

Investigation of Orbital Debris Impacts on Shuttle Radiator Panels

**James L. Hyde (1), Dr. Eric L. Christiansen (2), Dana M. Lear (3), Dr. Justin H. Kerr (4),
Frankel Lyons (5), Dr. Jason S. Herrin (6), Dr. Shannon J. Ryan (7)**

- (1) Barrios Technology/ESC Group, Houston, TX, 77058, james.l.hyde@nasa.gov
 - (2) NASA/JSC-KX, Houston, TX, 77058, eric.l.christiansen@nasa.gov
 - (3) NASA/JSC-KX, Houston, TX, 77058, dana.m.lear@nasa.gov
 - (4) NASA/JSC-MV6, Houston, TX, 77058, justin.h.kerr@nasa.gov
 - (5) Hamilton Sunstrand/ESC Group, Houston, TX, 77058, frankel.lyons-1@nasa.gov
 - (6) Jacobs Engineering/ESC Group, Houston, TX, 77058, jason.s.herrin@nasa.gov
 - (7) Lunar and Planetary Institute, Houston, TX, 77058, ryan@lpi.usra.edu
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Abstract

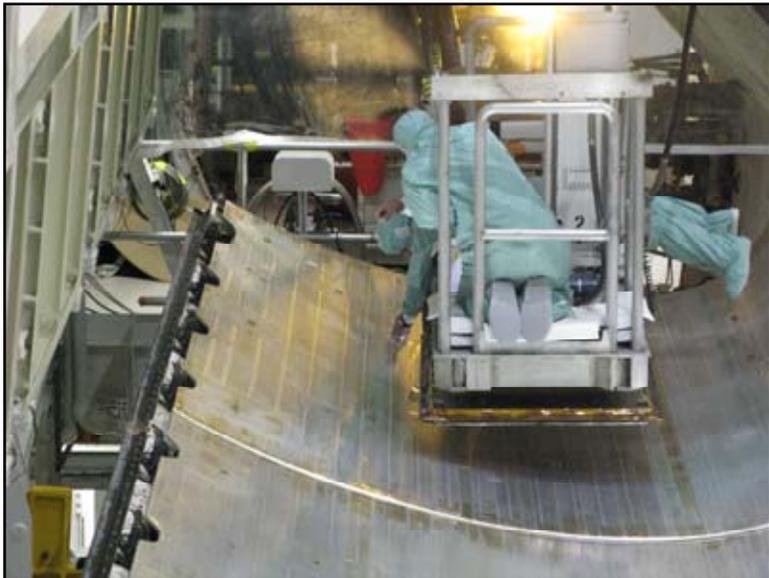
This paper documents the data collected from two hypervelocity micro-meteoroid orbital debris (MMOD) impact events where the shuttle payload bay door radiator sandwich panel was completely perforated. Scanning Electron Microscope/Energy-Dispersive x-ray Spectroscopy (SEM/EDS) analysis of impact residue provided evidence to identify the source of each impact. Impact site features that indicate projectile directionality are discussed, along with hypervelocity impact testing on representative samples conducted to simulate the impact event. The paper provides results of a study of impact risks for the size of particles that caused the MMOD damage and the regions of the orbiter vehicle that would be vulnerable to an equivalent projectile

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Introduction

NASA has flown the Space Shuttle for 122 flights through March 2008. As part of post-flight refurbishment activities, the Space Shuttle Orbiter vehicle is inspected for damage from micro-meteoroid and orbital debris (MMOD) impacts as well as other sources (ascent/landing debris impact, etc.). Hundreds of MMOD impact features have been documented on Orbiter vehicle surfaces, particularly the radiators, windows and wing leading edge (Ref. 4-6). Samples from the impact damage are routinely collected and examined via scanning electron microscope/energy dispersive x-ray spectrometric analysis (SEM/EDS) to assess whether the impact damage was caused by micro-meteoroid or orbital debris impact.

The Orbiter radiators (Figure 1) have several favorable qualities as witness plates to record MMOD impact damage. The silver-Teflon® thermal control coating of the radiators and uniform surface pattern of the radiator thermal tape permits the routine observation of defects as small as 1 mm in diameter. Also the large surface area (approximately 118 m²) of the radiators (front side only) increases the likelihood of experiencing an MMOD impact event. 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. In addition, since the



payload bay doors are closed prior to the shuttle returning to Earth, existing impact damage to the radiators are protected during re-entry. One drawback to the use of radiators as debris collectors is that commonly occurring aluminum orbital debris impactors can be difficult to discern in the SEM/EDS due to the strong aluminum “background” signature from the aluminum radiator face sheet.

Figure 1. Payload bay door radiator inspection.

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The payload bay door radiators are an important component of the Space Shuttle Orbiter active thermal control system. There is a total of eight individual 3.2m x 4.6m curved radiator panels per vehicle with four mounted on the inside of the payload bay doors on starboard and port sides of each the vehicle.

The forward radiator panels (labeled 1 and 2 in Figure 2) are an aluminum honeycomb sandwich construction with an overall thickness of 2.3 cm while the aft panels (3 and 4 in Figure 1) are 1.3 cm thick. The panels have 0.028cm thick 2024-T81 aluminum face sheets and 5056-H39 aluminum honeycomb cores. The 35.5° deployable forward radiator panels incorporate 68 parallel Freon-21 coolant tubes with 34 tubes per side, while the fixed aft panels are configured with 26 coolant tubes on one side. Figure 3 shows the locations of the coolant tubes in the panels. The figure also illustrates the aluminum doublers that have been added to the top of the flow tubes to augment protection from MMOD impacts (1).

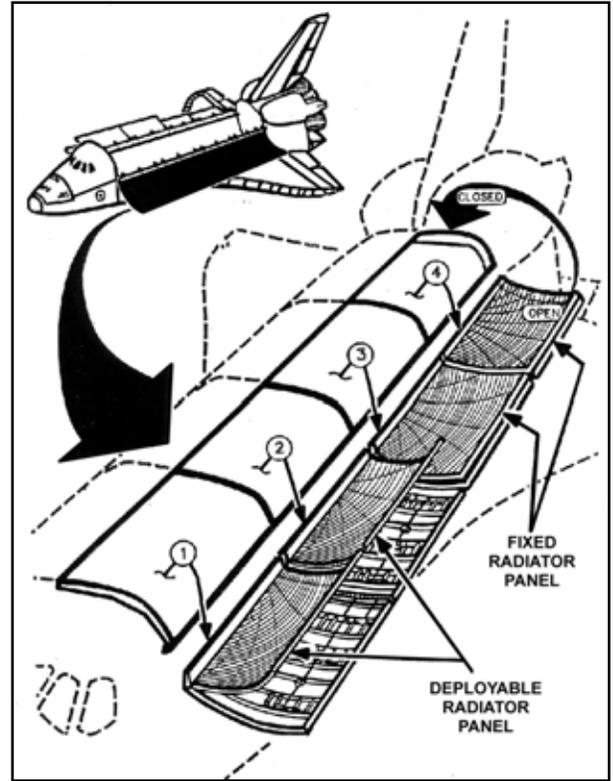


Figure 2. Orbiter radiator configuration.

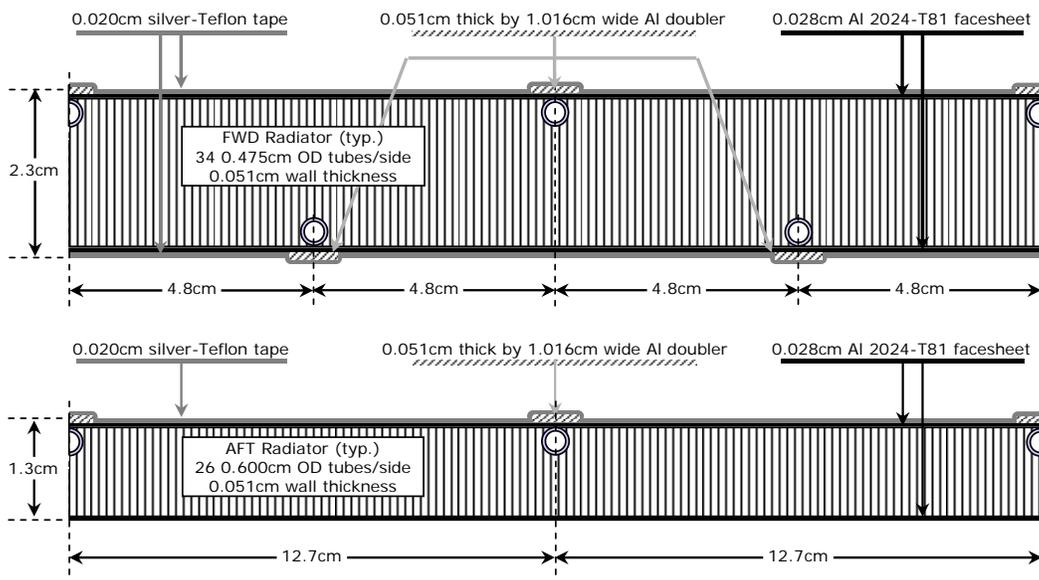
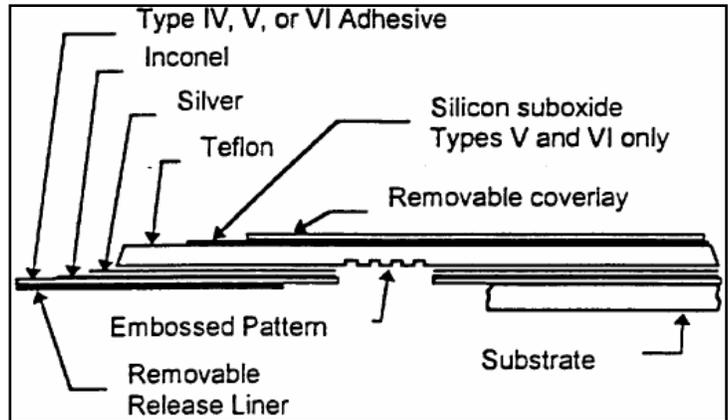


Figure 3. Radiator panel construction.

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Details of the type VI silver-Teflon® thermal control tape that covers the radiator face sheets can be found in figure 4 (2).

Figure 4. Cross section of silver-Teflon type VI tape.



Impact #1: STS-115 Right Hand Panel #4 (RH4) - Overview

Postflight inspections of shuttle OV-104 (Atlantis) at the Kennedy Space Center (KSC) following the STS-115 mission revealed a face sheet perforation near the hinge line on the RH4 payload bay door radiator panel (Figure 5). This was the largest of five MMOD impacts found on the radiators during the post STS-115 refurbishment flow. The general location of the damage site and the adjacent radiator panels can be seen in Figure 6.



Figure 5. STS-115 Radiator MMOD impact damage (front side).

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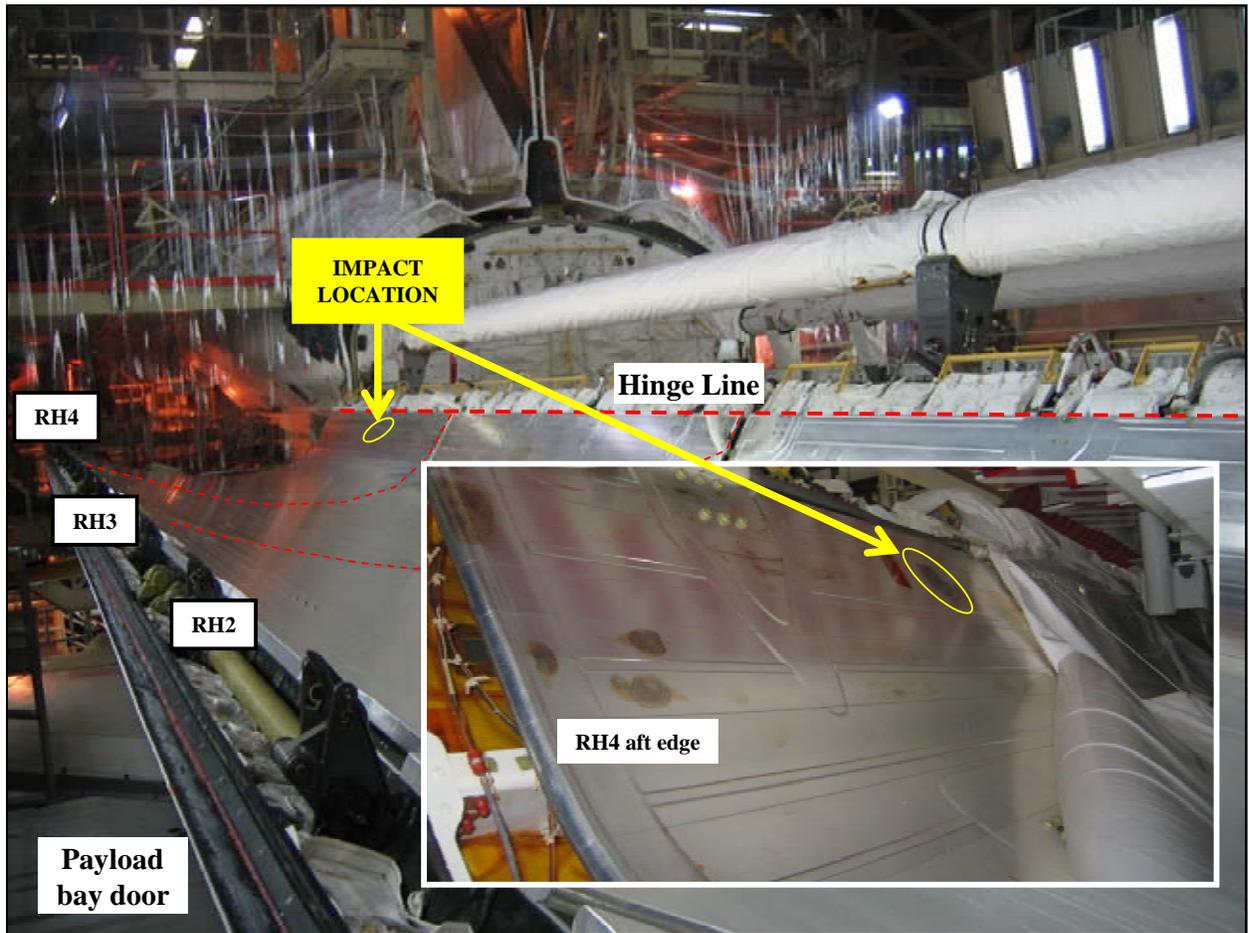


Figure 6. STS-115 panel RH4 impact location.

Measurements showed a 3.2 mm x 2.7 mm diameter entry hole in the face sheet. Figure 5 shows the initial front side damage, while figure 7 shows the front face sheet with the thermal tape removed in the area of damage. The right hand image in Figure 7 Ultrasonic testing indicated a maximum face sheet debond extent of approximately 25 mm from the entry hole. X-ray examinations revealed damage to an estimated 31 honeycomb cells with an extent of approximately 22 mm x 28 mm. Boroscope imaging through the entry hole (Figure 7) shows the orientation of the rear face sheet damage. Subsequent boroscope observations on the rear face sheet (Figure 8) show impact damage features including a 0.79 mm diameter hole, a ~1.3mm tall bulge and a larger ~5.1mm tall bulge that exhibited a crack over 6.8mm long.

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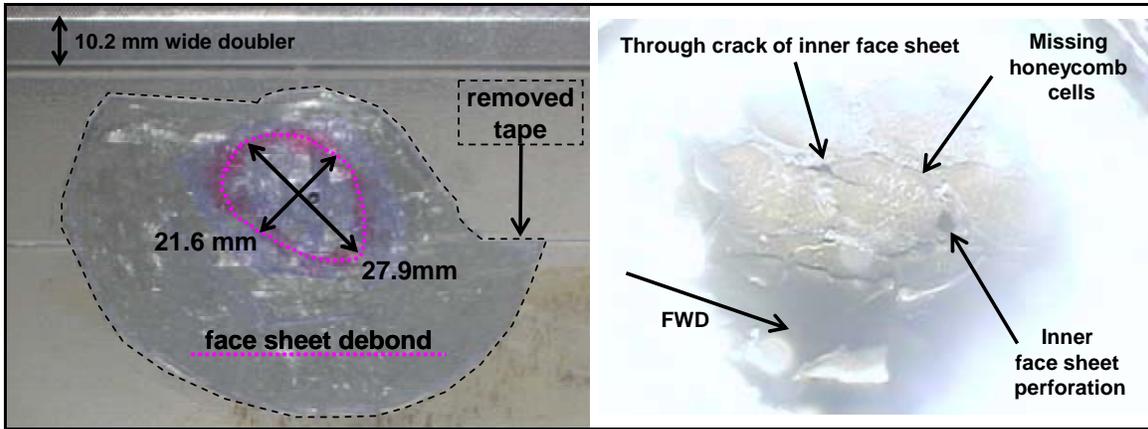


Figure 7. Front face sheet with thermal tape removed (left), view through entry hole into honeycomb panel (right).

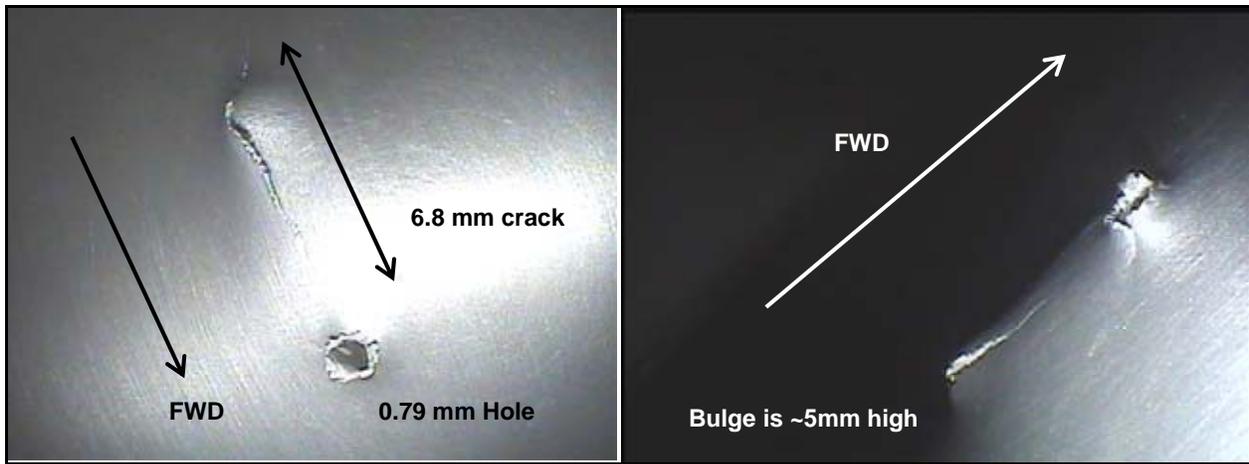


Figure 8. Two views of STS-115 RH4 rear face sheet damage.

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Impact #1: STS-115 RH4 - SEM/EDS Analysis

Several radiator sandwich panel components were recovered during the repair procedures at KSC including the thermal tape, front face sheet, honeycomb core, rear face sheet. These articles were examined at JSC using scanning electron microscope (SEM) with energy-dispersive x-ray spectrometry (EDS).

Figure 9. SEM images of hole in front face sheet. Asymmetric nature of lip can be seen in the oblique view.

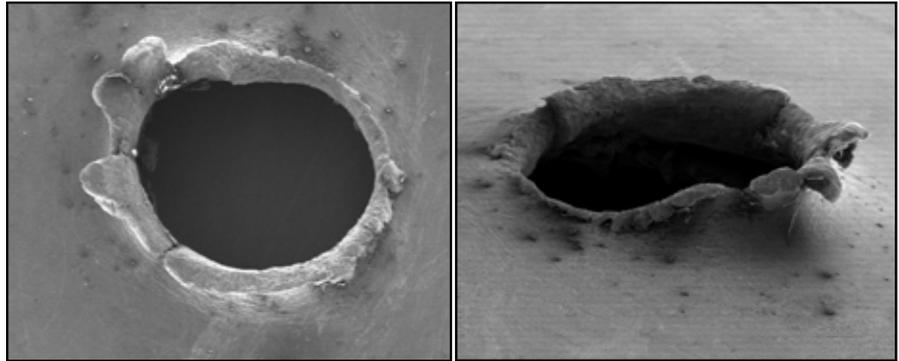
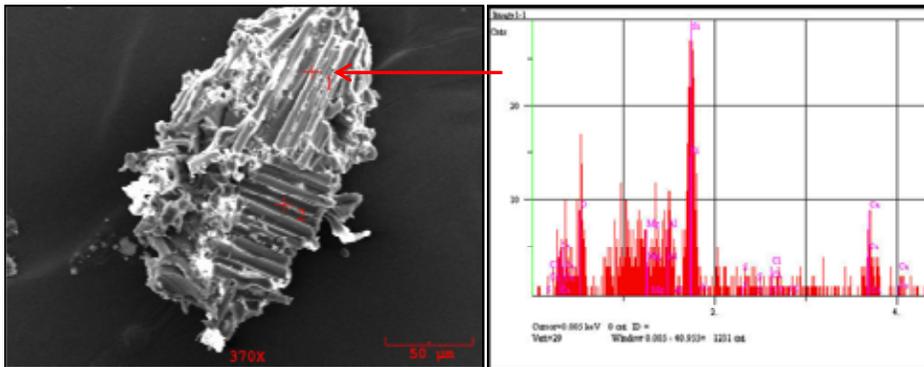


Figure 9 shows SEM images of the entry hole in the face sheet. The asymmetric height of the lip may be attributed to projectile shape and impact angle. Numerous instances of a ceramic fiber organic matrix composite were observed in the face sheet tape sample. The fibers were approximately 10 micrometers in diameter and variable lengths.

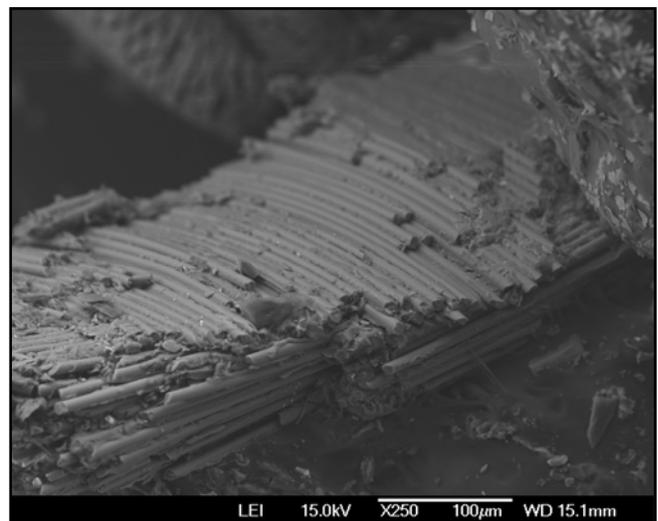


The fibers were approximately 10 micrometers in diameter and variable lengths.

Figure 10. Example SEM image and EDS spectra of circuit board fragment.

EDS analysis indicated a composition of Mg, Ca, Al, Si, and O. Figures 10 and 11 present images of the fiber bundles, which was believed to be circuit board material.

Figure 11. SEM image of circuit board fragment.



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Impact #1: STS-115 RH4 - Hypervelocity Impact Tests

A test program was conducted to simulate the observed damage to the radiator face sheet and honeycomb. Twelve test shots were performed using projectiles cut from a 1.6mm thick fiberglass circuit board (3). Results from test HITF07017, shown in figures 12 and 13, compares reasonably well with the observed impact features on the STS-115 radiator. The test was performed at 4.14 km/sec with an impact angle of 45 degrees using a 1.25 mm diameter cylindrical projectile with a length of 1.25 mm and mass of 2.53 mg. The fiberglass circuit board material has a density of 1.65 g/cm³.

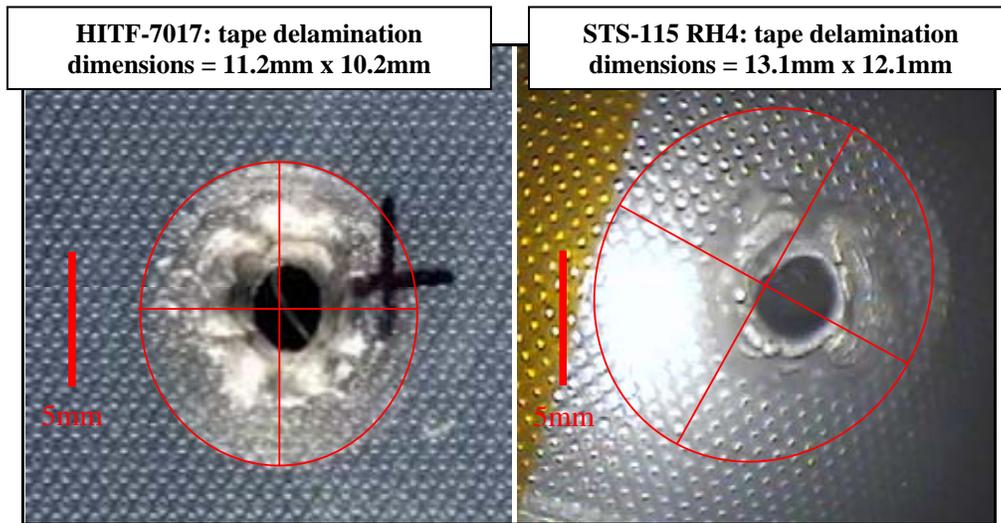


Figure 12. Entry hole in upper face sheet of NASA test HITF-7017 compared to STS-115 entry hole.

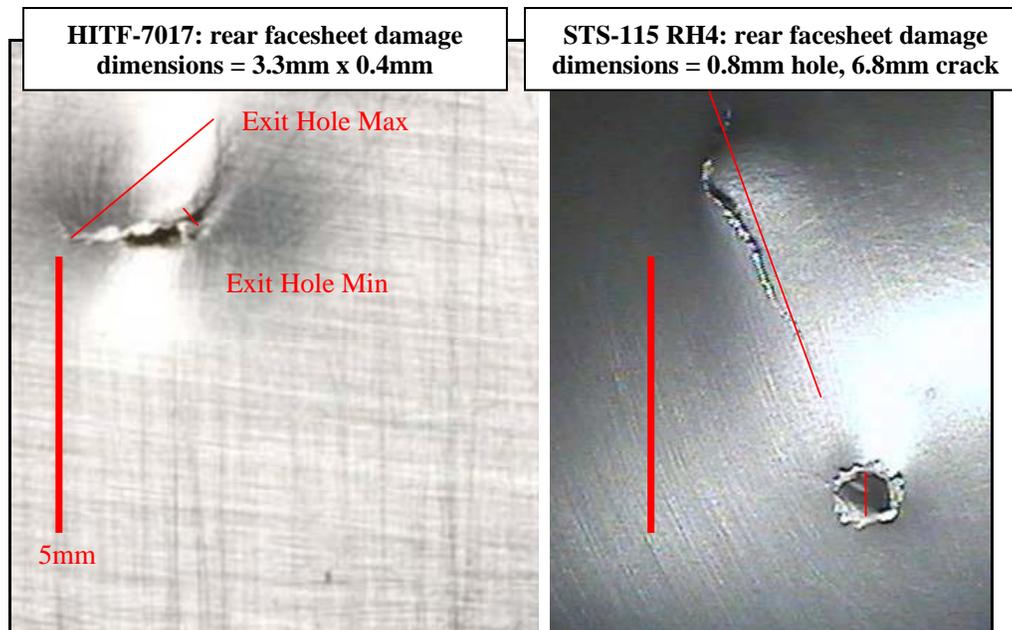


Figure 13. Exit hole in lower face sheet of NASA test HITF-7017 compared to STS-115 exit damage.

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Impact #1: STS-115 RH4 – Impact Risk

An analysis was performed using the Bumper code (9) to estimate the probability of impact to the shuttle from a 1.25 mm diameter particle. Table 1 shows a ~10% chance of a 1.25 mm or larger MMOD impact somewhere on the vehicle during a typical ISS mission (8).

Region	MMOD Impact Risk	Odds of Impact
Upper TPS	7%	1 in 15
Lower TPS	1.7%	1 in 59
Radiators	1.6%	1 in 62
Wing Leading Edge and Nose Cap RCC	0.4%	1 in 260
Windows	0.04%	1 in 2500
Total Vehicle	10%	1 in 10

Table 1. MMOD impact risk for a typical shuttle mission to ISS from particles 1.25 mm and larger.

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Impact #2: STS-118 Left Hand Panel #4 (LH4) - Overview

During the August 2007 STS-118 mission to the International Space Station, an MMOD particle impacted and completely penetrated a radiator panel and the underlying TCS blanket of shuttle OV-105 (Endeavour), leaving deposits on (but no damage to) the graphite epoxy sandwich panel payload bay door. Figure 14 illustrates the approximate location of the impact near the hinge line on the port side aft radiator panel (LH4). While it is not unusual for orbiters to be impacted by small MMOD particles, the damage from this impact is larger than any previously documented on the shuttle radiator panels.

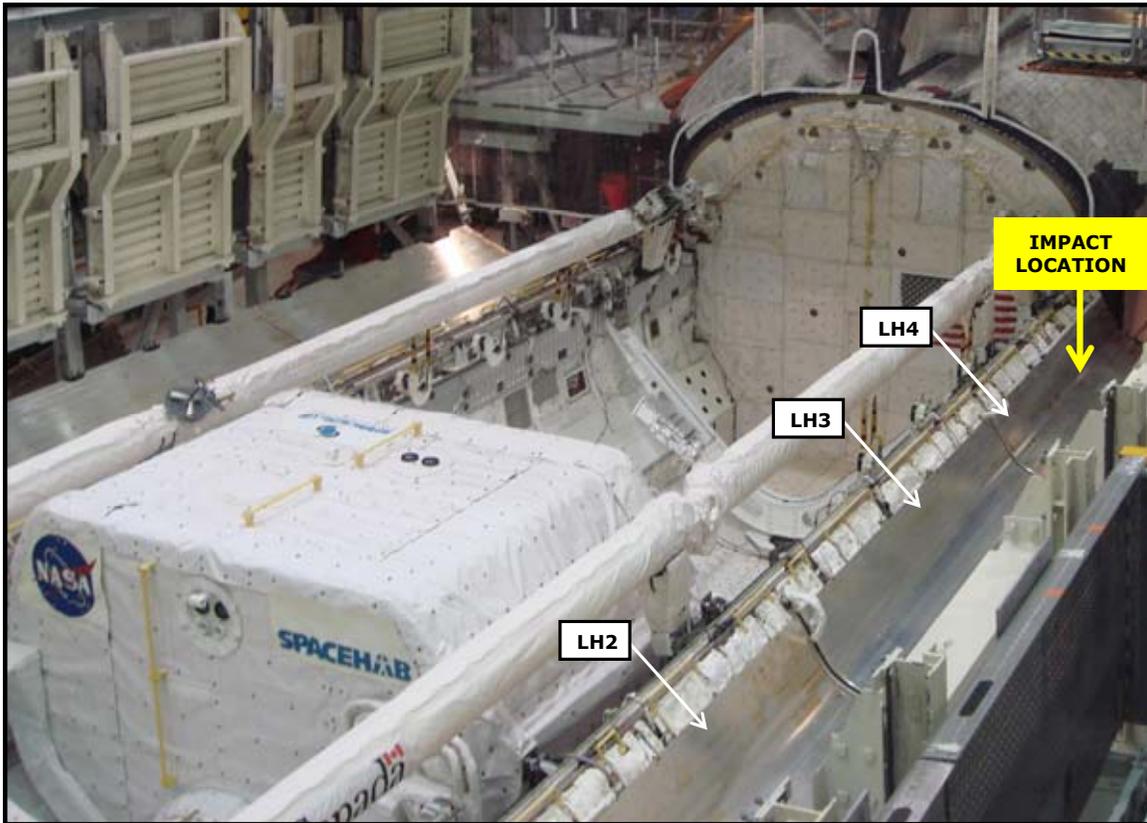


Figure 14. STS-118 panel LH4 impact location.

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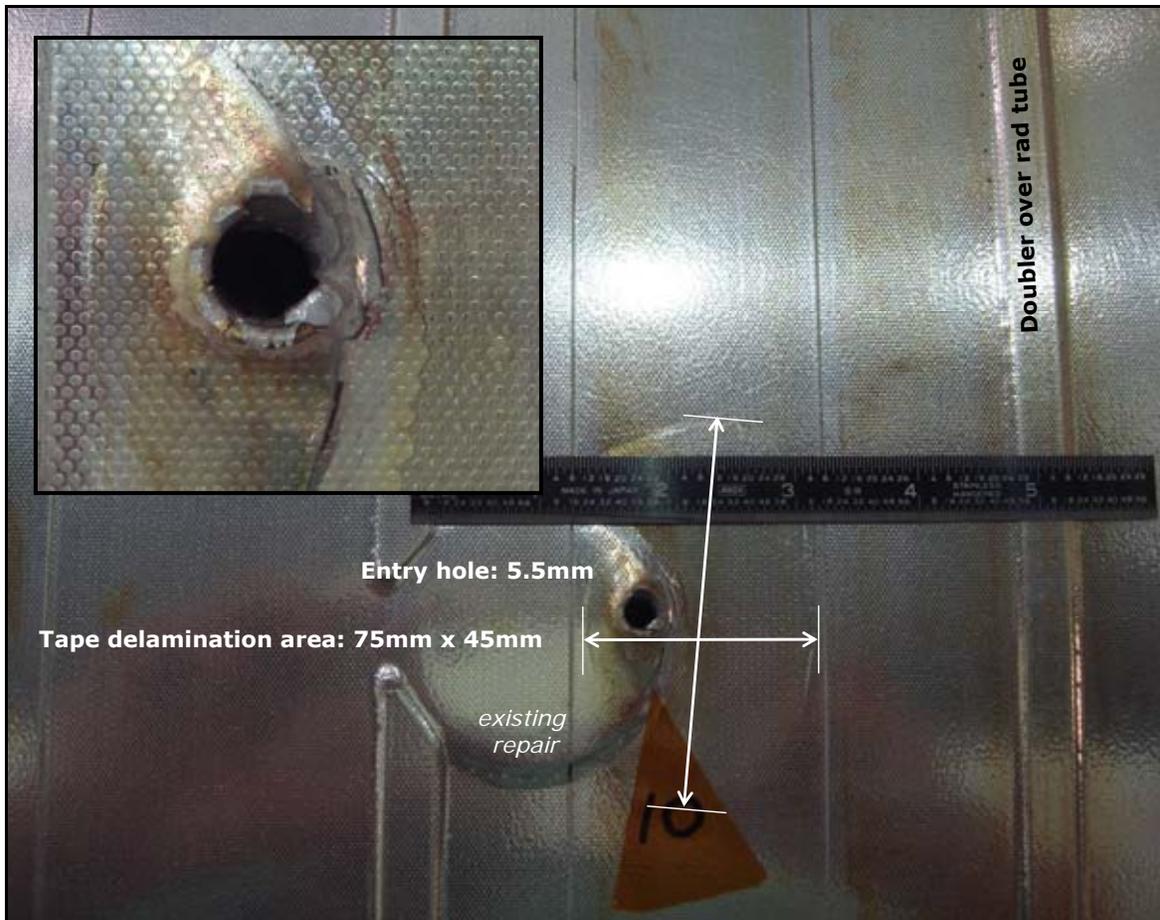


Figure 15. STS-118 LH4 entry hole.

A close-up photograph of the radiator impact entry hole is shown in Figure 15. The entry hole in the outer radiator face sheet measured 5.5 mm in diameter. The impactor also perforated an existing 0.305 mm doubler that had been bonded over the face sheet to repair previous damage. The resulting debris cloud caused considerable damage to the internal honeycomb core with approximately 20 honeycomb cells having been either completely destroyed or damaged.



Figure 16. STS-118 LH4 exit hole.

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Figure 16 is a view of the exit hole in the rear face sheet, and partially shows the extent of the honeycomb core damage and clearly shows the jagged “petaled” exit hole through the backside face sheet. The rear face sheet exit hole measured approximately 12 mm by 19 mm. The remnants of the impacting particle and radiator panel material transported through the rear face sheet hole perforated the TCS blanket approximately 125 mm behind the rear face sheet.

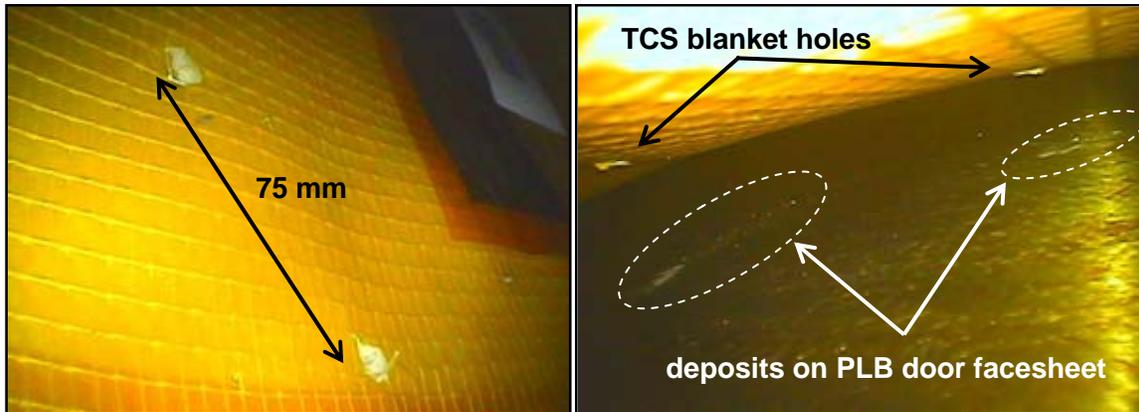


Figure 17. TCS blanket damage under STS-118 LH4.

Figure 17 shows these two impacts, which are located approximately 75 mm apart. The boroscope image on the left shows the area under the exit hole in radiator sandwich panel. The boroscope image on the right was acquired on the opposite side of the blanket between the TCS blanket and the payload bay door sandwich panel face sheet. Two exit holes can be seen in the blanket and residue can be seen on the graphite/epoxy face sheet of the payload bay door beneath the TCS blanket, but no additional damage was detected on the face sheet.

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Figure 18 illustrates the relationship of the face sheet entry hole to the TCS blanket damage, which may indicate the direction of the impacting particle. The image on the left side of figure 18 shows an overhead view of the damaged radiator after the face sheet holes were cored out of the panel. The entry hole location and the two underlying TCS blanket damage sites are annotated on the image. Section A-A, running through the entry hole and TCS blanket damage locations, describes a 25° angle from the longitudinal axis of the shuttle. The 2nd impact angle can be seen in section A-A on the right side of figure 18. An average 18° angle of impact to the surface normal was derived by measuring the angles of the two damage sites in TCS blanket to the entry hole. The damage offset between panel damage and blanket damage indicates impact direction was forward to aft of vehicle (with a 25° impact angle bias to the longitudinal axis). However, the 18° impact angle from surface normal was likely influenced by channeling effects of the honeycomb, and a more oblique impact angle could be possible.

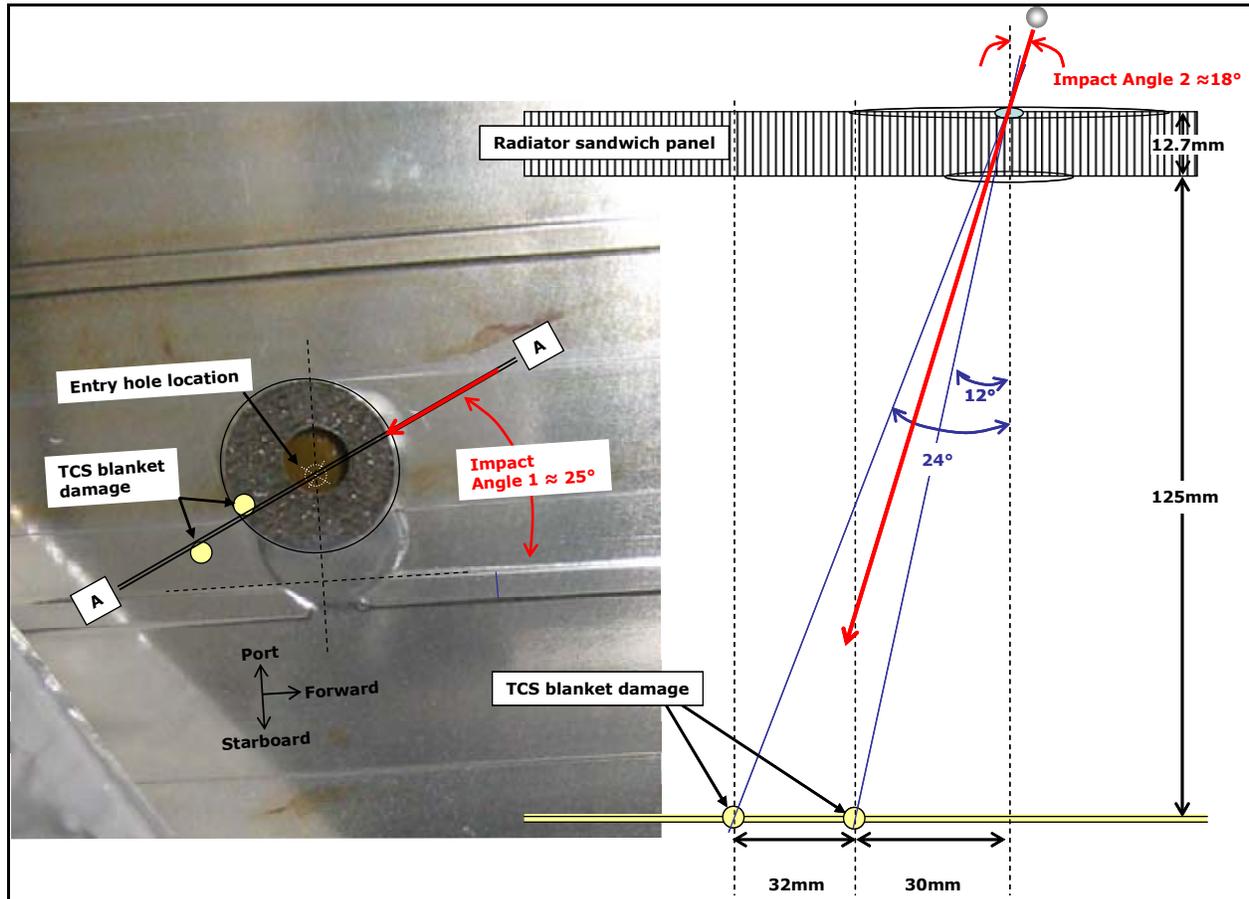


Figure 18. STS-118 LH4 estimated impact angles.

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Impact #2: STS-118 LH4 - SEM/EDS Analysis

Sample collection steps were inserted into the repair procedure. Six different areas were sampled during the repair operation (Figure 19). Intact samples were collected of the outer thermal tape, outer face sheet, honeycomb core, and rear face sheet. Swabs of the two impact damage areas on the TCS blanket were also collected. Micro-meteoroid and orbital debris impacts usually leave residual particulate from the impactor material in and around the damaged area. This residue is collected, analyzed, and in many cases, a determination can be made as to the impactor source as micro-meteoroid or orbital debris. In some cases, specific types of orbital debris particles can be identified, such as rocket propellant or electrical components. To perform this analysis, the samples were transferred to the NASA Johnson Space Center (JSC) Hypervelocity Impact Technology Facility (HITF) in Houston, Texas. Scanning Electron Microscope (SEM) equipped with energy-dispersive x-ray spectroscopy (EDS) tools were used to identify potential residue material from the impactor and to identify the elemental makeup of the impactor. Results from the analysis indicate that the impacting particle was a titanium-rich orbital debris particle containing traces of zinc and antimony (Figure 19).

Figure 19. Sample collection and results of SEM/EDS analysis.

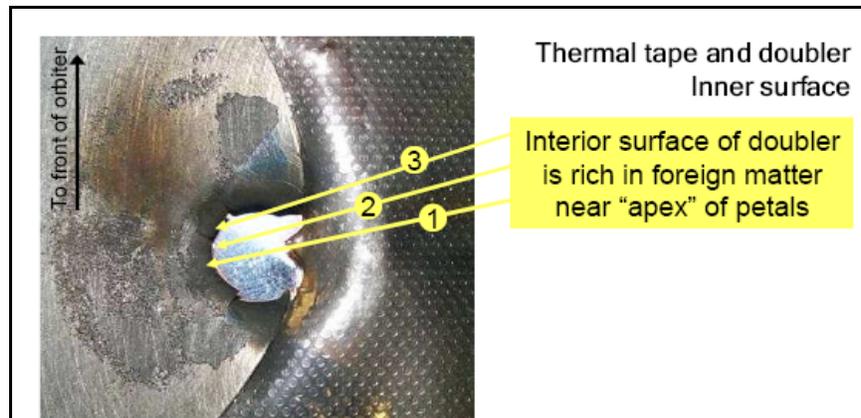
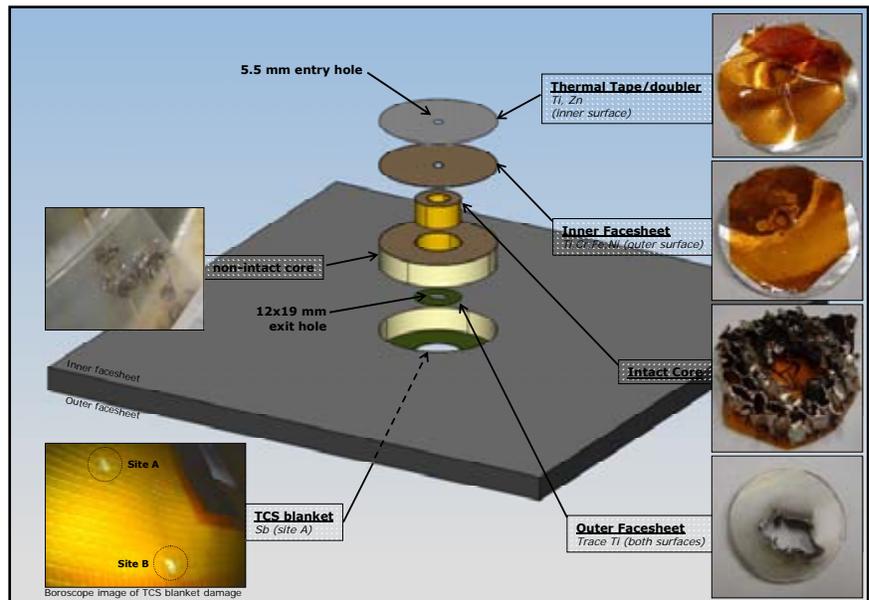


Figure 20. SEM/EDS analysis of tape and inner surface of doubler.

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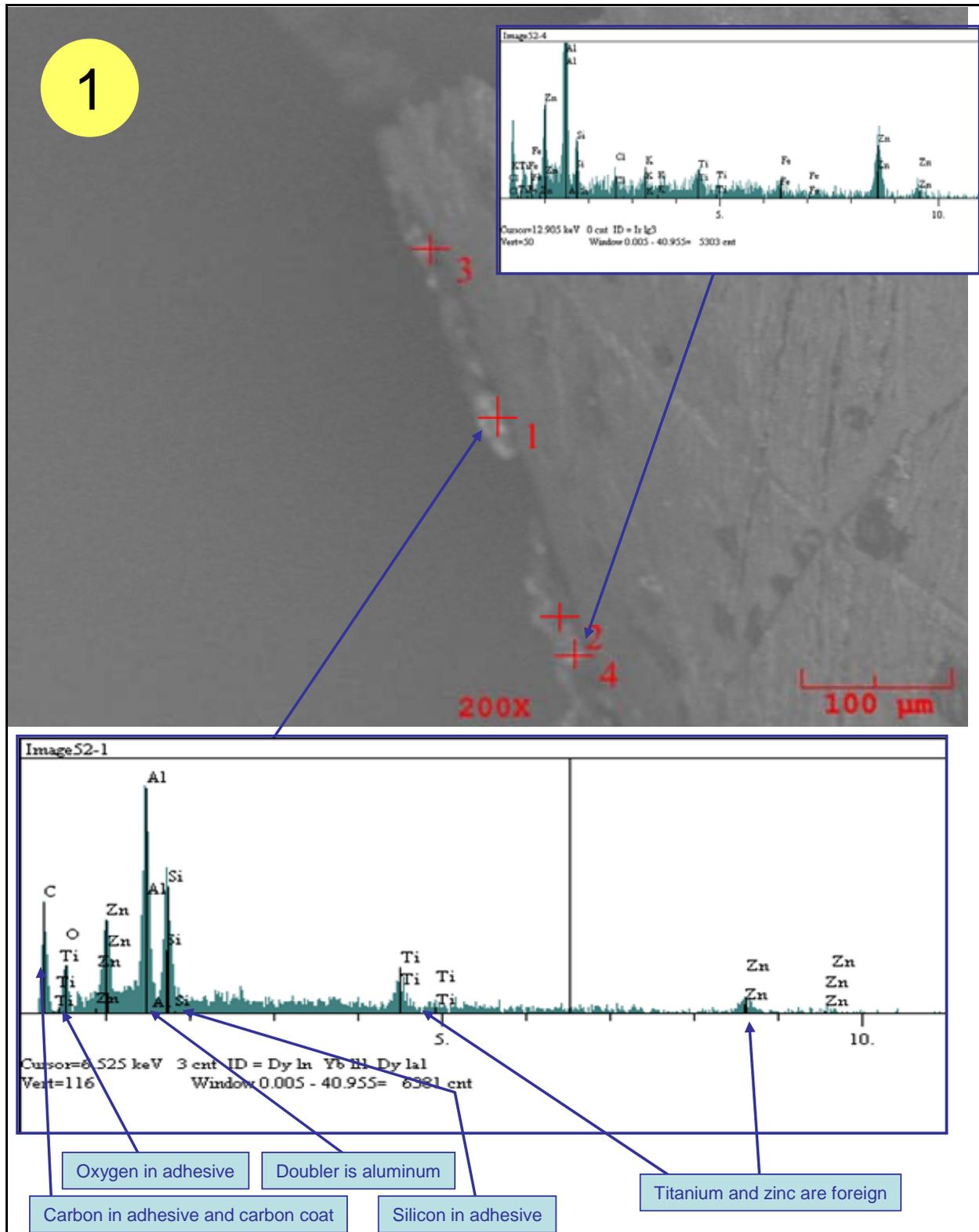


Figure 21. SEM/EDS analysis results of tape and inner surface of doubler (Area #1).

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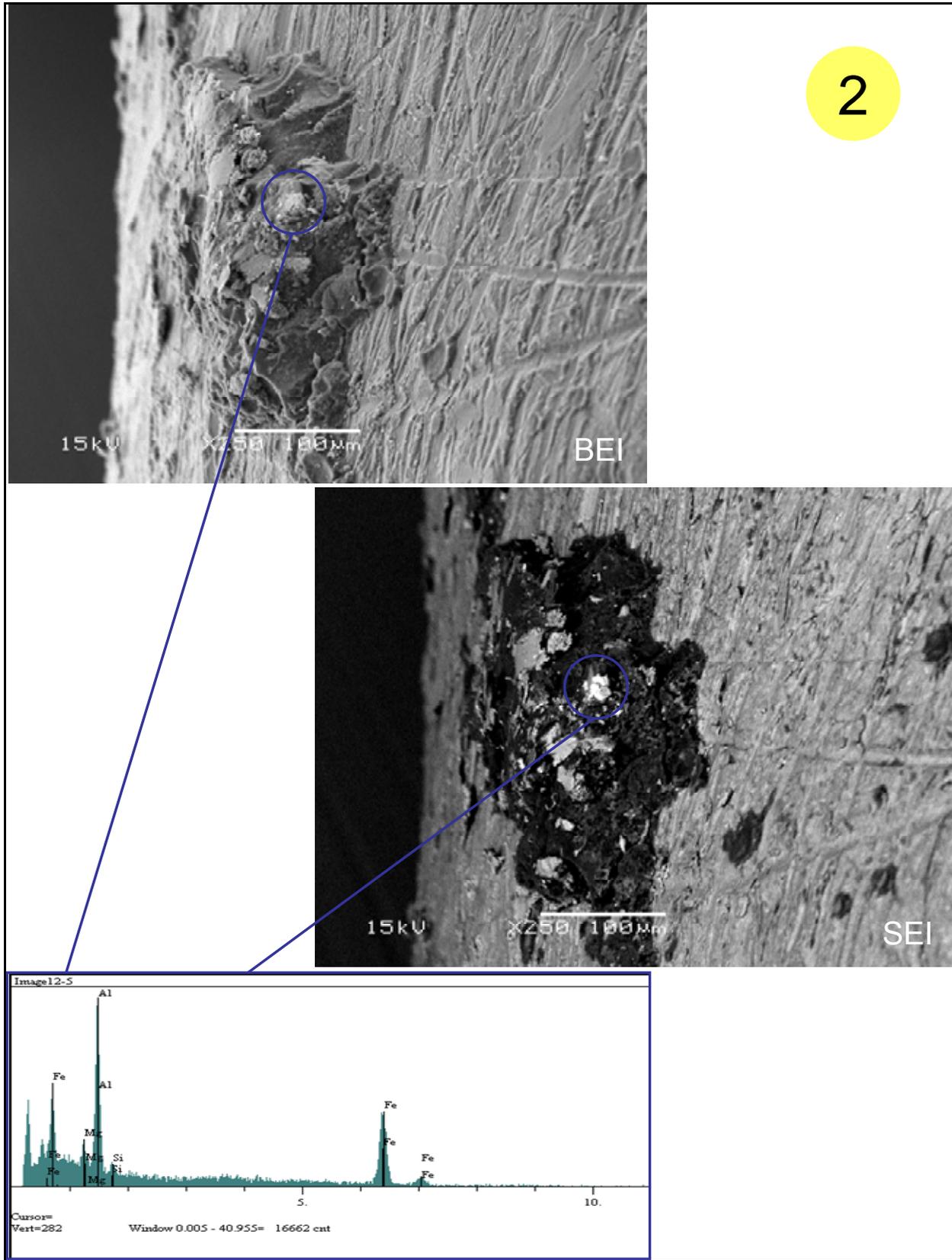


Figure 22. SEM/EDS analysis results of tape and inner surface of doubler (Area #2).

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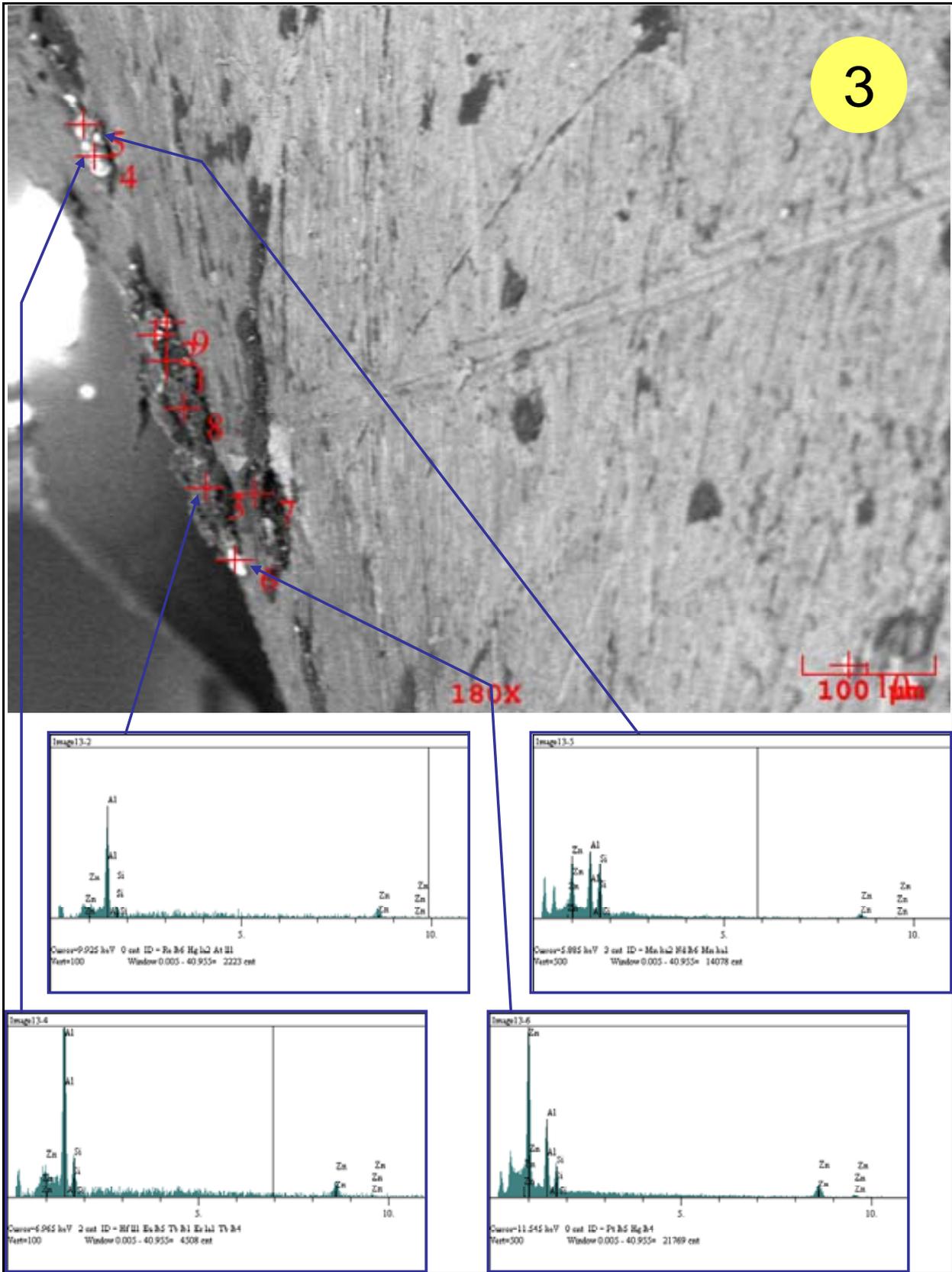


Figure 23. SEM/EDS analysis results of tape and inner surface of doubler (Area #3).

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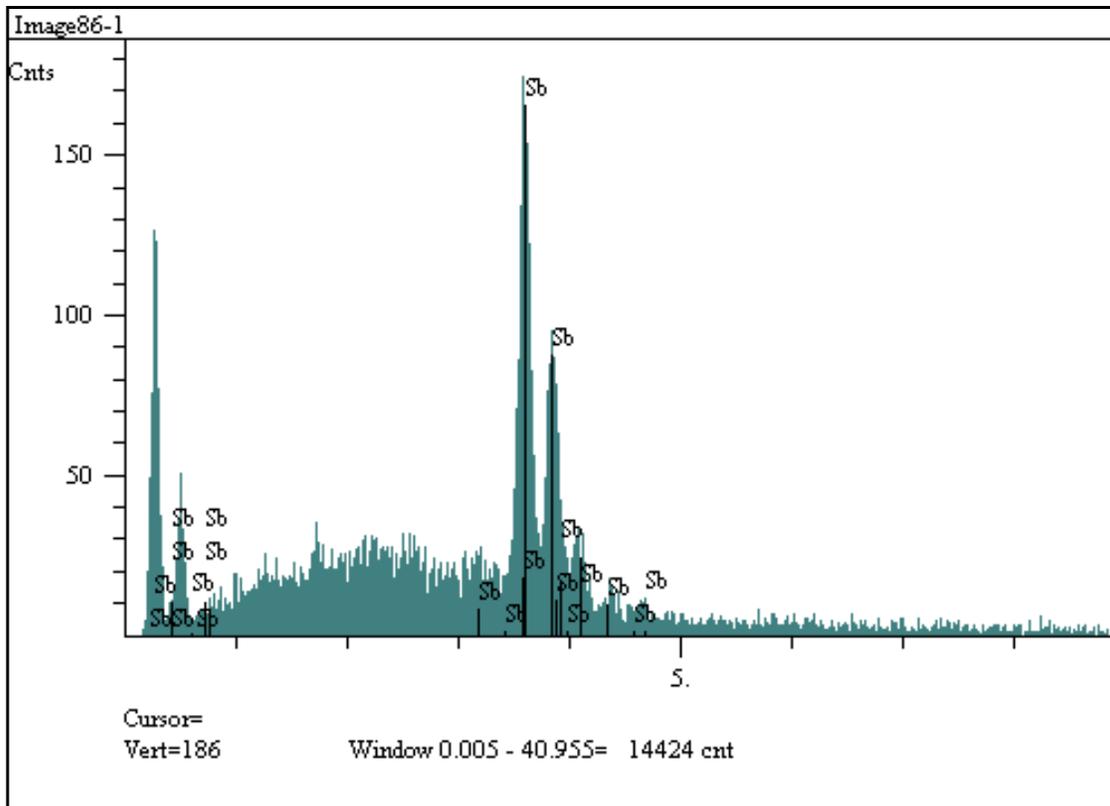
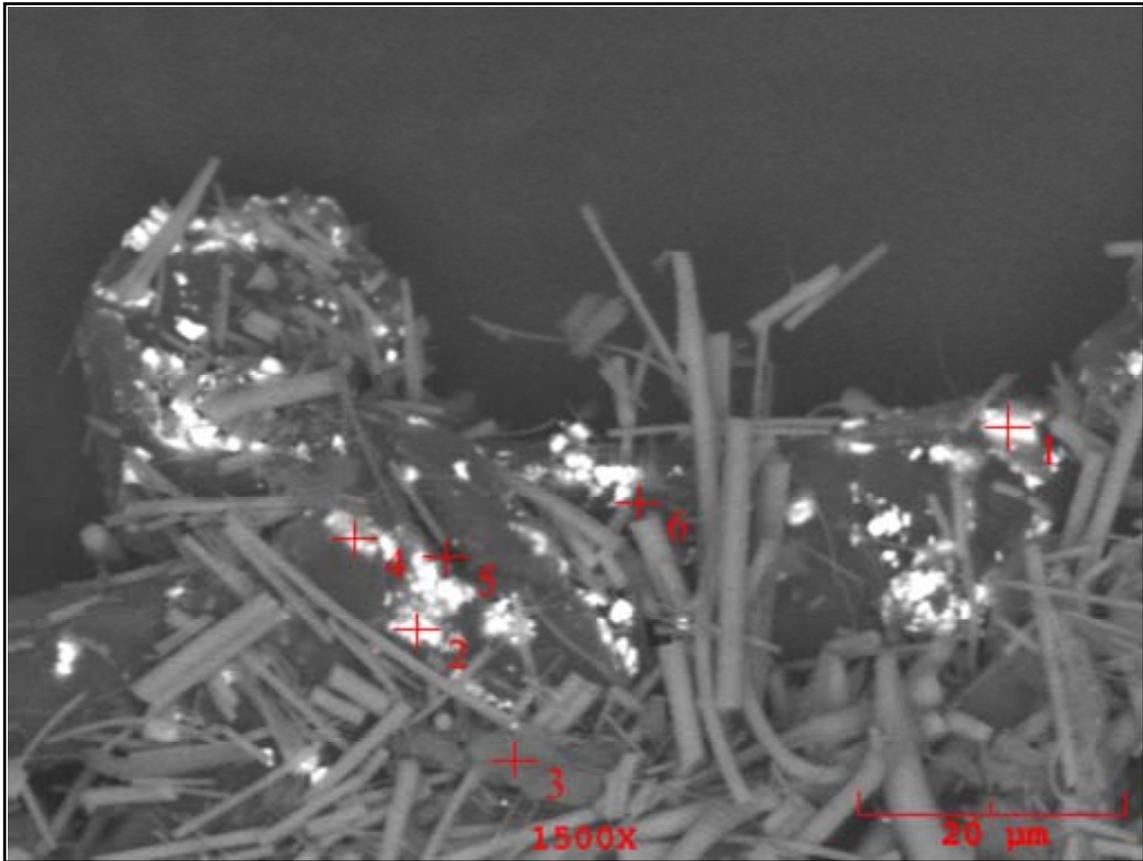


Figure 24. SEM/EDS analysis results, showing Sb intermingled with TCS blanket fibers.

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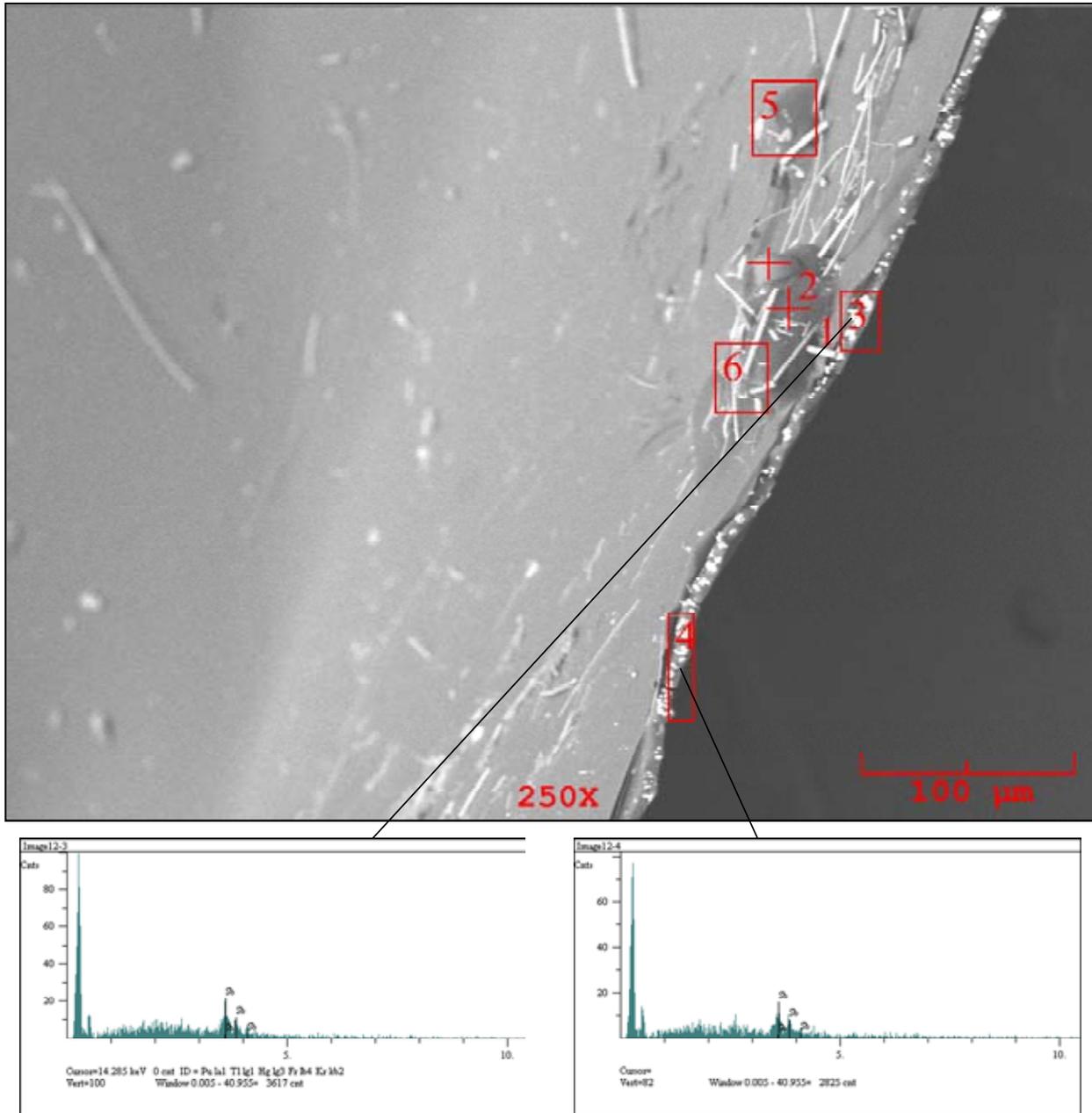


Figure 25. SEM/EDS analysis results of TCS blanket, showing Sb concentrations along some edges of surface layer.

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Impact #2: STS-118 LH4 – Hypervelocity Impact Tests

As with the STS-115 RH4 panel, a hypervelocity impact test program was performed in order to simulate the damage observed on the LH4 radiator panel of STS-118. A series of five impact tests were performed at the White Sands Test Facility (WSTF) using spherical aluminum (2017-T4) projectiles with a density of 2.79 g/cm². This density was considered representative of the titanium-heavy impactor material determined from the SEM analysis. All tests were performed at 45° incidence with velocities ranging from 6.79-7.09 km/s. Results from test HITF-7455 show the most favorable comparison with the RH4 radiator impact damage features. This test was performed at 6.79 km/s with a 1.42mm diameter projectile. The entry hole in the test (Figure 26) measured 8.5 mm × 8.2 mm, 50% larger than the entry hole observed on the flight hardware. There were three independent exit holes in the test, the largest of which measured 4.0 mm × 4.9 mm, less than a third of the size of the observed damage. About the perforation holes, the rear face sheet is bulged over an area measuring ~19 mm × 24 mm (Figure 27). It is considered that with a small increase in impact kinetic energy, the face sheet would exhibit a similar tearing failure mode as that observed on the flight hardware. The aluminum witness plate used in the test (Figure 28) showed a small number of fragment deposits and one 150µm deep crater which is comparable to the deposits found on the payload bay door.

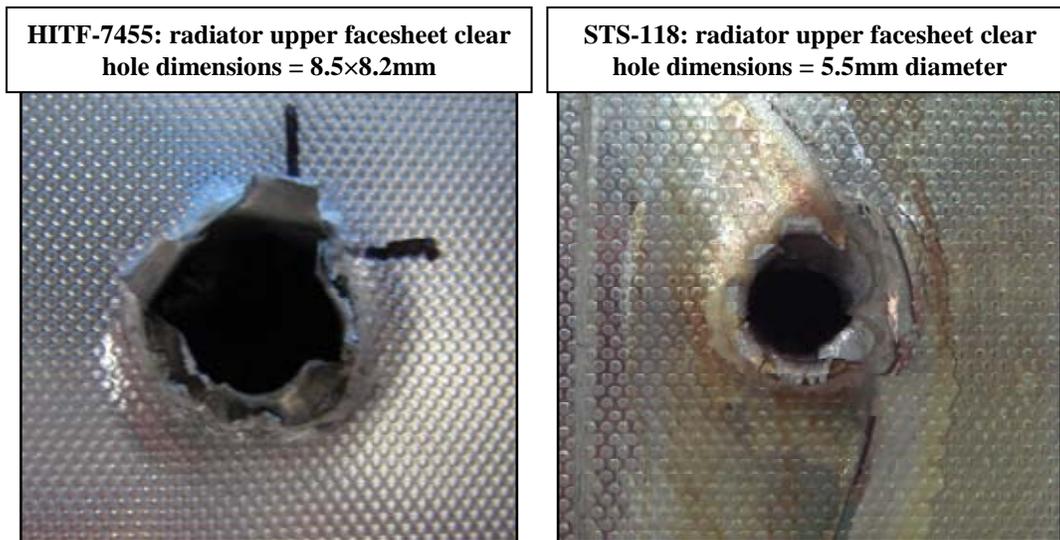


Figure 26. Entry hole in upper face sheet of NASA test HITF-7455 compared to STS-118 entry hole.

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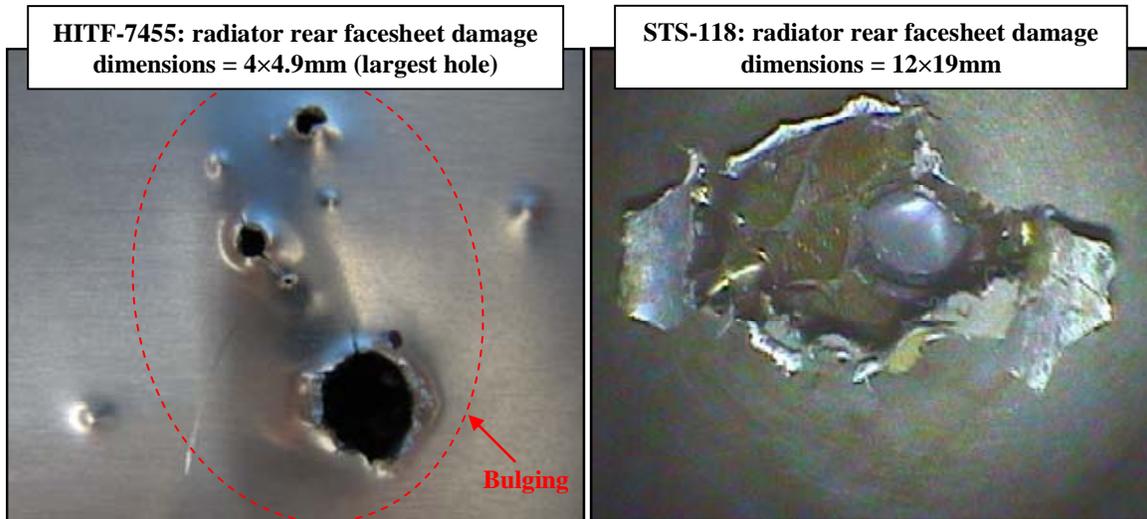


Figure 27. Exit damage in lower face sheet of NASA test HITF-7455 compared to STS-118 exit damage.

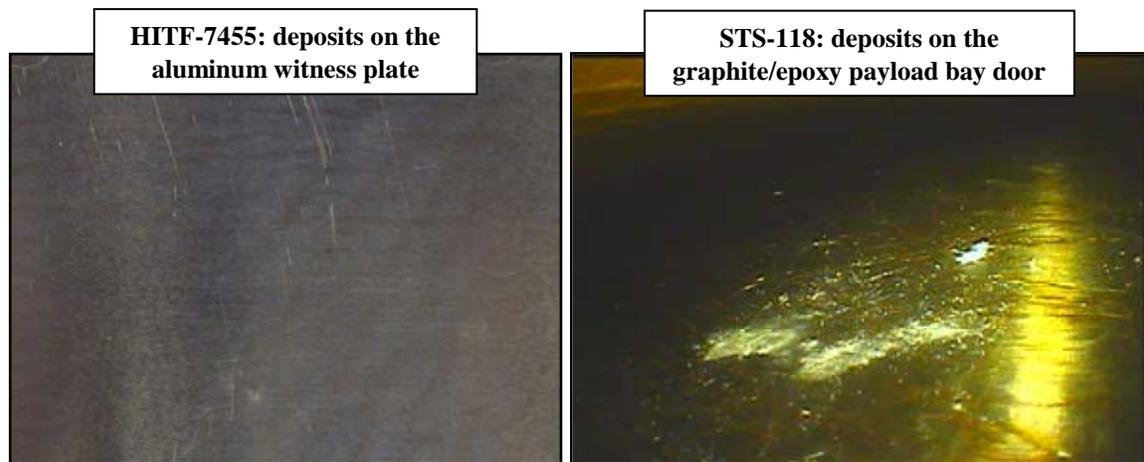


Figure 28. Witness plate damage of NASA test HITF-7455 compared to STS-118 graphite/epoxy payload bay door damage.

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Impact #2: STS-118 LH4 – Impact Risk

An analysis was performed using the Bumper code (9) to estimate the probability of impact to the shuttle from a 1.6 mm diameter particle. Table 2 shows a ~2.5% chance of a 1.6 mm or larger MMOD impact somewhere on the vehicle during a typical ISS mission (7).

Region	MMOD Impact Risk	Odds of Impact
Upper TPS	1.2%	1 in 81
Lower TPS	0.8%	1 in 127
Radiators	0.4%	1 in 285
Wing Leading Edge and Nose Cap RCC	0.1%	1 in 777
Windows	0.01%	1 in 8731
Total Vehicle	2.5%	1 in 40

Table 2. MMOD impact risk for a typical shuttle mission to ISS from particles 1.6 mm and larger.

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Discussion

A summary of the two face sheet perforations is presented below in table 3. The radiator sandwich panel hypervelocity impact damage characteristics documented in this paper are a function of a number of parameters:

- impact velocity and angle
- projectile size, density and shape
- face sheet thickness at impact site

Impact	Face Sheet	Entry Hole	H/C Damage	Exit Hole	Exit Damage
#1 STS-115 OV-104 RH4	0.28 mm	3.2 mm x 2.7 mm	~20 cells	0.76 mm x 0.76 mm	5.1mm bulge 6.8mm crack
#2 STS-118 OV-105 LH4	0.30 mm + 0.28 mm	5.5 mm x 5.5 mm	~20 cells	12 mm x 19 mm	TCS blanket holes

Table 3. Comparison of STS-115 and 118 radiator face sheet perforations.

Bumper code predictions have indicated that the odds of the orbiter radiators sustaining an impact from a particle large enough to perforate them are about 1 in 62. In other words, the expected radiator perforation rate is about once every 62 flights. With 122 shuttle flights completed and two radiator perforations recorded, the observed events correlate well with analytical predictions.

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After the Columbia accident, NASA implemented an alternate Space Station docking attitude strategy for the shuttle. With the intent of protecting the lower surfaces of the wing leading edge reinforced carbon-carbon (RCC) panels from MMOD damage (Figure 30), the shuttle/station stack is now rotated 180° about the station yaw axis (Figure 29). While significantly reducing the loss of crew/vehicle risk while docked to station, the change from a “belly forward” attitude to a “belly aft” attitude orients the payload bay door radiators more directly into the orbital debris flux. This contributes to a higher impact risk for the upper surfaces of the vehicle, which would include the radiators.

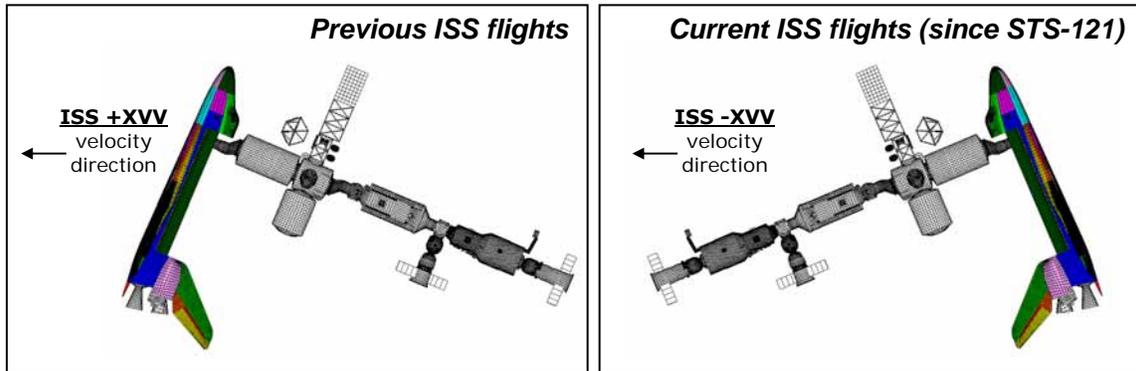


Figure 29. Post STS-114 changes in orbiter docking attitude.

The MMOD critical failure criteria for the orbiter wing leading edge RCC were updated for Bumper risk assessments performed on STS-114 and subsequent missions (Figure 28) after testing and analysis indicated that certain areas of the RCC were very sensitive to hypervelocity impact damage. The highlighted red, orange, yellow & light green areas in figure 30 would have experienced critical damage if impacted by a particle such as the one that hit the RH4 radiator panel on STS-115 or the LH4 panel during STS-118.

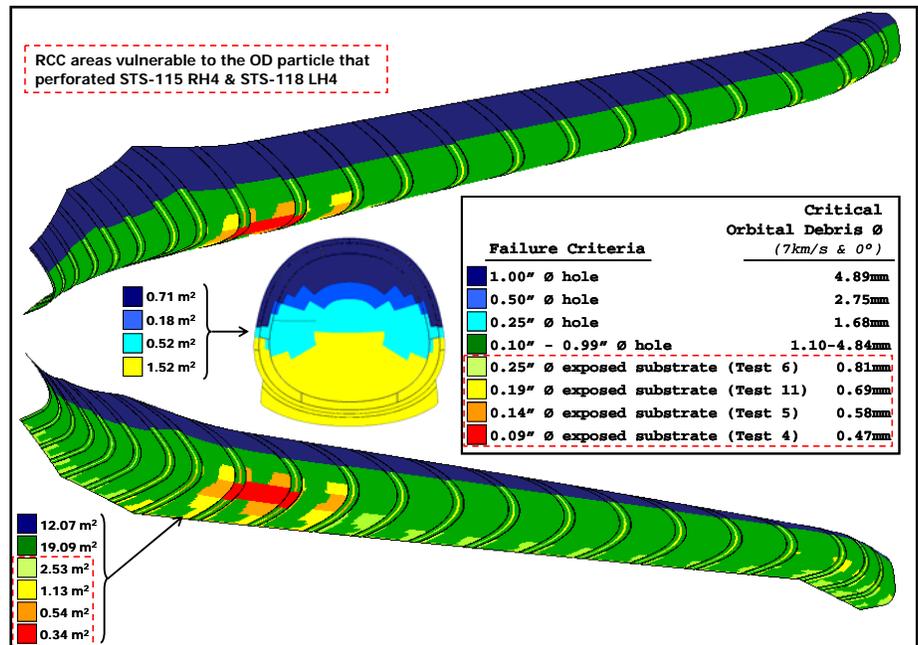


Figure 30. MMOD failure criteria for RCC: wing leading edge, nose cap & chin panel.

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- Z.P. Shaw (Department Manager)

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