

Hypervelocity Impact Characterization on Hubble Space Telescope Multi-Layer Insulation

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Abstract

Multi-layer insulation (MLI) is a common material used on rocket bodies and spacecraft to provide thermal regulation. This material is typically attached on the surface of the object in orbit and is thus exposed to the space environment and to micrometeoroid and orbital debris (MMOD) impacts. Occasionally, these exposed surfaces are returned and used by NASA's Orbital Debris Program Office (ODPO) for analysis. When used to assess impacts on surfaces over time, materials like MLI provide an opportunity for *in-situ* measurements to support the Orbital Debris Engineering Model (ORDEM) development and validation. During the 2009 Hubble Space Telescope (HST) Serving Mission, the MLI blankets covering the HST electronics bays 5, 8, and 10 were removed and subsequently analyzed by the ODPO in 2010. The bay 5 blanket was used in concert with ground-based hypervelocity impact tests on single layer MLI to validate the ORDEM 3.1 computer model of the OD environment, but further research was required to properly differentiate the impact features attributed to MM or OD. The ORDEM 3.1 validation effort identified several areas of further study to improve model validation and understanding of the space environment. Among these topics are the effects of underlying MLI layers on first layer impact feature characteristics, the effects of space weathering and associated damage to the surface on impact feature characteristics, and the transition from perforating to cratering regions. To better understand hypervelocity impact damage and long-term degradation of MLI surfaces, further hypervelocity impact testing was proposed and completed from 2020 to 2022. This paper discusses test conditions and parameters with resultant impact hole analyses of single layer versus multi-layered samples, space-exposed samples versus pristine, equivalent samples, and perforation versus cratering criteria in the difficult transition region. Damage equations, with associated uncertainties, are estimated from the test parameters and presented. The results of a feasibility study are described, in which the scanning electron microscopy/electron dispersive x-ray was used to examine the MLI layers to differentiate MM and OD impacts. Finally, the extension of HST MLI outcomes and analysis methodology as it applies to future returned MLI samples is discussed.

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1 Background

Multilayer insulation (MLI) is commonly used to protect spacecraft surfaces from the space environment's thermal changes and to provide protection from small micrometeoroid and orbital debris (MMOD) penetrating impacts. MLI covering the surface of the Hubble Space Telescope (HST) electronic bays 5, 8, and 10 was exposed to the space environment for a substantial time span (MLI on bay 5 and 8

was exposed for 19 years; bay 10 was exposed for 9.8 years). The HST MLI's large surface area and orbit altitude in low Earth orbit (LEO) provides historical *in-situ* MMOD data that can be used to improve interpretation on impact features for returned surfaces, as well as to validate space environment models, such as the Orbital Debris Program Office (ODPO)'s Orbital Debris Engineering Model (ORDEM). Successful validation work can be found in previous studies [1]. The validation effort also identified areas that needed to be further tested and studied. Hypervelocity impact (HVI) testing was proposed as an extension of the previous U.S. Government fiscal year 2010 (FY10) study in the 2019–2023 timeframe and completed in 2023. In this paper the effects to underlying MLI layers due to first layer impacts/penetrations are analysed, in addition to the characterization of these thin layers in reference to space weathering and impact morphology. During the characterization process, a new investigation was conducted to determine if the type of mounting attachment of the MLI in orbit manifests in the tension force or tautness that could potentially modify the impact characterization. As well, the previous study did not attempt to distinguish MM from OD, thus a feasibility study was completed using field emission scanning electron microscopy (FESEM) coupled with energy-dispersive x-ray spectroscopy (EDX), to determine if any impactor residue on the MLI could be identified.

2 Microscopy

Samples were excised from the HST bay 5 MLI (identified as “exposed HST”) and constructed pristine MLI samples (similar to HST MLI) for use during HVI testing. Exposed HST samples consist of a 17-layer MLI stack of 5 mil (127 μm) thick vapor deposited aluminum (VDA)-Teflon™ outer layers and 15 0.3 mil (7.62 μm) VDA-polyimide inner layers (the trademarked Teflon brand is manufactured by Chemours Company FC, LLC). The pristine samples' two outermost layers of the MLI were Teflon 126 μm thickness and the 15 inner layers aluminized polyimide, (10 μm thickness). In simulating the HST MLI, it was not possible to simulate the embossing of the inner layers, used to separate the inner layers in lieu of the more common artificial fiber netting. Impact features were characterized using non-destructive evaluation techniques: imaging, measuring diameters, and recording data from the MLI samples using a Keyence VHX-7000 digital microscope. Based on previous analysis as discussed in [1], the measurements of every impact feature on every perforated layer and the first non-perforated layer of MLI samples was conducted to calculate the outer diameter, as shown in Fig. 1. This measurement is critical for analysis to determine projectile size that directly supports ORDEM development.

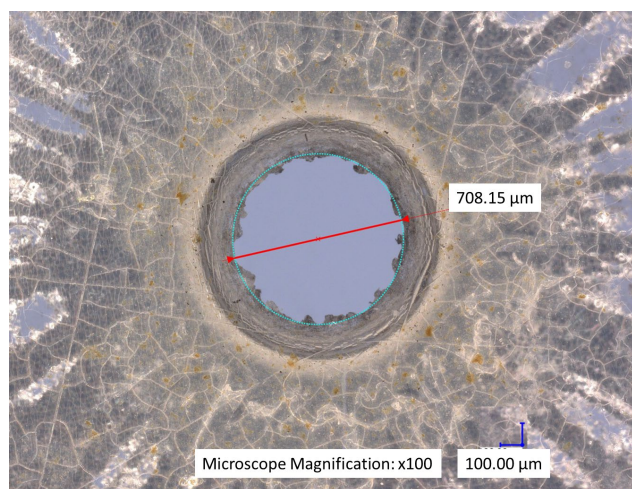


Fig. 1. Keyence VHX-7000 image and diameter measurement of an HVI impact feature on MLI. The measurement corresponds to the outer through hole (OTH) paradigm of [1].

3 Hypervelocity Impact Testing

HVI laboratory tests were designed to reconstruct impact test scenarios with parameters expected to have occurred in an orbit like the HST to estimate the reproducibility and variation in observed features. Extended parameters were added to the test matrix that fill in gaps from the earlier study using Design of Experiments models. The recent HVI programs are intended to compare results from FY10 HVI ground testing [1] using simple, pristine outer layer analog materials to correlate impact features found during this test series. The following is an overview of the hypervelocity testing results, specifically focused on the configuration of the MLI samples, MLI type (exposed to the space environment versus pristine, unflown), impact angle evaluation, and MLI attachment comparisons.

3.1 Hypervelocity Testing Results

A test target example in Fig. 2 shows the typical HVI testing attachment method of clamping using all-thread rods, washers, and nuts. The hook and loop attachment method was used to attach to the target frame instead of the clamping method. Unless otherwise noted as hook and loop type, all test samples were attached to the target in the typical attachment method. Nine test shots were completed in FY2023, bolded in Table 1, providing a total of 34 HVI tests completed and analyzed on the MLI samples. Projectiles for all tests ranged in size from 0.1 – 0.6 mm using various materials such as nickel (Ni), stainless steel (SS), aluminum (Al), soda lime glass, and poly(methyl-methacrylate) (PMMA). The “single” layer as indicated in Table 1 refers to testing the single top-layer, whereas the “multi” used the full 17-layer MLI stack. The starred (*) test cases indicate that the MLI was attached to the target frame using hook and loop method. The order listed is not necessarily the order the tests were completed.

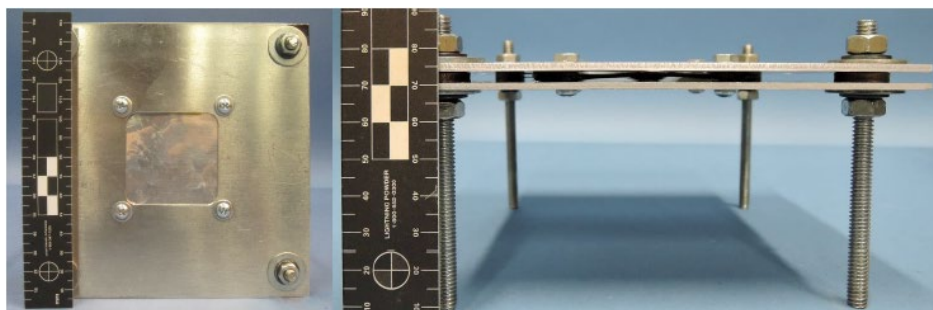


Fig. 2. Front and side view of a sample on a target using all-thread rods, washers, and nuts.

Table 1: HVI Test Shots and Associated Parameters for All MLI Samples Tested to Date.

Test #	MLI Type	Single/ Multiple layers	Projectile Material	Projectile Size (mm)	Velocity (km/s)	Angle (°)	1 st Layer Hole Diameter (±0.1 mm)
1	Exposed HST	Multi	Al	0.1	7.2	45	0.44
2	Exposed HST	Multi	Al	0.1	7.0	0	0.40
3	Exposed HST	Multi	Al	0.4	7.3	0	0.93
4	Exposed HST	Multi	Al	0.4	7.4	45	1.22
5	Exposed HST*	Multi	Al	0.1	7.3	45	0.43
6	Exposed HST*	Multi	Al	0.1	7.3	45	0.45
7	Exposed HST*	Multi	Al	0.1	7.1	0	0.32
8	Exposed HST*	Multi	Al	0.4	6.5	0	1.02
9	Exposed HST*	Multi	Al	0.4	7.2	45	1.35
10	Exposed HST	Multi	SS	0.2	5.0	0	0.49
11	Exposed HST	Multi	SS	0.2	7.0	0	0.71
12	Exposed HST	Multi	SS	0.3	7.0	0	0.67

Test #	MLI Type	Single/ Multiple layers	Projectile Material	Projectile Size (mm)	Velocity (km/s)	Angle (°)	1 st Layer Hole Diameter (±0.1 mm)
13	Exposed HST	Single	SS	0.36	8.2	0	0.89
14	Exposed HST	Multi	Al	0.1	5.0	0	0.39
15	Exposed HST	Multi	Al	0.1	7.0	0	0.41
16	Exposed HST	Multi	Al	0.2	7.0	0	0.65
17	Exposed HST	Multi	Al	0.3	7.0	0	0.71
18	Exposed HST	Multi	Glass	0.02	7.0	0	0.11
19	Exposed HST	Single	Glass	0.36	8.3	0	0.81
20	Exposed HST	Multi	PMMA	0.2	7.0	0	0.55
21	Exposed HST	Multi	PMMA	0.3	7.0	0	0.71
22	Exposed HST	Multi	PMMA	0.36	8.1	0	0.93
23	Exposed HST	Single	PMMA	0.2	7.0	0	0.61
24	Exposed HST	Single	PMMA	0.36	8.0	0	0.90
25	Pristine	Single	Ni	0.1	5.1	45	0.32
26	Pristine	Multi	SS	0.4	7.0	0	0.80
27	Pristine	Single	SS	0.4	7.0	0	0.77
28	Pristine	Single	Al	0.4	4.9	45	0.82
29	Pristine	Single	Al	0.6	4.6	45	1.08
30	Pristine	Multi	Glass	0.1	4.9	45	0.24
31	Pristine	Single	Glass	0.25	4.2	0	0.51
32	Pristine	Single	Glass	0.25	3.7	45	0.46
33	Pristine	Single	Glass	0.25	4.3	70	0.42
34	Pristine	Multi	PMMA	0.36	8.3	0	0.88

The resultant impact features from the HVI tests were compared to extend knowledge of the relationship between hole size and projectile parameters (Fig. 3). The impact hole-to-projectile size ratio was similar for the “angle” and “type” parameter and showed more variation with the “configuration” and “attachment” parameter change. For the shots compared below, only one parameter was varied for a given test run. Each parameter will be discussed individually in further detail. Ratios of approximately 2.3 for impact hole diameter to projectile size were found previously in MLI [2].

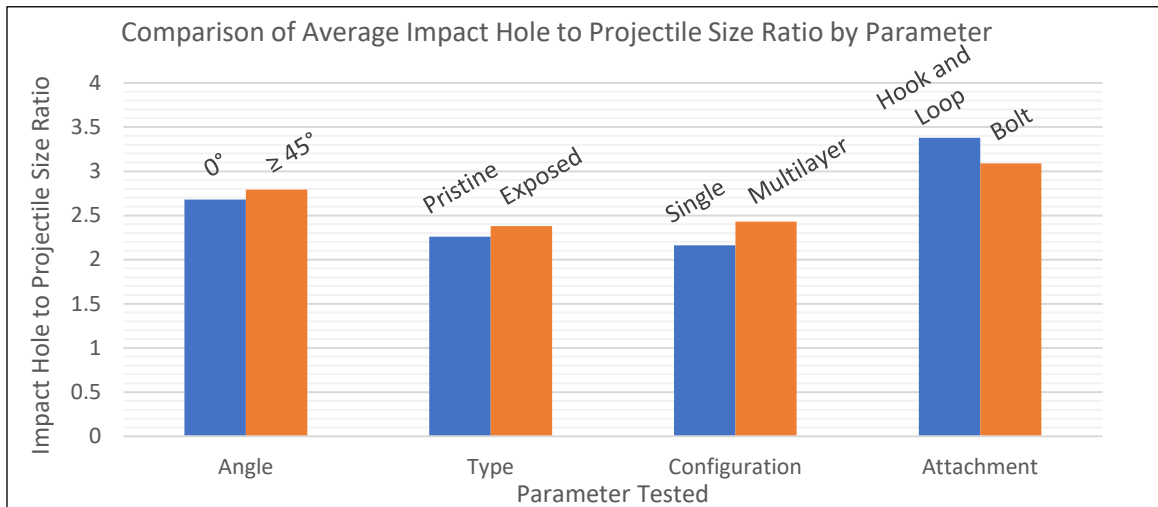


Fig. 3. Summary of the varied parameters in HVI testing, with relation impact hole to projectile size.

3.1.1 Configuration of MLI layers

HST MLI was tested in either a single, top layer or a 17-layer MLI stack. The purpose of this comparison is to observe whether damage to the interior of the stack of MLI layers creates any extra ejecta on the top layer of MLI or otherwise erodes the outer layer, thus altering the impact hole characteristics.

Figure 4 shows two images of exposed HST MLI samples, both shot with 0.36 mm PMMA projectiles at 0°, and speed of approximately 8 km/s. There are limited tests comparable for this configuration, but the preliminary analysis suggests an effect of ensuing layers, which removed top layer coating, causing more damage than the single layer sample on the left. This confirms that multiple layers attached to a sample will affect the resultant impact hole appearance and thus, the interpretation of impactor size. More tests with the same test configurations (*i.e.*, projectile size, material, and speed) are needed to confirm this result. The resultant impact hole diameters for the two configurations are similar, but the multilayered sample has a larger diameter in all cases.

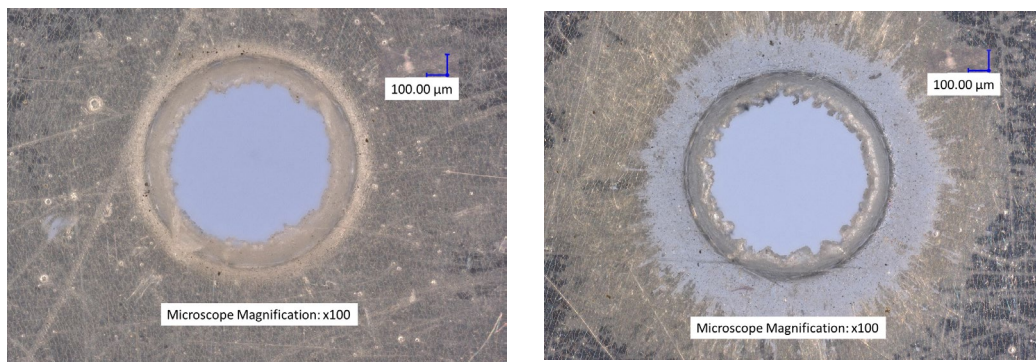


Fig. 4.: Resultant impact holes from single layer test article (left - 0.90 mm), and multi-layered stack of MLI (right - 0.93 mm). Both samples are flown MLI.

3.1.2 MLI type

To determine if previously exposed MLI degraded from the space environment affects impact feature characteristics, exposed HST and pristine manufactured samples were tested and compared. The diameter of the resultant impact hole for similar test runs (PMMA, 0.36 mm projectile, 0°, and speed of approximately 8 km/s) is smaller in the pristine samples versus the exposed samples. Exposed sample (Fig. 5 - left) has a 0.93 mm diameter and the pristine sample has an 0.88 mm diameter. Additionally, the sidewall structure of the perforation displays observable differences. In Fig. 5 on the left (exposed HST sample) noticeable cracking appears on the surface, which is known to occur on MLI on orbit [3].

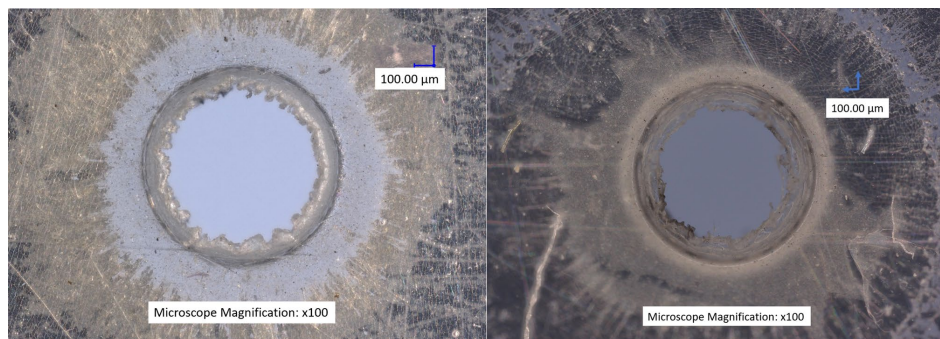


Fig. 5. Impact holes on an exposed (left - 0.93 mm) and pristine (right - 0.88 mm) MLI sample.

3.1.3 Impact angle evaluation

Extending the angle parameter beyond 0° normal incidence creates a more realistic scenario as it better reflects the (OD) flux-weighted angular distribution on-orbit. For example, this quantity for the HST displays a peak flux between 40° and 50° (Fig. 6, right). Thus, the alternate impact angle used in HVI testing was 45°. Resultant impact features in Fig. 6 (pristine MLI samples) were produced by 0.25 mm soda lime glass projectiles going approximately 4 km/s and the angle varied from 0° to 45°. The Fig. 6 left impact feature has a 0.51 mm diameter hole, and the Fig. 6 middle feature has a 0.46 mm diameter hole. The resultant impact hole becomes slightly elliptical as the angle increases, but it does not significantly affect the diameter measurement (for projectile sizes and angles used in this specific HVI test), since the smaller diameter measurement of the semi-major and semi-minor axis is used for an elliptical impact feature in these studies, as we know projectile shape (spherical) and diameter *ab initio*. Recall in the parameter comparison chart (Fig. 3) that the angle parameter showed the least amount of variation when compared. Based on prior testing, however, we would expect the eccentricity of the elliptical feature shape to increase as angle increases beyond 60°–70°.

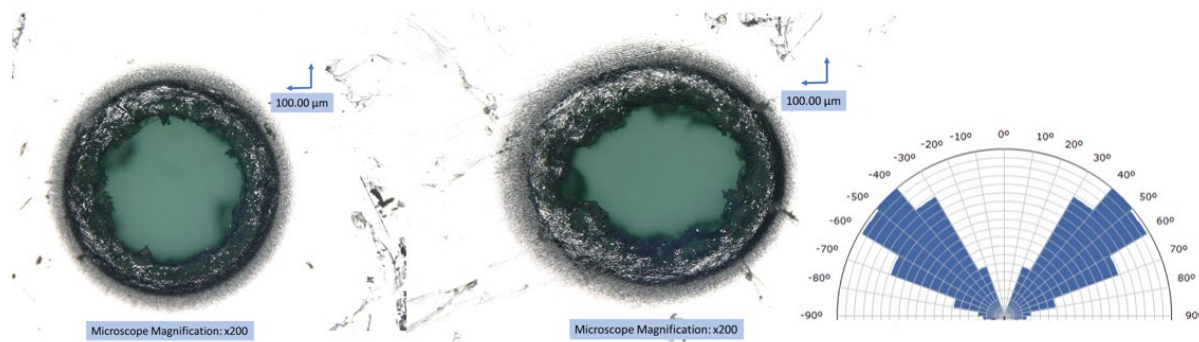


Fig. 6. Resultant impact holes seen from 0° impact angle (left - 0.51 mm), and the ellipticity of the hole as the impact angle goes wider (middle - 0.46 mm, 45°) Right: The flux-weighted azimuth distribution in the local horizontal plane of the HST orbit.

3.1.4 MLI attachment to target frame

The final HVI testing change is the MLI's attachment to target frame, in this case a hook and loop attachment versus the clamping method using all-thread rods, nuts, washers, and bolts. Hook and loop fasteners were used on the joints and main structure of exposed HST MLI by either being adhered to or sewn to the blanket [4]. Adhesive was used to attach the hook and loop fasteners from the MLI samples to the target frame for HVI testing. A projectile of 0.4 mm in size of Al at 0° and speed of approximately 7 km/s was used. Figure 7 left impact is a 0.90 mm diameter hole and the Fig. 7 right impact is a 0.93 mm diameter hole. It was noted that the hook and loop attachment tended to have a more secure fit on the target than the bolted attachment, though it was not possible to quantitatively measure the mounting tension force, and that cracking occurred on the MLI after the HVI test for the hook and loop attachment. The target attachment to the frame does seem to affect diameter and blown away coating is present in both impact features.

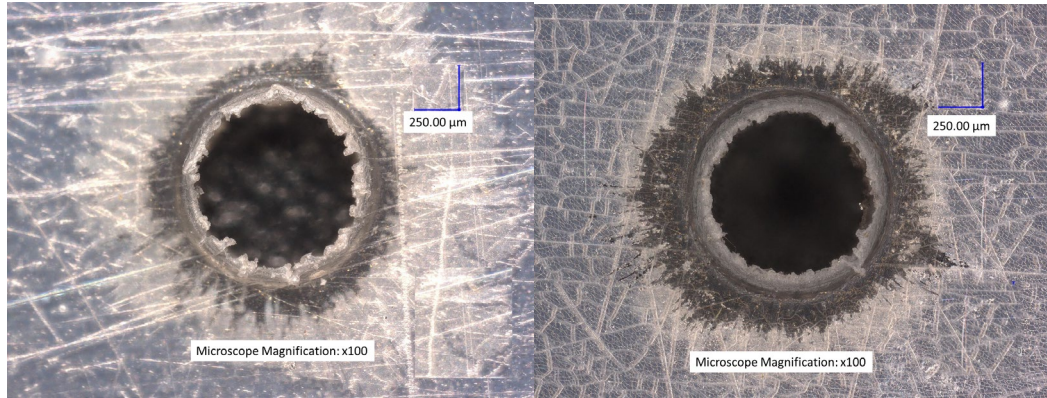


Fig. 7. Resultant impact feature hole from a hook and loop attached MLI (left - 0.90 mm) and all-thread rods, nuts, washers, and bolts attachment method (right - 0.93 mm).

4 Damage Equations

The 34 HVI test shots aided in estimating exponents for a generic damage equation. Damage equations relate known projectile size and impact parameters to observed target damage. There is currently no damage equation specifically for thin films, only the generic damage equation used in a previous study [1]. Additionally, all results using laboratory-derived impact damage equations use perforation data (no cratering damage equation is available currently). The generic damage (Eq. 1) for this study used:

$$d_h = c * d_p^\alpha * \rho_p^\beta * v^\gamma * (\cos\theta)^\delta, \quad (1)$$

where d_h (the diameter of the impact hole) and d_p (the projectile diameter) are in millimeters, and ρ_p (the projectile density) is in kilograms per cubic meter. The velocity of the projectile (v) is measured in kilometers per second, and the angle at which the projectile impacts (θ) is in degrees. The factor c and the exponent ensemble α , β , γ and δ (alpha, beta, gamma, delta) are to be estimated. Exponents for the generic damage equation were estimated by the least squares (best-fit) method. The damage equation above is slightly different from the damage equation used in [1]; it has uncoupled the velocity (v) and angle ($\cos\theta$) and is based on an assessment of exponents calculated and their error percentage in predicting projectile size.

Table 2. Estimated Exponents Using Least Squares Method from Previous Studies to Current

Calculation	Coupled/ Uncoupled	c	α	β	γ	δ
Previous study [1], single layer MLI	Coupled	0.991	0.866	0.293	0.196	
Previous study [1], single layer MLI	Uncoupled	0.730	0.859	0.243	0.436	0.195
All test shots to date (multi- and single layer)	Coupled	0.980	0.673	0.011	0.259	
All test shots to date (multi- and single layer)	Uncoupled	0.459	0.670	0.027	0.576	-0.031
All test shots to date, single layer	Uncoupled	0.901	0.694	0.002	0.307	0.173
All test shots to date, multilayer	Uncoupled	0.440	0.706	0.056	0.508	-0.366

Provided the exponent ensemble in Table 2, the parameters were fit into the generic damage equation using HVI laboratory testing parameters to determine if the damage equation accurately predicts the impact hole diameter. The measured impact hole diameters are plotted on a one-to-one line against the predicted impact hole diameters. In yellow, all the test shots were plotted together, and the trendline

fits well to the data points (Fig. 8, yellow box). Because there was an observed difference in the impact features between single layer MLI and multiple layers of MLI, the data was also separated into multilayer and single MLI datasets with the best fit line (Fig. 8, green and blue boxes) to determine if it was necessary to split multilayer and single layer MLI data. There is not a significant difference in the trendlines between the two.

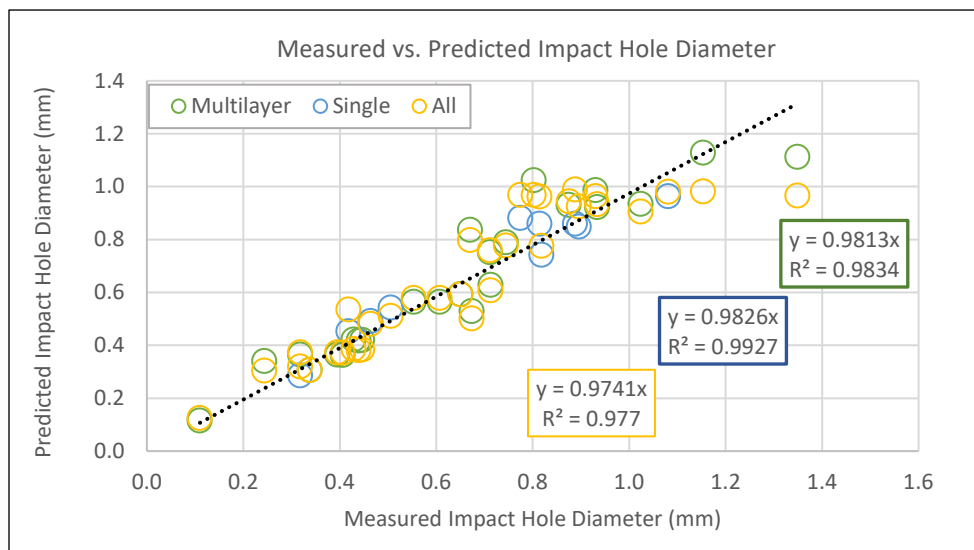


Fig. 8. Impact holes on an exposed (left - 0.93 mm) and pristine (right - 0.88 mm) MLI sample.

5 Field Emission Scanning Electron Microscopy (FESEM)

A critical extension of the MLI work, for model development and validation, requires that MM impacts be differentiated from OD impacts. This is done by using FESEM coupled with EDX to analyze and identify returned surface impact feature residues using a standard rubric. For this, the ODPO commissioned a feasibility study using three select samples excised from the HST Bay 5 MLI blanket. The JSC Astromaterials Research and Exploration Science's Basic and Applied Research Department analyzed any potential residue left on the surface in the immediate vicinity of the MLI impact hole for the penetrated layers, including potential projectile residue on the first non-penetrated layer, and examined whether the elements from the MLI itself perforated into a final impact hole/feature. Samples were successfully sputter-coated with platinum (Pt) and carbon (C) to prevent sample charging and reduce thermal degradation. This feasibility study found projectile residue on the exposed HST MLI samples. Specifically, residues were noted in relative abundance on the first (outer) layer, the second (first inner) layer, and the last perforated inner layer.

A major finding from the SEM/EDX analysis was that the key to finding projectile residue may be the presence of major/minor fluorine (F) in particle EDX spectra. The F was not present in subsequent layers, only the first layer. If there was F present, it was likely contributed from the coating substrate of the first layer, which was intermixed/melted with the projectile and subsequently deposited on underlying layers. Figure 9 displays low angle backscatter electron (LBE) images and SEM results from a HST MLI sample's layer 2 (left box) and 6 (right box). The spectra show both regions are rich in Al with the region in blue also containing C, Oxygen (O) and F which is emanating from the polyimide background. The melted Al sphere contains little C, O or F and is consistent with a metal.

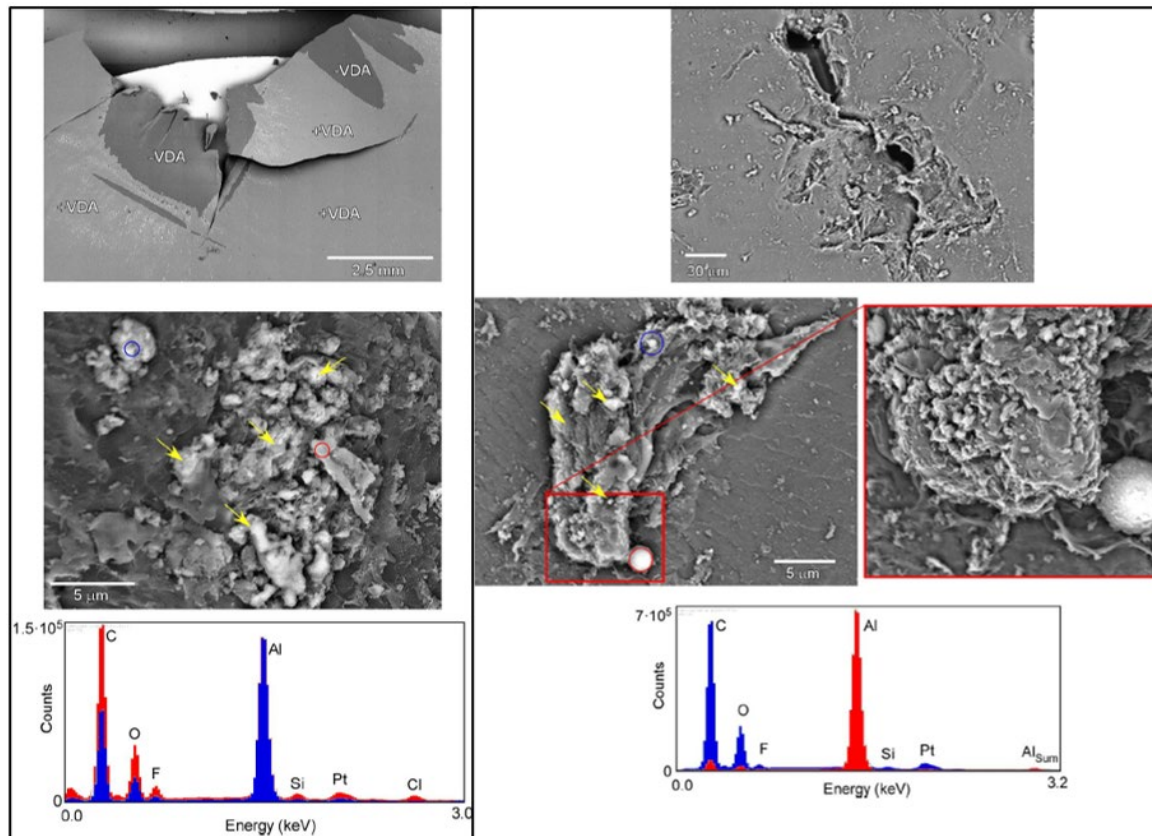


Fig. 9. FESEM/EDX analysis results from a HST MLI sample on layer 2 (left box) and 6 (right box). Left box, top: The VDA coating removed from the darker regions (designated '-VDA'). Left box, middle: LBE image of residue in the -VDA region, shown by arrows and circles, intermixed with the substrate. Left box, bottom: Overlapping EDX spectra of Al-rich melt regions/particles corresponding to the red and blue circles in the middle image. Right box, top: LBE image of region on layer 6. Right box, middle: A zoomed in view (left) that contained Al-rich particles shown by the yellow arrows and red and blue circles. At right is a magnified LBE view of the area highlighted by the rectangle at left. Right box, bottom: Overlapping EDX spectra of the Al-rich regions corresponding to the red and blue circles in the middle-left view.

The three samples were identified by SEM/EDX processing as OD. The successful outcome of this feasibility study confirms that MLI samples may be prepared, examined, and residues identified and differentiated into MM or OD.

6 Conclusion

HST MLI does double duty as a thermal regulator on orbit and – serendipitously – aids the ODPO in observing the small MMOD environment in LEO because of its large cross-sectional area, length of exposure time on orbit, and the ability to capture small MMOD impacts. HST bay 5 MLI was provided by the HST Program Office to the ODPO for inspection in 2010, analyzed, and the resultant data was used to validate the ODPO's ORDEM 3.1. The validation effort identified several areas of further study to improve model validation and understanding of the space environment. An extended study using HVI laboratory testing was completed in 2023 that replicated (in all degrees save average relative velocity) the impacts that would be likely seen in the HST orbit. To recreate the HVI features, HST MLI and replica

HST MLI test articles were used to compare with flown HST MLI. The extended study included smaller projectile sizes, wider angles other than a normal incidence (0°) impact angle, and the configuration of layers (MLI stack of 17 layers versus a single, top layer, or type of attachment of MLI to a surface). Results of the HVI testing were studied to determine how much these parameters are connected to the resultant impact hole. In all HVI shots, the hook and loop's attachment type of MLI impact feature showed more feature damage than the typically secured (clamped/bolted) target. In the parameter comparison chart, the angle parameter (0° versus 45°) displayed the least amount of variation when compared together, but this could also be due to our measurement technique and knowledge of the projectile and impact parameters. Further study of impact angle and projectile shape upon impact feature characteristics is ongoing. In the comparison of exposed on orbit versus pristine samples of MLI, exposed MLI tended to have a larger hole diameter. There appears to be an effect of interior layers of a multilayered MLI sample causing more damage to the outer layer than the single layer sample, confirming that multiple layers attached to a sample will affect the resultant impact hole and hence, interpretation of impactor size. Project priorities, tasking, and schedule prevented the anticipated presentation of an HST MLI cratering equation. A feasibility study was conducted to determine if SEM/EDX could supply useful information as to the projectile material in impacted MLI. Assuming all MLI blankets have an identical layering stack, the presence of fluorine may be a useful signature identifying particles associated with the original impactor on all MLI samples. The feasibility study was successful in finding projectile residue from MLI samples and SEM/EDX may be applied to additional HST MLI or other returned blankets.

7 References

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