MMOD-IMLI: Integrated Thermal Insulation and Micrometeoroid/Orbital Debris Protection

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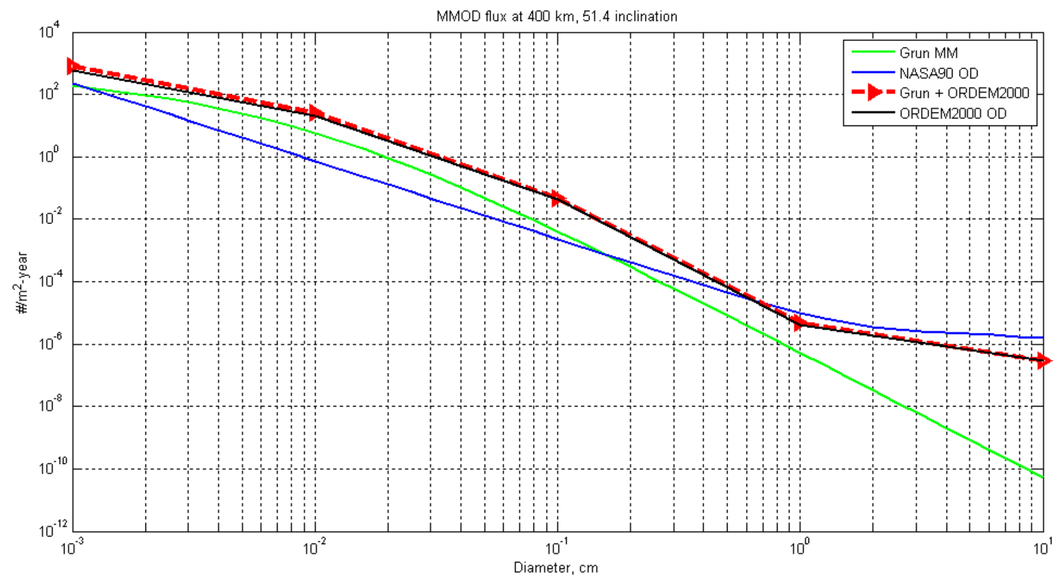
NASA SBIR Technologies Workshop
June 28, 2012

MMOD Protection

- Micrometeoroid/Orbital Debris (MMOD) is a risk for spacecraft, fuel depots and space stations
- Designers must provide MMOD protection, based on MMOD environment, size/geometry/orientation of spacecraft, duration of mission, and likelihood of critical damage



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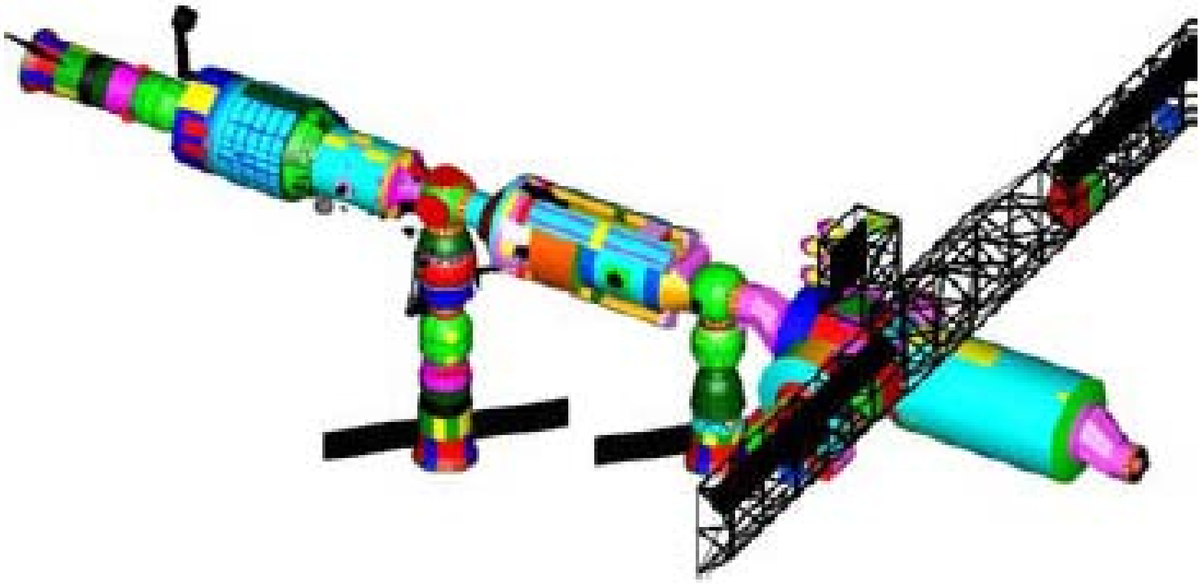
MMOD shielding on the ISS

- Adequate MMOD protection on the ISS is required for crew safety and mission success
- The ISS requires multiple MMOD shields
- Shield design based on risk assessments



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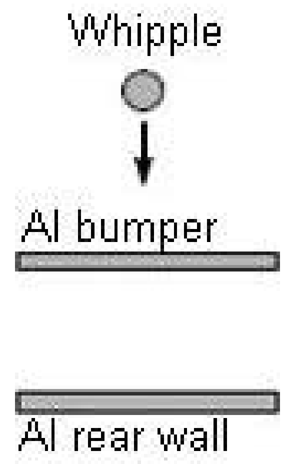
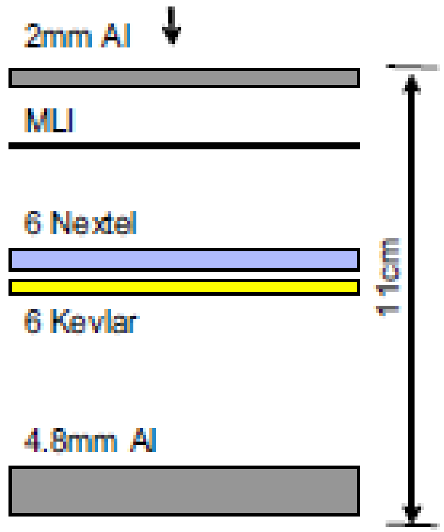
MMOD shields

- Whipple shields
  - Two plate shields
  - Spacing between outer bumper layer and spacecraft rear wall is critical to stopping power
  - To stop a 6.3mm particle @ 7km/s requires 20 kg/m^2



MMOD shields

- Stuffed Whipple shields
  - Uses additional high strength layers
  - Protects US Lab module of ISS
  - Designed to stop 1.3cm @ 7km/s
  - Massive at 27kg/m^2 (42kg/m^2 with rear wall)



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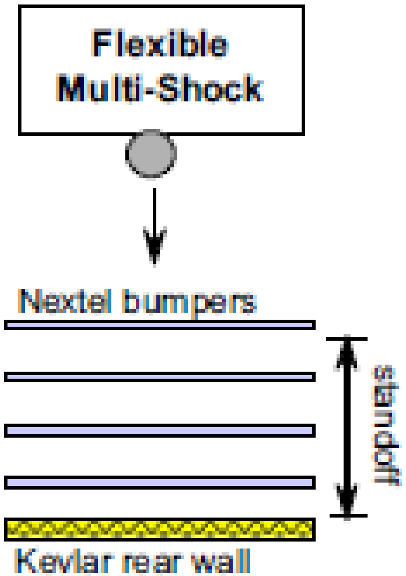
MMOD shields

- Nextel Multi-shock multiple layer shields
  - 4 layers Nextel ceramic fiber, Kevlar polyaramid layer
  - Penetration equations developed
  - Stopping power related to spacing and areal density

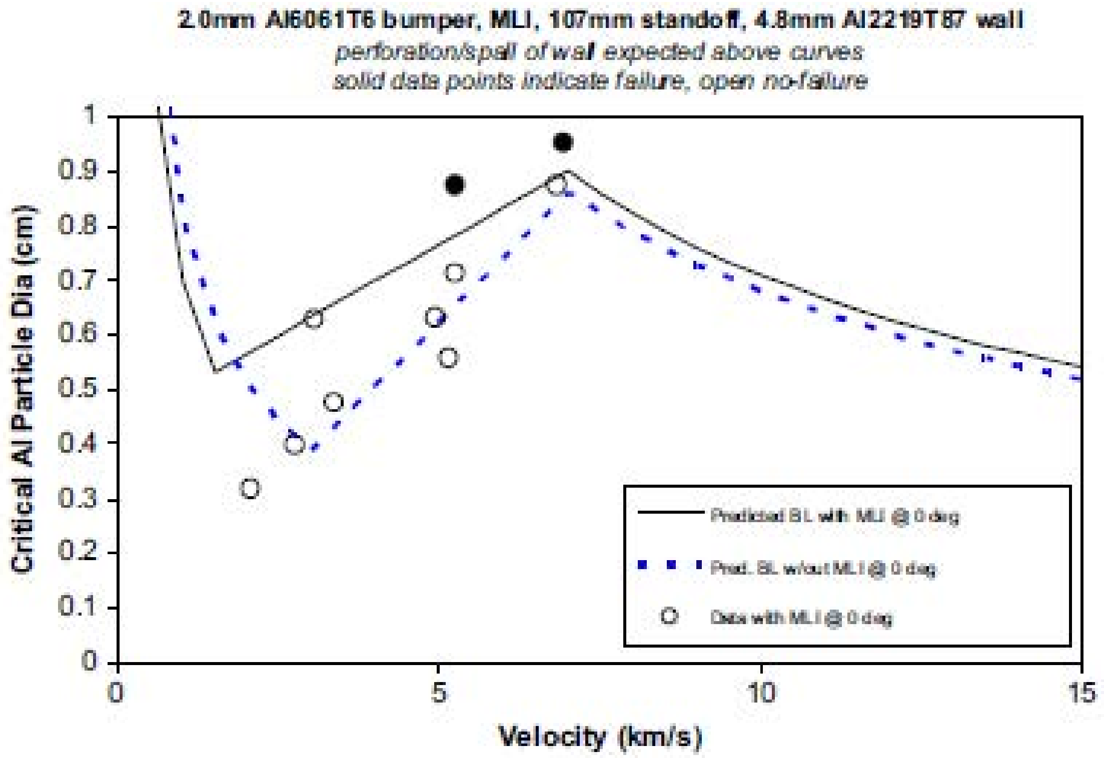


$$\text{Areal Density}_{\text{bumpers}} = 0.19 * \text{diameter}_{\text{particle}} * \text{density}_{\text{particle}}$$

$$\text{Areal Density}_{\text{rear wall}} = \frac{43.1 * \text{Mass}_{\text{particle}} * \text{Velocity}_{\text{particle}}}{\text{Spacing}^2 * (40/\text{Yield Stress}_{\text{rear wall}})^{0.5}}$$

MMOD shields

- Conventional MLI offers slight MMOD protection



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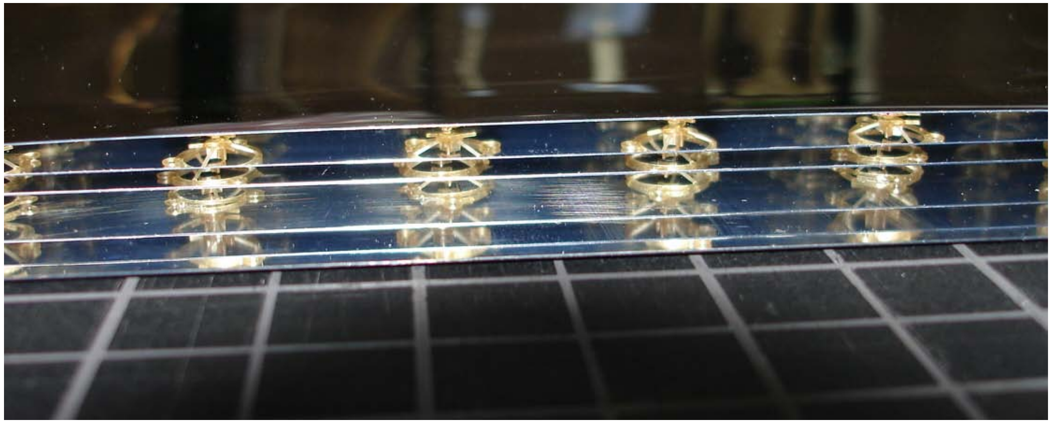
IMLI discrete spacers

- IMLI discrete spacer technology
  - Can provide large interlayer **spacing**
  - Can support high strength ballistic layers
  - Can provide high performance thermal insulation
  - Heavy bumper plate and standoffs not required



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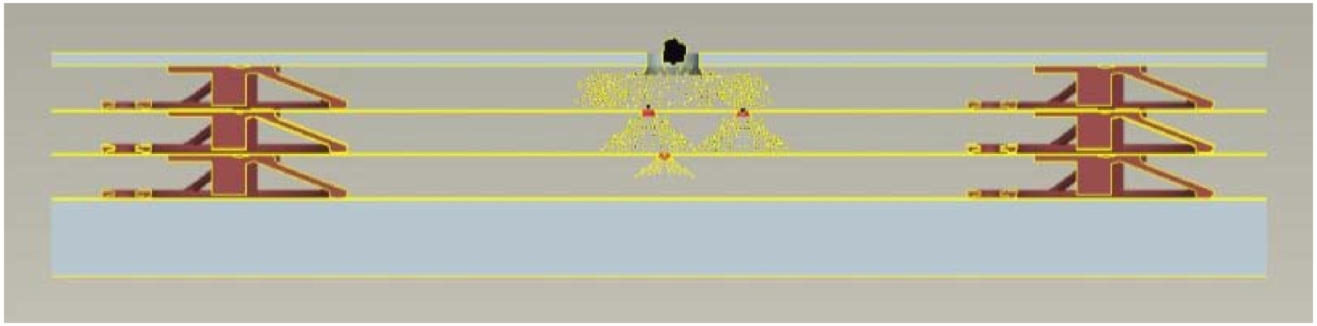
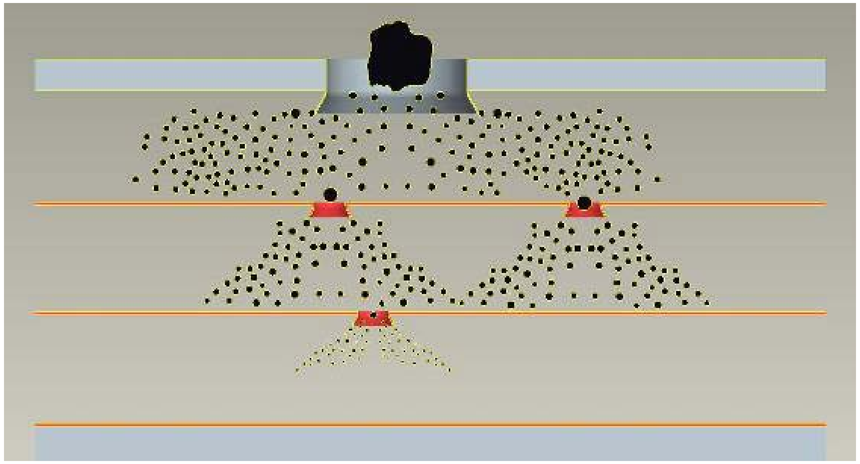
MMOD-IMLI concept





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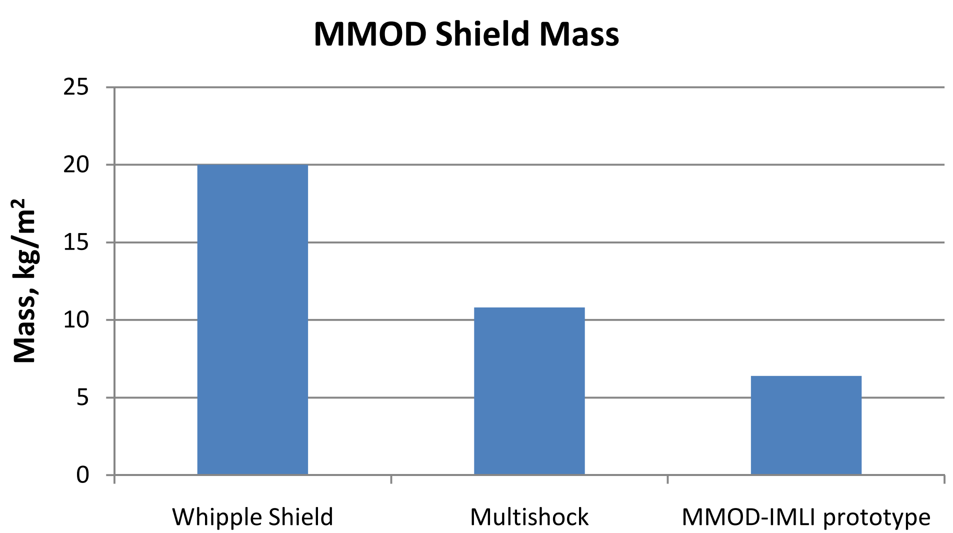
MMOD-IMLI mass

- Preliminary analysis shows mass to stop penetration by a 6.3mm particle at 7km/s:



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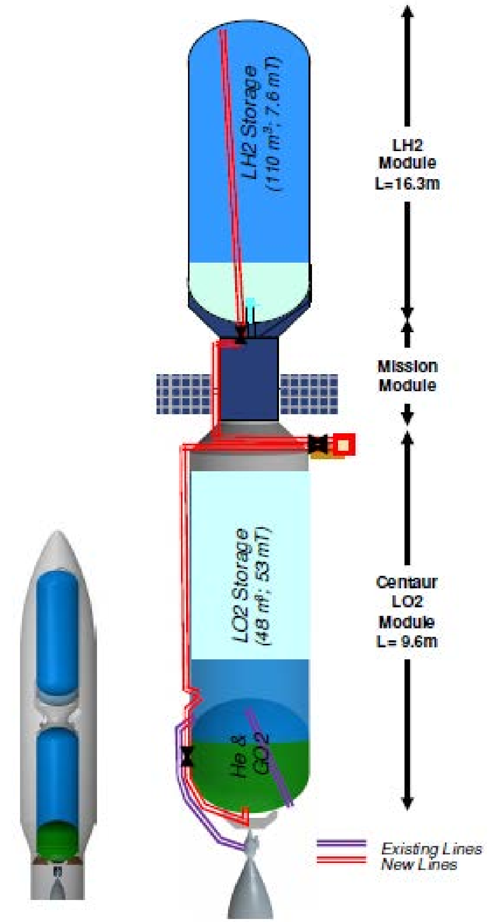
MMOD-IMLI Phase I goals

- Evaluate MMOD protection and thermal performance available from MMOD-IMLI structures
- Design and fabricate MMOD-IMLI prototypes
- Perform hypervelocity impact tests
- Measure thermal performance
- Determine feasibility of MMOD-IMLI

Orbital Fuel Depot mission

- Orbital Fuel Depot (OFD)
  - Requires near zero boiloff (thermal insulation)
  - 15 year mission
  - Colocated near ISS at 51.6°, 400km
  - Acceptable risk of failure set at 5% (95% PNP)



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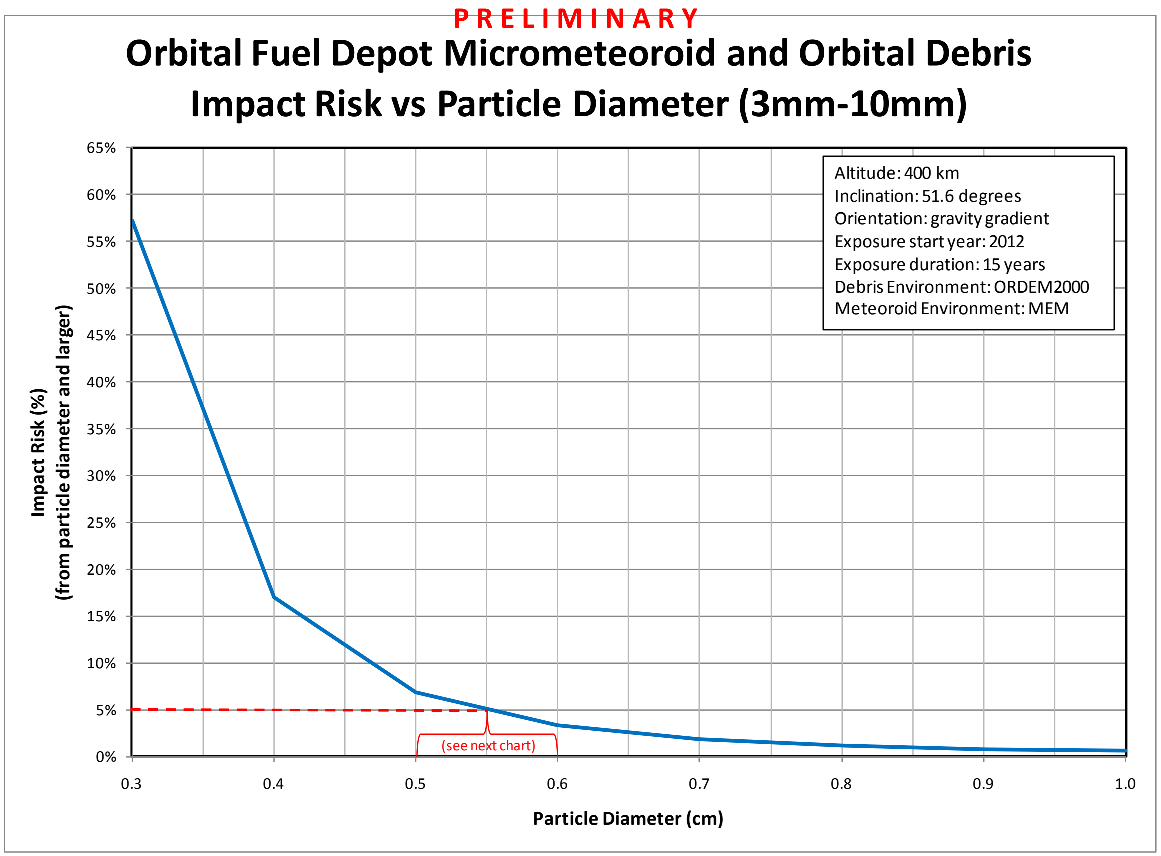
MMOD fluence and risk



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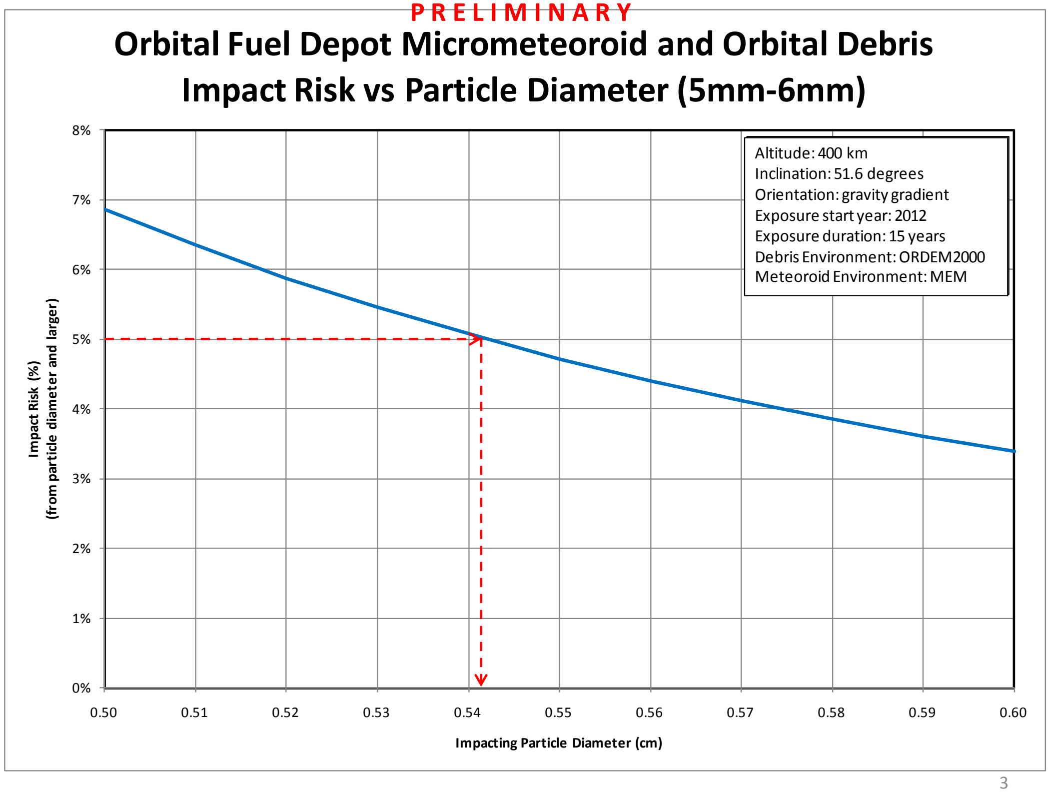
MMOD fluence and risk



- For PNP > 95%, critical particle is 5.4mm diameter.

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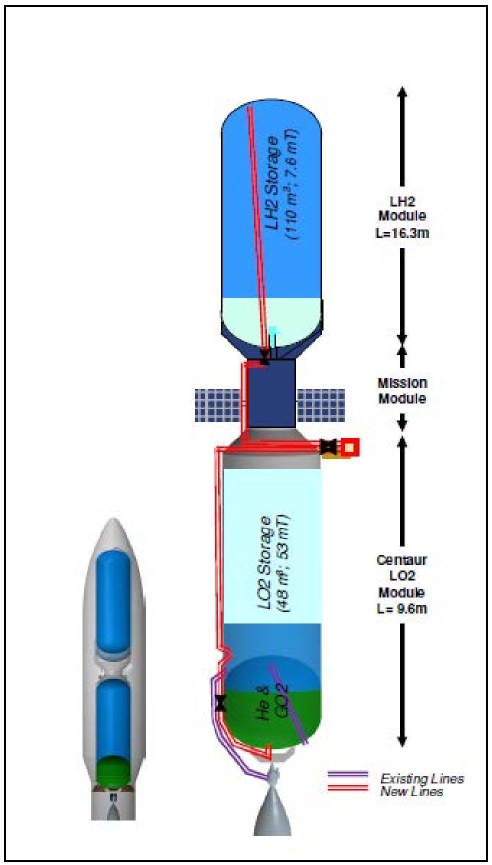
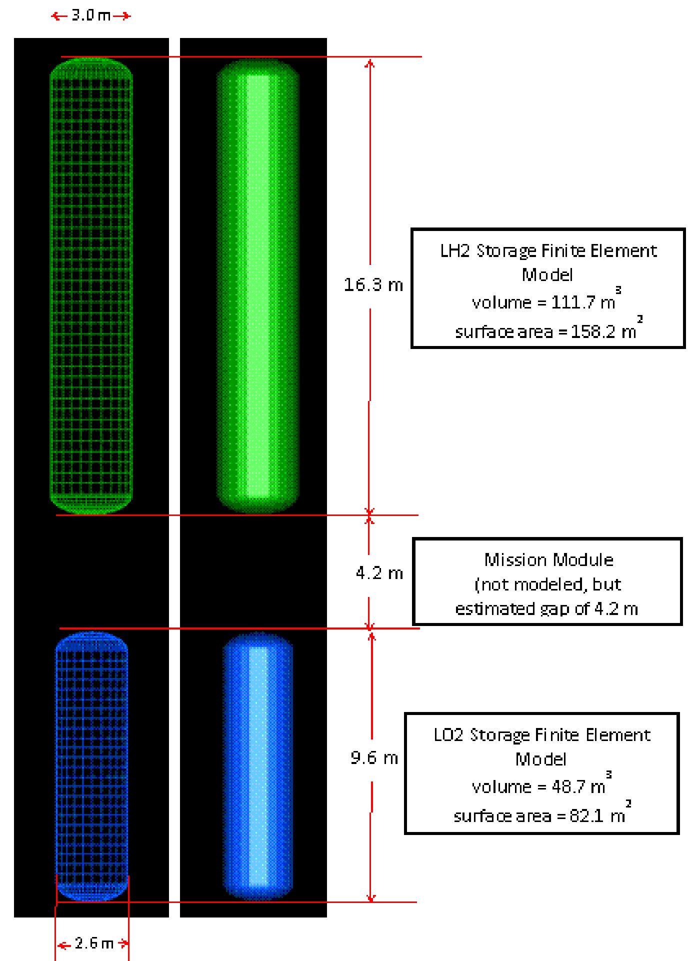
Orbital Fuel Depot FEM





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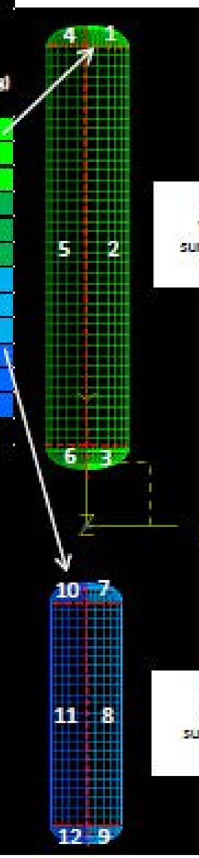
Orbital Fuel Depot FEM

OFD FEM Mapping

Orbital Fuel Depot MMOD Risk Assessment PID/EID/BLE Inputs

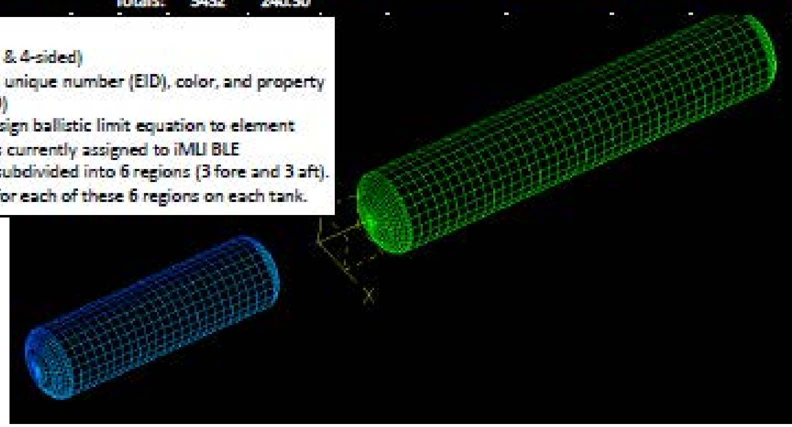
#	PID #	Region	From	To	# Elements	FEM Surface Area (m^2)	BLE	Nextel Bumper Areal Density (g/cm^2)	Kevlar Rear Wall Areal Density (g/cm^2)	Standoff (cm)	Critical Particle Diameter (7 km/s, 0-deg) (cm)
1	2	LH2 Endcap - fwd	5000	5275	276	4.832	IMLI	0.367	0.253	20.32	0.7162
2	2	LH2 Cylinder - fwd	5276	5743	468	69.440	IMLI	0.367	0.253	20.32	0.7162
3	2	LH2 Endcap - fwd	5744	6019	276	4.832	IMLI	0.367	0.253	20.32	0.7162
4	3	LH2 Endcap - aft	6020	6295	276	4.832	IMLI	0.367	0.253	20.32	0.7162
5	3	LH2 Cylinder - aft	6296	6763	468	69.440	IMLI	0.367	0.253	20.32	0.7162
6	3	LH2 Endcap - aft	6764	7039	276	4.832	IMLI	0.367	0.253	20.32	0.7162
7	4	LO2 Endcap - fwd	7040	7243	204	3.634	IMLI	0.367	0.253	20.32	0.7162
8	4	LO2 Cylinder - fwd	7244	7531	288	33.780	IMLI	0.367	0.253	20.32	0.7162
9	4	LO2 Endcap - fwd	7532	7735	204	3.634	IMLI	0.367	0.253	20.32	0.7162
10	5	LO2 Endcap - aft	7736	7939	204	3.634	IMLI	0.367	0.253	20.32	0.7162
11	5	LO2 Cylinder - aft	7940	8227	288	33.780	IMLI	0.367	0.253	20.32	0.7162
12	5	LO2 Endcap - aft	8228	8431	204	3.634	IMLI	0.367	0.253	20.32	0.7162
				Totals:	3432	240.30					



LH2 Storage FEM
volume = 111.7 m^3
surface area = 158.2 m^2
2,040 elements

LO2 Storage FEM
volume = 48.7 m^3
surface area = 82.1 m^2
1,392 elements

OFD FEM Mapping:
- "element"=1 polygon (3- & 4-sided)
- each element is assigned unique number (EID), color, and property identification number (PID)
- PID number is used to assign ballistic limit equation to element
- all LH2 and LO2 elements currently assigned to iMLI BLE
- LH2 and LO2 tanks each subdivided into 6 regions (3 fore and 3 aft).
- Bumper results queried for each of these 6 regions on each tank.



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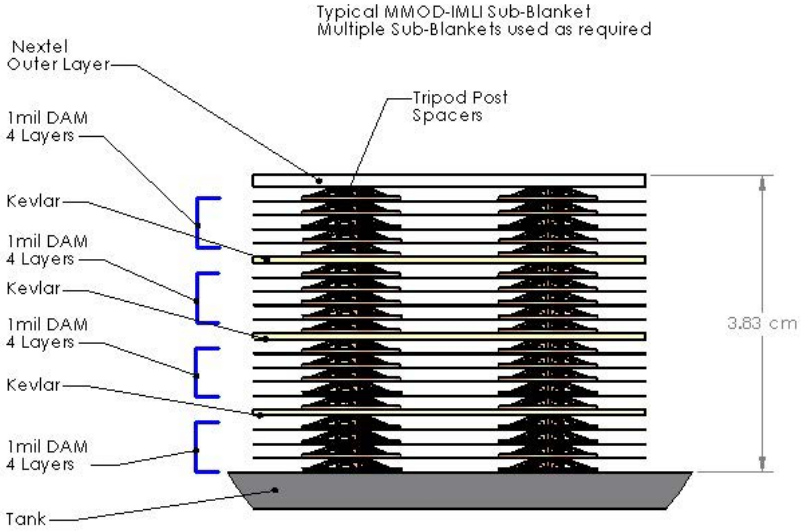
Hypervelocity Impact Technology (HVIT) Team

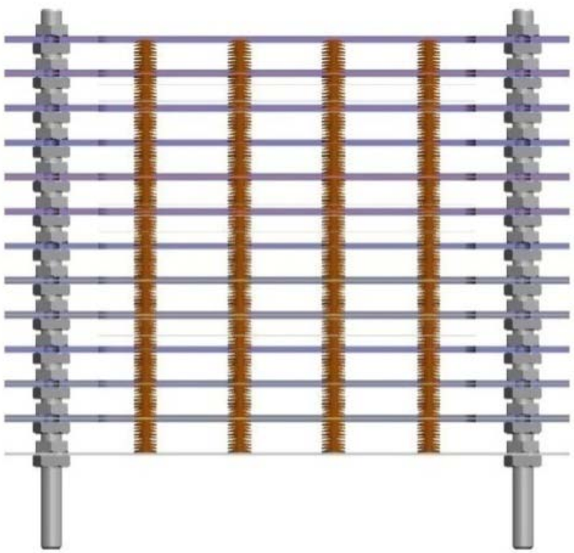
PRELIMINARY

MMOD-IMLI preliminary design



- MMOD-IMLI preliminary design:
  - Widely spaced layers
  - Supported 12 ballistic layers of Nextel and Kevlar
  - Integrated MMOD shielding and thermal insulation

MMOD-IMLI Areal Density



iMLI Areal Density Estimate (g/cm²)

Layer #	Location	Description	Layer Areal Density (g/cm^2)	# Layers	Material Conversion Factor	Areal Density (g/cm^2)
1	1	Nextel AF-10	0.0292	1	1.000	0.0292
2	1,2	Mylar	0.003556	9	1.000	0.032004
3	2	Nextel AF-10	0.0292	1	1.000	0.0292
4	2,3	Mylar	0.003556	9	1.000	0.032004
5	3	Nextel AF-10	0.0292	1	1.000	0.0292
6	3,4	Mylar	0.003556	9	1.000	0.032004
7	4	Nextel AF-10	0.0292	1	1.000	0.0292
8	4,5	Mylar	0.003556	9	1.000	0.032004
9	5	Nextel AF-10	0.0292	1	1.000	0.0292
10	5,6	Mylar	0.003556	9	1.000	0.032004
11	6	Nextel AF-10	0.0292	1	1.000	0.0292
12	6,7	Mylar	0.003556	9	1.000	0.032004
13	7	Kevlar KM2-705	0.0244	1	1.000	0.0244
14	7,8	Mylar	0.003556	9	0.667	0.021336
15	8	Kevlar KM2-705	0.0244	1	1.000	0.0244
16	8,9	Mylar	0.003556	9	0.667	0.021336
17	9	Kevlar KM2-705	0.0244	1	1.000	0.0244
18	9,10	Mylar	0.003556	9	0.667	0.021336
19	10	Kevlar KM2-705	0.0244	1	1.000	0.0244
20	10,11	Mylar	0.003556	9	0.667	0.021336
21	11	Kevlar KM2-705	0.0244	1	1.000	0.0244
22	11,12	Mylar	0.003556	9	0.667	0.021336
23	12	Kevlar KM2-705	0.0244	1	1.000	0.0244
24	13	Mylar	0.003556	9	0.000	0
25	WP	Al 2024-T3 (0.040")		0	0.000	0
					Bumper Areal Density:	0.367
					Rearwall Areal Density:	0.253
					Total Shield Areal Density:	0.620

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OFD Penetration Risk

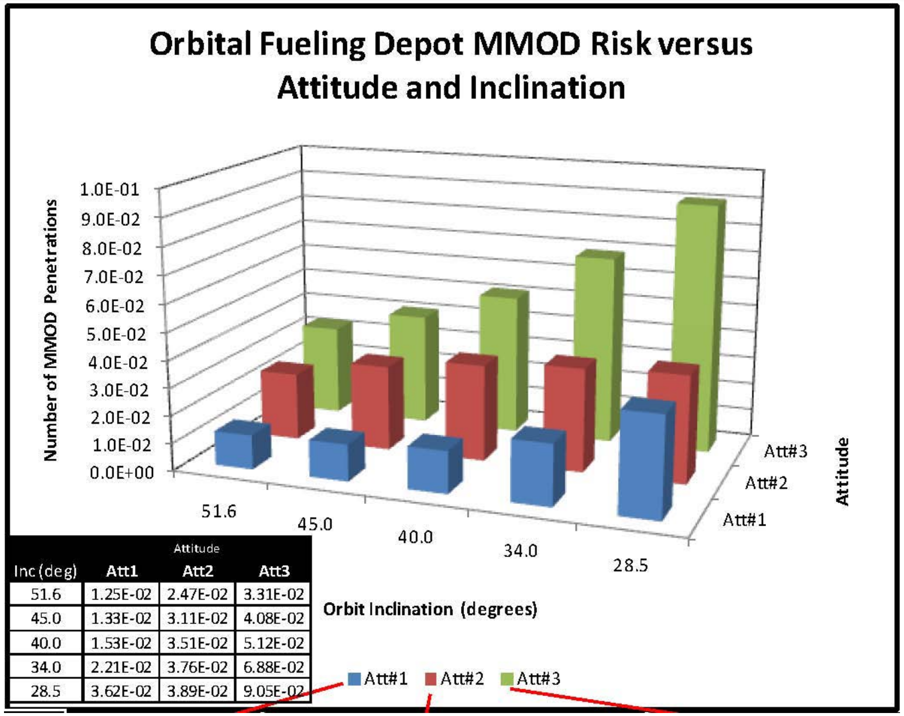
Orbital Fuel Depot MMOD Number of Penetrations (N)
(Inclination 51.6 deg, 2012+15 years exposure, 400 km altitude, ORDEM2000 & MEM)

#	Region	From	To	Attitude #1 (RPY=0,0,0) deb	Attitude #1 met	Attitude #1 both	Attitude #2 (RPY=0,0,90) deb	Attitude #2 met	Attitude #2 both	Attitude #3 (RPY=-90,0,0) deb	Attitude #3 met	Attitude #3 both
1	LH2 Endcap - fwd	5000	5275	8.57E-04	2.44E-05	8.82E-04	1.48E-04	8.58E-06	1.56E-04	3.56E-04	9.39E-06	3.65E-04
2	LH2 Cylinder - fwd	5276	5743	4.80E-03	4.17E-04	5.21E-03	7.09E-03	2.23E-04	7.31E-03	1.42E-02	4.65E-04	1.47E-02
3	LH2 Endcap - fwd	5744	6019	7.33E-04	2.33E-05	7.57E-04	6.38E-04	3.02E-05	6.68E-04	3.56E-04	3.35E-05	3.89E-04
4	LH2 Endcap - aft	6020	6295	5.26E-04	1.24E-05	5.38E-04	1.49E-04	8.52E-06	1.58E-04	1.33E-04	3.48E-06	1.37E-04
5	LH2 Cylinder - aft	6296	6763	1.74E-04	1.17E-04	2.91E-04	7.10E-03	2.20E-04	7.32E-03	6.16E-03	1.47E-04	6.31E-03
6	LH2 Endcap - aft	6764	7039	3.18E-04	1.12E-05	3.29E-04	6.37E-04	3.00E-05	6.67E-04	1.33E-04	1.64E-05	1.49E-04
7	LO2 Endcap - fwd	7040	7243	5.16E-04	1.75E-05	5.34E-04	1.09E-04	6.13E-06	1.15E-04	2.70E-04	7.02E-06	2.77E-04
8	LO2 Cylinder - fwd	7244	7531	2.33E-03	2.03E-04	2.54E-03	3.45E-03	1.08E-04	3.56E-03	6.92E-03	2.26E-04	7.15E-03
9	LO2 Endcap - fwd	7532	7735	6.41E-04	1.82E-05	6.59E-04	4.93E-04	2.49E-05	5.18E-04	2.70E-04	2.59E-05	2.95E-04
10	LO2 Endcap - aft	7736	7939	1.86E-04	8.33E-06	1.94E-04	1.10E-04	6.08E-06	1.16E-04	1.01E-04	2.60E-06	1.03E-04
11	LO2 Cylinder - aft	7940	8227	8.49E-05	5.68E-05	1.42E-04	3.45E-03	1.07E-04	3.56E-03	3.00E-03	7.18E-05	3.07E-03
12	LO2 Endcap - aft	8228	8431	3.97E-04	9.15E-06	4.06E-04	4.91E-04	2.48E-05	5.16E-04	1.01E-04	1.31E-05	1.14E-04
	Total Number of Penetrations (N):			**1.16E-02**	**9.18E-04**	**1.25E-02**	**2.39E-02**	**7.97E-04**	**2.47E-02**	**3.20E-02**	**1.02E-03**	**3.31E-02**
					PNP	**0.988**		PNP	**0.976**		PNP	**0.967**
					PNP_{req}	**0.950**		PNP_{req}	**0.950**		PNP_{req}	**0.950**
					N/N_{req}	**0.243**		N/N_{req}	**0.481**		N/N_{req}	**0.644**

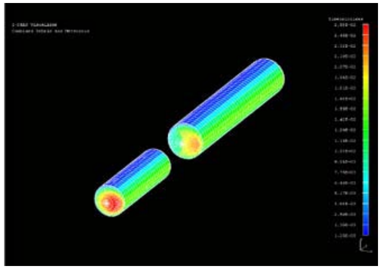
$PNP=e^{-N}$

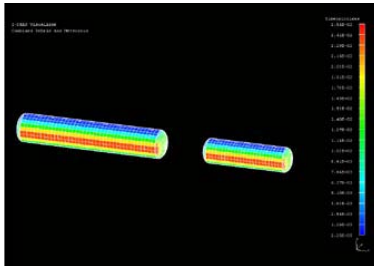
- Analysis predicts with 120-layer MMOD-IMLI:
  - For 100 m^2 OFD, 51.6° 400km orbit, 15 year mission:
  - There would be 0.0125 penetrations
  - PNP = 98.8% or 24% of the allowed risk

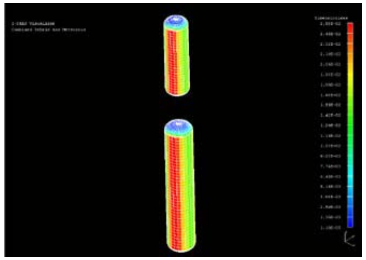
OFD Penetration Risk



	Attitude		
Inc (deg)	Att1	Att2	Att3
51.6	1.25E-02	2.47E-02	3.31E-02
45.0	1.33E-02	3.11E-02	4.08E-02
40.0	1.53E-02	3.51E-02	5.12E-02
34.0	2.21E-02	3.76E-02	6.88E-02
28.5	3.62E-02	3.89E-02	9.05E-02







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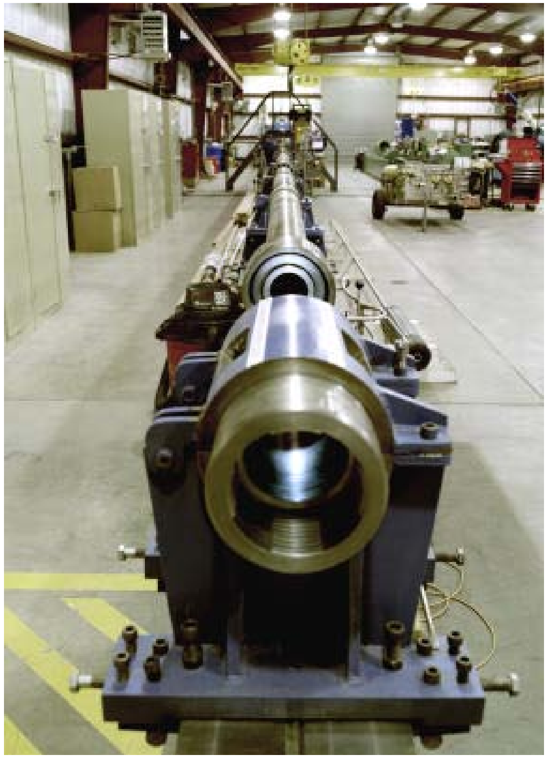
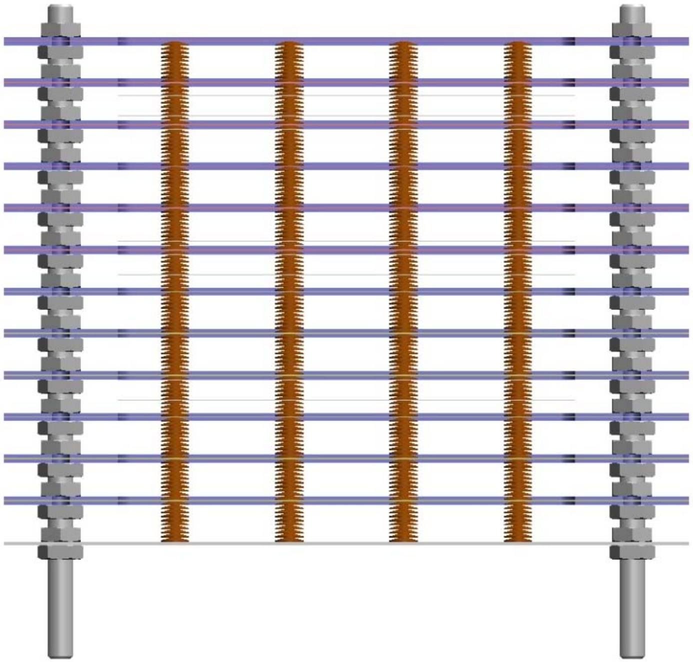
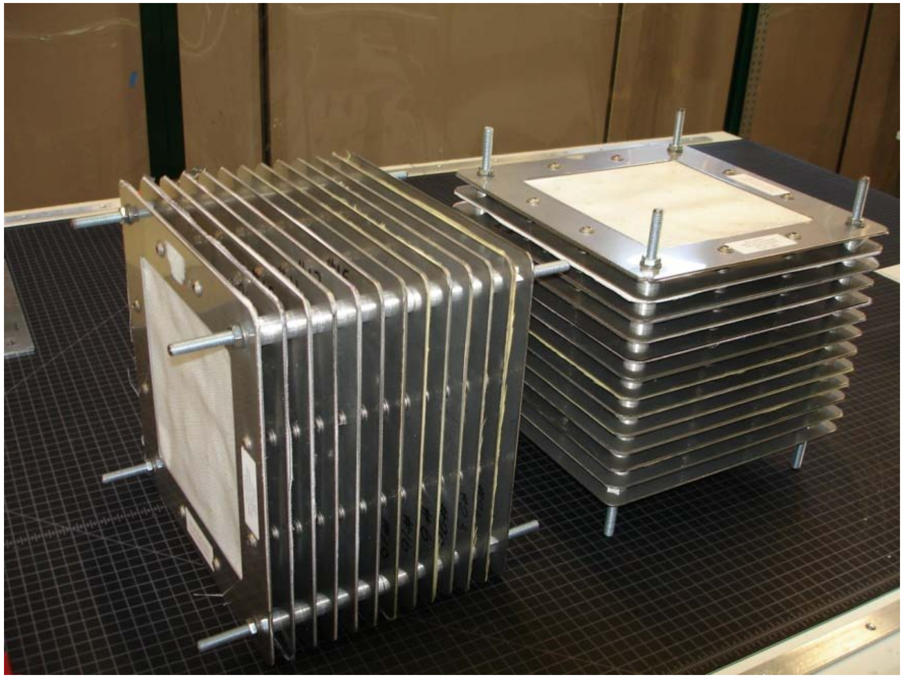
Hypervelocity Impact Testing



- Quest deemed HVI testing critical:
  - Quest paid for HVI shots at White Sands Test Facility
  - Two shots were planned, to give two data points for preliminary BLE development
  - One shot was an Al spherical particle, near the critical particle diameter for the selected mission, at 7 km/s (15,700 mph).

MMOD-IMLI prototype





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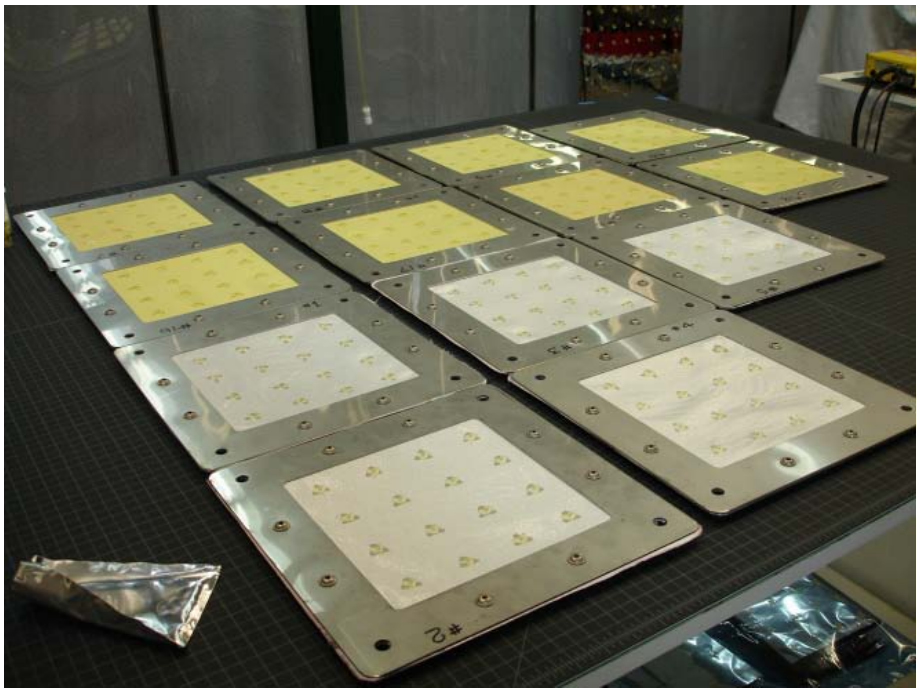
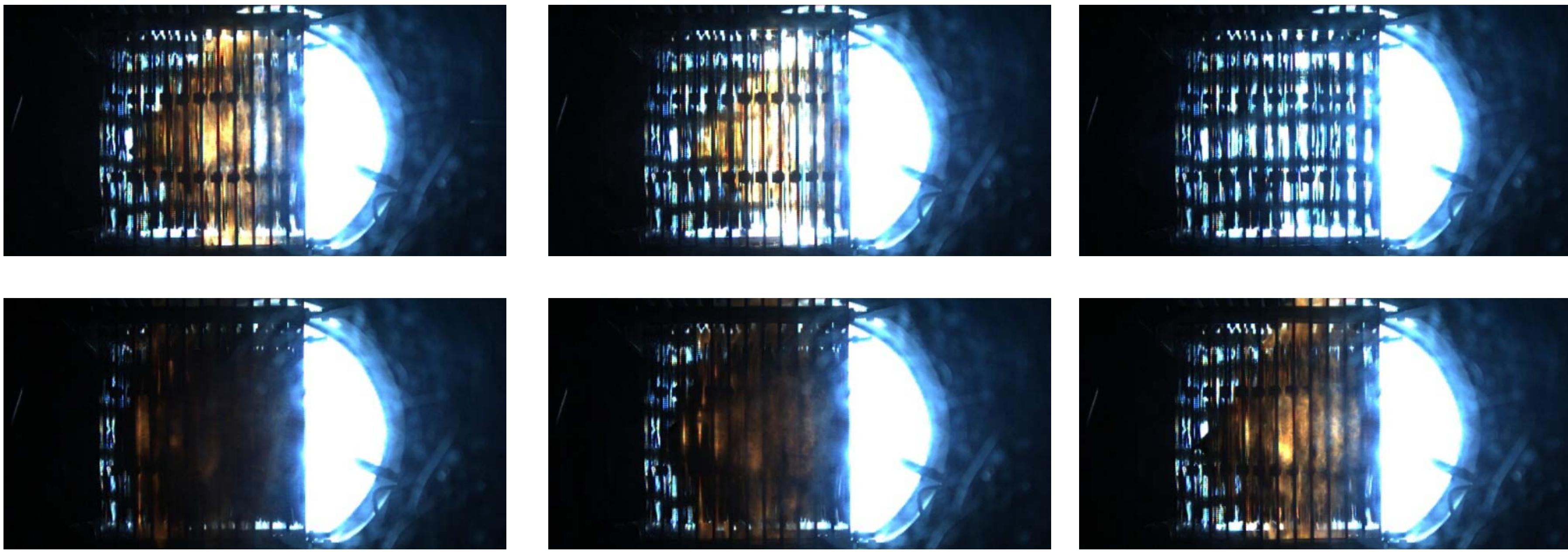
MMOD-IMLI prototype



Hypervelocity Impact Testing



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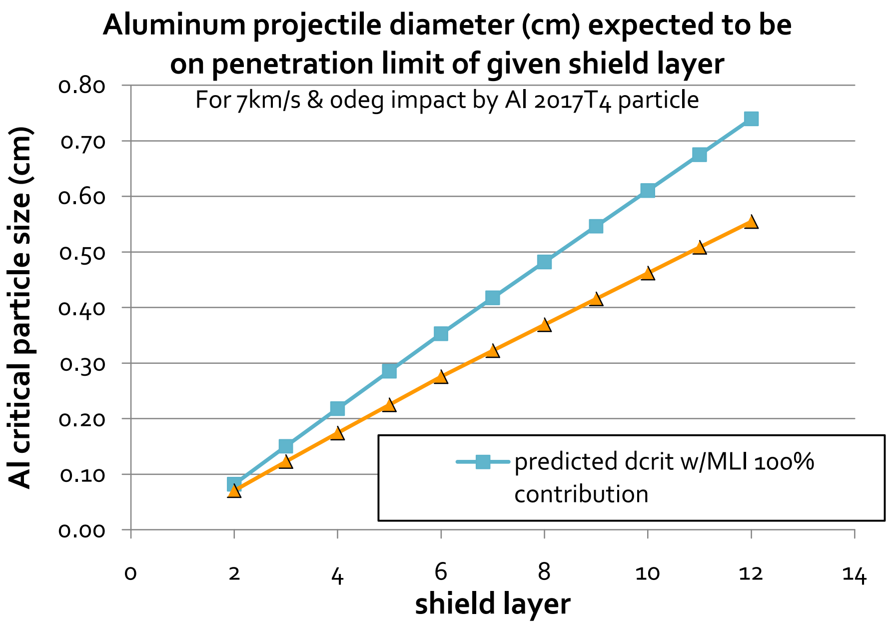
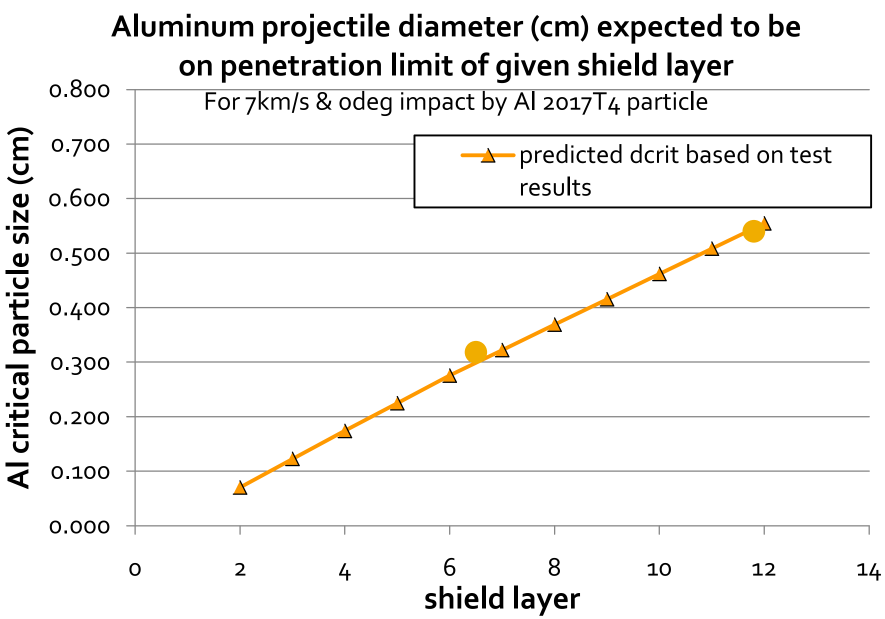
HVI Results

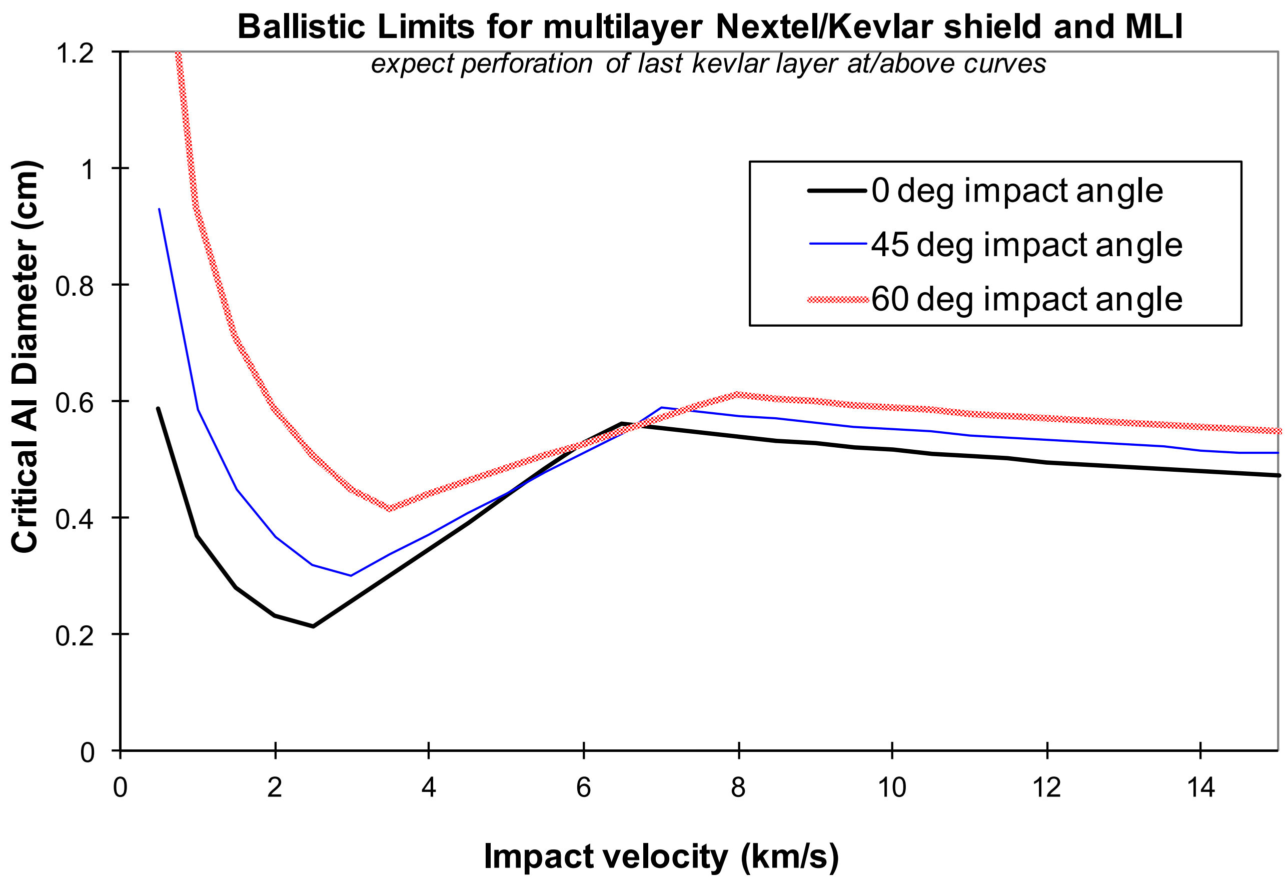


Aluminum projectile diameter (cm) expected to be on penetration limit of given shield layer
For 7km/s & 0deg impact by Al 2017T4 particle
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
2
4
6
8
10
12
14
shield layer
Al critical particle size (cm)
predicted dcrit w/MLI 100% contribution



Aluminum projectile diameter (cm) expected to be on penetration limit of given shield layer
For 7km/s & 0deg impact by Al 2017T4 particle
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
2
4
6
8
10
12
14
shield layer
Al critical particle size (cm)
predicted dcrit based on test results

Ballistic Limit Equations



Quest Thermal Group and Ball Aerospace Information

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MMOD-IMLI stopping power

Layer Number	m_{sh_eff} (g/cm^2)	S (cm)	Aluminum projectile diameter on failure threshold of each shield layer at 7km/s, 0^o d (cm)
1	NA	NA	NA
2	0.066	1.8	0.070
3	0.104	3.7	0.123
4	0.141	5.5	0.174
5	0.178	7.4	0.225
6	0.215	9.2	0.275
7	0.248	11.1	0.322
8	0.280	12.9	0.369
9	0.312	14.8	0.415
10	0.345	16.6	0.462
11	0.377	18.5	0.508
12	0.410	20.3	0.555

Ballistic Limit Equations

$$m_b = 0.185\, d \cdot \rho_p$$

$$m_w = 29\, M_p \cdot V_n \cdot S^{-2} = \frac{29\pi}{6} \cdot d^3 \cdot \rho_p \cdot V_n \cdot S^{-2}$$

MMOD shielding summary

- MMOD-IMLI structure performed nearly as modeled
- Completely stopped a 5.4mm particle at 6.6km/s without use of a rear wall
- MMOD-IMLI mass was 8.0 kg/m^2
- Has a theoretical mass 24% less than advanced multishock shields for same shielding
- Also provides thermal insulation in a single subsystem

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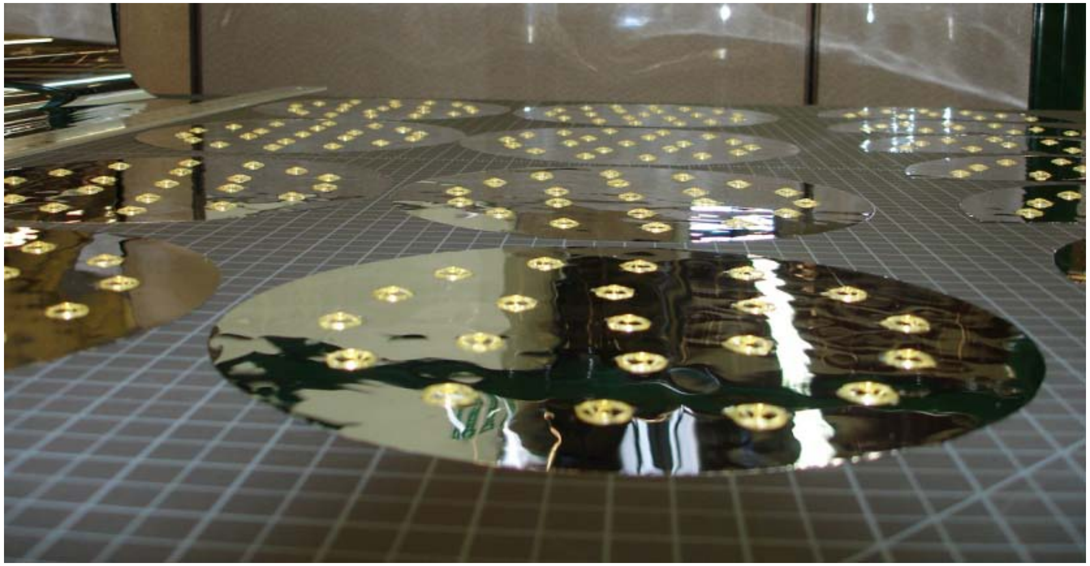
MMOD thermal testing on cryotank



MMOD thermal testing

- 8-layer MMOD-IMLI structure built and installed on 20L tank
- Heat flux measured via LN_2 boiloff calorimetry
- Thermal conductance was 1.58W/m^2
- Thermal conductivity was 0.12mW/m-K
- IMLI thermal conductivity is 0.066mW/m-K
- Estimated heat flux through full 120-layer MMOD-IMLI structure is 0.10W/m^2

Summary

- Feasibility of MMOD-IMLI was proven, TRL3 achieved
- MMOD-IMLI can provide both high performance thermal insulation and MMOD shielding
- MMOD-IMLI combines thermal barriers, precise layer spacing, and support for high strength ballistic layers
- Thermal performance matches our modeling closely
- MMOD performance can be estimated with BLEs
- MMOD-IMLI can be engineered to meet mission requirements

Acknowledgements

We'd like to acknowledge the support and collaboration of:

- Eric Christiansen, JSC, NASA MMOD Consultant
- Dana Lear, JSC, NASA MMOD Consultant
- Wesley Johnson, KSC, NASA Technical Monitor
- Bruce (Alan) Davis, Jacobs Technology, White Sands Test Facility, Test Manager
- Genevieve Duvaud, Ball Aerospace, MMOD Consultant
- Gary Mills, Ball Aerospace, Staff Engineer
- Phill Tyler, Quest Thermal Group, Mechanical Engineer
- Scott Dye, Quest Thermal Group, Principal Investigator
- Alan Kopelove, Quest Thermal Group, CEO

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