Observations of MMOD Impact Damage to the ISS

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ABSTRACT

This paper describes meteoroid and orbital debris (MMOD) damage observations on the International Space Station (ISS). Several hundred MMOD damage sites on ISS have been documented using imagery taken from ISS windows. MMOD damage sites visible from ISS windows are typically larger – approximately 5mm diameter and greater – due to the larger viewer-to-surface distance. Closer inspection of these surfaces by astronauts during spacewalks reveals many smaller features that are typically less distinct. Characterization of these features as MMOD or non-MMOD is difficult, but can be partially accomplished by matching physical characteristics of the damage against typical MMOD impact damage observed on ground-based impact tests.

Numerous pieces of space-exposed ISS hardware were returned during space shuttle missions. Subsequent ground inspection of this hardware has also contributed to the database of ISS MMOD impact damage. A handful of orbital replacement units (ORUs) from the ISS active thermal control and electrical power subsystems were swapped out and returned during the Space Shuttle program. In addition, a reusable logistics module was deployed on ISS for a total 59.4 days on 11 shuttle missions between 2001 and 2011 and then brought back in the shuttle payload bay. All of this returned hardware was subjected to detailed post-flight inspections for MMOD damage, and a database with over 1,400 impact records has been collected.

A description of the largest observed damage features is provided in the paper. In addition, a discussion of significant MMOD impact sites with operational or design aspects is presented. MMOD impact damage to the following ISS modules/subsystems is described: (1) Solar Arrays, (2) US and Russian windows, (3) Extravehicular Activity (EVA) handrails, (4) Radiators, and (5) Russian Functional Cargo Block (FGB) module.

1 INTERNATIONAL SPACE STATION

The International Space Station (ISS), the largest structure ever assembled in space, has been continuously occupied since November 2000. The ISS operates in low earth orbit (LEO) at an altitude of approximately 400km and an inclination of 51.6 degrees. The ISS can be divided into two segments. The Russian operational segment (ROS) is currently composed of five permanent modules and between two and four visiting vehicles, with plans to replace a current module with three new modules. NASA collaborated with space agencies from Europe and Japan on the 14 modules in the US operational segment (USOS), with Canada providing the remote manipulator system.

In the current mid-2019 configuration, the ISS has 19 pressurized modules with an approximate surface area of 1,887 m^2. In addition, there are eight 35-meter long solar array wing assemblies on the USOS (with an approximate surface area of 4,725 m^2) and four smaller solar array wings on the RS (with an approximate surface area of 328 m^2). The primary active thermal control system is comprised of six Heat Rejection System (HRS) radiator panels with an approximate surface area of 1,031 m^2. In addition, each of the four truss segments with solar array wing assemblies are outfitted with a dedicated Photovoltaic radiator (PVR), with an approximate surface area of 355 m^2. Solar array, radiator and robotic arm components are all mounted on seven US truss segments. Many ISS systems are designed to be serviced on orbit. These spare orbital replacement unit (ORU) components are stored on seven external stowage platforms. The USOS is equipped with exposed payload platforms on the ESA and JAXA modules with an additional facility planned for the ESA module in 2020. The approximate combined surface areas of the truss, external equipment and ORU platforms is approximately 4,277 m^2. The ISS is currently serviced by visiting vehicles from Russia for cargo (Progress) and crew transfer (Soyuz), from the US for cargo (Dragon & Cygnus) and from Japan for cargo (H-II Transfer Vehicle). Currently the SpaceX Cargo Dragon is the only ISS visiting vehicle that is available for post flight inspection. Near-term US vehicles planned for cargo (Sierra Nevada DreamChaser) and crew transfer (SpaceX Crew Dragon and Boeing Starliner) are all expected to be available for post mission MMOD inspections. Private astronaut missions have been announced for the ISS using the new US crew transfer vehicles, providing additional opportunities in the future for post flight inspections.

Table 1. ISS surface area summary

ISS Region	Approximate Surface Area (m^2)
USOS pressurized modules	1,284
RS pressurized modules	603
USOS solar arrays	4,725
ROS solar arrays	328
HRS radiators	1,031
PV radiators	355
Truss, External Equipment & ORUs	4,277
TOTAL	**12,603**

2 MMOD DAMAGE OBSERVATION CATEGORIES

2.1 Observation versus detection

This paper provides examples of different types of MMOD damage observations on the ISS and does not cover damage detection techniques. A survey of MMOD impact detection technologies is covered thoroughly in a recent Inter-Agency Space Debris Coordination Committee (IADC) document [1].

2.2 Returned space exposed hardware

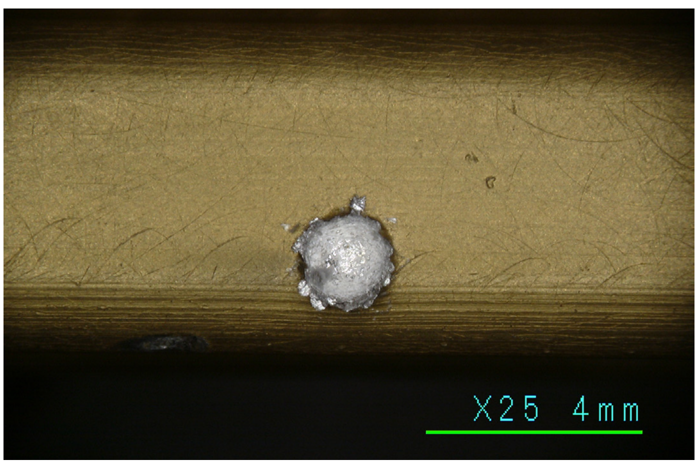

Fig. 1. MMOD impact crater on ISS handrail

Direct observation of surfaces subjected to the MM & OD environments permits detailed characterization of damage features. This technique also allows scanning electron microscopy and energy dispersive x-ray investigations to discern the impactor source. One drawback to the technique are potential changes to impact sites incurred during re-entry. When the shuttle program concluded in 2011 a significant source of returned surfaces was no longer available. Inspection campaigns of the shuttle crew module windows and payload bay door radiators were conducted over the life of the program [3]. In addition, detailed inspections of the wing leading edge reinforced carbon-carbon (RCC) panels were performed on the final 22 missions. During the assembly phase of the International Space Station (ISS) the shuttle returned a variety of ISS components in the payload bay, protecting the space exposed hardware from re-entry heating [4]. In addition, eleven shuttle missions delivered a temporary logistics module that was installed on the ISS while the shuttle was docked. At the end of each of these missions, the logistics module was stowed in the payload bay and returned. At this time (late 2019), the return of space exposed hardware from ISS is limited to items that can be carried in a SpaceX Cargo Dragon. Figure 1 provides an example of an MMOD impact crater observed on an aluminum handrail mounted on flight support equipment that was returned from the ISS in 2011.

2.3 EVR video and still images

Extravehicular Robotics (EVR) assets on the ISS include multiple digital cameras mounted on the truss, capable of acquiring video and still images. While these cameras can acquire images in high definition (HD) resolution, the distance to potential areas of interest on the ISS can be very long. Determination of small (<1mm diameter) MMOD features using these cameras is usually difficult. The robotic arm on the mobile servicing system (MSS) houses lower resolution standard definition (SD) video cameras that can be positioned much closer to areas of interest. An example of this type of imagery collection is the photographic survey of the Soyuz descent module conducted prior to the crew departure from ISS.

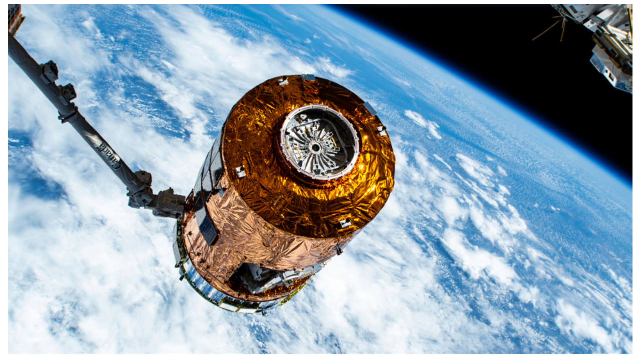

Fig. 2. Image of JAXA HTV-8 spacecraft acquired with external high definition camera EHDC3

Fig. 3. P4 battery EVA March 2019

2.4 EVA astronaut photography

At the time of this writing, there have been over 200 extravehicular activity (EVA) missions conducted on ISS by US and Russian crews [2]. Each US EMU suit is equipped with helmet mounted standard definition video cameras that provide point of view footage for each crew member. In addition, US EVA astronauts typically carry a 35mm handheld digital still camera or a digital video camera. Figure 3 is an example of EVA astronaut photography. Russian EVA cosmonauts have been deploying handheld digital video cameras as well as borrowing US EVA helmet cameras. Russian EVAs have also borrowed US 35mm handheld digital still cameras [5].

2.5 IVA astronaut photography

MMOD damage on has been documented on radiators, solar arrays and other ISS surfaces by astronauts inside the ISS during photographic intravehicular activities (IVA). This observation category can cover large areas of the ISS, but many surfaces are not visible due to the limited number of windows on the ISS. In its current configuration (late 2019) there are 13 windows on the USOS and 23 windows on the ROS. The majority of the IVA imagery of ISS from the USOS has been acquired from the six side windows of the cupola (Fig. 4). The only other USOS windows that can be used to view portions of the ISS are two 20” diameter windows on the outboard end of the Japanese Experiment Module. The remaining USOS windows are either facing earth or recessed in hatch alcoves. There are also a few windows on the ROS that provide useful views of ISS. During the ISS assembly phase, images of some station regions could be acquired through the shuttle crew module windows. MMOD damage areas of interest acquired from EVA and IVA sources mentioned here are collected in an image database managed by the Image Science and Analysis Group at the Johnson Space Center (JSC). There are currently 380 records tagged as “MMOD” in the database, although it should be noted that some of these records include multiple MMOD damages (i.e., there are more than 380 MMOD impacts represented in this database).

Fig. 4. Photographic survey of Cygnus Orb-1 from February 2014

3 ISS IMPACT DATABASE

3.1 Overview

The ISS impact database is maintained at the NASA/JSC by the Hypervelocity Impact Technology (HVIT) group. The database contains over 1,400 records of impact damage from ground-based observations of space-exposed hardware returned from ISS (Table 2). At this time, access to the ISS impact database is restricted to NASA only. The earliest observation in the database is from an EVA safety tether housing inspected in early 2001 and the most recent records come from a Battery Charge Discharge Unit (BCDU) ORU that was inspected July 2019. In its current form, the database is mainly comprised of separate Excel worksheets for each inspection item, although written descriptions of some of the inspection findings are provided elsewhere [4, 9].

Over 400 samples have also been collected during the course of the hardware inspections, which are shown in the "samples" column in Table 2, many of which have been examined by SEM to determine if the damage was from meteoroid or orbital debris.

Table 2. ISS Impact Database Tables

#	Database Table Name	Hardware Class	Exp. Days	Insp. Date	MMOD Impacts	Samples
1	Node 1 port CBM hatch cover	blanket/shield	3,182	Oct-07	16	16
2	PMA 1 MDM Sunshade	blanket/shield	2,984	Mar-08	15	1
3	Airlock shield panel 01-04B	blanket/shield	3,195	Feb-11	24	4
4	Airlock shield panel 02-04B	blanket/shield	3,195	Feb-11	34	6
5	PMA 2 cover	blanket/shield	596	Mar-16	26	6
6	EVA Safety Tether Housing	EVA	733	Feb-01	5	2
7	Node 3 Avionics Bag	EVA	579	Mar-16	30	0
8	MPLM FM1 Flight 1	Logistics	6.06	Apr-01	3	3
9	MPLM FM1 Flight 2	Logistics	6.20	Aug-01	3	1
10	MPLM FM2 Flight 2	Logistics	6.05	Dec-01	8	8
11	MPLM FM1 Flight 3	Logistics	6.08	Jun-02	12	12
12	MPLM FM2 Flight 3	Logistics	7.20	Aug-05	22	2
13	MPLM FM1 Flight 4	Logistics	7.20	Jul-06	24	24
14	MPLM FM1 Flight 5	Logistics	9.28	Dec-08	123	97
15	MPLM FM1 Flight 6	Logistics	7.22	Sep-09	64	25
16	MPLM FM1 Flight 7	Logistics	7.42	Apr-10	75	11
17	MPLM FM2 Flight 4	Logistics	7.03	Jul-11	64	6
18	SpaceX Demo 2	Logistics	5.82	Jun-12	18	18
19	SpaceX CRS-1	Logistics	18.11	Nov-12	18	8
20	SpaceX CRS-2	Logistics	23.02	Apr-13	14	7
21	SpaceX CRS-3	Logistics	28.09	May-14	17	4
22	SpaceX CRS-4	Logistics	32.13	Oct-14	20	0
23	SpaceX CRS-5	Logistics	29.35	Feb-15	13	2
24	SpaceX CRS-6	Logistics	34.01	May-15	25	2
25	SpaceX CRS-8	Logistics	31.08	May-16	20	2
26	SpaceX CRS-9	Logistics	36.97	Sep-16	17	1
27	SpaceX CRS-10	Logistics	23.94	Mar-17	14	6
28	SpaceX CRS-11	Logistics	27.70	Jul-17	15	3
29	SpaceX CRS-12	Logistics	31.88	Sep-17	12	2
30	SpaceX CRS-13	Logistics	26.96	Jan-18	11	3
31	SpaceX CRS-14	Logistics	31.11	May-18	9	3
32	SpaceX CRS-15	Logistics	32.24	Aug-18	18	4
33	SpaceX CRS-16	Logistics	36.47	Jan-19	20	4
34	SpaceX CRS-17	Logistics	27.92	Jun-19	9	1

35	TUS-2 housing and cable	ORU	1,561	Oct-07	13	13
36	S-band Ant. Support Assy (SASA) E-box	ORU	1,842	Jan-08	48	12
37	P1 Nitrogen Tank Assembly (NTA)	ORU	1,906	Mar-08	26	17
38	SASA mast	ORU	1,842	Mar-08	24	18
39	S1 Nitrogen Tank Assembly (NTA)	ORU	2,239	Jan-09	24	13
40	P6 battery	ORU	3,149	Aug-09	92	18
41	P1 Ammonia Tank Assembly (ATA)	ORU	2,474	Oct-09	51	5
42	S1 Ammonia Tank Assembly (ATA)	ORU	2,736	Apr-10	49	4
43	P6 battery	ORU	3,447	Jun-10	34	3
44	P6 battery	ORU	3,447	Jun-10	29	2
45	P6 battery	ORU	3,447	Jun-10	16	0
46	P6 battery	ORU	3,447	Jun-10	21	2
47	P6 battery	ORU	3,447	Jun-10	20	1
48	P6 battery	ORU	3,447	Jul-10	21	2
49	4B guidewire cable	ORU	2,527	Oct-10	1	1
50	Pump Module Assembly	ORU	3,196	Aug-11	37	8
51	Large Adapter Plate Assembly (LAPA)	ORU	3,196	Aug-11	19	2
52	BCDU	ORU	4,631	Jul-19	64	0
		Totals	**66,992**		**1,407**	**415**

3.2 Logistics Module Datasets

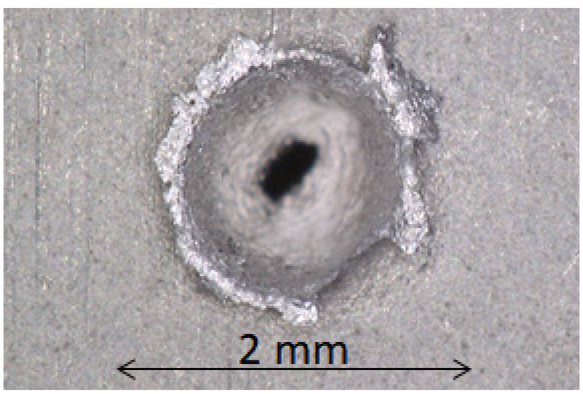

Fig. 5. Impact crater in aluminum MPLM shield

The records in the logistics module dataset are sourced from two different types of space exposed hardware. The Multi-Purpose Logistics Module (MPLM) was a large pressurized container used on Space Shuttle missions to transfer cargo to and from the International Space Station. Impacted surfaces were primarily bare aluminum sheets, with very distinct impact craters (Fig. 5). The SpaceX Cargo Dragon is a reusable spacecraft that provides cargo transfers to and from ISS. Impacted areas are primarily coated thermal protection system surfaces, with less distinct impact features. Nearly half of the impact records in the ISS database reside in the Logistics Modules dataset (668), but the 546.5 day exposure time for the 27 MPLM and SpX missions comprises less than 1% of the total duration in the database.

3.3 ORU Datasets

The ISS database contains impact records for ten different orbital replacement unit (ORU) types. Typical impact surfaces for this hardware are multilayer insulation (MLI) with betacloth (woven silica fiber cloth) outer face, with distinct impact features (Fig. 6). There were also components with bare aluminum surfaces. 42% of the items in this dataset (589 records) are responsible for more than 78% of the exposure time in database (51,981 days).

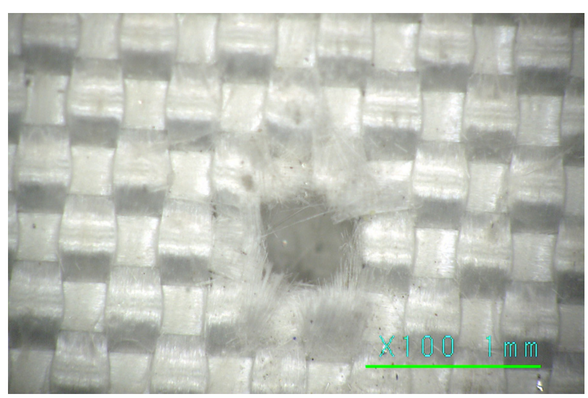

Fig. 6. Impact feature in betacloth

3.4 Blanket/Shield Datasets

The impacted surfaces in blanket/shield dataset are similar to surfaces in the previous two datasets. Most of the 115 records were observed in betacloth covered MLI similar to the ORU hardware in Fig. 6 [9]. The accumulated exposure time in this dataset (13,152 days) is 20% of the exposure time in the database.

3.5 EVA Hardware Datasets

With 35 records, this dataset accounts for 2% of the total number of observations. The 1,312 exposure days represents 2% of the total time. Impacted surfaces were divided into aluminum (Fig. 5) and betacloth (Fig. 6).

4 OBSERVATIONS OF SIGNIFICANT ISS DAMAGE

ISS crew have observed and photographed numerous MMOD impacts by hand-held cameras through ISS windows and during EVA. A description of several of the largest MMOD damage features observed on ISS, as well as damages that resulted in anomalies or issues to ISS operations are reported in this section. In particular, the ISS modules/subsystems discussed here are: (1) solar arrays, (2) Extravehicular Activity (EVA) handrails and EVA tools, (3) radiators, (4) windows, and (5) Russian Functional Cargo Block (FGB) module.

4.1 Solar Arrays

There are eight US solar array wings (SAWs) on ISS, each of which contain two solar array blankets and a supporting mast measuring 35 m long and 12 m wide. Many hundreds of MMOD craters and penetrations are apparent in high-resolution photos of the arrays. Figure 7 shows one of the largest damages observed on an ISS solar array due to MMOD impact, although most of the damage occurred from heating after MMOD impact on the solar array. A 7 mm diameter MMOD perforation resulted in a severed by-pass diode, which is a circuit device that protects a solar array string in normal operation. Because the by-pass diode was broken, a buildup of current occurred within the string and caused severe over-heating of the solar array in a local area, resulting in a nearly 40 cm long burn-through along the edges of 3 cells. The result of this excess heating was failure of an entire string of solar cells containing 400 cells. Although this is not a major loss considering there are over 250,000 cells in total for all SAWs, Fig. 8 illustrates other similar damage to the solar arrays. The steady degradation of power generated from the ISS solar arrays over time, due to MMOD and other causes, has necessitated planning to augment the ISS solar arrays in the future with additional solar array panel overlays.

An even larger amount of solar array damage occurred from a small impact on a solar array guidewire. Figure 9 shows two large tears that developed in the 4B SAW when the solar array was being redeployed after being moved to its final location during STS-120 due to a snagged guidewire. EVA crew removed the snagged guidewire and installed "cuff-link" reinforcements to stabilize the array. The guidewire was returned to the ground where it was examined and clear evidence of MMOD impact was observed by the melted material found at the location of the snag (Fig. 10).

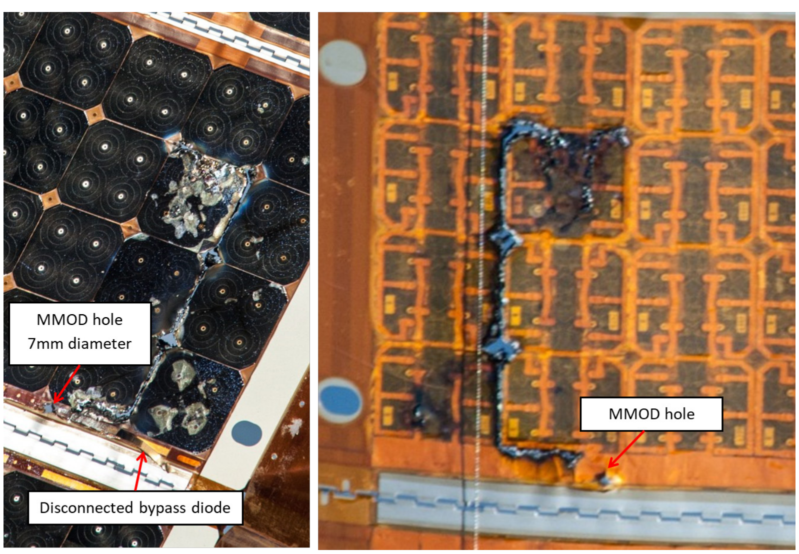

Fig. 7. Damage observed to ISS solar array 3A, panel 58 (cell side on left, Kapton backside on right). Note by-pass diode is disconnected due to MMOD impact.

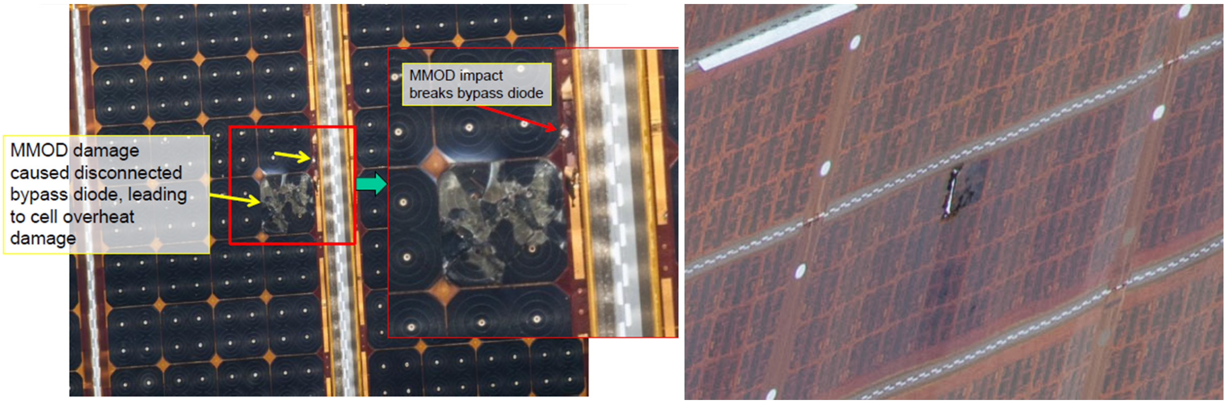

Fig. 8. Additional examples of ISS solar array overheat damage. On left, an MMOD strike caused a disconnected bypass diode resulting in loss of a string on solar array 2A panel 66. At right, an observed burn-through in solar array 3A panel 42; although no obvious MMOD damage is apparent, a failed bypass diode is a possibility.

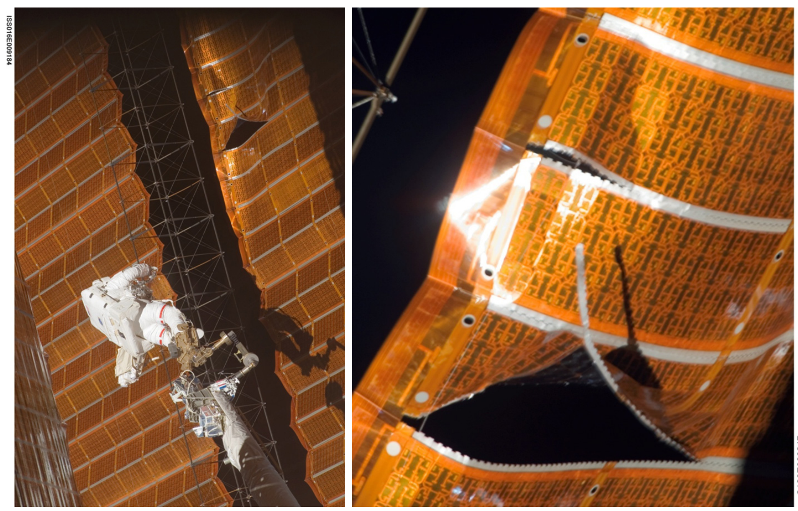

Fig. 9. During STS-120, two solar array wings were removed from the ISS Z1 truss and relocated to the P6 location. The 4B solar array wing tore in two places during redeployment due to a guidewire, which snagged in a grommet.

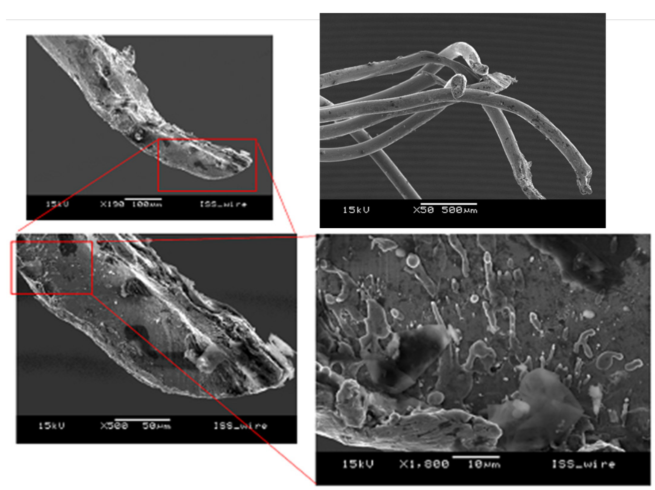

Fig. 10. The guidewire contains 21 twisted steel wires, seven (7) of which were severed. The lower images illustrate melted material at the ends of several of the severed wires, clearly indicating hypervelocity impact damage.

4.2 Handrails and EVA tools

Figure 1 illustrates one of the many MMOD craters observed on EVA handrails. Because the handrails are aluminum, the sharp edges that occur at the lips of the MMOD craters have caused cuts in the outer layers of EVA gloves and fingertips [6]. One cut glove example resulted in an early end to an EVA during the STS-118 mission (Fig. 11). Consequently, the EVA gloves were reinforced to reduce the risk of cuts from sharp edges of MMOD craters. In addition, a clamp was designed and used to isolate craters on handrails in highly traveled areas of ISS, such as near the airlock egress/ingress hatch. Figure 12 illustrates another MMOD crater found on a D-handle EVA tool that measured nearly 5 mm across. This tool had been stored on the ISS exterior, and was brought inside and repaired by the crew prior to use in March 2008, using adhesive tape wrapped around the MMOD damage.

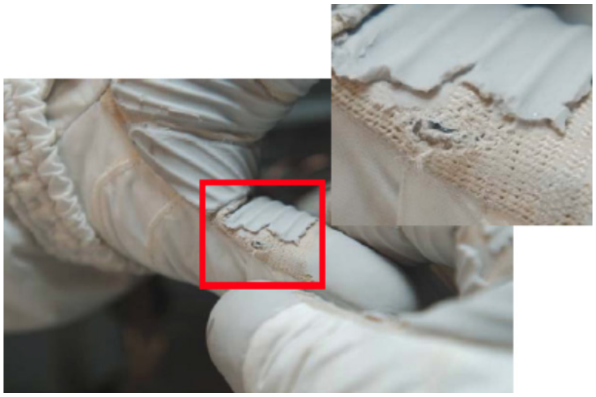

Fig. 11. Cut in outer layer of EVA glove (STS-118).

Fig. 12. Crater and detached spall on EVA D-handle tool.

4.3 Radiators

Figure 13 shows one of the ISS radiator panels, with several MMOD impacts observed on the radiator surface. The ISS radiator coolant flow-channels had been hardened before flight by locating the lines in the interior of the radiator panel [7] (not adjacent to the outer face sheet, which was common practice prior to ISS). So far, MMOD impacts have not been confirmed as the cause of any of the coolant leaks that have occurred to the thermal control system to-date. The largest damage observed on ISS radiators from MMOD impact (Fig. 14) measures 13cm by 10cm, with coolant flow channels visible, but unbroken.

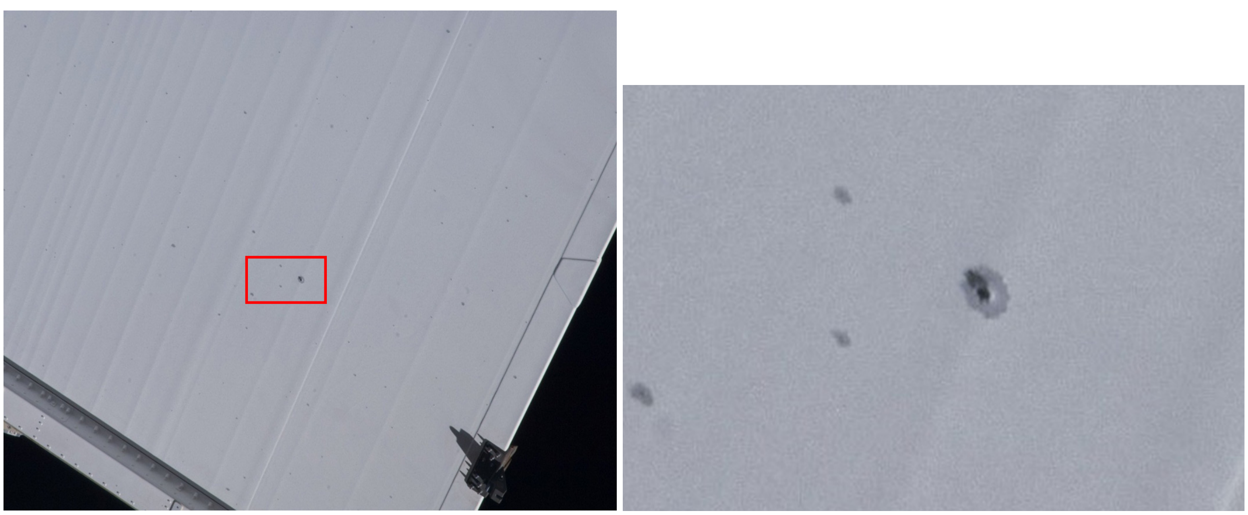

Fig. 13. Surface of one ISS radiator panel photographed during increment 36 (dark spots are typical MMOD damages). Red outline area expanded on right.

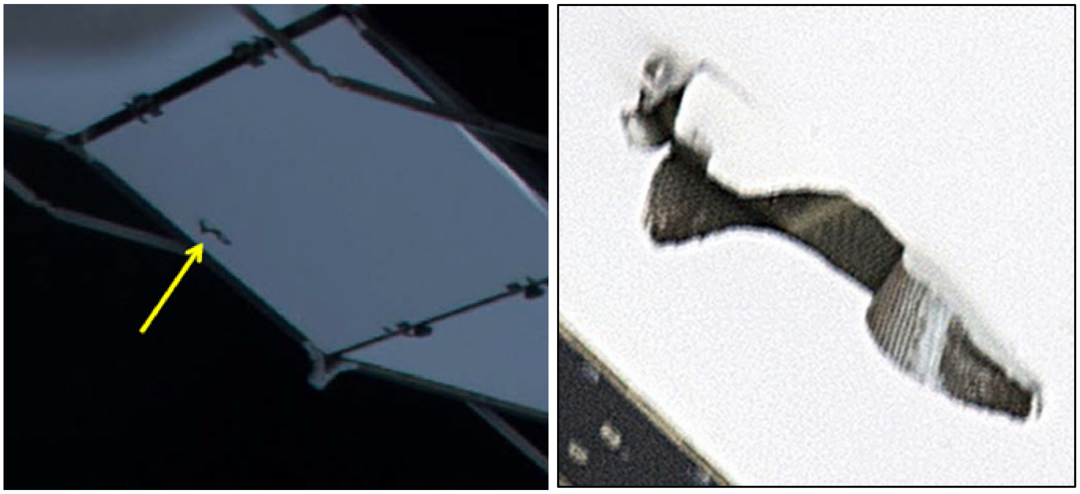

Fig.14. MMOD damage located on port photovoltaic radiator panel (exit damage).

4.4 US and Russian Windows

The current ISS configuration (late 2019) has 36 windows on nine different modules, usually consisting of multiple glass panes with the outer pane typically of silica glass. External shutters often (not always) protect the glass from MMOD damage [8]. MMOD strikes have occurred to the ISS windows leaving a crater on the exterior surface of the outer pane. None of these impacts have left more than a crater on the outer pane. Figure 15 shows a 3 mm to 5 mm diameter impact crater that occurred to window #7 on the Russian Service Module Zvezda.

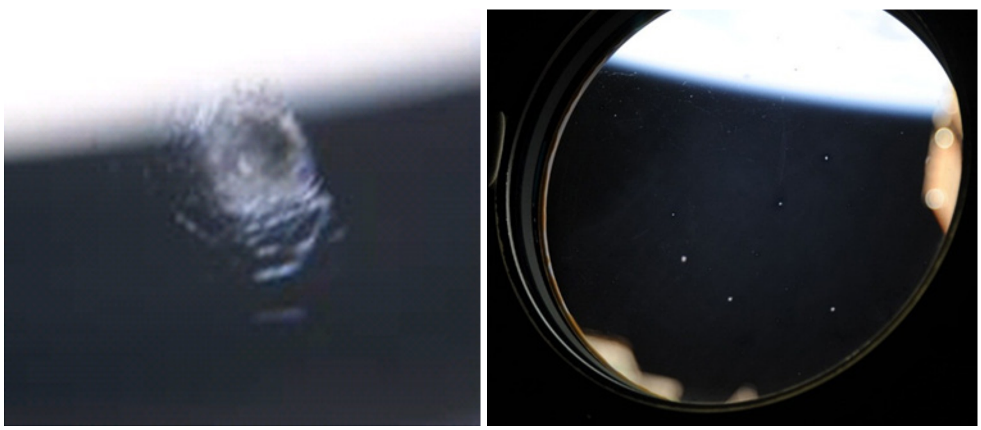

Fig. 15. ISS window port on right. Service Module window #7 damage on left.

4.5 FGB

During Russian EVA-19 (7 June 2007), the crew reported MMOD damage to FGB thermal blanket over the forward compressor measuring 30mm x 60mm in the outer fabric cover of an multi-layer insulation (MLI) thermal blanket, and a 5mm x 9mm size hole in the underlying layers of the MLI thermal blanket (Fig. 16). Based on hypervelocity impact tests, the damage appears to be from an oblique MMOD impact of a millimeter or more in diameter.

Fig. 16. FGB compressor thermal blanket MMOD damage.

5 CONCLUSIONS

ISS has been subjected to hundreds of MMOD strikes causing damage observed in photographs of the exterior surface of ISS and found in ground-inspection of returned hardware. Fortunately, ISS has successfully weathered these impacts without major failures, such as breech of the pressure integrity of the crew modules. However, some of these damages have resulted in noticeable effects to ISS systems and/or operations, such as power degradation due to damage to solar arrays, cut-gloves from craters on EVA handrails, and an unplanned EVA to stabilize tears in a solar array from a snagged guidewire caused by damage from MMOD.

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