A Survey of ISS and Visiting Vehicle Returned Surfaces for Environmental Characterization and Computer Model Development

Phillip Anz-Meador[1], Melissa Murray[2], James Hyde[3], Eric Christiansen[4], and Heather Cowardin[5]

[1]Jacobs, NASA Orbital Debris Program Office, Johnson Space Center, Mail Code XI5-9E, Houston, TX 77058, USA; phillip.d.anz-meador@nasa.gov
[2]Craig Technologies, KBR IMOC III, Flight Dynamics Division – Trajectory Branch, NASA Johnson Space Center, Mail Code CM4, Houston, TX 77058, USA; melissa.murray@nasa.gov
[3]Barrios Technology-Jacobs JETS II Contract, NASA Hypervelocity Impact Technology, NASA Johnson Space Center, Mail Code XI5, Houston, TX 77058, USA; james.l.hyde@nasa.gov
[4]NASA Hypervelocity Impact Technology, NASA Johnson Space Center, Houston, TX, 77058, USA; eric.l.christiansen@nasa.gov
[5]NASA Orbital Debris Program Office, NASA Johnson Space Center, Houston, TX, 77058, USA; heather.m.cowardin@nasa.gov

Abstract

The Orbital Debris Engineering Model (ORDEM) developed by the NASA Orbital Debris Program Office (ODPO) is a data-driven model — extensive radar, optical, laboratory, and *in situ* measurement data sets have been used to build the model since its earliest versions. A salient aspect of professional software development is the verification and validation (V&V) process. Verification answers the question "Is the model built correctly?" while validation addresses the question "Did we build the correct model?" Less extensive, reserved, or independent data sets serve the validation requirement. Due to the dynamic nature of the orbital debris environment, it is critical to use contemporaneous data sources that represent the current environment to support ORDEM development and validation. ORDEM has utilized *in situ* data collected from Space Shuttle and Hubble Space Telescope surface inspections, now over a decade old. This historical dataset is fundamental for providing baseline *in situ* measurement data for sizes between 10-300 microns, but new data sources are being evaluated using returned surfaces from or near the International Space Station (ISS). This paper reviews a general microscopic survey of ISS soft goods, the Pressurized Mating Adapter 2 (PMA-2) blanket, and a limited-scope feasibility study conducted on the Space Exploration Technologies Corp. (SpaceX) Dragon capsule's Thermal Protection System (TPS) material. The PMA-2 blanket, exposed to the space environment between 09 July 2013 and 25 February 2015, is an approximately 3.7 m^2-area blanket composed of a betacloth outer layer and multiple ballistic fabric inner layers. The SpaceX Cargo Dragon capsule regularly visited the ISS from 2012 through 2020 and potentially provides a timely and well-characterized source of data for modeling purposes. The capsule's lateral surfaces use SpaceX Proprietary Ablative Material (SPAM) TPS material, a syntactic foam, for thermal management during all mission phases. Seven SPAM extracted samples have been analyzed to date. This paper will provide an overview of the characterization completed for impact features by size, depth, impactor diameter, and the impactor residues chemical analyses, allowing a differentiation between micrometeoroids and orbital debris and a categorization by mass density and density class. Impactor diameter is estimated using damage equations generated in ground-based hypervelocity impact testing. The orbital debris impactors are compared to the current ORDEM 3.2 model of the environment at ISS altitudes. We briefly discuss the meteoroid impactors, including constituents and mass densities, in the general context of current models.

1 Introduction and Background

This paper considers returned surface materials from the operational altitudes of the International Space Station (ISS), specifically the ISS Pressurized Mating Adapter (PMA-2) cover (primarily oriented in the ISS “ram” direction, or direction of motion) and the SpaceX Proprietary Ablator Material (SPAM) from various SpaceX Commercial Resupply Missions (CRS) to the ISS. This activity, sponsored by the NASA’s Orbital Debris Program Office (ODPO), is a collaboration between the ODPO, NASA’s Hypervelocity Impact Technology (HVIT) group, and the Astromaterials Research Office’s Basic and Applied Research Department (BARD). A fundamental objective for analyzing returned surfaces is to determine the number of impacts and associated feature sizes from micrometeoroid and orbital debris (MMOD) that can be used for flux estimates in environmental modeling. Impact feature residues identified as either micrometeoroid (MM), orbital debris (OD), or unknown (UNK) in origin allow insight into high-probability projectile origins (natural versus human-made) and statistical mass density assessments in the *in-situ* flux data. BARD’s Scanning Electron Microscope (SEM)/Energy Dispersive X-Ray (EDX) analysis of impact features allows for resolving residue constituent elements. Using established rubrics and analyst experience, this helps identify materials as high-likelihood MM, OD, or UNK. The PMA-2 cover, portrayed in Fig. 1A, was the prime analysis candidate due to the legacy SEM/EDX analyses for impactor residue characterization and classification [1], enabling a recent effort to achieve completeness to a limiting impact feature size of 0.5 mm on the blanket’s beta cloth outer layer [2]. Beta cloth consists of polyimide-coated glass fibers, woven as a fabric, and is a common thermal management material; the rear (non-exposed) side was aluminized, and the next layer consisted of Nextel™ Fiber 312 fabric, manufactured by 3M™. Figure 1B is a microphotograph of a penetration of the blanket’s weft and warp weave. While below the 0.5 mm threshold, it illustrates typical attributes of a beta cloth penetration and the approximate minimum threshold condition for inclusion is the original survey [1]: an entire weave bundle is severed by the impact.

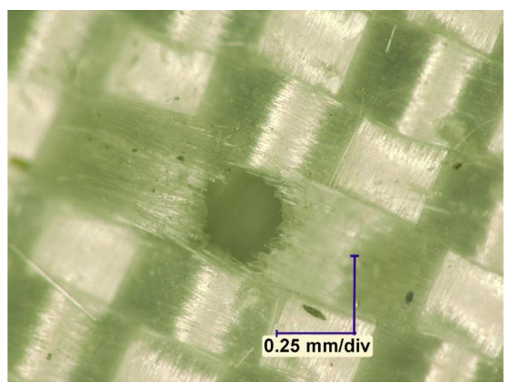
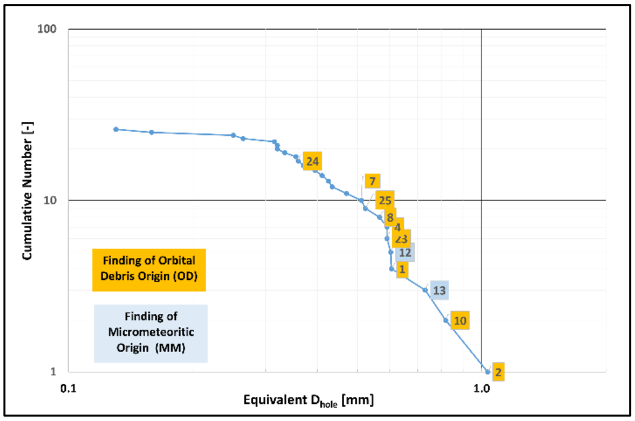


Fig. 1A. (left) The ISS Node 3 axial port’s PMA-3 cover. The PMA-2 cover, on the ISS *Harmony* module’s PMA, is otherwise identical, though no on-orbit imagery appears to exist. Credit: NASA photo #iss035e037061. Fig. 1B. (right) A penetration of the beta cloth’s weave. The event creates impact-related melting of both the beta cloth and the projectile, the latter typically residing as micron-sized droplets on this outer layer and occasionally the first inner layer.

After recovery, HVIT was provided the PMA-2 cover, motivating the original survey summarized in Fig. 2A. Samples for the SEM/EDX surveys, extracted with hammer and punch, were of sufficient size to be manipulated, prepared, and examined in the SEM. Of the original 26 impact features, 11 have complete SEM/EDX analyses: 9 are identified as OD and 2 are identified as MM. No samples from the PMA-2 blanket were identified as unknown origin. For the extended effort, five approximately

20 x 20 cm square samples were provided to the ODPO by HVIT; which were oriented in the ram, port, starboard, zenith, and nadir directions with respect to the ISS/PMA, as depicted in Fig. 2B.



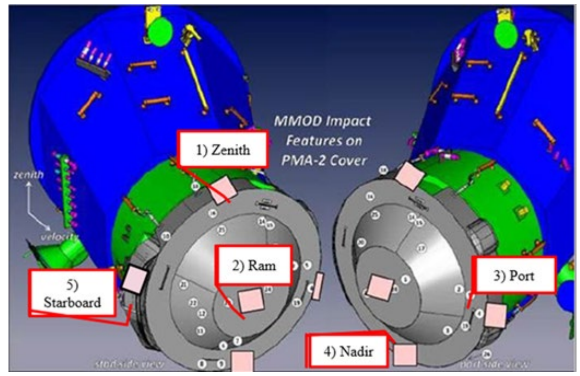


Fig. 2A. (left) Catalogued penetrations in the first examination of the PMA-2 blanket. OD impactors are indicated by a yellow label with sample (or catalog) number, while light blue labels indicate MM. Unlabeled points were not probed using SEM/EDX and are a subject of this paper. Fig. 2B. (right) Gray model faces are the blanket, with pink squares identifying approximate extended sampling locations.

SPAM is a syntactic foam ablative material used as a thermal protection material on the Dragon I capsule's lateral surface. The primary goal of SPAM examination is to determine the feasibility of assessing impactor residue from a foam for discriminating MM and OD residues, necessary for building OD modeling data sets. A secondary goal was to provide one or more single data points for model validation if at least one OD sample was positively identified. Unlike the PMA-2 data set, a size-dependent flux distribution was not feasible, since samples span across missions over the course of several years; however, computing individual flux attributable to the samples given their respective exposure dates, durations, and CRS vehicle's surface areas examined can still be done.

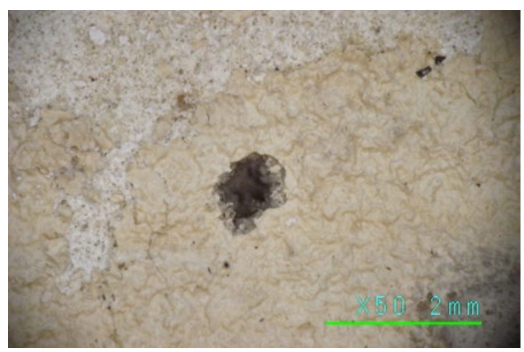


Fig. 3A. (left) The SpaceX Dragon capsule flown on CRS-17. The conical capsule's lateral surface is SPAM TPS material. Credit: NASA photo #iss059e043284. Fig. 3B. (right) Microphotograph (50X magnification) of a typical SPAM impact feature.

SpaceX provided HVIT with samples cored from the damaged SPAM surfaces, generally as approximately 25 mm diameter pucks. Forty core samples are available for analysis and described graphically in Fig. 4. This figure presents the core sample's diameter versus depth characteristics and the heavy dashed line represents the 2:1 (diameter to depth) line of a perfect "bowl shaped" (hemispherical) crater, as might be expected for a ductile material like aluminum. This figure also presents the relative maturity of the analytical effort, with the three samples used in the feasibility study shown in green squares and four additional samples (partially analyzed in an expanded effort) in amber circles. The ODPO investigative effort commenced looking at the largest features and is proceeding from “larger” to “smaller” features along the 2:1 line, from upper right to lower left. In addition to larger features being generally easier to examine, this procedure offers the benefit of yielding meaningful single point flux estimates, when plotted as cumulative number or flux versus size. Figure 4 illustrates considerable variation about this line, perhaps indicative of the friable nature of the SPAM material.

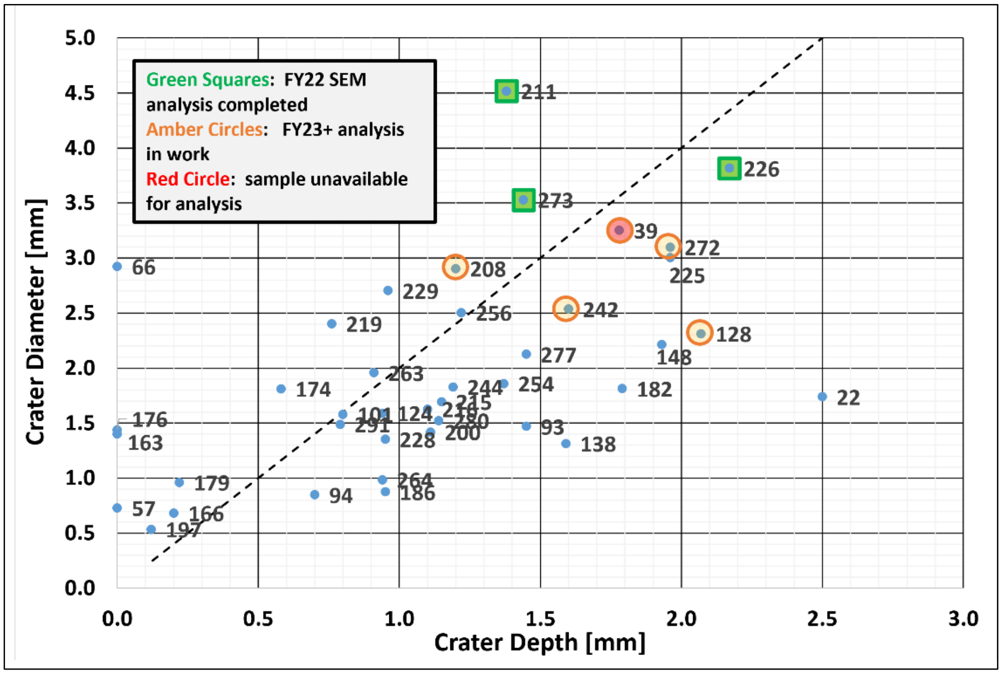


Fig. 4. Demo 2 and CRS 1–19 SPAM core samples available. Features above the 2:1 line are shallower than a hemispherical crater while those below are deeper than a hemispherical crater.

2 Sample Preparation and Classification

Both sample materials are complex and present challenges to the analyst; PMA-2 flexible fibrous samples require delicate handling and SPAM is a challenge due to its frangible nature and the depth/impact feature volume. This section reviews sample preparation, including a unique approach applied to the SPAM samples, and presents SEM/EDX classification of residues identified.

The PMA-2 outer and first inner layer was sputtered with a conductive carbon (C) coating to reduce the effects of sample charge build-up. Each region of interest (ROI) was characterized using a JEOL 7600 Field Emission SEM equipped with a Thermo Scientific EDX detector. Low angle backscatter electron (LABE) images were obtained for samples at a 25–2000X magnification range.

SPAM samples suitable for the JEOL SEM’s working chamber were extracted from the larger, original sample pucks as cubes of approximately 5 mm × 5 mm × 12 mm. The individual sample was embedded in transparent epoxy to preserve the impact feature during handling and analysis. It was cut using a wire saw with a 150 µm-diameter diamond wire to the line of interest identified by the ODPO. After cutting, the surface of the exposed crater was placed back in the epoxy, followed by subsequent polishing and sputtering with a ~ 15 nm-thick conductive C-coating. The sample was then characterized using the JEOL 7600 equipped with an Oxford Instruments Ultim® Max EDX detector. Imaging of ROIs was performed at 15 kV (~ 2 nm resolution) using both secondary electron (SEI) and LABE imaging modes.

The SEM/EDX classification outcomes, including primary elements and tentative identifications (*e.g.*, stainless steel [SS]), are listed in Tables 1 and 2.

Table 1. SPAM Sample SEM/EDX Results

CRS Mission ID	Sample Number	Largest Damage dimension (mm)	RESULT (MM, OD, or Unknown)	Constituents
CRS-13	211	4.79	OD	Fe, Cr, Ni (or SS), Ba, Calcite
CRS-15	226	4.15	MM	S, Fe, Ni
CRS-18	273	3.635	OD	Pt, Pt & Fe, Cu & Zn, Zr and Ca

Table 2. PMA-2 Sample SEM/EDX Results

PMA-2 sample number	Largest Damage dimension (mm)	Result (MM, OD, or Unknown)	Constituents
1	0.62	OD	SS, ZnS, Ti
2	1.19	OD	SS, NiO
4	0.60	OD	Zn, Fe
7	0.55	OD	Ti and Fe, Ti and S, Ba and S
8	0.60	OD	Fe, Cr, Mn, SS, Fe & Ni
10	0.93	OD	SS, Fe
12	0.73	MM	Ca, Mg, Fe, S, O
13	0.75	MM	Fe, Ni, S
23	0.61	OD	Fe, Cu, Ti
24	0.37	OD	SS, TiO, FeO
25	0.58	OD	Ti, Fe+Cu, Mo, Co, Fe, Cr, Ni

In Tables 1 and 2, analysis and characterization outcomes are described as MM or OD. No Unknown outcomes were observed, based on the rubric applied by BARD analysts.

In addition to SEM/EDX analyses, the ODPO and HVIT have utilized KEYENCE EA-300 Element Analyzer digital microscopes to further support elemental analyses on materials of interest. The EA-300 uses laser-induced breakdown spectroscopy (LIBS) to destructively classify elements within an approximately 9 µm-diameter spot size. Limited use of the EA-300 was made to examine the general surface (background) constituents, ROIs, and potential melt observed in the vicinity of any additional features discerned during the survey. For the SPAM samples, the EA-300 was used to identify possible ROIs for proposed further SEM/EDX analysis. Table 3 presents the ODPO's findings for the PMA-2 blanket extended study. While the first row, representing the nadir-pointing sample, did not offer up any additional penetration features during the initial survey, constituents representative of the blanket materials are presented as a baseline. Otherwise, results indicate other elements identified at and near the feature(s). Figure 5 presents two of the blanket penetration features located in the survey.

Table 3. EA-300 Analysis Results for the 5 PMA-2 Large Samples

PMA2 Blanket Sample	Additional Perforations Observed	Feature: Damage Dimension(s) (mm)	EA-300 Constituents
Nadir	0	n/a	C, F, O, Si, H, K (blanket baseline elements)
Port	0	n/a	n/a
Ram	2	A:0.193 x 0.086, and B:0.201 x 0.082	Ca, Na
Starboard	1	0.19	AlO_x, Fe
Zenit	0	n/a	n/a

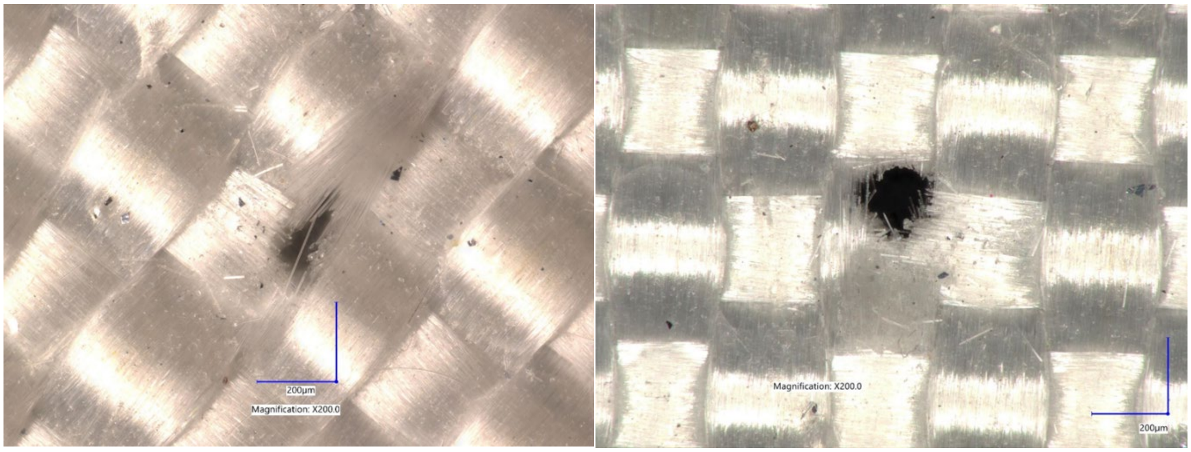


Fig. 5A. (left) Table 3's "Ram" (direction of motion) sample's Feature "A." Fig. 5B. (right) Table 3's "Starboard" sample's penetration feature.

As Fig. 2A illustrates, SPAM samples 128 (CRS-08), 208 (CRS-13), 242 (CRS-16), and 272 (CRS-18) have been identified for proposed further SEM/EDX analysis. Multiple ROI's on and in each sample were examined using the EA-300 to determine if any projectile material was left inside the impact feature volume of each sample. Only small amounts of iron were found in sample number 128. The EA-300 analysis is meant for preliminary inspection of samples and determination of ROI points before requesting BARD to conduct SEM/EDX analyses and is not intended to be complete in itself.

3 Impactor Attribute Assessment

3.1 Impactor Size

The NASA HVIT team has used ground-based, hypervelocity impact testing to develop simple relationships between projectile size and impact feature (penetration hole or crater dimensions) for the challenging PMA-2 and SPAM materials. These are:

$$d_{impactor} = d_{hole}/2.3 \qquad \text{[Eq. 1]}$$

and

$$d_{impactor} = d_{hole}/8 \qquad \text{[Eq. 2]}$$

for the PMA-2 blanket and SPAM, respectively. For elliptical impact features, d_{hole} is the geometric average of the major and minor dimensions. Being linear in impactor (projectile) size and independent of other possible dependencies, no variation or uncertainty associated with the transformation from impact feature or hole diameter to impactor diameter is presented in the work following. Figure 6 illustrates the results of employing Eq. 1 and 2 to the data sets considered in this paper.

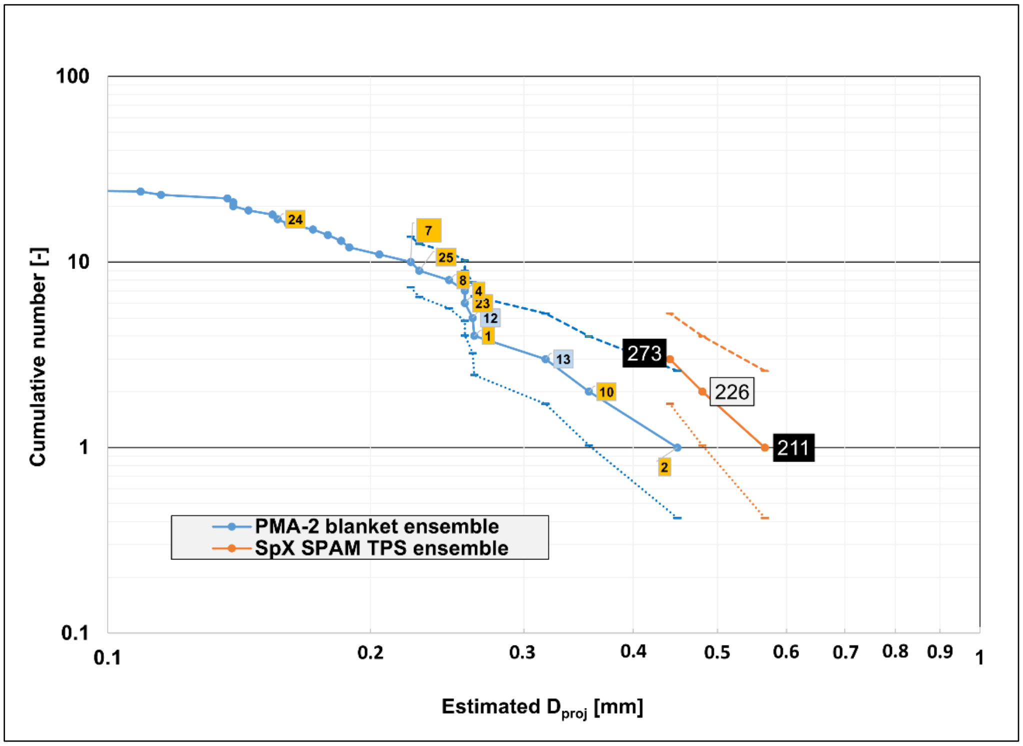


Fig. 6. The PMA-2 and SPAM data ensembles compared as cumulative number as a function of estimated impactor diameter. PMA-2 blanket annotations as in Fig. 2A. SPAM annotation by sample number and assessed origin (OD: black; MM: gray). Dotted lines indicate the ± 1σ Poisson sampling uncertainty.

3.2 Mass Density

The ODPO currently describes mass density "ρ" families as carbon fiber reinforced plastic (CFRP, $\rho = 1.46$ g/cm^3), sodium potassium (NaK, $\rho = 1.9$ g/cm^3), low density (LD, $\rho < 2$ g/cm^3), medium-low density (MD-low, 2-4 g/cm^3), medium-high density (MD-high, 4-6 g/cm^3), and high density (HD, $\rho > 6$ g/cm^3). The SPAM (Table 1) and PMA-2 (Table 2) constituent elements display, in all cases, elements in the ORDEM mass density family structure's HD category. Some combinations, in particular SPAM sample number 273, may represent paint pigments; typical binder constituents, as identified with regularity in the NASA STS Impact Database [3], are conspicuous by their absence. Due to this uncertainty and considering the paucity of samples in some density families, it is recommended that these data be employed in the aggregate (PMA-2 data *set*) or singly (SPAM data points) in lieu of comparing any observed density family's flux to the corresponding modeled density-dependent flux. This recommendation may change after conducting further characterization studies on these surfaces to extend the limiting feature size below 0.5 mm, or to extend the analysis to partial bundle penetrations or non-perforating impact features (PMA-2 blanket), and/or to process additional SPAM samples on a regular basis.

4 Orbital Debris Flux Estimation and Model Comparison

With origin (MM or OD) identified and impactor size estimated, the PMA-2 blanket's area-time product is applied to compute the cumulative cross-sectional area flux as a function of size. This distribution is presented in Fig. 7 for the PMA-2 blanket for all 9 samples, with one exception. Sample number 24 is a legacy finding and, because its impact feature size is below the completeness threshold of 0.5 mm and multiple impacts lie between it and the threshold, is not presented in the cumulative number-size and flux-size distributions at this time.

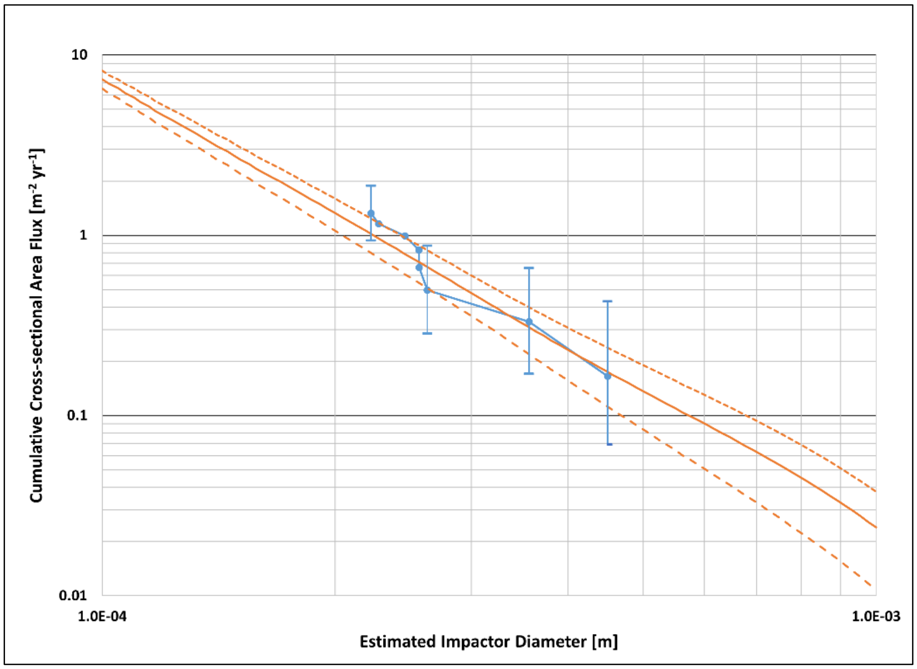


Fig. 7. PMA-2 blanket OD impacts.

In Fig. 7, the vertical uncertainties represent 1 sigma (σ) Poisson sampling uncertainties. These are presented at four sizes only due to the bunching of data points between 200 and 300 µm. The orange solid line indicates the ORDEM 3.2 flux for an ISS orbit during the PMA-2 blanket's exposure; orange dashed lines indicate the model's 1 σ uncertainties. The blanket data-based flux estimate and ORDEM 3.2 model flux are in good general agreement. For ± 1 σ uncertainties one would expect the model to lie within the data's bounds approximately 68% of the time, and this is the case observed.

With only two SPAM samples identified as OD, from CRS missions separated by over a year, an aggregate cumulative number-size or flux-size distribution has not been constructed. Two data points are presented instead that may be used for ORDEM validation in a similar manner as several Space Shuttle payload door radiator perforations have been used previously in ORDEM validation efforts [4]. To convert from number to flux, the HVIT record of flight duration (in hours and years) and surface area was used to construct the conversion factor between number and flux. The ISS Node 2 berthed duration was used to express the exposure times as 25.89 days (CRS-13), 32.24 days (CRS-15), and 30.84 days (CRS-18).

The total lateral SPAM-covered surface area of the Dragon 1 capsules was not completely surveyed; from a different perspective, the entire capsule's lateral surface area is not covered by SPAM. Both the total and surveyed areas, however, are available to correctly interpret the actual surface areas exposed to the environment and from which samples were drawn. The resulting surface area flux must be converted to a cross-sectional area flux to be consistent with PMA-2 results and ORDEM standard output. This latter factor is accomplished by taking the ratio of the capsule's lateral surface area to the corresponding cross-sectional area of the frustum of a cone (of the capsule's dimensions) as an analogue to the cross-section presented to the OD environment when docked. Figure 8 presents the scaled, singular SPAM data points on a cumulative cross-sectional area flux-size scatterplot. Like the PMA-2 interpretation, the 1:1 damage equation prevents an estimate of the uncertainty in estimated impactor diameter and uncertainties in flux represent ±1 σ Poisson sampling uncertainties.

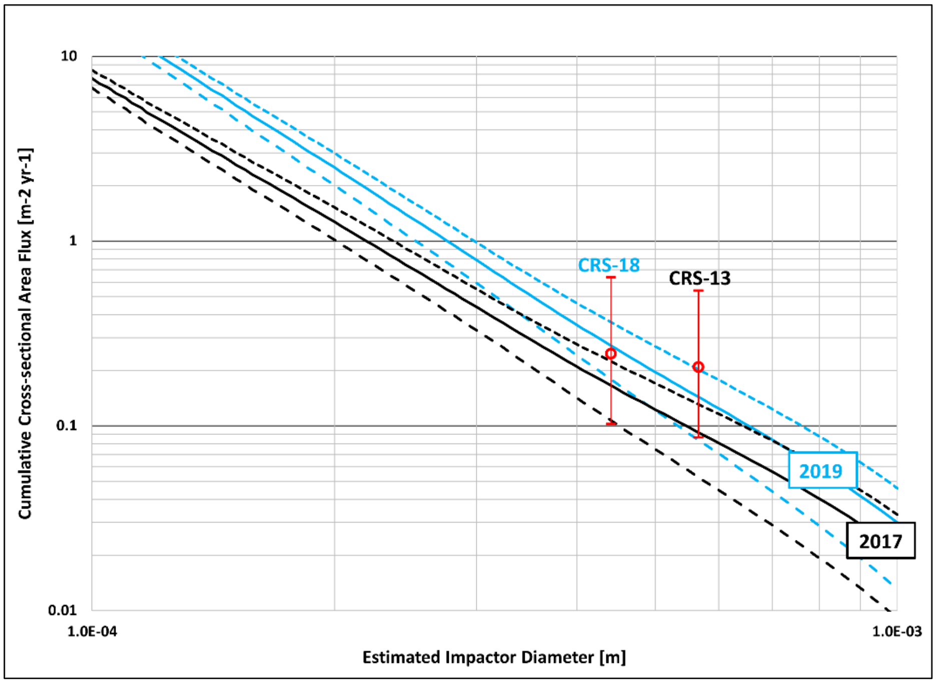


Fig. 8. SPAM OD impacts.

To place these estimates in context, two ORDEM 3.2 files for a representative ISS target orbit in 2017 (applicable to CRS-13) and 2019 (applicable to CRS-18) were computed and plotted. The upper and lower dotted lines represent ± 1 σ ORDEM uncertainties in the mean flux. The comparison reveals general agreement over the size domain available.

No formal investigation of the MM impactors identified in Tables 1 and 2 or comparison of those to the current micrometeoroid environment model has taken place. Micrometeoroids display a mass density distribution that may be correlated with asteroidal or cometary sources. For example, Halley-type, nearly isotropic comets, and Oort Cloud comets display a mass density range of 0.2 to 1.9 g/cm^3, corresponding to the ODPO LD category, while Jupiter-family comets and Kuiper Belt comets, at 3.1 ± 0.3 g/cm^3, fall into the MD-low family, and asteroidal sources would fall in the MD-high category at 4.2 g/cm^3 [5]. Mass density and directionality (*via* source) couple with LD micrometeoroids (0.857 g/cm^3) predominantly in the apex and anti-apex directions while MD-low micrometeoroids (3.792 g/cm^3) emanate predominantly from the Helion and Antihelion directions [6].

Since all MM identified by SEM/EDX, for the PMA-2 blanket, fall into the HD family there may exist a counting bias that manifests as lacking in LD perforations of the blanket. Low density category residues may be present in the known abrasions on the blanket's outer layer. Indeed, this hypothesis provided one of the original motivations for the PMA-2 blanket extended study. At the time of writing evaluating this hypothesis remains an objective for future work. Any such finding would potentially be applicable to other beta cloth blanket materials returned from space.

5 Conclusions and Future Work

This paper has described recent ODPO *in situ* data collection and analytical efforts conducted in collaboration with NASA HVIT and BARD analysts. The analysis, including the SEM/EDX identification of impactor constituents to differentiate MM and OD, is complete for the PMA-2 blanket down to a limiting feature size of 0.5 mm. An extended survey was conducted of five large samples extracted from the blanket and a limited number of additional penetrations below the size threshold of the original HVIT survey was observed. Other features, such as scuffing, abrasion, or other non-perforating impact events are difficult to discern on the beta cloth surface yet provide impetus for further study.

The ODPO commissioned a feasibility study to determine if impactor trace residues could be identified within impact features noted in the Dragon 1 capsule's SPAM thermal protection material and, if so, differentiated by source. This effort has demonstrated that the samples can be prepared, examined by SEM/EDX, and impactor residues located and identified by origin. While the PMA-2 blanket ensemble provides a well-defined measure of the ISS-local space environment over its exposure time in 2013-2015, the limited set of SPAM results suggests that the analysis of appropriate ISS recoverable visiting vehicle surfaces can provide an ongoing measure of the MMOD environment at and near ISS altitudes.

Future activities associated with these surfaces are, as suggested by this current work, to examine the smaller and non-perforating features observed on the PMA-2 blanket in an extended study and to process additional SPAM samples via SEM/EDX. This includes working through Fig. 2's 2:1 line to extend the analyses to ever smaller MMOD. Continuing the analysis to the CRS-20 mission and current CRS-series missions will enhance the *in-situ* data set available for ORDEM model development by providing a timely and well-defined means of assessing the MMOD flux at the ISS.

6 References

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