# EVALUATING MICROMETEOROID AND ORBITAL DEBRIS RISK ASSESSMENTS USING ANOMALY DATA

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## ABSTRACT

The accuracy of micrometeoroid and orbital debris (MMOD) risk assessments can be difficult to evaluate. A team from the National Aeronautics and Space Administration (NASA) Engineering and Safety Center (NESC) has completed a study that compared MMOD-related failures on operational satellites to predictions of how many of those failures should occur using NASA's MMOD risk assessment methodology and tools. The study team used the Poisson probability to quantify the degree of inconsistency between the predicted and reported numbers of failures for a selected group of robotic satellites. Many elements go into a risk assessment, and each of those elements represent a possible source of uncertainty or bias that will influence the end result. There are also challenges in obtaining accurate and useful data on MMOD-related failures.

## 1. INTRODUCTION

Micrometeoroid and orbital debris (MMOD) particles traveling at more than 70 km/s (micrometeoroids travel at the highest velocities, orbital debris velocities are up to ~15 km/s) can potentially strike any orbiting spacecraft, and MMOD damage is the highest risk factor for most spaceflight missions. Spacecraft designers and mission planners must satisfy MMOD risk requirements in order to ensure that the vehicle can protect human occupants, satisfy mission objectives, and preserve the minimum capacity needed to perform end-of-mission disposal. MMOD risk assessments (MRAs) quantify that impact potential based on several factors including the spacecraft's configuration, location, construction, operational status, and tolerance to damage. The values provided by the MRAs are used to satisfy MMOD requirements. So the users of MRAs are interested in understanding the accuracy of the MRAs in predicting the probability of a failure for their respective spacecraft.

A team formed by the National Aeronautics and Space Administration (NASA) Engineering and Safety Center (NESC) sought to define how well NASA's MRA methodology quantified risk by comparing the values produced by MRAs to operational spacecraft history. Ideally, a study of this kind would use a large dataset including many different satellites to obtain an average MMOD failure rate and compare this value to an MRA average predicted failure rate for that dataset. However, this kind of bulk comparison was not practical. Where spacecraft failure and anomaly data are available (which was not always the case), the team found a wide disparity in reporting and cause attribution making it inappropriate to combine results. Furthermore, MRAs are time and resource intensive, and performing a large number of them to encompass a variety of spacecraft was not realistic.

So the team decided to take a "micro-analysis" approach and select a few satellites based on the possibility of obtaining the data necessary to both determine MMOD failures and perform detailed MRAs. The study achieved a statistically significant number of data points by using satellite constellations, where the same vehicle design was used in several individual spacecraft. This allowed a common MRA for the spacecraft but applied throughout the constellation. In addition, the MRAs were not performed for the spacecraft as a whole, but for individual components. For example, the MRA for Spacecraft #1 resulted in a predicted number of failures not for the spacecraft but for Spacecraft #1's tanks and batteries. This increased the dataset size and allowed the team to concentrate on those spacecraft components where an MMOD impact failure was relatively easy to diagnose (e.g. an MMOD tank failure results in a catastrophic rupture of the tank). Finally, with the values of predicted number of failures and reported number of failures in place, the team could compare them and judge the level of consistency between the two, which would in turn reflect the relative agreement between the MRA and the reported history.

## 2. NASA's MRA PROCESS

NASA's Hypervelocity Impact Technology (HVIT) group is responsible for most of the MRAs performed to support NASA's programs. Fig. 1 shows HVIT's MRA process and how spacecraft operators and designers use it to evaluate MMOD risk and design MMOD protection. The MRA tool, Bumper, is at the center of the MRA process. As shown in the diagram, Bumper uses input including orbital debris and micrometeoroid environment models, spacecraft geometry, failure criteria for each component and shield included in the analysis, ballistic limit equations (BLEs), and operating parameters including spacecraft orbit and attitude. Each of these input elements can contribute to uncertainty, bias, or error in the overall assessed risk produced by Bumper.

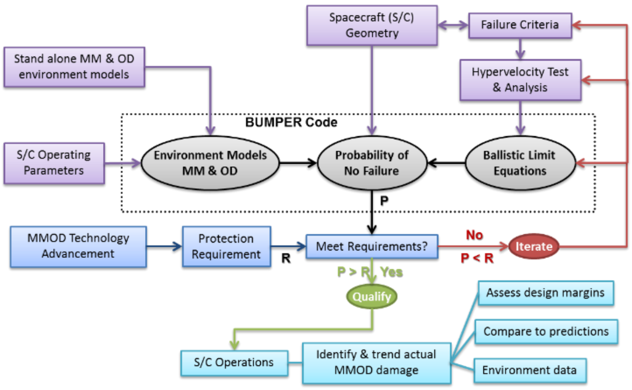


*Figure 1. NASA's Bumper MRA Process [2]*

The Bumper code uses this information to produce the number of events predicted to occur over a given time. For simplicity, these events are referred to here as "penetrations," but those events can be MMOD penetrations, impacts, or failures, depending on the criteria set for the analysis. This result is typically presented as a probability of no penetration (PNP), determined using Eq. 1:

$$PNP = e^{(-N)} \qquad (1)$$

where e = the base of the natural logarithm (~2.718...), and N = number of penetrations calculated. The probability of penetration (PP) is simply 1-PNP. PNP and PP are typically presented as percentages or odds (e.g., 1% or 1 in 100).

The Bumper MRA process is used to iteratively design and improve MMOD protection. During design, if a Bumper MRA results in a risk greater than what can be tolerated, then some of the input parameters can be adjusted to observe what the effect on risk will be. The predicted number of penetrations is what is predicted to occur during a given time period in the future. However, for this study, it was necessary to look backward and use the MRA to predict how many penetrations (or failures) should have occurred starting a given time in the past. One of the ramifications of this was a difficulty in obtaining some of the needed configuration data for spacecraft that have been flying for many years after they were designed.

## 3. POISSON PROBABILITY

The Bumper MRA provides a single value for the number of predicted failures, and this was compared to the number of failures reported to the team. The team desired a simple way to quantify this comparison and used the Poisson probability for this purpose. The Poisson probability is calculated using the generalized version of Eq. 1:

$$P(k) = \frac{\lambda^k e^{-\lambda}}{k!} \qquad (2)$$

where P(k) = the Poisson probability, λ = the predicted number of occurrences, and *k* = the reported number of occurrences. The value for λ is calculated by the MRA, and the value for *k* comes from the failure history. The Poisson probability indicates the level of consistency between the reported number of occurrences and what was predicted to occur. Typically a threshold of 5% or below is used to indicate inconsistency. The Poisson probability is interpreted as follows:

> There is a P(k)% chance that k occurrences will occur given a prediction of λ occurring.

If P(k) is low, then that indicates an inconsistency between the reported and predicted, and the cause may be either the reporting or predicting or both. The Poisson probability should not be confused with the PNP. The PNP is an alternative expression of λ, while the Poisson probability quantifies how well the PNP agrees with reported data.

## 4. ROBOTIC SPACECRAFT FAILURE ANALYSIS

### 4.1. Baseline Analyses

For this study, the team evaluated three satellite designs comprising two constellations and one single satellite. This represented a total of 73 individual spacecraft. The team performed MRAs for each of the spacecraft's pressurized tanks and batteries; determining a failure for these components was relatively unambiguous compared to other components. The total exposure time for all of the components was 1436.3 years, and the total exposed area-time product (i.e., area x time) was 2847.6 $m^2$-year. The individual MRA results are shown in Tab. 1.

*Table 1. Failure MRA Results for Robotic Assets*

| Asset | Component | Area-Time Product ($m^2$-year) | Number of Failures Predicted |
|---|---|---|---|
| **Satellite#1** | Battery Cell | 39.4 | 0.8 |
| | Tank | 12.1 | 1.1 |
| **Satellite#2** | Battery | 349 | 0.05 |
| | Tank | 2253 | 5.0 |
| **Satellite#3** | Battery Cell | 65.1 | 4.0 |
| | Tank | 129 | 0.4 |
| **Total** | | **2847.6** | **11.3** |

It is important to note that the MRAs for these assets were performed based on failure, meaning an MMOD impact would have to not only strike the component, but must damage it to a degree that the component fails, which for tanks is a rupture and batteries is the removal of that battery from service (and possibly a rupture also).

The results in Tab. 1 show that there is a wide variation between the number of failures predicted from as low as 0.05 up to a high of 5.0. The predicted failures can be thought of as a failure rate over the respective time frame for each satellite (they are different for each satellite system). The total number of predicted failures was 11.3 over the life of the spacecraft assessed. Tab. 2 shows that a total of two failures were recorded for the same components over the same time period. Tab. 2 also shows the Poisson probabilities for each of the assessed components based on the predicted versus reported failures.

*Table 2. Poisson Probabilities for Robotic Assets*

| Asset | Component | Number of Failures Reported | Poisson Probability |
|---|---|---|---|
| **Satellite#1** | Battery Cell | 0 | 44% |
| | GN2 Tank | 0 | 33% |
| **Satellite#2** | Battery | 0 | 95% |
| | Tank | 1 | 4% |
| **Satellite#3** | Battery Cell | 0 | 9% |
| | Tank | 1 | 70% |
| **Total** | | **2** | **0.096%** |

The Poisson probability gives the probability that the number of failures reported is consistent with the number predicted. For example, there is a 44% probability that there would be zero failures of one of Satellite#1's battery cells given the predicted failure rate of 0.8 (from Tab. 1). This indicates that the predicted risk and the reported failures are consistent. Conversely, the Satellite#2 tank reported one failure (Tab. 2), but 5.0 were predicted (Tab. 1), resulting in a 4% probability that if the prediction was correct, there would be 1 failure. It is appropriate to sum the predicted and reported numbers of failures to calculate an overall Poisson probability for these satellites. Tab. 2 shows that this overall probability is only 0.096%, indicating very low consistency.

### 4.2. Sensitivity Studies—Tank Wall Thickness

As shown in Section 2, NASA's Bumper MRA process has several elements that contribute to the result, and uncertainties and errors in any of them can have a substantial effect on the final result. Elements related to how robust exposed regions of the spacecraft are to MMOD are important to accurately portray in the MRA. For example, because it is integral to the ability of the tank to withstand an MMOD impact, the tank wall thickness has a substantial effect on the MRA risk. To observe the sensitivity of the MRA to tank wall thickness, the team performed MRAs with alternative thicknesses for Satellite#1 and Satellite#2.

The initial MRAs performed for Satellite#1 included a hydrazine tank, but the team later discovered that this tank was only used during ascent. After ascent, the tank was isolated from the rest of the hydrazine system and any liquid in the tank was allowed to freeze. This meant that any MMOD impacts into the tank either may not rupture the tank, or might not be detected because that subsystem was no longer monitored. The MRAs that did include the tank resulted in substantially higher predicted failures than when the tank was removed from the MRA. There were also conflicting data received by the team on the thickness of this tank's wall. The effects including this tank and altering its wall thickness had on the MRA and the Poisson probability can be seen in Tab. 3 (there were zero reported failures for this tank).

*Table 3. Effect of Tank Wall Thickness on Satellite#1 Poisson Probability*

| Tank Wall Thickness (cm) | Predicted Number of Failures | Poisson Probability for Satellite#1 Tank | Total Poisson Probability for all Satellites |
|---|---|---|---|
| **Tank Not Included (Baseline)** | NA | NA | 0.096% |
| **0.178** | 7.3 | 0.1% | 0.0002% |
| **0.254** | 3.2 | 4.1% | 0.006% |
| **0.343** | 1.5 | 22.3% | 0.03% |

For the greatest thicknesses (0.343 cm from Tab. 3), the predicted number of failures is relatively consistent with the no failures reported, resulting in a Poisson probability of 22.3%. However, if thinner tank walls are chosen, the predicted numbers of failures are greater by a factor of two or three and practically guarantee that every satellite in the constellation should have experienced a tank penetration and failure. As expected, the Poisson probabilities indicate much higher inconsistency between predicted and zero reported for the tanks with smaller wall thicknesses.

The team found challenges securing consistent configuration tank wall thickness data for Satellite#2 like they did for Satellite#1. Two different sources provided different thicknesses for the Satellite#2 tank, and neither source was judged to be more or less credible than the other. For the baseline MRA, 1.0 mm was used as the tank thickness because it resulted in a more conservative result. A thickness of 1.5 mm was the alternative thickness reported to the team. The effect of the difference was to reduce the predicted number of failures by more than half and reduce the Poisson probability by an order of magnitude as shown in Tab. 4.

*Table 4. Effect of Tank Wall Thickness on Poisson Probability for Satellite#2*

| Tank Wall Thickness (mm) | Predicted Number of Failures | Poisson Probability for Satellite#2 Tank | Total Poisson Probability for all Satellites |
|---|---|---|---|
| **1.0 (Baseline)** | 5.0 | 4% | 0.096% |
| **1.5** | 1.9 | 43% | 1.15% |

Again, the 0.5 mm variation between tank wall thicknesses resulted in a significant change in the resulting risk prediction.

### 4.3. Sensitivity Study—Failure Reporting

For Satellite#3, the team modified the reported number of failures instead of changing MRA input. Analysis of the calculated size and path (provided by the satellite operator) of the presumed MMOD particle that penetrated the one battery cell that failed revealed that to hit the battery cell that failed would have required an unlikely (but possible) path to negotiate a crowded region in front of the target. Another cause of the battery failure, which would have had to produce not only the loss of performance but also an observed attitude perturbation to the spacecraft, was unlikely but also possible. If this second scenario had occurred, then the reported number of MMOD failures for this component would have been reduced from one to zero. Tab. 5 shows that for the battery alone, the Poisson probability decreases from a marginally inconsistent 9% to a strongly inconsistent 2% when removing the single reported failure. The effect on the total Poisson probability for all of the assets is negligible; the baseline value was already very low (i.e., very low consistency), and the change only reinforced that. When trying to determine the size particle that caused a recorded perturbation, there are numerous assumptions and guesses that have to be made including the velocity, size, composition, direction, and shape of the particle. These parameters are interrelated in how they produce the perturbation witnessed by the spacecraft operators, and changes in one will affect the estimated and calculated values for the others.

*Table 5. Effect of Number of Reported Failures on Poisson Probability*

| Number of Reported Battery Failures Due to MMOD | Predicted Number of Failures | Poisson Probability for Satellite#1 Tank | Total Poisson Probability for all Satellites |
|---|---|---|---|
| **1 (baseline)** | 4.0 | 9% | 0.096% |
| **0** | 4.0 | 2% | 0.015% |

## 5. ROBOTIC SPACECRAFT IMPACT ANALYSIS

The MRAs described in Section 4 were failure risk assessments, meaning the criteria used to establish the risk (i.e. predicted number of events) were component failures. However, each spacecraft, and each component, is impacted by many more MMOD particles that do not cause a failure than those that do. An *impact* risk assessment, as opposed to a *failure* risk assessment, will predict the number of impacts a component will experience. Impact MRAs do not require as much data concerning the material characteristics and damage modes since what is sought is simply how many times the spacecraft is hit. However, it is much more difficult to determine when a component is impacted if there is no indication (failure is an obvious indication) visible to the spacecraft controllers.

Fortunately, one of the spacecraft operators that provided the team with failure data also provided the team orbit perturbation events that occurred on some of their spacecraft that did not result in a failure. These were uncommanded changes in the spacecraft velocity, which resulted in changes to the vehicle altitude, and pitch, yaw, and roll. The spacecraft operator determined that the probable cause of these events was MMOD impacts. The locations in the orbit of each of the impacts were consistent with orbital debris (as opposed to micrometeoroid or other failure causes). This is seen in Fig. 2, which displays the cumulative distribution of satellite latitude where each anomaly occurred (blue line) against what would be predicted by NASA's orbital debris environment model, the Orbital Debris Engineering Model Version 3.0 (ORDEM3.0) (red line). The black dashed line represents where the data would fall if it were random, as would be expected with micrometeoroids.

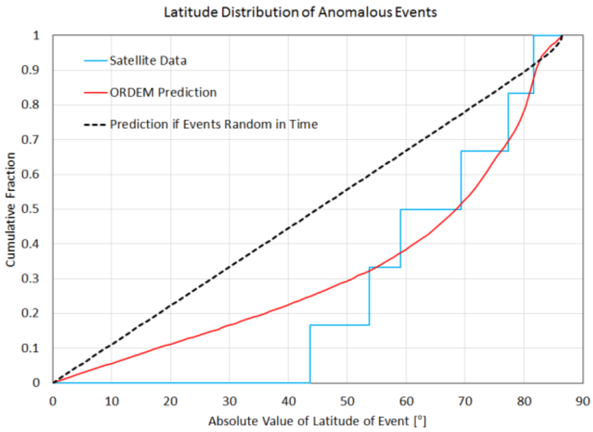

*Figure 2. Latitude Distribution of Anomaly Events*

The team used these measurements to determine the momentum imparted to the spacecraft and the momentum of the MMOD particle. The momentum could then be converted to a particle size dependent on assumptions of velocity and shape. The average orbital debris particle velocity at that altitude is 13.94 km/s according to ORDEM3.0, so that was taken as the impact velocity. With a velocity, the team could calculate a mass. ORDEM3.0 is expressed in terms of characteristic length ($L_C$), a measure of the average of the longest dimension of the particle and the two dimensions orthogonal to that longest dimension (e.g., for a sphere, all three of those dimensions are equal). To get the $L_C$ from a mass requires assuming a shape and density. In most MRAs, and all those performed by NASA/HVIT, the shape of each piece of orbital debris is assumed to be spherical. However, a sphere has the highest mass possible for a given $L_C$, so using this assumption results in the highest particle mass, and greatest assessed risk possible. Looking at it another way, the mass for the sphere will result in the smallest possible $L_C$. Using the spherical assumption and the density of aluminum, the particle size (i.e., $L_C$ ) for each of the impact events was estimated using the calculated momenta. The impact frequency for these size particles was then compared to what would be expected using ORDEM3.0.

An additional consideration is the momentum enhancement factor (MEF). This is the additional momentum that is imparted to the satellite from the impact ejecta. Because this ejecta has mass originating from the spacecraft and is travelling in the direction opposite the direction of the incoming MMOD particle, a force is directed against the spacecraft in the same direction as the simple momentum exchange of the MMOD particle to the spacecraft. This MEF has been experimentally measured for different types of materials [8, 9, 10], and is estimated for this case to be between 1-3 (i.e., an MEF of 1 would mean no additional momentum is exchanged). Assuming an MEF of 1, ORDEM3.0 would predict 24 impacts in the size range observed/calculated. When an MEF of 2 is assumed, the predicted number of impacts increases to 70 because smaller particles are required to produce the same net momentum observed, and there are more smaller particles—thus more impacts. If an MEF of 3 is chosen, there would be 164 impacts. Any of these values is greater than the six impacts registered.

The team then investigated the results if a shape other than a sphere was used for the orbital debris. Different shapes were applied to the results including oblate ellipsoids and octahedrons. A sphere with voids was also explored, which resulted in a reduced net density that varied as a function of critical length ($L_C^{-0.25}$, $L_C^{-0.5}$, $L_C^{-0.75}$, $L_C^{-1.0}$) . This "voided sphere" is analogous to a debris particle that may have material folded over on itself or crumpled like a sheet of paper, resulting in a nonhomogeneous density. When these different shapes were applied to ORDEM3.0, the number of impacts was reduced. The degree of reduction varied depending on the shape assumed. Fig. 3 shows the curves for each of the shape/voided spheres plotted on a log-log scale as a function of momentum versus flux. The blue line on the graph represents the baseline spherical assumption, the red lines represent the impacts (one red line includes a catastrophic impact in addition to the other six), and the other lines are different shapes as indicated in the legend. As can be seen on the figure, the data for the impacts are more consistent with the curves for the voided spheres and the octahedron than for spheres.

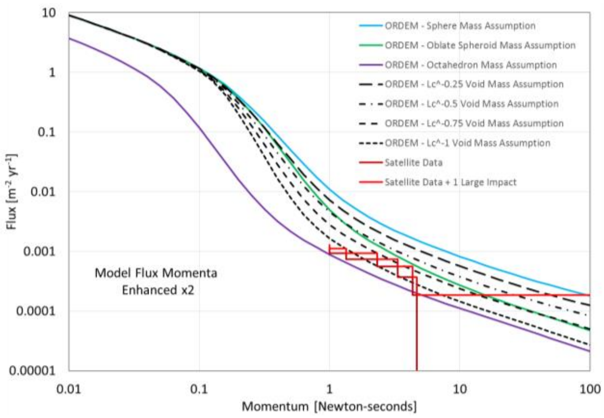


*Figure 3. Predicted Orbital Debris Flux as a Function of Impact Momentum (MEF=2)*

Any decrease in flux as a function of momentum (i.e., any of the lines in Fig. 3 below the blue one) would represent a reduction in risk when applied to an MRA. So if alternative shapes to spheres are applied to ORDEM3.0 and Bumper, then the end result would be a reduction in risk. However, the shape and orientation of an impacting projectile can influence the penetration characteristics of the projectile. Consider the different damage that would be caused by a rod-shaped particle if that particle impacted on the pointed end versus the flat side. These penetration characteristics would need consideration and may, to some degree, counteract risk improvements made with alternative shapes.

## 6. CAUSES OF INCONSISTENCIES

The overall results for this very limited number of robotic spacecraft indicate that the predicted number of failures is inconsistent with the reported number. This means that either the failure predictions are overpredicted, failures are under-reported, or a combination of these factors is responsible. Most likely, the inconsistencies are a result of a combination of error or bias that stem from uncertainties present in several sources on the prediction and reporting sides. This section discusses some of these sources of uncertainty that can result in inaccurate and/or inconsistent results.

Some of the causes of uncertainty or bias in the MRAs are:

- Sensitivity to design parameters, such as dimensions and materials (e.g., the ambiguity of the tank wall thicknesses discussed in Section 4). Design and construction details are routinely unavailable, difficult to obtain, or contain unusual construction features and might require assumptions based on engineering judgment. This is especially true for spacecraft already on orbit and far removed from design and construction, as was the case in this study. Even for spacecraft currently in development, there can be issues obtaining accurate input information due to proprietary or classified data or the actual build differing from drawings.

- MMOD shape represented as solid spheres in ORDEM3.0 and Bumper. As discussed in Section 5, spheres represent the maximum possible mass for a given characteristic length and density. The impact assessment showed that using different shapes and voided spheres results in reduced assessed risk. However, the complex interaction of mass, shape, orientation, and size-dependent debris flux affects the overall risk of nonspherical particles compared to that of the solid sphere assumption.
- A lack of applicable test data for most robotic spacecraft MRAs. NASA uses BLEs derived from testing and analysis for crewed vehicles, which differ in materials and layup from typical satellite construction.
- Limitations of HVI testing. BLEs must be extrapolated in order to represent on-orbit collision velocities since most HVI testing is typically only up to 10 km/s. Compare that to orbital debris relative impact velocity up to 15 km/s, and up to 72 km/sec for micrometeoroids.
- Worst-case assumptions for component failure conditions, especially in first order risk assessments. As more information is gathered and a more detailed and accurate spacecraft configuration is applied to the MRA, the assessed risk tends to decrease.
- Limited HVI test data to derive BLEs. Statistically-based uncertainty bounds are not normally derived due to limited HVI data.

Challenges associated with using spacecraft failure and anomaly data include:

- A lack of consistency in categorizing and reporting anomalies across the aerospace community.
- Lack of experience in the process of associating failures to causative mechanisms. Observed failures may be the result of a combination of multiple events occurring on the spacecraft.
- Lack of motivation on the part of spacecraft operators to fully investigate the root cause of an anomaly or failure. Many commercial operators prioritize returning the spacecraft to service rather than spending resources troubleshooting and identifying the cause of an anomaly.
- Reluctance on the part of spacecraft operators to share anomaly data due to privacy fears or a perception that public disclosure of failures will reflect negatively on the company.
- A lack of adequate onboard sensors, and requirements to provide those sensors, to measure physical perturbations to better correlate particulate impacts to failure mechanisms.
- Unavailability of telemetered data, especially after a catastrophic failure.
- Lack of understanding and natural variability in other MMOD failure mechanisms (e.g., plasma) other than physical penetration and ejecta.

## 7. CONCLUSION

A primary conclusion of this study is that verifying the accuracy of the MRAs can be very challenging. For the limited sample set used in this study, there is an overall inconsistency between the magnitude of predicted risk and the actual number of MMOD-induced failures reported. There are uncertainties for both the prediction and the reported that could be contributing to the inconsistencies. The team used Poisson probabilities as a tool to illustrate the inconsistencies quantitatively. These values are not meant to be applied to other spacecraft.

Much attention recently has been given to ORDEM3.0 as a contributor to uncertainty. MRAs performed using ORDEM3.0 have, in many cases, resulted in higher assessed risk. Indeed, the impact analysis in this study looking at spacecraft perturbations shows that perhaps the number of impacts expected by the model is greater than what is occurring. However, those results are only focused on a narrow range of particle sizes—particles large enough to perturb the orbit of the affected satellites. The study did not gain any insight to how well ORDEM3.0 is representing particles smaller or larger than ~3-5 mm. The team also showed promising data in evaluating a more appropriate shape for orbital debris and how this may improve this element of the risk assessment. At least two tests have been performed where a grounded satellite has been impacted by a hypervelocity projectile under laboratory conditions, and the resulting debris was counted, measured, and catalogued by shape [11, 12]. The data from these experiments might be useful to characterize orbital debris shape for use in MRAs.

The component failure analyses for the robotic spacecraft revealed a wide range of Poisson probabilities for the different components, even on the same spacecraft. This seems to imply that there is more contributing to MRA uncertainty than simply ORDEM3.0 since all of the component MRAs used the same ORDEM3.0, but not all had the same degree of inconsistency. The team showed how important knowing the accurate design parameters of the spacecraft/component is by varying tank wall thicknesses and getting very different predicted failure results. If a tank wall thickness was a little thicker than originally thought, then it would take a larger MMOD particle to penetrate that tank, and the population of MMOD particles decreases as they get larger. Other sources of error and uncertainty as discussed in Section 7, while not targeted in this study, offer contributions that may be in the same order of magnitude as the shape effect and tank wall thicknesses as far as influencing the inconsistencies in this study and in general.

There are opportunities for improvement on the MRA side and the anomaly tracking side. *In situ* measurement of MMOD impacts and continued use of returned impacted surfaces will help refine and upgrade environment models. HVI testing on materials and components specific to the spacecraft being assessed (when possible) will help to improve damage prediction and assignment of failure criteria. Standardization of anomaly reporting and characterization, and a greater willingness to share that information, will help to understand actual failure rates. With robotic spacecraft having to meet end-of-mission disposal requirements, the robotic community is taking a greater interest in MMOD protection than previously—a risk that has been familiar to the crewed missions for a long time.

## 8. ACKNOWLEDGEMENTS

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