SpaceX Dragon Spacecraft Post Flight MMOD Inspection Campaign

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Abstract

The SpaceX Dragon spacecraft performed 20 resupply flights to the International Space Station (ISS) between 2012 and 2020. After each mission, a team led by the NASA Johnson Space Center Hypervelocity Impact Technology (HVIT) Group inspected each Dragon vehicle exterior for hypervelocity impact damage. A general description of the inspected vehicle areas is provided as well as mission details such as exposure duration and launch dates. This paper documents the general inspection procedure for collection of data and the post inspection data analysis process. It also provides details of the observation data collected in addition to the spectroscopic analysis results of intact samples collected to discern the source of the impacting particle. A comparison between observed impacts and the expected number of damage features calculated by Bumper 3 with the latest micrometeoroid and orbital debris (MMOD) environments are also presented. Statistics on the >300 impact features documented in the database will provide insight into the depth to diameter ratios and other relationships. The quality of the comparison between the observations and code predictions are dependent on several factors. The paper provides details of each of these variables.

1 Introduction

Only a small fraction of the mass that humans have sent into space is returned intact. Fortunately, the Space Shuttle Orbiter and ISS programs have provided NASA with many opportunities to inspect returned space-exposed surfaces for damage from MMOD impacts [1][2]. There are three primary reasons for continuing to perform this work.

1.1 Comparison With Current Predictions

After a mission is completed, it is useful to the flight programs and to NASA MMOD environment modelling teams to know how well the observations match with the predicted number of impacts using current engineering environments such as Orbital Debris Engineering Model version 3.2 (ORDEM 3.2) and Meteoroid Engineering Model version 3 (MEM 3).

1.2 Damage Trending

As a flight program accumulates exposure time, the ability to identify changes in damage magnitude or frequency in sensitive regions of a spacecraft can prompt design or operational changes that improves the risk posture of future missions.

1.3 Engineering Environment Updates

Damage size data, combined with projectile composition obtained via energy dispersive X-ray spectroscopy (EDX)analysis can be used in a region-specific ballistic performance equation to estimate a particle size. This data can be combined with as-flown area-time products to inform updates to engineering environments such as ORDEM 3.2 [5].

2 Cargo Dragon Spacecraft Overview

The SpaceX Dragon 1 was a reusable spacecraft used by NASA for ISS cargo resupply and return. In Fig. 1A, the main components of the Dragon 1 spacecraft can be seen. A nose cone that covers the berthing mechanism during ascent was released early in the mission. A majority of the pressurized capsule's base heatshield was protected by an unpressurized trunk module, which is often used to transport cargo to ISS and jettisoned during the Earth return phase of each mission.

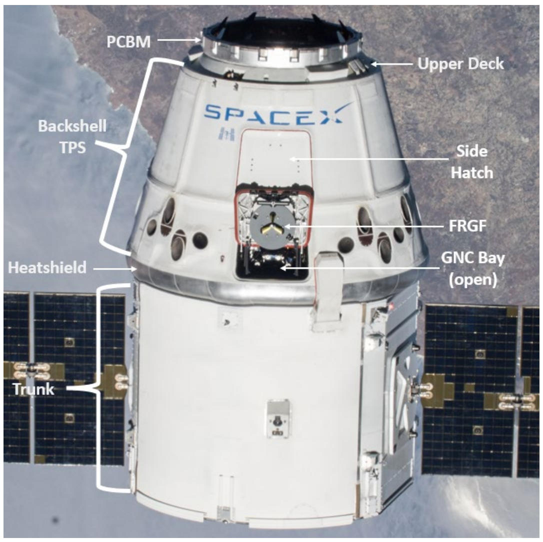

Figure 1A: SpX-15 Dragon spacecraft approaching ISS (NASA image iss056e073506)

Figure 2B: SpX-4 Dragon spacecraft on ISS Node 2 nadir port (NASA image iss041e046700)

Above the pressure section is the Upper Deck and Passive Common Berthing Mechanism (PCBM) structural ring. Both areas are covered with the same SpaceX Proprietary Ablator Material (SPAM) Thermal Protection System (TPS) material as the backshell areas. The heat shield is located between the backshell TPS and the Trunk and consists of a SpaceX proprietary version of the NASA Phenolic Impregnated Carbon Ablator (PICA), designated as "PICA-X." The shoulder area of the base heatshield is visible as the silver-colored band in both figures. In Fig.1A, the guidance, navigation, and control (GNC) bay door has been opened to expose the grapple fixture for berthing with ISS.

2.1 Mission Profile

Fig. 1B shows the SpaceX Dragon 1 berthed at the Node 2 nadir port. This oriented the "leeward" TPS on the vehicle in the ram direction of ISS, where the orbital debris flux is higher. The "windward" TPS, which experiences elevated reentry heating, sees reduced orbital debris flux on the wake side of ISS. The typical exposure time on Node 2 nadir for these cargo missions was about 30 days. After recovery in the Pacific Ocean off Los Angeles, the Dragon 1 would be moved overland to the SpaceX Texas Test Site in McGregor for post flight servicing. This is where the NASA/JSC HVIT team performed most of the post flight MMOD inspections.

2.2 Flight History

As shown in Table 1, the Dragon 1 flight program consisted of 20 missions to ISS between May 2012 and April 2020. The program totaled over 1.5 years of exposure time docked to the ISS

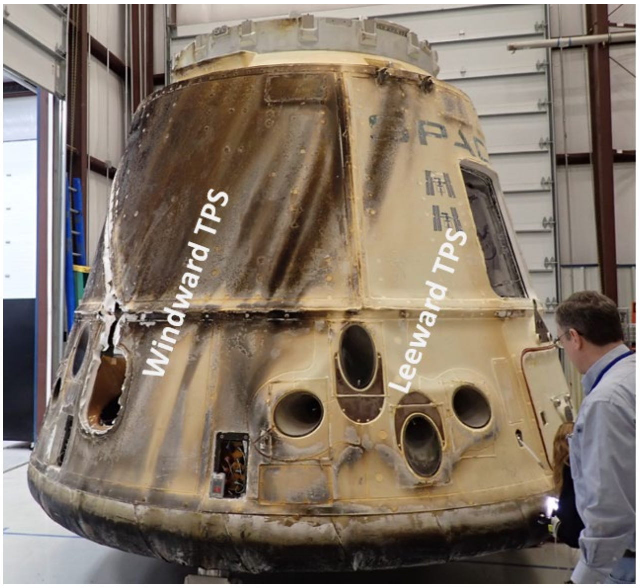

Figure 2A: SpX-19 Dragon-1 spacecraft on test stand at SpaceX Texas Test Site.

Figure 2B: MMOD post flight inspection initial screening technique

3 Inspection Campaign

Figure 2A shows a Dragon 1 spacecraft resting on a stand in a building at the SpaceX Texas Test Site. The post flight MMOD inspections tended to focus on the leeward regions of the vehicle, which were much less charred than the windward areas. The charring on the windward sides makes it very difficult to locate MMOD impacts. In Fig. 2A, the darker charred portion of the TPS can be seen on the left-hand side of the image.

3.1 Inspection Limits

Post flight MMOD inspections on the SpaceX Dragon 1 attempted to find damage features produced by hypervelocity impacts (HVI). Due to the nature of both orbital debris and naturally occurring meteoroids, the particle flux is inversely proportional to size. Therefore, small impact features will be much more common than large ones. In general, the lower cut-off size of damage observations in the acreage SPAM areas of the Dragon 1 were on the order of 1 millimeter. Much smaller feature sizes were observable on the coated aluminum surface of the Flight Releasable Grapple Fixture (FRGF).

3.2 Inspection Procedure

The process involves an initial screening step performed with a flashlight and 15x loupe, where the light source is roughly tangent (or parallel) to the spacecraft surface (Fig. 2B). This technique tends to reveal surface features better than direct perpendicular lighting. During this initial screening, regions of interest (ROI) are flagged for additional characterization. The flagged ROI are evaluated for their similarity to known non-MMOD causes such as tool marks and handling damage. Sites with high confidence as non-MMOD nature are not evaluated further. The remaining suspected MMOD sites are subjected to several additional characterization steps. First, details of the specific location on the spacecraft are recorded. Next, imagery of the damage feature is recorded with a 25-200x handheld video microscope. The final characterization step involves multiple crater depth measurements with an optical micrometer.

The focus of the inspection was the leeward Backshell SPAM (Fig. 2A). Other SPAM-covered inspection areas are the upper deck and side hatch. The leeward shoulder area of the base heatshield (covered with a different TPS) was always inspected. The Draco engine nozzles and surrounding region were typically available for inspection. Finally, the interior of the GNC bay and the grapple fixture on the GNC bay door were occasionally available. Refer to Fig.3 for an illustration of the Dragon 1 inspection regions and their associated surface areas.

The final step after each inspection was completed involved a comparison between preflight baseline configuration imagery of the spacecraft TPS (provided by SpaceX) and the pictures of the damage features acquired during the inspection. Typical postflight image comparisons would change the status of a few ROIs from “suspected MMOD” to “not MMOD”.

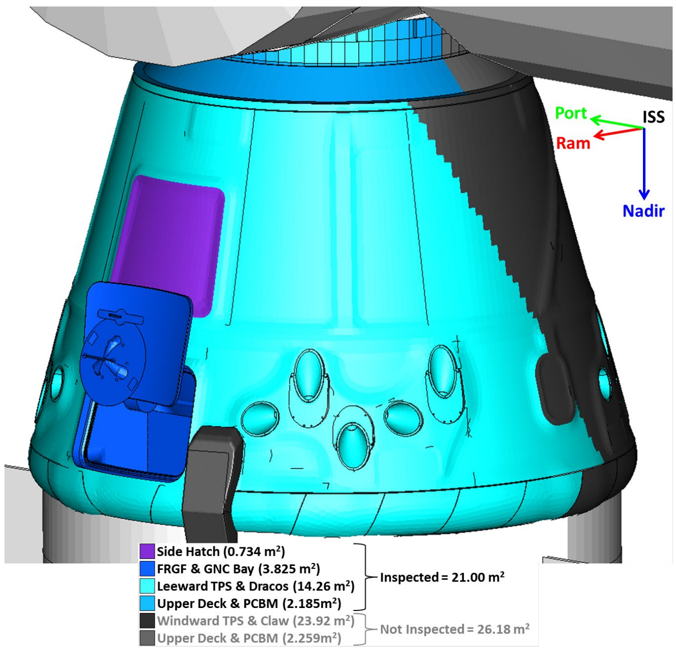

Figure 3. Dragon 1 post flight MMOD inspection areas

3.3 Sampling

During the inspection the entry hole size is estimated, and the depth is measured for each feature. At the conclusion of the inspection, a few sites are selected for intact extraction based on feature volume and degree of confidence that the damage was caused by MMOD. Before sampling, each area was usually covered by Kapton tape to reduce the introduction of contaminates into the crater. SpaceX would cut the TPS around the damage site with a hole saw to a sufficient depth that allows the cylinder of material to be removed by inducing shear failure at the bottom. The samples were archived at NASA/JSC building 267 prior to being analysed optically in cross-section by a scanning electron microscope (SEM), and elemental characterization can be conducted using an attached EDX detector to discern the projectile source [3].

Table 1. Dragon 1 MMOD Inspection Campaign Results

Flight	Year	Alt. (km)	Exp. Time (hr)	Inspected Regions*	Inspected Area (m^2)	Area-Time Product (m^2hr)	MMOD Sites	Impact Rate (#/hr)	Max. SPAM Depth (mm)	Max. SPAM Diam. (mm)
D2	2012	399	139.7	S,G,L,U	21.00	2,933	18	0.129	---	1.00
CRS-1	2012	414	434.5	S,G,L,U	21.00	9,127	18	0.041	2.50	2.82
CRS-2	2013	409	552.4	S,G,L,U	21.00	11,603	14	0.025	1.78	3.25
CRS-3	2014	416	674.2	S,G,L,U	21.00	14,161	17	0.025	---	2.92
CRS-4	2014	414	771.1	L,U	16.45	12,680	20	0.026	1.32	1.85
CRS-5	2015	405	704.3	L,U	16.45	11,583	13	0.018	1.45	1.47
CRS-6	2015	400	816.1	S,L	14.99	12,237	25	0.031	0.94	1.59
CRS-8	2016	405	746.0	S,G,L,U	21.00	15,668	20	0.027	2.07	2.31
CRS-9	2016	405	887.2	S,G,L,U	21.00	18,636	17	0.019	1.93	2.22
CRS-10	2017	405	574.4	S,L,U	17.18	9,868	14	0.024	1.05	1.81
CRS-11	2017	405	664.8	S,L,U	17.18	11,421	15	0.023	1.79	1.82
CRS-12	2017	405	765.2	G,L,U	20.27	15,510	12	0.016	1.11	1.42
CRS-13	2017	405	349.0	G,L,U	20.27	7,074	11	0.017	1.38	4.52
	2018		298.0	G,L,U	20.27	6,040				
CRS-14	2018	405	746.7	G,L,U	20.27	15,136	9	0.012	1.15	2.44
CRS-15	2018	405	773.7	G,L,U	20.27	15,683	18	0.023	2.17	3.82
CRS-16	2018	405	563.6	S,G,L,U	21.00	11,838	20	0.023	1.60	2.53
	2019		311.6	S,G,L,U	21.00	6,544				
CRS-17	2019	410	670.0	S,G,L,U	21.00	14,074	9	0.013	0.94	1.96
CRS-18	2019	410	740.1	S,L	14.99	11,097	17	0.023	1.96	3.52
CRS-19	2019	419	563.2	L,U	16.45	9,262	13	0.018	0.79	1.96
	2020		150.0	L,U	16.45	2,466				
CRS-20	2020	419	698.7	L,U	16.45	11,490	15	0.021	1.36	1.77

*Note: S = Side Hatch (0.734 m^2), G = GNC Bay (3.825 m^2), L = Leeward TPS (14.26 m^2), U = Leeward Upper Deck & PCBM (2.185 m^2)

3.4 Inspection Results

A summary of the inspection campaign results can be found in Table 1. The “Exp. Time” column lists the exposure time for each Dragon 1 spacecraft while berthed to ISS Node 2 nadir (i.e., pre and post berth free-flight exposure times are not tabulated here). If the Commercial Resupply Services (CRS) mission spanned two calendar years, the exposure time for each year is provided. The inspected areas for each mission varied depending on hardware availability. Table 1 list four different combinations of inspected areas and the associated area-time products. The “MMOD Sites” column lists the number of observations for each mission that remained after the post-flight imagery comparison. The “Impact Rate” column presents a ratio of the number of MMOD observations and the berthed exposure time for each mission. Excluding the Demo 2 mission, the average impact rate for the Dragon 1 flight program (CRS-1 through CRS-20) was just over 0.5 impacts/day. The distribution of all 315 MMOD observations spanning the 20 Dragon 1 missions are compared in Fig. 4. The plot also includes the maximum depth and diameters observed in the SPAM material for each mission. There is no apparent correlation between crater count and maximum damage size.

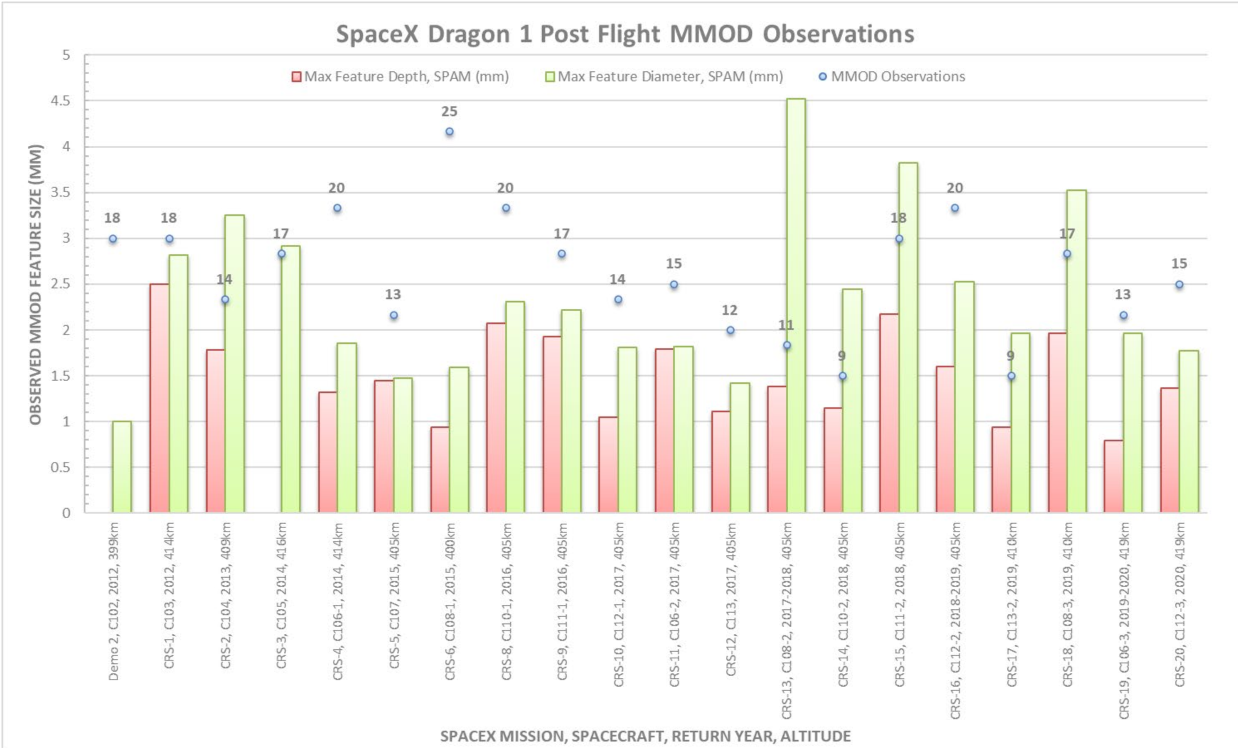

Figure 4. Results of Dragon 1 post flight inspection campaign

3.5 Database Overview

The Dragon 1 inspection database documents location, feature dimensions, sample status and estimated projectile diameter for 315 impact records. Table 2 summarizes the results for the 30 sites associated with the largest estimated particle diameters. Only a handful of sites have been analyzed with SEM/EDX.

Table 2. SpaceX Dragon 1 Post Flight Inspection Results (Top 30 Projectile Sizes)

Mission	Index #	Region	Impacted Material	Depth (mm)	Dimensions (mm x mm)	Samples	SEM/EDX Analysis Results	Feature Size / Projectile Diameter	Estimated Projectile Diameter (cm)
CRS-13	14	PS1	SPAM	1.38	4.79 x 4.26	CORE	OD (Fe,Cr,Ni)	10	0.045
CRS-15	3	PS5	SPAM	2.17	4.15 x 3.51	CORE	MM (S,Fe, Ni)	10	0.038
CRS-18	3	PS2	SPAM	1.44	3.64 x 3.42	CORE	OD (Pt,Fe,Cu,Zn)	10	0.035
CRS-02	3	SS6	SPAM	1.78	3.39 x 3.12	CORE	OD (Fe,C)	10	0.033
CRS-16	13	ST10	PICA-X	0.87	5.05 x 2.53	none	none	11	0.032
CRS-18	2	SS7	SPAM	1.96	3.19 x 3.01	CORE	not analyzed	10	0.031
CRS-15	2	PS1	SPAM	1.96	3.11 x 2.90	CORE	not analyzed	10	0.030
CRS-03	17	PS1	SPAM	---	2.96 x 2.89	CORE	not analyzed	10	0.029
CRS-13	8	PS1	SPAM	1.20	2.94 x 2.87	CORE	not analyzed	10	0.029
Demo 2	10	ST20	PICA-X	2.92	3.81 x 2.54	mold+tape	OD (Sn, Cu)	11	0.028
CRS-01	8	PS1	SPAM	---	2.95 x 2.70	TAPE 2X	not analyzed	10	0.028
CRS-15	7	PS1	SPAM	0.96	2.73 x 2.68	CORE	not analyzed	10	0.027
CRS-01	10	PS1	SPAM	---	2.89 x 2.45	TAPE 2X	not analyzed	10	0.027

CRS-16	1	SS1	SPAM	1.60	2.68 x 2.40	CORE	not analyzed	10	0.025
CRS-16	19	PS1	SPAM	1.22	2.55 x 2.46	CORE	not analyzed	10	0.025
CRS-14	5	PS1	SPAM	0.43	2.54 x 2.35	none	none	10	0.024
CRS-14	7	PS1	SPAM	0.76	2.51 x 2.30	CORE	not analyzed	10	0.024
CRS-08	4	PS1	SPAM	2.07	2.51 x 2.13	CORE	not analyzed	10	0.023
CRS-01	18	ST23	PICA-X	---	2.78 x 2.19	none	none	11	0.022
CRS-09	3	PS1	SPAM	1.93	2.22 x 2.21	CORE	not analyzed	10	0.022
CRS-02	11	PS1	SPAM	---	2.55 x 1.78	none	none	10	0.021
CRS-18	7	PS1	SPAM	1.45	2.57 x 1.76	CORE	not analyzed	10	0.021
CRS-01	15	ST1	PICA-X	0.580	2.39 x 2.22	TAPE 2X	not analyzed	11	0.021
CRS-02	13	PS5	SPAM	0.71	2.27 x 1.89	none	none	10	0.021
CRS-04	13	ST7	PICA-X	0.94	2.61 x 1.94	none	none	11	0.020
CRS-09	4	ST4	PICA-X	1.45	2.63 x 1.91	none	none	11	0.020
CRS-17	2	PS1	SPAM	0.91	2.13 x 1.80	CORE	not analyzed	10	0.020
CRS-19	14	SS6	SPAM	0.37	2.01 x 1.91	none	none	10	0.020
CRS-20	15	FRGF	coated Al	n/a	1.88 x 1.87	none	none	10	0.019
CRS-16	16	PS1	SPAM	1.37	1.86 x 1.86	CORE	not analyzed	10	0.019

Fig. 5 provides two views of the 4.79 x 4.26 mm damage site observed in the SPAM TPS of the Dragon 1 spacecraft used for the CRS-13 mission. The image on the left is a perpendicular view of the feature with the light source positioned directly above. The image on the right was acquired with a different instrument positioned at angle to the spacecraft surface using ambient room light. This oblique view provides insight into the asymmetric nature of the crater shape, which had a measured depth of 1.38 mm. The SEM/EDX results of iron, nickel and chromium indicate that a high-density (steel) orbital debris projectile produced this damage feature.

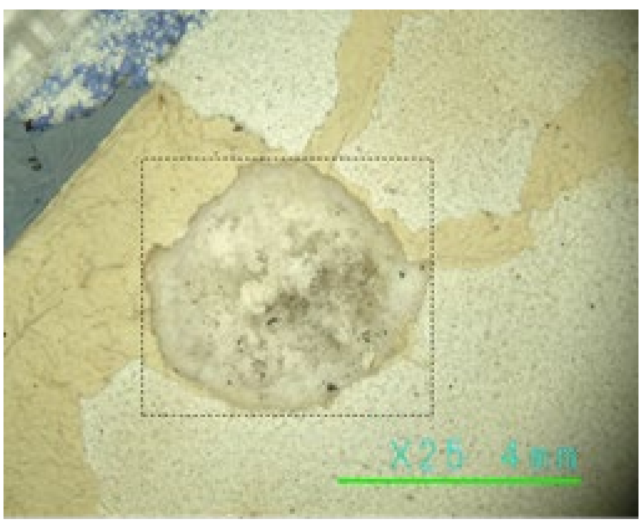

Figure 5A: CRS-13 impact feature #14 in SPAM
(perpendicular view)

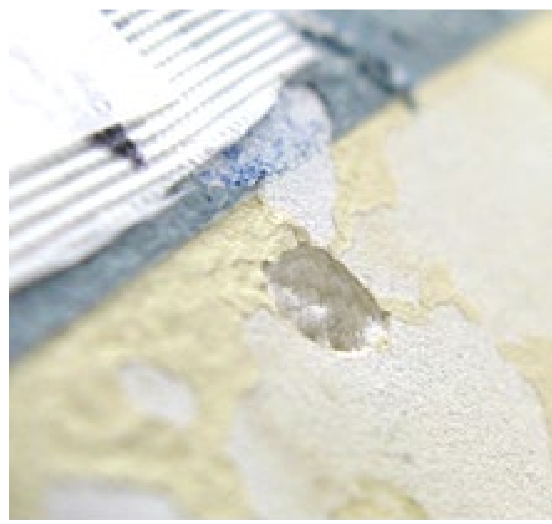

Figure 5B: CRS-13 impact feature #14 in SPAM
(oblique view)

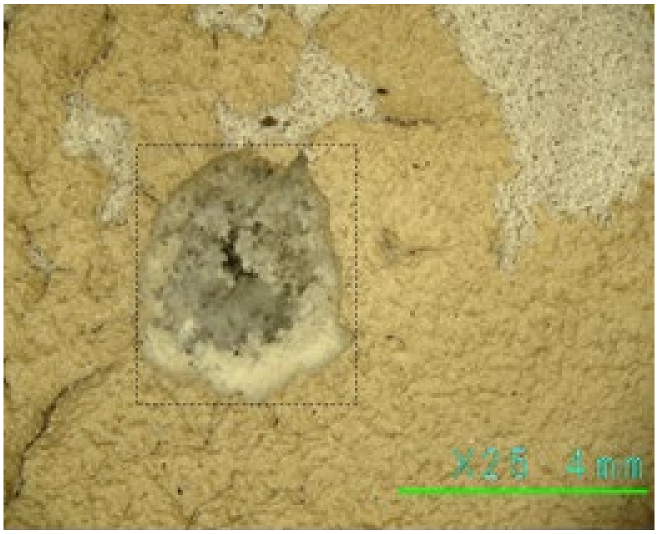

Figure 6A: CRS-15 impact feature #3 in SPAM (perpendicular view)

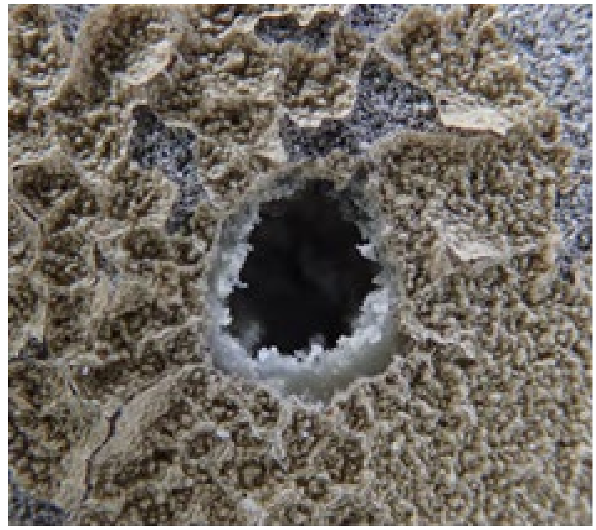
Figure 6B: CRS-13 impact feature #3 in SPAM (perpendicular view, wide-ring light source)

Fig. 6 provides two views of another SPAM impact feature with entry hole dimensions of 4.15 x 3.51 mm and a depth of 2.17 mm observed on the CRS-15 Dragon 1 spacecraft. The image on the left is a perpendicular view of the feature with the light source positioned directly above. The image on the right was acquired at the same orientation but used a different light source. The SEM/EDX results of sulphur, iron and nickel indicate that a high-density meteoroid projectile produced this damage feature.

4 As-flown Comparison

After each Dragon 1 post flight MMOD inspection, a comparison of observed and predicted damage was performed using the Bumper 3 risk assessment tool [4]. Crater depth measurement was not possible on about 30% of the 315 damage sites, so entry hole dimensions were used to estimate the projectile diameter. A rolled-up comparison of all 20 missions in the inspection campaign was produced using Bumper 3 predictions with the latest orbital debris [5] and meteoroid [6] engineering models.

4.1 Damage Equations

An estimate of SPAM damage size as a function of projectile size was derived from multiple HVI tests using projectile densities between 1.2 and 7.667 g/cm^3. Most of the tests were conducted at a velocity of 7 km/s, with two tests at 5 km/s and two more at 10 km/s. Projectile sizes varied between 0.02 and 0.14 cm. Figure 7A shows a cross-plot of the damage feature size (including coating spall) and projectile diameter. The fit to the data indicates a feature size to projectile ratio of ~10. Figure 7B provides a similar cross-plot for five PICA-X HVI tests. The results of the linear regression of the data shows a feature size to projectile ratio of ~11 for the PICA-X material.

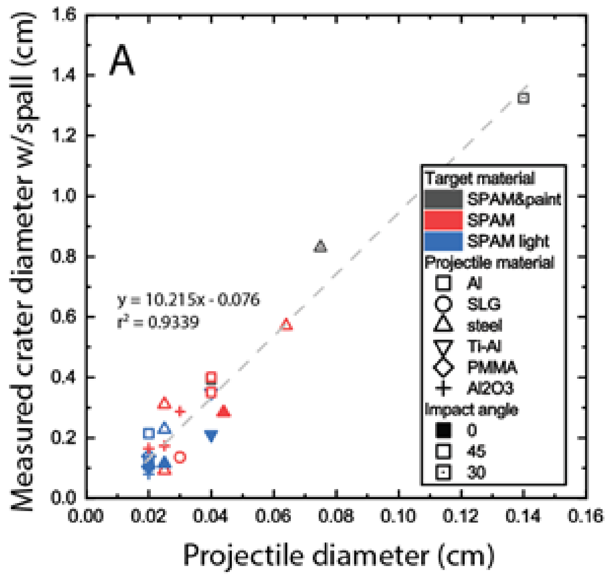

Figure 7A: Cross-plot of SPAM damage feature size and projectile diameter

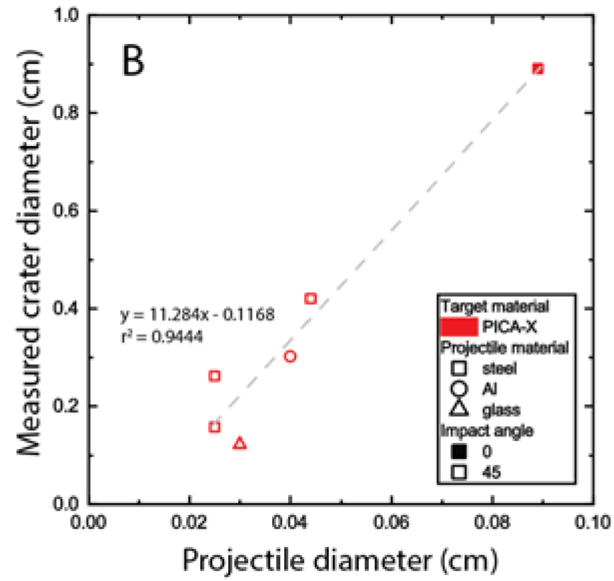

Figure 7B: Cross-plot of PICA-X damage feature size and projectile diameter

Table 3 summarizes the damage size to projectile size ratios used in the following analysis for all ten surface types in the Dragon 1 impact database. Coated metal surfaces were set to 10, assuming that the damage measurement included coating spall (not the central pit diameter). A factor of 4 was assumed for all other surface types, based on engineering judgement.

Table 3. Feature Size to Projectile Diameter Ratios for Impacted Surfaces on Dragon 1

Dragon 1 Material	**Location on Spacecraft**	**Impact Feature Count**	**% Total**	**Feature Size / Projectile Size**
SPAM	Backshell	205	65.1%	10
PICA-X	Heatshield shoulder	65	20.6%	11
coated aluminum	Grapple fixture	28	8.9%	10
coated C103	Thruster nozzle	8	2.5%	10
RTV	Side hatch & GNC bay door	4	1.3%	4
bare aluminum	GNC bay	1	0.3%	4
coated Steel	GNC bay	1	0.3%	10
phenolic fiberglass	GNC bay door attach	1	0.3%	4
polycarbonate	Upper hatch	1	0.3%	4
anodized aluminum	Upper hatch	1	0.3%	4
TOTAL		**315**		

4.2 Results

For each of the 20 Dragon 1 missions to ISS, an expected number of impacts from a representative set of particle diameter were computed for the MEM3 and ORDEM 3.2 environments considering the mission year, exposure time and inspected areas using the Bumper 3 analysis tool. The predicted number of impacts for the Dragon 1 flight program is plotted in Fig. 8 as a solid black line. Estimated sizes of impactors (based on feature size) are plotted in ascending order. Observations are grouped by SPAM, PICA-X and "others" and the SPAM impacts dominate the larger diameters and the "others" (mostly coated aluminum (Al) & niobium alloy (C-103) are more common at the lower end of the size spectrum. In general, the Bumper 3 predictions match the observations well.

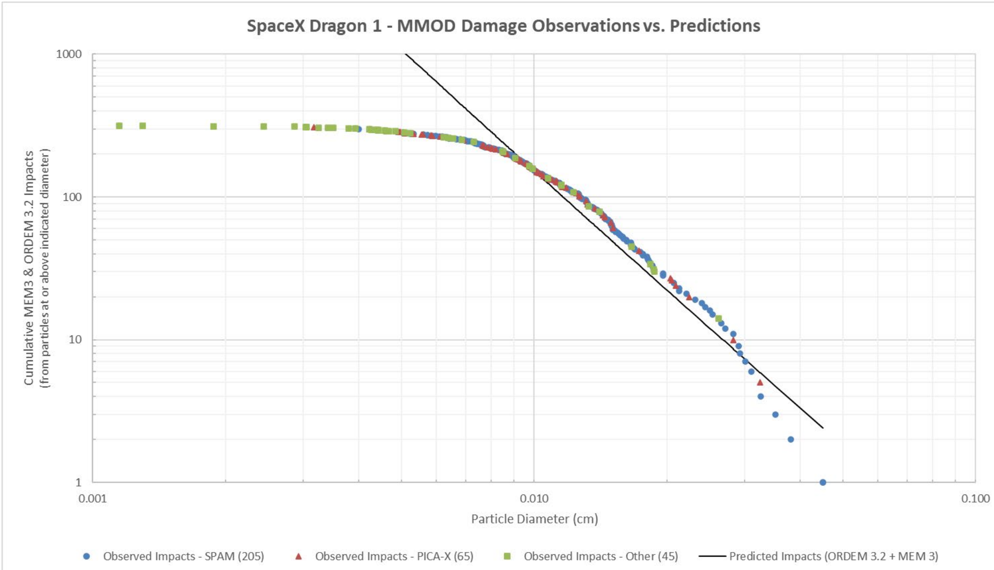

Figure 5. MMOD damage observations compared to Bumper 3 predictions

5 Conclusions/Discussion

The CRS-20 mission concluded the Dragon 1 flight program. As of late 2023 there have been 18 flights with the Dragon 2 spacecraft. SpaceX has completed nine cargo and six crew missions to ISS for NASA. Two private astronaut missions have flown to the ISS Dragon 2 spacecraft and there has been one free flyer mission (Inspiration 4). Post flight inspection data was collected after most of these missions and will be the subject of future reporting. Work continues on improved damage equations that consider projectile and target properties. Only 6 of the 40 collected core samples from Dragon 1 inspections have been processed by SEM/EDX. Increasing this number will reduce uncertainty on future projectile size calculations as well as provide data for future updates to the orbital debris environment model.

6 References

1. Hyde, J.L., Christiansen, E.L., Lear, D.M., “Shuttle MMOD Impact Database”, Procedia Engineering, Vol. 103, 2015. https://www.sciencedirect.com/science/article/pii/S1877705815007183
2. Hyde, J.L., Christiansen, E.L., Lear, D.M., “Observations of MMOD Impact Damage to the ISS”, 1st International Orbital Debris Conference, 2019, https://ntrs.nasa.gov/citations/20190033989
3. Anz-Meador, P., Murray, M., Christiansen, E.L., Hyde, J.L., Cowardin, H. M., “A Survey of ISS and Visiting Vehicle Returned Surfaces for Environmental Characterization and Computer Model Development,” 2nd International Orbital Debris Conference, 4-7 Dec. 2023
4. Lear, D.M., Christiansen, E.L., Hyde, J.L., “Bumper: A Tool for Analyzing Spacecraft Micrometeoroid and Orbital Debris Risk”, 1st International Orbital Debris Conference, 9-12 Dec. 2019, NASA Technical Report Server: https://ntrs.nasa.gov/citations/20205011690
5. NASA Orbital Debris Program Office (ODPO), Orbital Debris Quarterly Newsletter, “Orbital Debris Engineering Model 3.2 Release”, Volume 26, Issue 1, March 2022.
6. Moorhead, A.V., NASA Meteoroid Engineering Model (MEM) Version 3, NASA Technical Memorandum, NASA/TM-2020-220555, 2020.