Comparison of Risk from Orbital Debris and Meteoroid Environment Models on the Extravehicular Mobility Unit

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ABSTRACT

A well-known hazard associated with exposure to the space environment is the risk of vehicle failure due to an impact from a micrometeoroid and orbital debris (MMOD) particle. Among the vehicles of importance to NASA is the extravehicular mobility unit (EMU) “space-suit” used while performing a US extravehicular activity (EVA). An EMU impact is of great concern as a large leak could prevent an astronaut from safely reaching the airlock in time resulting in a loss of life. For this reason, a risk assessment is provided to the EVA office at the Johnson Space Center (JSC) prior to certification of readiness for each US EVA.

US EVA risk assessments to date use the ORDEM 3.0 orbital debris and the MEM R2 meteoroid environment models. The EVA risk assessment indicates that the gloves, arms and legs are the riskiest regions of the EMU with respect to failures as a result of MMOD. For each EVA worksite, the body orientation with respect to the MMOD environment and “shadowing” from nearby spacecraft structure can reduce the risk to these more vulnerable regions of the EMU. Updates to the environment models (i.e. to the velocity, directionality and particle size distributions) will change the EMU failure risk. Recently released updates (ORDEM 3.1 and MEM R3) to both environment models therefore necessitates a comparison of the risk change between the models.

1 EVA ASSESSMENT OVERVIEW

EVA assessments are performed using standard risk assessment methodology illustrated in Figure 1. Central to the process is the Bumper risk assessment code (Figure 2), which calculates the critical penetration risk based on geometry, shielding configurations and flight parameters.

The assessment process begins by building a Finite Element Model (FEM) of the extravehicular mobility unit (EMU), which defines the size and shape of the EMU as well as the locations of the various shielding configurations. Each region of the EMU having a different shield configuration and/or failure criteria are given a unique property identifier (PID) number in the FEM. The model was built using the NX I-deas software package from Siemens PLM Software. The FEM was constructed using triangular and quadrilateral elements that define the outer shell of the EMU. Bumper-3 uses the model file to determine the geometry of the EMU for the analysis.

The next step of the process is to identify the failure criteria and appropriate ballistic limit characteristics for the various regions of the FEM. The two failure criteria for the EMU are perforation threshold failure and a critical hole size threshold failure of the EMU bladder. Perforation threshold failure would result in any size leak in the EMU bladder while the critical hole size threshold failure (>4mm hole in the bladder) would result in an uncontrolled leak. The ballistic limit equations define the critical size particle that will cause failure (as defined by the failure criteria) at a given impact angle and impact velocity. When the finite element model is built, each individual element is assigned a PID to act as an index for its shielding properties. Ballistic limit equations are based on results from impact tests on samples that are representative of the vehicle shields. The appropriate ballistic limit equations (BLEs) are added to the Bumper-3 code as needed for each and every PID in the model.

The final stage of the analysis is to determine the predicted number of failures for the EMU. This is calculated using the micrometeoroid and orbital debris (MMOD) environment definitions that are specified by the spacecraft design. The MMOD environment models predict an impacting particle flux based on inputs for orbital parameters, spacecraft attitude and analysis date. Using Poisson statistics, and combining the previously defined geometry, shielding characteristics and ballistic limit equations with the MMOD environment model calculations, the Bumper-3 code determines a predicted number of failures for the EMU.

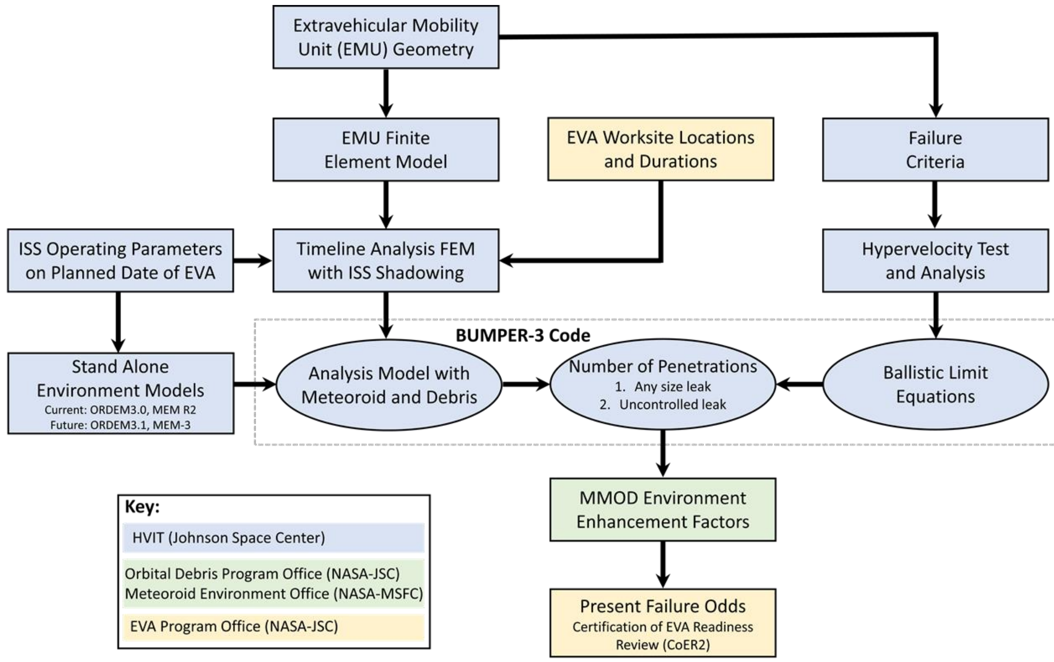


Fig. 1. EVA MMOD Risk Assessment Flowchart

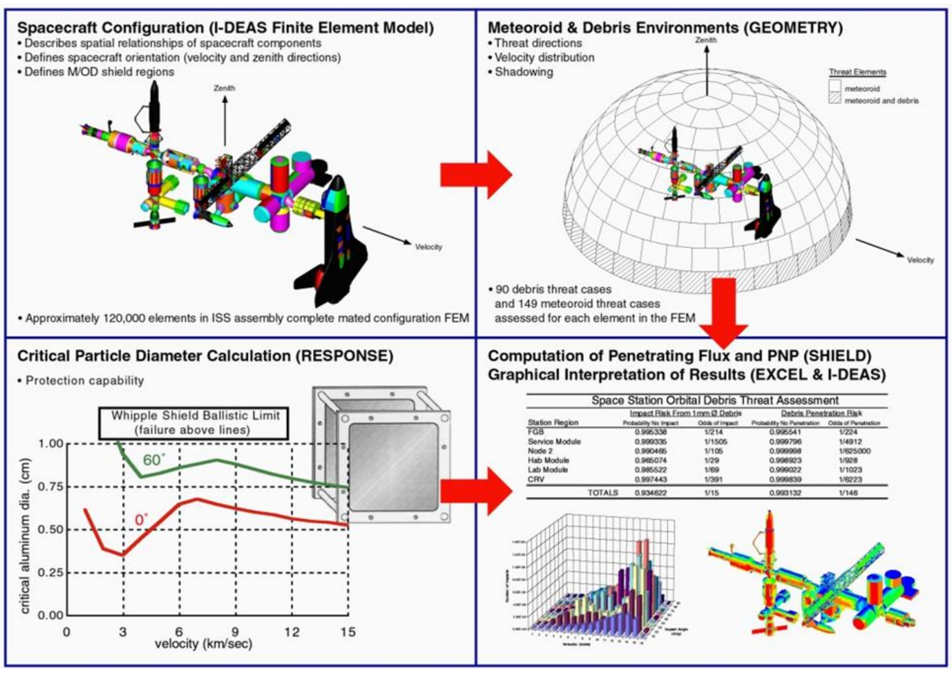


Fig. 2. Bumper-3 MMOD Risk Assessment Code

1.1 US EVA Timeline Analysis

For every US EVA, a timeline MMOD risk analysis is provided to the EVA office at JSC prior to the certification of EVA readiness. With assistance from the EVA office, a summary of EMU positions (including body orientation) for the specific EVA worksite locations on the International Space Station (ISS) is produced using detailed EVA summaries/presentations and/or EVA training run videos from the Neutral Buoyancy Lab (NBL.) From this information, the analysis FEMs are built by orienting an EMU FEM at each worksite location on a simplified ISS

FEM. When one or more worksites require multiple body orientations, additional analysis FEMs are built. The analysis FEM used for the US 52 and 53 EVAs is shown in Figure 3.

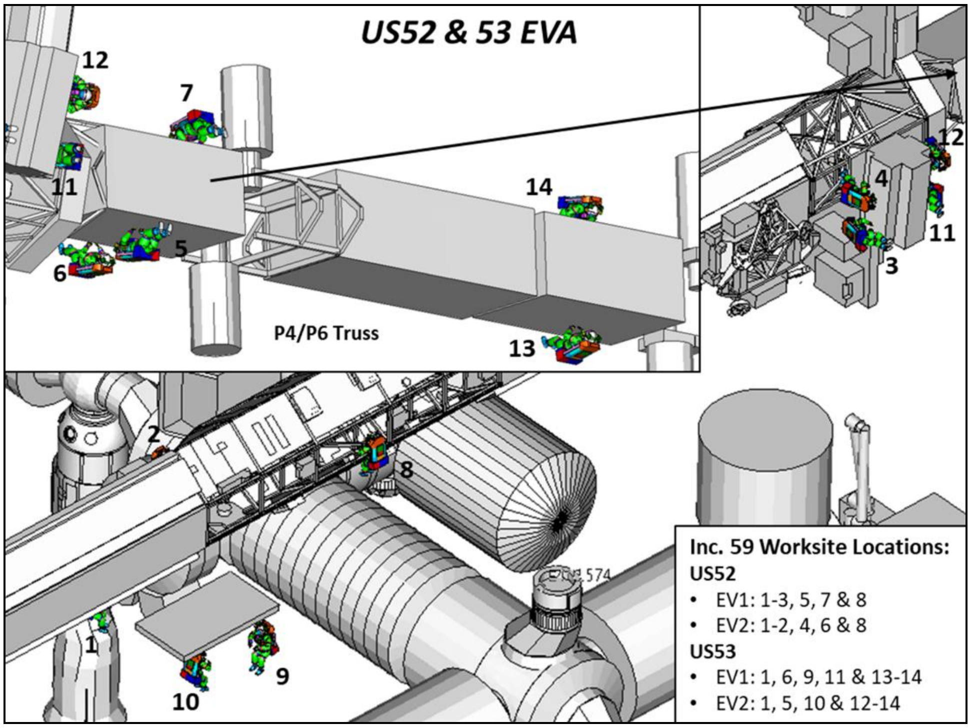


Fig. 3. Increment 57 (US EVAs 52 & 53) Meteoroid Environment Enhancement Factors

The analysis FEM(s), environment files and BLE parameters are inputted into the Bumper-3 code to obtain the expected number of failures at each worksite for a one year exposure. These results are scaled based on actual worksite exposure duration to generate total EVA risk and individual EMU risk for two failure criteria: perforation threshold risk of the bladder (which would result in EVA abort) and critical hole size threshold (catastrophic, uncontrolled leak; > 4mm hole in the bladder.) Meteoroid and orbital debris enhancement factors (see Section 1.2) are applied to obtain the failure odds for the planned EVA date.

1.2 Meteoroid and Orbital Debris Enhancement Factors

The meteoroid and orbital debris environment files used for the timeline analysis provide the average flux for a single year exposure duration. Due to the short exposure duration of 6 to 7 hours, EVAs are more sensitive to sporadic events outside of the single year background environment (i.e. orbital debris breakups and meteor showers.) Environment enhancement factors are used to account for these events. For every US EVA, the Meteoroid Environment Office (MEO) at Marshall Space Flight Center (MSFC) provide 6-hour meteoroid enhancement factors for each day of the EVA window. The fluence factor is for particles with a kinetic energy of at least 6.7 J (the kinetic energy of a 0.04 cm diameter meteoroid traveling at 20 km/s.) For example, meteoroid enhancement factors provided by the MEO for the December 2018 window are shown in Figure 4 and indicate a peak fluence enhancement factor of nearly 40% for an EVA performed during the Geminids meteor shower on December 14th, 2018. Likewise, the Orbital Debris Program Office (ODPO) at JSC provide an orbital debris enhancement factor to account for any recent orbital debris breakups that might increase the flux at ISS orbit.

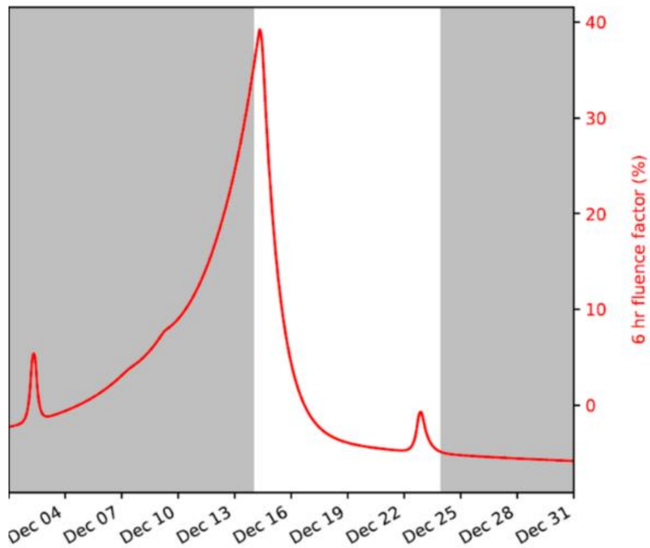
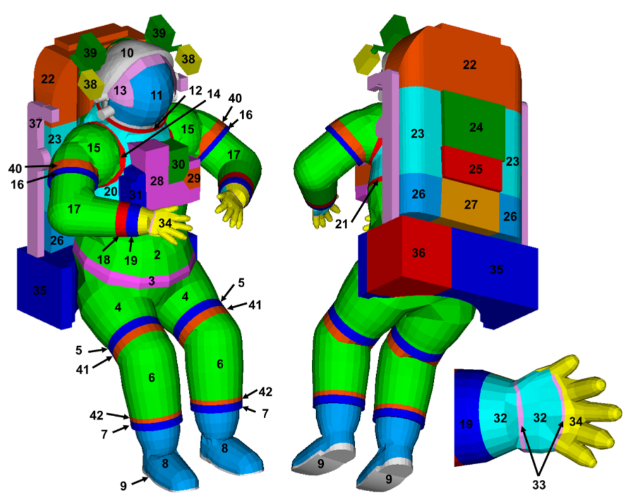


Fig. 4. Increment 57 (US EVAs 52 & 53) Meteoroid Environment Enhancement Factors

2 EMU FINITE ELEMENT MODEL

A detailed finite element model (FEM) of the EMU (shown in Figure 5) has been created which has regions for the various shielding configurations. Each shielding configuration is based on the layers and materials over the innermost bladder layer that maintains the acceptable atmospheric environment for the astronaut. The EMU outer mold line is defined by over 14,500 quadrilateral and triangular elements. The color changes in the model views shown in Figure 5 illustrate the 42 different surface property ID (PID) types.



Extravehicular Mobility Unit (EMU) FEM

Region *	PID	Code	Region	Color	BLE
Lower Torso Assembly	2	L1	Waist TMG	Green	soft goods, 1
	3	L2	Waist Bearings/Sizing Rings	Light Magenta	KE, 39 J
	4	L3	Thigh TMG	Green	soft goods, 1
	5	L4	Thigh Bearings/Sizing Rings	Blue	KE, 39 J
	6	L5	Lower Leg TMG	Green	soft goods, 1
	7	L6	Ankle Bearings/Sizing Rings	Blue	KE, 39 J
	8	L7	Boot TMG	Light Blue	soft goods, 1
	9	L8	Boot Heel & Sole	White	softgoods, 4, AD 5.860
Helmet	10	H1	EVVA Helmet Shell	White	KE, 71 J
	11	H2	Face Plate	Light Blue	KE, 71 J
	12	H3	Helmet Bearings/Sizing Rings	Red	KE, 39 J
	13	H4	Helmet Eyeshades	Pink	KE, 71 J
	38	H1	Helmet Lights	Yellow	shadow
	39	H2	Light Base & Head Mount	Dark Green	shadow
Arms	14	A1	Shoulder Bearings/Sizing Rings	Red	KE, 39 J
	15	A2	Shoulder TMG	Green	soft goods, 1
	16	A3	Upper Arm Bearings/Sizing Rings	Blue	KE, 39 J
	17	A4	Forearm TMG	Green	soft goods, 1
	18	A5	Gauntlet/TMG	Red	softgoods, 3
	19	A6	Gauntlet/Wrist Connect	Blue	KE, 39 J
Hard Upper Torso	20	T1	Hard Upper Torso (HUT)	Cyan	KE, 44 J
	21	T2	HUT Bearings/Sizing Rings	Red	KE, 39 J
Primary Life Support System	22	P1	PLSS - Other Equipment (upper)	Orange	KE, 15 J
	23	P2	PLSS - Primary O2	Cyan	KE, 60 J
	24	P3	PLSS METOX CCC	Dark Green	KE, 21.4 J
	25	P4	PLSS Advanced Battery	Red	KE, 3.5 J
	26	P5	Secondary O2	Light Blue	KE, 13.4 J
	27	P6	PLSS - Other Equipment (lower)	Golden Orange	KE, 15 J
Display and Control module	28	D1	DCM	Light Magenta	shadow
	29	D2	DCM Controls & Display	Orange	shadow
	30	D3	DCM Multiple Connector	Dark Green	shadow
	31	D4	DCM Critical Region	Blue	KE, 10 J
Gloves	32	G1	Glove Palm	Cyan	softgoods, 4, AD 1.285
	33	G2	Glove Gimbals & Palm Bar	Pink	KE, 39 J
	34	G3	Glove Back & Fingers	Yellow	softgoods, 2
SAFER Assembly	35	S1	SAFER Base (non-tank)	Blue	shadow
	36	S2	SAFER Base - N2 tank	Red	KE, 20 J
	37	S3	SAFER Thrusters & Supports	Pink	shadow
Overlap Regions	40	O1	Upper Arm SSA TMG Overlap	Orange	KE, 20 J
	41	O2	Thigh SSA TMG Overlap	Orange	KE, 20 J
	42	O3	Ankle SSA TMG Overlap	Orange	KE, 20 J

* Color corresponds to the regional risk breakdown bar charts

Fig. 5. Extravehicular Mobility Unit (EMU) Finite Element Model (FEM)

3 HYPERVELOCITY IMPACT TESTING

The EMU can be subdivided into two major shielding configurations: soft goods and hard goods. The soft goods consists of fabric layers called the thermal meteoroid garment (TMG) over an inner bladder and includes the arms, legs, lower torso, gloves and boots overlap regions. The hard goods (TMG over metallic, composite and/or plastic components) include the helmet, face plate, sizing rings, hard upper torso (HUT), portable life-support system (PLSS), and the display and control module (DCM.)

Testing of the EMU TMG has shown that it performs as a mini bumper shield. The ortho-fabric layers induce a shock pulse that breaks up the projectile and creates an expanding debris cloud. The inner layers of the TMG (MLI and ripstop) as well as the pressure garment restraint layer help with further particle breakup and create spacing for the debris cloud to expand before reaching the bladder or underlying critical component. Testing of the soft goods layup included both pressurized and unpressurized bladders with no difference found in the ballistic limit with pressurization. Testing results were used to set the ballistic limit equations (BLE) for each shielding configuration. Figure 6 shows the ballistic limit equations for the basic EMU soft goods layup (TMG over bladder) for both aluminum and steel debris.

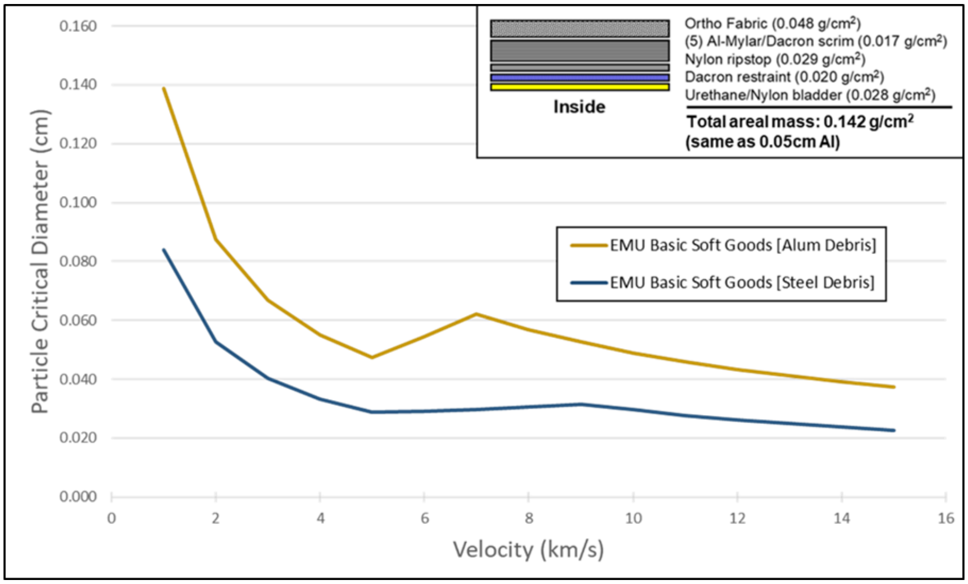


Fig. 6. Extravehicular Mobility Unit (EMU) Soft Goods Ballistic Limit Equation (Normal, 0° Impacts)

4 EMU RANDOM ORIENTATION RISK STUDY

A risk assessment of the EMU was performed using the MEM R2 and MEM-3 meteoroid environment models as well as the ORDEM 3.0 and ORDEM 3.1 orbital debris environment models. Twenty-four distinct attitude (body orientation) runs of the unshadowed EMU FEM (Figure 7) were made for the exposure period of 2018 to 2024 at the ISS altitude and inclination of 400km and 51.6°. Results from the 24 distinct attitudes were averaged for a 100 hour exposure duration.

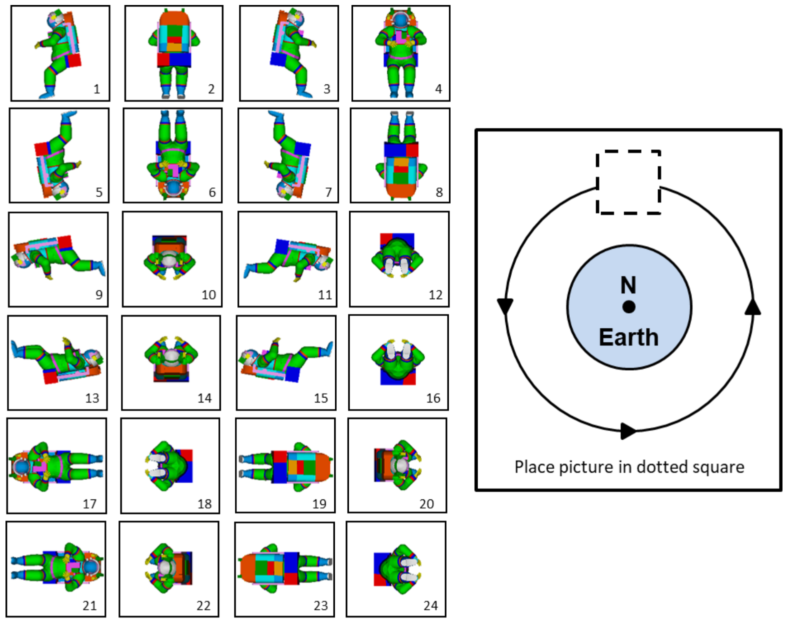


Fig. 7. EMU Unshadowed 24-attitude/body Orientations

4.1 Meteoroid and Orbital Debris Models

Meteoroid environment models are provided by the Marshall Space Flight Center Meteoroid Environment Office (MEO) while orbital debris environments are provided by the JSC Orbital Debris Program Office (ODPO.) From 2014 through August 2019, the MEM-R2 environment model was used for EVA timeline assessments. The MEM-3 meteoroid environment model (released by MEO in July 2019) has been used since August 2019. The MEM-R2 meteoroid environment model assumed a density of 1.0 g/cm^3 for all meteoroids while MEM-3, considers multiple density distributions (low-density and high-density) with density varying from 0.125 g/cm^3 up to 7.975 g/cm^3. ORDEM 3.0 is the current approved debris model for the EVA timeline assessments. ORDEM 3.1 is an upcoming update from ODPO to the orbital debris environment model. As ORDEM 3.1 has not been released, the risk assessments provided here are preliminary, for indication only (may be changed after ORDEM 3.1 is finalized and released.)

4.2 Meteoroid Model Comparison (MEMR2 vs. MEM-3)

Results of this assessment for meteoroids (Table 1 and Figure 8) show that the MEM-3 meteoroid environment model contributes 71% more risk (any size leak penetration) than MEM-R2. The risk difference is attributable to the addition of high density populations to the MEM-3 meteoroid environment. Softgoods (gloves, arms, legs, lower torso) continue to be the risk driver, accounting for 89% of the risk difference.

Table 1. Meteoroid Environment Model Comparison - EMU Any Size Leak Risk

EMU MMOD Study - Risk by Component					
	Number of Failures (100 hour exposure, 24 attitude average)			MEM-3 to MEMR2	% of Total
Region	MEMR2	MEM-3	Difference	Factor	Difference
Lower Torso Assembly	2.37E-04	4.51E-04	2.14E-04	1.9	46%
Gloves	1.55E-04	2.81E-04	1.25E-04	1.8	27%
Arms	9.62E-05	1.82E-04	8.58E-05	1.9	18%
Primary Life Support System	1.37E-04	1.71E-04	3.43E-05	1.3	7%
SAFER Assembly	2.28E-05	2.89E-05	6.08E-06	1.3	1%
Helmet	5.93E-06	7.64E-06	1.72E-06	1.3	0.4%
Display and Control module	5.27E-06	6.58E-06	1.31E-06	1.2	0.3%
Hard Upper Torso	3.19E-06	4.09E-06	8.99E-07	1.3	0.2%
Softgoods	**4.66E-04**	**8.85E-04**	**4.19E-04**	**1.9**	**89%**
Hardgoods	**1.96E-04**	**2.47E-04**	**5.04E-05**	**1.3**	**11%**
Total	**6.63E-04**	**1.13E-03**	**4.69E-04**	**1.7**	**100%**

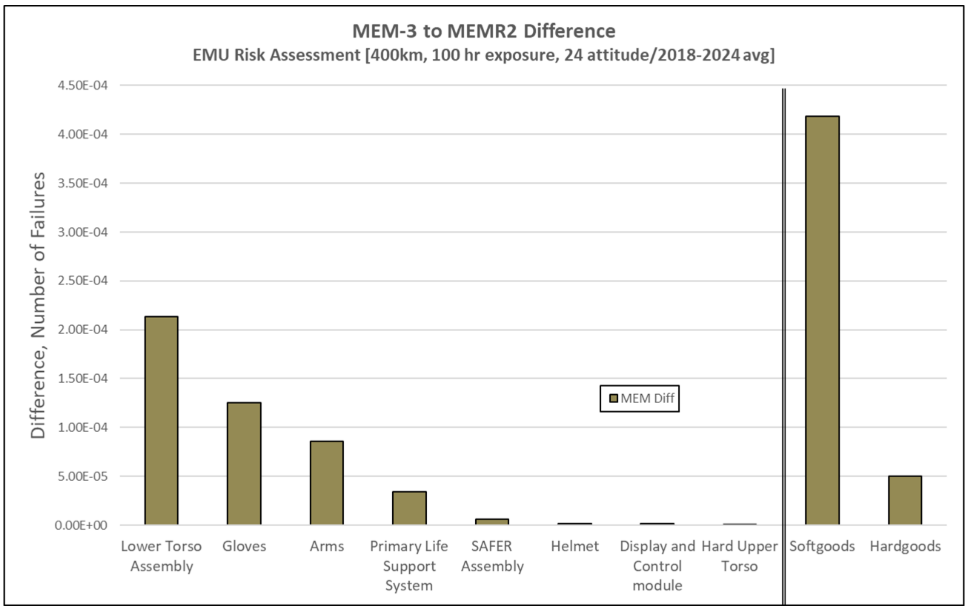


Fig. 8. Meteoroid Environment Model Comparison - EMU Any Size Leak Risk

4.3 Orbital Debris Model Comparison (ORDEM 3.0 vs. ORDEM 3.1)

In contrast to risk increase from the latest meteoroid environment model (MEM-3), results show that the ORDEM 3.1 environment model contributes 13% less risk (any size leak penetration) than ORDEM 3.0. The majority of the risk difference (99.7%) comes from the high and medium density populations which is consistent with ORDEM 3.1 updates to the particle size distributions for these populations.

Table 2. Orbital Debris Environment Model Comparison - EMU Any Size Leak Risk

EMU MMOD Study - Risk by Component					
	Number of Failures (100 hour exposure, 24 attitude average)			OD3.1 to OD3.0	% of Total
Region	OD3.0	OD3.1	Difference	Factor	Difference
Lower Torso Assembly	8.23E-04	7.12E-04	2.14E-04	0.9	52%
Arms	3.42E-04	2.94E-04	8.58E-05	0.9	22%
Primary Life Support System	2.41E-04	2.05E-04	6.08E-06	0.8	17%
SAFER Assembly	5.04E-05	4.20E-05	8.99E-07	0.8	4%
Gloves	2.15E-04	2.08E-04	1.31E-06	1.0	3%
Helmet	2.22E-05	1.96E-05	1.25E-04	0.9	1%
Hard Upper Torso	1.01E-05	8.63E-06	3.43E-05	0.9	1%
Display and Control module	8.84E-06	7.52E-06	1.72E-06	0.9	1%
Softgoods	**1.32E-03**	**1.17E-03**	**5.04E-05**	**0.9**	**72%**
Hardgoods	**3.91E-04**	**3.31E-04**	**4.69E-04**	**0.8**	**28%**
Total	**1.71E-03**	**1.50E-03**	**4.19E-04**	**0.9**	**100%**

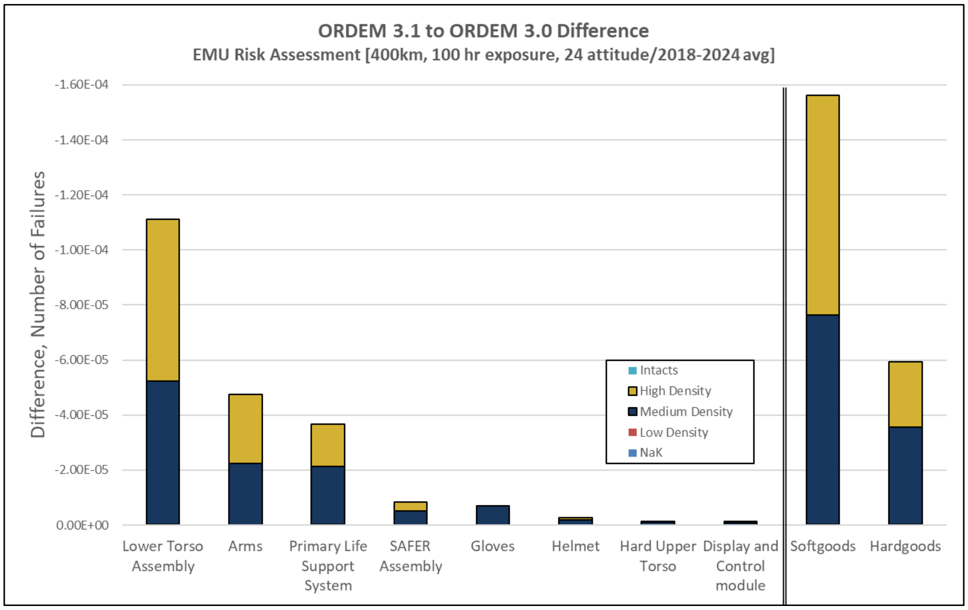


Fig. 9. Orbital Debris Environment Model Comparison - EMU Any Size Leak Risk

4.4 Combined MMOD Comparison

The cumulative MMOD penetration (any size leak) risk (Table 3) is 11% more for MEM-3 and ORDEM 3.1 versus MEM-R2 and ORDEM 3.0. The risk decrease from the ORDEM 3.1 orbital debris environment is offset by the risk increase from the MEM-3 meteoroid environment. As with the MEM-R2/ORDEM 3.0, the ORDEM 3.1/MEM-3 risk is concentrated (78%) in the softgoods regions (gloves, arms, legs and lower torso) of the EMU.

Table 3. Orbital Debris Environment Model Comparison - EMU Any Size Leak Risk

EMU Risk Assessment	Number of Failures (400km, 100 hour exposure, 24 attitude/2018-2024 average)							
	Orbital Debris						Meteoroid	MMOD
Description	*NaK*	*LD*	*MD*	*HD*	*Intacts*	Total	Total	Total
ORDEM 3.1 and MEM-3	*0.00E+00*	*4.22E-07*	*3.43E-04*	*1.15E-03*	*2.18E-09*	1.50E-03	1.13E-03	2.63E-03
ORDEM 3.0 and MEMR2	*2.71E-09*	*1.01E-06*	*4.54E-04*	*1.26E-03*	*1.18E-09*	1.71E-03	6.63E-04	2.38E-03
Factor	*0.0*	*0.4*	*0.8*	*0.9*	*1.8*	**0.9**	**1.7**	**1.1**

Although there is an increase in the cumulative MMOD risks, this risk is relatively small for a typical 6.5 hour ISS EVA (Table 4), no matter what environment models are used. The risks in Table 4 are for example only as MMOD risks vary by location, duration, year of EVA, and other factors.

Table 4. Orbital Debris Environment Model Comparison - EMU Any Size Leak Risk

Failure Mode	MMOD Risk Odds	
	MEM R2 and ORDEM 3.0	MEM 3 and ORDEM 3.1
Any size leak	1 in 5,000	1 in 4,500
Critical leak	1 in 28,000	1 in 26,000

5 CONCLUSION

Updated meteoroid and environment models (MEM-3 and ORDEM 3.1) necessitate studying the change in risk to the EMU. Results indicate 11% more cumulative MMOD penetration (any size leak) risk. The risk increase is attributable to the addition of high-density particle distributions to the MEM-3 meteoroid environment. Softgoods regions of the EMU continue to drive risk, and contribute 78% of the cumulative MMOD penetration risk. MMOD risk remains small for a typical 6.5 hour EVA, no matter what MMOD environments are used.

6 ACKNOWLEDGEMENTS

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