Orion Spacecraft MMOD Protection Design and Assessment

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Abstract

The Orion spacecraft will replace the Space Shuttle Orbiter for American and international partner access to the International Space Station by 2015 and, afterwards, for access to the moon for initial sorties and later for extended outpost visits as part of the Constellation Exploration Initiative. This work describes some of the efforts being undertaken to ensure that the Constellation Program, Orion Crew Exploration Vehicle design will meet or exceed the stringent micrometeoroid and orbital debris (MMOD) requirements set out by NASA when exposed to the environments encountered with these missions. This paper will provide a brief overview of the approaches being used to provide MMOD protection to the Orion vehicle and to assess the spacecraft for compliance to the Constellation Program's MMOD requirements.

Keywords: Orion, MMOD, Shielding Design, Constellation, HVIS.

1. Introduction

The Orion vehicle is being assessed for micrometeoroid and orbital debris (MMOD) risk for 210 day missions to the International Space Station (ISS), short duration missions to the moon (Lunar Sortie) and long duration (210 day) missions to the moon (Lunar Outpost) to ensure compliance with the Constellation Program's MMOD requirements. The assessed vehicle consists of a Crew Module (CM) and a Service Module (SM) in a configuration that is similar to the architecture of the Apollo spacecraft. The SM provides propulsion capabilities as well as other support utilities such as, water, compressed gases, active thermal control and power to the CM. The CM houses the crew and provides the thermal protection system (TPS) that is necessary for Earth entry. The CM separates from the SM prior to Earth re-entry and lands using parachutes.

NASA's Bumper-II software and the latest micrometeoroid and orbital debris environments are being used to assess the Orion vehicle for MMOD risk with the three mission types. The assessed risk levels are then checked against the requirements to ensure compliance. Lockheed Martin developed pre and post processing macros and spreadsheets are used to streamline and reduce the chance for human error with Bumper-II data input and output. A detailed Orion vehicle analysis finite element surface model is produced directly from the Orion computer aided design (CAD) model and is effectively "flown" thru the MMOD environments using the Bumper-II assessment software.

Nomenclature

BH_w	Brinell Hardness of Rear Wall (BHN)
BH_{AL}	Brinell Hardness of Aluminum (BHN)
$c_{s,w}$	Sound Speed of Rear Wall (km/s)
$c_{s,AL}$	Sound Speed of Aluminum (km/s)
ρ_b	Density of Bumper (g/cm^2)
ρ_w	Density of Rear Wall (g/cm^2)
ρ_{AL}	Density of Aluminum (g/cm^2)
σ_w	Yield Strength of Rear Wall (ksi)
σ_{AL}	Yield Strength of Aluminum (ksi)
t_b	Bumper Thickness (cm)
t_w	Rear Wall Thickness (cm)
$t_{b.eq}$	Bumper Equivalent Thickness (cm)
$t_{w,eq}$	Rear Equivalent Wall Thickness (cm)

2. Orion MMOD Risk Analysis Tools

2.1 Bumper-II Assessment Software

NASA's standard MMOD assessment software, BUMPER-II, is used to assess the Orion spacecraft for MMOD loss of crew (LOC) and loss of mission (LOM) risk levels. BUMPER-II has a long track record of use on various NASA manned programs, such as on mission analysis for the Space Shuttle and ISS. NASA's latest anisotropic meteoroid and orbital debris environments are used with the BUMPER-II software to assess the micrometeoroid and orbital debris impact damage that exceeds failure criteria limits. Input and output data are pre- and post-processed using EXCEL spreadsheets and macros. Bumper-II software refinements have been made in order to reduce assessment times, eliminate unnecessary calculations and incorporate new and refined ballistic limit equations (BLEs). With respect to assessment time refinements, the processing time for the complete set of runs making up an ISS mission assessment has recently been reduced from over 13 hours to approximately 6.5 hours even though the number of separate runs increased from 36 to 48. Further modifications have been made to BUMPER-II by NASA to enable use of the new Meteoroid Engineering Model (MEM) input files which are discussed in Section 3. All modifications to BUMPER-II are reviewed and approved through an Orion Bumper-II Change Control Board (CCB).

2.2 Pre-Processing Tools

In order to speed analysis run preparations while reducing the chance of input error, Excel macros are used to create script files that contain the analysis response inputs for BUMPER-II. The properties for each of the vehicle model's property identifier (PID) regions are maintained in Excel spreadsheets. The Excel macros convert the data into the script file format that Bumper-II requires. This approach provides the response file inputs in the required cryptic format needed by Bumper-II while enabling easy review and report table generation using Excel worksheets. The Excel PID spreadsheets are also configured to provide ease of property modifications as required for trade study and design optimization sensitivity assessments.

Similarly, the shield script files are created using a script file creator that automatically establishes the element ranges needed for results reporting based on the model's PIDs. With the large number of PIDs and elements associated with the Orion model this saves much labor and reduces the chance of human error.

2.3 Post-Processing Tools

Enormous amounts of data are created and post-processed while assessing the Orion missions for MMOD risk and it is common to run hundreds of complete sets of mission runs for sensitivity studies. Therefore, automation is necessary for post-processing of the Bumper-II output data. And, as with pre-processing, automation reduces the chance of error. The output macro combines the output sum file results for 34 separate Bumper-II runs in assessing complete lunar missions. ISS missions require 48 separate runs. Additionally, the output macro accounts for component and system redundancies in rolling up overall mission LOC and LOM risk.

3. MMOD Environments

Orion MMOD analyses use ORDEM2000 as the orbital debris environment generator and MEMCxP/LunarMEM as the meteoroid environment generator. The ORDEM2000 environment as implemented by the NASA/JSC orbital debris program office is used for all low earth orbit (LEO) mission phases [1]. The MEMCxP v2.0 meteoroid environment for Earth orbital spacecraft as developed by the NASA/MSFC Meteoroid Environment Office (MEO) is used for all meteoroid analyses up to the lunar sphere of influence (66,000 km to the moon). The LunarMEM v2.0 as developed by the NASA/MSFC MEO is used for lunar orbital spacecraft within the lunar sphere of influence.

The MEM environments account for the directionality of the helion, anti-helion, and the north and south apex and toroidal micrometeoroid flux populations [2]. Additionally, based on radar data, the average of the velocity distribution is higher than that of the older SSP-30425 environment. The average velocity increased from 19 km/s to approximately 24 km/s. With MEM, the micrometeoroid density is assumed to be 1.0 gm/cm^3.

4. MMOD Vehicle Model

4.1 Orion Vehicle Model

Micrometeoroid and orbital debris analysis, using the BUMPER-II code, uses detailed finite element models (FEM) for the spacecraft that are produced using the I-DEAS® CAD System. The FEM is created starting from CAD 3D models that are translated into I-DEAS from Pro-Engineer® Wildfire 3® vehicle models.

The BUMPER-II analysis code can only process surface models, thus all critical components inside the vehicle are projected onto the outer mold line (OML) of the vehicle. These outer surfaces are broken up into separate PID regions enabling assignment of specific wall and shield properties to the PID regions in accordance with their corresponding vehicle design properties. Then the regions are meshed using 2D surface elements. Figure 1 shows the most recent Orion MMOD analysis FEM. It is made up of approximately 86000 elements and 480 unique PID regions.

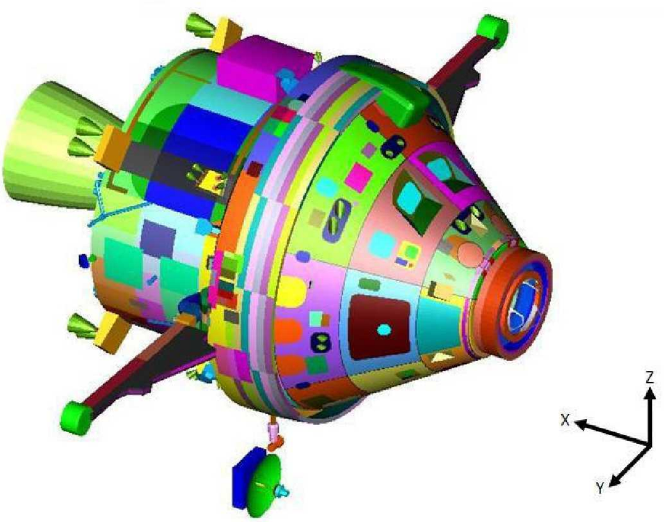

Fig. 1. Orion MMOD Vehicle Model

4.2 Ray-Tracing Tool

A new tool being developed by the Lockheed Martin Orion MMOD analysis team leads to a more refined modeling technique for creating the model PID regions and for defining their properties. The tool is a ray tracing program written using the ProToolkit add-on in Pro Engineer, which allows the user to generate C based macros. The ray tracing tool generates a ray based on the z-component of a user selected coordinate system. The points of surface intersection are captured and the macro outputs various parameters used in the MMOD analysis cycle. Post processing routines then transform the data into a more readable format.

Figures 2 and 3 show the ray tracing tool being applied for a shot line through the underside of the forward region of the Service Module into a cold plate. At the first point of intersection with the shield, an approximation of the turndown angle is applied and 25 additional rays are generated to approximate spreading of a debris cloud. For each of these rays a complete layup is given for the shot line including part name, material, thickness, standoff, and impact angle. This information is then used to more accurately model the PID region. Work is continuing to improve modeling of the debris cloud's direction and spread.

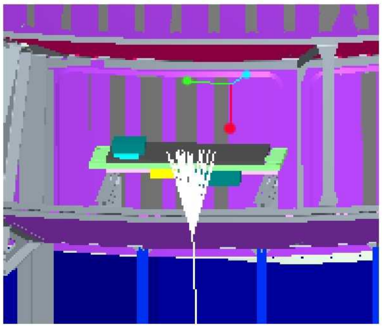

Fig. 2. Shot line through the Avionics Ring into a Cold Plate

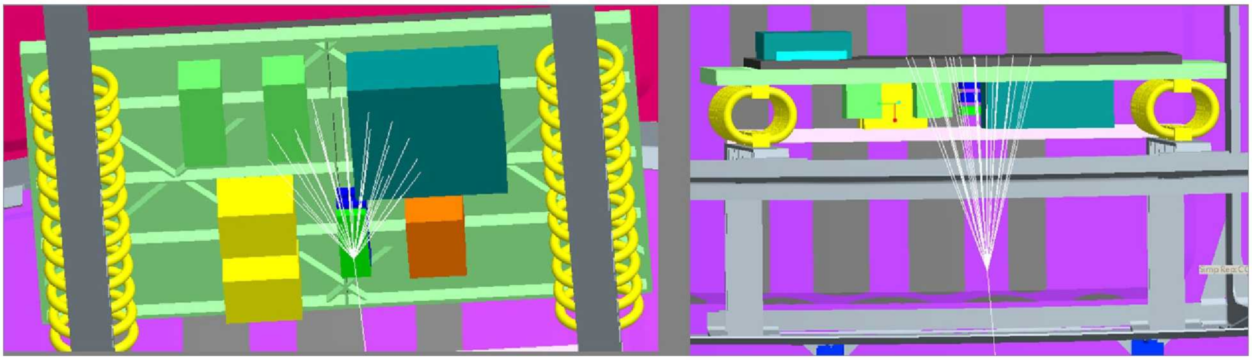

Fig. 3. Shot line after breakup of the particle. Twenty-five additional rays approximate the debris cone.

Traditionally, PIDs are defined using a fair amount of engineering judgment by the modeler. Component profiles are projected out to the model surface and are given a conservative shot line layup. The main advantage in using this tool is that it helps facilitate better understanding of the effects of turndown and debris cloud. It also provides the modeler a more verifiable approach for approximating PID regions. Development is continuing on this ray tracer tool.

5. Failure Criteria

A failure criterion is established for each component that is modeled and assessed as part of the vehicle analysis. This criterion defines the degree of damage that when exceeded counts as a failure. With the Orion spacecraft, the CM backshell thermal protection system (TPS) is the largest risk driver and hence, the vehicle's overall risk levels are quite sensitive to the backshell failure criterion. Failure of the backshell TPS is counted when the level of damage to the TPS exceeds the limit determined by reentry thermal analyses. A sizable effort is well underway to refine the failure criteria for the TPS. This is an area that is getting a lot of attention for further MMOD and thermal (arc jet) testing and analysis. Another major area of emphasis is the failure criteria of pressure vessels. An analysis and testing program is underway to better define the failure criteria of metallic and composite overwrapped pressure vessels.

An Excel spreadsheet is used to track and maintain failure criteria for all critical components and systems. The spreadsheet also tracks the applicability of a given failure criteria to LOC and LOM for each phase of a mission with the corresponding level of redundancy. For example, SM propellant tanks fail via rupture when the failure threshold is exceeded so they are tracked as LOC for all phases for all missions. For another example, with the lunar missions, when one of the two SM coolant loops is lost, a LOM is applicable during all phases up to when mission objectives have been completed (prior to the vehicles journey to reentry); however, a LOC is applicable only for the loss of both SM coolant loops but in all mission phases.

6. Ballistic Limit Equations

One or more ballistic limit equations (BLEs) are associated with each PID region (shield/wall type). The Bumper-II program uses the BLEs to determine the critical diameter that just exceeds the failure criteria for each combination of impact velocity and obliquity. Initially, where BLEs were not already available, they were adapted from existing "standard" forms using scaling factors and critical diameter summing. Since that time they have been updated based on data from hypervelocity impact testing performed by NASA and/or Lockheed Martin. Hydrocode analyses using Autodyn® and CTH® have been used to fine tune test plans and to supplement test results.

Beginning early in the program, existing, standard BLEs were adapted to provide approximate performance modeling for unique Orion wall/shield configurations. Impact testing results were not yet available due to the program just getting started, the evolving design and the time needed to set up test facility subcontracts, produce test plans and procure test specimen. Therefore, initial BLEs needed to be derived from existing standard equations. In general this consisted of applying scaling factors to shield and wall material properties and thicknesses to model ballistic limit performance using the Single Sheet Protection equation, the Aluminum Whipple Shield equations and the Stuffed Whipple Shield equations [3] [4]. Where necessary to approximate the performance of supplemental shield layers within a shield/wall stack, BLEs were configured to account for the overall performance by summing the critical diameters of the subparts.

The models used to characterize performance of these three shield designs are all empirical, thus, requiring extensive experimental validation of the fitted material parameters. The BLEs were generally based on aluminum bumper and wall materials, so when the Orion design uses materials other than aluminum, compensations must be made for the different material properties. As the critical mass (the mass of the MMOD threat that fails the shield) has been found to be roughly proportional to the thickness of the shield material, the approach used to generate the shield model for Orion is to determine the equivalent aluminum thickness of the shield materials that compensates for the actual material properties.

For the cases where a double-wall or a stuffed, double-wall shield design is used, the method for scaling shield (bumper) materials to aluminum equivalent thicknesses, $t_{b,eq}$, is

$$t_{b,eq} = t_b \frac{\rho_b}{\rho_{Al}}, \tag{1}$$

where ρ_{Al} is the density of the referenced material (6061-T6 aluminum at 2.71 g/cm^3 (0.098 lb/in^3)), and

t_b and ρ_b are the thickness and density of the actual Orion shield wall, respectively. It is also necessary to scale the rear wall (critical component's housing) as the rear walls are not generally constructed of aluminum. The approach for scaling the thicknesses of metallic rear walls, $t_{w,eq}$, is

$$t_{w,eq} = t_w \frac{\rho_w}{\rho_{Al}} \left(\frac{\sigma_w}{\sigma_{Al}}\right)^{1/2}, \tag{2}$$

where σ_{Al} is the yield strength of the reference material (6061-T6 aluminum at 35 ksi), and t_w, ρ_w, and σ_w are the as designed thickness, density, and yield stress of the rear wall, respectively. In both of these cases, the scaling equations are derived directly from the existing BLEs as incorporated in BUMPER-II.

The final regions where scaling relations are necessary are the regions of monolithic metal. For these regions the scaling determined from the monolithic BLE in BUMPER-II is

$$t_{w,eq} = t_w \left(\frac{BH_w}{BH_{Al}}\right)^{1/4} \left(\frac{c_{s,w}}{c_{s,Al}}\right)^{2/3} \left(\frac{\rho_w}{\rho_{Al}}\right)^{1/2}, \tag{3}$$

where BH and c_s are the Brinell hardness and isentropic speed of sound, respectively.

As hypervelocity impact testing enabled replacement of the approximation BLEs with BLEs developed for the Orion wall/shield designs, it was found that generally the scaling approaches used with the standard BLEs were providing critical diameters that could be called rough at best. This highlights the need for early testing, increased use of hydrocode modeling, and perhaps, the need for a standard library of BLEs. In the case of Orion, the ballistic limit approximations that over performed tended to counter the ones that underperformed such that the overall vehicle results were not severely far removed from reality. And, the resulting error has generally been in the conservative direction due to the tendency of the analyst to sway the approximation equations and input properties in that direction.

The Orion MMOD LOC and LOM assessments are now based on BLEs that have been developed or refined based on impact testing of the design configurations. Additional testing will provide additional data points for further refinement of the Orion specific BLEs. Post critical design review (CDR) testing will ensure that the final flight hardware design BLEs are verified.

7. Orion MMOD Requirements

Loss of crew (LOC) MMOD Systems Requirement Document (SRD) requirements were defined for each of the Orion mission types at the beginning of the Orion program. The requirements have evolved somewhat but the LOC requirement is 1 in 800 for ISS missions, 1 in 1000 for lunar sortie missions and 1 in 500 for lunar outpost missions. In addition, loss of mission (LOM) and LOC flow down requirement allocations for overall vehicle LOC and LOM reliability were recently defined for the lunar sortie and ISS missions. The MMOD LOC allocations are 1 in 2400 for lunar sortie and 1 in 1200 for ISS missions. The LOM allocations are 1 in 1700 for lunar sortie and 1 in 160 for ISS missions. Lunar outpost reliability LOC and LOM allocations have yet to be defined. The long delay in receiving lunar sortie and ISS mission reliability allocations, and the continued lack of such allocations for lunar outpost missions, proved the importance of having separately defined MMOD SRD requirements for a program such as this.

8. Orion Design/Assessment Approach

Feedback is provided to the Orion design organization based on scrutiny of assessment results. By-PID results are sorted by number of failures and failures/exposed area so that it can be determined where additional protection is required and where protection mass can be reduced. Many factors influence the determination of the proper balance of MMOD risk across the modules and component areas. The MMOD Team works closely with the spacecraft designers, mass properties, and other analysis disciplines to find this proper balance.

Additionally, the MMOD Team participates in and provides inputs on special trade studies that are charged with determining the best design approach between various options that are under consideration. Generally, the team assesses the impact of the various options on the MMOD risk levels and provides feedback on each option's impact on MMOD mass, cost and schedule. Various sensitivities are also performed to assess design and operational variations enabling evolution to a superior spacecraft configuration and mission approach.

9. Innovation

A number of innovative design approaches have been used with the Orion vehicle in providing MMOD protection. An example is in the use of Kevlar fabrics and open cell foam to act as a rear wall or to supplemental rear wall protection for propellant tanks and other components on which they are directly mounted. The Kevlar and foam protection is utilized behind Whipple bumpers or Stuffed Whipple bumpers and fabric layers. In some cases Kevlar layers act wholly as the rear wall in insuring that no surface damage is sustained by the protected component and in other cases Kevlar layers supplement the protection that is inherent in the component's outer wall. In both cases, the Kevlar fabric layers are separated from the surface being protected or supplemented by a layer of open-cell polyimide foam. Depending on the design intent, the Kevlar is used to either fully stop or greatly slow the debris cloud constituents. Upon debris cloud impingement, the Kevlar stretches and deflects as the foam layer locally compresses between the Kevlar and component wall. This design approach appears to allow the Kevlar to build up membrane stresses in slowing or stopping penetration. The foam thickness and compressive strength is selected to limit surface damage to the component while allowing the impact momentum to be reacted by the protected component. Development testing has shown the Kevlar and foam design to be very effective in limiting damage to the component being protected.

Other innovative design solutions include the use of multi-functional materials such as MMOD rear walls that also perform as redundant reentry thermal barriers, or structural members, and using an extension of the SM outer wall to protect the heat shield. Also, testing has shown that the use with Orion of composite structural layers instead of titanium within the TPS reduces the likelihood of penetration of the crew pressure wall located behind it.

10. Orion MMOD Protection

The Orion MMOD protection has evolved to a configuration that meets the program requirements. Figure 4 provides a vehicle layout showing locations of supplemental MMOD protection.

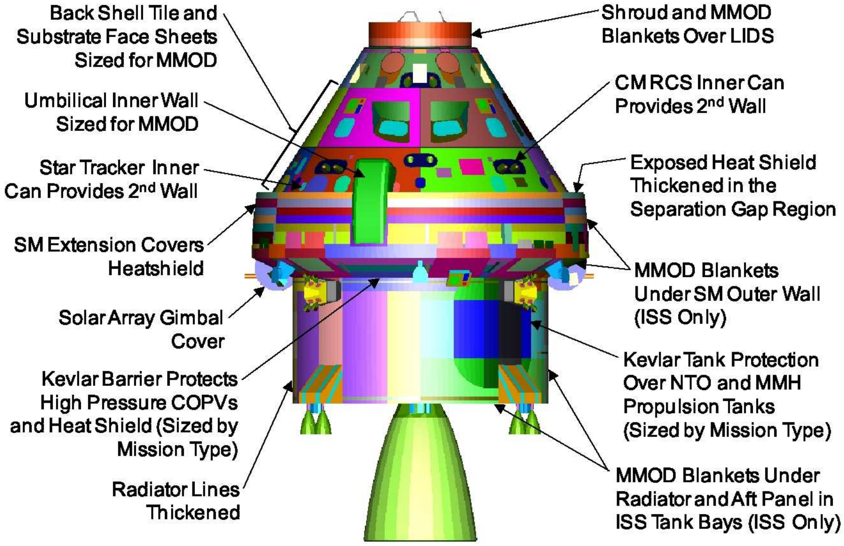

Fig. 4. Supplemental MMOD Protection Locations

Supplemental MMOD protection is added to the CM in a number of areas. An outer "bumper" shroud is added around the outside of the Low Impact Docking System (LIDS) creating a Whipple Shield for protection of its pressure wall. With ISS missions, additional MMOD fabrics are added behind the LIDS bumper providing Stuffed Whipple Shield type protection. Inner housings are added around star trackers and Reaction Control System (RCS) pods behind the TPS to provide thermal redundancy after MMOD damage. TPS backshell tile and substrate thicknesses are adjusted to enable meeting overall vehicle requirements. Also, to reduce the risk of the heat shield TPS material receiving damage beyond allowable reentry depth limits, it is thickened in the shoulder region. This is the only area of the heat shield that has some limited direct exposed to MMOD flux.

The SM also has supplemental MMOD protection. The forward segment of the SM is extended over the CM's heat shield to minimize direct exposure of the heat shield to MMOD flux. "Stuffed Whipple fabrics" are added under this extension as well as under most of the rest of the SM's outer wall to protect the heat shield and other critical components such as tanks and cold plates from MMOD with ISS missions. For lunar missions the blankets are left out since the Whipple Shield configuration is adequate in the less severe lunar MMOD environment. The smaller diameter portion of the SM is covered with Active Control System (ATCS) radiators. The coolant lines and manifolds that are located inside of the radiator panel are thickened towards the outside for MMOD protection. The panel itself helps to protect the radiator lines and manifolds as well as functioning as the "bumper" shield for the main propulsion tanks and various other critical items located within that region of the SM. There is a MMOD fabric wall protecting components within the forward portion of the SM that have credible shot lines for damage from MMOD angling forward through the radiator panels. There is Whipple shield protection added to the various utilities running within the umbilical and to critical solar array actuators. Also, due to the criticality of protecting the large propulsion fuel tanks there is specialized MMOD blankets and foam shielding that is used to directly protect critical surfaces from damage from shot lines through the radiators and the SM's aft closeout panel. The references in the text are missing. You may want to add them in the text. I think there is a need for a reference on ORDEM just like there is reference on MEM.

References

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[3] Christiansen EL. Design and Performance Equations for Advanced Meteoroid and Debris Shields. *Int. J. Impact Engng.*, 1993; Vol 14: 145-156.

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Orion is the first man-rated reentry vehicle designed to stringent MMOD requirements for a variety of missions

- **Missions to both the ISS and moon are considered against requirements that address unique attributes of each mission**
  - **Missions to asteroids, L2 and other locations are possible**
- **The MMOD protection is adaptable to a wide range of threat fluxes due to the variety in mission types and durations**
- **The BumperII code is used to analyze over 500 shield configurations of the Orion vehicle**
- **The analysis of the Orion vehicle uses the most recent Orbital Debris Engineering Model (ORDEM2000) and the Meteoroid Engineering Model (MEM CxP and Lunar MEM) to specify the operational environments**
- **On-going test efforts are examining the failure mechanisms as well as shield performance of the Orion vehicle**

Unprecedented MMOD Design Influence

Orion is designed to service the ISS

Up to 212 day missions to the International Space Station – Orion serves as a crew escape vehicle while it is docked

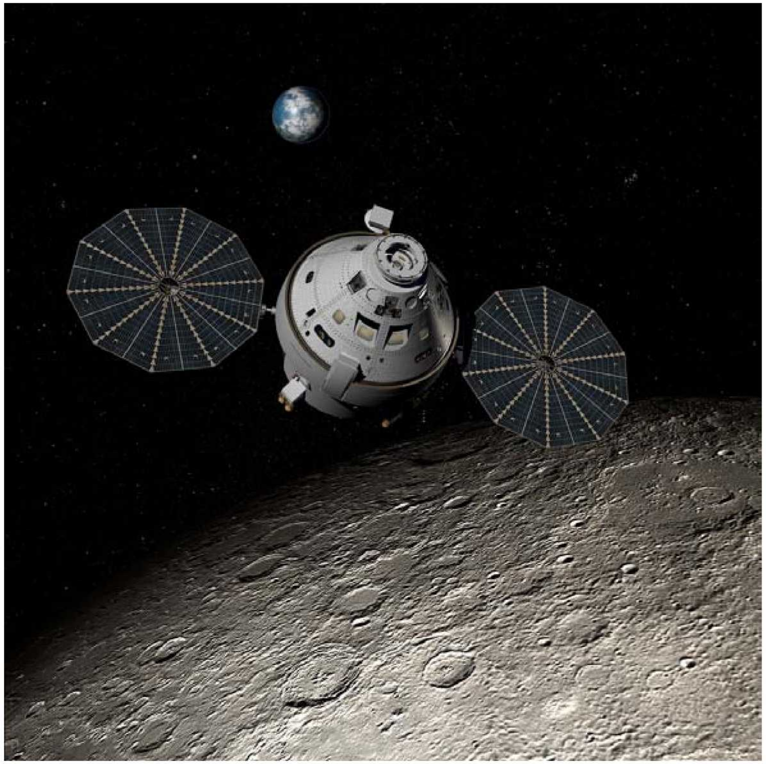
- Loss of Crew – includes damage to the Orion vehicle that results in loss of life either while in orbit or during reentry
  - Crew safe haven is used to account for crew safety from reentry failures while Orion is docked to the ISS.
  - Catastrophic damage such as rupture of pressure vessels while docked or while in transit is counted as loss of crew
- Loss of Mission – includes damage that results in a mission abort or causes the vehicle to unsafe to reenter
  - Redundancy of critical components is assessed

Orion is designed to perform up to 225 day lunar missions

Sortie missions provide 7 days in low lunar orbit and up to an additional 15 days in transit

Outpost missions provide up to 210 days in low lunar orbit and up to an additional 15 days in transit

- Loss of Crew – includes damage to the Orion vehicle that results in loss of life either while in space or during reentry
  - All vehicle damage that results in loss of life is counted
- Loss of Mission – includes damage that results in a shortened mission or prevents meeting science/mission objectives
  - Redundancy of critical components is assessed



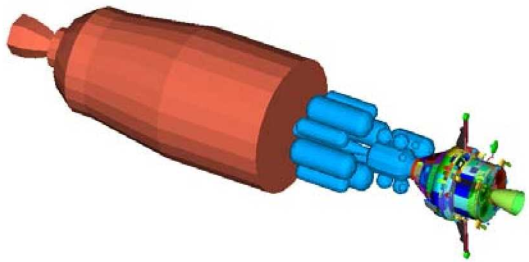
Stringent loss of crew and loss of mission MMOD requirements have been defined

Maximum Allowable MMOD Risk Level for Each Mission Type

ISS	Lunar Sortie	Lunar Outpost
LOC = 1 in 1200	LOC =1 in 2400	LOC = 1 in 500
LOM = 1 in 160	LOM = 1 in 1700	

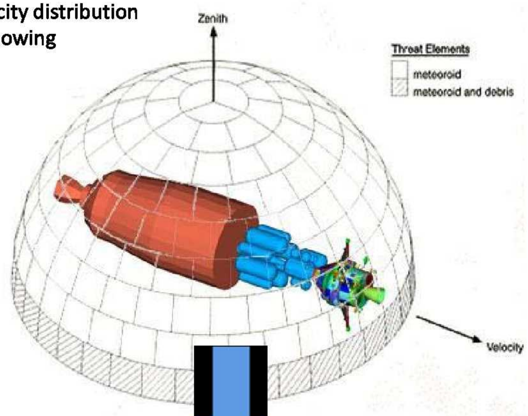
BumperII combines model inputs with environments to determine risks

Spacecraft Configuration (I-DEAS)

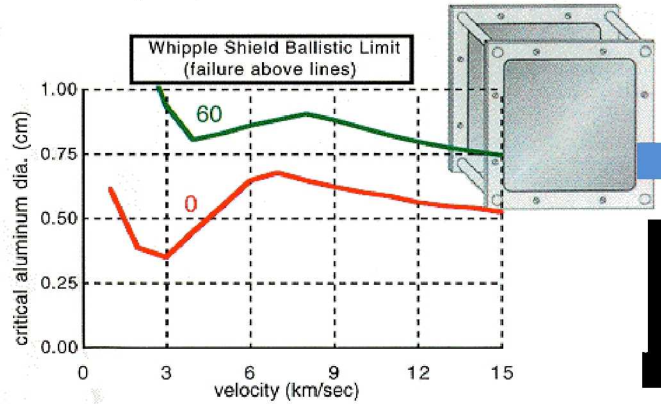


I-DEAS Finite Element Model
- Describes spatial relationships of spacecraft components
- Defines spacecraft orientation (velocity and zenith directions)
- Defines MM/OD shield regions

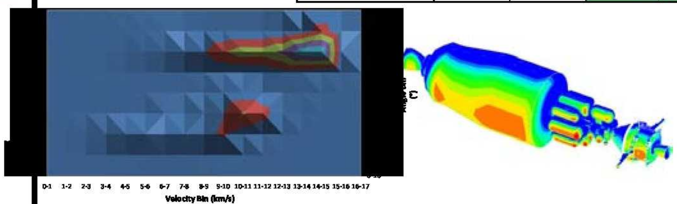
Meteoroid & Debris Environments (GEOMETRY)
- Threat directions
- Velocity distribution
- Shadowing



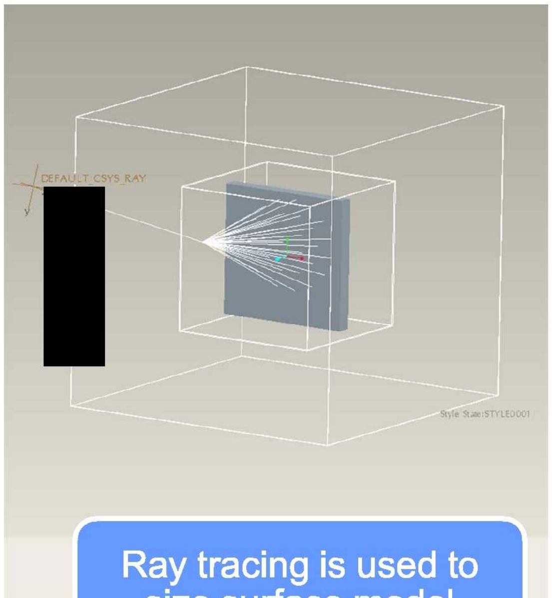
Critical Particle Diameter Calculation (RESPONSE)
- Protection capability



CEV - Orion Micrometeoriod and Orbital Debris Theat Assessment			
System	Loss of Crew		
	PNCL	LOC	Risk 1-in-X
CM Backshell (AETB8)	0.99960946	0.00039054	2,561
SM Propellant Tanks	0.99997665	0.00002335	42,827
LIDS	0.99998500	0.00001500	66,667
SM HP COPV Tanks	0.99998983	0.00001017	98,284
Umbilical	0.99999636	0.00000364	274,618
CM Docking Hatch (AFRSI)	0.99999682	0.00000318	314,021
SM Avionics / ECLSS	0.99999732	0.00000268	372,544
CM Other Thermal Barriers	0.99999764	0.00000236	423,105
CM Windows	0.99999767	0.00000233	429,014
Heatshield	0.99999836	0.00000164	609,417

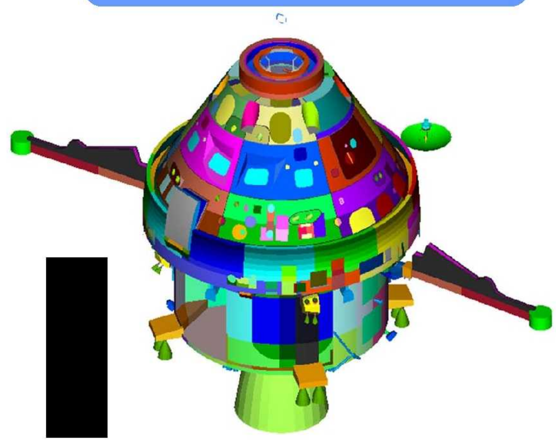


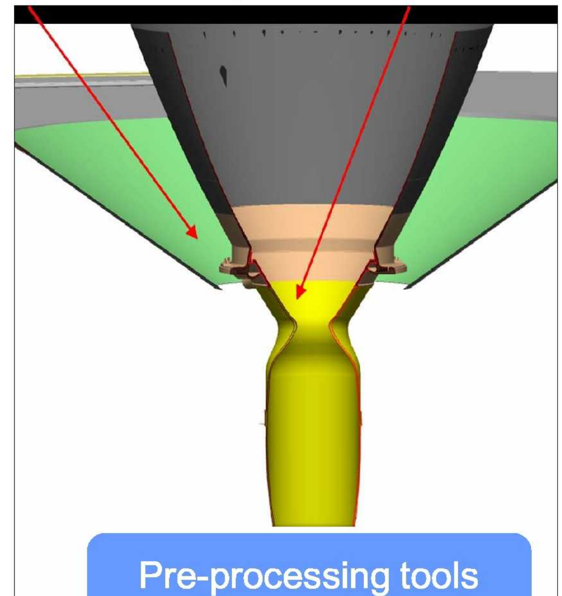
Orion BumperII surface model addresses over 500 shield configurations



Ray tracing is used to size surface model elements from the 3D engineering model

A surface model is generated that represents over 500 shield configurations

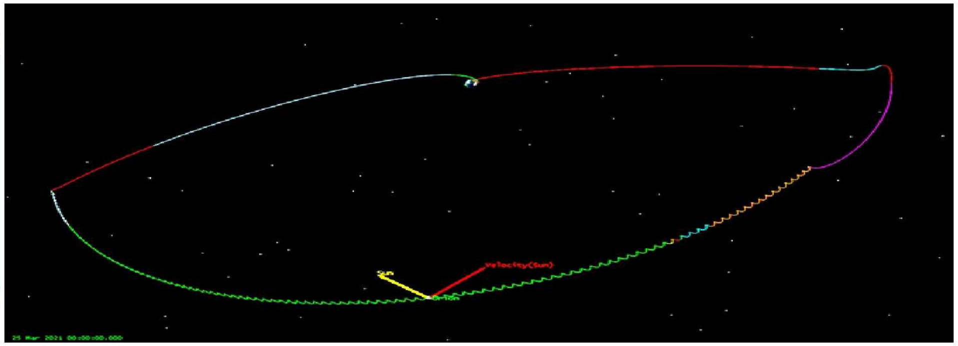




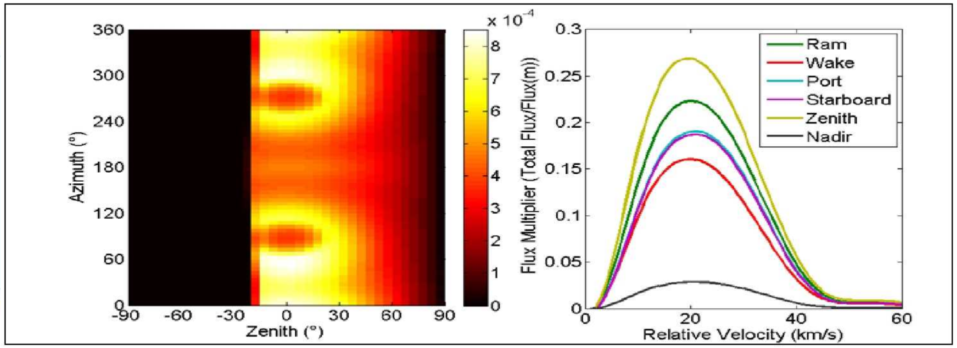
Pre-processing tools combine model inputs and shield configurations for BumperII input

ORDEM/MEM environments are combined with Orion attitudes and trajectories

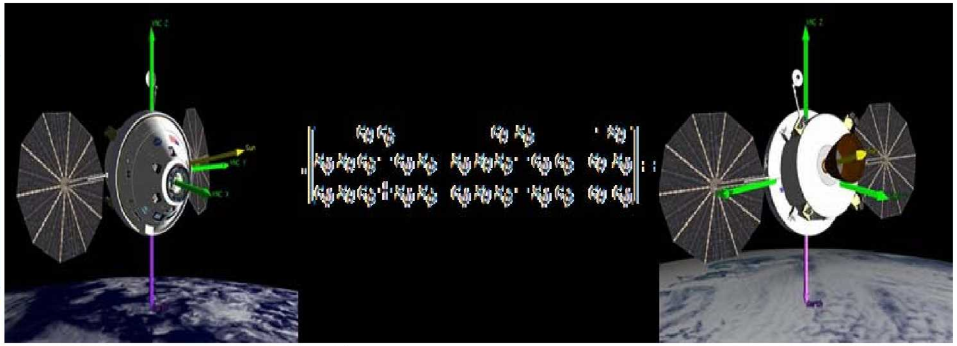
Mission scenario state vectors provide input



MEM and ORDEM calculate directional flux

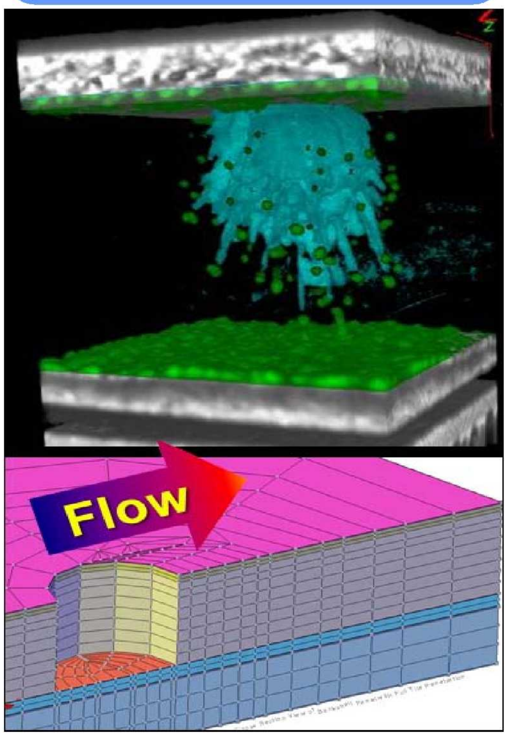


Vehicle model is rotated to account for attitude

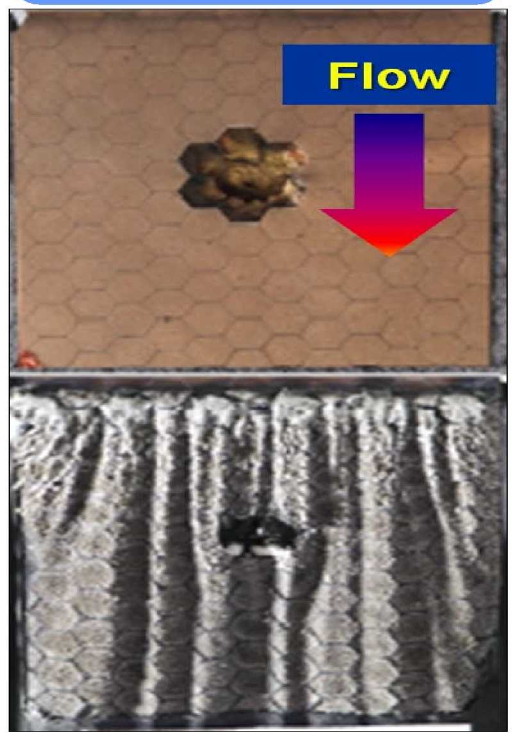


Testing and analysis are performed to identify and refine failure mechanisms

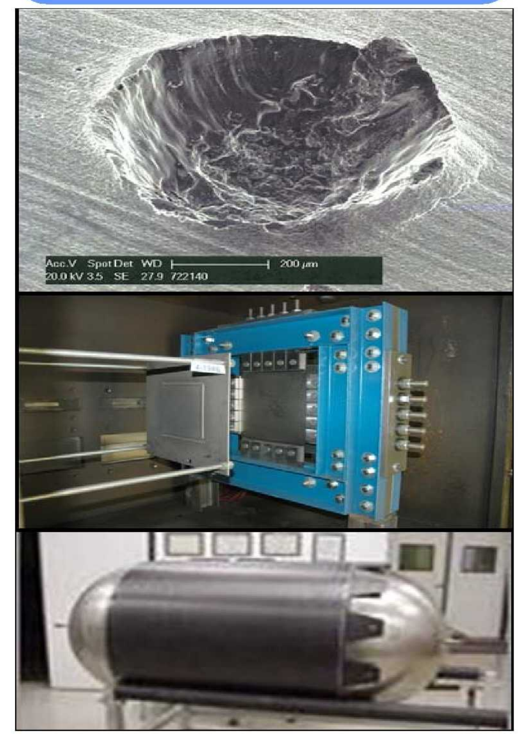
Backshell TPS



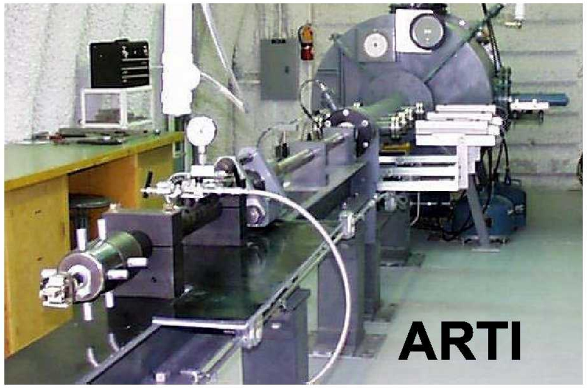
Heatshield TPS



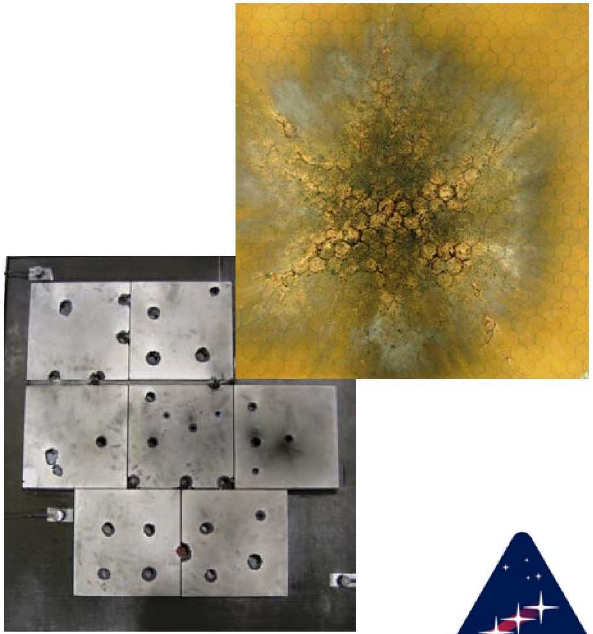
Pressure Tanks



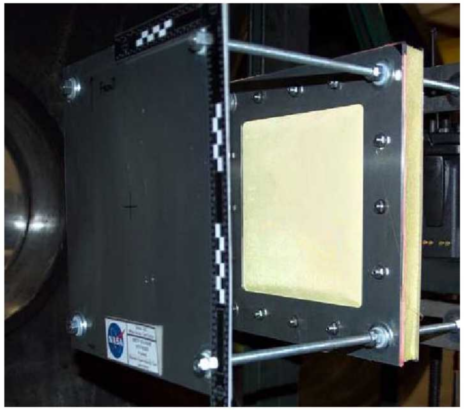
Testing of Orion shield configurations are used to establish the thresholds of failure

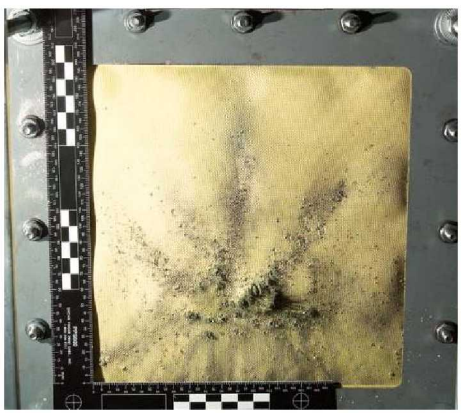


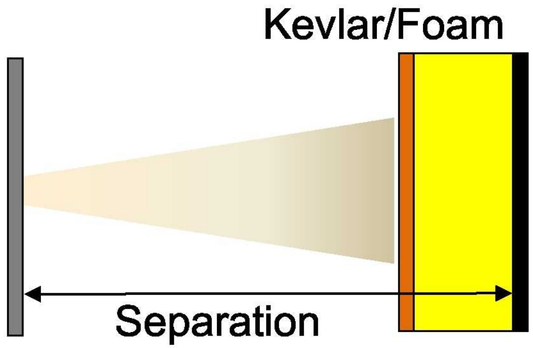
- **Orion test facilities include:**
  - **UDRI with maximum velocities of ~10 km/s**
  - **WSTF with maximum velocities of ~8.5 km/s**
  - **ARTI with maximum velocities of ~6.5 km/s**
- **To date almost 150 shots have been performed on Orion shields**
- **SLA, AETB-8 tile, PICA, AVCOAT, engine nozzles, propellant tank surrogates, radiators, composite structures and many more material configurations have been tested**



Innovative Kevlar shields over tanks show good performance over metallic shields

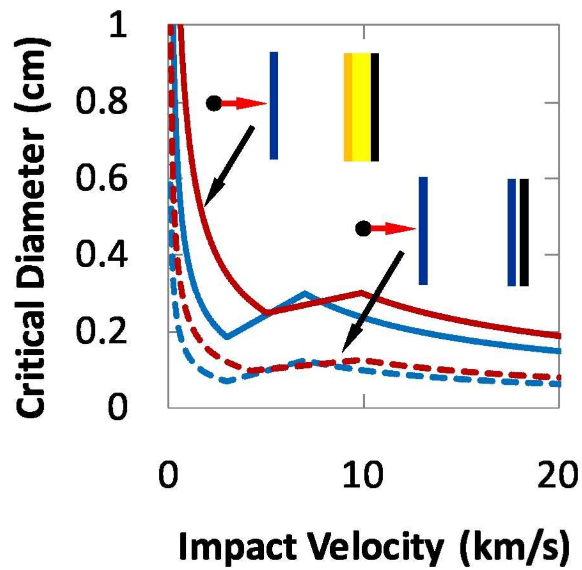




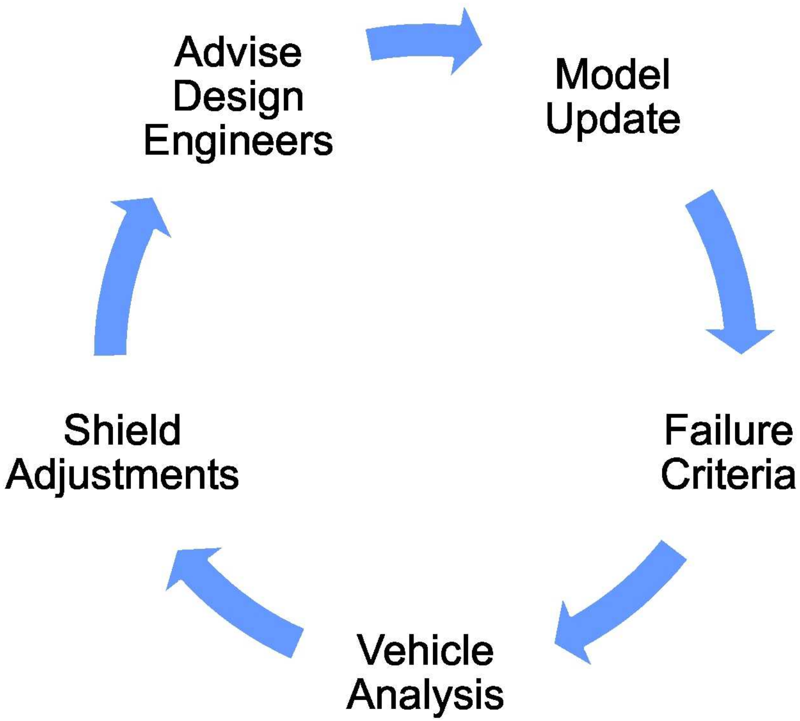


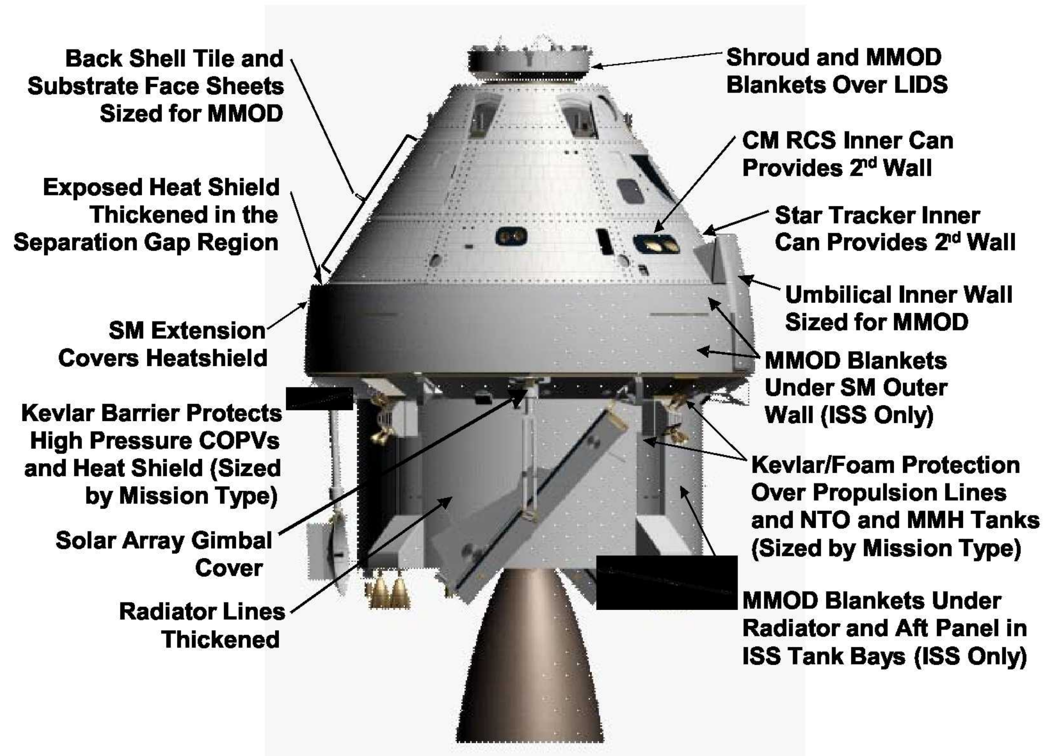
- Initial wall breaks up projectile
- Expanded projectile is caught by Kevlar fabric
- Low-density foam allows room for Kevlar to absorb energy
- Very low impulse over large area leaves shielded component relatively unaffected
- Intermediate Nextel and Kevlar fabric layers are added, and the number of Kevlar layers are adjusted, based on mission risk

Kevlar shield is 2.5x better than equal mass double-wall Al



Through design and advanced shields Orion meets safety requirements





Mission	MMOD Risk	
	LOC	LOM
ISS	1208	160
Lunar Sortie	2822	1685
Lunar Outpost	536	259

Orion will provide safe crew access to LEO and will support a flexible path for manned exploration beyond

- Orion MMOD design is robust and will meet stringent requirements for crew safety and mission success
- Orion MMOD protection is tailored for the mission type
  - Meets protection requirements for high MMOD risk missions while keeping vehicle mass on low MMOD risk missions in line with the level of risk
- Institutes late TPS inspection with the higher risk ISS missions to improve crew safety while minimizing the vehicle mass
- Forward work is planned to continue impact testing and vehicle analysis to optimize and verify Orion MMOD protection

Unprecedented MMOD Design Influence