

Orion Artemis I as flown MMOD analysis

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Abstract

The Orion spacecraft conducted the Artemis I flight around the Moon from November 16 through December 11, 2022. After the flight, the NASA Johnson Space Center (JSC) Hypervelocity Impact Technology (HVIT) Group performed a Micrometeoroid and Orbital Debris (MMOD) analysis using the Bumper 3 risk assessment tool to predict the number of small impacts that would likely have occurred during the mission. Separately, the same group inspected the Orion capsule for hypervelocity impact damage features. The results of the inspection were compared to those of the analysis to aid in improving the analysis, including the environment models. The comparison showed that Bumper analysis predictions were generally within one integer value of the damage found, which is considered high accuracy. As this was the first large, non-ablative returned surface from a lunar mission, this effort extends the MMOD community's insight beyond low Earth orbit into cis-lunar space.

1 Introduction

NASA inspects hardware returned from space for damage from Micrometeoroids and Orbital Debris (MMOD) to inform the development of MMOD environment models and analysis. Comparing to these damage findings provides a useful gauge of MMOD analyses using the Bumper risk assessment tool and the environment models it uses, including the Orbital Debris Engineering Model (ORDEM), currently on version 3.2, and the Micrometeoroid Engineering Model (MEM), currently on version 3.

These inspections have been conducted across the lives of the Space Transportation System (STS) and International Space Station (ISS) programs, providing invaluable data on the Low Earth Orbit (LEO) environment. Inspections of the Orion spacecraft after Artemis missions will extend this data source to cis-lunar environments, as well as LEO altitudes above those flown by the Shuttle and ISS. While Apollo capsules used ablative thermal protection, which resulted in the loss of small craters in the material surface as it ablated during reentry, Orion uses non-ablating thermal tiles on its conical Backshell (highlighted in Figure 1, along with windows capable of recording the smallest of impacts), thus Orion will provide more useful recording area to collect small impacts than has ever been returned from deep space before.

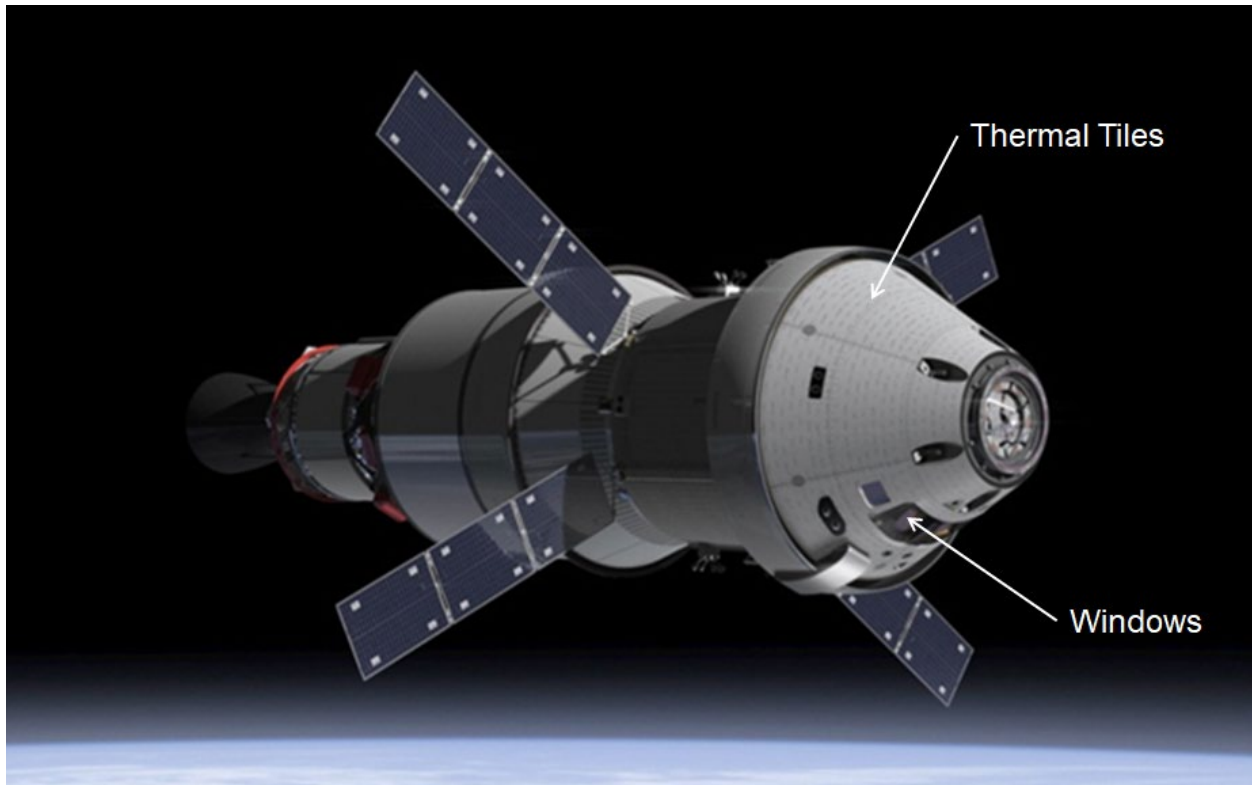


Figure 1: Orion Spacecraft

This paper details a prediction of small damages sustained by the Orion Crew Module (CM) during its Artemis I mission in November and December 2022 and compares this prediction to the results of the post-flight inspection of the CM. It will show that Bumper analysis predictions were generally within one integer value of the damage found, which is considered high accuracy.

2 Artemis I Mission

The Artemis I mission launched on November 16, 2022. Following a single, elliptical check-out orbit around Earth, a Trans-Lunar Injection (TLI) burn by the launch vehicle's upper stage placed Orion on an approximately 5-day trajectory to the Moon. Orion spent about two weeks in the vicinity of the Moon, largely in a Distant Retrograde Orbit (DRO), before an approximately 6-day return directly to Earth reentry and splashdown in the Pacific Ocean on December 11, 2022.

The exact trajectory flown was recorded during the flight, including vehicle attitude. This trajectory information [1] was provided by NASA Johnson Space Center (JSC)'s Aeroscience and Flight Mechanics Division for use in conjunction with the ORDEM 3.2 and MEM 3 environment modeling tools to create models of particle flux impacting the spacecraft throughout the mission. Meteoroid shower forecast information [2] was also included to account for additional particle flux associated with meteoroid showers.

3 Backshell Tile

The Alumina-Enhanced Thermal Barrier (AETB) thermal tile used on the Orion Backshell is composed of a porous block of silica fibers coated with Toughened Unipiece Fibrous Insulation (TUFI), Reaction Cured

Glass (RCG), and reflective tape. A Ballistic Limit Equation (BLE) developed for the Orion program to describe crater depth into monolithic porous Thermal Protection System (TPS) materials was used in this assessment. Just prior to the assessment, a series of hypervelocity impact tests [3] were performed at the White Sands Test Facility (WSTF) to provide data supporting use of this BLE in the specific application of small craters into Orion tile with all the layers listed above.

Figure 2 graphs the crater depth as a function of particle diameter for impacts by a variety of particle materials (by color) at 0° (normal to the surface, solid lines) and 45° (dashed lines), all at 7 km/s. The squares (0° impacts) and triangles (45° impacts), coded by color based on material, show nine hypervelocity impact test results. Six of the nine particle diameters (green boxes) are within 15% of the predicted value, the two (yellow boxes) that are off by between 25% and 50% are off in opposite directions—the BLE underpredicts the particle size in one case and overpredicts the particle size in the other—such that the BLE remains as accurate as achievable, and the test result (red box) farthest from the BLE prediction is also inconsistent with other test results and can therefore be discarded. In total, this validates the BLE as accurately predicting the particle size-crater depth relationship for tiny craters into Orion thermal tile.

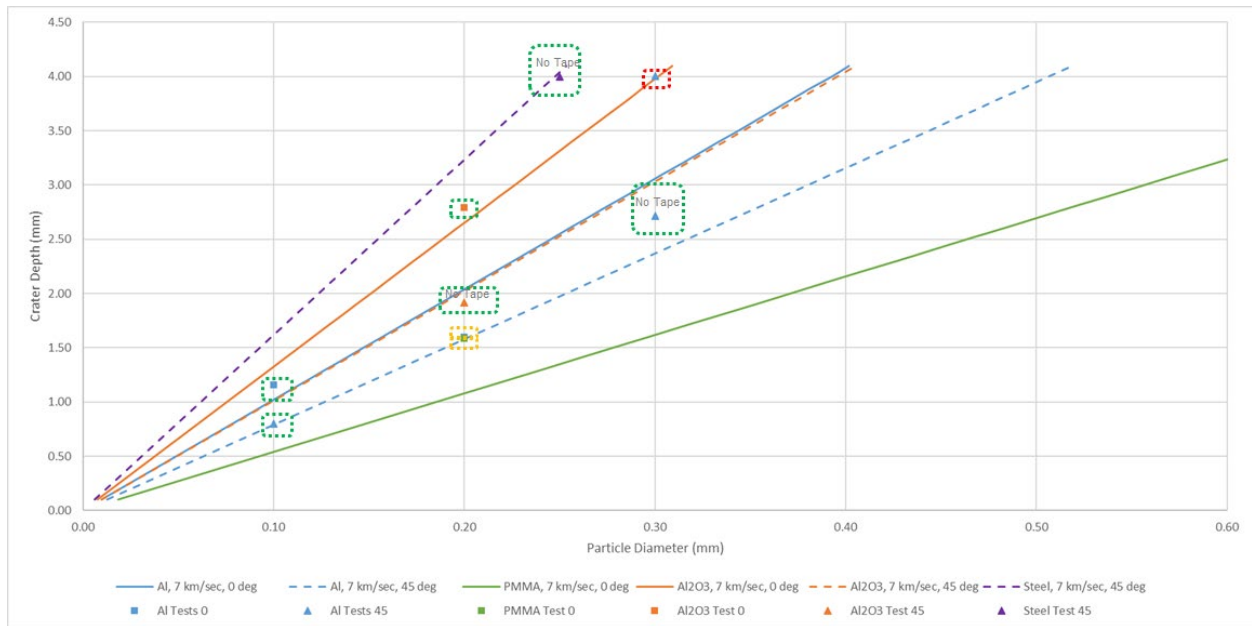


Figure 2: Comparison of Orion Thermal Tile Small Crater BLE to Test Data

The primary post-flight inspection of the thermal tile was conducted at Kennedy Space Center on January 24-25, 2023. The thermal tiles remained bonded to substrate panels that had been removed from the vehicle. While the reflective tape had mostly burned off during reentry, some pieces remained on the tiles.

Five potential MMOD impact sites in the thermal tiles were identified and preliminarily characterized [4]; further laboratory characterization is planned. These Regions of Interest (ROIs) are pictured in Figure 3.

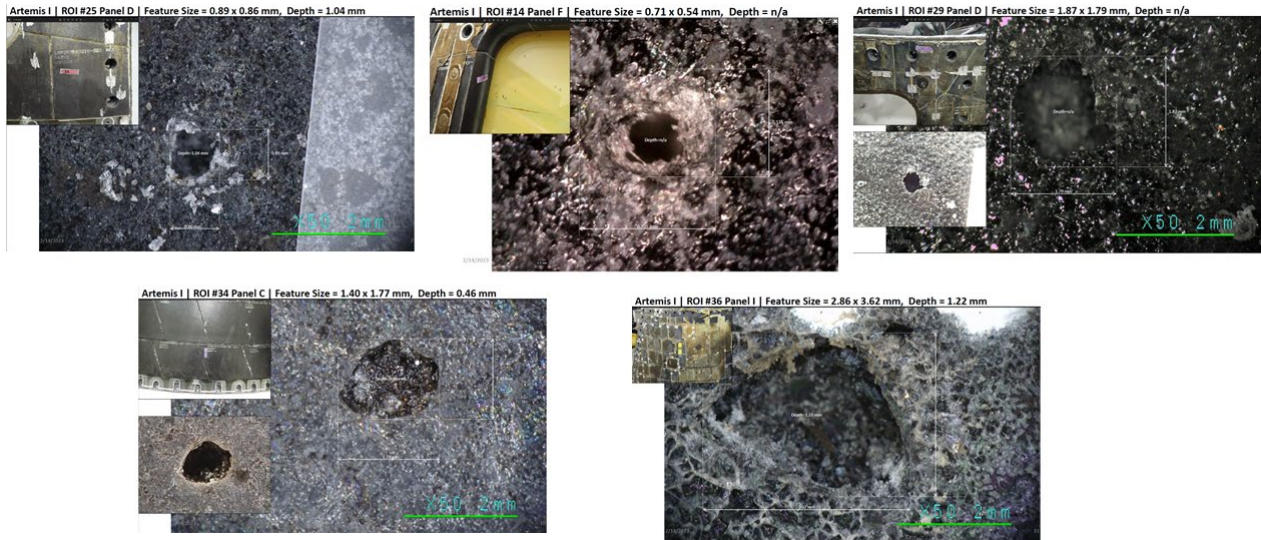


Figure 3: Five Regions of Interest in the Orion Thermal Tiles

Figure 4 compares the results of the as-flown prediction to the post-flight inspection for the thermal tile. The lines show the cumulative number of craters of a given size (depth) or larger due to the micrometeoroid environment (red, 80% or more of the total), orbital debris environment (blue), or both combined (purple). The points are the five ROIs similarly plotted. Being a cumulative count of that crater or larger, the largest crater is plotted with a value of 1, the next largest crater as 2 (itself and one larger), etc. The three solid circles are those with depth measurements taken onsite, while the two open circles are those with a depth estimated by comparing the opening diameter to test data because a depth could not be determined during the initial inspection—these depths should be considered provisional pending further investigation of the cavities. All craters found by inspection are graphed in purple because they have not yet been categorized as micrometeoroid or debris, pending further examination.

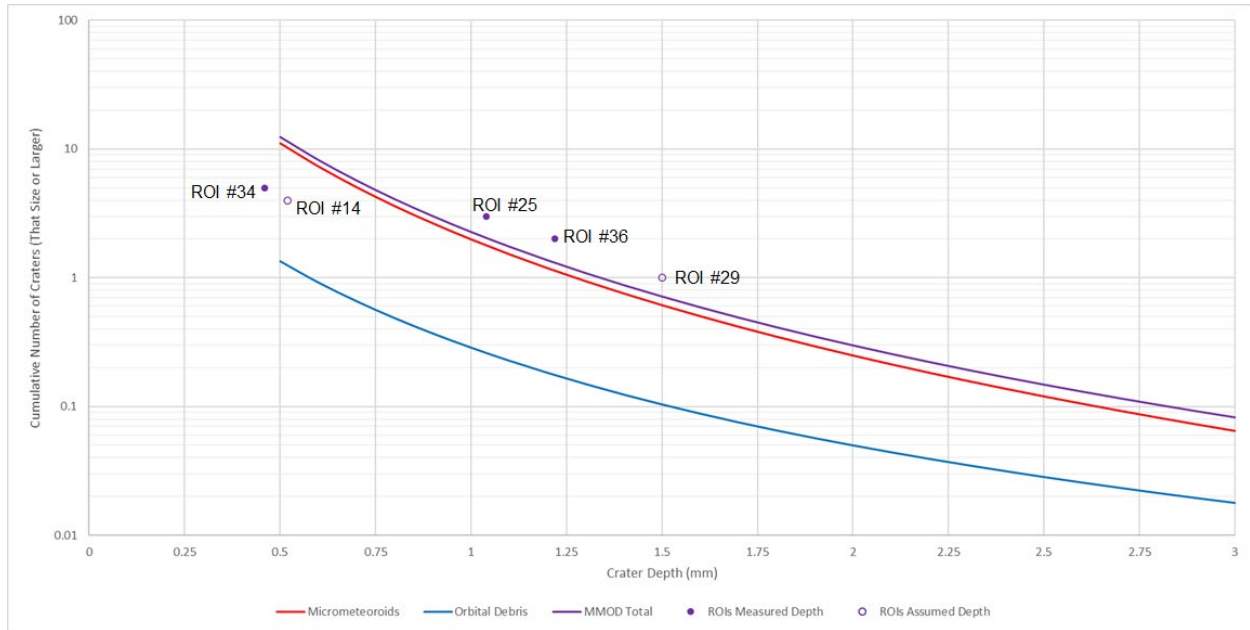


Figure 4: Comparison of Thermal Tile As-Flown Prediction to Post-Flight Inspection

The three larger craters found are slightly above the curve, implying that Bumper is underpredicting the risk of such craters. It should be noted, however, that all three are within one integer. While a probabilistic analysis can specify a fractional number of craters, in reality, only whole numbers of craters are possible. Therefore, being within one integer is as close the analysis and inspection can be physically expected. At smaller sizes, Bumper predicts more craters than are found. This has been a common trend historically and may be explained by the difficulty of finding such small craters, particularly on the Artemis I tile surface, which was littered with residue from the tape burning off and reentry-related factors.

4 Remaining Backshell Tape

Reflective tape was applied to the thermal tiles to achieve various desired properties for the flight. While most of the tape burned off during reentry, some tape remained, especially on the panel where the main windows are located. Scattered small squares of tape remained across the whole capsule; these squares had joined adjacent larger pieces of tape. Figure 5 shows the areas of intact tape in gold on a view of the Backshell along with imagery of the large swaths on the left and scattered small squares on the right.

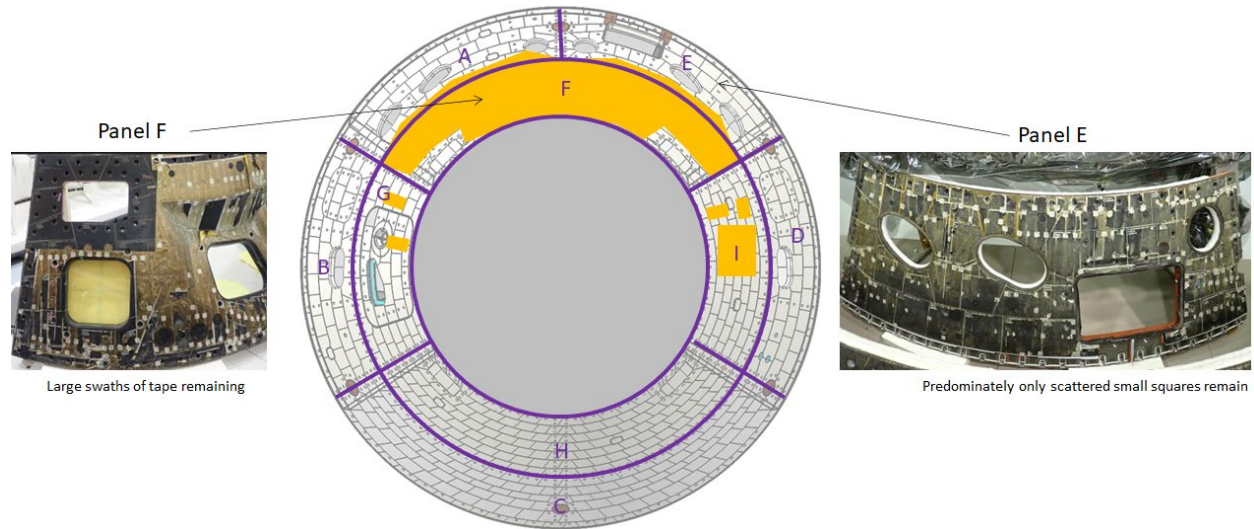


Figure 5: Remaining Reflective Tape on the Thermal Tiles

A Bumper analysis was performed to calculate the number of tape damages expected to be caused by MMOD. Very limited hypervelocity impact test data was available to support analysis of damage solely into tape on a thermal tile. Because the tape can be considered a single wall, the Cour-Palais Single Wall BLE was used with an artificial wall thickness to match it to a best-estimated critical particle diameter at a single impact condition. The analysis began by calculating the number of damages that would have occurred across the whole Backshell, then included an adjustment for how much tape remained.

The predicted number of tape damages was consistent with number found. Because most of the tape had burned off, only 18% of predicted impacts were on remaining tape. It was expected that two tape holes would be found on Panel F, the most complete panel, and one ROI was found. The expectation was also to find one more ROI somewhere on the vehicle, and one was found on Panel D. Figure 6 shows these two found ROIs [4] alongside a table indicating the number of expected tape holes by panel (panel lettering referencing the figure above), both for the fully-tape covered panel and, after considering the percentage of the panel still covered in tape, the remaining tape-covered portions.

Location	Full Panel Number of Tape Holes	Remaining Tape	Adjusted Number of Tape Holes
Panel A	1.59	10%	0.16
Panel B	2.01	5%	0.10
Panel C	3.63	2%	0.07
Panel D	1.11	5%	0.06
Panel E	1.05	7.5%	0.08
Panel F	2.87	70%	2.01
Panel G	1.05	10%	0.10
Side Hatch	0.86	5%	0.04
Panel H	3.56	5%	0.18
Panel I	1.15	40%	0.46
Total	18.88		3.41

Found 2 ROIs

Found 1 ROI

Found 1 ROI

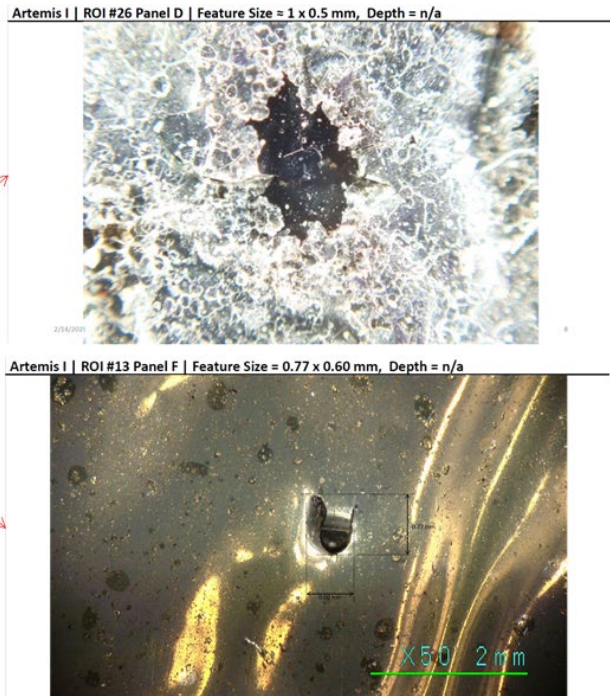


Figure 6: Comparison of Remaining Reflective Tape As-Flown Prediction to Post-Flight Inspection

5 Windows

The Orion windows are made of fused silica glass for reentry thermal properties. This smooth, transparent material is ideal for recording extremely small craters because its surface allows for detecting tiny damages more effectively than most other surfaces.

The Bumper analysis is predicated on a BLE for crater size developed for the ISS program. In the cross section of a traditional fused silica crater shown in Figure 7, this equation determines the particle size that causes the total crater diameter indicated by the widest arrows.

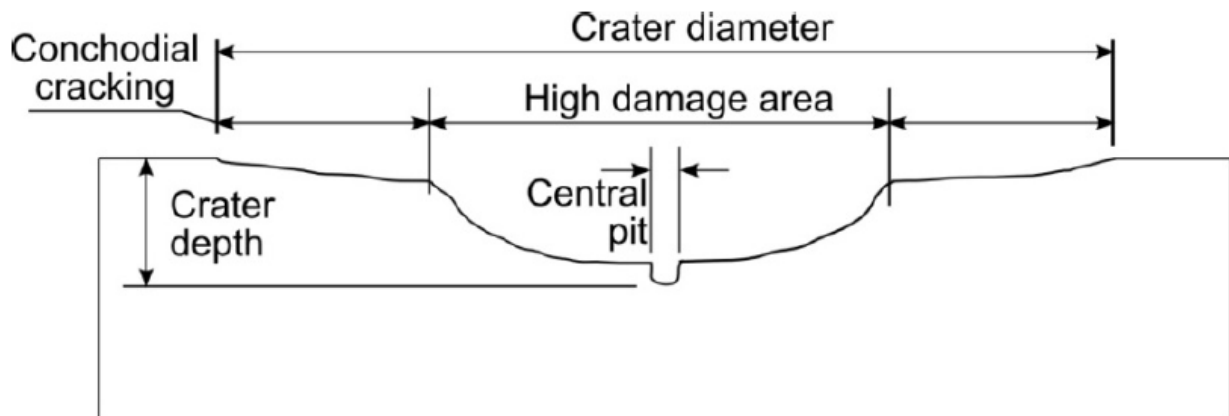


Figure 7: Fused Silica Crater Cross-Section

Two craters were found in post-flight inspection of the Orion windows [4], shown in Figure 8. While typical glass damages include missing material across the three regions depicted above, dental molds taken of these craters indicated that only the inner two regions were missing material and the that outer ring of visible damage was cracking within the glass that did not detach material. To best match the intent of the BLE, the diameters of these ROIs were taken as including the outer cracked glass area (dashed red circle), despite no material loss, due to the outer ring's similarity with the traditional crater definition. For ROI #2 (right), glass cracking extends only in one direction (to the right); this may be due to the obliquity of the impact. To capture the full extent of the damage in a manner consistent with crater formation generally interpreted from normal impacts, the crater diameter was derived from a radius measured from the central pit to the outer ring of cracked glass at its fullest extent. The red crosshairs on the central pit help to show this circle definition.

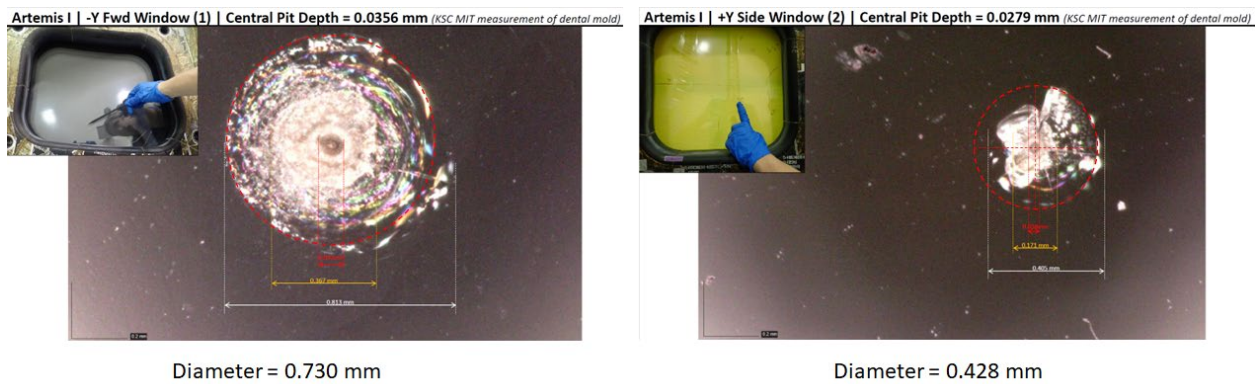


Figure 8: Fused Silica Regions of Interest

Figure 9 compares the results of the as-flown prediction to the post-flight inspection for the four main windows. Similar to the thermal tile comparison above, the cumulative number of craters of a given diameter or larger is graphed for the prediction in lines—red, blue, and purple for micrometeoroids (95% of the total), orbital debris, and both, respectively—and ROIs in circles, which are purple because they have not been categorized as micrometeoroid or debris. Like in the thermal tile, the two craters found are slightly above the curve, implying that Bumper is underpredicting the risk of such craters. It should be noted, again, that both are within one integer and thus as close the analysis and inspection can be physically expected. Again, at smaller sizes, Bumper predicts more craters than are found. This has been a common trend historically and may be explained by the difficulty of finding such small craters, even in glass.

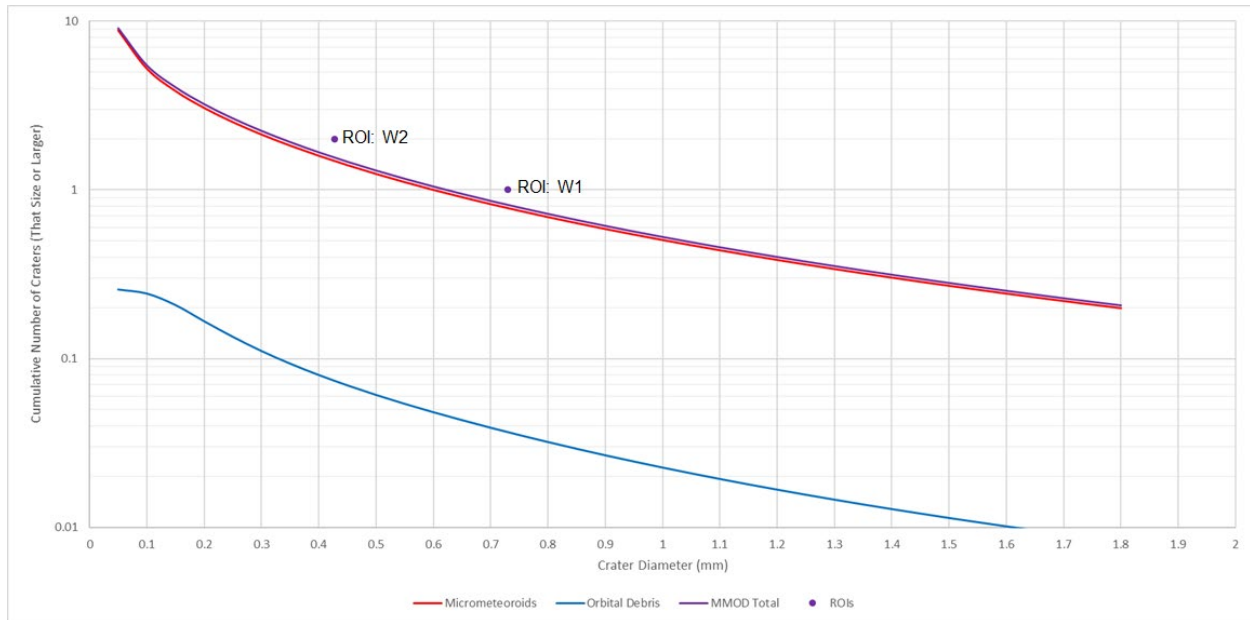


Figure 9: Comparison of Fused Silica As-Flown Prediction to Post-Flight Inspection

6 Other Regions

The Orion CM includes smaller regions composed of other materials, most notably Felt Reusable Surface Insulation (FRSI) on and around the docking hatch. The Bumper analysis predicted that two craters large enough to identify would be found on these surfaces. The inspection recorded seven ROIs that are under consideration as MMOD damage, though the shapes of many of these features leaves their origin unclear. Further investigation is being attempted, though the material was disrupted during removal—some of it lost—such that a definitive conclusion may not be possible.

Remaining regions include:

- CM Reaction Control System (RCS) thruster nozzles
- Structural pads
- Structural and mechanical features on the Side Hatch
- Wells in which the launch Abort System (LAS) is mounted

The Bumper analysis predicted that no craters of a size large enough to see would be found in any of these remaining regions and none were.

7 Conclusion

Similar to past programs, after the Artemis I mission of November and December 2022, NASA inspected the Orion capsule for possible MMOD damage and, separately, a Bumper risk assessment was performed to predict the number of craters expected to be found.

Five potential MMOD craters ranging from half a millimeter to well over one millimeter in depth were found in the Backshell thermal tile. The prediction accurately modeled the number of craters and their size distribution for craters greater than one millimeter deep. For shallower craters, Bumper predicted more craters than were found, which is consistent with historical trends and may be explained by the

difficulty in finding very small craters. Extraction of the five potential MMOD damage site tiles is in work to provide more data to improve this assessment.

Two holes in the remaining reflective tape were also found and may have been caused by MMOD. The analysis predicted, after considering the amount of tape remaining, that three such holes should have been found. This is a reasonably close prediction, especially with one of the holes being on the panel assessed as most likely to have such a hole.

Two potential MMOD craters were found in the main windows. The prediction accurately modeled the number of craters and their size distribution for craters down to less than half a millimeter wide. Bumper predicted even shallower craters than were found, which is consistent with historical trends and may be explained by the difficulty in finding very small craters.

These comparisons demonstrate a high degree of accuracy in Bumper risk assessment. Additionally, the inspection findings will aid future refinement of environment models to improve accuracy still further.

8 References

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3. Lyons F. Test Plan for Orion MPCV AETB-8 Tile Using Microparticle Hypervelocity Impact. August 2023
4. Hyde J., *et al.* Artemis I Postflight Inspection Results. February 2023.