MMOD Risk to the International Space Station and its Sensitivity to Particle Size

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ABSTRACT

This paper will provide a summary of the latest meteoroid and orbital debris (MMOD) risk assessment of the International Space Station (ISS) produced by the Hypervelocity Impact Technology (HVIT) group at the NASA Johnson Space Center. Major updates include using the most current orbital debris engineering model (ORDEM 3.2) and the latest meteoroid environment model (MEM 3). Failure criteria associated with this baseline risk analysis is defined as threshold perforation of a pressurized module and it incorporates a simplified seven-step assembly sequence to model the time between first element launch in November 1998 and the assembly complete stage in February 2010. Updated model configurations were used to represent changes to the ISS for the period between 2010 and 2025. In addition to failures that could lead to depressurization of both the U.S. and Russian segments, data will be presented about the risks to other non-critical hardware that may lead to operational failures by impacts from smaller MMOD particles.

Analysis scope includes permanent pressurized modules, as well as Soyuz and Progress visiting vehicles. Exposure times and docking locations for the Soyuz and Progress missions were compiled from the latest ISS as-flown flight plans. US crew vehicles such as the Space Shuttle, Crew Dragon and Starliner, as well as cargo vehicles such as the H-2 Transfer Vehicle (HTV), Cygnus and Dragon were not included in the assessment. Potential risk reductions from shadowing by the U.S. solar arrays and radiators were not considered in the analysis. The flux output from the latest Orbital Debris Engineering Model (ORDEM) is sensitive to altitude, and over the ISS lifetime, the apogee/perigee has varied considerably. For the updated analysis to be presented in this paper, yearly altitude averages compiled from as-flown data were used to generate the ORDEM environment data files used. In a similar fashion, the as-flown attitude history of the ISS was simplified for the purpose of this work. Along with describing the process of running this analysis through the Bumper code, this paper will provide the MMOD failure results and risk distribution details for the breakdown of the risk from both meteoroids and orbital debris, inclusive of all density bins included in each respective environment model. A direct comparison of MMOD risk for Russian and US segments will be provided, including the relevant ballistic limit equations and critical particle sizes.

1 ISS BACKGROUND

The ISS has a complicated development history over the past 27 years as an on-going collaboration within five space agencies [1]. One of the complications is the separation of the ISS into US and Russian segments. The United States On-orbit Segment (USOS) includes hardware from the European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA) and the Canadian Space Agency (CSA). The Russian orbital segment (ROS) hardware was provided by two organizations: S.P. Korolev Rocket and Space Corporation "Energia" and Khrunichev State Research and Production Space Center, both under the direction of Roscosmos, the space agency of the Russian government.

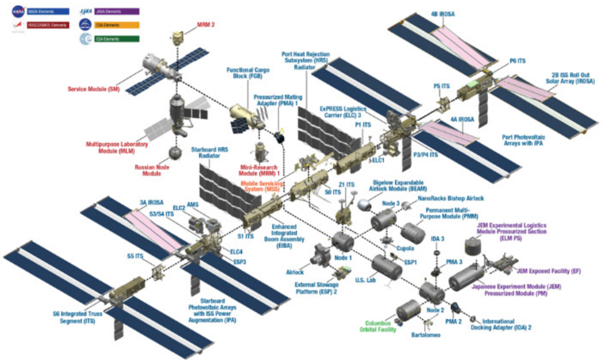

Figure 1. ISS components

Fig. 1 illustrates the ISS configuration (circa 2022). The size and scope of the ISS necessitated a multi-stage assembly sequence. Most of the USOS components were delivered to the ISS in the payload bay of the Space Shuttle, while most of the ROS hardware arrived at the station directly on Russian rockets. The USOS assembly was completed in 2011 with the addition of the Alpha Magnetic Spectrometer #2 (AMS-02) payload. The final ROS module – the Russian "Node Module" - was

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delivered in late 2021. Since the ISS has been continuously crewed since November 2, 2000, there have also been over 150 [2] uncrewed cargo resupply missions by multiple space agencies including NASA, ESA, JAXA and Roscosmos - And over 100 [3] crew rotation flights provided by the Russian Soyuz, NASA Space Shuttles and SpaceX Crew Dragon spacecraft. In addition to the assembly, resupply, and crew rotation flights, over 270 [4] extra vehicular activity (EVA) operations have occurred in support of ISS during this time.

2 SCOPE

ISS collision risk with orbital debris can be divided into three regimes. Larger objects (≥10cm) can be tracked [5] and the risk mitigated by debris avoidance maneuvers, with 38 performed as of February 2024 [6]. Risk from smaller particles is controlled by shielding. MMOD penetration risk to ISS is found in the "protection gap", the middle region between particles that are too small for avoidance and large enough to defeat the deployed shielding. This analysis calculates the risk of an MMOD impact on critical ISS components from first element launch (FEL) in 1998 through the year 2030. The analysis scope covers every permanent module and the Russian visiting vehicles. The following sections provide specific details of the analysis.

2.1 Tools

The risk analysis was performed with the NASA-Johnson Space Center (JSC) HVIT Bumper3 software [7]. When provided with spacecraft geometry, orbital parameters and a definition of failure criteria, Bumper estimates the expected number of MMOD penetrations. Thousands of hypervelocity impact tests have been performed on representative samples of ISS shields and subsystems to determine MMOD impact parameters at the failure limits. The resulting ballistic limit equations are coded in Bumper and provide a common framework to predict if a specific impact condition (e.g., particle size, speed, impact angle, particle density) can be expected to cause a failure for each specific shielding configuration .

Bumper3 uses the latest orbital debris engineering model (ORDEM) produced by the NASA-JSC Orbital Debris Program Office (ODPO)[8] to calculate penetrating flux values from orbital debris for each impact condition in an analysis. In a similar fashion, Bumper3 uses the latest Meteoroid Engineering Model (MEM) flux data produced by the NASA Marshall Space Flight Center (MSFC) Meteoroid Environment Office (MEO) [9]. In Bumper3, spacecraft outer surfaces are represented by finite element models (FEMs). These surfaces are represented within the FEM as two-dimensional quadrilateral and triangular "elements" located in three-dimensional space using the corner "nodes" of each element. Bumper3 calculates the MMOD risk for each element.

2.2 Failure Criteria

The analysis intent was to estimate the risk of an ISS component failure due to an impact from an MMOD particle. For the purposes of this analysis "ISS components" and "failure" are defined in Tab. 1. Consequences of MMOD penetrations on the different regions of ISS are beyond the scope of this paper but have been examined by HVIT [10].

Table 1. MMOD Failure Criteria

Component	Example	Failure
Crew compartment pressure shell	Permanent modules and visiting vehicles	threshold perforation of pressure shell
External pressurized commodities	Nitrogen and ammonia tanks	threshold perforation of metallic tank wall
External pressurized commodities (COPV)	High Pressure Gas Tanks on US Airlock	threshold perforation of metallic tank shield (no touch)
Energized components	Control Moment Gyros on Z1 truss	threshold perforation
Windows	Permanent modules and visiting vehicles	detached spall in the redundant pressure pane

2.3 Input Models

Geometry data (module dimensions) and MMOD shielding definitions (thickness and materials of construction) for the ROS modules were provided in a series of bilateral technical interchange meetings between NASA and Roscosmos. Similar data for the USOS modules and components were generally sourced from contractor MMOD requirements compliance reports.

To simplify the analysis, crew and cargo spacecraft from the US, Europe, and Japan were not included in this effort. While it is non-conservative to omit these vehicles, prior analysis has shown that the contribution from these vehicles is small in comparison to the permanent modules and the visiting Soyuz/Progress vehicles. An "analysis simplification" rationale was also used to omit the US solar arrays and radiators. Previous assessments have shown that the flux shadowing from these missing elements influences penetration risk, but it is more conservative to leave these contributions out. The recent arrivals of the supplemental ISS Roll-Out Solar Arrays (IROSA) were also not considered in the current analysis.

Shutters on the seven Cupola windows were assessed as being closed between 2010 and 2015, and open from 2015 through the end of analysis timeframe. Window shutters on the Service Module, Multipurpose Laboratory Module (MLM) and Japanese Experiment Module (JEM) were modeled in the open position. It was assumed that the inner hatches for both Pressurized Mating Adapters (PMA) were closed 99% of the exposure time and a 1% “use factor” was applied to these regions which is believed to be consistent with operations for this hardware. This factor is implemented in post-processing as a simple multiplicative constant on the expected number of failures that are calculated for a 1-year exposure time. Similar use factors were also assumed for the inflatable USOS Bigelow Expandable Activity Module (BEAM), NanoRacks Airlock, and the Russian MLM airlock. After cracks were observed in the pressure shell of the Service Module transfer tunnel (ПрК) in 2019, the aft compartment was essentially sealed off from the rest of ISS. Tab. 2 provides a summary of the exposure time fractions that were assumed for the current analysis. The remaining volumes in the ISS were assumed to be continuously used (factor = 1.0).

Table 2. Assumed Exposure Time Fractions

ISS Component	Exposure Time Fraction	Applicable Years
PMA2 and PMA3	1%	1998-2030
BEAM	5%	2016-2030
NanoRacks Airlock	5%	2021-2030
MLM Airlock	5%	2021-2030
SM ПрК module, Progress	0%	2020-2030

The first of six service module augmentation panels [11] were assumed to be in place starting with the Block 3 model in 2001. The full complement of 23 panels were assumed to be in place starting with the Block 4 model in 2006. It was assumed that the Progress cargo module transitioned from the base shielding to full augmentation starting with 47P mission in April 2012. Starting with the 30S flight in May 2012, full augmentation [11] of Soyuz orbital module shielding was assumed. The solar arrays on the Russian Zarya module used in all stages were modeled in the partially retracted position. In the early stages of the ISS, the Zarya solar arrays were fully extended, but they were retracted in the 2006/2007 timeframe to provide clearance to deploy the full complement of US radiators.

2.4 Environment Models

Output from the ORDEM 3.2 orbital debris environment is a function of exposure year, spacecraft altitude and orbit inclination. To obtain risk output for each exposure year, ORDEM 3.2 data files were generated for each year between 1998 and 2030 using single altitude values to represent an entire year. Since output from the MEM 3 meteoroid environment is not dependent on year and is relatively insensitive to altitude, MEM data files for nominal 400 km and 416 km circular orbits were used throughout the analysis.

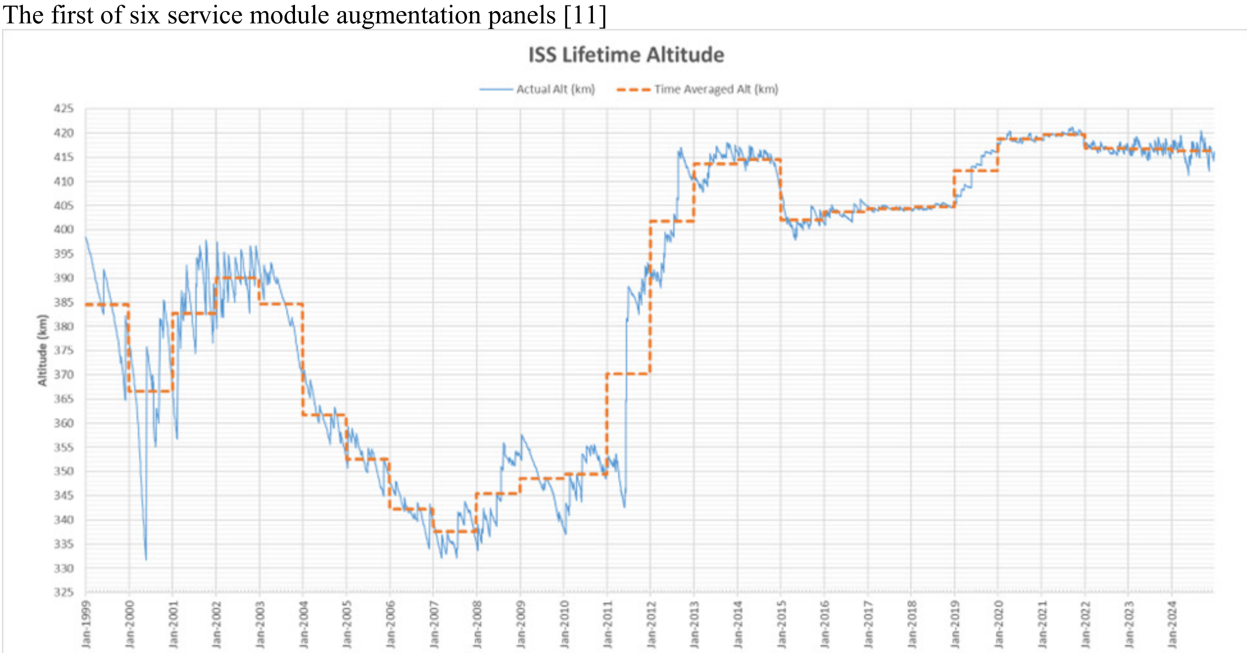


Figure 2. Time-weighted ISS altitudes between 1/1/99 and 12/31/24

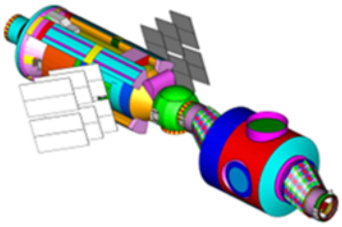
2.5 Altitude and Attitude

The orange dashed line in Fig. 2 shows the time-weighted average altitudes for exposure years between 1999 and 2024 that were computed from as-flown data (indicated by the solid blue line). Since the ISS orbit has always been roughly circular, each entry in the time-weighted average calculations is in turn based on an average of the individual apogee and perigee values of each orbit segment. For future years (2025-2030), a nominal 416km altitude was assumed.

To simplify the analysis, each of the core model blocks (except for the initial “Block 1” configuration) were represented by a single fixed attitude, expressed in the ISS Yaw, Pitch, Roll (YPR) nomenclature. The "X nadir spin" attitude used for Block 1 (Fig. 3) orients the forward Pressurized Mating Adapter (PMA2) to point in the nadir direction. The "spin" component was represented with four 90-degree increments in the roll angle. Attitudes for the early "ISS assembly" stages Block 1 (Fig. 3) through Block 5 (Fig. 7) were sourced from a Space Station Program document titled "ISS Certification Baseline Volume 3: Flight Attitudes (SSP 50699-03)". Values for the post "Assembly Complete" stages Block 6 (Fig. 8) and Block 7 (Fig. 9) were obtained from a 2019 PowerPoint file produced by the ISS Vehicle Integrated Performance Environments and Resources (VIPER) Team. Attitudes for the standalone visiting vehicle models were matched to the associated block configurations.

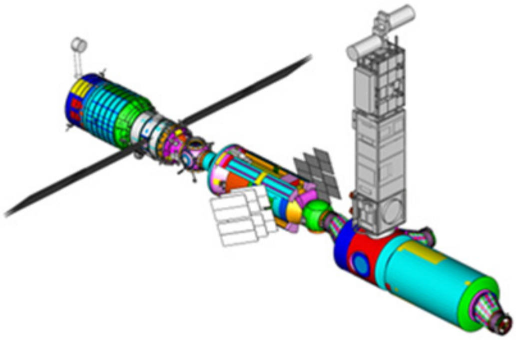
2.6 Assembly Sequence

The multistep assembly process for the permanent station modules was simplified into seven stages, spanning from first element launch in 1998 to the current configuration in 2025. A separate set of standalone models were assembled to represent nine different docking locations of the Soyuz and Progress visiting vehicles. Orientations of the vehicles on the different docking ports were modeled as indicated in the document "Space Station Reference Coordinate Systems (SSP 30219 Revision K)".



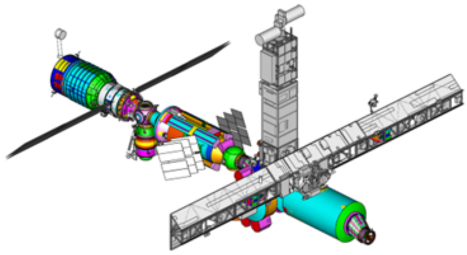
						Block 1			
					Exposure year	1998	1999	2000	
					Attitude (YPR)	X nadir spin (90° increments)			
					ORDEM 3.2 (km)	384.7	384.5	366.6	
					MEM 3 alt (km)	400	400	400	
					end date	12/31/98	12/31/99	07/26/00	
Assembly				Exposure (Years)		Time per Year			Block 1
FEM	Stage	Module	Date	Total	Increment	1998	1999	2000	Totals
Block 1	1A/R	FGB	**11/20/98**	32.13	0.04	0.11	1.00	0.57	1.68
Block 1	2A	N1, PMA1, PMA2	12/06/98	32.09	1.64	0.07	1.00	0.57	1.64
Block 1 (11/20/1998 - 7/26/2000)					**1.68**				

Figure 3. Block 1 exposure time, attitude, and environment details



						Block 2		
					Exposure year	2000	2001	
					Attitude (YPR)	0°,-15.0°,0°		
					ORDEM 3.2 (km)	366.6	382.7	
					MEM 3 alt (km)	400	400	
					end date	12/31/00	07/14/01	
Assembly				Exposure (Years)		Time per Year		Block 2
FEM	Stage	Module	Date	Total	Increment	2000	2001	Totals
Block 2	1R	SM	07/26/00	30.45	0.22	0.43	0.53	0.97
Block 2	3A	Z1, PMA3	10/13/00	30.24	0.14	0.22	0.53	0.75
Block 2	4A	P6	12/02/00	30.10	0.19	0.08	0.53	0.61
Block 2	5A	Lab	02/09/01	29.91	0.19		0.42	0.42
Block 2	6A	SSRMS	04/21/01	29.72	0.23		0.23	0.23
Block 2 (7/26/2000 - 7/14/2001)					**0.97**			

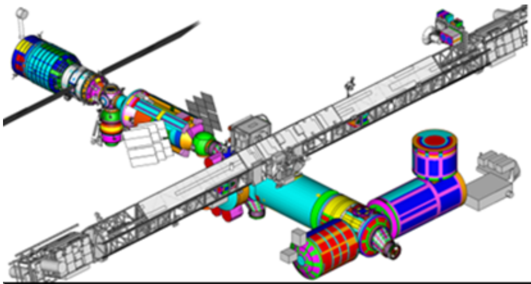
Figure 4. Block 2 exposure time, attitude, and environment details



	Block 3					
Exposure year	2001	2002	2003	2004	2005	2006
Attitude (YPR)	-10.0°,-10.0°,0°					
ORDEM 3.2 (km)	382.7	390.0	384.6	361.7	352.5	342.2
MEM 3 alt (km)	400	400	400	400	400	400
end date	12/31/01	12/31/02	12/31/03	12/31/04	12/31/05	09/11/06

Assembly				Exposure (Years)		Time per Year						Block 3
FEM	Stage	Module	Date	Total	Increment	2001	2002	2003	2004	2005	2006	Totals
Block 3	7A	Airlock	07/14/01	29.48	0.18	0.47	1.00	1.00	1.00	1.00	0.70	5.16
Block 3	4R	DC1	09/17/01	29.31	0.56	0.29	1.00	1.00	1.00	1.00	0.70	4.99
Block 3	8A	S0	04/10/02	28.75	0.50		0.73	1.00	1.00	1.00	0.70	4.42
Block 3	9A	S1	10/09/02	28.25	0.13		0.23	1.00	1.00	1.00	0.70	3.93
Block 3	11A	P1	11/25/02	28.12	3.80		0.10	1.00	1.00	1.00	0.70	3.80
Block 3 (7/14/2001 - 9/11/2006)					5.16							

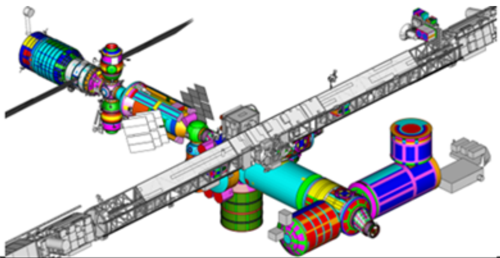
Figure 5. Block 3 exposure time, attitude, and environment details



	Block 4			
Exposure year	2006	2007	2008	2009
Attitude (YPR)	-3.0°,-3.0°,+1.0°			
ORDEM 3.2 (km)	342.2	337.5	345.4	348.5
MEM 3 alt (km)	400	400	400	416
end date	12/31/06	12/31/07	12/31/08	03/17/09

Assembly				Exposure (Years)		Time per Year				Block 4
FEM	Stage	Module	Date	Total	Increment	2006	2007	2008	2009	Totals
Block 4	12A	P3/P4	09/11/06	24.32	0.75	0.30	1.00	1.00	0.21	2.52
Block 4	13A	S3/S4	06/10/07	23.58	0.38		0.56	1.00	0.21	1.77
Block 4	10A	Node 2	10/25/07	23.20	0.29		0.18	1.00	0.21	1.39
Block 4	1E	Columbus	02/09/08	22.91	0.09			0.89	0.21	1.10
Block 4	1JA	JEM-ELM	03/13/08	22.82	0.22			0.80	0.21	1.01
Block 4	1J	JEM-PM	06/02/08	22.59	0.79			0.58	0.21	0.79
Block 4 (9/11/2006 - 3/17/2009)					2.52					

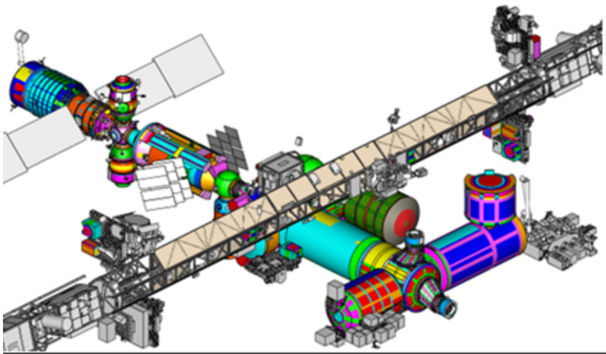
Figure 6. Block 4 exposure time, attitude, and environment details



	Block 5						
Exposure year	2009	2010	2011	2012	2013	2014	2015
Attitude (YPR)	-3.0°,-3.0°,+1.0°						
ORDEM 3.2 (km)	348.5	349.4	370.2	401.7	413.6	414.5	402.1
MEM 3 alt (km)	416	416	416	416	416	416	400
end date	12/31/09	12/31/10	12/31/11	12/31/12	12/31/13	12/31/14	12/31/15

Assembly				Exposure (Years)		Time per Year							Block 5
FEM	Stage	Module	Date	Total	Increment	2009	2010	2011	2012	2013	2014	2015	Totals
Block 5	15A	S6	03/17/09	21.81	0.66	0.79	1.00	1.00	1.00	1.00	1.00	1.00	6.79
Block 5	5R	MRM2	11/12/09	21.15	0.25	0.13	1.00	1.00	1.00	1.00	1.00	1.00	6.14
Block 5	20A	Node 3, Cupola	02/10/10	20.90	0.26		0.89	1.00	1.00	1.00	1.00	1.00	5.89
Block 5	ULF4	MRM1	05/16/10	20.64	0.78		0.63	1.00	1.00	1.00	1.00	1.00	5.63
Block 5	ULF5	PMM (@N1n)	02/26/11	19.86	4.85			0.84	1.00	1.00	1.00	1.00	4.85
Block 5 (3/17/2009 - 12/31/2015)					6.79								

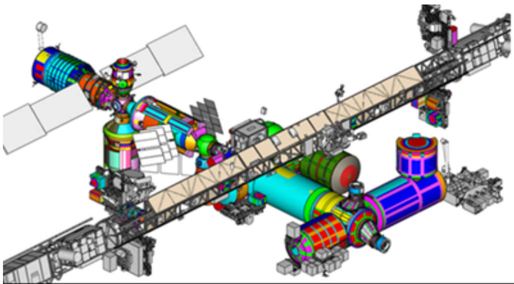
Figure 7. Block 5 exposure time, attitude, and environment details



	2016	2017	2018	2019	2020	2021
Block 6						
Exposure year	2016	2017	2018	2019	2020	2021
Attitude (YPR)	-4.0°,-5.4°,+0.9°					
ORDEM 3.2 (km)	403.7	404.4	404.7	412.2	418.8	416.0
MEM 3 alt (km)	400	400	400	416	416	416
end date	12/31/16	12/31/17	12/31/18	12/31/19	12/31/20	07/26/21

Assembly				Exposure (Years)		Time per Year						Block 6
FEM	Stage	Module	Date	Total	Increment	2016	2017	2018	2019	2020	2021	Totals
Block 6		AMS-02	12/31/15	15.01	0.29	1.00	1.00	1.00	1.00	1.00	0.57	5.57
Block 6		BEAM (@N3a)	04/16/16	14.72	0.34	0.71	1.00	1.00	1.00	1.00	0.57	5.28
Block 6		IDA2 on N2f	08/17/16	14.38	0.61	0.37	1.00	1.00	1.00	1.00	0.57	4.94
Block 6		PMA3 to N2z	03/26/17	13.78	0.01		0.77	1.00	1.00	1.00	0.57	4.34
Block 6	US EVA 41	PMA3 port and stbd shields, U-41	03/30/17	13.76	0.00		0.75	1.00	1.00	1.00	0.57	4.33
Block 6	US EVA 41	Node 3 axial shield, U-41	03/30/17	13.76	0.00		0.75	1.00	1.00	1.00	0.57	4.33
Block 6	US EVA 41	APAS cover removal, U-41	03/30/17	13.76	0.12		0.75	1.00	1.00	1.00	0.57	4.33
Block 6	US EVA 42	PMA3 forward shield, U-42	05/12/17	13.65	2.28		0.64	1.00	1.00	1.00	0.57	4.21
Block 6	US EVA 55	IDA3 on PMA3/N2z	08/21/19	11.37	0.61				0.36	1.00	0.57	1.93
Block 6	SpX-20	Bartolomeo on Columbus	04/01/20	10.76	0.56					0.75	0.57	1.32
Block 6		62S depart (begin single Soyuz config)	10/21/20	10.20	0.16					0.19	0.57	0.76
Block 6	SpX-21	NanoRacks Airlock on N3 axial	12/19/20	10.04	0.60					0.03	0.57	0.60
Block 6 (12/31/2015 - 7/26/21)					5.57							

Figure 8. Block 6 exposure time, attitude, and environment details



	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Block 7										
Exposure year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Attitude (YPR)	-4.0°,-5.4°,+0.9°									
ORDEM 3.2 (km)	416.0	416.0	416.0	416.0	416	416	416	416	416	416
MEM 3 alt (km)	416	416	416	416	416	416	416	416	416	416
end date	12/31/21	12/31/22	12/31/23	12/31/24	12/31/25	12/31/26	12/31/27	12/31/28	12/31/29	12/31/30

Assembly				Exposure (Years)		Time per Year									
FEM	Stage	Module	Date	Total	Increment	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Block 7	77P	remove DC1	07/26/21	9.44	0.01	0.43	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Block 7	3R	MLM	07/29/21	9.43	0.33	0.42	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Block 7	6R	RS Node on MLM	11/26/21	9.10	1.39	0.10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Block 7	RS EVA 56	Radiator from MRM-1 to MRM	04/19/23	7.71	0.04			0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Block 7	RS EVA 57	Airlock from MRM-1 to MLM	05/03/23	7.67	0.02			0.66	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Block 7	RS EVA 58	MLM radiator deploy	05/12/23	7.64	0.24			0.64	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Block 7	RS EVA 60	Install MMOD shields on MRM1	08/09/23	7.40	7.40			0.39	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Block 7 (7/26/2021 - 12/31/2030)					9.44										

Figure 9. Block 7 exposure time, attitude, and environment details

2.7 Exposure Times

Fig. 3 document the exposure time calculations for the first of seven simplified stages of the ISS assembly process. In the first row, the Functional Cargo Block module (FGB) represents first element launch on 11/20/98. Total expected exposure time for this element from arrival to end of calendar year 2030 is 32.13 years. The time increment between the arrival of FGB and the next elements (Node 1, PMA1 and PMA2) is shown as 0.04 years. The yearly exposure time for each segment is also provided. Each figure also provides the attitude used for the multiyear Block configuration as well as the altitudes used in the development of the ORDEM and MEM environment data files. Yearly exposure times for each Soyuz and Progress docking location were sourced from a document titled "ISS As Flown Flight Program History" produced by the Flight Program Integration Panel and are summarized in Tab. 3 and Tab. 4. Scheduled exposure times for years 2025 and 2026 were extracted from a mid-January 2025 edition of the ISS Flight Plan and were assumed to be equivalent for years 2027 through 2030.

Table 3. Soyuz Exposure Time (Years)

	Soyuz @				
Year	**SM**	**DC1**	**MRM1**	**MRM2**	**MLM**
2000	0.161				
2001	0.342	0.693			
2002		1.038			
2003		1.030			
2004		1.038			
2005		1.036			
2006		1.038			
2007		1.055			
2008		1.049			
2009	0.510	0.277	0.800		
2010	0.142		0.811	0.378	
2011			0.863	0.773	
2012			0.863	0.839	
2013			0.937	0.918	
2014			0.915	0.910	
2015			0.871	0.970	
2016			0.921	0.833	
2017			0.833	0.945	
2018			0.956	0.773	
2019	0.293		0.553	0.929	
2020	0.295		0.213	0.637	
2021			0.923	0.112	0.052
2022			0.521		0.534
2023			0.532	0.107	0.477
2024			0.568		0.499
2025			0.392		0.671
2026			0.471		0.545
2027			0.392		0.671
2028			0.471		0.545
2029			0.392		0.671
2030			0.471		0.545
Total	**1.744**	**8.255**	**14.67**	**9.122**	**5.210**

Table 4. Progress Exposure Time (Years)

	Progress @			
Year	**SM**	**DC1**	**MRM2**	**MLM**
2000	0.232	0.049		
2001	0.718	0.104		
2002	0.967			
2003	0.978	0.233		
2004	0.934			
2005	0.970	0.022		
2006	0.748	0.978		
2007	0.581	0.964		
2008	0.158	0.637		
2009	0.148	0.660		
2010	0.718	0.959		
2011	0.304	0.951		
2012	0.167	0.915		
2013	0.499	0.984		
2014	0.436	0.973		
2015	0.737	0.792		
2016	0.803	0.956		
2017	0.534	0.693		
2018	0.636	0.715		
2019	0.425	0.778		
2020	0.0	0.959		
2021	0.0	0.545	0.301	0.099
2022	0.0		0.858	
2023	0.0		0.729	
2024	0.0		0.978	
2025	0.0		0.997	0.044
2026	0.0		0.704	0.447
2027	0.0		0.997	0.044
2028	0.0		0.704	0.447
2029	0.0		0.997	0.044
2030	0.0		0.704	0.447
Total	**11.69**	**13.87**	**7.970**	**1.570**

2.8 Ballistic Limit Equations

MMOD shield performance is defined in the Bumper code by ballistic limit equations (BLEs). The equations are generally tied to hypervelocity impact testing and are used in the code to define the particle size that fails a shield at a specific impact angle and velocity. The ballistic properties of the ISS modules were described by 847 unique property IDs (PIDs) using 22 different BLEs. The Soyuz module (Fig. 10) had 65 PIDs and 5 different BLEs, while the less detailed Progress model (Fig. 11) was described with 21 PIDs and 2 BLEs.

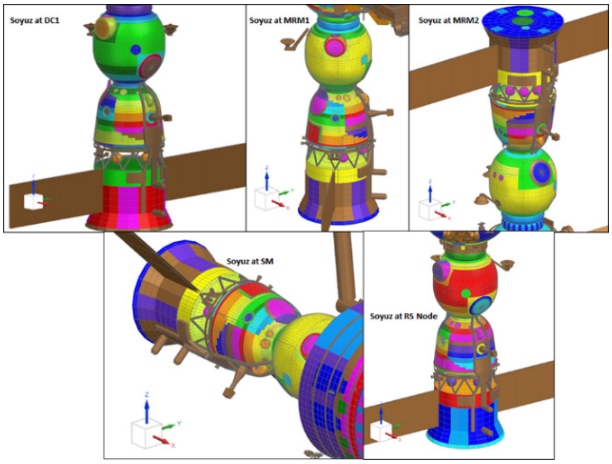


Figure 10. Soyuz FE Models

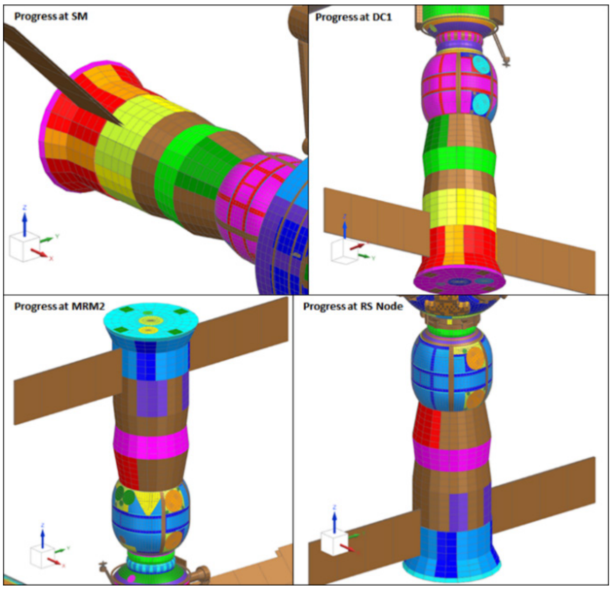


Figure 11. Progress FE Models

Shield configurations and capabilities vary significantly across the ISS, but the most common shield type by area on the core modules is the two-wall aluminum "Whipple" shield. Approximately 50% of the core module area is protected by this shield. Many of the of the forward-facing ISS MMOD shielding regions were designed to resist a higher expected debris flux with a "Stuffed Whipple" shield [12], that enhances the baseline double wall configuration with intermediate layers of ballistic fabrics. In general, these enhanced shields can protect against 10mm diameter aluminum projectiles at 7km/s [13]. Fig. 12 provides a comparison between the general configuration of a Stuffed Whipple shield and the "augmented" Soyuz Orbital Module and Progress Cargo Module shield. Even with the augmentation, the Soyuz/Progress shield can stop aluminum particles up to about 2.5mm at 7km/s. From 2000 to 2012 (prior to augmentation) these Soyuz and Progress shields would fail when impacted by 2mm particles at the same conditions.

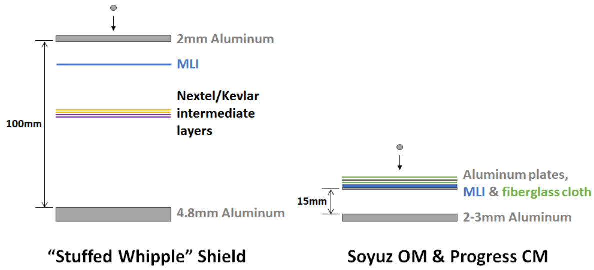


Figure 12. ISS Shielding Examples

Fig. 13 is a plot of the nominal ORDEM 3.2 flux for a 400km ISS orbit in the year 2025. The debris flux prediction decreases rapidly between 1 (indicated with the dotted line) and 2mm size (solid line), with approximately two orders of magnitude difference. The slope of the flux curve flattens out between 2mm and 10mm size (dashed line), so the change in flux is less drastic.

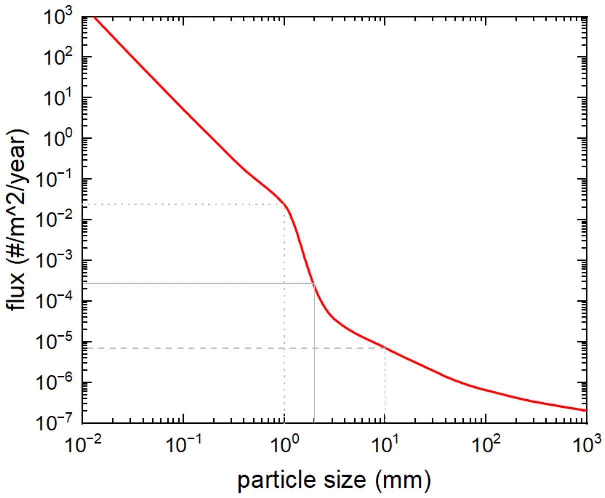


Figure 13. ISS flux plot from ORDEM 3.2

3 RESULTS

For the years 1998 through 2030 the risk of critical penetrations to ISS from ORDEM 3.2 and MEM 3 is 78.6%. Tab. 5 summarizes the results of the analysis for US and Russians modules as well as the Soyuz and Progress vehicle. The "% Total" row in table 5 indicates that the Russian visiting vehicles account for 71.0% of the penetration risk over the life of ISS and when contribution from the fixed modules on the Russian side is added in the total is 92.3%, the USOS accounting for 7.7% of the risk.

Table 5. Rolled-up Analysis Results (1998-2030)

	Modules		Visiting Vehicles (VV)		Total		
	USOS	**ROS**	**Soyuz**	**Progress**	**Modules**	**VV**	**ISS**
Expected # of Failures (N)	0.1182	0.3284	0.6631	0.4301	0.4466	1.0932	**1.5398**
Probability of No Failure (e^{-N})	0.8885	0.7201	0.5152	0.6504	0.6398	0.3351	**0.2144**
Failure Risk (1-PNF)	11.1%	28.0%	48.5%	35.0%	36.0%	66.5%	**78.6%**
% Total	*7.7%*	*21.3%*	*43.1%*	*27.9%*	*29.0%*	*71.0%*	

Table 6. ISS Module-level Analysis Results (1998-2030)

Module	Exposure	ORDEM 3.2						MEM 3			MMOD	%
	Time (Yr)	*TOTAL*	*NaK*	*LD*	*MD*	*HD*	*Intacts*	*TOTAL*	*LD*	*HD*	Total	Total
JEM	23.80	1.85E-02	0.00E+00	1.78E-04	7.68E-03	1.03E-02	3.39E-04	4.31E-03	2.15E-03	2.16E-03	2.28E-02	1.48%
PMM	19.84	1.26E-02	0.00E+00	1.11E-04	3.01E-03	9.39E-03	7.14E-05	6.95E-03	2.98E-03	3.98E-03	1.95E-02	1.27%
CMG	30.22	1.20E-02	0.00E+00	4.31E-05	8.35E-04	1.11E-02	3.06E-06	7.02E-03	4.05E-03	2.97E-03	1.90E-02	1.24%
Columbus	23.89	8.00E-03	0.00E+00	1.14E-04	3.83E-03	3.93E-03	1.31E-04	3.11E-03	1.40E-03	1.71E-03	1.11E-02	0.72%
PMA	32.07	7.65E-03	0.00E+00	1.68E-05	3.18E-03	3.51E-02	8.36E-06	2.72E-03	7.53E-04	1.97E-03	1.04E-02	0.67%
Cupola	20.89	7.36E-03	0.00E+00	6.70E-06	3.78E-04	6.97E-03	4.60E-06	8.96E-04	2.93E-04	6.02E-04	8.26E-03	0.54%
TCS	29.10	4.49E-03	0.00E+00	1.09E-04	3.03E-03	1.29E-03	6.24E-05	2.35E-03	1.25E-03	1.10E-03	6.84E-03	0.44%
Node2	24.18	3.04E-03	0.00E+00	5.87E-05	2.15E-03	7.64E-04	6.89E-05	2.84E-03	1.44E-03	1.40E-03	5.89E-03	0.38%
Airlock	29.47	2.81E-03	0.00E+00	6.49E-05	2.26E-03	4.08E-04	7.61E-05	1.42E-03	8.06E-04	6.18E-04	4.23E-03	0.27%
Node3	20.89	1.46E-03	0.00E+00	3.18E-05	1.08E-03	3.08E-04	3.81E-05	2.31E-03	1.27E-03	1.04E-03	3.77E-03	0.24%
Lab	29.89	2.02E-03	0.00E+00	3.23E-05	1.58E-03	3.20E-04	9.21E-05	6.59E-04	3.48E-04	3.11E-04	2.68E-03	0.17%
Node1	32.07	9.66E-04	0.00E+00	1.37E-05	6.09E-04	3.19E-04	2.43E-05	1.64E-03	9.22E-04	7.15E-04	2.60E-03	0.17%
AMS	15.00	4.66E-04	0.00E+00	3.99E-07	1.47E-05	4.51E-04	1.86E-07	9.80E-05	2.75E-05	7.05E-05	5.64E-04	0.04%
BEAM	14.71	2.63E-04	0.00E+00	9.44E-07	2.95E-05	2.33E-04	3.11E-07	3.28E-05	2.15E-05	2.19E-05	2.96E-04	0.02%
NRAL	10.00	1.01E-04	0.00E+00	2.26E-07	1.11E-05	8.94E-05	2.33E-07	7.64E-06	3.06E-06	4.58E-06	1.09E-04	0.01%
PCU	30.22	5.42E-05	0.00E+00	9.04E-07	4.32E-05	8.45E-06	1.60E-06	1.31E-05	7.33E-06	5.76E-06	6.73E-05	0.004%
SM	30.43	1.35E-01	0.00E+00	3.33E-04	8.40E-03	1.26E-01	7.92E-05	1.15E-01	6.20E-02	5.33E-02	2.50E-01	16.2%
DC1	19.85	1.19E-02	0.00E+00	1.28E-04	2.00E-03	9.73E-03	1.98E-05	1.33E-02	7.14E-03	6.11E-03	2.51E-02	1.63%
MRM2	21.13	6.87E-03	0.00E+00	7.92E-05	1.65E-03	5.12E-03	1.89E-05	1.12E-02	5.83E-03	5.34E-03	1.80E-02	1.17%
MLM	9.42	1.38E-02	0.00E+00	1.53E-04	5.93E-03	7.63E-03	1.16E-04	3.21E-03	1.86E-03	1.35E-03	1.70E-02	1.11%
FGB	32.11	4.33E-03	0.00E+00	5.91E-05	2.15E-03	2.05E-03	6.85E-05	1.09E-02	6.08E-03	4.82E-03	1.52E-02	0.99%
RS Node	9.10	1.23E-03	0.00E+00	2.34E-05	1.04E-03	1.50E-04	2.30E-05	2.82E-04	1.54E-04	1.28E-04	1.51E-03	0.10%
MRM1	20.63	1.05E-03	0.00E+00	1.84E-05	7.81E-04	2.21E-04	2.99E-05	2.87E-04	1.70E-04	1.17E-04	1.34E-03	0.09%
MLM airlock	9.42	8.96E-05	0.00E+00	2.46E-06	6.44E-05	2.21E-05	6.12E-07	4.67E-05	2.45E-05	2.21E-05	1.36E-04	0.01%
USOS		**8.18E-02**	0.00E+00	***7.83E-04***	***2.97E-02***	***8.10E-02***	***9.22E-04***	**3.64E-02**	***1.77E-02***	***1.87E-02***	**1.18E-01**	**7.7%**
ROS		**1.74E-01**	0.00E+00	***7.97E-04***	***2.20E-02***	***1.51E-01***	***3.55E-04***	**1.54E-01**	***8.33E-02***	***7.12E-02***	**3.28E-01**	**21.3%**
Soyuz MRM1	14.67	2.27E-01	0.00E+00	6.39E-04	1.50E-02	2.12E-01	5.02E-05	3.42E-02	1.69E-02	1.73E-02	2.61E-01	17.0%
Soyuz DC1	8.25	9.01E-02	0.00E+00	5.13E-05	4.25E-03	8.58E-02	1.01E-05	6.18E-02	3.27E-02	2.92E-02	1.52E-01	9.87%
Soyuz MRM2	9.12	1.24E-01	0.00E+00	3.31E-04	7.16E-03	1.17E-01	2.70E-05	2.01E-02	9.98E-03	1.01E-02	1.45E-01	9.39%
Soyuz RSNode	5.21	7.82E-02	0.00E+00	2.47E-04	6.41E-03	7.16E-02	2.44E-05	6.29E-03	2.76E-03	3.53E-03	8.45E-02	5.49%
Soyuz SM	1.74	1.24E-02	0.00E+00	2.09E-05	5.09E-04	1.19E-02	1.83E-06	8.15E-03	4.46E-03	3.69E-03	2.06E-02	1.34%
Soyuz Total		**5.33E-01**	***0.00E+00***	***1.29E-03***	***3.33E-02***	***4.98E-01***	***1.14E-04***	**1.31E-01**	***6.67E-02***	***6.38E-02***	**6.63E-01**	**43.1%**
Progress DC1	13.87	1.53E-01	0.00E+00	4.06E-04	8.53E-03	1.44E-01	2.68E-05	4.19E-02	2.23E-02	1.96E-02	1.95E-01	12.6%
Progress MRM2	7.97	1.19E-01	0.00E+00	3.47E-04	9.80E-03	1.08E-01	3.00E-05	1.32E-02	6.67E-03	6.49E-03	1.32E-01	8.55%
Progress SM	11.69	4.37E-02	0.00E+00	4.05E-05	1.25E-03	4.24E-02	9.21E-06	3.78E-02	2.11E-02	1.67E-02	8.16E-02	5.30%
Progress RSNode	1.57	1.98E-02	0.00E+00	8.00E-05	1.03E-03	1.87E-02	5.65E-06	2.36E-03	1.21E-03	1.15E-03	2.21E-02	1.44%
Progress Total		***3.35E-01***	***0.00E+00***	***8.73E-04***	***2.06E-02***	***3.13E-01***	***7.16E-05***	**9.52E-02**	***5.13E-02***	***4.39E-02***	**4.30E-01**	**27.9%**
ISS Total		**1.1232**	*0.0000*	***0.0037***	***0.1057***	***1.0430***	***0.0015***	**0.4166**	***0.2190***	***0.1976***	**1.5398**	
		72.9%		*0.2%*	*6.9%*	*67.7%*	*0.1%*	**27.1%**	*14.2%*	*12.8%*		

Tab. 6 indicates that the Service Module (16.2%) contributes the majority of the core module penetration risk. The variation in MMOD penetration risk per year between first element launch in 1998 and the peak of 10.1% in 2011 can be seen in Fig 14. The effect of augmentation on the Soyuz and Progress modules can be seen in the risk decrease between 2012 and 2013 (from 9.01% to 5.17%). The Soyuz/Progress exposure time totals decrease in 2020 with the US crewed vehicle (USCV) replacing a Soyuz on the manifest.

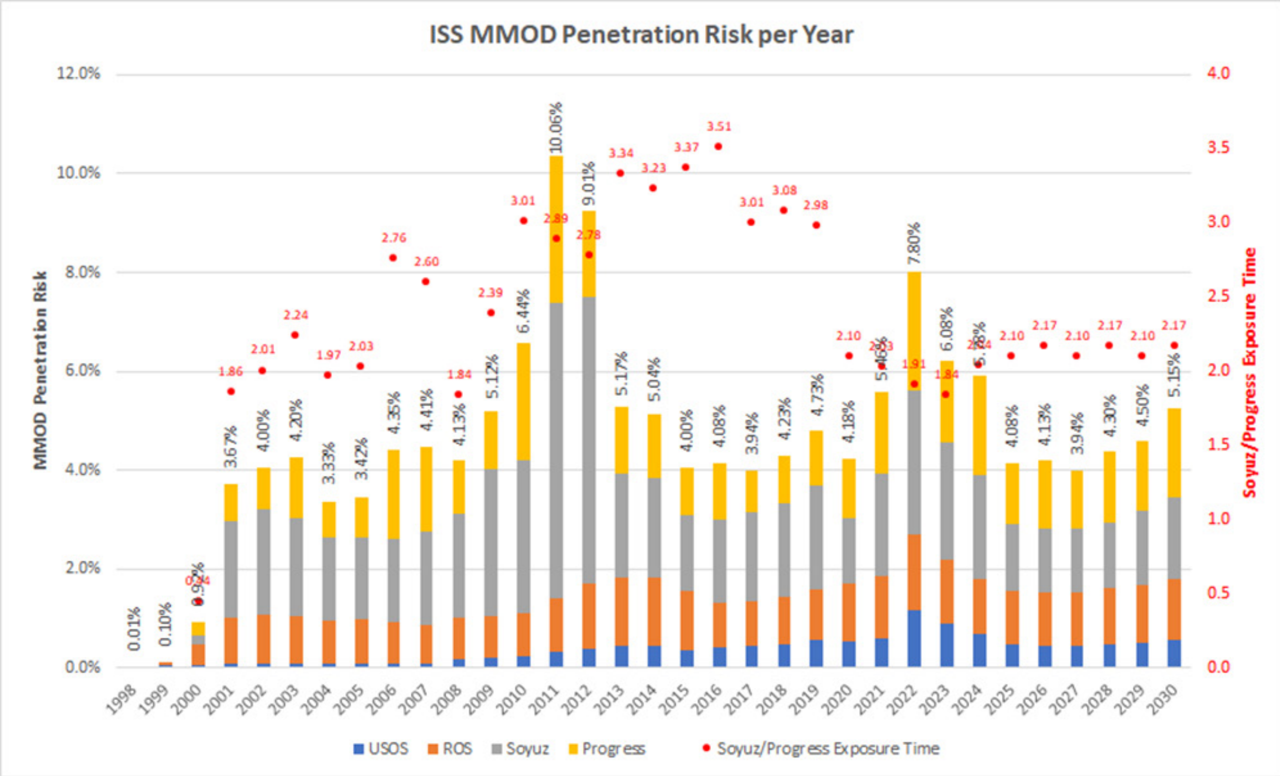


Figure 14. MMOD Penetration Risk per Year

Table 7. Top 15 ISS Risk Drivers

Module	Range	Area	PID	BLE	Critical OD Diam (cm) @ 7.5km/s & 0°				1998-2030			% Total Risk	
					Baseline		Soyuz/Progress Aug.		OD32	MEM3	MMOD Total		
		m^2			*MD*	*HD*	*MD*	*HD*				*range*	*cumulative*
Progress DC1	Cargo module - thin shell 2.0mm w add shield 0.5mm	6.411	405	Progress CM 2023	0.184	0.108	0.236	0.150	9.18E-02	2.42E-02	**1.16E-01**	7.54%	7.54%
Soyuz MRM1	Orbital module fwd - Shell 1.4mm w\AddSh	2.260	848	SoyuzOM 2023	0.145	0.085	0.210	0.131	8.29E-02	1.09E-02	**9.38E-02**	6.09%	13.63%
SM	781 SM WM FWD CYL (5)(669)	3.094	781	NNO	0.192	0.110			6.82E-02	2.42E-02	**9.24E-02**	6.00%	19.63%
Soyuz MRM1	Orbital module fwd - Shell 2.0mm w\AddSh	5.280	860	SoyuzOM 2023	0.184	0.108	0.236	0.150	7.97E-02	1.09E-02	**9.06E-02**	5.88%	25.51%
Soyuz DC1	Orbital module fwd - Shell 2.0mm w\AddSh	5.280	860	SoyuzOM 2023	0.184	0.108	0.236	0.150	4.08E-02	2.43E-02	**6.51E-02**	4.23%	29.73%
Soyuz DC1	Orbital module fwd - Shell 1.4mm w\AddSh	2.260	848	SoyuzOM 2023	0.145	0.085	0.210	0.131	3.75E-02	2.66E-02	**6.42E-02**	4.17%	33.90%
Progress SM	Cargo module - thin shell 2.0mm w add shield 0.5mm	6.411	405	Progress CM 2023	0.184	0.108	0.236	0.150	3.12E-02	2.55E-02	**5.66E-02**	3.68%	37.58%
Soyuz MRM2	Orbital module fwd - Shell 1.4mm w\AddSh	2.260	848	SoyuzOM 2023	0.145	0.085	0.210	0.131	5.00E-02	4.92E-03	**5.49E-02**	3.56%	41.14%
Soyuz MRM2	Orbital module fwd - Shell 2.0mm w\AddSh	5.280	860	SoyuzOM 2023	0.184	0.108	0.236	0.150	4.68E-02	5.85E-03	**5.26E-02**	3.42%	44.56%
Progress MRM2	Cargo module - thin shell 2.0mm w add shield 0.5mm	6.411	405	Progress CM 2023	0.184	0.108	0.236	0.150	4.40E-02	2.06E-03	**4.60E-02**	2.99%	47.55%
Progress MRM2	Cargo module - thin shell 2.0mm	0.927	410	Progress CM 2023	0.184	0.108			3.82E-02	5.07E-03	**4.33E-02**	2.81%	50.36%
SM	763 SM WM RAD CYL (6) (651)	14.698	763	SM-NASA	0.347	0.189			1.99E-02	1.82E-02	**3.81E-02**	2.47%	52.84%
SM	working mod "radiator cyl" (10) (2.0 mm)	22.794	789	SM-RSCE	0.384	0.209			1.72E-02	2.04E-02	**3.76E-02**	2.44%	55.28%
Progress DC1	Cargo module - thin shell 2.0mm	0.927	410	Progress CM 2023	0.184	0.108			2.98E-02	5.54E-03	**3.54E-02**	2.30%	57.58%
Soyuz RSNode	Orbital module fwd - Shell 1.4mm w\AddSh	2.260	848	SoyuzOM 2023	0.145	0.085	0.210	0.131	3.08E-02	8.48E-04	**3.16E-02**	2.05%	59.63%

4 DISCUSSION/CONCLUSIONS

Tab. 7 illustrates how the MMOD penetration risk for ISS is concentrated in a relatively small area. These top 15 risk drivers account for 60% of the total risk. On a surface area basis, these regions are less than 4% of the ISS. As discussed in Fig. 13, staying above the 1-2mm particle size range in this ISS orbit is the key factor to avoid high risk. It can be seen that the critical particle sizes in these high-risk areas are generally less than 2mm.

The ISS program requirements for MMOD protection are defined for the US On-Orbit Segment in SSP-41162, and the allowable PNP for the Russian Segment is specified in SSP-41163. Due to the age of the ISS, the PNP requirements levied by the program specify obsolete orbital debris and meteoroid environments. The analysis documented in this paper used the most current environment models, so a comparison between the current results and the program PNP requirements was not performed.

Given the disparity of the fluxes defined by the environment models during the design phase of the ISS, and the current flux environment, the current analysis resulted in a relatively high risk for MMOD penetrations. Thankfully, there have been no known penetrations of critical regions on the ISS to date.

4.1 Undetected Penetrations

The failure criterion for pressure shell failure is "threshold perforation", occurring when (in metallic walls) the leading edge of the initial damage feature (generally a crater) meets the cavity created by detached spall on the back side. By definition, this damage mode can result in very small openings in a pressure shell. Due to outfitting constraints, direct views of the pressure walls on most of the ISS is not possible. So, it is possible that an impact feature of this type could go undetected by the crew. The accompanying loss of cabin pressure from an undetected MMOD strike could be conflated with existing pressure losses from known (non-MMOD) structural defects.

4.2 OD Environment

ISS risk is dominated by the population of high-density particles >6 g/cm^3 (i.e., steel and copper) in ORDEM 3.2, referred to as the "high density population". For the overall vehicle risk these high-density particles contribute 66% of the total, and when only considering the "top 15" risk-driving areas of the vehicle (see Tab. 7) the contribution from this high-density projectile population increases to 73%. However, we know that there are considerable uncertainties in some of the debris fluxes, especially in the millimeter size ranges where the Russian elements are especially sensitive and where data sources are sparse. The uncertainties in this size range output from the model can be as much as a factor of 2 or more in some cases. This means that the cumulative risk could be as low as 50% or as high as 90% based on these uncertainties alone.

4.3 Ballistic Limit Equations

The Ballistic performance of every risk-bearing region on the ISS is described by one of a few dozen analytical ballistic limit equations. BLEs for specific ISS hardware were developed based on hypervelocity impact testing at speeds up to about 7km/s. This upper limit on testable speeds in the laboratory cannot fully interrogate the entire range of impact speeds expected from either orbital debris or meteoroid particles. Extending the useability of this test data can be achieved through complementary hydrocode impact simulations that are first benchmarked under testable conditions, and then used to verify MMOD shield response from impacts occurring at much higher speeds. The results of these efforts are factors that can be applied to the BLEs to account for ballistic performance in this extreme speed regimes. While this scaling has been applied for common, and relatively simple, single- and double-wall MMOD shield configurations, not all of the unique shielding configurations have benefitted from this extended type of study.

4.4 Finite Element Models

The decision to omit the US solar arrays and radiators in the finite element model used in the current summary analysis simplified the risk assessment process. Including these large areas would have resulted in a smaller number of predicted failures due to the concomitant shadowing effects that would be included during the Bumper-code analysis, and as consequence, would have yielded lower risk numbers. On the other hand, risk contributions from visiting vehicles on the USOS side were also neglected, which is a non-conservative assumption as this resulted in unaccounted penetration risk from these vehicles. In short, the external configuration the actual ISS modules are more complicated than the model used in the current analysis, but overall trends of risk-bearing areas would be unaffected.

4.5 Future Work

Research for the new ORDEM 4.0 model has indicated that debris shape can have a significant effect on damage equations and thus on overall computed risk [14]. That is why the new environment model will include debris shape to help improve the quality and fidelity of risk calculations. Once ORDEM 4.0 is complete, this analysis will be repeated with the new environment to demonstrate how debris shapes change the penetration risk to ISS.

5 REFERENCES

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