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

iss066e081130.jpg

NASA/Johnson Space Center

Astromaterials Research and Exploration Science (ARES) Division

Hypervelocity Impact Technology Group

Jim Hyde | Barrios Technology

Dana Lear | NASA/XI5

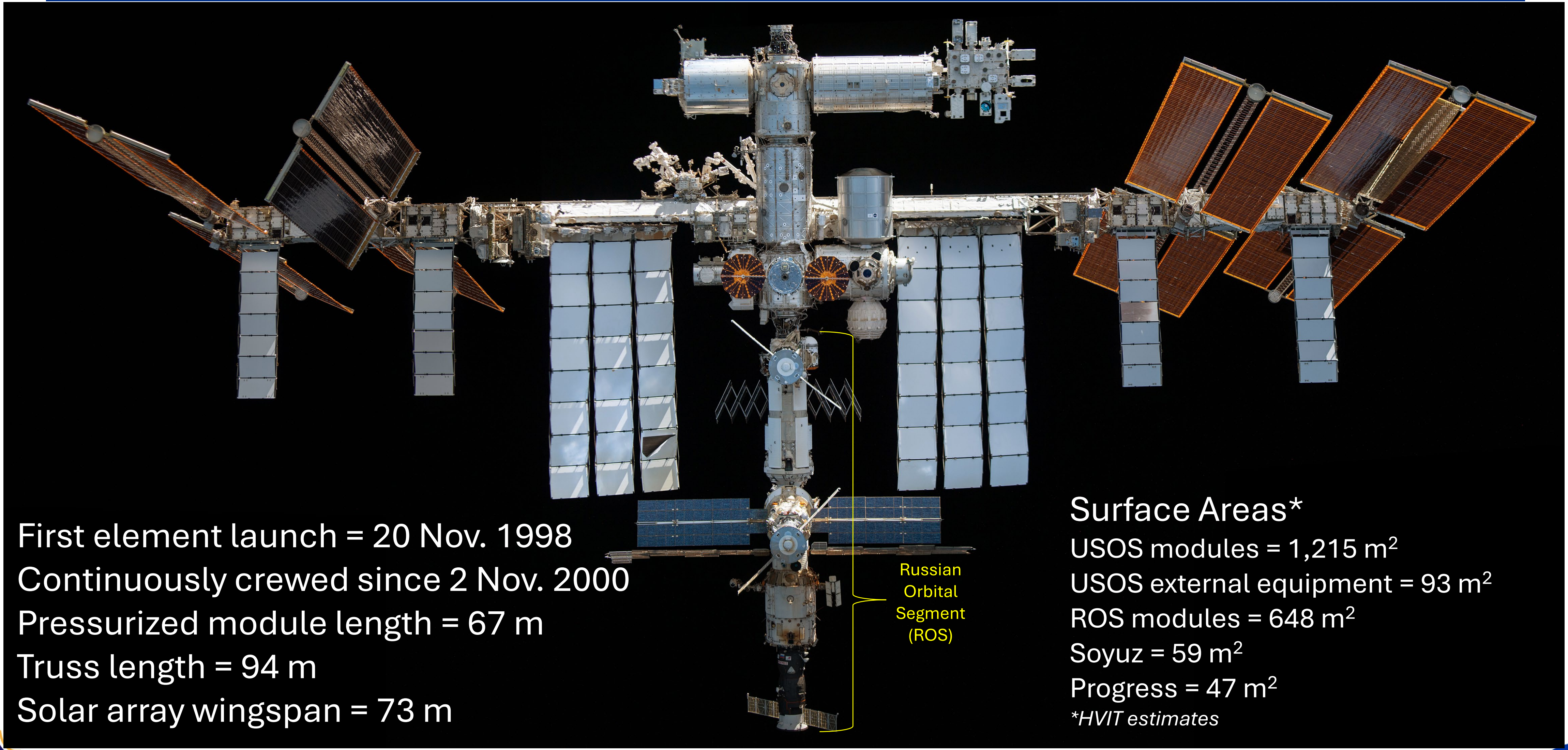
Christopher J. Cline II | NASA/XI5

Outline

- ISS Overview
- Analysis
  - *Tools*
  - *Failure Criteria*
  - *Environment Models*
  - *Altitude & Attitude*
  - *Assembly Sequence*
  - *Exposure Times*
  - *Ballistic Limit Equations*
- Results
  - *Rolled-up Risk*
  - *Discussion*

iss061e005542.jpg

ISS Overview

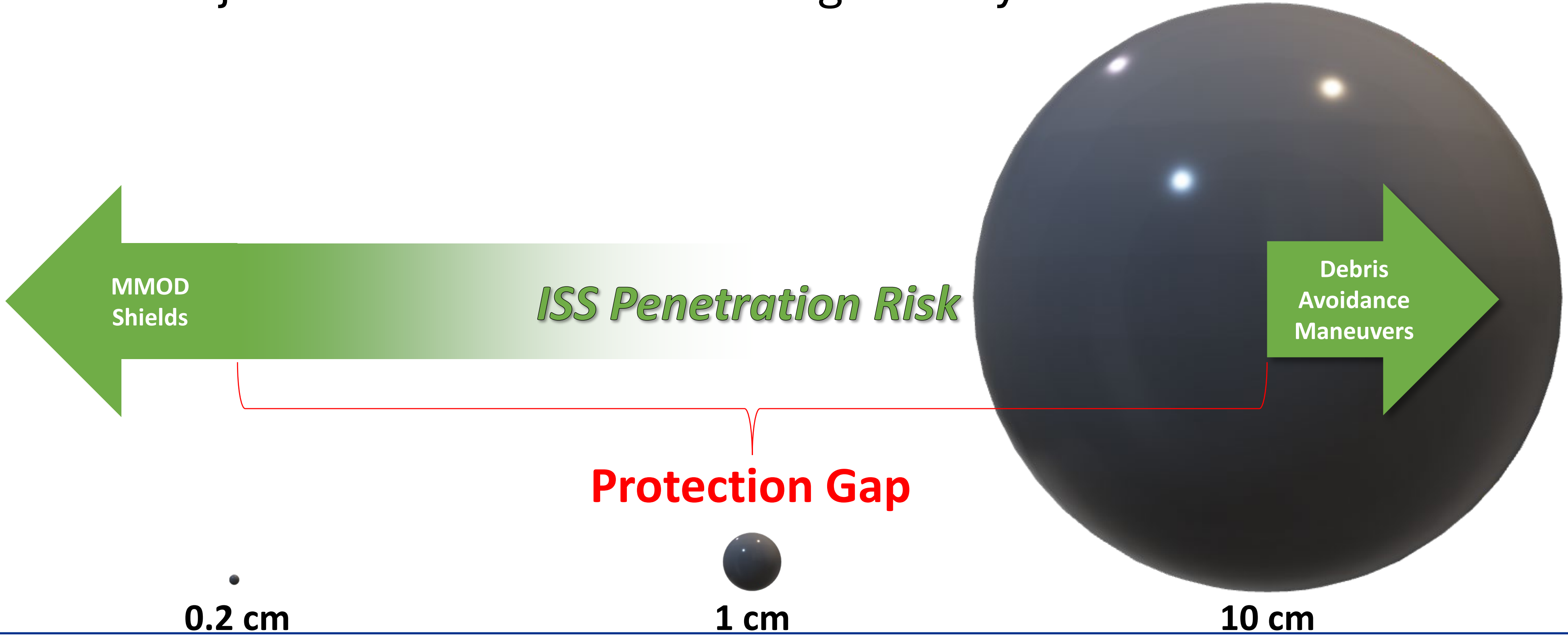


First element launch = 20 Nov. 1998
Continuously crewed since 2 Nov. 2000
Pressurized module length = 67 m
Truss length = 94 m
Solar array wingspan = 73 m

Surface Areas*
USOS modules = 1,215 m^2
USOS external equipment = 93 m^2
ROS modules = 648 m^2
Soyuz = 59 m^2
Progress = 47 m^2
**HVIT estimates*

MMOD Protection Gap

- MMOD Shields
  - *ROS: Regions w/limited protection can defeat particle diameters up to about 2 mm*
  - *USOS: High performance areas can stop particle diameters up to about 10 mm*
- Tracked objects >10 cm diameter can generally be avoided



Analysis Overview (1/4)

- Start: 11/20/1998 (first element launch)
- End: 12/31/2030 (nominal EOL)
- Scope
  - *Permanent*
    - 7 Russian segment modules: SM, FGB, MRM1, MRM2, MLM, Airlock, RS Node **(648 m^2)**
      - *Note: DC1 (33 m^2) was replaced in 2021 with MLM and Airlock (48 m^2)*
    - 14 USOS modules: Node1, Node2, Node3, PMA1, PMA2, PMA3, Lab, Airlock, Columbus, JEM, Cupola, PMM, BEAM, NanoRacks Airlock **(1,215 m^2)**
    - 4 USOS critical items: CMG, TCS, PCU, AMS **(93 m^2)**
  - *Visiting Vehicles*
    - Soyuz **(59 m^2)** & Progress **(47 m^2)**
- Items not included
  - *US visiting vehicles (crew and cargo)*
  - *US solar arrays and radiators*

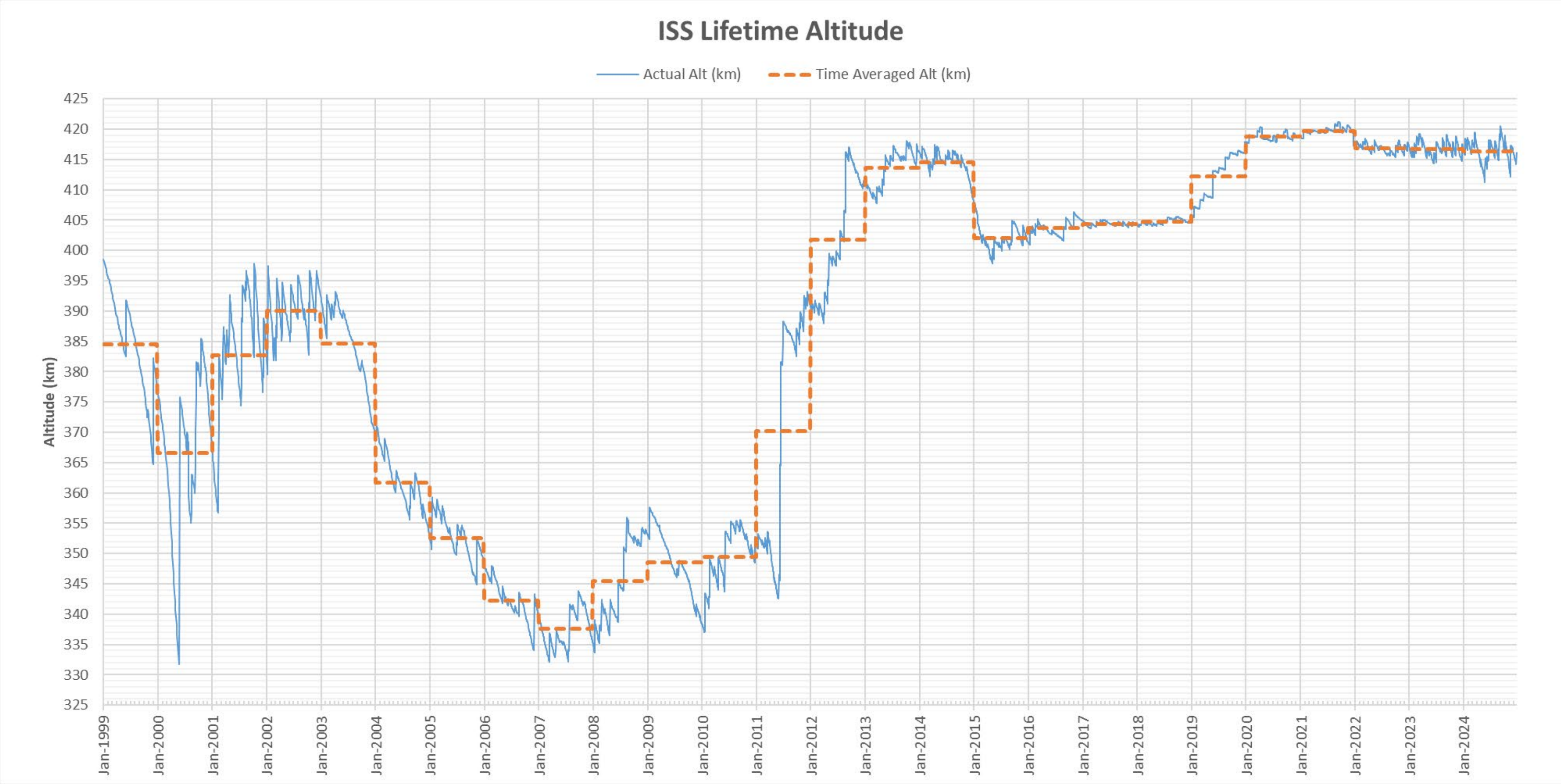
Max. exposure time (FGB) = 32.11 years
Min. exposure time (RS Node) = 9.10 years

Analysis Overview (2/4)

- Risk Analysis Code
  - *Bumper 3*
- Environments
  - *ORDEM 3.2*
  - *MEM 3*
- Attitude
  - *Single orientation assumed for most segments*
- Assembly Sequence
  - *Permanent modules: simplified into 7 blocks*
  - *Visiting vehicles: individual models for each docking location*
- Exposure Times
  - *Permanent modules: adjusted for assembly stage arrival times*
  - *Visiting vehicles: adjusted based on as-flown flight program history*

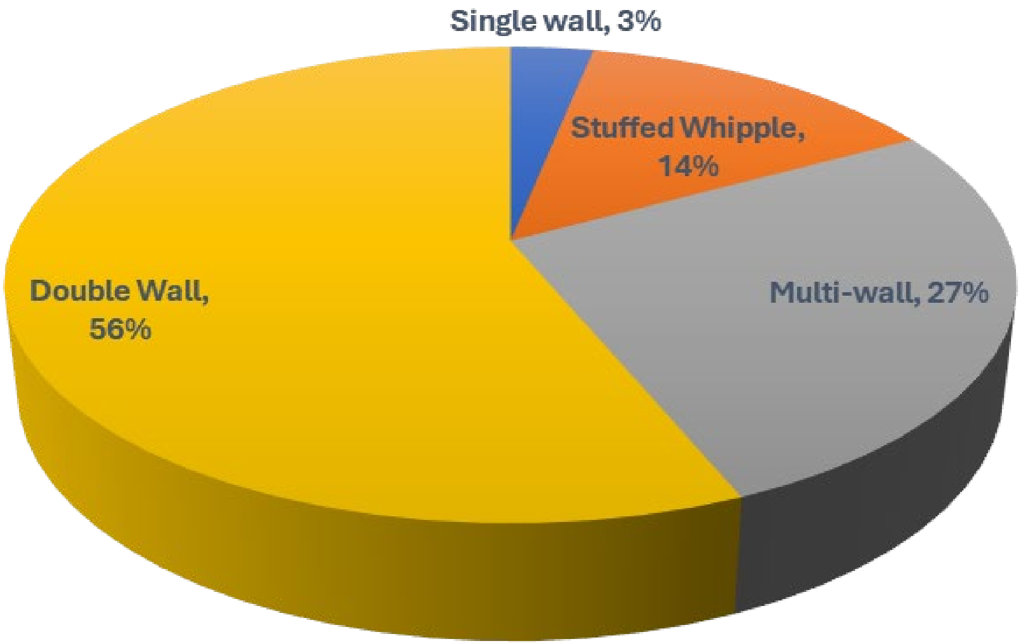
Analysis Overview (3/4)

- Altitude
  - *1998-2024: Constant time-averaged value per year*
  - *2025-2030: Assumed 416 km*



Analysis Overview (4/4)

- Ballistic Limit Equations
  - *25 distinct BLEs, w/multiple subtypes*

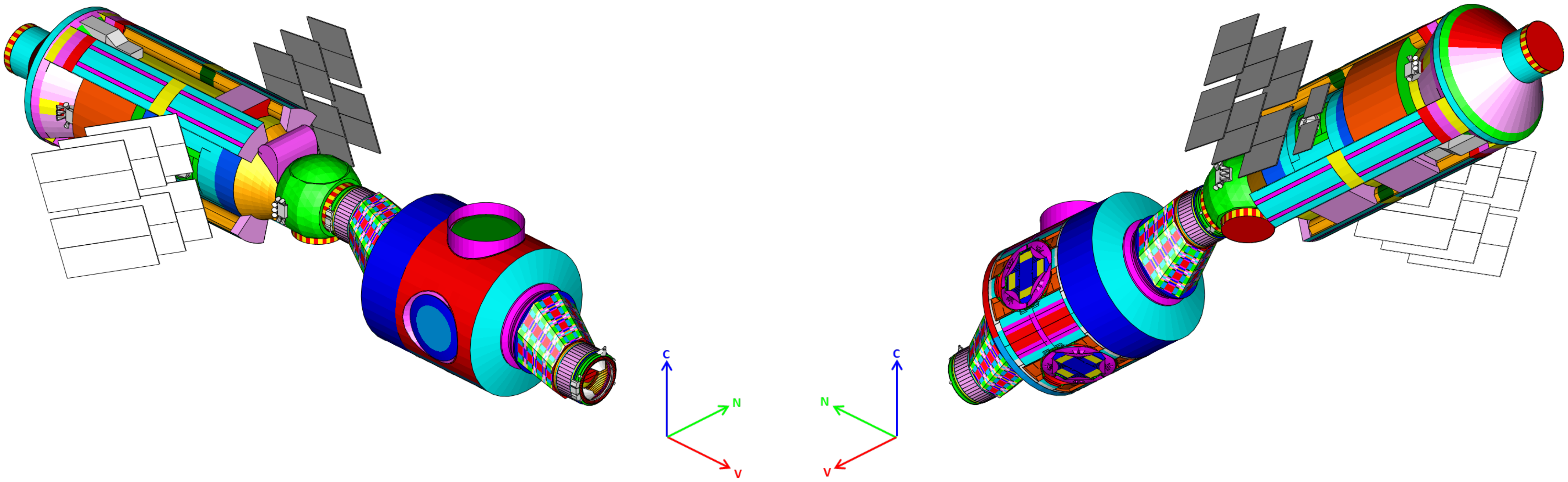


- Failure Criteria

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

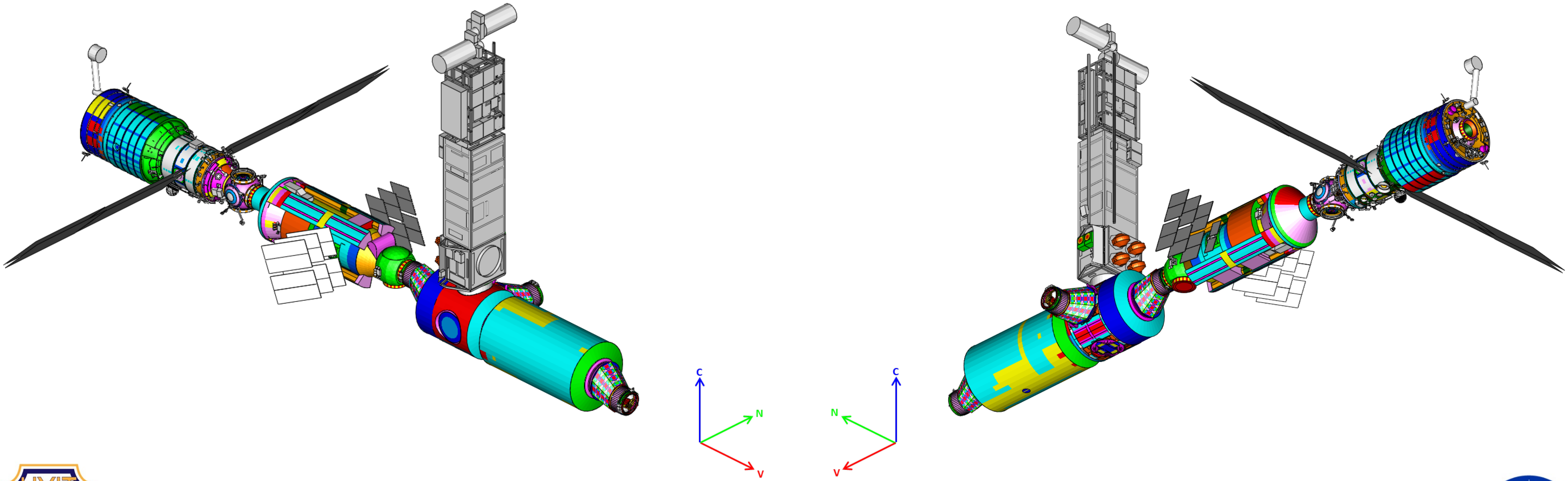
Assembly Sequence (1/7)

Block 1
20-Nov-98 thru 26-Jul-00 (1.68 years)
FGB, Node 1, PMA 1 & PMA 2
Attitude = X nadir spin



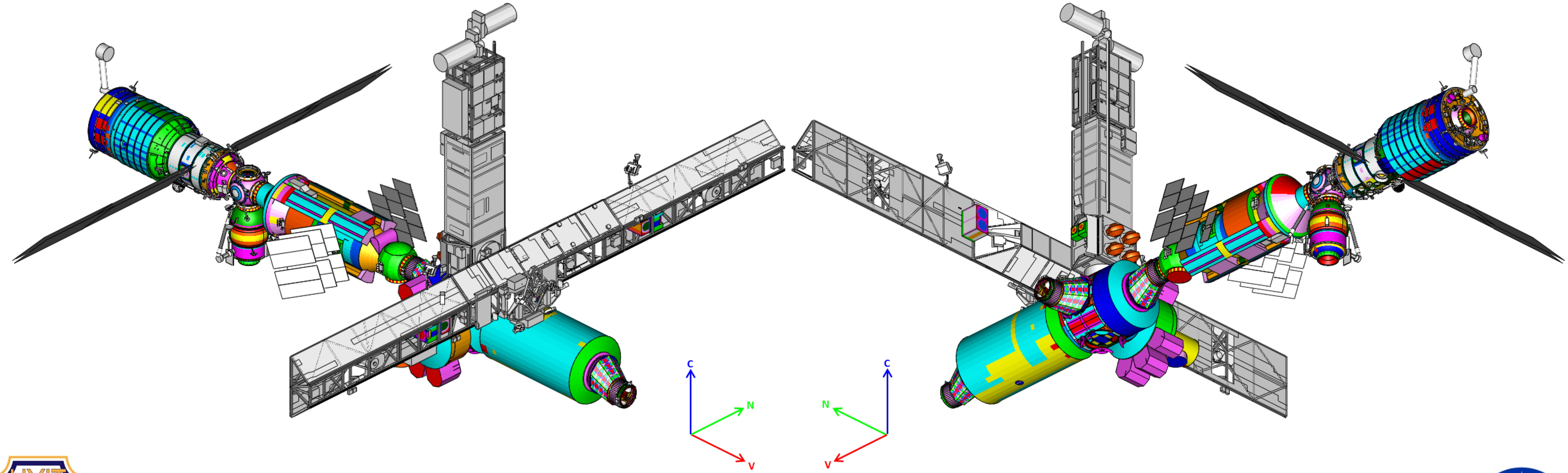
Assembly Sequence (2/7)

Block 2
26-Jul-00 thru 14-Jul-01 (0.97 years)
add Service Module, Z1, PMA 3, P6, US Lab
Attitude = +XVV Z nadir (YPR=0°, 345°, 0°)



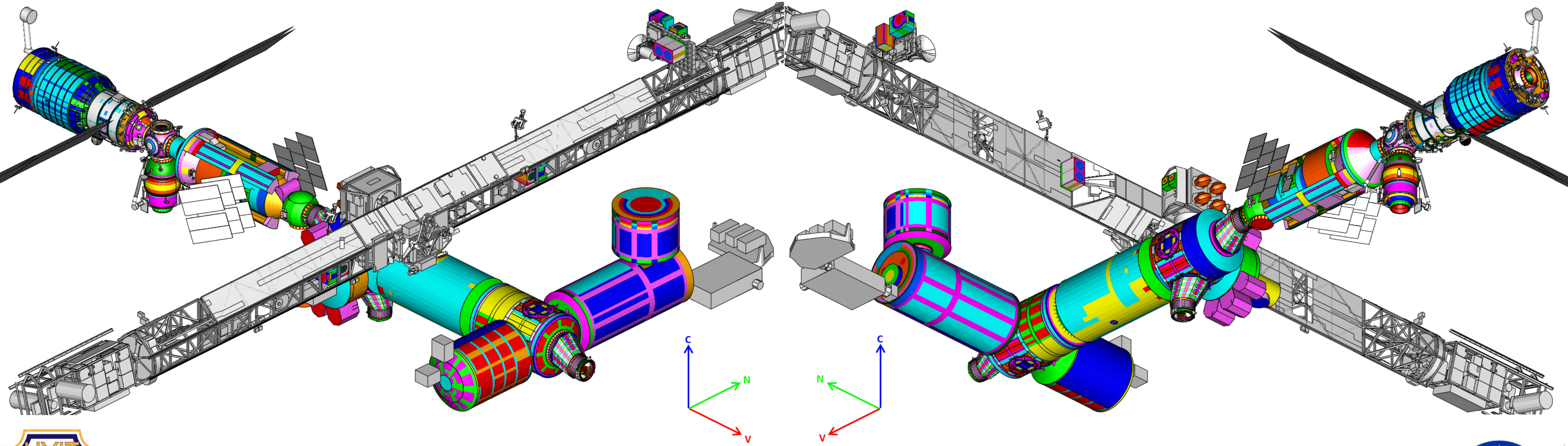
Assembly Sequence (3/7)

Block 3
14-Jul-01 thru 11-Sep-06 (5.16 years)
add Airlock, DC1, S0, S1, P1 & SMDP #1-3,7-9
Attitude = XVV Z nadir (YPR=350°, 350°, 0°)



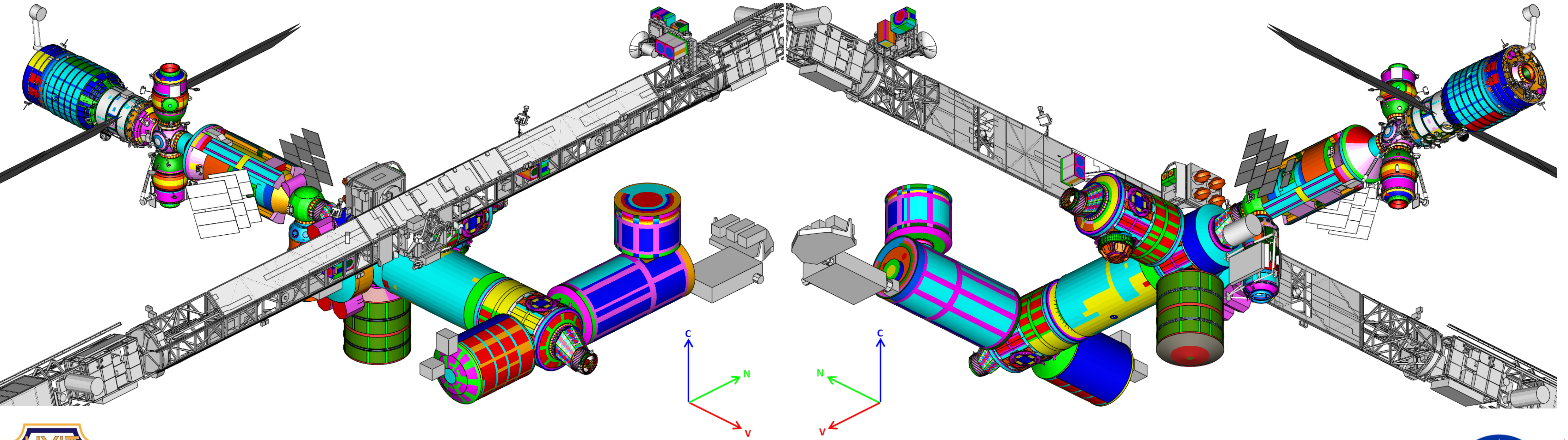
Assembly Sequence (4/7)

Block 4
11-Sep-06 thru 17-Mar-09 (2.52 years)
add P3/4, S3/4, Node 2, Columbus, JEM & SMDP #4-6, 10-23
Attitude = XVV Z nadir (YPR=357°, 357°, 1°)



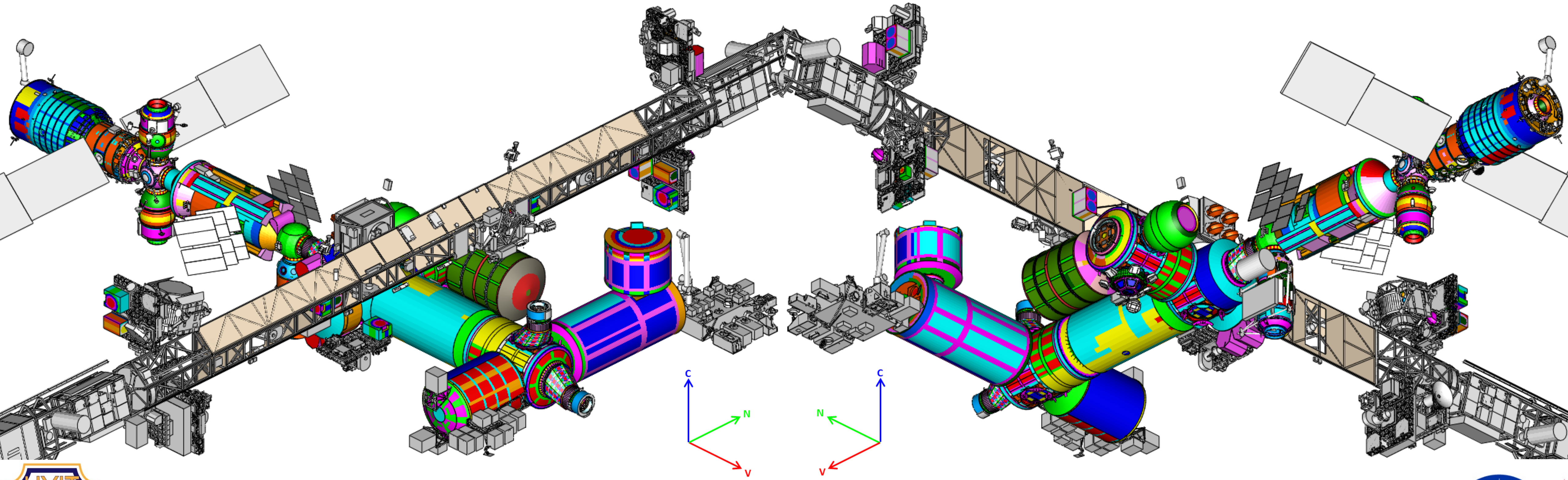
Assembly Sequence (5/7)

Block 5
17-Mar-09 thru 31-Dec-15 (6.79 years)
add S6, MRM2, Node 3, Cupola, MRM1, PMM
Attitude = XVV Z nadir (YPR=357°, 357°, 1°)



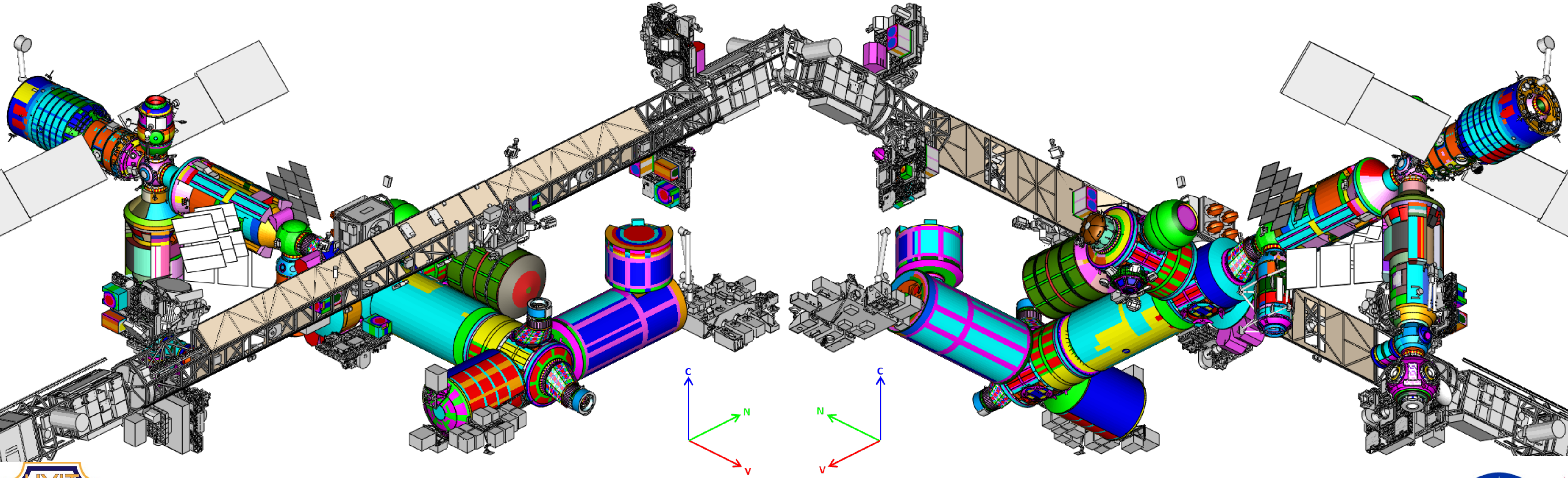
Assembly Sequence (6/7)

Block 6
31-Dec-15 thru 26-Jul-21 (5.57 years)
PMM moves to N3f, add BEAM, IDA2, PMA3/IDA3 moves to N2z
Attitude = XVV Z nadir (YPR=356°, 355°, 1°)

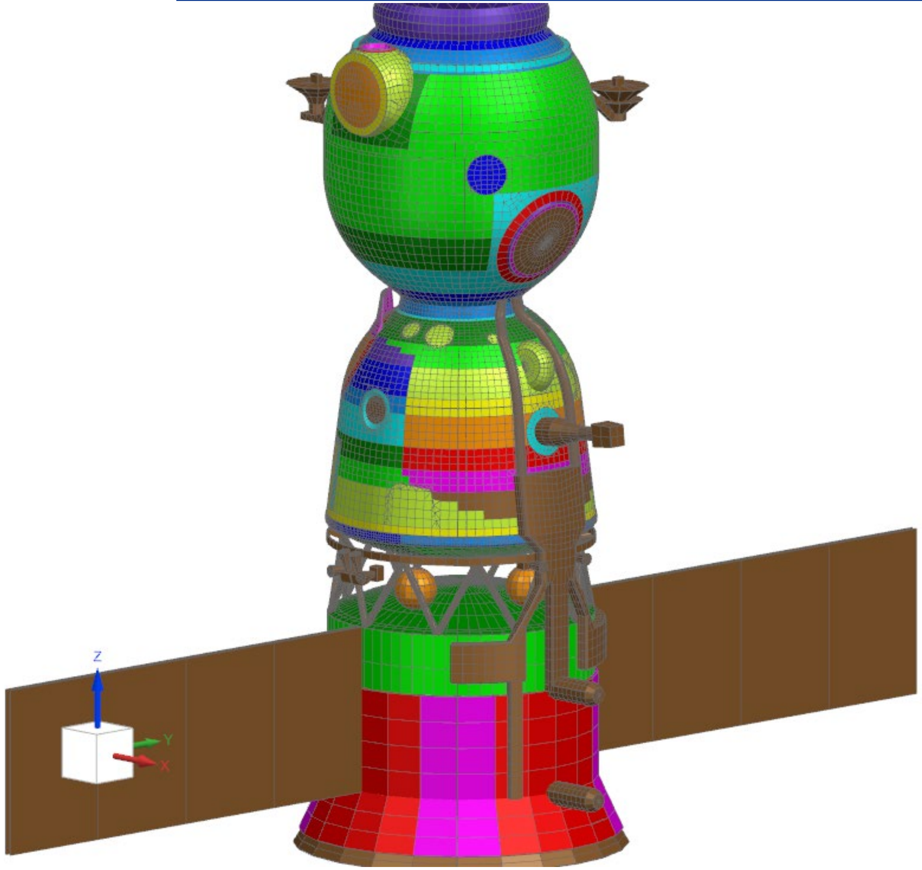


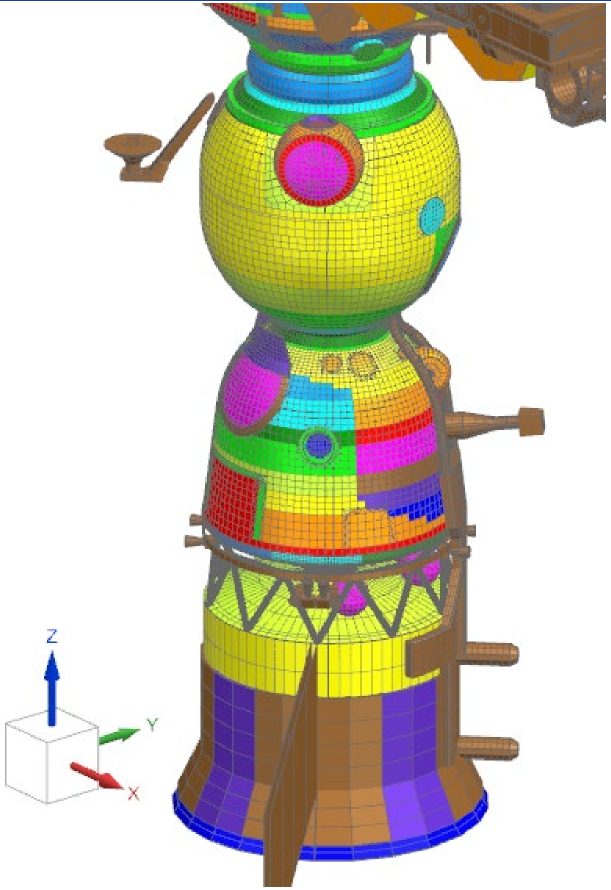
Assembly Sequence (7/7)

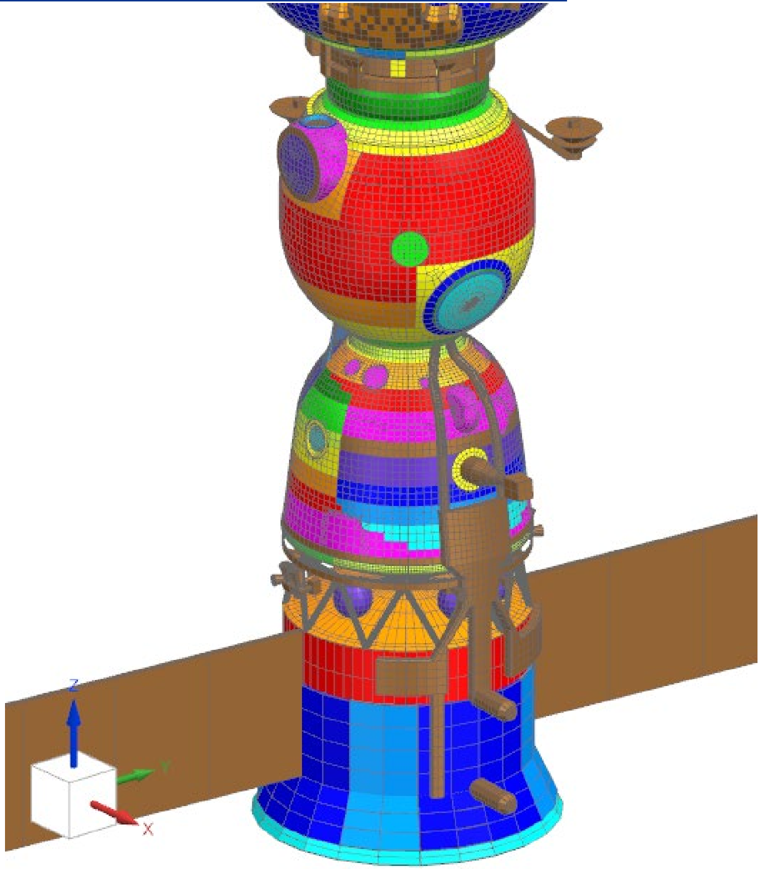
Block 7
26-Jul-21 thru 31-Dec-30 (9.44 years)
Add NanoRacks Airlock, MLM replaces DC1, RS Node, radiator & airlock from MRM1 to MLM
Attitude = XVV Z nadir (YPR=356°, 355°, 1°)



Visiting Vehicles (1/4)





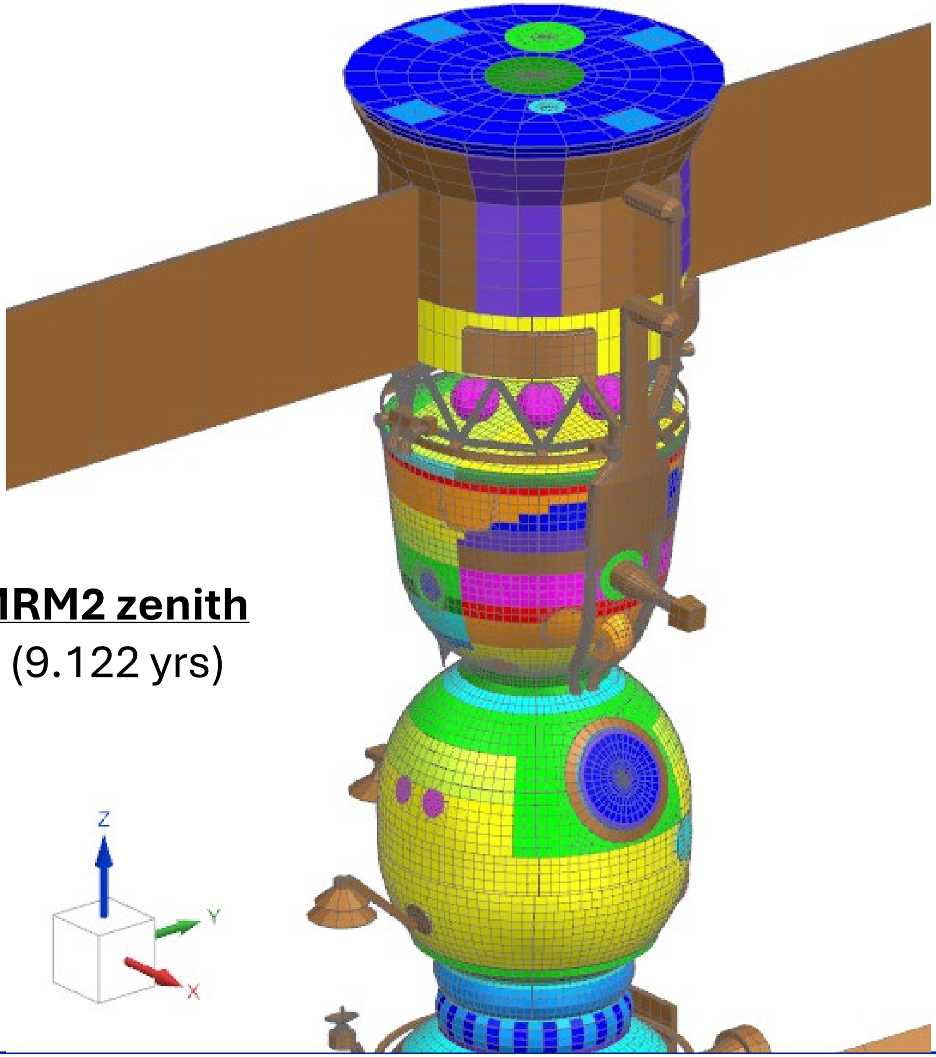


<u>Soyuz at DC1 nadir</u>
2001-2009 (8.255 yrs)

<u>Soyuz at MRM1 nadir</u>
2009-2030 (14.67 yrs)

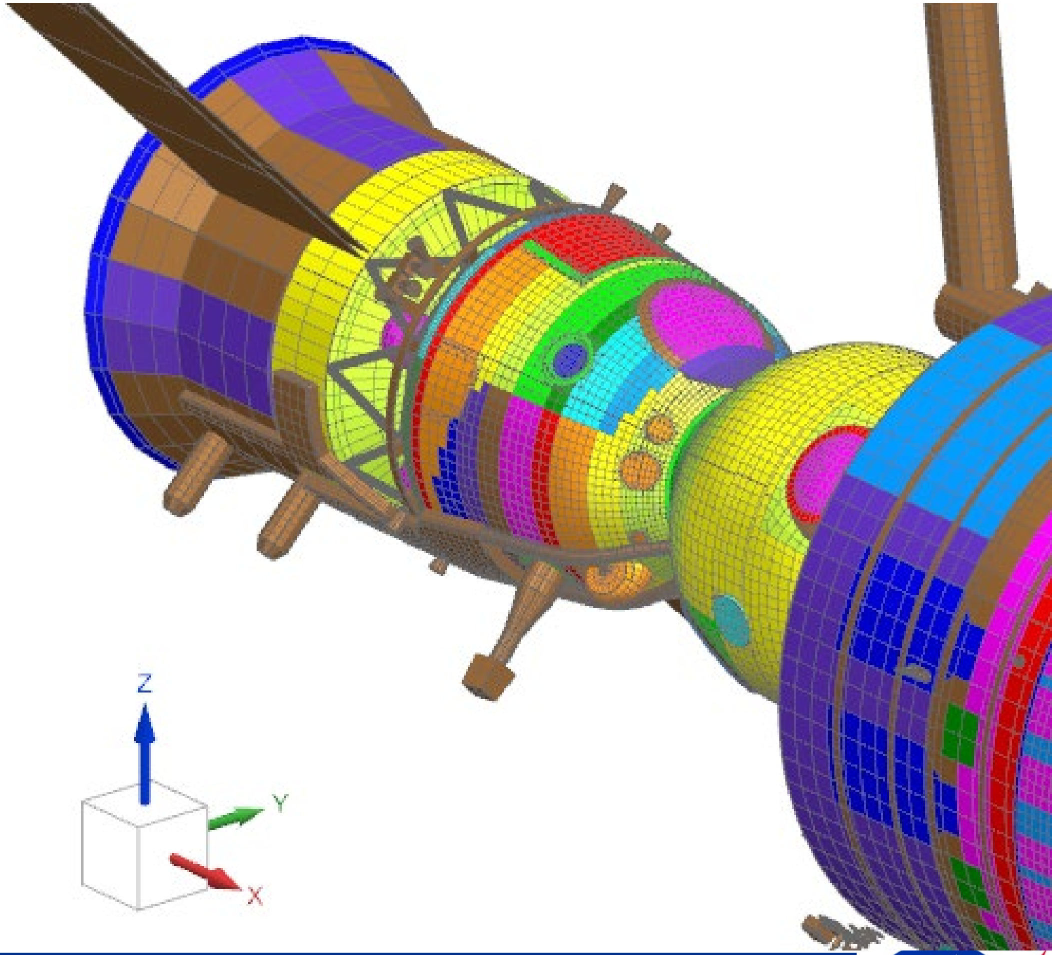
<u>Soyuz at MLM/RS Node nadir</u>
2021-2030 (5.210 yrs)

Visiting Vehicles (2/4)

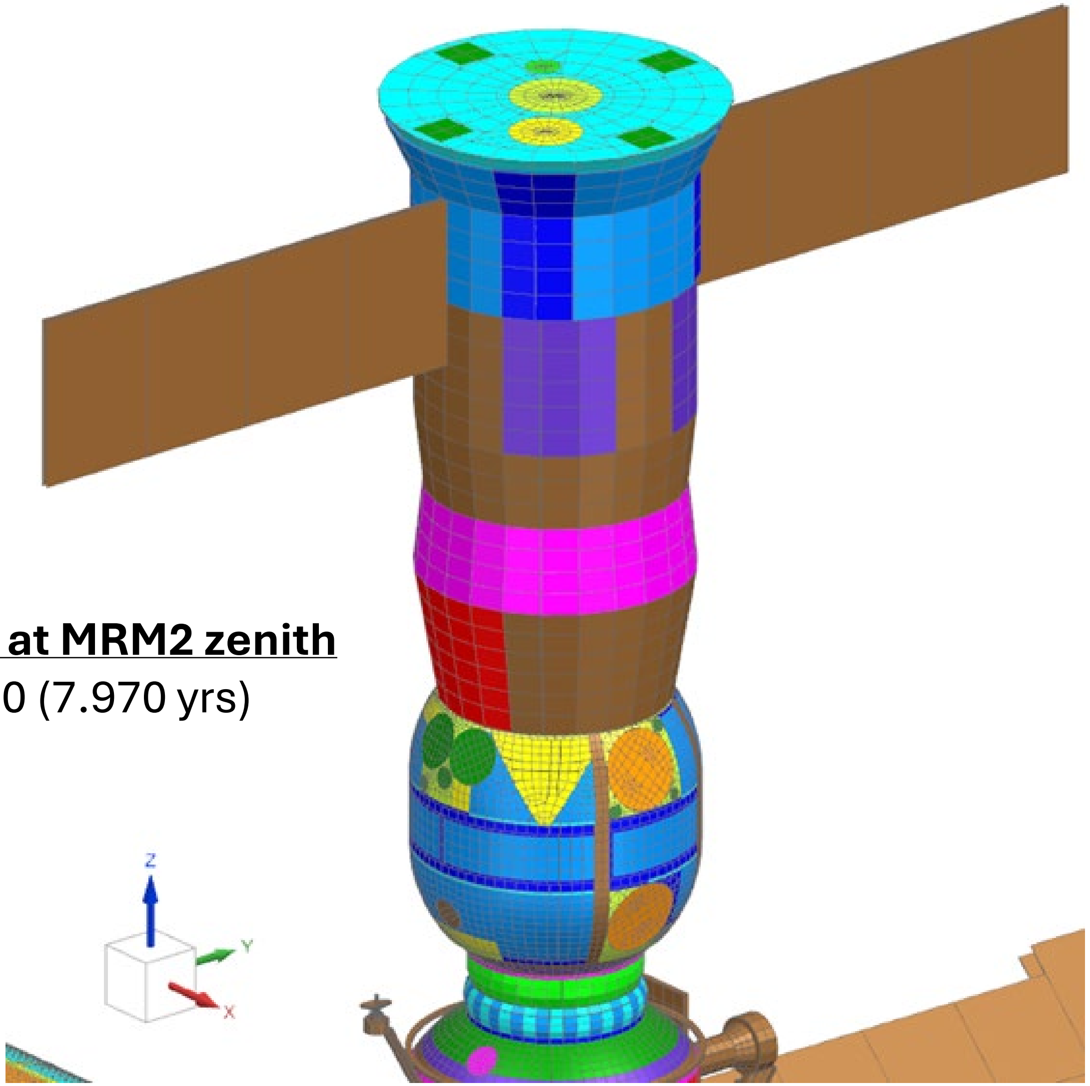


<u>Soyuz at MRM2 zenith</u>
2010-2023 (9.122 yrs)

<u>Soyuz at SM aft</u>
2000-2020 (1.744 yrs)

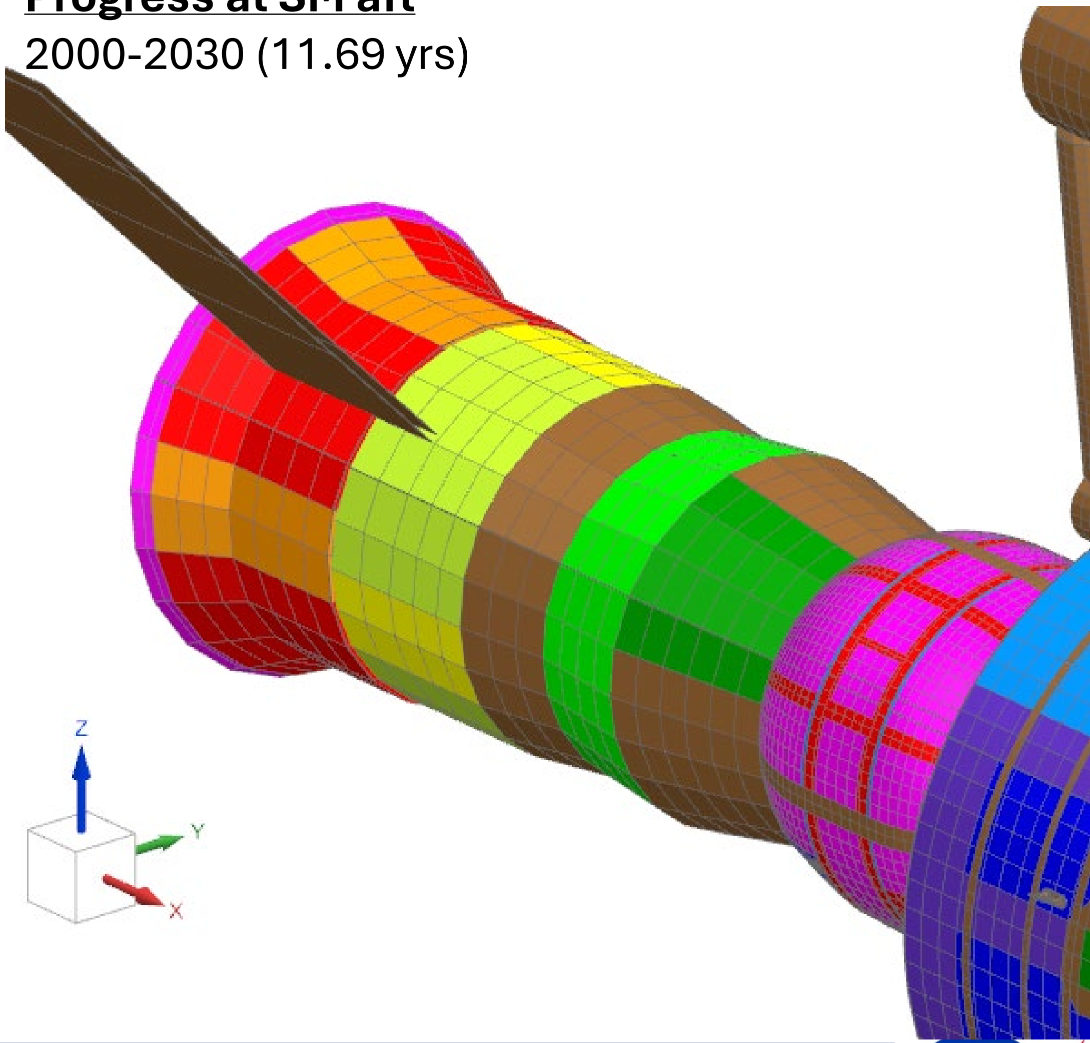


Visiting Vehicles (3/4)

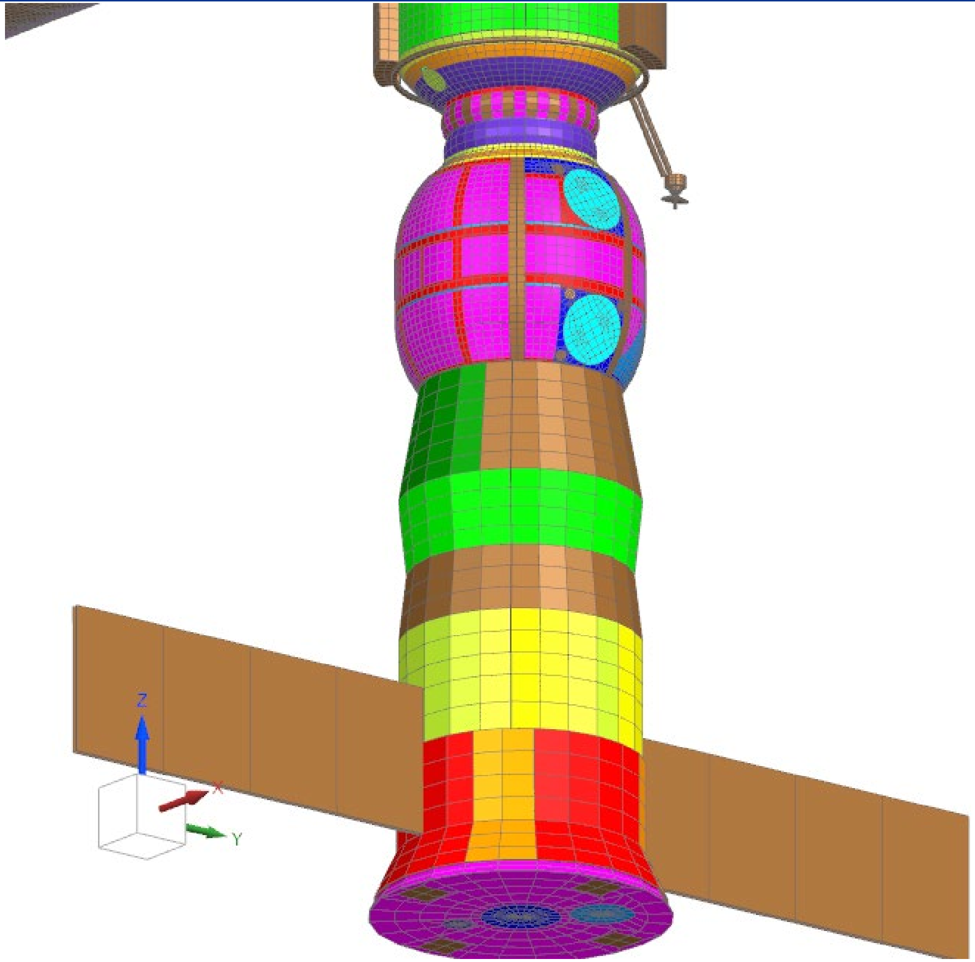


Progress at MRM2 zenith
2021-2030 (7.970 yrs)

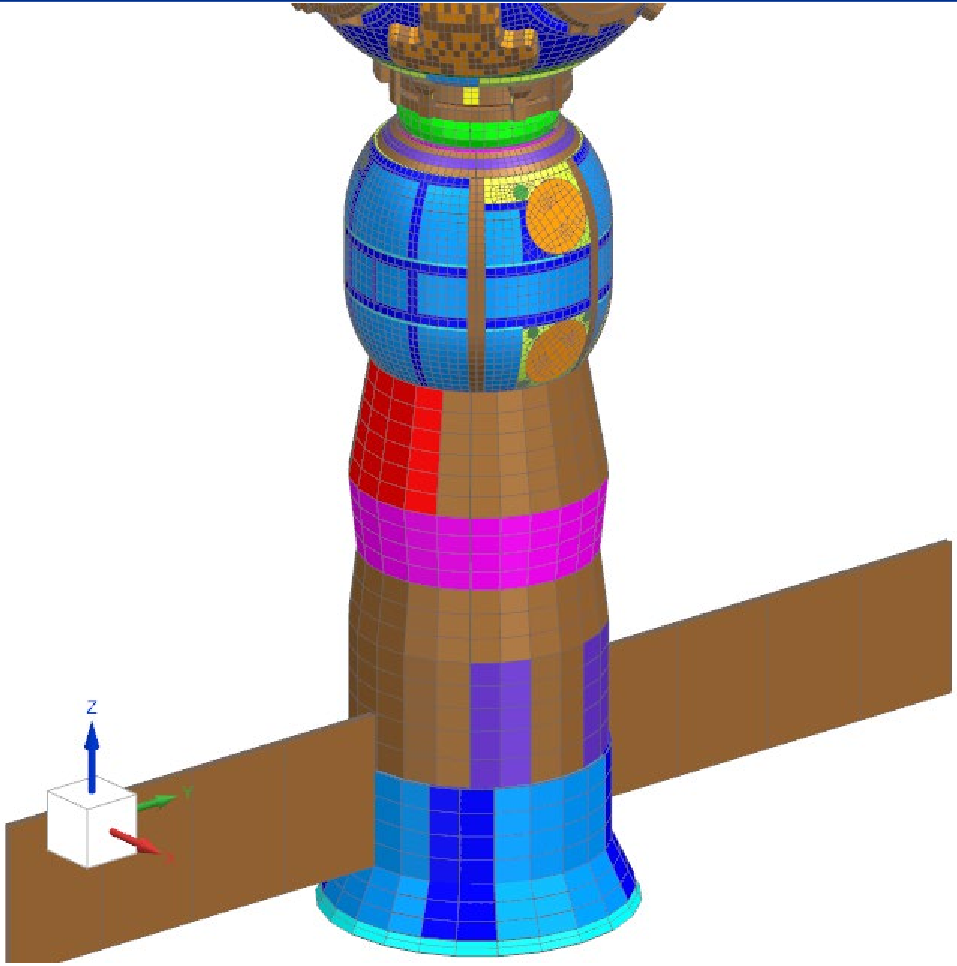
Progress at SM aft
2000-2030 (11.69 yrs)



Visiting Vehicles (4/4)



<u>**Progress at DC1 nadir**</u>
2000-2021 (13.87 yrs)



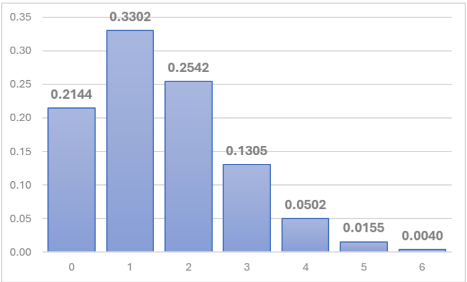
<u>**Progress at MLM/RS Node nadir**</u>
2021-2030 (1.570 yrs)

Results (1998-2030)

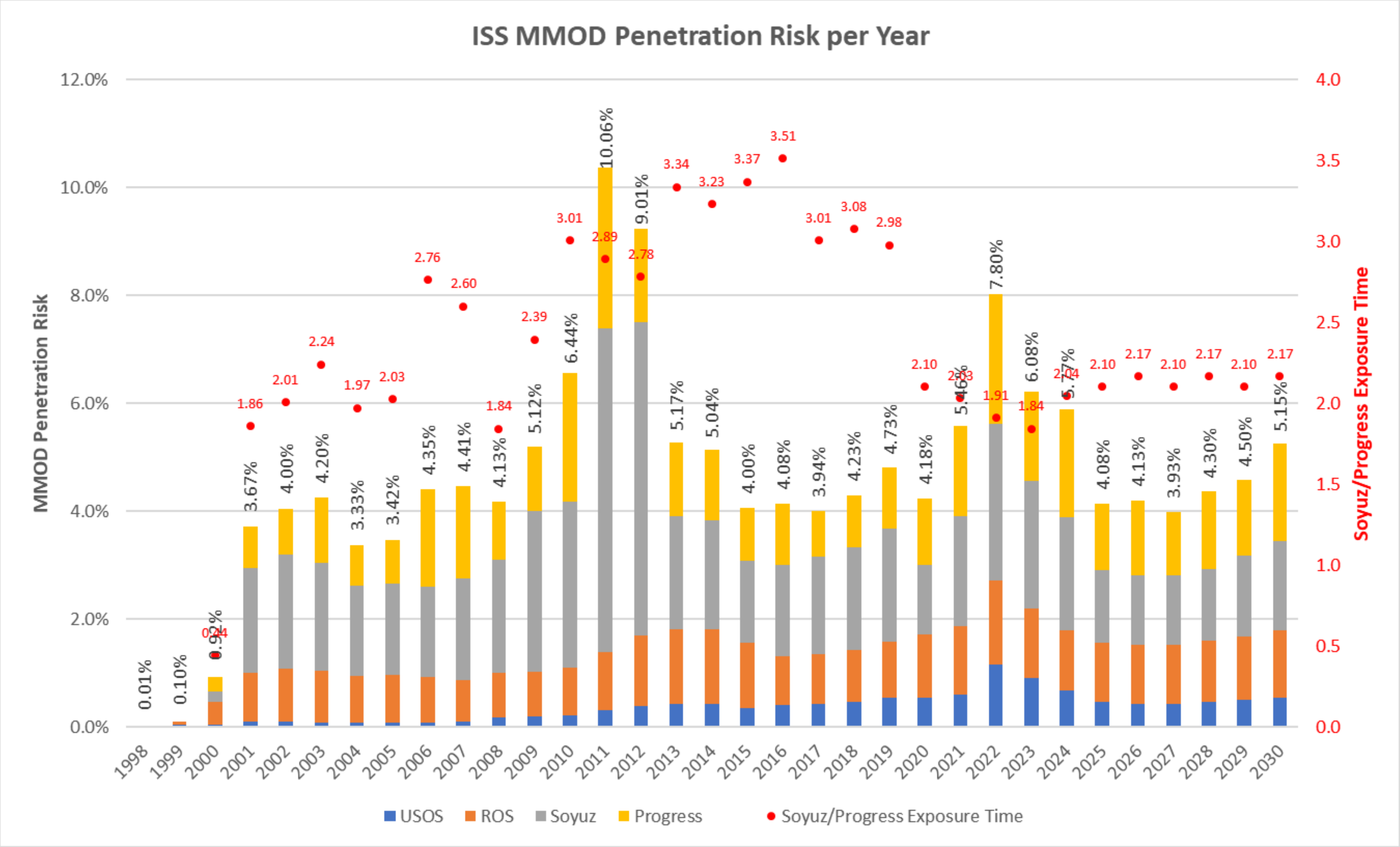
ORDEM 3.2 + MEM 3	Modules		Visiting Vehicles (VV)		Total		
1998 - 2030	*USOS*	*ROS*	*Soyuz*	*Progress*	*Modules*	*VV*	*ISS*
Expected # of Failures (N)	0.1182	0.3284	0.6631	0.4301	0.4466	1.0932	1.5398
Probability of No Failure (e^{-N})	0.8885	0.7201	0.5152	0.6504	0.6398	0.3351	0.2144
Failure Risk (1-PNF)	**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%*	

- Bumper output assumes a Poisson probability distribution
  - *P(k)* = $\frac{N^k e^{-N}}{k!}$
  - *N = mean number of failures (independent events)*
  - *k = number of events (failures)*
  - *When k=0, P(k) simplifies to* $\mathbf{e^{-N}}$ *(0.2144)*
  - *Probability of* *1 or more failures* *is* ***1-PNF*** *(0.7856)*
  - *Probability of* *1 failure* *is* *0.3302*

k	P(k)	1-P(k)
0	0.2144	0.7856
1	0.3302	0.6698
2	0.2542	0.7458
3	0.1305	0.8695
4	0.0502	0.9498
5	0.0155	0.9845
6	0.0040	0.9960



Results (1998-2030)



Results (1998-2030)

Module	Exposure Time (Yr)	ORDEM 3.2						MEM 3			MMOD Total	% Total
		TOTAL	*NaK*	*LD*	*MD*	*HD*	*Intacts*	*TOTAL*	*LD*	*HD*		
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	7.64E-03	0.00E+00	4.85E-06	7.67E-04	6.86E-03	3.95E-06	2.72E-03	7.52E-04	1.97E-03	1.04E-02	0.67%
Cupola	20.89	7.36E-03	0.00E+00	6.69E-06	3.78E-04	6.97E-03	4.60E-06	8.95E-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		**8.182E-02**	0.000E+00	**7.706E-04**	**2.731E-02**	**5.282E-02**	**9.171E-04**	**3.638E-02**	**1.772E-02**	**1.867E-02**	**1.182E-01**	**7.7%**
ROS		**1.739E-01**	0.000E+00	**7.974E-04**	**2.201E-02**	**1.507E-01**	**3.555E-04**	**1.545E-01**	**8.327E-02**	**7.120E-02**	**3.284E-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		**5.326E-01**	0.000E+00	**1.289E-03**	**3.330E-02**	**4.979E-01**	**1.136E-04**	**1.306E-01**	**6.674E-02**	**6.382E-02**	**6.631E-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		**3.349E-01**	0.000E+00	**8.730E-04**	**2.062E-02**	**3.134E-01**	**7.164E-05**	**9.520E-02**	**5.128E-02**	**4.393E-02**	**4.301E-01**	**27.9%**
ISS Total		**1.1232**	0.0000	**0.0037**	**0.1032**	**1.0148**	**0.0015**	**0.4166**	**0.2190**	**0.1976**	**1.5398**	
		72.9%		0.2%	6.7%	65.9%	0.1%	**27.1%**	14.2%	12.8%		

Highest MMOD risk in permanent modules

Highest MMOD risk in visiting vehicles

USOS = 7.7% of total MMOD Risk

ROS = 21.3% of total MMOD Risk

Soyuz = 43.1% of total MMOD Risk

Progress = 27.9% of total MMOD Risk

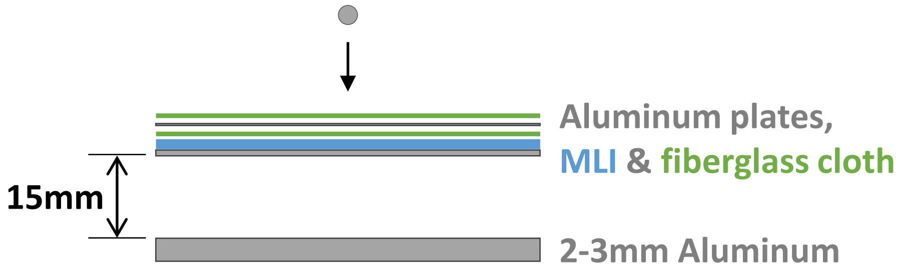
Results (1998-2030)

- Top 15 risk drivers for ISS
  - *60% of MMOD risk*
  - *4% ISS surface area*
- Dominated by Soyuz OM & Progress CM
  - *OM=Orbital Module*
  - *CM=Cargo Module*

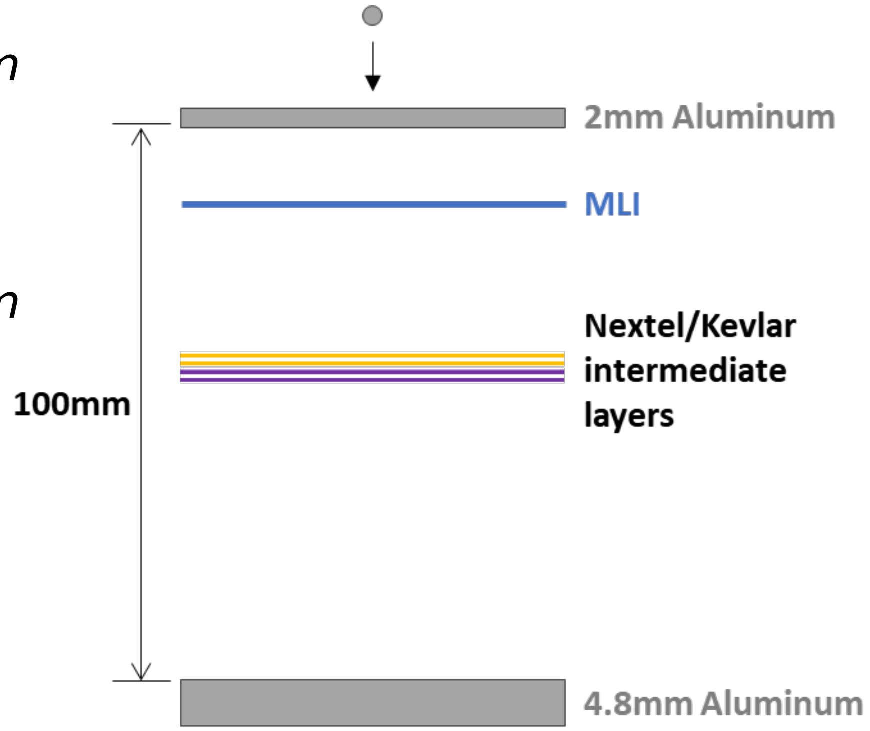
Module	Range	Area	PID	BLE	Critical OD Diam (cm) @ 7.5km/s & 0°				1998-2030			% Total Risk	
					Baseline		Soyuz/Progress Aug.		OD32	MEM3	MMOD Total		
		m^2			*MD*	*HD*	*MD*	*HD*				*range*	*cumulative*
Progress DC1	Cargo module - thin shell 2.0mm w add shield 0.5mm	6.411	405	Progress CM 2023	0.184	0.108	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%

ISS Shield Comparison

- Ballistic performance of Soyuz OM & Progress CM shields is limited by standoff and rear wall thickness
  - *Critical Al diameter at 7.5 km/s and 0° ≈ 0.2 cm*
- "Stuffed Whipple" shield
  - *Larger standoff & thicker rear wall*
  - *Critical Al diameter at 7.5 km/s and 0° ≈ 1.0 cm*



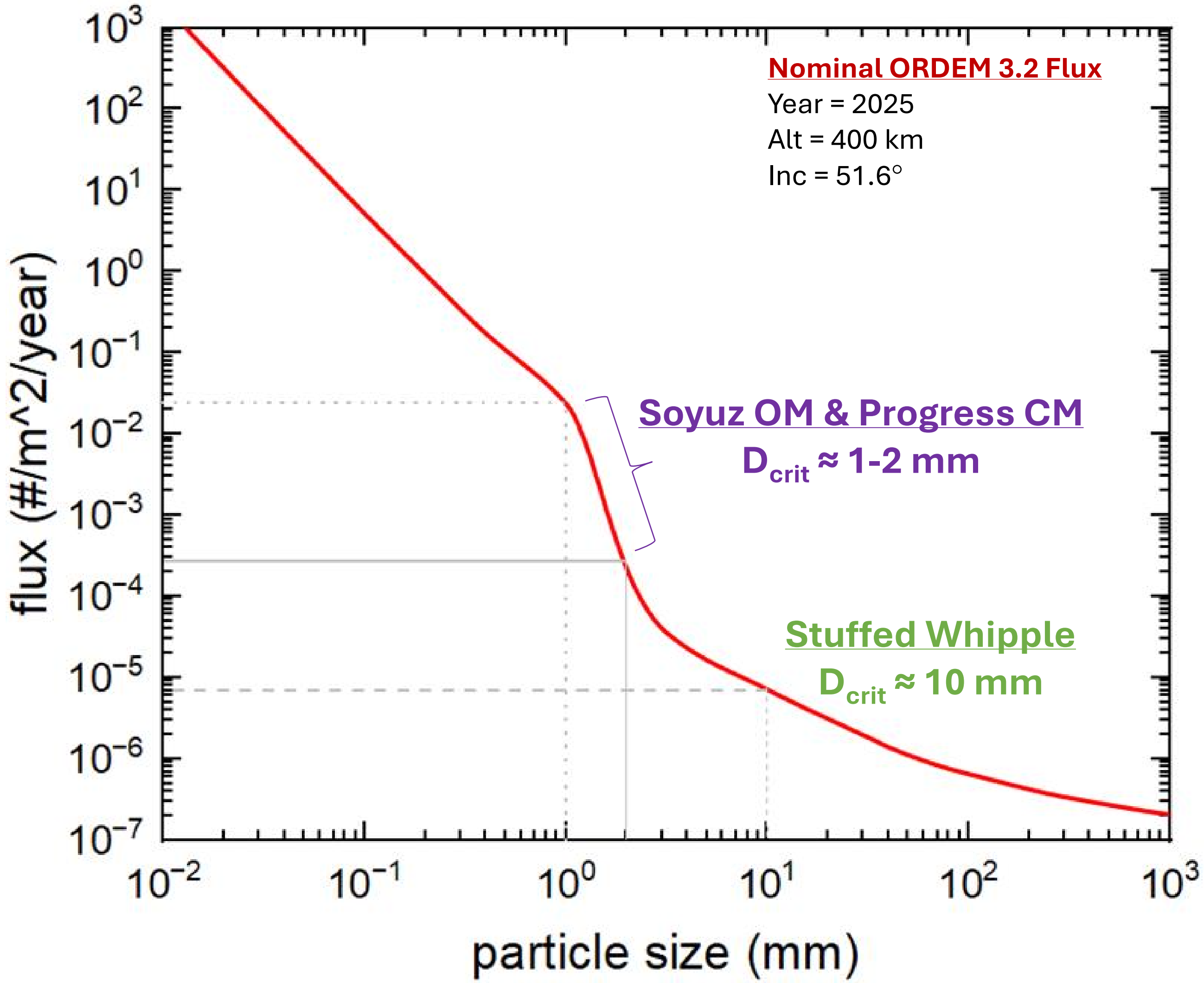
Soyuz OM & Progress CM



"Stuffed Whipple" Shield

ORDEM 3.2 Flux

- ISS risk is controlled by ORDEM 3.2
- Flux curve between 1 and 3 mm particle sizes is rapidly decreasing
- Flux is 3 orders of magnitude smaller at 10 mm

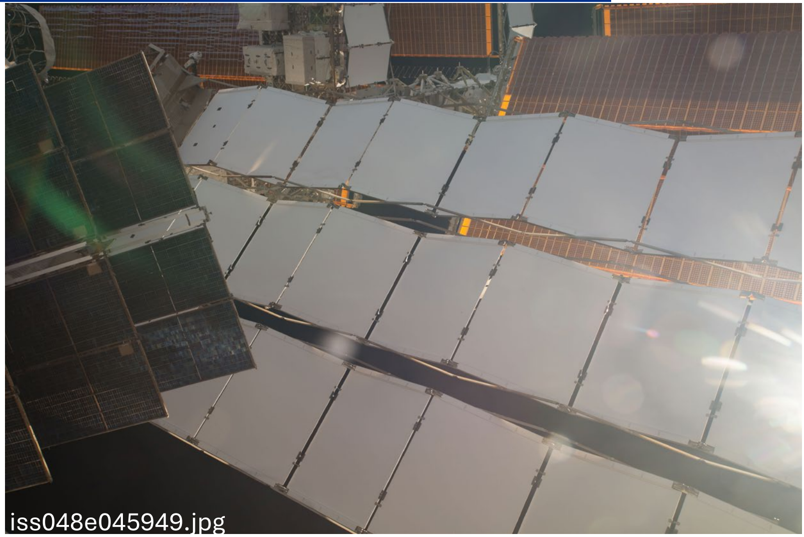


Factors Effecting ISS MMOD Risk Predictions (1/2)

- ISS has not experienced a critical penetration
- Undetected penetrations
  - *Pressure shell failure criterion is "threshold penetration"*
  - *The transition in a rear wall from cratering to detached spall to perforation can be subtle (small damage feature)*
  - *Most of the pressure shell is obscured by equipment racks →*
- Orbital debris environment
  - *There is considerable uncertainty in some of the debris flux predictions, most significantly in the millimeter size ranges 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*

Factors Effecting ISS MMOD Risk Predictions (2/2)

- ISS Configuration Choices
  - *To simplify the assessment, US solar arrays and radiators were not included (conservative)*
  - *Risk contributions neglected from USOS visiting vehicles*
    - Shuttle, Crew Dragon & Starliner
    - Cargo Dragon, Cygnus, HTV, HTV-X, ATV



- Ballistic Limit Equations (BLE)
  - *ISS uses site-specific as well as generic single and multi-wall equations*
  - *All are based on testing at speeds up to ~7 km/s*
  - *Complimentary hydrocode simulations have been used model the performance of the double-wall equation at >7 km/s*
- Shape Effects
  - *Research has indicated that debris shape can have a significant effect on risk. Analysis will be repeated as future work with ORDEM 4.0*

Thanks & Acknowledgements

- NASA/JSC Hypervelocity Impact Technology Group
  - *Dr. Eric Christiansen (Retired 2024)*
  - *Dana Lear (Retired 2025)*
  - *Kevin Deighton*
  - *Sam Treadgold*
  - *Dr. Kornel Nagy (NASA/JSC ES2)*
- NASA/JSC Orbital Debris Program Office
  - *Dr. Heather Cowardin*
  - *Dr. Mark Matney*
- NASA/JSC ISS Systems Engineering & Integration Office
  - *Charlie Gray*