6 provides a summary of the impact totals. After the STS-111 mission, two windows were removed and replaced with one from a meteoroid impact and the other from an orbital debris impact.

Only one impact was recorded on the payload bay door radiators, and it was a penetration of the facesheet. There were no hypervelocity impact sites detected on the wing leading edge RCC panels. Two impact sites were identified on the payload bay door FRSI.

There were no hypervelocity impacts detected on the Ku-band antenna or the deployed electronics assembly box. Additional areas inspected by JSC personnel included TPS blankets and tiles in the vertical stabilizer and orbital maneuvering system pod regions. No signs of hypervelocity impacts were observed in these regions.

Table 6. STS-111 Impact Damage Summary

Orbiter Region	Debris	Meteoroid	Unknown	TOTAL	Max. Diameter (mm)	
					Crater	Particle
Windows	6	5	17	28	0.84	0.05
Radiators	0	1	0	1	3.20	0.40
FRSI	1	0	1	2	1.20	0.15
RCC	0	0	0	0	---	---
SSME-3	0	0	1	1	0.58	---
	7	6	19	32		

STS-111 impact data have been added to the Shuttle Impact Database (figure 26) [Shuttle Hypervelocity Impact Database]. Note, a password is required to access the Shuttle Assessment Archive; please contact the author with account requests.

http://hitf.jsc.nasa.gov/hitfpub/shuttle/Reports/ShuttleImpactDB.xls

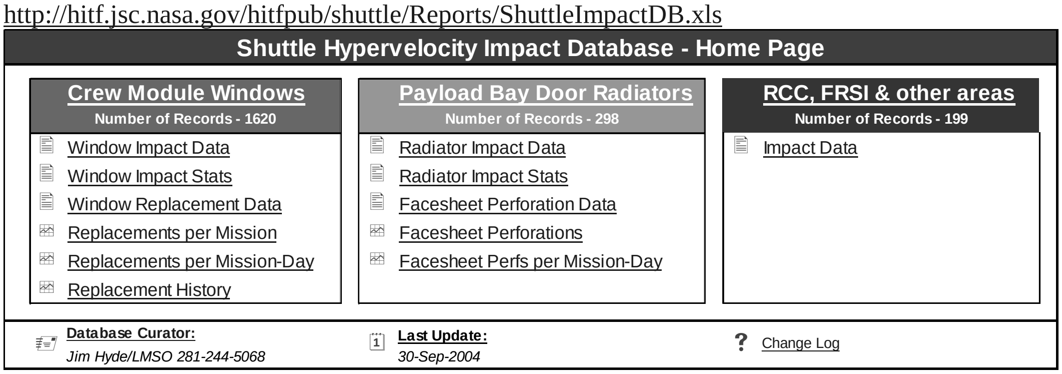


Figure 26. Shuttle impact database.

CHAPTER 2 – AS-FLOWN ASSESSMENT

Introduction

As part of the Agency's effort to characterize and evaluate the M/OD environment in low Earth orbit, postflight surveys of the Space Shuttle Orbiter are conducted to identify damage caused by hypervelocity impacts from M/OD. Personnel analyze samples extracted from the impact sites using an SEM equipped with EDXA spectrometers. Such techniques allow engineers to determine whether the impactor was a naturally occurring meteoroid or human-made orbital debris [Christiansen et al., 1998]. In addition, comparisons to HVI experiments allow engineers to determine the approximate size and impact velocity of the orbital debris. These data are used by the orbital debris program to validate the existing M/OD environment and to improve its fidelity. The postflight damage analysis in Section 1 of this document records M/OD impacts on the crew module windows, payload bay door radiators, payload bay door FRSI, and wing leading edge RCC panels. With sufficient forensic evidence, impactor chemistry can be discerned and, in turn, particle sizes can be estimated.

Prior to each Space Shuttle mission, a Flight Readiness Review (FRR) M/OD threat assessment is performed to determine critical penetration risk for the vehicle, radiator tube leak risk, and window replacement risk. Estimated values of M/OD analysis parameters, such as vehicle attitude, exposure time, and altitude, are used as inputs for the assessment [Shuttle Meteoroid and Orbital Debris Assessment Archive].

After each mission, an as-flown M/OD threat assessment can be made using actual attitudes, altitudes, and exposure times. While the as-flown analysis can be performed to assess the FRR products (critical risk, radiator leak, and window replacement), it can also be used to calculate the expected number of impacts on Orbiter regions from specific particle diameters. When these "analysis" diameters are coordinated with observed damage, predictions and observations can be compared.

This report draws upon the preflight FRR risk assessment, the postflight damage analysis, and the as-flown calculations to present four comparisons:

1. Preflight and as-flown risk predictions vs. postflight observations.
2. As-flown impact damage predictions vs. postflight observations for STS-111.
3. As-flown impact damage predictions vs. postflight observations for a family of missions.
4. M/OD damage on windows and radiators vs. Orbiter program history.

Analysis Procedure

The following section documents the assessment methodology that was used to produce the as-flown results. The complete analysis can be broken down into the following phases:

- Pre-processing – Collect and parse as-flown flight parameters.
- Calculation – Calculate risk assessment using the BUMPER code.
- Post-processing – Merge output files and observed data.

Pre-processing

The pre-processing phase leverages orbit parameters with new postflight data to create a mission profile that is used as input for the BUMPER risk assessment code. The STS-111 postflight M/OD risk assessment was performed using as-flown data obtained from the following sources:

- Mission Event List – https://ssveo.jsc.nasa.gov/mel/evpage2.htm
- Attitude Timeline (ATL) – JSC Orbiter Data Reduction Center (ODRC)

As-flown ATLs were generated from ODRC quaternion data that were provided by the JSC Space Shuttle Vehicle Engineering Office. These ATLs were written to a resolution of 300 seconds, which means that the Orbiter's attitude was defined in 5-minute time steps throughout the mission. The timeline files for each mission were imported into an Excel spreadsheet that performed a quaternion-to-Euler-angle conversion. Euler angle output from the spreadsheet is used as input for an ATL parsing program written in support of Shuttle FRR. The ATL parse program processes Orbiter roll-pitch-yaw Euler attitudes into a discrete number of local vertical local horizontal (LVLH) attitudes compatible with the BUMPER program. The parse program categorizes similar attitudes in user-specified bins according to two criteria: The first is “dead band,” which is the variability tolerance of each rotation angle that is used to describe an attitude. The second variable is the “cut-off time,” in minutes, defined as the time below which miscellaneous attitudes (those that do not fall into a bin with similar attitudes) are not categorized.

The product of the timeline parse program is multiple sets of attitude cases that are used in the BUMPER program. Multiple dead band/cut-off time value pairs were examined in an attempt to determine an efficient number of attitude cases while keeping the percent contribution of miscellaneous attitudes to a minimum. The “parsed” attitude timeline for the STS-111 as-flown assessment consisted of 55 discrete attitude cases spread out over three analysis groups with a total mission time of 19,855 minutes. The angle dead band was ±15 deg and the cut-off time was 10 minutes, yielded a 96.6-percent value for the “defined” attitudes. The remaining 670 minutes (3.4 percent) were equally distributed among the attitude groups. Please refer to Appendix A for a summary of the ATL Parse program output for the STS-111 assessment.

Table 7 provides a summary of the relevant analysis parameters that were used for the previously documented preflight FRR calculations and the postflight as-flown assessment that is the focus of this section. The primary differences between the preflight and postflight assessments can be found in overall mission duration and the number of Orbiter attitudes.

Table 7. STS-111 Assessment Details

STS-111 Mission Parameters	Assessment Type	
	Preflight FRR	As-Flown
Mission Duration	11d 16.4h 280.44h	13d 18.9h 330.92h
Pre-dock Altitude (%mission time)	398 km	296 km (12.8%)
Docked Altitude (% mission time)		389 km (57.4%)
Post-dock Altitude (% mission time)		370 km (29.8%)
Orbit Inclination	51.6 deg	
Flight Year	2002	2002
Solar Flux ($F_{10.7}$)	ORDEM2000 default	
Distinct Attitudes	24 LVLH	55 LVLH
Finite Element Models	orb_v6.13: Orbiter @SSw/MPLM on Node 1 orb_v6.14: Orbiter w/MPLM in payload bay	
Orbital Debris Environment	ORDEM2000	
Orbital Debris Particle Density Meteoroid Environment	constant, 2.8 g/cc SSP30425, Rev. B	
Meteoroid Particle Density	constant 0.5 g/cc	
Meteoroid Velocity Distribution	variable, SSP30425	
Meteoroid Showers	basic shower enhancement factor included in SSP 30425	

BUMPER code is used to calculate the number of M/OD impacts on radiators and windows from particles with diameters at or above the values shown in the bins labeled “All Dings” and “Bin Dings” in table 8. The impact predictions for these two bins are used in the comparisons with the postflight observations.

Table 8. STS-111 Meteoroid and Debris Particle Diameter Bins

	“All Dings” Bin	**“Big Dings” Bin**
Radiator	≥ 0.10 mm	≥ 0.40 mm
Window	≥ 0.01 mm	≥ 0.025 mm

Two finite element models were used in the as-flown assessment (figure 27). The "orb_v6.14" model was used in the beginning and ending phases of the mission, while the "orb_v6.13" version was used to model the middle phase of the mission.

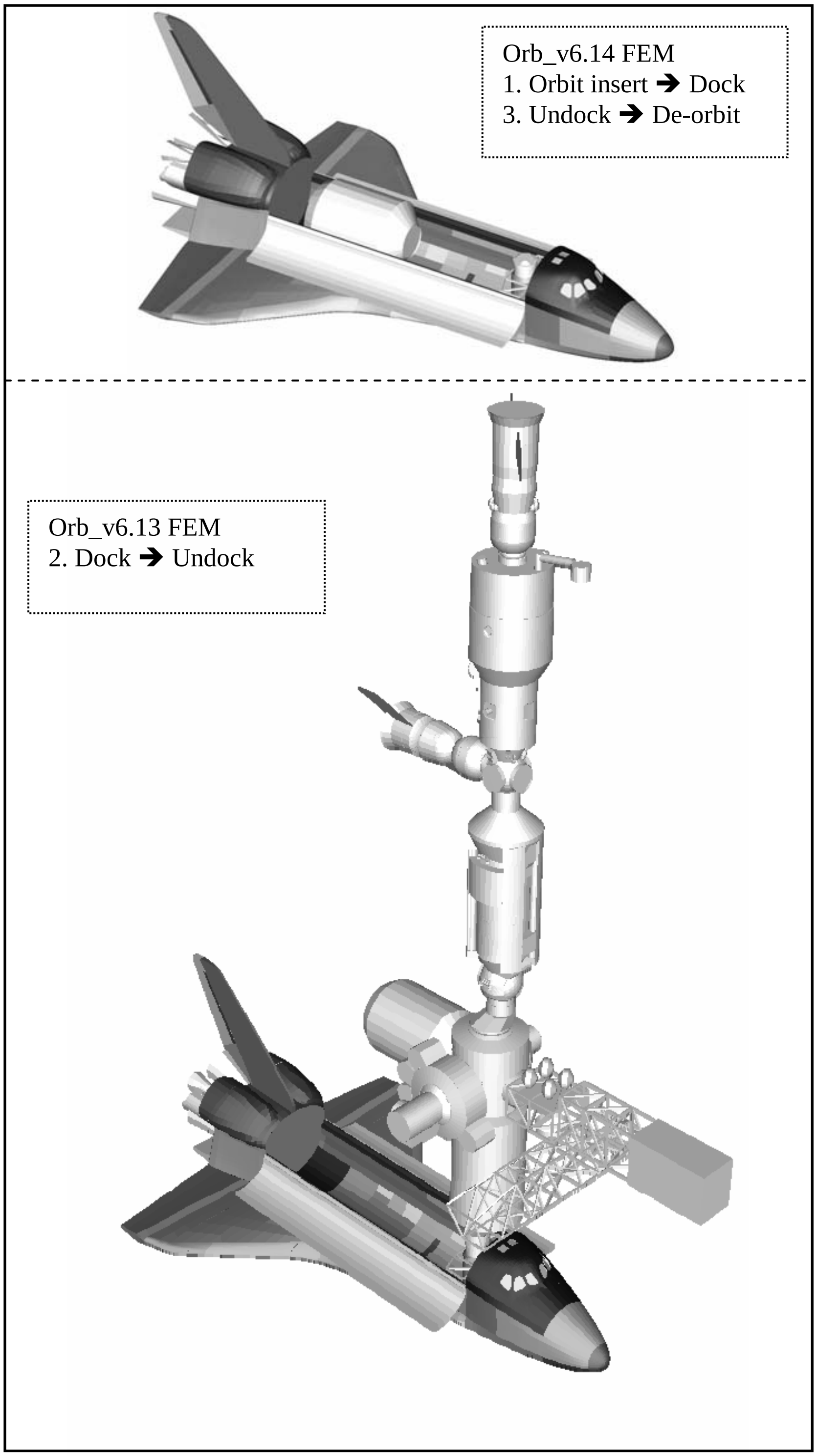


Figure 27. STS-111 as-flown assessment finite element models.

Calculation Details

The as-flown analysis was performed using BUMPER, an engineering analysis tool originally developed by Boeing for the Space Station Freedom Program. The code, which is configuration controlled at the JSC Hyper-velocity Impact Technology Facility (HITF), BUMPER is regularly updated to reflect the latest understanding of Orbiter material response under hypervelocity loading conditions [Hyde, 2001].

BUMPER is used to calculate M/OD impact risks to specific Orbiter surfaces. In particular, analysts determine normalized probability of no critical penetration, probability of no radiator leak, and number of expected window replacements for each attitude of interest. An integrated mission assessment is completed using Poisson statistics and knowledge of the distribution of times spent in each unique Orbiter attitude (attitude timeline) [Christiansen et al., 1992]. For additional detail, the Orbiter risk assessment process is defined in JSC ISO work instruction SN3-WI-003. Figure 28 provides an overview of the calculation process.

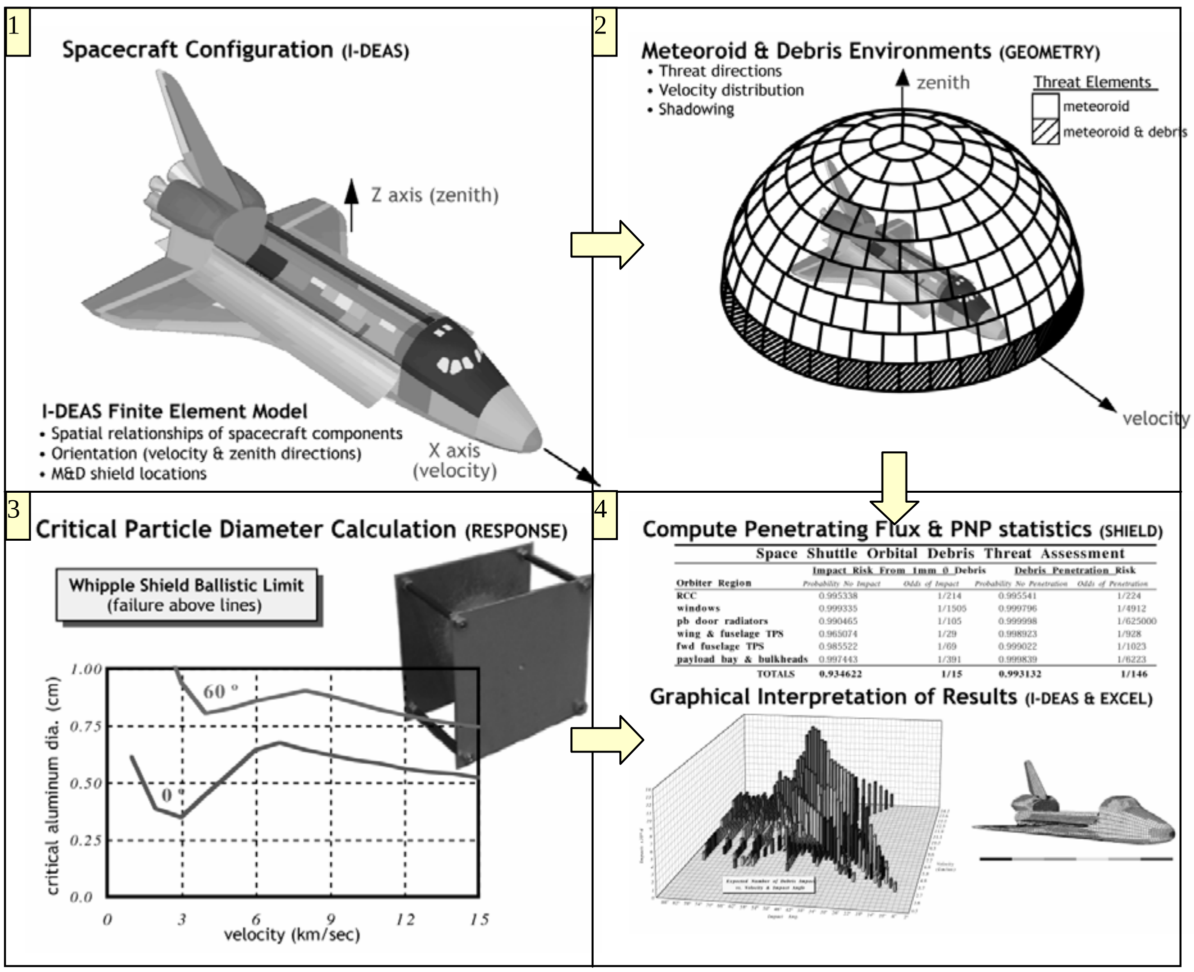


Figure 28. BUMPER code functional overview.

Post-processing

The post-processing phase brings together calculated risk values and postflight damage observations. Figure 29 illustrates the tasks that are performed in the post-processing phase of the assessment.

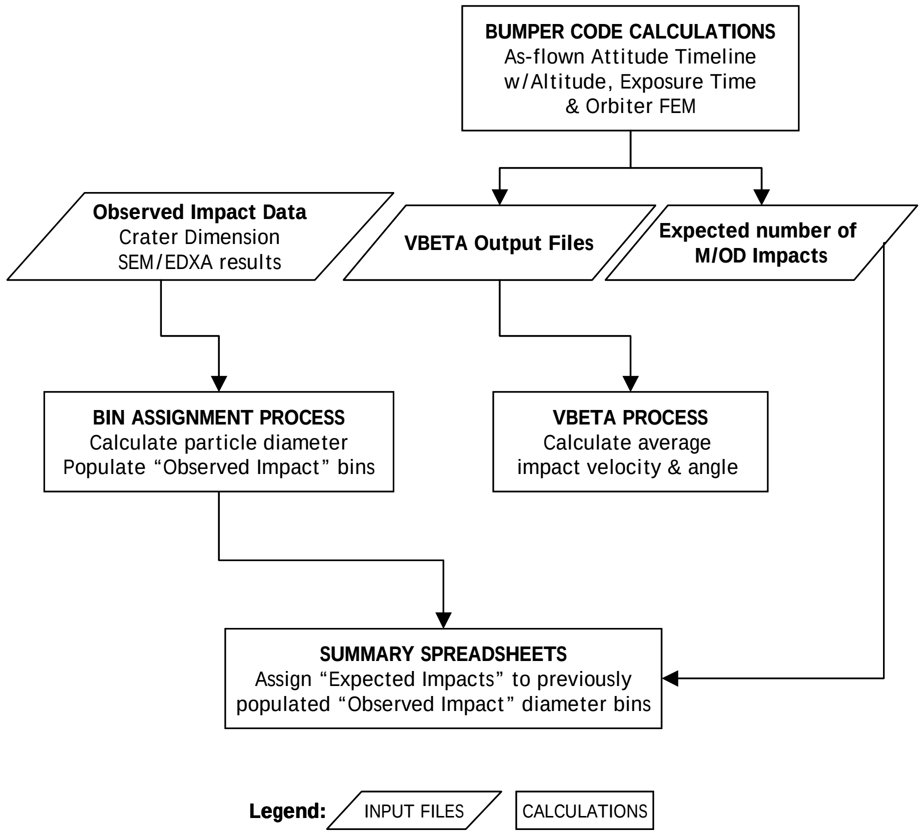


Figure 29. Post-processing workflow.

After the BUMPER code has predicted the number of M/OD impacts on radiators and windows, the following steps are involved in estimating a particle diameter from a crater size:

1. Determine impacting particle type (meteoroid or orbital debris) using SEM/EDXA results.
2. Assume particle density based on step 1.
3. Assign impact velocity and angle:
   - Meteoroids – Assume a velocity of 19 km/s and an angle of 45 deg (SSP-30425 Rev. B).
   - Debris – Use average velocity and angle output from BUMPER
4. Calculate particle diameter using the following penetration equations:
   - Windows – equation 2 (Christiansen et al., 1998, page 60)
   - Radiators – equation 6 (Christiansen et al., 1998, page 61)

The penetration equations are derived from a database of HVI test results on Orbiter materials. The HITF is conducting HVI tests on Orbiter fused silica and radiator panel samples; these tests are expected to improve the fidelity of the penetration equations.

Analysis Products

Preflight and As-Flown Risk Predictions vs. Postflight Observations

Table 9 compares preflight FRR predictions and as-flown assessment results with actual damage. Preflight and as-flown risks vary because of the increase in mission time and differences in altitude and attitude between the two assessments. The "Actual Damage" column shows that no critical impacts or radiator tube leaks were sustained during the STS-111 mission; it also shows that two windows were replaced after the mission due to HVI damage.

Table 9. Actual Damage vs. FRR Predictions and As-Flown Assessment Results

STS-111 M/OD Risk		FRR Prediction	As-Flown Assessment	% difference in risk	Actual Damage
Critical Penetration (Loss of vehicle and crew)	Probability of No Penetration Penetration Risk Odds of Penetration	0.9966 0.34% 1 in 290	0.9970 0.30% 1 in 334	-13%	no critical impacts
Radiator Tube Leak (Mission Abort)	Probability of No Tube Leak Tube Leak Risk Odds	0.9971 0.29% 1 in 343	0.9969 0.31% 1 in 326	5%	no tube leaks
Window Replacement	Replacement Risk Number of Replacements	60% 0.9	65% 1.0	8%	2

Note: two windows were replaced due to M/OD and there were no critical penetrations or radiator tube leaks

On the following page, figures 30 and 31 provide a comparison between the Orbiter attitudes used for preflight FRR assessments (based on the final edition of the attitude/pointing office's ATL) and the attitudes that were actually flown (based on ODRC data with a 5-minute reporting period). For comparison purposes, each as-flown and FRR attitude was generalized into one of 24 "cardinal" attitudes. These cardinal attitudes are the three Euler angles (roll, pitch, and yaw) that describe the vehicle's orientation in the LVLH reference frame in angular increments of 90 deg. The X-axis of the plots gives the local vertical (LV) and velocity vector (VV) orientations of the vehicle.

For each of the 55 as-flown attitude cases, the exposure time contribution was compared to the amount of critical risk that was contributed to the total mission risk. Every attitude case where the "%Risk/%Time" ratio was greater than 2.0 was flagged as "High Risk." Calculations indicated that, during the STS-111 mission, OV-105 did not spend any time in attitudes with ratios greater than 2.0. An examination of the final FRR attitude timeline showed that none of the planned attitudes exceeded the 2.0 risk ratio.

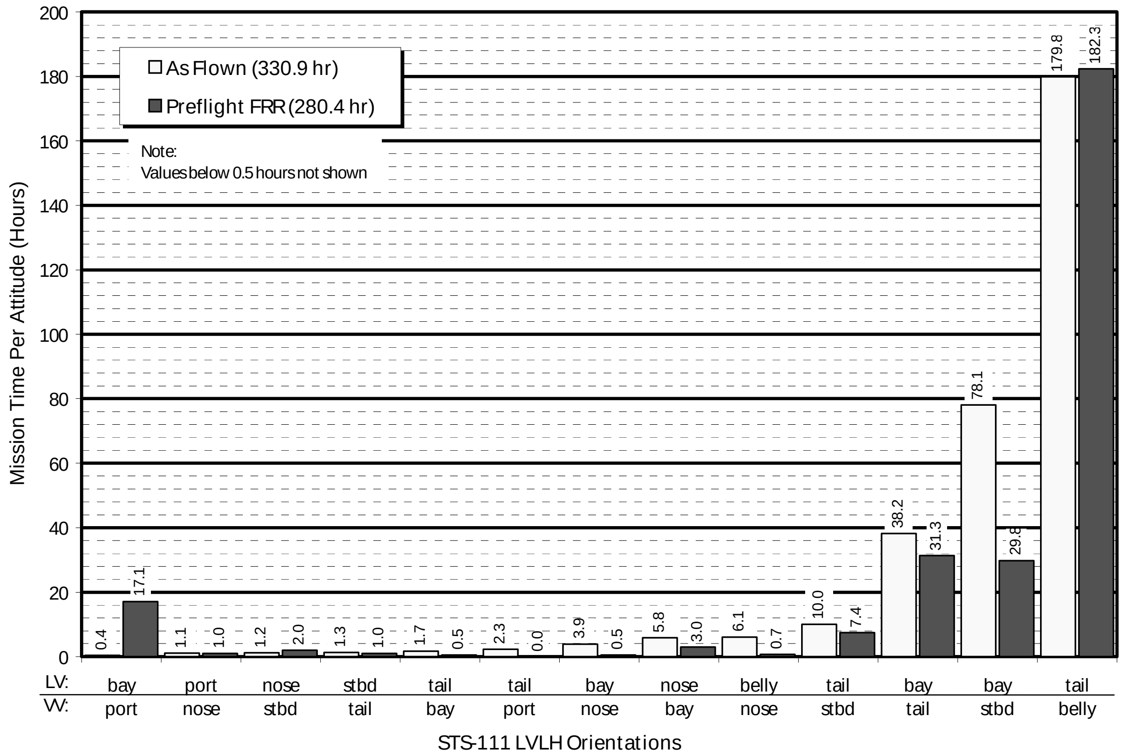


Figure 30. Preflight FRR and as-flown attitude comparison 1 – hours per attitude.

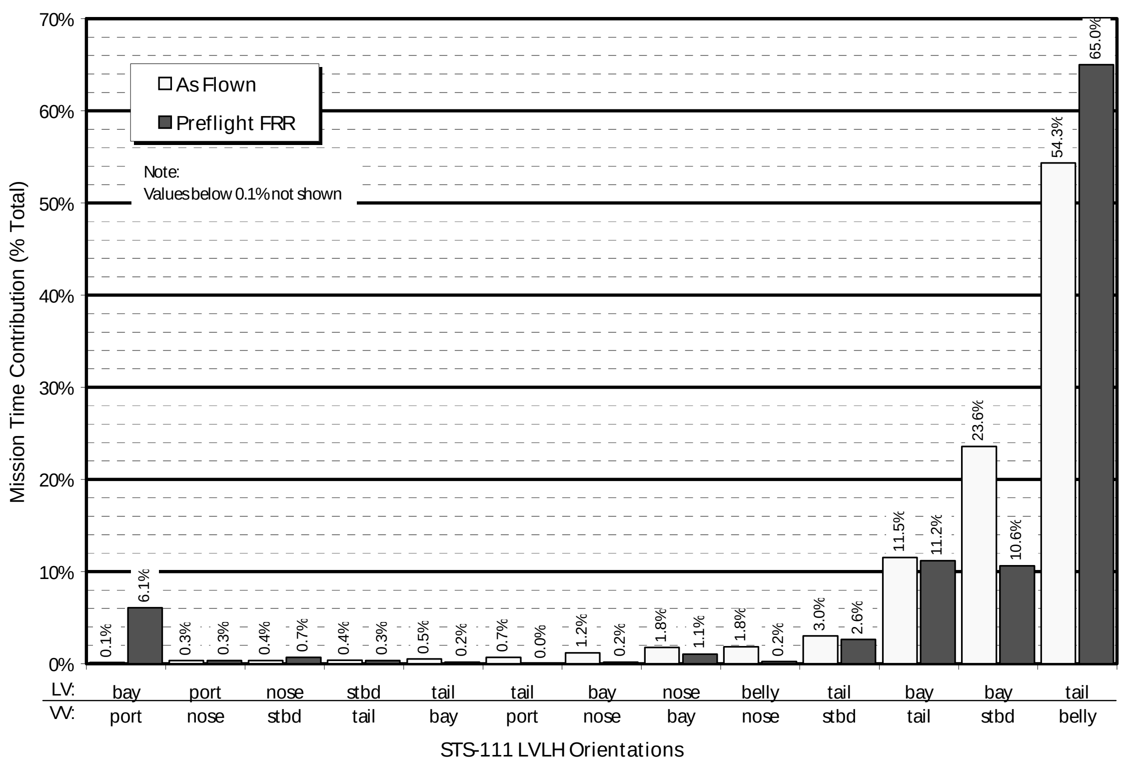


Figure 31. Preflight FRR and as-flown attitude comparison 2 – percent mission time per attitude.

As-Flown Impact Damage Predictions vs. STS-111 Postflight Observations

After the STS-111 mission, window and radiator regions of the OV-105 vehicle were examined for HVIs. This section compares actual M/OD damage to predicted values using the BUMPER code with as-flown STS-111 mission parameters as inputs.

One of the activities performed on sites with HVI damage characteristics is the collection of impactor deposition products from the craters. The residue is analyzed at JSC in an attempt to determine the source of the impacting particle. Identification is accomplished when the SEM/EDX spectra are successfully matched to known standards. The comparisons were made for impactors in two diameter bins. “Big Dings” for the radiator region were characterized by 0.4-mm-diameter particles, while the “Big Ding” particles diameter for the crew module windows was set at 0.025 mm. The “All Dings” bin had a radiator impactor diameter of 0.1 mm and a window impactor of 0.01 mm. The BUMPER assessment tool was used to calculate the expected number of impacts on the windows and radiators from M/OD particles at or above the diameter values in the “Big Dings” and “All Dings” diameter bins. Figure 32 shows the observed and predicted differences only for the STS-111 window impacts, since the radiator impact data were insufficient for a meaningful comparison.

Impact Type	Windows					
	"All Dings"			"Big Dings"		
	Predicted	*Observed*	*% Diff*	*Predicted*	*Observed*	*% Diff*
Meteoroids	5.8	5	14%	1.8	3	-67%
Debris	8.3	5	40%	2.4	2	17%
Unknown	*n/a*	17	n/a	*n/a*	4	n/a
TOTALS	**14.1**	**27**	**-92%**	**4.2**	**9**	**-114%**

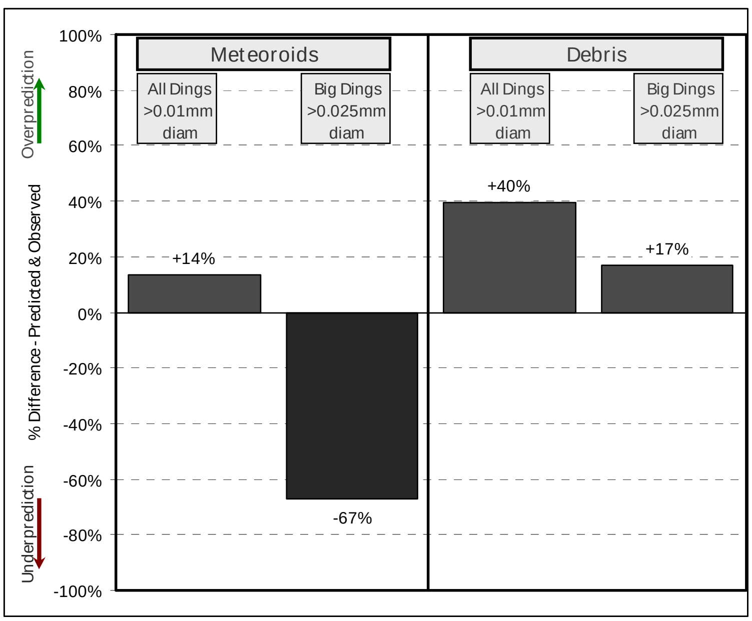


Figure 32. Comparison of observed and predicted M/OD impacts on STS-111 windows.

The single recorded impact is considerably less than the typical per-mission impact rate of six [Shuttle Hypervelocity Impact Database]. Overall, the window impacts predictions were less than observations. Both the “All Dings” and “Big Dings” particle diameter bins were under-predicted.

Table 10 compares the number of crew module window replacements calculated during the as-flown assessment to the number of scrapped windows. The table shows the replacement risk for each of the 11 windows. The table also indicates that the relative amount of replacement risk from M/OD. The replacement of W6 from a debris impactor matches the predictions well, but the replacement of window 8 was considerably less likely.

Table 10. Expected vs. Actual Window Replacements

Crew Module Window # (Location)	Replacement Criteria Crater Depth (cm)	EXPECTED NUMBER of REPLACEMENTS				ACTUAL REPLACEMENTS		
		Debris	Meteoroids	Total	Risk Distribution	Debris	Meteoroids	Total
1 (port side)	0.0069	0.22	0.06	0.28	23%	0	0	0
6 (stbd side)	0.0069	0.33	0.13	0.46	37%	**1**	0	**1**
2 (port mid)	0.0142	0.04	0.01	0.05	4%	0	0	0
5 (stbd mid)	0.0142	0.08	0.02	0.11	9%	0	0	0
3 (port fwd)	0.0185	0.02	0.01	0.03	2%	0	0	0
4 (stbd fwd)	0.0185	0.03	0.01	0.04	3%	0	0	0
7 (stbd over)	0.0076	0.02	0.01	0.03	2%	0	0	0
8 (port over)	0.0076	0.02	0.01	0.04	3%	0	**1**	**1**
9 (stbd aft)	0.2793	0.00	0.00	0.00	0%	0	0	0
10 (port aft)	0.2793	0.00	0.00	0.00	0%	0	0	0
11 (hatch)	0.2457	0.15	0.04	0.19	16%	0	0	0
	TOTALS	**0.92**	**0.31**	**1.23**		**1**	**1**	**2**
	Risk Distribution	75%	25%					

The as-flown assessment was also used to calculate the expected number of the perforations in the facesheets of the payload bay door radiators. Table 11 shows that one or two facesheet perforations were expected during the STS-111 mission (one was observed during the postflight inspection) and that a debris particle was more likely to cause a facesheet perforation. The port/starboard distribution was nearly equal.

Table 11. Expected vs. Actual Facesheet Perforations

Payload Bay Door Radiator Panel	RADIATOR FACESHEET PERFORATIONS					
	Expected			Observed		
	Debris	Meteoroids	Total	Debris	Meteoroids	Total
PORT	0.55	0.12	0.67 (40%)	0	0	0
STARBOARD	0.77	0.25	1.02 (60%)	0	1	1
	1.322 (78%)	0.372 (22%)	1.694	0	1	1

Impact Damage Predictions vs. Postflight Observations

Figure 33 compares the cumulative number of observed orbital debris impacts on the payload bay door radiators (plotted as points) to a curve that represents the predicted number of debris impacts.

The observed data, presented for a group of 30 Shuttle missions dating back to STS-50, are matched well by the prediction until the counts for the smaller particle diameters start tailing off. In this regime (less than 0.1 mm), the typical impact crater diameter is much less than the 1-mm field observation threshold (see table 1) making the recording of their existence less likely than craters produced by larger particles.

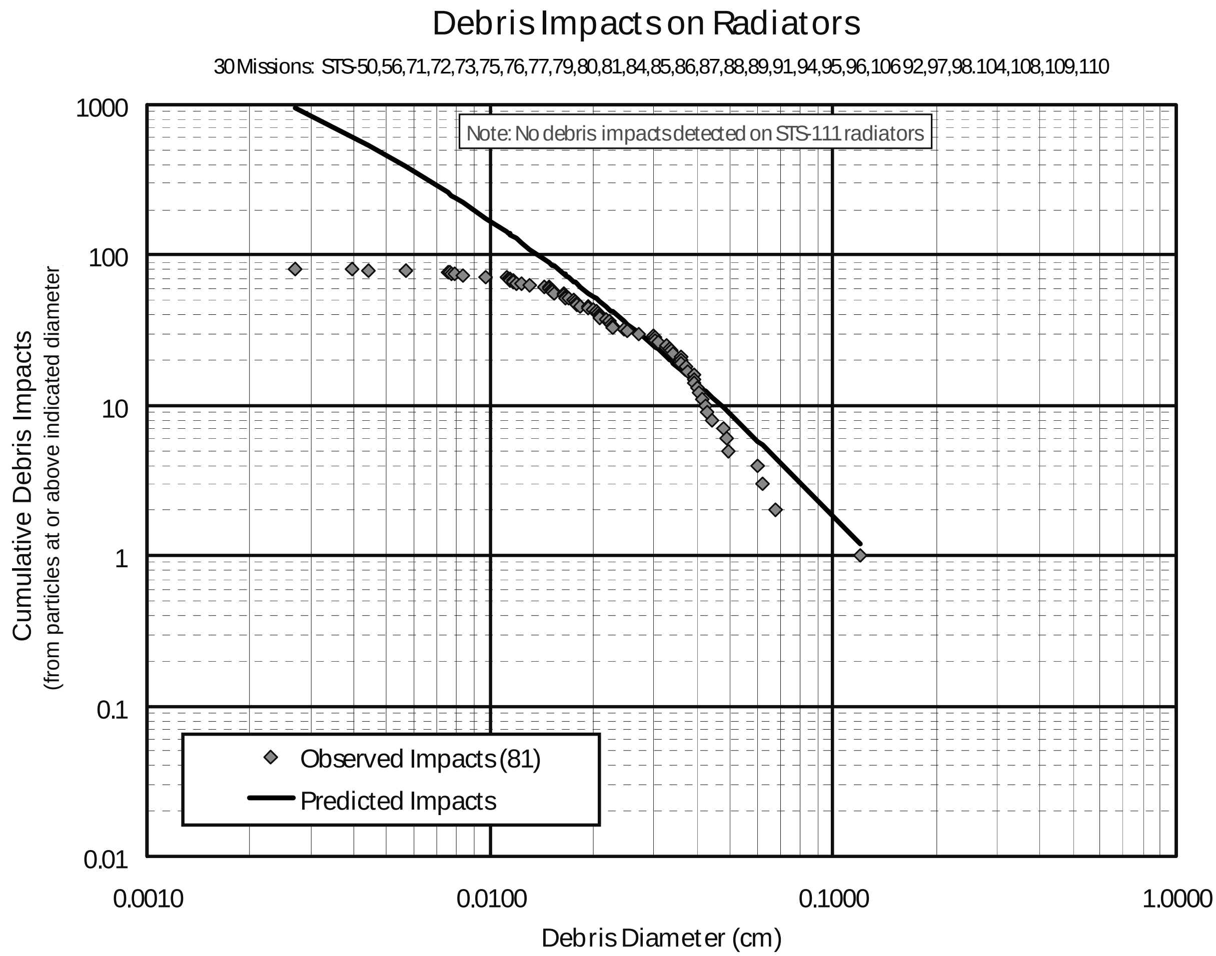


Figure 33. Observed vs. predicted radiator impacts (30 missions).

Figure 34 compares the cumulative number of observed orbital debris impacts on the crew module windows (plotted as points) to a curve that represents the predicted number of debris impacts. The observed data, representing a group of 30 Shuttle missions dating back to STS-50, are matched well by the prediction for all diameters.

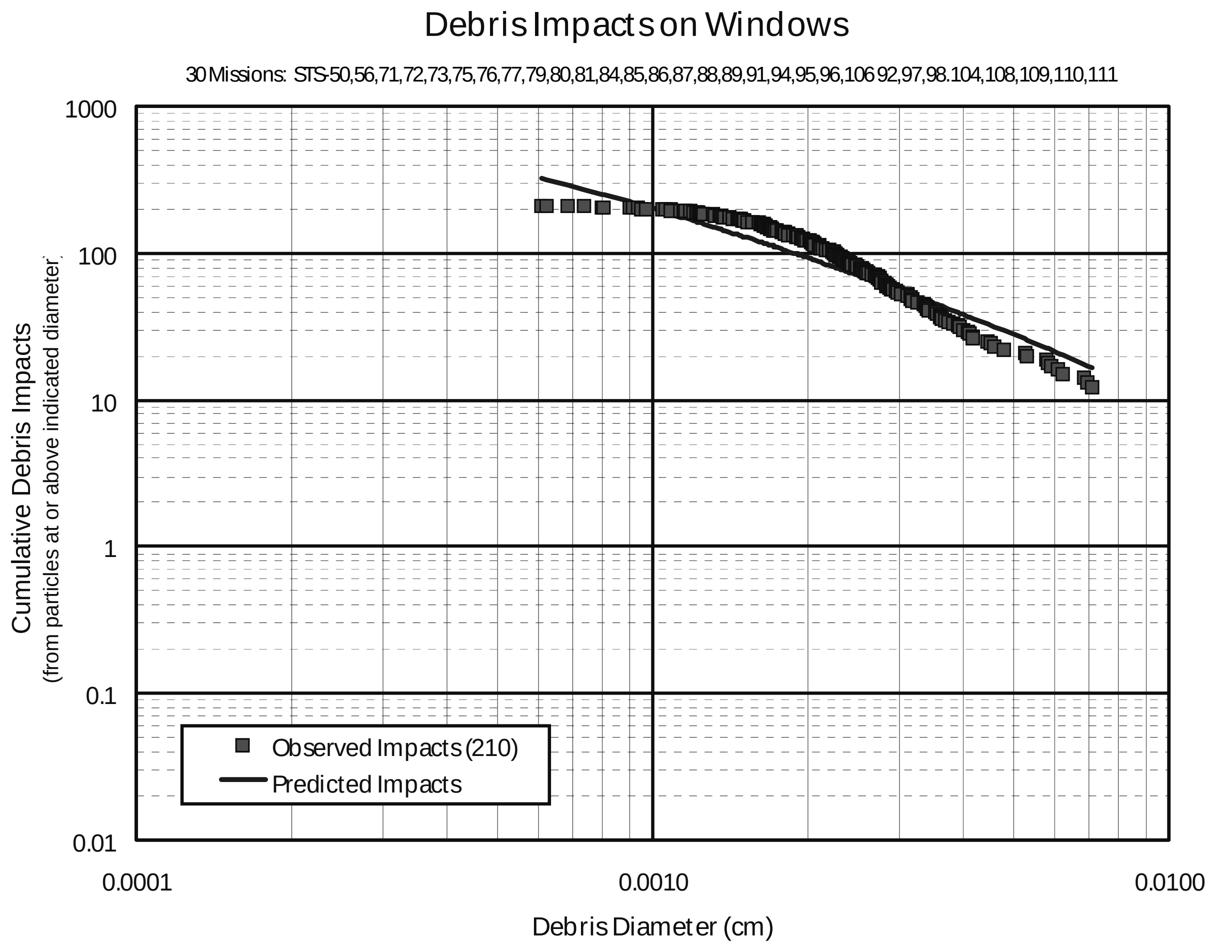


Figure 34. Observed vs. predicted window impacts (30 missions).

STS-111 M/OD Radiator and Window Damage vs. Program History

Figure 35 shows a plot of the number of recorded radiator facesheet perforations since STS-50. The results of the STS-111 inspection are highlighted. Figure 36 shows the number of facesheet perforations per mission day. A five-point moving average trend line is overlaid on both plots.

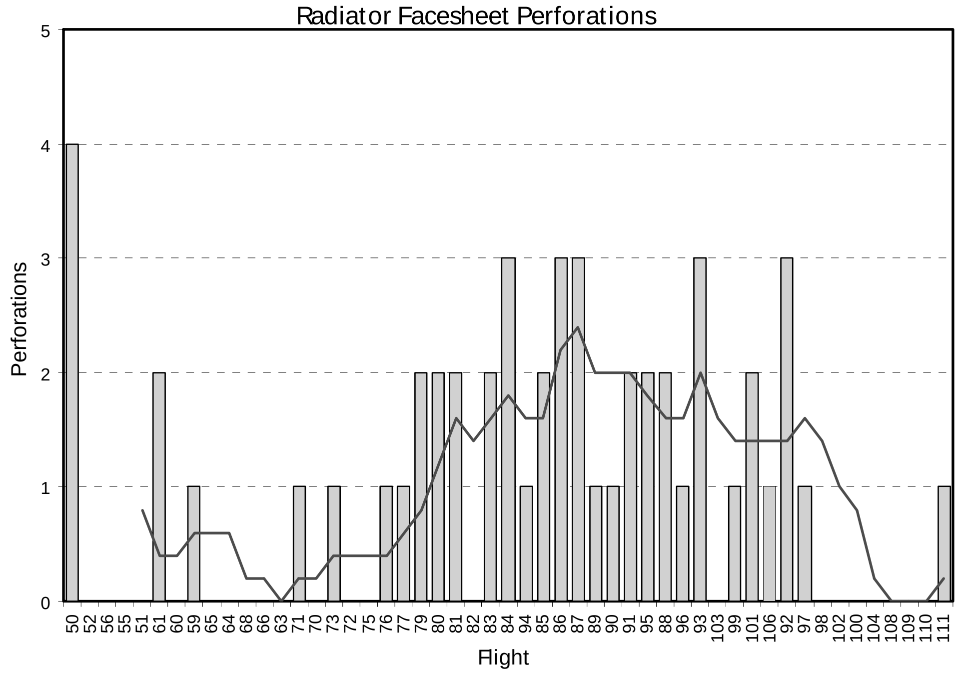


Figure 35. Radiator facesheet perforation history, 1992 – 2002 (51 flights).

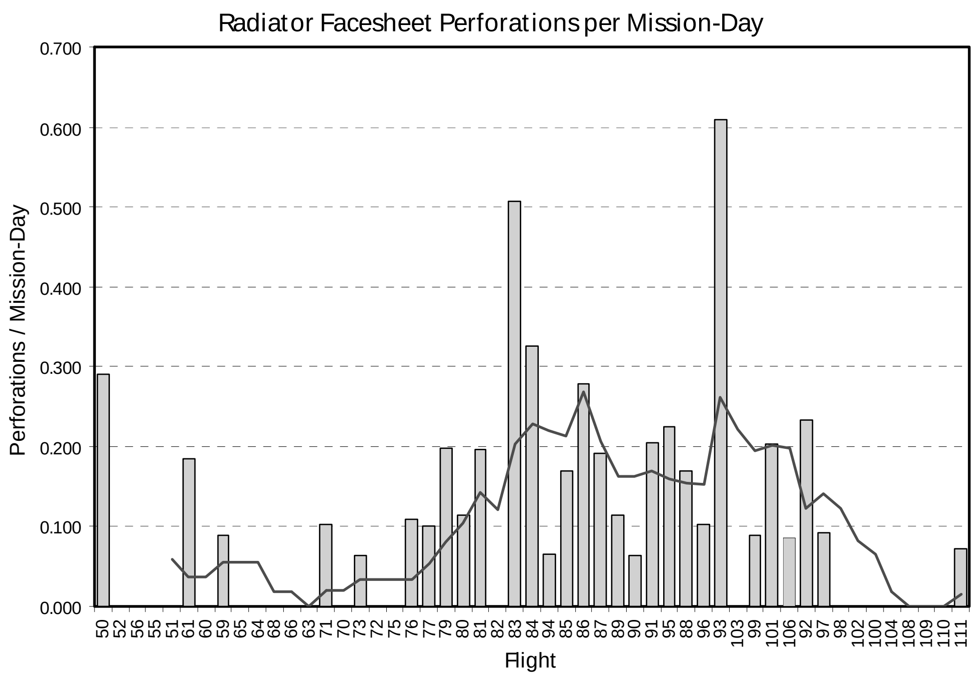


Figure 36. Radiator facesheet perforation rate, 1992 – 2002 (51 flights).

Figure 37 shows a plot of the window replacement history for the entire program, with the STS-111 results highlighted.

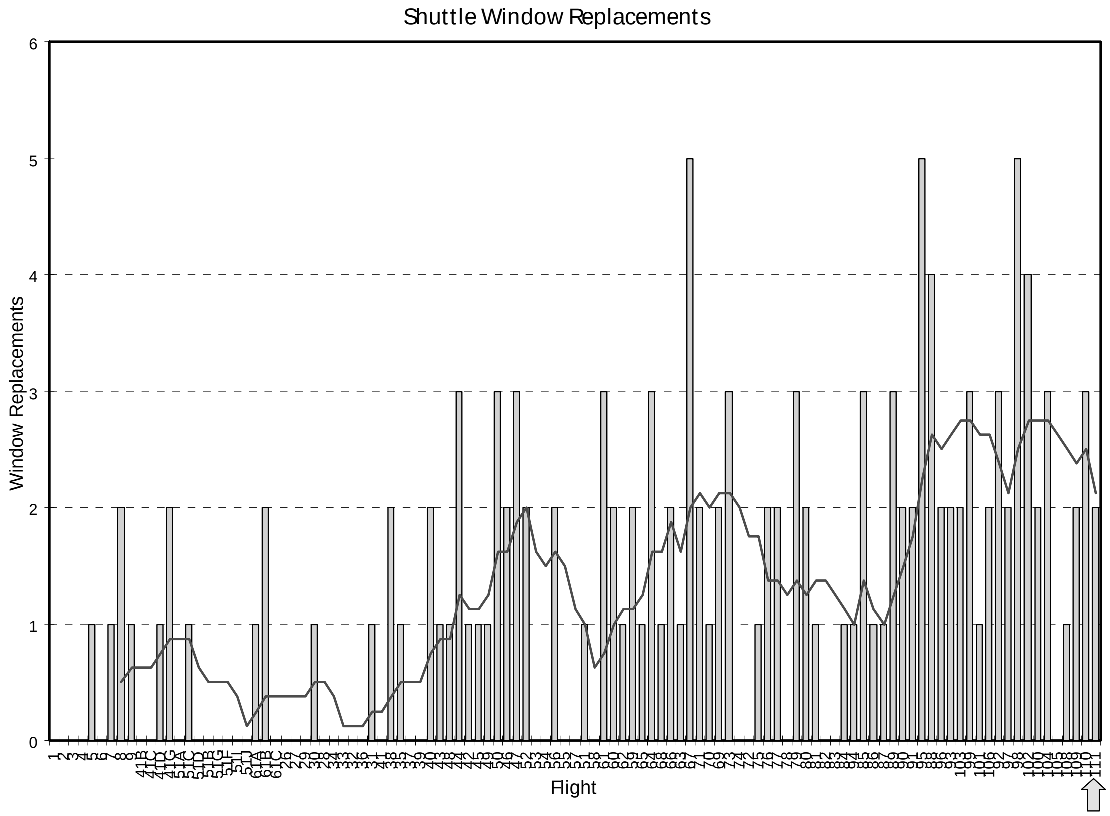


Figure 37. Window replacement history, 1981 – 2002 (109 flights).

Figure 38, which appears on the following page, shows the number of window replacements per mission day for the same missions.

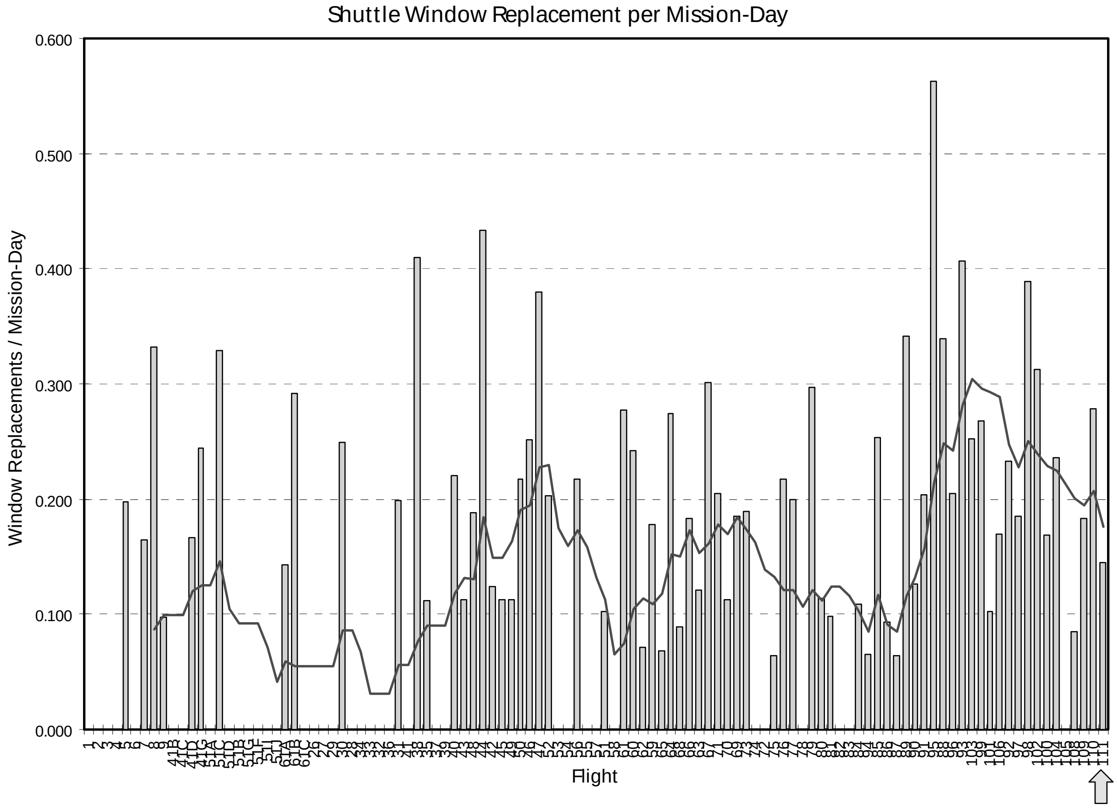


Figure 38. Window replacement rate, 1981 – 2002 (109 flights).

Summary

Following the STS-111 mission, an M/OD impact assessment was performed using the BUMPER code with "as-flown" flight parameters. Fifty-five different LVLH attitude cases were used to model 96.6 percent of the mission, with the remaining 3.4 percent of the mission time uniformly redistributed. One finite element model was used to represent the vehicle before arriving at the International Space Station and after separation. Another was used to model the vehicle while the Shuttle was docked to the Station.

BUMPER code was used to calculate the number of M/OD impacts from particles that were at or above two size bins on Orbiter radiators and windows. The as-flown parameters were also used to calculate standard FRR analysis products: overall crew risk, plus the expected number of radiator tube penetrations and window replacements. Particle diameters were estimated from observed impact data using penetration equations derived from hypervelocity testing of Orbiter materials.

The as-flown M/OD assessments risk for critical penetration was 13 percent lower than the preflight FRR M/OD assessments, while the radiator tube penetration risk was 5 percent higher and window replacement risk was 8 percent higher than FRR predictions. Two windows were replaced due to HVI damage, and one replacement was predicted. No holes were observed in the outer metal facesheet of the radiator panels, when at least one was predicted by the as-flown assessment.

Normalized window replacement and radiator perforation rates were calculated using on-orbit exposure hours and observed damage values. Table 12 shows that the normalized radiator perforation rate for the STS-111 mission was very close to the program average. The normalized window replacement rate for the STS-111 mission almost exactly matched the program average replacement rate.

Table 12. STS-111 Damage vs. Program Averages

Radiator Facesheet Perforations / Mission-Day	
Average (STS-50 through STS-111)	**0.092**
STS-111	**0.073**
Window Replacements / Mission-Day	
Average (STS-1 through STS-111)	**0.144**
STS-111	**0.145**

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APPENDIX A – ATL PARSE PROGRAM OUTPUT

Table A-1. As-Flown Attitudes

Attitude Group	#	Altitude (nm)	FEM	ROLL	PITCH	YAW	Exposure Time (Minutes) Original	% TOTAL	Increment	Final
A	1	160	orb_v6.14	-180.0	0.0	-180.0	1895	9.54	166.4	**2,061**
A	2	160	orb_v6.14	-180.0	0.0	-90.0	225	1.13	19.8	**245**
A	3	160	orb_v6.14	0.0	80.0	0.0	115	0.58	10.1	**125**
A	4	160	orb_v6.14	0.0	-90.0	0.0	35	0.18	3.1	**38**
A	5	160	orb_v6.14	-180.0	40.0	0.0	15	0.08	1.3	**16**
A	6	160	orb_v6.14	0.0	20.0	0.0	20	0.1	1.8	**22**
A	7	160	orb_v6.14	0.0	60.0	0.0	15	0.08	1.3	**16**
A	8	160	orb_v6.14	0.0	0.0	0.0	15	0.08	1.3	**16**
						Various Attitudes	205	1.03		
						GROUP "A" TOTALS	**2,540**	**12.8**	**205.0**	**2,540**

Attitude Group	#	Altitude (nm)	FEM	ROLL	PITCH	YAW	Exposure Time (Minutes) Original	% TOTAL	Increment	Final
B	1	210	orb_v6.13	180.0	-60.0	-180.0	9050	45.58	124.7	**9,175**
B	2	210	orb_v6.13	-163.3	-58.5	160.6	1145	5.77	15.8	**1,161**
B	3	210	orb_v6.13	-180.0	-70.0	-90.0	520	2.62	7.2	**527**
B	4	210	orb_v6.13	170.0	-70.0	-180.0	140	0.71	1.9	**142**
B	5	210	orb_v6.13	-180.0	-30.0	0.0	150	0.76	2.1	**152**
B	6	210	orb_v6.13	0.0	-90.0	0.0	60	0.3	0.8	**61**
B	7	210	orb_v6.13	180.0	-90.0	0.0	70	0.35	1.0	**71**
B	8	210	orb_v6.13	0.0	30.0	0.0	30	0.15	0.4	**30**
B	9	210	orb_v6.13	0.0	0.0	0.0	15	0.08	0.2	**15**
B	10	210	orb_v6.13	174.5	-67.7	-152.7	25	0.13	0.3	**25**
B	11	210	orb_v6.13	-165.5	-67.7	-152.7	25	0.13	0.3	**25**
B	12	210	orb_v6.13	-172.7	-67.7	-115.5	20	0.1	0.3	**20**
						Various Attitudes	155	0.87		
						GROUP "B" TOTALS	**11,405**	**57.6**	**154.0**	**11,405**

Attitude Group	#	Altitude (nm)	FEM	ROLL	PITCH	YAW	Exposure Time (Minutes) Original	% TOTAL	Increment	Final
C	1	200	orb_v6.14	-180.0	0.0	-90.0	4420	22.26	244.7	**4,665**
C	2	200	orb_v6.14	-180.0	0.0	-180.0	115	0.58	6.4	**121**
C	3	200	orb_v6.14	0.0	-90.0	0.0	60	0.3	3.3	**63**
C	4	200	orb_v6.14	31.8	-9.8	-10.2	55	0.28	3.0	**58**
C	5	200	orb_v6.14	28.2	9.8	-10.2	40	0.2	2.2	**42**
C	6	200	orb_v6.14	-150.0	0.0	-170.0	65	0.33	3.6	**69**
C	7	200	orb_v6.14	-133.3	58.5	-160.6	70	0.35	3.9	**74**
C	8	200	orb_v6.14	-60.0	80.0	-90.0	60	0.3	3.3	**63**
C	9	200	orb_v6.14	4.5	67.7	-27.3	40	0.2	2.2	**42**
C	10	200	orb_v6.14	-146.4	19.7	-169.4	35	0.18	1.9	**37**
C	11	200	orb_v6.14	21.7	39.3	-13.0	75	0.38	4.2	**79**
C	12	200	orb_v6.14	74.6	-75.9	-45.4	55	0.28	3.0	**58**
C	13	200	orb_v6.14	165.4	-75.9	-134.6	35	0.18	1.9	**37**
C	14	200	orb_v6.14	-166.7	-58.5	-160.6	40	0.2	2.2	**42**
C	15	200	orb_v6.14	-155.7	-29.5	-168.5	40	0.2	2.2	**42**
C	16	200	orb_v6.14	-141.7	39.3	-167.0	25	0.13	1.4	**26**
C	17	200	orb_v6.14	-180.0	20.0	-180.0	15	0.08	0.8	**16**
C	18	200	orb_v6.14	180.0	-30.0	-180.0	15	0.08	0.8	**16**
C	19	200	orb_v6.14	-160.0	0.0	-90.0	15	0.08	0.8	**16**
C	20	200	orb_v6.14	24.3	-29.5	11.5	15	0.08	0.8	**16**
C	21	200	orb_v6.14	-81.7	39.3	13.0	20	0.1	1.1	**21**
C	22	200	orb_v6.14	-86.4	19.7	10.6	15	0.08	0.8	**16**
C	23	200	orb_v6.14	-90.0	0.0	10.0	15	0.08	0.8	**16**
C	24	200	orb_v6.14	-93.6	-19.7	10.6	15	0.08	0.8	**16**
C	25	200	orb_v6.14	-106.7	-58.5	19.4	25	0.13	1.4	**26**
C	26	200	orb_v6.14	101.7	-49.0	164.7	30	0.15	1.7	**32**
C	27	200	orb_v6.14	91.8	-9.8	169.8	20	0.1	1.1	**21**
C	28	200	orb_v6.14	45.7	-29.5	-11.5	40	0.2	2.2	**42**
C	29	200	orb_v6.14	56.7	-58.5	-19.4	35	0.18	1.9	**37**
C	30	200	orb_v6.14	84.3	29.5	168.5	15	0.08	0.8	**16**
C	31	200	orb_v6.14	78.3	49.0	164.7	15	0.08	0.8	**16**
C	32	200	orb_v6.14	64.5	67.7	152.7	15	0.08	0.8	**16**
C	33	200	orb_v6.14	-64.5	67.7	27.3	20	0.1	1.1	**21**
C	34	200	orb_v6.14	180.0	-60.0	-180.0	15	0.08	0.8	**16**
C	35	200	orb_v6.14	105.5	-67.7	152.7	15	0.08	0.8	**16**
						Various Attitudes	310	1.56		
						GROUP "C" TOTALS	**5,910**	**29.8**	**282**	**5,910**

"Other/Various" TOTAL	**670**
STS-111 MISSION TOTAL	**19,855**

APPENDIX B – PREDICTED VS. OBSERVED IMPACTS

The origin of the values shown in figure 30 is detailed in this appendix. Table B-1 provides the port and starboard radiator impact data for meteoroid and debris impacts; while table B-2 gives details for the eight crew module windows. Each table is subdivided into impactor diameter bins (ALL DINGS and BIG DINGS). The results are also broken out by environment (meteoroid and orbital debris). The "Expected" column lists the results of the BUMPER calculation for each of the Orbiter regions listed. The "Observed" column summarizes the results of the diameter bin assignment process for each of the Orbiter regions.

Table B-1. STS-111 Radiator Expected vs. Observed

STS-111 METEOROID Impacts - Expected vs. Observed				
	ALL DINGS >0.1mm Diam		BIG DINGS >0.4mm Diam	
Orbiter Region	**Expected**	**Observed**	**Expected**	**Observed**
PLBD Radiator (port)	1.071	1	0.028	1
PLBD Radiator (stbd)	1.853	0	0.049	0
Radiator Meteoroid Impacts	**2.924**	**1**	**0.077**	**1**

STS-111 ORBITAL DEBRIS Impacts - Expected vs. Observed				
	ALL DINGS >0.1mm Diam		BIG DINGS >0.4mm Diam	
Orbiter Region	**Expected**	**Observed**	**Expected**	**Observed**
PLBD Radiator (port)	4.397	0	0.193	0
PLBD Radiator (stbd)	6.155	0	0.270	0
Radiator Debris Impacts	**10.552**	**0**	**0.463**	**0**

Table B-2. STS-111 Window Expected vs. Observed

STS-111 Meteoroid Impacts - Expected vs. Observed				
	ALL DINGS >0.01mm Diam		BIG DINGS >0.025mm Diam	
Orbiter Region	**Expected**	**Observed**	**Expected**	**Observed**
CM Window #1 (port side)	0.7739	0	0.2397	0
CM Window #6 (stbd side)	1.4140	2	0.4379	0
CM Window #2 (port mid)	0.7080	1	0.2193	1
CM Window #5 (stbd mid)	1.1533	7	0.3572	2
CM Window #3 (port fwd)	0.5834	5	0.1807	1
CM Window #4 (stbd fwd)	0.7362	5	0.2280	3
CM Window #7 (stbd over)	0.1908	0	0.0591	0
CM Window #8 (port over)	0.2336	1	0.0723	0
Window Meteoroid Impacts	**5.793**	**21**	**1.794**	**7**

STS-111 Debris Impacts - Expected vs. Observed				
	ALL DINGS >0.01mm Diam		BIG DINGS >0.025mm Diam	
Orbiter Region	**Expected**	**Observed**	**Expected**	**Observed**
CM Window #1 (port side)	1.6100	0	0.4694	0
CM Window #6 (stbd side)	2.0888	0	0.6080	0
CM Window #2 (port mid)	1.1019	1	0.3190	1
CM Window #5 (stbd mid)	1.5149	1	0.4399	0
CM Window #3 (port fwd)	0.7172	1	0.2075	0
CM Window #4 (stbd fwd)	0.8943	2	0.2596	1
CM Window #7 (stbd over)	0.1665	0	0.0481	0
CM Window #8 (port over)	0.1937	0	0.0562	0
Window Debris Impacts	**8.287**	**5**	**2.408**	**2**

Table B-3 summarizes the observed impact totals for the STS-111 mission. The values in the table are drawn from tables B-4 (radiators) and B-5 (windows).

Table B-3. Observed Totals for Windows and Radiators

Orbiter Region	STS-111 -- Cumulative OBSERVED Number of Radiator Tape Holes from Meteoroid, Debris & Unknown Sources												
	<0.1mm Diam			ALL DINGS >0.1mm Diam			BIG DINGS >0.4mm Diam			Observed Totals			
	Met	Deb	Unk	Met	Deb	Unk	Met	Deb	Unk	Met	Deb	Unk	Total
PLBD Radiator (stbd)	0	0	0	1	0	0	1	0	0	1	0	0	1
PLBD Radiator (port)	0	0	0	0	0	0	0	0	0	0	0	0	0
Totals	0	0	0	1	0	0	1	0	0	1	0	0	1

Orbiter Region	STS-111 -- Cumulative OBSERVED Number of Window Craters from Meteoroid, Debris & Unknown Sources												
	<0.01mm Diam			ALL DINGS >0.01mm Diam			BIG DINGS >0.025mm Diam			Observed Totals			
	Met	Deb	Unk	Met	Deb	Unk	Met	Deb	Unk	Met	Deb	Unk	Total
CM Window #1 (port side)	0	0	0	0	0	0	0	0	0	0	0	0	0
CM Window #6 (stbd side)	0	0	0	2	0	0	0	0	0	2	1	0	3
CM Window #2 (port mid)	0	0	0	1	1	0	0	1	0	1	1	0	2
CM Window #5 (stbd mid)	0	0	0	7	1	0	2	0	0	7	1	0	8
CM Window #3 (port fwd)	0	0	0	5	1	0	1	0	0	5	1	0	6
CM Window #4 (stbd fwd)	0	0	0	5	2	0	3	1	0	5	2	0	7
CM Window #7 (stbd over)	0	0	0	0	0	0	0	0	0	0	0	0	0
CM Window #8 (port over)	0	0	0	0	0	0	0	0	0	1	0	0	1
CM Window #9 (stbd PB)	0	0	0	0	0	0	0	0	0	0	0	0	0
CM Window #10 (port PB)	0	0	0	0	0	0	0	0	0	0	0	0	0
CM Window #11 (hatch)	0	0	0	1	0	0	0	0	0	1	0	0	1
Totals	0	0	0	21	5	0	6	2	0	22	6	0	28

Table B-4 shows the particle diameter estimates for each observed radiator impact damage site documented after the STS-111 mission. Table B-5 provides diameter estimates for the windows. Each calculated diameter is assigned a logical diameter bin to facilitate comparisons. Meteoroid particles are assumed to have a density of 1.0 g/cc, an impact velocity of 19 km/sec, and an impact angle of 45 deg. The debris particles are analytically assigned impact angle and velocity values using BUMPER calculation results based on Orbiter region and as-flown mission values.

Window impacts from "unknown" sources are assumed to meteoroids. In general, impacts from aluminum particles on radiators are not detected because the panels are made of aluminum. Radiator impactors of unknown origin are assigned to an environment (debris or meteoroids) based on the ratio of aluminum to non-aluminum debris impactors on the crew module windows.

Table B-4. Estimated Particle Diameters – Radiator Impacts

1 Impacts: 1 Met 0 Deb

Panel #	Sample #	EDXA Results	Tape Hole Diameter (mm)	Particle type	Particle density (g/cc)	Impact Data Velocity (km/s)	Impact Data Angle (deg)	Impact Data V_{norm} (km/s)	Calculated Particle Diam (mm)	Met Diameter Bin Assignments	Deb Diameter Bin Assignments
STARBOARD 3	5	Meteoritic (Si, Fe, S, Ni)	3.200	met	1.0	19.0	45.0	13.44	0.4	**Bin 2**	

Note:

- Radiator Bin 1 ("All Ding") particles have a diameter greater than 0.1 mm
- Radiator Bin 2 ("Big Ding") particles have a diameter greater than 0.4 mm

Table B-5. Estimated Particle Diameters – Window Impacts

28 Impacts: 22 Met 6 Deb

			Crater		Particle		Impact Data			Projectile		Met	Deb
Window	PR	SEM/EDX Results	Diameter (mm)	Depth (mm)	type	density (g/cc)	Velocity (km/s)	Angle (deg)	V_{norm} (km/s)	Diameter (mm)	Length (mm)	Diameter Bin Assignments	
2	30	Meteoritic: (Al, Si, Mg, Fe)	0.333	0.038	met	1.0	19.0	45.0	13.44	0.0251	0.019	Bin 1	
2	36	Orbital Debris:Alum (Al, Mg)	0.350	0.062	Al	2.8	8.1	49.5	5.24	0.025	0.033		Bin 2
3	5	Unknown	0.305	0.043	met	1.0	19.0	45.0	13.44	0.024	0.021	Bin 1	
3	7	Meteoritic: (Si, Al, Mg, Fe)	0.840	0.076	met	1.0	19.0	45.0	13.44	0.050	0.036	Bin 2	
3	9	Unknown	0.355	0.044	met	1.0	19.0	45.0	13.44	0.026	0.022	Bin 1	
3	10	Unknown	0.300	0.037	met	1.0	19.0	45.0	13.44	0.023	0.018	Bin 1	
3	12	Unknown	0.375	0.043	met	1.0	19.0	45.0	13.44	0.027	0.021	Bin 1	
3	13	Orbital Debris: (Fe, Ni, Cr)	0.430	0.055	SS	7.9	8.3	47.9	5.54	0.021	0.018		Bin 1
4	144	Orbital Debris: Paint (Ti, Zn, Al, K)	0.300	0.043	paint	2.5	8.2	43.0	5.98	0.022	0.023		Bin 1
4	145	Unknown	0.380	0.056	met	1.0	19.0	45.0	13.44	0.028	0.027	Bin 2	
4	150	Unknown	0.415	0.051	met	1.0	19.0	45.0	13.44	0.030	0.025	Bin 2	
4	160	Orbital Debris: Paint (Zn, Ti, Na, Cl)	0.480	0.048	paint	2.5	8.2	43.0	5.98	0.032	0.026		Bin 2
4	169	Unknown	0.280	0.040	met	1.0	19.0	45.0	13.44	0.022	0.020	Bin 1	
4	178	Unknown	0.288	0.043	met	1.0	19.0	45.0	13.44	0.023	0.021	Bin 1	
4	193	Unknown	0.505	0.069	met	1.0	19.0	45.0	13.44	0.034	0.033	Bin 2	
5	41	Meteoritic: (Al, Mg, Fe, S)	0.430	0.056	met	1.0	19.0	45.0	13.44	0.030	0.027	Bin 2	
5	44	Unknown	0.280	0.028	met	1.0	19.0	45.0	13.44	0.022	0.014	Bin 1	
5	46	Unknown	0.353	0.041	met	1.0	19.0	45.0	13.44	0.026	0.020	Bin 1	
5	47	Unknown	0.330	0.040	met	1.0	19.0	45.0	13.44	0.025	0.020	Bin 1	
5	52	Orbital Debris: Paint (Ti, Zn, Cl)	0.400	0.048	paint	2.5	8.1	38.2	6.33	0.027	0.025		Bin 1
5	64	Unknown	0.330	0.064	met	1.0	19.0	45.0	13.44	0.025	0.031	Bin 2	
5	69	Unknown	0.320	0.038	met	1.0	19.0	45.0	13.44	0.024	0.019	Bin 1	
5	74	Unknown	0.350	0.046	met	1.0	19.0	45.0	13.44	0.026	0.023	Bin 1	
6*	2	Orbital Debris: Paint (Zn, Al, Cl)	0.618	0.028	paint	2.5	8.1	32.6	6.81	0.037	0.014		Bin 1
6	3	Unknown	0.330	0.037	met	1.0	19.0	45.0	13.44	0.025	0.018	Bin 1	
6	4	Unknown	0.350	0.035	met	1.0	19.0	45.0	13.44	0.026	0.018	Bin 1	
8*	1	Meteoritic: (Al, Mg, Fe, Ni, S)	0.273	0.025	met	1.0	19.0	45.0	13.44	0.022	0.013	Bin 1	
11	1	Meteoritic: (Fe, Ni, S)	0.320	0.031	met	1.0	19.0	45.0	13.44	0.024	0.016	Bin 1	
					28						TOTAL	22	6

Note:

- Window Bin 1 ("All Ding") particles have a diameter greater than 0.01 mm
- Window Bin 2 ("Big Ding") particles have a diameter greater than 0.025 mm

APPENDIX C – PREVIOUS ASSESSMENTS

	Authors	Report Name	Document	Date
1	Kerr and Bernhard	STS-87 Orbiter M/OD Impact Damage Analysis	JSC-28404	Aug-98
2	Kerr, Petersen, and Bernhard	STS-89 Orbiter M/OD Impact Damage Analysis	JSC-28499	Nov-98
3	Kerr, Petersen, and Bernhard	STS-91 Orbiter M/OD Impact Damage Analysis	JSC-28496	Dec-98
4	Kerr, Petersen, and Bernhard	STS-90 Orbiter M/OD Impact Damage Analysis	JSC-28495	Mar-99
5	Kerr, Petersen, and Bernhard	STS-95 Orbiter M/OD Impact Damage Analysis	JSC-28497	Apr-99
6	Kerr and Bernhard	STS-88 Orbiter M/OD Impact Damage Analysis	JSC-28641	Sep-99
7	Kerr and Bernhard	STS-96 Orbiter M/OD Impact Damage Analysis	JSC-28642	Dec-99
8	Kerr, Bernhard, and Hyde	STS-99 Orbiter M/OD Impact Damage Analysis	JSC-29134	Oct-00
9	Kerr, Bernhard, and Hyde	STS-101 Orbiter M/OD Impact Damage Analysis	JSC-29135	Oct-00
10	Kerr, Bernhard, and Hyde	STS-103 Orbiter M/OD Impact Damage Analysis	JSC-29136	Oct-00
11	Kerr, Bernhard, and Hyde	STS-93 Orbiter M/OD Impact Damage Analysis	JSC-29263	Nov-00
12	Kerr, Bernhard, and Hyde	STS-106 Orbiter M/OD Impact Damage Analysis	JSC-29273	Dec-00
13	Kerr, Bernhard, and Hyde	STS-92 Orbiter M/OD Impact Damage Analysis	JSC-29318	Jan-01
14	Kerr, Bernhard, and Hyde	STS-97 Orbiter M/OD Impact Damage Analysis	JSC-29373	Mar-01
15	Christiansen, Kerr, and Hyde	STS-106 As Flown Orbiter M/OD Assessment	JSC-29360	Apr-01
16	Kerr, Bernhard, and Hyde	STS-98 Orbiter M/OD Impact Damage Analysis	JSC-29472	Jun-01
17	Kerr, Bernhard, and Hyde	STS-102 Orbiter M/OD Impact Damage Analysis	JSC-29503	Jul-01
18	Christiansen, Kerr, and Hyde	STS-92 As Flown Orbiter M/OD Assessment	JSC-29502	Aug-01
19	Christiansen, Kerr, and Hyde	STS-97 As Flown Orbiter M/OD Assessment	JSC-29532	Aug-01
20	Kerr, Bernhard, and Hyde	STS-100 Orbiter M/OD Impact Damage Analysis	JSC-29533	Aug-01
21	Christiansen, Kerr, and Hyde	STS-98 As Flown Orbiter M/OD Assessment	JSC-29560	Sep-01
22	Christiansen, Kerr, and Hyde	STS-104 As Flown Orbiter M/OD Assessment	JSC-29702	Mar-02
23	Christiansen, Kerr, and Hyde	STS-108 As Flown Orbiter M/OD Assessment	JSC-29783	Jul-02
24	Christiansen, Bernhard, and Hyde	STS-109 As Flown Orbiter M/OD Assessment	JSC-29815	Sep-02
25	Christiansen, Bernhard, and Hyde	STS-110 M/OD Post Flight Assessment	JSC-29816	Dec-02

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13. ABSTRACT *(Maximum 200 words)*

STS-111 was the eighteenth flight for the Space Shuttle Endeavour. This UF-2 mission to the International Space Station (ISS) involved a crew rotation and the delivery of new supplies and experiments in the multi-purpose logistics module. The mission, which took place between June 5 and June 19, 2002, had an orbital inclination of 51.6 deg and an altitude of about 389 km (210 n. mi.). This report on the meteoroid/orbital debris (M/OD) experienced during the mission of STS-111 is divided into two sections: The "As-Flown Assessment" section, which compares the results of a risk analysis using postflight attitude data with postflight damage observations and preflight risk predictions, and the "Postflight Damage Inspection" section, which documents the M/OD that was observed during inspections at the NASA Kennedy Space Center following the mission. Preflight and postflight assessments were performed using BUMPER-II code with the ORDEM 2000 orbital debris environment and the SSP-30425 meteoroid environment. At Shuttle/ISS altitudes, the new environment predicts a higher number of particles in the 0.01-mm-to-4-mm-diameter range and a few number of particles in the 4-mm-to-10-cm-diameter range.

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