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Orion Meteoroid and Debris Analysis with a Single Kevlar® Layer Enhancement to the Propulsion Subsystem Multi-Layer Insulation

Comparison of the observed data and the adjusted ballistic models

*Joshua E. Miller, Ph.D.
University of Texas at El Paso, El Paso, Texas
Johnson Space Center, Houston, Texas*

*Kevin D. Deighton
Lockheed Martin Space, Littleton, Colorado*

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National Aeronautics and
Space Administration

*Johnson Space Center
Houston, TX 77058*

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Abstract

In a continual mass optimization effort for the Orion vehicle by NASA and its prime contractor Lockheed Martin Space, along with the European Space Agency (ESA) and its contractors Airbus and Thales Alenia Space-Italy (TAS-I), a series of shield characterization shots have been performed to quantify the ballistic enhancement of a single-layer of Kevlar® in multi-layer insulation (MLI). This enhanced MLI is part of Orion's propulsion subsystem, and it is planned to replace a double-layer Kevlar® configuration starting at the Artemis IV mission. This effort has included fifty-two shield characterization shots for five different shield configurations over the four Orion propellant storage vessels. These storage vessels are located in the European Service Module (ESM). This shield characterization has been managed by the Hypervelocity Impact Technology (HVIT) group in NASA Astromaterials Research and Exploration Sciences at Johnson Space Center (JSC) for the NASA Engineering and Safety Center (NESC) and the Multi-Purpose Crew Vehicle (MPCV) program office in coordination with Lockheed Martin Space and Thales Alenia Space-Italy (TAS-I). The shield characterization has used the two-stage, light-gas-gun at the Remote Hypervelocity Test Laboratory (RHTL) of NASA JSC White Sands Test Facility (WSTF) for acceleration of projectiles to representative orbital impact speeds. From this shield characterization effort, a revised ballistic limiting equation (BLE) has been developed for each of the five representative shielding configurations of the ESM pressure vessels. This document provides a brief description of the shield configurations considered for the Orion program and the shield characterization findings. These results are compared to the assumed BLE for each configuration going into the Artemis missions that utilize this version of ballistic enhanced MLI. The models are integrated into a fourteen day High Lunar Orbit (HLO) mission as a representative reliability prediction impact for Orion, and it has been found that the predicted risk of a loss-of-crew (LOC) event is actually a little less than half of the assumed value that launched this design modification opportunity.

Introduction

The Orion vehicle, Figure 1a, is being built for the mission of transporting crew members back and forth through Earth's atmosphere to longer term habitats either in orbit around the Moon or to lunar lander systems for lunar surface operations [1]. The Orion vehicle consists of three main components that can be seen in this image: the crew module (conical section) where the crew resides during ascent and descent through Earth's atmosphere, as well as, some phases of flight, the avionics ring adaptor (large cylindrical section) that includes numerous avionics and protects the atmospheric reentry heat shield, and the European Service Module (ESM) that contains most of the vehicles consumables for flight and propulsion systems as seen in Figure 1b [2]. These three sections are not only designed to perform necessary functions of crewed flight, but they are also designed to operate in the natural environments of space flight, which among other considerations, includes the threat of solid particles in the form of meteoroids and orbital debris (MMOD) [3].

The threat posed by natural environments, including MMOD, is related to mission parameters like duration of flight and exposure parameters like surface area. The ESM is a significant fraction of the exposed surface of Orion, and as a consequence, it has a significant impact on the Orion vehicle's ability to reliably perform its mission in the presence of MMOD. While numerous mission critical components reside in the ESM, as can be seen in Figure 1b, the propellant tanks stand out as principal occupants of the ESM. These propellant tanks store hazardous fuels and oxidizers

that are essential for maneuvering safely and returning from lunar orbits. Furthermore, to ensure these propellants are moved readily when necessary, these commodities are stored and maintained at pressure during flight, which means if these storage vessels structurally fail, there could be an energetic release of materials into surrounding critical components. These hazardous aspects of propellant storage necessitate protections against MMOD.

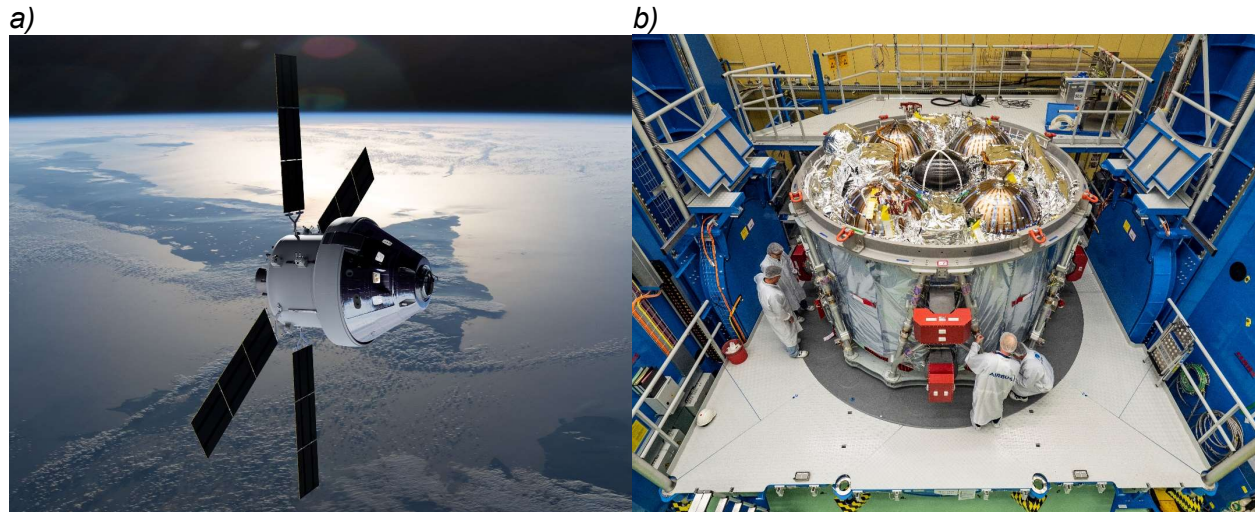


Figure 1 A computer assisted artistic rendition of the Orion vehicle [4] is shown in a) where the three main components of Orion are easily seen. The components are: crew module (cone shaped module), the avionics ring adaptor (center cylindrical section where the reentry heatshield is located), and the ESM (aft cylindrical section that includes the solar arrays). The ESM for Artemis I at Bremen, Germany prior to shipping to NASA Kennedy Space [5] b) shows the large storage vessels for the propulsion system as well as the other avionics that reside in this mission critical flight module that needs to be protected from meteoroids and orbital debris.

While the propellant tanks have some level of robustness to impacts by virtue of design safety factors and the large dimensions relative to the localized area of an impact, this robustness on its own is not sufficient for satisfactory operation of Orion. The first design accommodation made to the ESM to ensure safe operation of these tanks is that they are completely enclosed by an external wall. In the case of the cylindrical area, the external wall is the thermally required radiator panel that is used to reject excess heat from Orion to the space environment. In the aft portion of the ESM, an aluminum, external wall with additional thermal blankets protects the ESM from the heat of thruster firings. In both cases, these external walls aren't necessarily sufficient to stop impacting particles on their own, but they do initiate break-up of solid particles at expected impact speeds above several kilometers per second. The resulting debris cloud propagates inside the module encountering other internal materials before hitting the propellant tanks.

Chief among the internal materials between the closeout walls and the pressure vessels is an encompassing multi-layer insulation (MLI) blanket, which is placed there to thermally isolate the innermost components from the radiator. These blankets, in addition to their thermal function, also acts as a filter to the debris cloud from the initial break-up of MMOD. These blankets have been enhanced by the inclusion of Kevlar® to increase the filtering capability of the blanket assembly, which in turn, means the tanks are protected from even more massive MMOD particles. As the number of particles rapidly decreases with increasing particle size, increasing the damage threshold quickly improves the reliability of Orion with respect to MMOD.

In early design phases, Orion designs included up to five layers of Kevlar® KM2® 705 as a ballistic enhancement to the MLI [6, 7, 8]; however, dry mass of Orion is a premium and balancing the dry mass with overall vehicle reliability has been routinely pursued by NASA and ESA. With these reliability balancing efforts, Orion's ESM MLI design has moved from five layers of Kevlar® KM2® 705 to two layers for the second and third missions [9]. This two-layer enhancement has been reviewed and approved at many levels, but the desire to further reduce dry mass for the fourth and subsequent mission sets has driven an effort to explore the use of a single layer of Kevlar® KM2® Plus 775 [10].

To address this opportunity for further dry mass reduction for Orion, the Hypervelocity Impact Technology (HVIT) group of NASA Astromaterials Research and Exploration Sciences at Johnson Space Center (JSC) has worked with the NASA Engineering and Safety Center (NESC), the Multi-Purpose Crew Vehicle (MPCV) program office and European Space Agency (ESA) with its contractors Airbus and Thales Alenia Space-Italy (TAS-I) to study how KM2® Plus 775 compares with KM2® 705 [11]. This effort has developed threshold failure models for titanium propellant components in five representative configurations of shielding with two different threshold criteria for propellant components: first is no damage to the titanium components and the second is a level of cratering in the components that is less than the total thickness of the components.

In order to develop these threshold failure models for the propulsion components, a series of fifty-two, shield characterization shots have been performed at several kilometers per second into all five representative configurations. Particles of known size and material have been accelerated to these speeds by way of two-stage, light-gas-guns at the Remote Hypervelocity Test Laboratory (RHTL) of NASA JSC White Sands Test Facility (WSTF). This research paper reviews the materials and methods used to evaluate the five different shield configurations at space environment relevant conditions, discusses the analysis performed to synthesize these results into threshold failure models, and provides conclusions based on the use of these models.

Materials and Methods

Orion is analyzed for operation in both Earth orbit and in deep space operation, and as a consequence, both meteoroids and orbital debris are assessed for design and operation on every mission. Currently, Orion is being analyzed by NASA and Lockheed Martin Space using the Orbital Debris Engineering Model version 3.1.2 (ORDEM3.1.2) and Meteoroid Engineering Model version 3 (MEM3); whereas, ESA and TAS-I are analyzing Orion using the Orbital Debris Engineering Model version 2 (ORDEM2000) and Meteoroid Engineering Model version 1 (MEM1). These environments break out classes of solid particles. In the case of ORDEM3.1.2, the material classes are split into low density (1.4 g/cm^3), medium density (2.8 g/cm^3) and high density (7.9 g/cm^3), and ORDEM2000 assumes all debris is medium density (2.8 g/cm^3). MEM3 uses a double peak distribution of meteoroids based on densities with the first peak at about 0.9 g/cm^3 and the second peak about 3.9 g/cm^3 , and MEM1 treats all meteoroids as having a density of 1 g/cm^3 .

To address these different material classes, HVIT and WSTF-RHTL have selected Nylon (1.15 g/cm^3) to represent low density meteoroids and low density orbital debris, Al2017 (2.8 g/cm^3) to represent medium density orbital debris, Al₂O₃ (3.9 g/cm^3) to represent high density meteoroids, and SS440C (7.68 g/cm^3) to represent high density debris and FeNi meteoroids; although, characterization priority has been given to low density meteoroids because it is present in both sets of analyses, NASA and ESA, and for the longest exposure duration. This means that four different projectiles are potentially used to characterize a shield configuration.

With five shield configurations and up to four different projectile categories to address, fifty-two shield characterization shots have been performed for MPCV and NESC at several kilometers

per second (generally at 7 km/s) into the ESM. The main configuration studied is the large surface area consisting of the aluminum radiator panels and the cylindrical sections of the titanium propellant tanks. In addition to the radiator configuration, two aft bulkhead configurations to the domes and sides of the propellant tanks have been considered. A third aft configuration considers impacts of propellant tubes with a small separation between the tubes and the aft bulkhead. A fifth configuration formed by a closeout panel between the bottom of the radiator and the outside of the aft bulkhead has also been considered. Each of these five configurations are discussed here along with the observed results from the shots performed for characterization.

Radiator assembly (RA) shield configuration

The first configuration considered is the radiator assembly (RA), which is through the cylindrical section of the ESM as illustrated in Figure 2a. This configuration represents a substantial portion of the exposed ESM surface area at $\sim 20.6 \text{ m}^2$ ($\sim 59\%$ of the exposed ESM). In this configuration, there are three main material layers as shown in Figure 2b: the radiator panel surrogate, the ballistic-enhanced MLI blanket and the propellant tank wall surrogate.

The radiator panel surrogate is 1.3 mm thick Al6063-T6, and it has a radius of curvature of 2.035 m. The ballistic-enhanced MLI is concentric with the radiator at a constant 10 cm separation; however, in this work, the blanket is held flat. The ballistic-enhanced MLI consists of a single aluminized Kapton[®] layer followed by nineteen repeating layers of aluminized Mylar[®] and scrim with a total mass per unit area of 0.035 g/cm^2 . These layers are followed by a single layer of Kevlar[®] KM2[®] Plus 775 with a mass per unit area of 0.023 g/cm^2 , and the whole blanket is backed by Mylar[®] with an internal Dacron[®] net (0.009 g/cm^2). The ballistic-enhanced MLI blanket mass is 0.067 g/cm^2 .

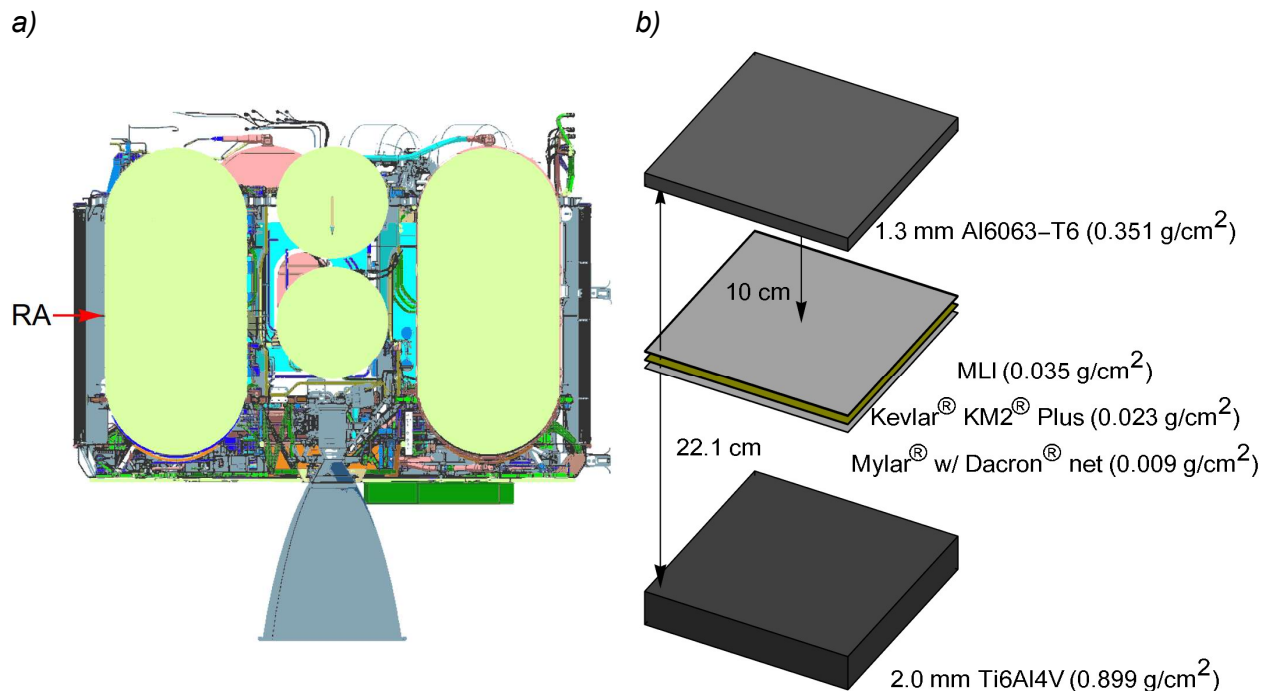


Figure 2 Radiator assembly (RA) shield configuration a) shot-line through the barrel section of the ESM with an b) annotated illustration of the material configuration (wall materials scaled to areal density; separations not to scale).

As a surrogate for the propellant tank walls, a 2 mm thick, flat-plate of Ti6Al4V-T6 is used. This plate is separated from the radiator panel surrogate by 22.1 cm, which is equivalent to the shortest distance between the radiator and the propellant tank walls. For the purposes of evaluation of Orion’s reliability, a series of twenty-one shots that range from charring the surface of the titanium witness plate to cratering the plate. The results are summarized in Table 1.

Table 1 Radiator assembly (RA) results matrix [10, 11]

Test Number	Projectile Material	Impact Speed (km/s)	Impact Obliquity (°)	Projectile Diameter (cm)	Projectile Mass (g)	Ti Crater Max Depth (mm)
HITF18329	Nylon	7.03	0	0.437	0.05002	0.03
HITF18330	Nylon	7.01	0	0.755	0.25700	0.60
HITF18331	Nylon	6.85	45	0.194	0.00436	0.10
HITF18332	Nylon	6.97	45	0.357	0.02717	0.40
HITF18333	Nylon	7.27	60	0.276	0.01251	0.09
HITF18334	Al2017	6.89	0	0.556	0.25114	0.00
HITF18335	SS440C	7.10	0	0.357	0.18261	1.60
HITF20171	Nylon	6.94	0	0.437	0.04997	0.09
HITF20172	Nylon	6.98	0	0.673	0.18158	0.19
HITF20173	Nylon	7.24	45	0.191	0.00413	0.04
HITF20174	Al2017	6.96	0	0.699	0.50023	0.08
HITF20175	Al ₂ O ₃	6.95	0	0.480	0.22581	0.00
HITF20176	SS440C	7.10	0	0.275	0.08387	0.35
HITF20177	SS440C	7.05	45	0.237	0.05329	0.49
HITF20189	Nylon	7.08	0	0.397	0.02830	0.00
HITF20190	Nylon	7.00	45	0.240	0.00829	0.20
HITF20191	Al ₂ O ₃	6.97	0	0.605	0.45146	0.11
HITF20192	SS440C	7.06	45	0.209	0.03657	0.39
HITF20204	Nylon	7.35	60	0.276	0.01248	0.00
HITF20279	Nylon	5.17	0	0.240	0.00826	0.06
HITF20280	Nylon	7.04	0	0.357	0.02721	0.00

The radiator is exposed to space shortly after ascent is complete; therefore, the RA configuration needs to be examined for both orbital debris and meteoroid environments. Because both orbital debris and meteoroid environments are of concern, all four projectile materials (Nylon, Al2017, Al₂O₃, and SS440C) have been considered. As can be seen in Table 1 most of the impacts are within 0.5 km/s of 7 km/s, but the impact obliquity (angle between the target surface normal and the projectile velocity vector) has been varied from a normal impact (0°) to impacts that are 60° from normal impact. For each impact condition, a level of damage metric to the Ti6Al4V witness (depth of the deepest crater) is recorded as a function of the size of the impacting projectile. When depth is recorded as zero, either debris didn’t reach the witness or only left superficial deposits on the surface.

Aft spiderweb (SW) mounted shield configuration

The second configuration considered is the aft spiderweb (SW) mounted MLI shield configuration, which is through the aft bulkhead of the ESM as illustrated in Figure 3a. The aft section of the ESM is covered by the Earth departure stage of the Space Launch System until after the translunar insertion burn is complete; therefore, the aft section is only exposed after departing Earth orbit. This configuration also represents a substantial portion of the exposed ESM surface area at ~9.1 m² (~26% of the exposed ESM). In this configuration, there are four main material

layers as shown in Figure 3b: a thick high temperature protection (HTP) blanket, the aft bulkhead surrogate, the ballistic-enhanced MLI blanket and the propellant tank wall surrogate.

The HTP blanket is an 11 mm thick blanket consisting of Saffil that is sewn between Nextel fabric with a total areal density of 0.22 g/cm^2 . The aft bulkhead surrogate is a flat, 1.3 mm thick Al6063-T6 plate. The separation between the back of the HTP blanket and the front of the aft bulkhead surrogate is 1 cm. The ballistic-enhanced MLI is parallel to the aft bulkhead surrogate at a constant 25.3 cm separation. The ballistic-enhanced MLI in the aft section consists of a single aluminized Kapton® layer followed by nine repeating layers of aluminized Mylar® and scrim with a total mass per unit area of 0.019 g/cm^2 . These layers are followed by a single layer of Kevlar® KM2® Plus 775 with a mass per unit area of 0.023 g/cm^2 , and the whole blanket is backed by Mylar® with an internal Dacron® net (0.009 g/cm^2). The aft, ballistic-enhanced MLI blanket mass is 0.051 g/cm^2 .

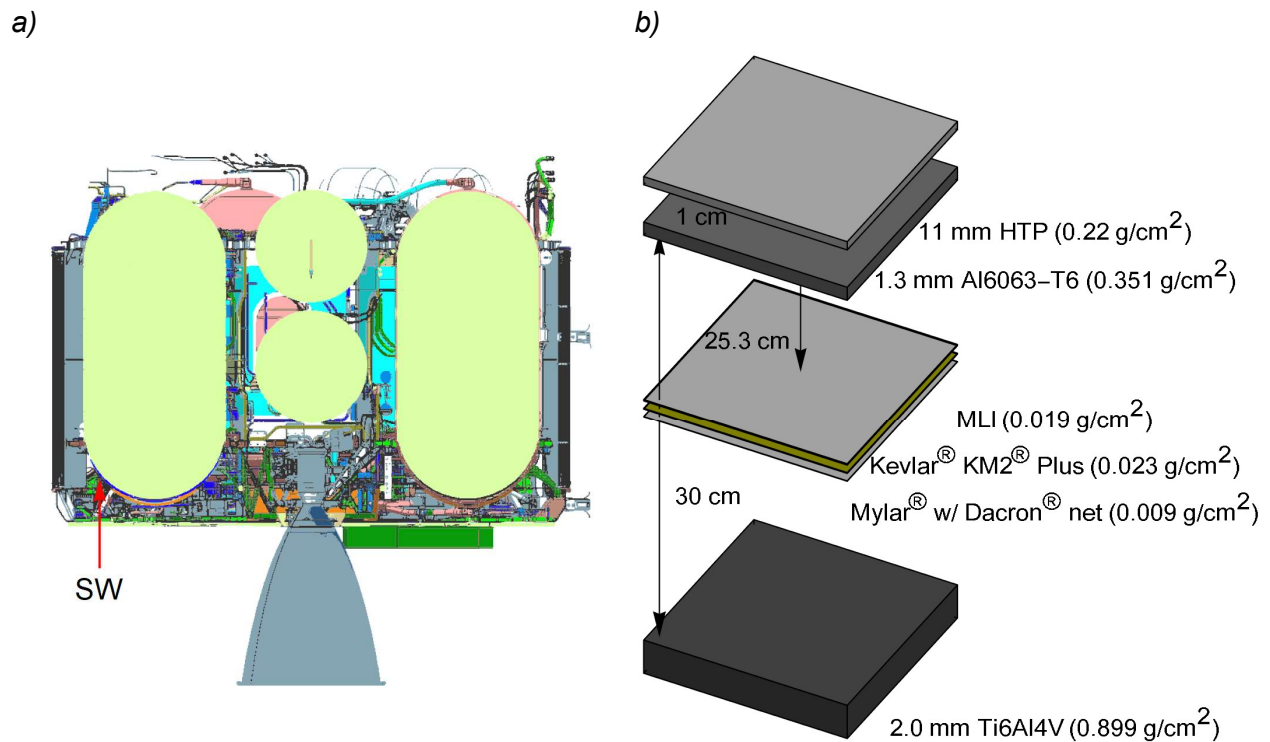


Figure 3 Aft MLI blanket attached to a SpiderWeb (SW) support structure a) shot-line through the aft closeout panel of the ESM with an b) annotated illustration of the material configuration (wall materials scaled to areal density; separations not to scale).

Similar to the RA configuration, the propellant tank walls are simulated by a 2 mm thick, flat-plate of Ti6Al4V-T6. This plate is separated from the aft bulkhead surrogate by 30 cm, which is equivalent to the mean distance between the aft bulkhead and the propellant tank dome. This configuration has been considered with a series of thirteen shots that range from charring the surface of the titanium witness plate to cratering the plate. The results are summarized in Table 2.

Table 2 Aft MLI blanket attached to a spiderweb (SW) support structure results matrix [11]

Test Number	Projectile Material	Impact Speed (km/s)	Impact Obliquity (°)	Projectile Diameter (cm)	Projectile Mass (g)	Ti Crater Max Depth (mm)
HITF20178	Nylon	7.03	0	0.358	0.02729	0.00
HITF20179	Nylon	7.08	45	0.437	0.04996	0.00
HITF20180	Al ₂ O ₃	7.01	0	0.176	0.01109	0.00
HITF20181	Al ₂ O ₃	7.00	45	0.200	0.01622	0.00
HITF20193	Nylon	7.00	0	0.514	0.08089	0.00
HITF20194	Nylon	6.90	45	0.673	0.18148	0.24
HITF20195	Al ₂ O ₃	7.06	0	0.240	0.02830	0.08
HITF20196	Al ₂ O ₃	6.97	45	0.400	0.13055	0.35
HITF20205	Nylon	5.28	0	0.501	0.07489	0.09
HITF20206	Nylon	6.93	60	0.797	0.30610	0.04
HITF20208	Nylon	6.90	0	0.478	0.06529	0.23
HITF20212	Nylon	6.89	0	0.478	0.06521	0.04
HITF20386	Nylon	6.93	0	0.397	0.03725	0.06

As a result of the shadowing by the Earth departure stage, only the meteoroid environment is applicable to this section of the ESM; therefore, only Nylon and Al₂O₃ projectiles have been considered for this configuration. As can be seen in Table 2 most of the impacts are within 0.5 km/s of 7 km/s, and impact obliquity range is similar to the RA.

Aft tank assembly (TA) shield configuration

The third configuration considered is the aft tank assembly (TA) shield configuration. This configuration is nearly identical to the SW configuration except in this configuration the ballistic-enhanced MLI is mounted directly to the dome of the tank as seen in Figure 4a and that the standoff distance from the aft bulkhead to the MLI is reduced.

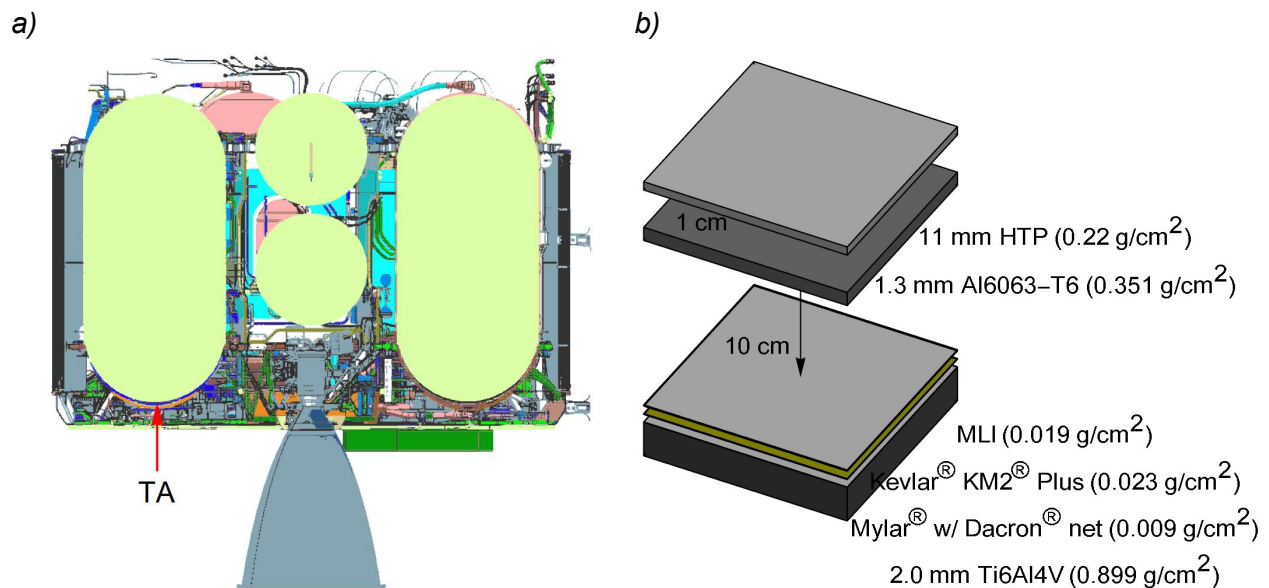


Figure 4 Aft conformal MLI blanket mounted on top of the tank (TA) a) shot-line through the aft closeout panel of the ESM with an b) annotated illustration of the material configuration (wall materials scaled to areal density; separations not to scale).

This configuration represents a much smaller exposed area of the ESM at $\sim 1.6 \text{ m}^2$ ($\sim 5\%$ of the exposed ESM). The materials are identical to the SW configuration as shown in Figure 4b except the separation between the propellant tank wall surrogate and the aft bulkhead surrogate is reduced to 10 cm, which corresponds to the minimum distance at the apex of the propellant tank dome to aft bulkhead. The ballistic-enhanced MLI is directly on top of the propellant tank wall surrogate. As a result of the similarity between the SW and TA configuration, only a small number of meteoroid environment conditions common to both NASA and ESA analyses have been considered and are summarized in Table 3.

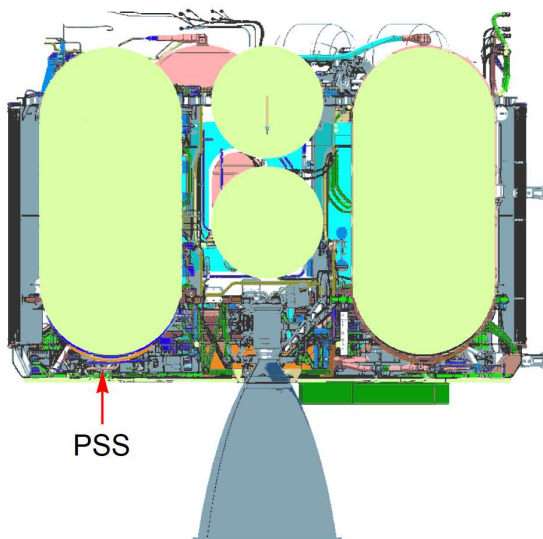
Table 3 Aft conformal MLI blanket mounted on top of the tank (TA) results matrix [11]

Test Number	Projectile Material	Impact Speed (km/s)	Impact Obliquity ($^\circ$)	Projectile Diameter (cm)	Projectile Mass (g)	Ti Crater Max Depth (mm)
HITF20182	Nylon	7.09	0	0.358	0.02730	0.00
HITF20183	Nylon	7.07	45	0.501	0.07483	0.00
HITF20197	Nylon	6.99	45	0.555	0.10185	0.00
HITF20211	Nylon	6.92	0	0.478	0.06521	0.10

Aft propulsion subsystem (PSS) tubing shield configuration

The fourth configuration considered is also an aft configuration, but considers the propulsion subsystem (PSS) tubing that is very near the aft bulkhead as seen in Figure 5a. This configuration is identical to the SW and TA configuration up to the aft bulkhead, but the rear critical component are Ti3Al2.5V tubes with a 1.9 cm diameter and 25 cm length. The tubes are filled with water to represent the fuel and oxidize as seen in Figure 5b.

a)



b)

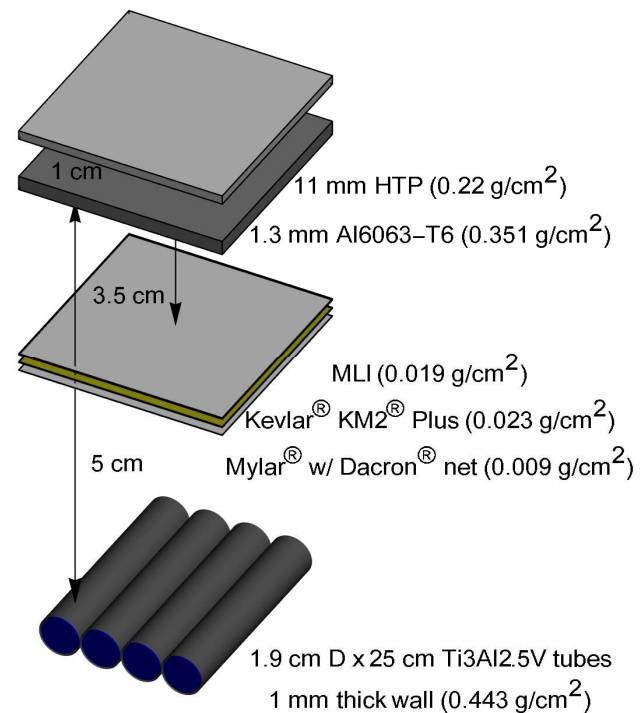


Figure 5 Aft propulsion subsystem (PSS) tubing a) shot-line through the aft closeout panel of the ESM with an b) annotated illustration of the material configuration (wall materials scaled to areal density; separations not to scale).

This configuration represents $\sim 1.4 \text{ m}^2$ of the exposed area of the ESM ($\sim 4\%$ of the exposed ESM). The separation between the aft bulkhead surrogate and the aft, ballistic-enhanced MLI is 3.5 cm, and the separation between the aft bulkhead surrogate and the Ti3Al2.5V tubing is 5 cm as shown in *Figure 5b*. As a result of the similarity between the SW and TA configuration, only a small number of meteoroid environment have been considered and are summarized in Table 4.

Table 4 Aft propulsion subsystem (PSS) tubing results matrix [11]

Test Number	Projectile Material	Impact Speed (km/s)	Impact Obliquity ($^\circ$)	Projectile Diameter (cm)	Projectile Mass (g)	Ti Crater Max Depth (mm)
HITF20184	Nylon	6.96	0	0.437	0.04990	0.00
HITF20198	Nylon	6.98	0	0.515	0.08140	0.33

Cover-plate (COV) closeout shield configuration

The final configuration considered is the cover-plate (COV) closeout, which is at the bottom of the cylindrical section of the ESM and the outside of the aft bulkhead as illustrated in *Figure 6a*. This configuration represents $\sim 2.2 \text{ m}^2$ of the exposed ESM ($\sim 6\%$ of the exposed ESM). In this configuration, there are four main material layers: external MLI package, a cover-plate surrogate that fills the gap between the radiator panel and the aft bulkhead, the ballistic-enhanced MLI blanket and the propellant tank wall surrogate.

The cover-plate surrogate is 1.27 mm thick Al6061-T6. As this plate is exposed to some of the radiant heat from the ESM thrusters, an external MLI package is attached to the cover-plate. The external MLI consists of a single layer of beta cloth (0.029 g/cm^2), single aluminized Kapton[®] layer followed by nineteen repeating layers of aluminized Mylar[®] and scrim with a total mass per unit area of 0.035 g/cm^2 , and is backed by Mylar[®] with an internal Dacron[®] net (0.009 g/cm^2).

As the cover-plate has a somewhat complex geometry, viable impact paths to the propellant tanks is also complicated. For the purposes of characterizing this region of the ESM, two impact vectors (one normal to the cover-plate and one 45° to the normal of the cover-plate) have been considered and are illustrated in *Figure 6a*.

The material configuration for the normal to the cover-plate impact is shown in *Figure 6b*. In this configuration, the aft, ballistic-enhanced MLI surface normal is 55° from the projectile velocity vector, and it is set back 35 cm from the cover-plate surrogate panel along the projectile velocity vector. The 2 mm thick, Ti6Al4V propellant tank surrogate's surface normal is oriented 15° from the projectile velocity vector, and it is separated by 43 cm from the cover-plate surrogate panel.

The material configuration for the 45° to normal of the cover-plate impact is shown in *Figure 6c*. In this configuration, the aft, ballistic-enhanced MLI surface is orthogonal to the cover-plate surrogate panel, and the aim point is such that the separation along the flight path between the cover-plate surrogate panel and the aft, ballistic-enhanced MLI is 15 cm. The 2 mm thick, Ti6Al4V propellant tank surrogate's surface normal is aligned with the projectile velocity vector, and it is separated by 35 cm from the impact point of the cover-plate surrogate panel.

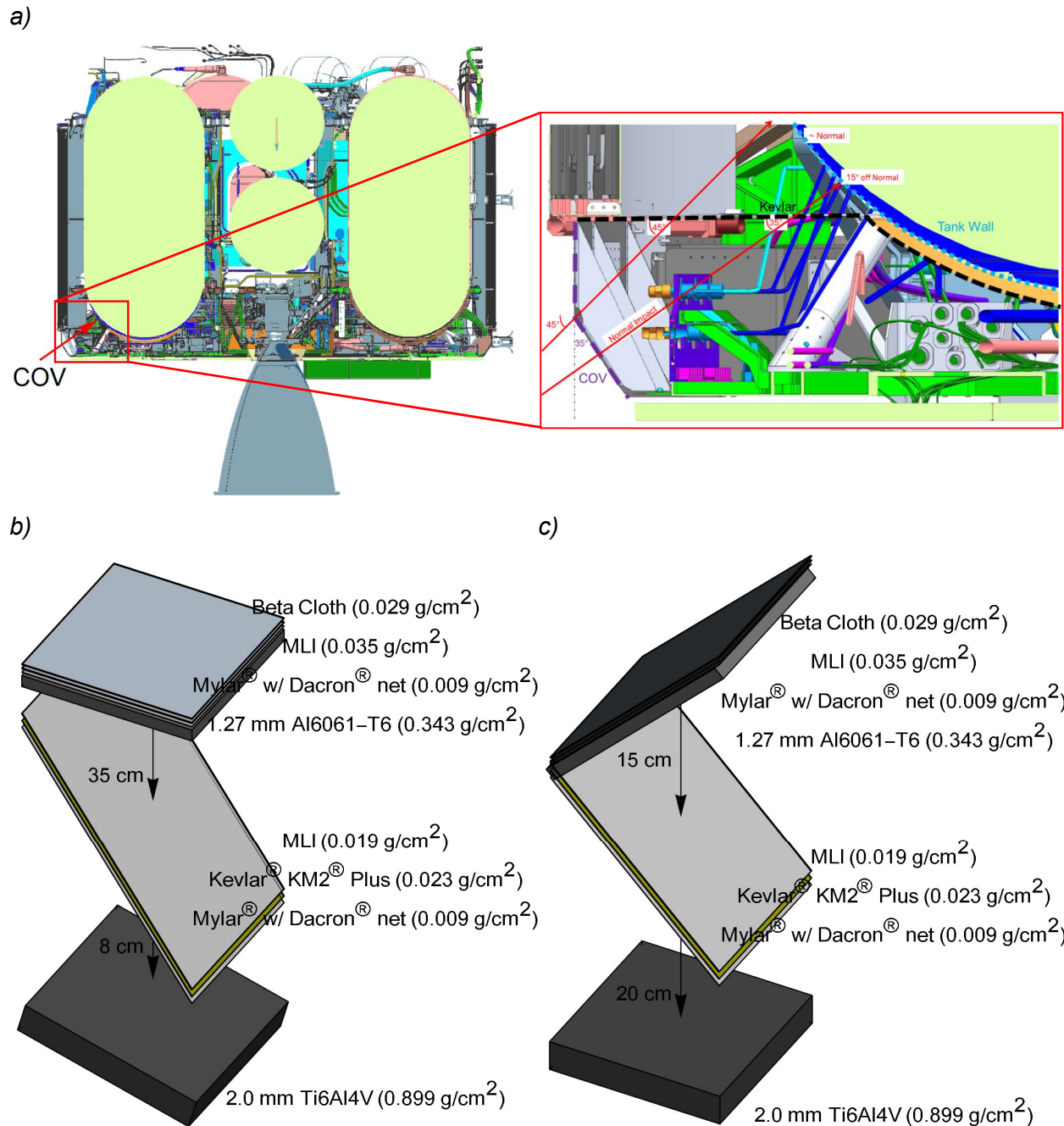


Figure 6 Cover-plate (COV) closeout a) shot-line through the side closeout with an expanded view of normal and oblique shot-lines. An b) annotated illustration of the material configuration for a normal impact of the cover plate and an c) annotated illustration of the material configuration for an oblique impact to the cover plate (wall materials scaled to areal density; separations not to scale).

Like the radiator, the cover-plate closeout is exposed to space shortly after ascent is complete; therefore, the COV configuration needs to be examined for both orbital debris and meteoroid environments. Because both orbital debris and meteoroid environments are of concern, all four projectile materials (Nylon, Al2017, Al₂O₃, and SS440C) have been considered. As can be seen in Table 5 all of the COV impacts are within 0.5 km/s of 7 km/s, and both impact obliquity

configurations have been studied. As with all other configurations, depth of the deepest crater as a function of the size of the impacting projectile has been recorded.

Table 5 Cover-plate closeout panel (COV) results matrix [11]

Test Number	Projectile Material	Impact Speed (km/s)	Impact Obliquity (°)	Projectile Diameter (cm)	Projectile Mass (g)	Ti Crater Max Depth (mm)
HITF20185	Nylon	7.03	0	0.275	0.01247	0.06
HITF20186	Nylon	6.97	45	0.408	0.04060	0.00
HITF20187	SS440C	7.06	0	0.199	0.03156	0.08
HITF20188	Al ₂ O ₃	7.08	0	0.240	0.02830	0.00
HITF20199	Nylon	7.09	0	0.240	0.00833	0.00
HITF20200	Nylon	6.95	45	0.478	0.06529	0.00
HITF20201	SS440C	6.96	0	0.299	0.10767	0.49
HITF20202	Al ₂ O ₃	6.95	0	0.480	0.22584	0.15
HITF20207	Al2017	7.14	0	0.299	0.03922	0.02
HITF20209	Al2017	7.11	45	0.410	0.10095	0.19
HITF20210	Nylon	6.90	45	0.595	0.12585	0.29

Discussion

The collected information on damage level as a function of projectile material and size as well as the applicable impact speed and obliquity have been used to define threshold damage equations, which are necessary for reliability analysis of the ESM. These data have been initially consolidated into a penetration equation:

$$P = P_o \left(\frac{\rho_p \rho_B}{\rho_W^2} \right) \left(\text{Exp} \left[\frac{D_p}{D_T} - 1 \right] - 1 \right), \quad 1$$

where P , ρ_p , D_p and D_T are the crater depth and the projectile density and diameter from the shield characterization shot, and a threshold projectile diameter at the onset of cratering in the titanium propulsion surrogate, respectively. The terms ρ_B and ρ_W are the density of the bumper and the witness, which are 2.7 g/cm^3 and 4.43 g/cm^3 . The term P_o is a fitting parameter related to the shield type.

The European Space Agency and its contractors have decided to assume that propellant pressure vessels have no inherent damage tolerance; therefore, the threshold projectile diameter for the onset of cratering is the desired condition used in their analysis. As such, D_T in Eqn. 1 is where NASA analysis is linked to ESA analysis. This threshold has been published by TAS-I in TASI-MSM-PBR-1415, and it has been implemented in Bumper for use by NASA and LM Space. There are three main equations: one for the RA shield configuration, one for all aft shield configurations and finally a COV shield configuration.

NASA and LM Space do assume damage tolerance in the pressure vessels at 20% cratering depth in the propellant tank walls and 41% cratering depth in PSS tube walls. These damage tolerances translate in penetration depths of 0.4 mm and 0.24 mm in the cylindrical and hemispherical sections of the propellant tanks, respectively, and 0.41 mm in the PSS tubing. Solving Eqn. 1 in terms of the diameter to reach these depths yields the ballistic limit equation, D_c , used by NASA and LM Space for ESM titanium pressure components:

$$D_c = D_T \left(\text{Log} \left[\left(\frac{\rho_W^2}{\rho_p \rho_B} \right) \frac{P_c}{P_o} + 1 \right] + 1 \right), \quad 2$$

where P_c is the maximum allowed penetration depth of the propulsion element.

In the following section, both the damage threshold limiting equations, D_T , used by ESA, Airbus and TAS-I, and the ballistic limiting equations, D_c , used by NASA and LM Space are shown for the five configurations of the ESM along with the shield characterization data. In all cases, all four classes of projectiles considered (low density meteoroid/orbital debris, medium density orbital debris, high density meteoroid, and high density orbital debris/FeNi meteoroid) are shown. In addition to the comparison between the ballistic models and the obtained shield characterization data, the ballistic models “assumed” going into the detailed shield characterization effort that motivated this design modification as a potential opportunity and the “adjusted” models that have been adapted to better reflect the shield characterization data subsequent are also shown. The comparison between the “adjusted” and the “assumed” provide an illustration of how the characterization effort sponsored by NESC and MPCV improved Orion reliability analyses. Finally, a forecast of reliability predictions for Artemis Mission IV are given, which is when the single layer Kevlar® enhancement is expected to go into effect.

Radiator assembly (RA) shield configuration

A comparison of the “assumed” (dashed) and the “adjusted” (solid) threshold limiting equations used for the propellant tanks by TAS-I for the ESA failure criterion in the RA shield configuration are shown in Figure 7. The threshold limiting equations are color segregated by impact obliquity where blue corresponds to normal impacts, orange corresponds to 45° to normal impacts, and green corresponds to 60° to normal impacts. In addition to the threshold limiting equations, the data from Table 1 is shown as empty circles if no damage in the witness has been observed, and filled circles if damage in the witness has been observed. For the threshold limiting equation to accurately reflect the data of Table 1, the threshold limiting equation should pass in between the empty and filled data points.

The four environment classes (low density meteoroid/orbital debris, medium density orbital debris, high density meteoroid, and high density orbital debris/FeNi meteoroid) from Table 1 have been separated into four plots: Nylon in Figure 7a, Al2017 in Figure 7b, Al₂O₃ in Figure 7c and SS440C in Figure 7d. Each of these plots shows the critical diameter in centimeters that triggers the ESA failure condition as a function of the relative impact speed between the Orion ESM and the natural environment threat. All particle sizes above the damage threshold limiting equation are considered catastrophic for Orion by ESA, and all particle sizes below the damage threshold limiting equation are considered within the design limits of Orion by ESA.

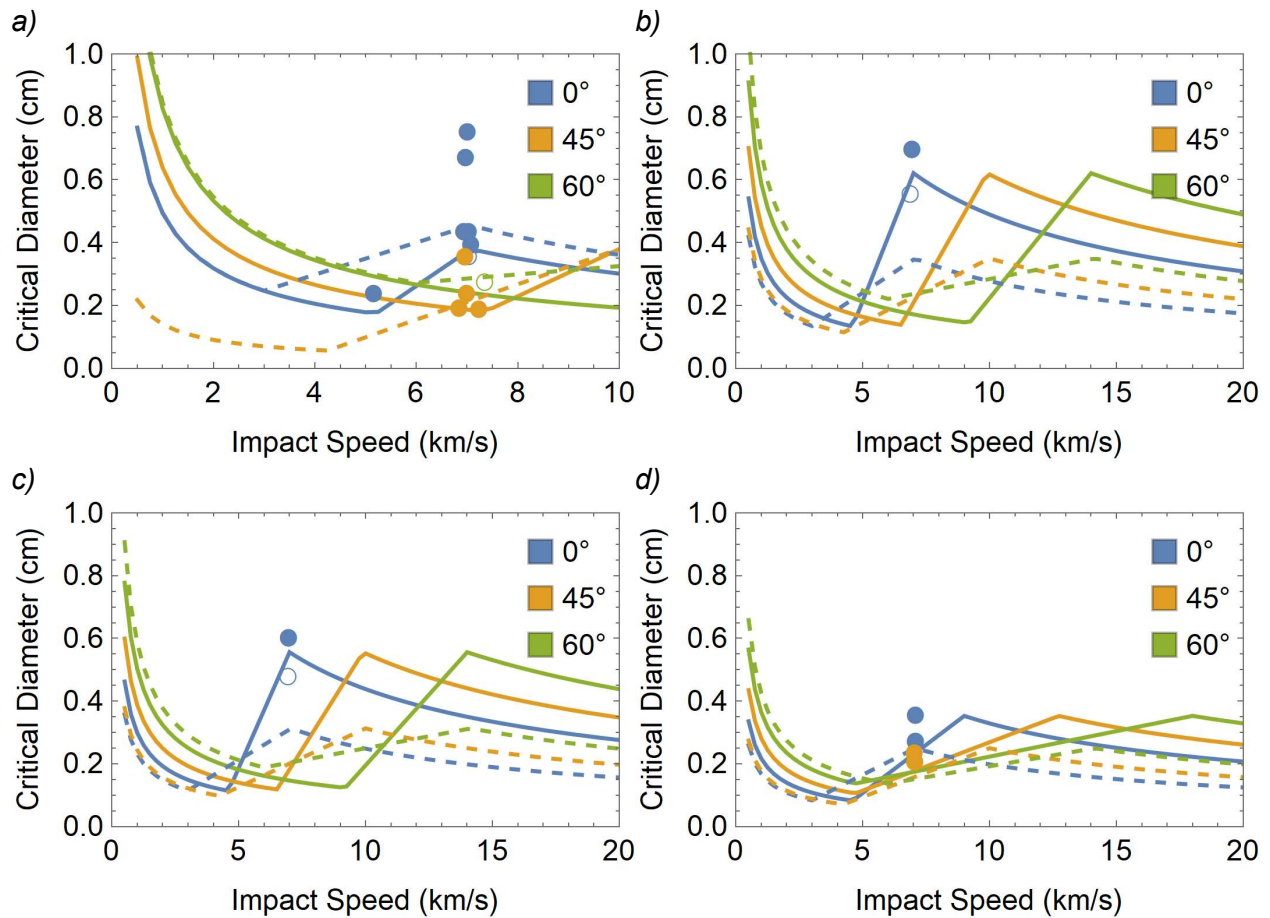


Figure 7 Radiator assembly (RA) with ESA failure criterion of “no damage” a) low density Nylon (1.15 g/cm³), b) medium density metallic Al2017 (2.8 g/cm³), c) high density rocky Al₂O₃ (3.9 g/cm³), and high density metallic SS440C (7.68 g/cm³).

Similar to the damage limit thresholds, a comparison of the “assumed” (dashed) and the “adjusted” (solid) ballistic limiting equations used for the propellant tanks by LM Space for the NASA failure criterion in the RA shield configuration are shown in Figure 8, where Nylon is in Figure 8a, Al2017 is in Figure 8b, Al₂O₃ is in Figure 8c and SS440C is in Figure 8d. Implicit in these curves is that a particle that induces less than a 0.4 mm crater in the propellant tank wall considered within the design limits of Orion. As with the threshold limiting equations, the ballistic limiting equations are color segregated by impact obliquity where blue corresponds to normal impacts, orange corresponds to 45° to normal impacts, and green corresponds to 60° to normal impacts.

The data from Table 1 is now shown as empty circles if less than 0.4 mm crater depth in the propellant tank witness has been observed, and filled circles if the damage in the witness exceeds 0.4 mm in crater depth. As noted for the ESA failure condition, the ballistic limiting equation accurately reflects the data of Table 1 when the curve passes in between the empty and filled data points; however, as depth information is available for this condition, the distance between the curves and the data corresponds to the difference between observed depth and the desired acceptable depth. All particle sizes above the ballistic limiting equation are considered catastrophic for Orion by NASA, and all particle sizes below the ballistic limiting equation are considered within the design limits of Orion by NASA.

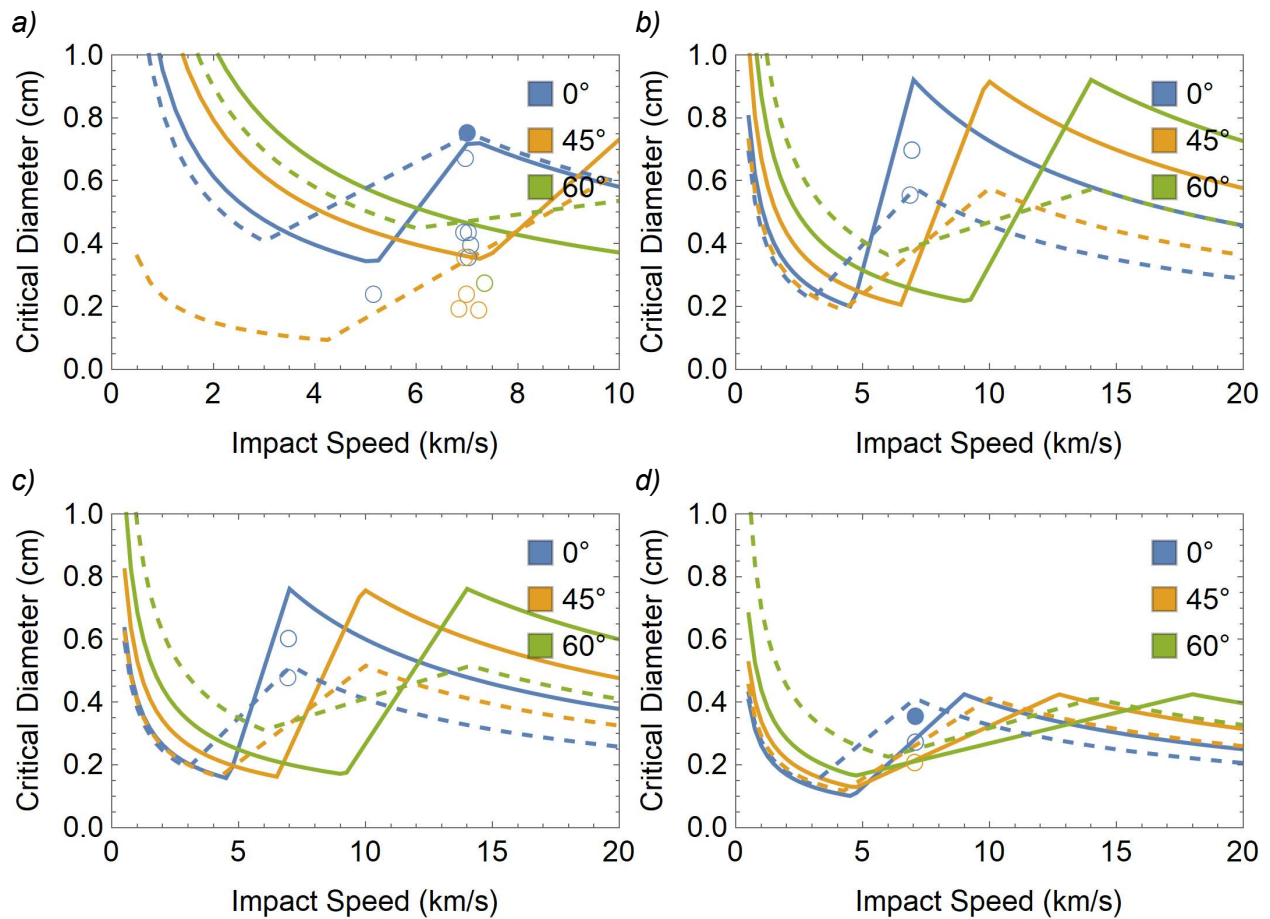


Figure 8 Radiator assembly (RA) with NASA failure criterion of 0.4 mm maximum crater depth a) low density Nylon (1.15 g/cm^3), b) medium density metallic Al2017 (2.8 g/cm^3), c) high density rocky Al_2O_3 (3.9 g/cm^3), and high density metallic SS440C (7.68 g/cm^3).

Aft spiderweb (SW) mounted shield configuration

A comparison of the “assumed” (dashed) and the “adjusted” (solid) threshold limiting equations used for the propellant tanks by TAS-I for the ESA failure criterion in the SW shield configuration are shown in Figure 9. The threshold limiting equations are color segregated by impact obliquity where blue, orange and green corresponds to normal impacts, 45° to normal impacts, and 60° to normal impacts, respectively. In addition to the threshold limiting equations, the data from Table 2 is shown as empty circles for no damage and filled circles when damage in the witness has been observed. For the threshold limiting equation to accurately reflect the data of Table 2, the threshold limiting equation should pass in between the empty and filled data points.

The four environment classes from Table 2 have been separated into four plots: Nylon in Figure 9a, Al2017 in Figure 9b, Al_2O_3 in Figure 9c and SS440C in Figure 9d. Each of these plots shows the critical diameter in centimeters that triggers the ESA failure condition as a function of the relative impact speed between the Orion ESM and the natural environment threat. All particle sizes above the damage threshold limiting equation are considered catastrophic for Orion by ESA, and all particle sizes below the damage threshold limiting equation are considered within the design limits of Orion by ESA.

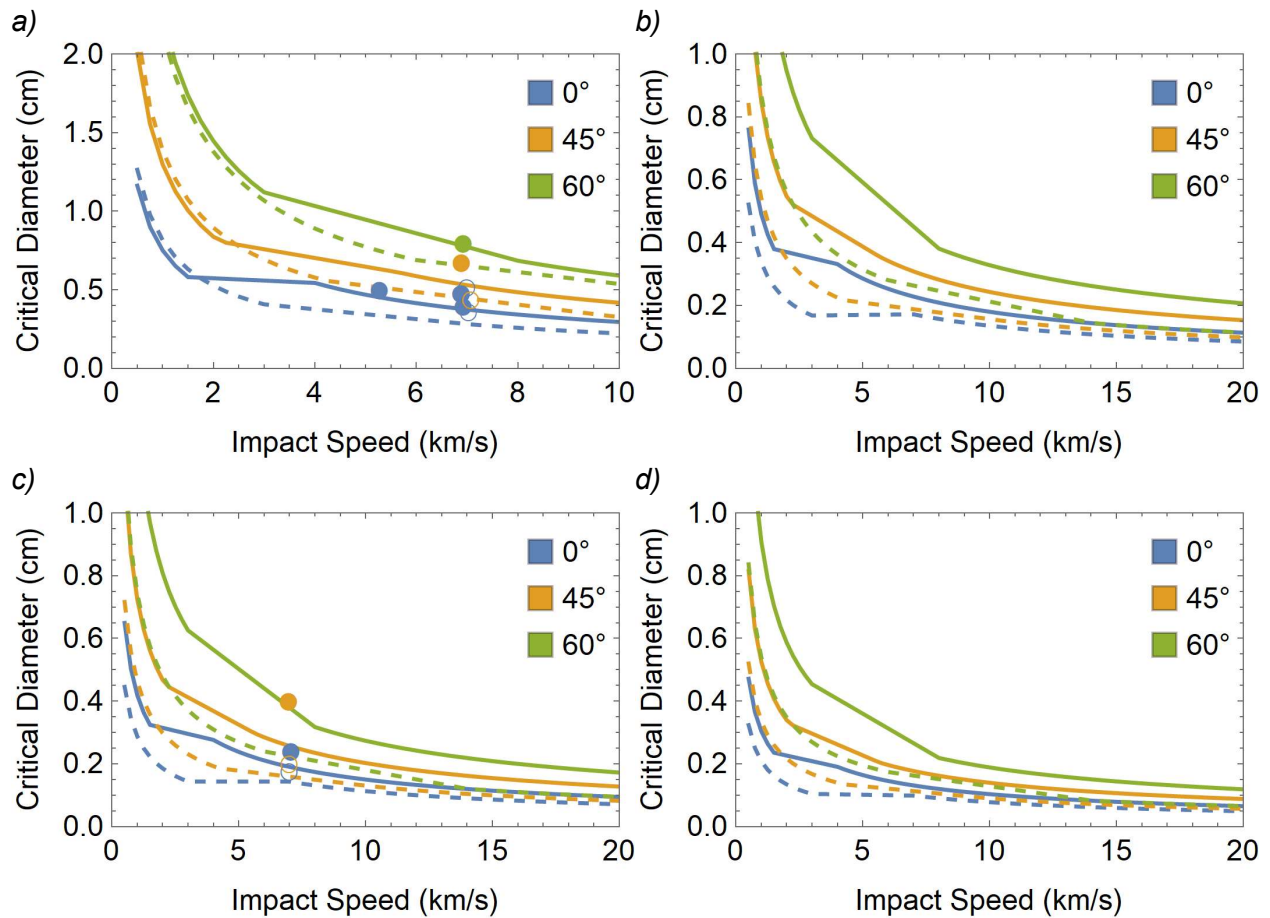


Figure 9 MLI blanket mounted on a spiderweb (SW) cargo strap with ESA failure criterion of “no damage” a) low density Nylon (1.15 g/cm³), b) medium density metallic Al2017 (2.8 g/cm³), c) high density rocky Al₂O₃ (3.9 g/cm³), and d) high density metallic SS440C (7.68 g/cm³).

Similar to the damage limit thresholds, a comparison of the “assumed” (dashed) and the “adjusted” (solid) ballistic limiting equations used for the propellant tanks by LM Space for the NASA failure criterion in the SW shield configuration are shown in Figure 10, where Nylon is in Figure 10a, Al2017 is in Figure 10b, Al₂O₃ is in Figure 10c and SS440C is in Figure 10d. Implicit in these curves is that a particle that induces less than a 0.24 mm crater in the propellant tank wall is considered within the design limits of Orion. As with the threshold limiting equations, the ballistic limiting equations are color segregated by impact obliquity where blue corresponds to normal impacts, orange corresponds to 45° to normal impacts, and green corresponds to 60° to normal impacts.

The data from Table 2 is now shown as empty circles if less than 0.24 mm crater depth in the propellant tank witness has been observed, and filled circles if the damage in the witness exceeds 0.24 mm in crater depth. As noted for the ESA failure condition, the ballistic limiting equation accurately reflects the data of Table 2 when the curve passes in between the empty and filled data points; however, as depth information is available for this condition, the distance between the curves and the data corresponds to the difference between observed depth and the desired acceptable depth. All particle sizes above the ballistic limiting equation are considered catastrophic for Orion by NASA, and all particle sizes below the ballistic limiting equation are considered within the design limits of Orion by NASA.

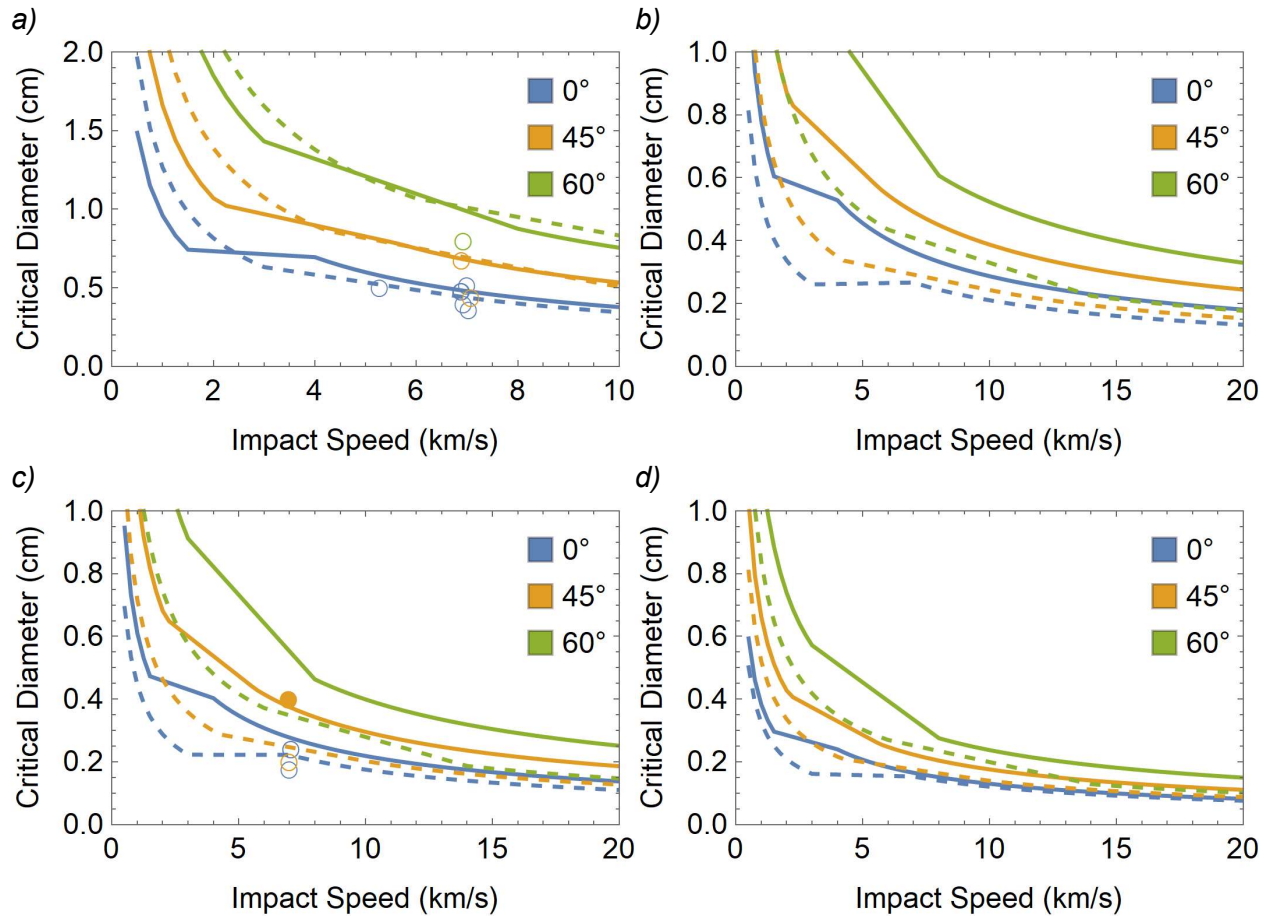


Figure 10 MLI blanket mounted on a spiderweb (SW) cargo strap with NASA failure criterion of 0.24 mm maximum crater depth a) low density Nylon (1.15 g/cm³), b) medium density metallic Al2017 (2.8 g/cm³), c) high density rocky Al₂O₃ (3.9 g/cm³), and high density metallic SS440C (7.68 g/cm³).

Aft tank assembly (TA) shield configuration

A comparison of the “assumed” (dashed) and the “adjusted” (solid) threshold limiting equations used for the propellant tanks by TAS-I for the ESA failure criterion in the TA shield configuration are shown in Figure 11. The threshold limiting equations are color segregated by impact obliquity where blue, orange and green corresponds to normal impacts, 45° to normal impacts, and 60° to normal impacts, respectively. In addition to the threshold limiting equations, the data from Table 3 is shown as empty circles for no damage and filled circles when damage in the witness has been observed. For the threshold limiting equation to accurately reflect the data of Table 3, the threshold limiting equation should pass in between the empty and filled data points.

The four environment classes from Table 3 have been separated into four plots: Nylon in Figure 11a, Al2017 in Figure 11b, Al₂O₃ in Figure 11c and SS440C in Figure 11d. Each of these plots shows the critical diameter in centimeters that triggers the ESA failure condition as a function of the relative impact speed between the Orion ESM and the natural environment threat. All particle sizes above the damage threshold limiting equation are considered catastrophic for Orion by ESA, and all particle sizes below the damage threshold limiting equation are considered within the design limits of Orion by ESA.

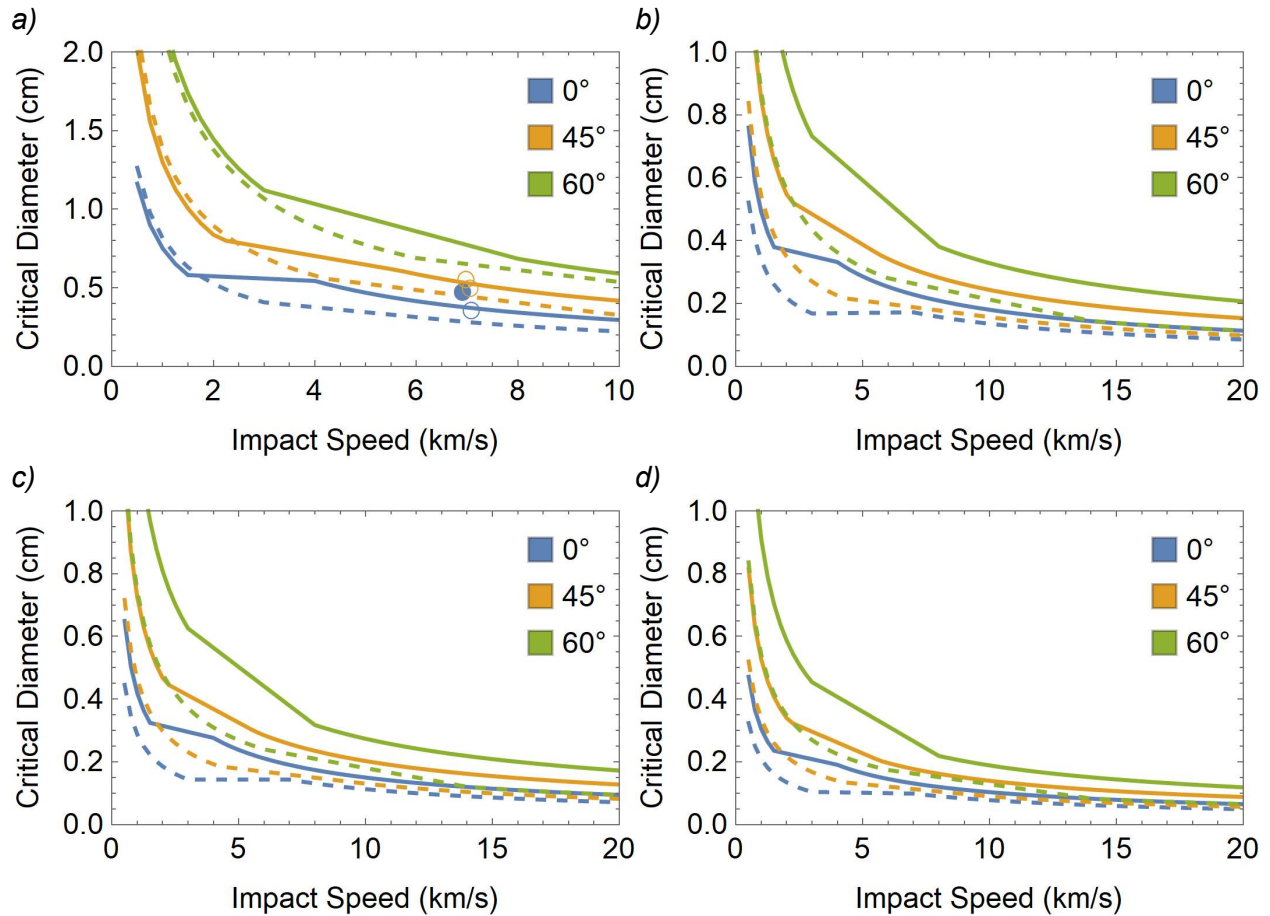


Figure 11 MLI blanket mounted on top of the tank (TA) with ESA failure criterion of “no damage” a) low density Nylon (1.15 g/cm^3), b) medium density metallic Al2017 (2.8 g/cm^3), c) high density rocky Al_2O_3 (3.9 g/cm^3), and d) high density metallic SS440C (7.68 g/cm^3).

Similar to the damage limit thresholds, a comparison of the “assumed” (dashed) and the “adjusted” (solid) ballistic limiting equations used for the propellant tanks by LM Space for the NASA failure criterion in the TA shield configuration are shown in Figure 12, where Nylon is in Figure 12a, Al2017 is in Figure 12b, Al_2O_3 is in Figure 12c and SS440C is in Figure 12d. Implicit in these curves is that a particle that induces less than a 0.24 mm crater in the propellant tank wall is considered within the design limits of Orion. As with the threshold limiting equations, the ballistic limiting equations are color segregated by impact obliquity where blue corresponds to normal impacts, orange corresponds to 45° to normal impacts, and green corresponds to 60° to normal impacts.

The data from Table 3 is now shown as empty circles if less than 0.24 mm crater depth in the propellant tank witness has been observed, and filled circles if the damage in the witness exceeds 0.24 mm in crater depth. As noted for the ESA failure condition, the ballistic limiting equation accurately reflects the data of Table 3 when the curve passes in between the empty and filled data points; however, as depth information is available for this condition, the distance between the curves and the data corresponds to the difference between observed depth and the desired acceptable depth. All particle sizes above the ballistic limiting equation are considered catastrophic for Orion by NASA, and all particle sizes below the ballistic limiting equation are considered within the design limits of Orion by NASA.

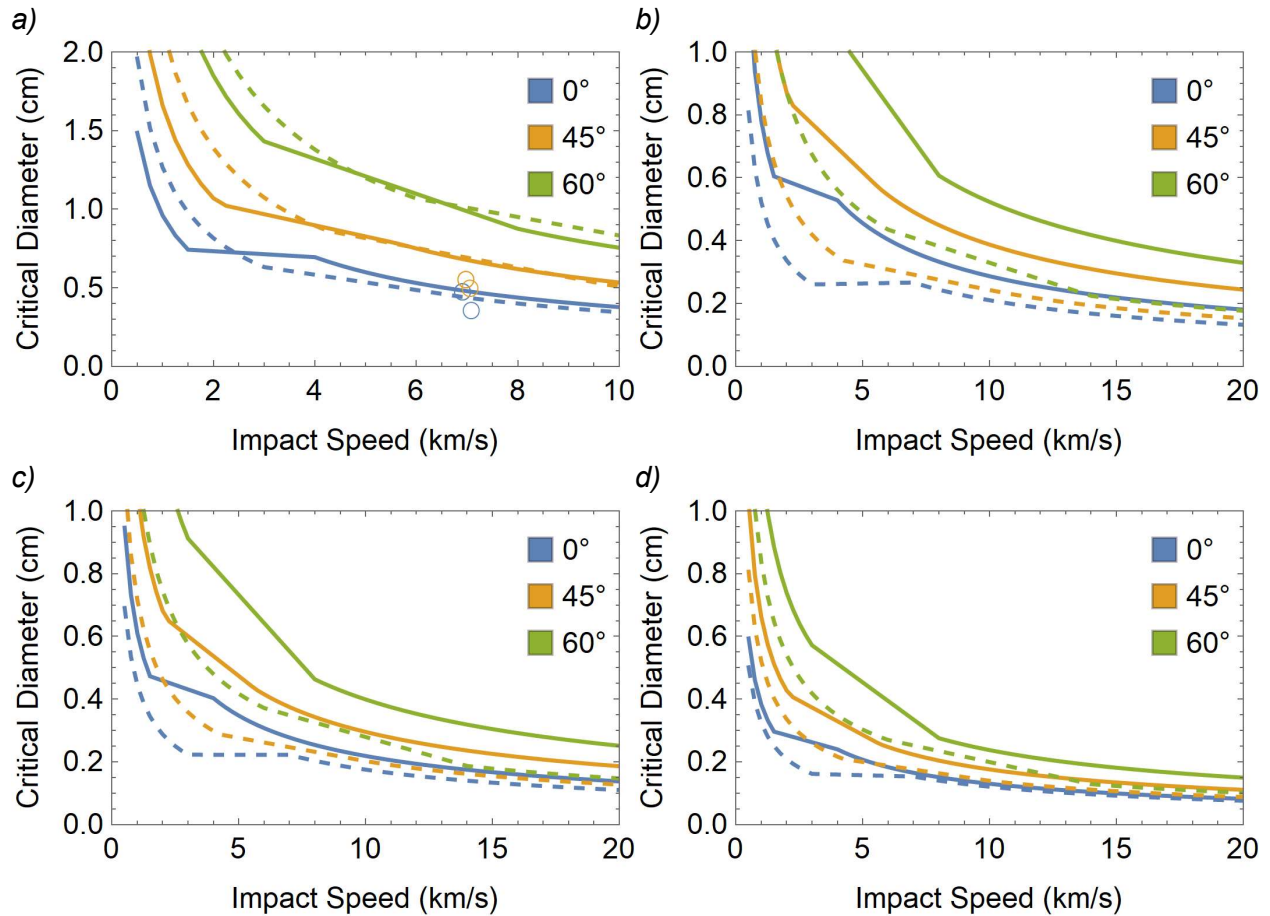


Figure 12 MLI blanket mounted on top of the tank (TA) with NASA failure criterion of 0.24 mm maximum crater depth a) low density Nylon (1.15 g/cm^3), b) medium density metallic Al2017 (2.8 g/cm^3), c) high density rocky Al_2O_3 (3.9 g/cm^3), and high density metallic SS440C (7.68 g/cm^3).

Aft propulsion subsystem (PSS) tubing shield configuration

A comparison of the “assumed” (dashed) and the “adjusted” (solid) threshold limiting equations used for the propellant tanks by TAS-I for the ESA failure criterion in the PSS shield configuration are shown in Figure 13. The threshold limiting equations are color segregated by impact obliquity where blue, orange and green corresponds to normal impacts, 45° to normal impacts, and 60° to normal impacts, respectively. In addition to the threshold limiting equations, the data from Table 4 is shown as empty circles for no damage and filled circles when damage in the witness has been observed. For the threshold limiting equation to accurately reflect the data of Table 4, the threshold limiting equation should pass in between the empty and filled data points.

The four environment classes from Table 4 have been separated into four plots: Nylon in Figure 13a, Al2017 in Figure 13b, Al_2O_3 in Figure 13c and SS440C in Figure 13d. Each of these plots shows the critical diameter in centimeters that triggers the ESA failure condition as a function of the relative impact speed between the Orion ESM and the natural environment threat. All particle sizes above the damage threshold limiting equation are considered catastrophic for Orion by ESA, and all particle sizes below the damage threshold limiting equation are considered within the design limits of Orion by ESA.

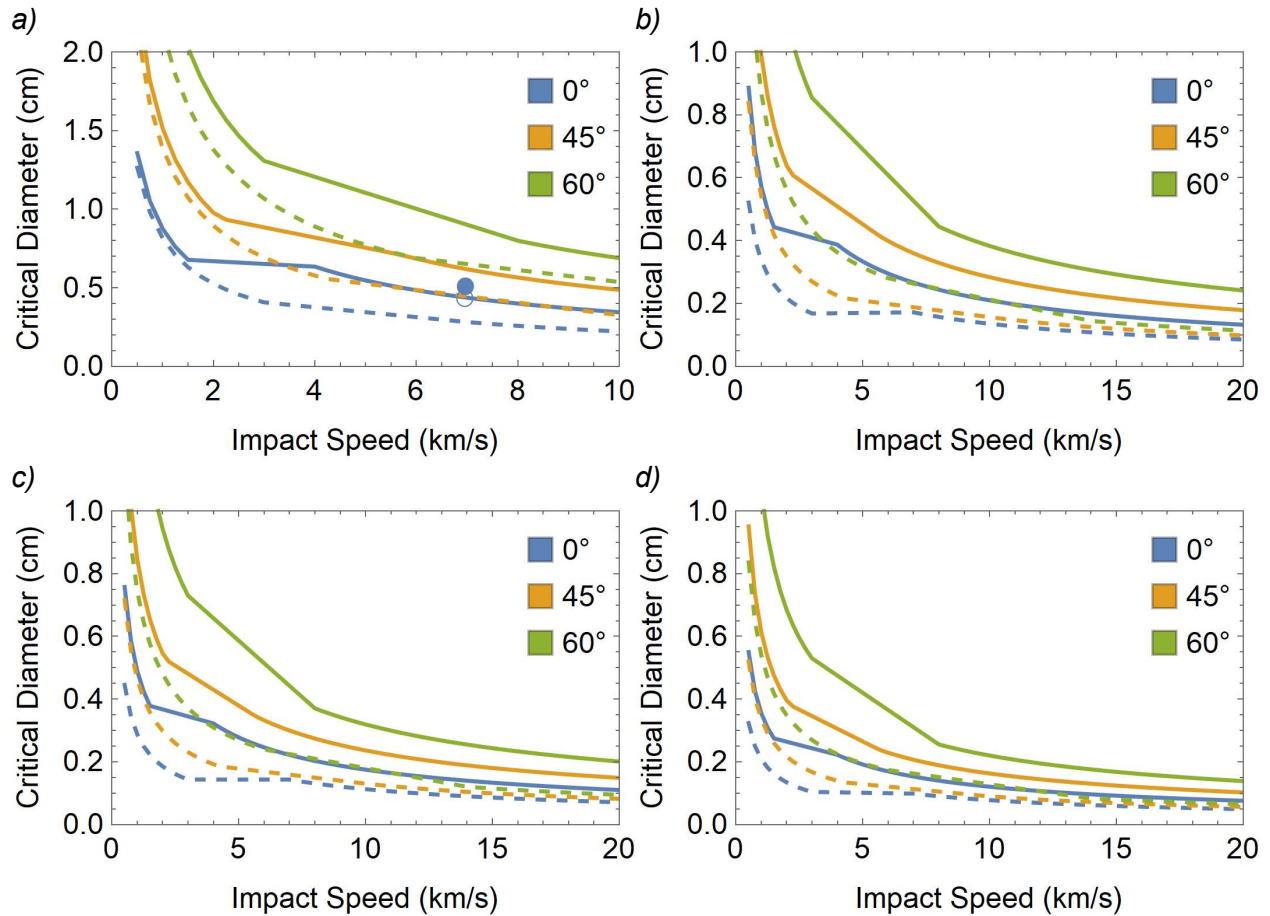


Figure 13 Aft propulsion subsystem (PSS) tubing with ESA failure criterion of “no damage” a) low density Nylon (1.15 g/cm^3), b) medium density metallic Al2017 (2.8 g/cm^3), c) high density rocky Al_2O_3 (3.9 g/cm^3), and high density metallic SS440C (7.68 g/cm^3).

Similar to the damage limit thresholds, a comparison of the “assumed” (dashed) and the “adjusted” (solid) ballistic limiting equations used for the propellant tanks by LM Space for the NASA failure criterion in the PSS shield configuration are shown in Figure 14, where Nylon is in Figure 14a, Al2017 is in Figure 14b, Al_2O_3 is in Figure 14c and SS440C is in Figure 14d. Implicit in these curves is that a particle that induces less than a 0.41 mm crater in the propellant tank wall is considered within the design limits of Orion. As with the threshold limiting equations, the ballistic limiting equations are color segregated by impact obliquity where blue corresponds to normal impacts, orange corresponds to 45° to normal impacts, and green corresponds to 60° to normal impacts.

The data from Table 4 is now shown as empty circles if less than 0.41 mm crater depth in the propellant tank witness has been observed, and filled circles if the damage in the witness exceeds 0.41 mm in crater depth. As noted for the ESA failure condition, the ballistic limiting equation accurately reflects the data of Table 4 when the curve passes in between the empty and filled data points; however, as depth information is available for this condition, the distance between the curves and the data corresponds to the difference between observed depth and the desired acceptable depth. All particle sizes above the ballistic limiting equation are considered catastrophic for Orion by NASA, and all particle sizes below the ballistic limiting equation are considered within the design limits of Orion by NASA.

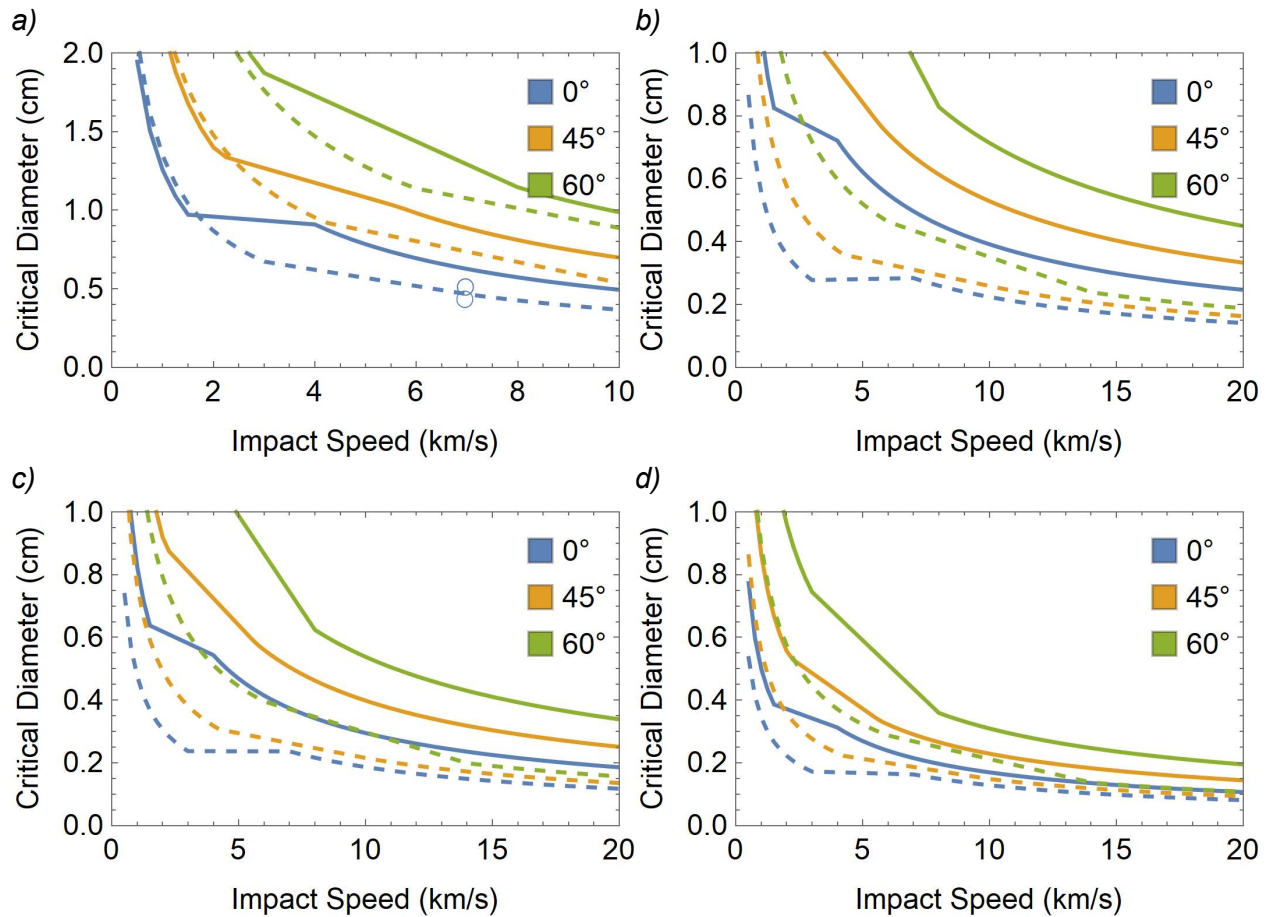


Figure 14 Aft propulsion subsystem (PSS) tubing with NASA failure criterion of 0.41 mm maximum crater depth a) low density Nylon (1.15 g/cm^3), b) medium density metallic Al2017 (2.8 g/cm^3), c) high density rocky Al_2O_3 (3.9 g/cm^3), and high density metallic SS440C (7.68 g/cm^3).

Cover-plate (COV) closeout shield configuration

A comparison of the “assumed” (dashed) and the “adjusted” (solid) threshold limiting equations used for the propellant tanks by TAS-I for the ESA failure criterion in the COV shield configuration are shown in Figure 15. The threshold limiting equations are color segregated by impact obliquity where normal impacts are blue and 45° to normal impacts are orange. In addition to the threshold limiting equations, the data from Table 5 is shown as empty circles for no damage and filled circles when damage in the witness has been observed. For the threshold limiting equation to accurately reflect the data of Table 5, the threshold limiting equation should pass in between the empty and filled data points.

The four environment classes from Table 5 have been separated into four plots: Nylon in Figure 15a, Al2017 in Figure 15b, Al_2O_3 in Figure 15c and SS440C in Figure 15d. Each of these plots shows the critical diameter in centimeters that triggers the ESA failure condition as a function of the relative impact speed between the Orion ESM and the natural environment threat. All particle sizes above the damage threshold limiting equation are considered catastrophic for Orion by ESA, and all particle sizes below the damage threshold limiting equation are considered within the design limits of Orion by ESA.

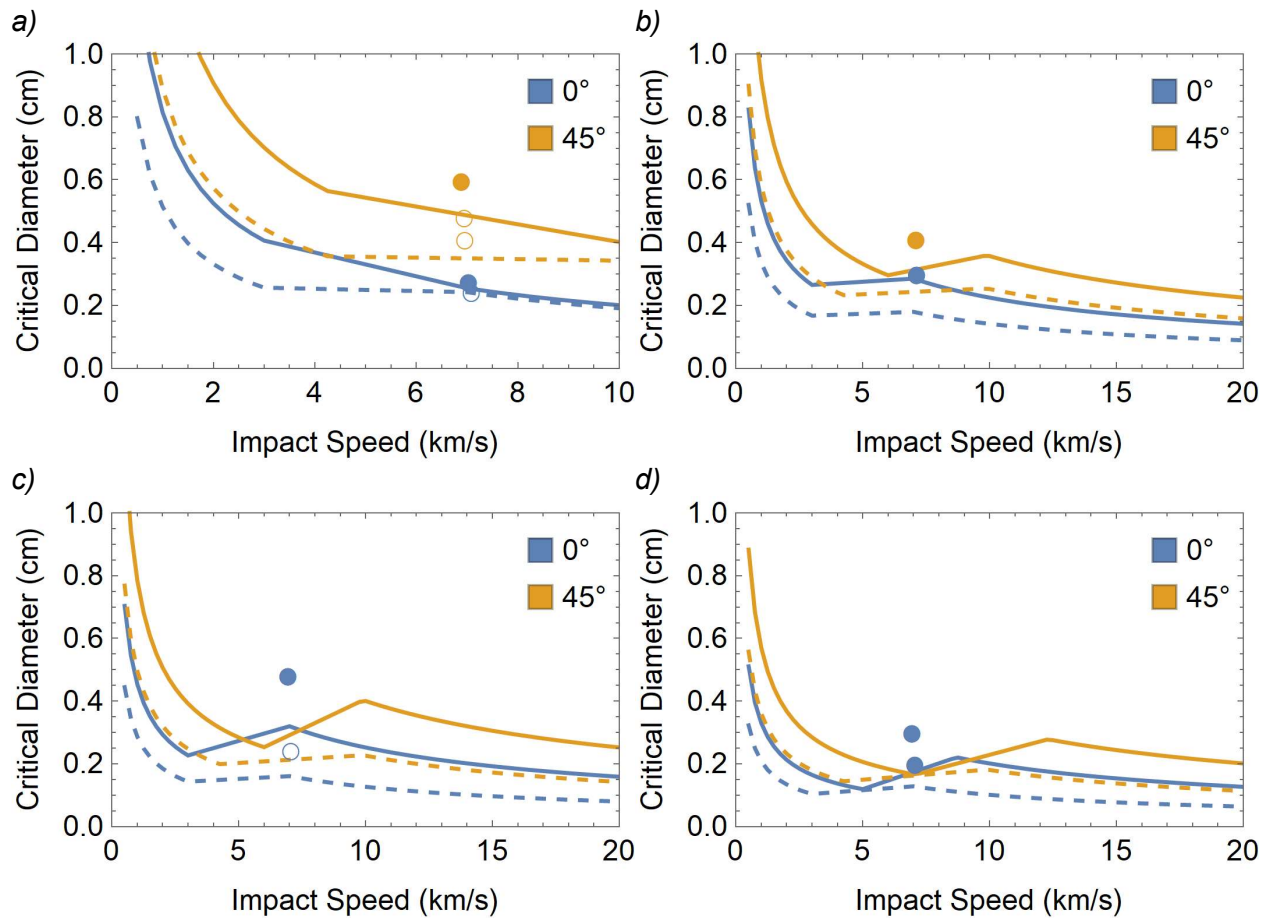


Figure 15 Cover-plate (COV) closeout with ESA failure criterion of “no damage” a) low density Nylon (1.15 g/cm^3), b) medium density metallic Al2017 (2.8 g/cm^3), b) high density rocky Al_2O_3 (3.9 g/cm^3), and high density metallic SS440C (7.68 g/cm^3).

Similar to the damage limit thresholds, a comparison of the “assumed” (dashed) and the “adjusted” (solid) ballistic limiting equations used for the propellant tanks by LM Space for the NASA failure criterion in the COV shield configuration are shown in Figure 16, where Nylon is in Figure 16a, Al2017 is in Figure 16b, Al_2O_3 is in Figure 16c and SS440C is in Figure 16d. Implicit in these curves is that a particle that induces less than a 0.24 mm crater in the propellant tank wall is considered within the design limits of Orion. As with the threshold limiting equations, the ballistic limiting equations are color segregated by impact obliquity where blue corresponds to normal impacts and orange corresponds to 45° to normal impacts.

The data from Table 5 is now shown as empty circles if less than 0.24 mm crater depth in the propellant tank witness has been observed, and filled circles if the damage in the witness exceeds 0.24 mm in crater depth. As noted for the ESA failure condition, the ballistic limiting equation accurately reflects the data of Table 5 when the curve passes in between the empty and filled data points; however, as depth information is available for this condition, the distance between the curves and the data corresponds to the difference between observed depth and the desired acceptable depth. All particle sizes above the ballistic limiting equation are considered catastrophic for Orion by NASA, and all particle sizes below the ballistic limiting equation are considered within the design limits of Orion by NASA.

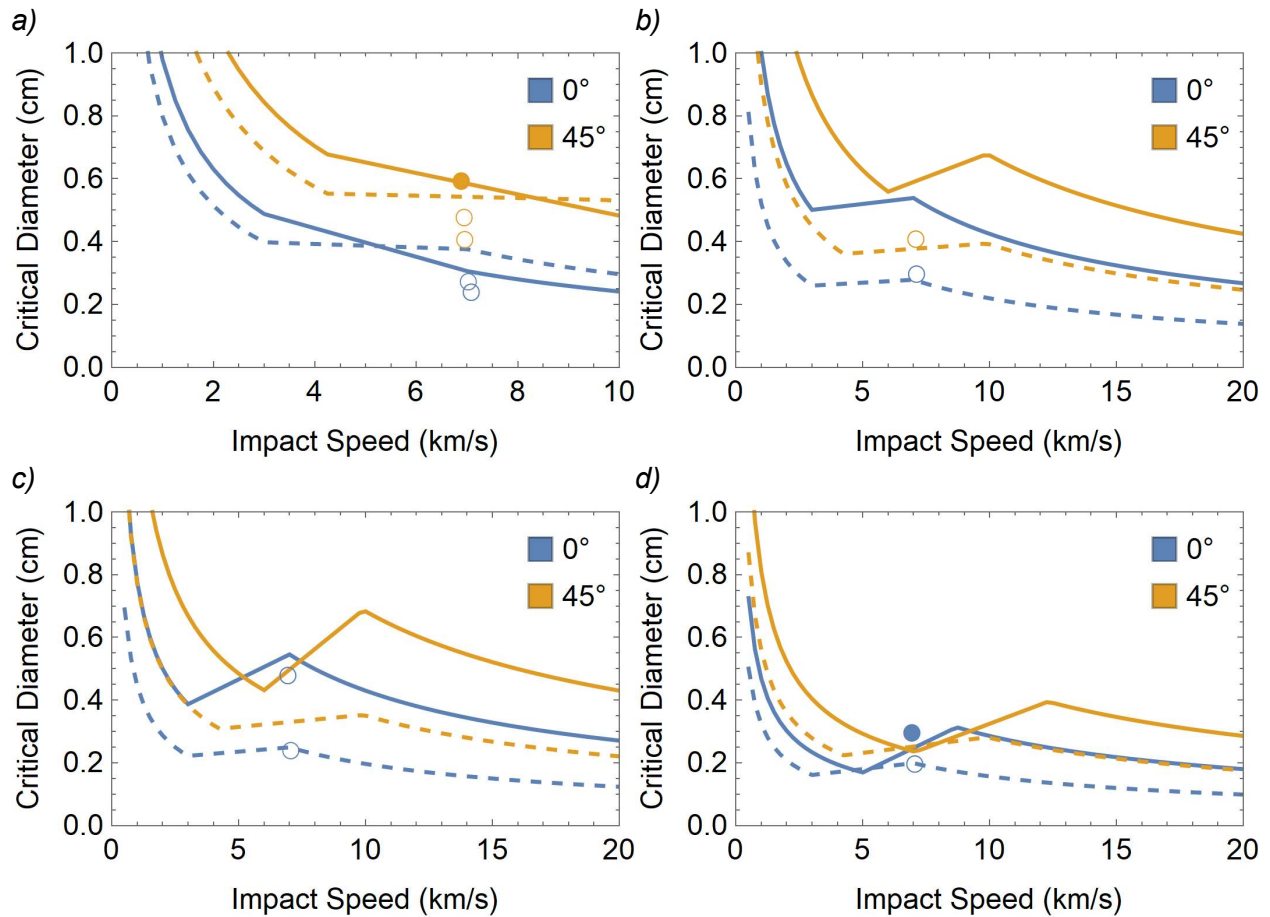


Figure 16 Cover-plate (COV) closeout with NASA failure criterion of 0.24 mm maximum crater depth a) low density Nylon (1.15 g/cm³), b) medium density metallic Al2017 (2.8 g/cm³), c) high density rocky Al₂O₃ (3.9 g/cm³), and d) high density metallic SS440C (7.68 g/cm³).

Orion ESM reliability prediction observations

After collecting results from fifty-two shield characterization shots of the five shield configurations of the Orion ESM, the ballistic limit equations have been updated based on the findings of shield performance as discussed in the previous sections. These models represent the lower bound for the shields' capability to maintain mission critical components. As these equations are the lower bound, with all particle sizes bigger than these limits being a critical threat, the higher these curves are the less likely the Orion ESM will produce a loss-of-crew (LOC) event.

As detailed earlier, the Orion ESM is currently tracking two damage tolerance assumptions: an ESA assumption that underlying structures have no damage tolerance, and a NASA assumption that structural integrity is maintained if damage does not exceed a maximum allowable. As NASA assumes some level of damage is acceptable to maintain structural integrity, the ballistic limit curves used by NASA/LM Space are higher than those for ESA and Airbus/TAS-I. As illustrated in the previous sections, the assumed curves under both damage tolerance assumptions going into the design decision have been generally lower than what has been found from subsequent analysis after shield characterization; hence, the predictions for a LOC event are lower under both assumptions after the shield characterization efforts.

The calculated risk for the five main shields of the ESM with the ESA damage tolerance assumption is shown in Table 6. In the table, the LOC prediction (in terms of 1 in #) based upon the threshold equations of the previous sections (dashed curves) using a fourteen day High Lunar Orbit (HLO) mission trajectory. The higher the number in the table the smaller the risk of LOC due to that shield arrangement. As can be seen, the going in assumption for LOC risk for the ESM (all five shield configurations) was 1:1,288; however, as a result of the shield characterization effort, it has been shown that the risk is more like 1:3,152. In addition, it has been found that the shield configuration that carries the most risk is the spiderweb (SW) mounted ballistic-enhanced MLI blanket at 1:6,724 of incurring any damage on this mission profile.

Table 6 LOC prediction with the ESA failure criterion (1 : #)

	Total	RA	SW	TA	PSS	COV
Previous	1,288	13,257	2,034	10,501	11,398	37,415
Revised	3,152	10,312	6,724	34,397	37,395	63,474

As for the NASA damage tolerance assumption, the LOC risk is shown in Table 7. This table uses the ballistic limit equations of the previous sections (solid curves) also with fourteen day High Lunar Orbit (HLO) mission trajectory. As can be seen, the going in assumption for LOC risk for the ESM was 1:7,437; however, as a result of the shield characterization effort, it has been shown that the risk is more like 1:17,507. Like with the ESA acceptable damage assumption, it has been found that the SW carries the most risk at 1:29,807 of incurring a catastrophic damage.

Table 7 LOC prediction with the NASA failure criterion (1 : #)

	Total	RA	SW	TA	PSS	COV
Previous	7,437	104,882	11,170	55,156	76,267	240,149
Revised	17,507	129,824	29,807	142,908	268,961	194,120

While the summation to determine the probability of a LOC event is complicated and depends on many mission aspects, it is necessary to contemplate these loss potentials to effectively evaluate design modifications. These tables reflect flying a standardized design reference mission rather than any currently planned mission. The first mission planned to fly with only a single ballistic-enhancement blanket to the thermal blanket of the ESM is Artemis IV. A detailed analysis of this mission using the revised ballistic limit equations described in this paper has been performed for the Artemis IV preliminary mission integration review, and this analysis supports the acceptability of additional impact risk as a consequence of mass reduction. While the exact risk levels will vary based on analysis parameters, both across missions and as individual missions are refined over time, but the overall trends seen here are expected to hold. As has been illustrated, no negative surprises have been discovered through the shield characterization effort, and that the risk of a LOC event is actually a little less than half of the assumed value that launched this design modification opportunity.

Conclusions

In this paper, a mass reduction opportunity for the Orion ESM has been studied for acceptability to Artemis mission reliability. Five main shield configurations of the ESM have been characterized by fifty-two impact shots to determine the dependence of the damage induced to a propulsion element as a function of impactor properties, size and conditions. The shields considered are either through the ESM radiator, the aft bulkhead or through a close-out that connects the radiator to the aft bulkhead. While these configurations represent a great simplification to the complex internal structure of the Orion ESM, they are meant to highlight the driving concerns for the Orion ESM in a balanced way.

The five main configurations all consist of a two wall shield system with a ballistic-enhanced MLI package between the two walls. The ballistic enhancement is the inclusion of a single layer of Kevlar® KM2® 705 or Kevlar® KM2® Plus 775. These shield configurations have been characterized with a broad range of projectile types, projectile diameters and impact obliquities to determine their effect on resultant craters in a titanium (Ti6Al4V) witness plate behind the enhanced MLI blanket for each material. While an expected scatter resulted from this characterization effort, the damage measurements provided enough information to develop smooth models for extrapolating back to the conditions necessary for the onset of damage to the witness or to a predefined acceptable level of damage.

These models allowed the calculation of the probability of a LOC event for the Orion ESM under the various assumptions needed for an Artemis mission that includes a fourteen day High Lunar Orbit as a design reference standard. From these efforts, it has been determined that assumptions going into the trade are actually more restrictive and that the Orion ESM is even more robust than initially assumed. These predictions reflect flying a standardized design reference mission rather than any currently planned mission, and the analysis of the first mission planned to gain advantage from the proposed mass reduction, Artemis IV, will continue to mature, but the overall trend is expected to hold across missions and as more refinement on mission timeline and environment comes with proximity to flight date. As has been illustrated, no negative surprises have been discovered through the shield characterization effort. Additional characterization shots and simulations to improve extrapolations would help and especially in consideration of how the ballistic limit equations extrapolate from 7 km/s. With those additional needs noted, this work demonstrates that at this time the transition to a single ballistic-enhancement blanket to the thermal blanket of the ESM exceeds initial expectations, and model improvements have been made so that improved predictions can be made in the future for evolving mission parameters.

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