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Space Shuttle debris and meteoroid impacts

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Abstract

This paper describes observations and analyses of meteoroid and debris impact damage to the Space Shuttle Orbiter over the past decade. Since 1992, NASA Space Shuttle Orbiter post-flight inspection procedures have been altered to allow systematic identification and sampling of meteoroid/debris impacts in selected areas of the vehicle. These areas include the crew module windows and radiator panels that line the interior of the payload bay doors. In addition, other significant impact damage is identified and sampled on other critical surfaces or exposed structures such as wing leading-edge panels, external thermal-protection materials, radiator interconnect lines, and Ku-band antenna components. Samples of the impact damage are obtained and subjected to scanning electron microscope energy dispersive X-ray analysis to determine elemental composition of impactor materials recovered from the impact site. Based on these results, the source of the impact damage is categorized as meteoroid or debris, and debris particle types are identified. Historical trends indicate a large variability in debris impact rates from mission-to-mission with higher impact rates than average occurring more regularly since 1998. Predictions of post-flight damage are compared to observed damage using BUMPER code and as-flown attitude timelines.
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Keywords: Space debris; Space Shuttle; Meteor impact; Debris impacts

1. Shuttle design and operational changes to reduce impact damage

The first confirmed orbital debris impact to a Space Shuttle Orbiter Vehicle (OV) occurred on STS-7, by a piece of paint which left a 3.8-mm diameter and 0.43-mm deep pit in the right-side middle window (#5) of OV-099. In June 1992, STS-50 was the first extended duration orbiter (EDO) mission conducted over 13.8 days in a predominately payload bay forward attitude. After STS-50, 43 impact damage sites were found on the radiators, four of which perforated the outer thermal tape and underlying aluminum facesheet (Christiansen et al., 1993). In addition, six impacts occurred to STS-50 windows, with three windows replaced. Orbital debris impacts, from paint and titanium metal, were responsible for the largest damages to STS-50 radiators and windows, respectively. The level of damage found after STS-50 represented about 10 missions worth of damage under typical flight conditions at the time. Subsequently, several major reviews of Shuttle meteoroid/orbital debris (M/OD) risks were undertaken in the 1992–1997 time frame, with several operational and vehicle design changes implemented to reduce M/OD risks as described below.

1.1. Operational risk reduction techniques

The long duration in a payload bay forward attitude was established as the single most likely reason for the increased damage sustained on the STS-50 mission. Flight rules and mission planning guidelines were implemented in October 1992 to limit the amount of time in unfavorable attitudes (payload bay forward) and to baseline "preferred" Shuttle attitudes for debris protection, namely tail forward, payload bay toward Earth (Levin and Christiansen, 1997). Collision avoidance from tracked (>10-cm diameter) debris has been

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practiced by Shuttle operations since 1988 (Loftus et al., 1999). Another operational method to reduce M/OD risk was inaugurated for STS-73 mission, which was the first mission that used a partially closed payload bay (PLB) door as a "bumper" shield. This 15.9-day mission flew in a predominately port wing forward, nose space attitude, with the port side payload bay door open only one-third of normal (the port PLB door was opened only 52°, whereas a fully open door is 172°). The PLB door in the partially closed position protected the radiator surfaces and the payload bay contents including the SpaceLab and cryogenic oxygen/hydrogen tanks in the EDO pallet.

1.2. Vehicle design modifications to reduce impact risks

Modifications to improve the survivability of the Orbiter in the meteoroid/debris environment were considered by the "Schneider Team" study conducted from 1995 to 1996 (Loftus et al., 1997). The team examined hypervelocity impact data as well as BUMPER risk assessments using penetration equations from the tests that showed the coolant tubes in the radiator panels were vulnerable to puncture from small M/OD impacts. Because there are only two independent coolant loops, any tube puncture would lead to a significant reduction in cooling capability and would result in early mission termination. After considering actual impact damage reported by the STS-50 post-flight survey as well as surveys from other missions, the team recommended changes in order to enhance the survivability of the Orbiter active thermal control system. The Shuttle Program adopted these including the addition of 0.5-mm thick aluminum "doublers" added over the radiator panel coolant tubes and adding automatic shut-off valves in the coolant systems (Loftus et al., 1997). Another recommended change was to enhance Vehicle/crew safety by including Nextel ceramic fabric within insulators of the structural attachments of the wing leading-edge (WLE) panels. The added insulation improved the capability of the vehicle to sustain perforations in the WLE reinforced carbon–carbon (RCC) panels without subsequent structural failure from ingestion of hot gas during reentry, allowing more liberal "failure criteria" for the wing leading-edge panels and reduced M/OD risks. These design upgrades were implemented on all Orbiter Vehicles in the 1998–2000 time frame.

Another design modification resulted from post-flight M/OD impact damage surveys (Fig. 1). After STS-86 in September 1997, an impact was found on an exterior radiator manifold that connects separate radiator panels on the Orbiter. Subsequent interior inspection of the radiator line showed a region of detached spall under the impact site. The Shuttle Program responded to this near perforation of the interconnect lines by adding a double-layer β-cloth sleeve to reduce the vulnerability of the interconnect lines. The National Research Council report (1997) and Jensen et al. (1999) provide additional information on operational changes and design modifications to the Shuttle to reduce M/OD impact damage risks.

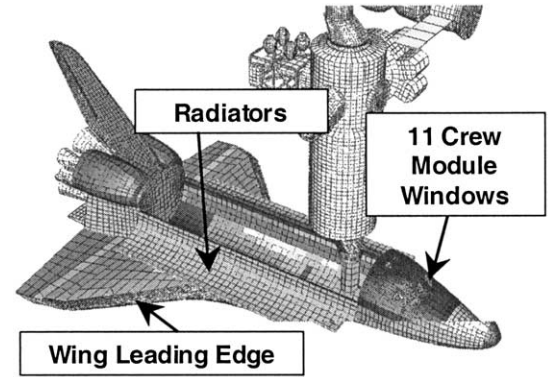

Fig. 1. Orbiter surfaces inspected for M/OD impact damage.

2. Meteoroid and orbital debris impact surveys

Since 1992, the normal vehicle refurbishment process following each Space Shuttle mission has been modified to allow for specific identification of meteoroid/debris damage. Samples of impact damage with identifiable hypervelocity impact features are identified by NASA Kennedy Space Center workers assisted by Johnson Space Center meteoroid/debris personnel. Samples of the impact damage are returned to the JSC meteoroid/debris laboratory for analysis. Of the 62 missions flown from STS-50 (June 1992) through STS-110 (February 2002), 50 have had post-flight inspections to identify meteoroid and debris impacts. Orbiter radiator and windows represent the majority of regularly sampled surfaces (~10% of the total surface area of the vehicle), as thermal tiles and other surfaces exposed to reentry heating are not as suitable for sampling (Fig. 1). The samples are subjected to analysis by scanning electron microscope equipped with energy dispersive X-ray (SEM/EDX) spectrometers to determine elemental constituents of projectile residues. From this data, a determination is made as to type of impactor (meteoroid or debris) and category for the debris damage (e.g., paint, aluminum structure, solid rocket motor exhaust, electrical component, etc.) using standard procedures (Bernhard et al., 1997). Particle size causing the damage is calculated based on assessment of average impact conditions using BUMPER code and damage equations derived from hypervelocity impact test data (Christiansen et al., 1998). Flight-by-flight data on damage to Orbiter surfaces, SEM/EDX analysis results, estimated particle size, data trends, and statistical information are contained in an excel worksheet maintained on the NASA Johnson Space Center Hypervelocity Impact Technology Facility (2003) web site (http://hitf.jsc.nasa.gov/hitfpub/shuttle/archives-report.cfm?page = arc).

2.1. Window damage

The largest impact to an Orbiter window occurred on STS-92, which was International Space Station (ISS) Flight 3A. A crater of 10-mm diameter and 1.9-mm deep was found on the port-middle (#2) debris pane (Fig. 2). SEM/EDX analysis indicated the cause of the damage was a piece of paint (orbital debris). The window was replaced. Based on average impact conditions for this mission (impact velocity of 9.3 km/s and impact angle of 45°), the crater geometry can be best explained by a 0.76-mm diameter by 0.3-mm thick paint chip that impacts the window in an edge-on orientation.

Generally there are many small impacts found on the Shuttle windows that do not cause any concern. In some cases, the impacts are large enough to require the window to be replaced, because of the potential for flaw growth during subsequent launch/landing cycles. The replacement criteria vary for each window on the Orbiter and location of the flaw, because of the different stresses experienced by the windows during launch. Although 1578 impacts were recorded on the windows, only 98 were large enough to cause the window to be replaced due to hypervelocity impact damage over the 50 missions sampled for meteoroid/debris damage from STS-50 to STS-110. Of the 98 impact replacements, SEM/EDX analysis revealed 41 were from orbital debris, 18 from meteoroids, 10 were unknown (no definitive SEM/EDX results), and 29 had no sample returned. Fig. 3 illustrates the composition of orbital debris for the 41 debris impacts that caused a window replacement. Aluminum and paint particles resulted in a majority of the window replacements, although steel and

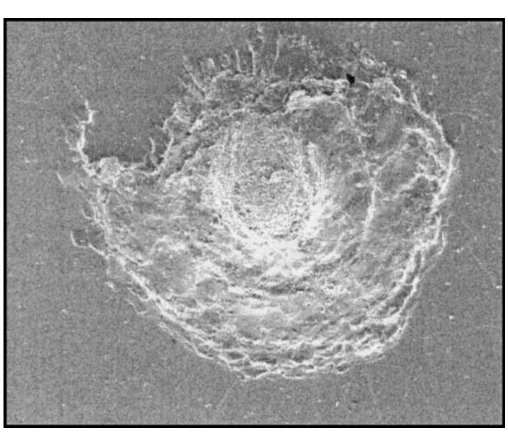

Fig. 2. STS-92 left-hand #2 window crater (10-mm diameter by 1.9-mm deep) caused by orbital debris (paint).

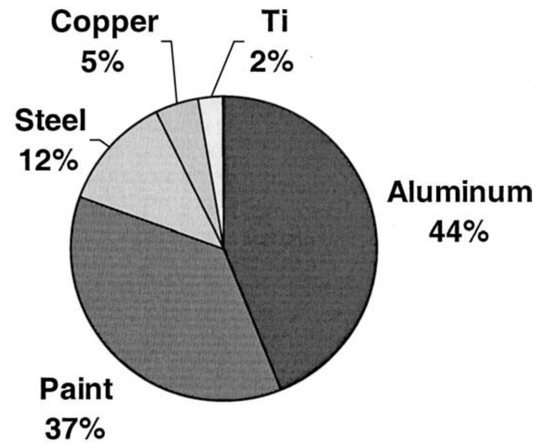

Fig. 3. Composition of orbital debris particles that caused 41 window replacements during the period from STS-50 (June 1992) to STS-110 (April 2002).

titanium, while less frequent, have caused some of the largest impact damages to windows and radiators. There have been 121 windows replaced due to M/OD impact from STS-1 (April 1981) through STS-110, with the trend illustrated in Fig. 4 indicating generally higher replacements than historical averages since 1998. Clearly, the missions depicted in Fig. 4 vary in terms of mission duration, altitude and other factors which influence meteoroid and orbital debris impact rates. However, the figure illustrates two things: (1) the variability in impact rates from mission to mission and (2) the general upward trend in impact rates causing window replacement over the life of the program.

2.2. Radiator damage

The Orbiter radiators consist of a silver–teflon thermal control coating over a honeycomb panel with aluminum facesheets. Their large area (117 m^2) and relatively smooth surface provides an excellent witness plate to observe the effects of M/OD impacts. However, their aluminum construction makes it extremely difficult under most circumstances to differentiate aluminum projectile materials from the strong background signal in SEM/EDX analysis of collected damage samples. For the 50 surveys conducted between STS-50 and STS-110, there have been 295 M/OD impacts detected on the radiators, with 50 of these large enough to perforate the thermal tape and facesheet of the radiator. None of the M/OD impacts caused a perforation of the coolant flow tubes that are bonded beneath the facesheet of radiator at periodic intervals; however, undoubtedly in some cases they had the energy to perforate but fortunately missed a tube. Radiator construction details can be found in Christiansen et al. (1993). Of the perforations, 22 were determined from SEM/EDX analysis of impact samples to be orbital debris, 19 meteoroids, and 9

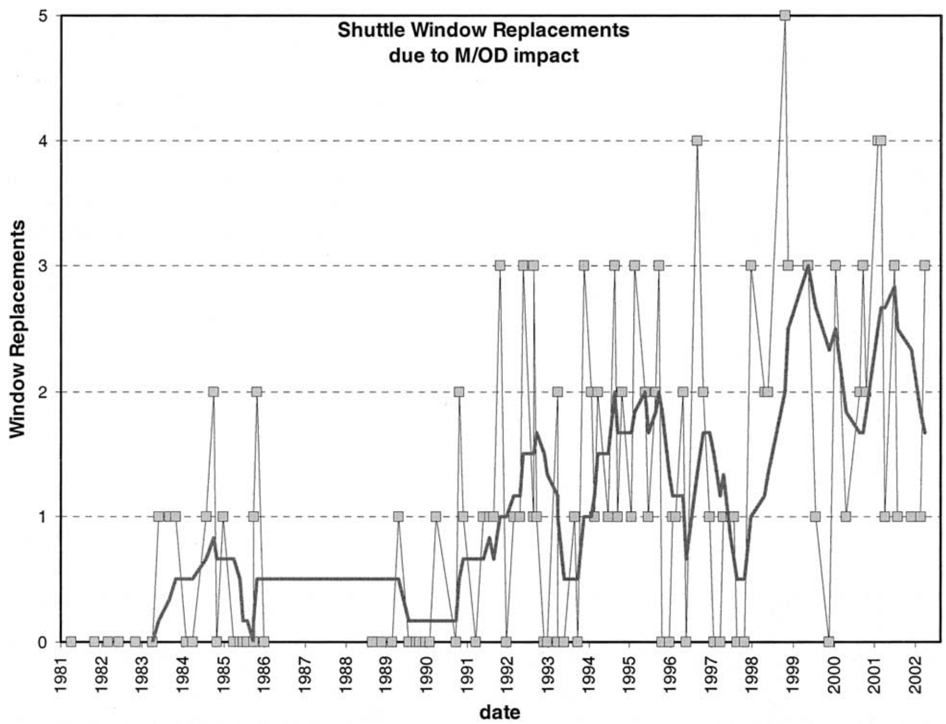

Fig. 4. Window replacements from M/OD impact with the bold line indicating the trend over a 6-mission running average.

unknown. Fig. 5 illustrates the composition of the orbital debris that resulted in radiator facesheet perforations.

Probably the severest impact to the Shuttle fleet as it represents a "near miss" of a major problem is the impact found on a radiator line after STS-86 (Hyde et al., 2001). Post-flight inspection of OV-104 (*Atlantis*) radiator panels after mission STS-86 found a significant hypervelocity impact in the external manifold hard line that extends along the two forward radiator panels. The impact penetrated through a β cloth cover, crossed a 6.4-mm (0.25 inch) gap, and left a 0.8-mm diameter by 0.47-mm deep crater in the manifold hard line (Fig. 6). The aluminum external hard lines are 0.9-mm (0.035 in.) thick in the impacted region. From hypervelocity impact data, the crater depth-to-wall thickness ratio of 0.52 indicated that spall effects were likely on the inside of the line at the point of impact. A borescope inspection of the line interior was conducted to assess internal damage and a small area of detached spall was found on the inside of the tube under the impact site. This indicates that the impact very nearly put a hole in the external manifold that would have caused a leak of freon cool-

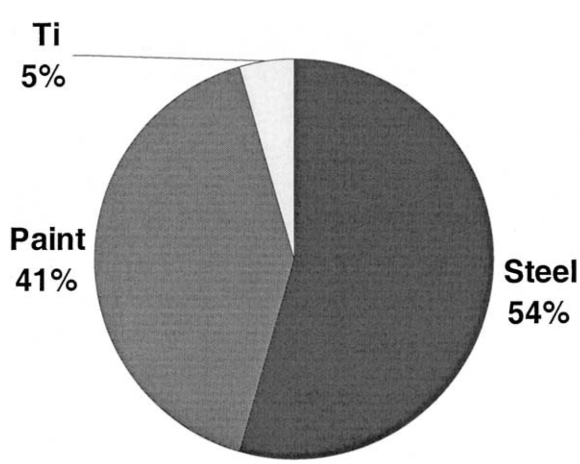

Fig. 5. Composition of orbital debris causing 22 perforations of the radiator facesheet over 50 missions from STS-50 to STS-110.

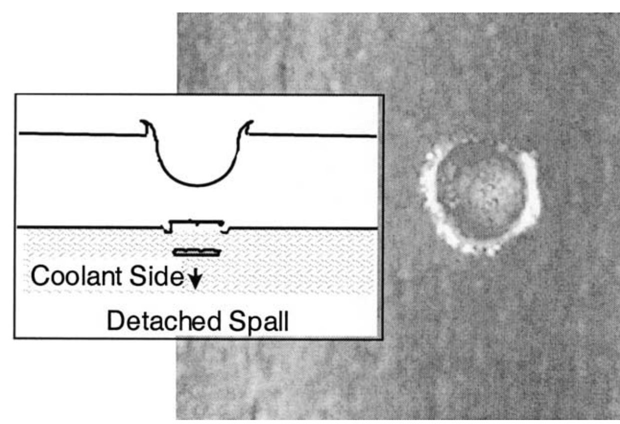

Fig. 6. Deep crater (0.8-mm diameter by 0.47 mm) in 0.9-mm thick aluminum interconnect line. Inset illustrates how detached spall occurred from under the crater. SEM/EDX indicated a steel debris impactor.

ant, potentially shortening the mission. Flight rules dictate that a leak in one of the Orbiter's two radiator systems will result in early mission termination. The Orbiter Project Office determined that an upgrade to the meteoroid/debris protection of the radiator external lines was needed, and additional two-ply β-cloth sleeves were installed on all external radiator lines. Samples obtained for SEM/EDX analysis included the perforated β cloth thermal cover and tape pull samples from the external line. Analysis found iron (Fe), chromium (Cr), and nickel (Ni) on the β cloth (teflon–glass background) and in the external line samples, indicating the damage was caused by a stainless steel orbital debris particle (approximately 0.4-mm diameter as indicated in Table 1).

2.3. Top 20 meteoroid/debris impacts

Table 1 summarizes the data for the 20 most significant impacts that occurred to the Orbiter from STS-50 to STS-110. The impacts are presented by estimated impactor size and mission number for three different Orbiter areas: windows, radiators, and other surfaces. Of the 20, orbital debris caused a clear majority of the total damage (16) and also resulted in the largest damage for each of the three location categories.

The largest confirmed orbital debris impact was from an estimated 1-mm diameter by 3-mm long piece of lead–tin solder which was recovered in a 17-mm diameter cavity in the fibrous insulation material (FRSI) used on the exterior of the port side payload bay door (Fig. 7). STS-73 was the mission that used a partially closed payload bay door as a ''bumper'' shield to protect the radiator, SpaceLab, and cryogenic oxygen/hydrogen tanks within the EDO pallet. The semi-closed payload door proved to be an effective shield. Post-flight analysis indicates the impacting particle had a trajectory that intersected the LO_2 and LH_2 tanks contained on the EDO pallet. Had the door not been positioned in the debris protect orientation, this particular impact (3 mm × 1 mm lead–tin solder particle) could have easily penetrated the lightweight thermal blanket surrounding the EDO pallet and damaged or ruptured a pressurized LO_2/LH_2 tank.

Table 1
Top 20 meteoroid/orbital debris impacts identified on Orbiter windows, radiators, and other surfaces from STS-50 to STS-110

Mission #	Orbiter components and payloads				
	Impact location	Damaged material	Hole diameter (mm)	Particle type (SEM/EDXA results)	Estimated particle diameter (mm)
STS-73	FRSI LH #4	Nomex felt	17.0	Orbital debris: Pb, Tin, Ag (solder)	3.0 length × 1.0 diameter
STS-72	Rudder Speed Brake	Inconel	3.4	Orbital debris: aluminum	1.30
STS-75	Payload Pallet Trunnion	Titanium	1.0	Orbital debris: aluminum	0.80
STS-90	DBA Box/Ku-band	Ag–teflon/Al	2.0	Orbital debris: steel	0.60
STS-56	Ku-band antenna	Graphite epoxy	1.4	Meteoritic	0.60
STS-92	Conical Seal Vert. Stab.	Inconel	1.2	Orbital debris: steel	0.42
STS-96	RCC Panel RH2 top	SiC/Carbon	1.2 × 0.85 deep	Orbital debris: aluminum	0.40
Mission #	Payload bay door radiators				
	Impact location	Tape hole diameter (mm)	Facesheet hole diameter (mm)	Particle type (SEM/EDXA results)	Estimated particle diameter (mm)
STS-103	RH #2	4.20	0.70	Orbital debris (Na, K)	1.09
STS-73	LH #4	8.30	1.10	Orbital debris: paint	1.07
STS-109	RH #3	4.00	0.60	Orbital debris: paint	0.86
STS-59	RH #1	5.25	0.95	Meteoritic	0.72
STS-85	RH #4	5.00	1.30	Meteoritic	0.68
STS-71	RH #4	3.10	Unknown	Orbital debris: human waste	0.64
STS-83	RH #4	4.67	0.57	Meteoritic	0.62
STS-93	LH #4	4.10	0.80	Orbital debris: paint	0.60
STS-86	Exterior manifold 1	0.9 diameter	0.5 depth	Orbital debris: steel	0.40
Mission #	Crew module windows				
	Impact location	Average crater diameter (mm)	Crater depth (mm)	Particle type (SEM/EDXA results)	Estimated particle diameter (mm)
STS-92	#2 LH Middle	10.0	1.90	Orbital debris: paint	0.33 × 0.76
STS-110	#2 LH Middle	7.9	0.38	Orbital debris: paint	0.28 × 0.20
STS-94	#7 RH overhead	7.1	0.55	Orbital debris: aluminum	0.25 × 0.28
STS-59	#11 Side Hatch	6.9	0.57	Orbital debris: paint	0.22 × 0.23

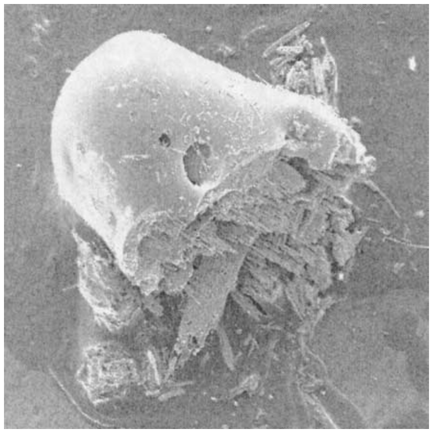

Fig. 7. SEM image of 1.5 mm × 1 mm × 1 mm lead/tin particle extracted from STS-73 FRSI impact crater. From its morphology and structure, this grain appears to be a piece of solder with small amounts of electric circuit board attached at an end. The fibers in the circuit board contain silicon and calcium with minor aluminum present.

3. Particle size estimates

An estimated projectile size for each impact is determined using results from hypervelocity impact tests and analysis (Crews and Christiansen, 1992). The penetration equations that are used in this assessment are described in detail elsewhere (Christiansen et al., 1993; Christiansen and Friesen, 1997). SEM/EDX analysis results were used to specify the density of the particle for the penetration equations used to estimate particle size. In addition, the projectile size estimates are based on the average impact velocity conditions for the meteoroid and debris environment. The calculations assume a 45° average impact angle. Potential particle sizes causing the damage can be higher or lower depending on assumed velocity of impact. A sensitivity analysis on estimated projectile size has been accomplished. The sensitivity analysis indicates that the range of potential projectile sizes for a particular impact (within a 1σ velocity range centered on the mean) is influenced more by the low velocity component than the high end of the velocity range (Fig. 8). This analysis indicates average estimated particle size causing orbital debris damage given in Table 1 is biased toward the lower end of the potential size range.

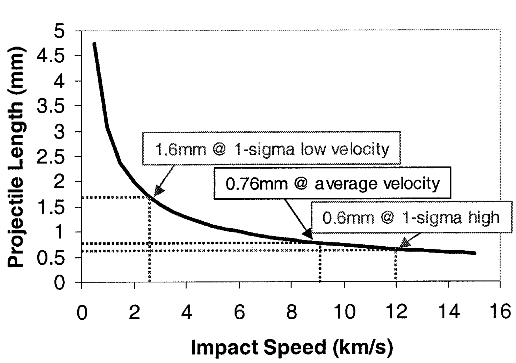

Fig. 8. Particle size sensitivity analysis considering 1σ variation in possible debris impact velocities for the STS-92 window #2 impact shown in Fig. 3.

4. Comparison of orbiter impact damage to bumper predictions using ORDEM2000 debris environment model

BUMPER code is the NASA standard meteoroid/debris analysis code. BUMPER includes the meteoroid and debris environment models documented in NASA (1993) and Liou et al. (2002). Orbiter hypervelocity impact damage and penetration equations are implemented in BUMPER to predict Orbiter impact damage (Christiansen, 1999). The as-flown attitude time-line (ATL) is decomposed into typically 100–200 different attitude/duration combinations for each mission in the post-flight predictions using BUMPER. The geometry models include shadowing effects from large structures such as ISS or MIR that are present during a portion of some missions (Fig. 1). Comparison of cumulative predicted to actual orbital debris damage over 28 shuttle missions assessed using the ATL is given in Fig. 9. As shown, there is good agreement between predictions using BUMPER with ORDEM2000 and actual radiator and window damage. Note that actual data counts “trail” off as expected at small sizes due to incompleteness of inspection results as size decreases.

It should be noted that all “Unknowns” and “No Samples” in the window impact database have been classified as “meteoroids”, so that the on-orbit debris impact total shown in Fig. 9 potentially undercount debris impacts to the windows. In addition, radiator observations are not sensitive to aluminum impactors, therefore the radiator impact predictions have been adjusted by a 50% factor to account for the expected component of aluminum impactors in the orbital debris

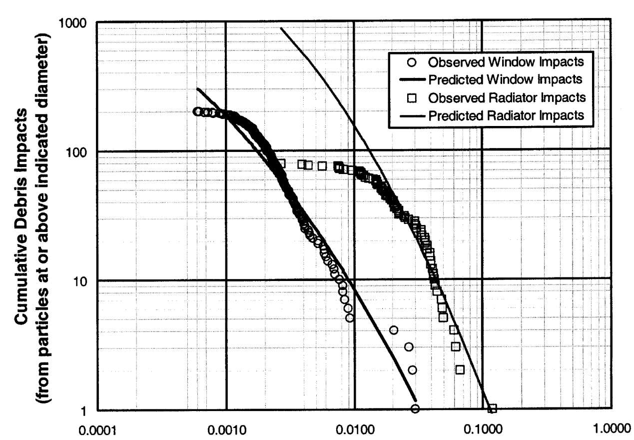

Fig. 9. Comparison of actual window (in squares) and radiator (in circles) damage to predicted (lines) cumulative for 28 flights: STS-50, 56, 71, 72, 73, 75, 76, 77, 79, 80, 81, 84, 85, 86, 87, 88, 89, 91, 94, 95, 96,106, 92, 97, 98, 104, 108, and 109.

flux. More details on these assessments can be found elsewhere (Hyde et al., 2001).

5. Concluding remarks

The Shuttle Program has implemented design and operational changes to reduce the risk from meteoroid/debris impact. To date, meteoroid/debris damage has not resulted in significant effects to Shuttle missions; i.e., no mission has been terminated early and no damage has compromised crew safety. Meteoroid/orbital debris damage has resulted in replacement of windows, repair to radiator surfaces, and repair/refurbishment of other hardware.

A database has been created that now documents over 2000 meteoroid/debris impacts that have occurred on Orbiter windows, radiators, and other exposed surfaces from STS-50 (June 1995) to STS-110 (April 2002). The largest impacts (16 of the top 20 impacts) to windows, radiators, and other surfaces have been due to orbital debris. A majority of the most damaging and most numerous orbital debris particles impacting Orbiter components consist of steel, aluminum, and paint.

Actual damage from orbital debris matches well with predicted values using BUMPER and the 2000 Orbital Debris Model (ORDEM2000). Forward work includes updating the M/OD assessments for the latest mission results, continued surveillance to determine the effects of orbital debris, and meteoroid impacts on Orbiter systems during future missions, identifying and resolving any potential issues with Orbiter performance through operational upgrades and design enhancement.

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