MMOD Protection and Degradation Effects for Thermal Control Systems

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Agenda

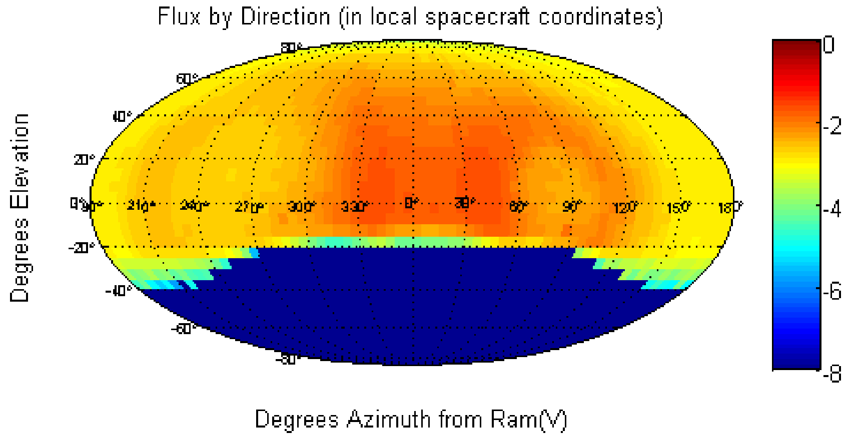
- **Micrometeoroid and orbital debris (MMOD) environment overview**
- **Hypervelocity impact effects & MMOD shielding**
- **MMOD risk assessment process**
- **Requirements & protection techniques**
  - ISS
  - Shuttle
  - Orion/Commercial Crew Vehicles
- **MMOD effects on spacecraft systems & improving MMOD protection**
  - Radiators
    - Coatings
  - Thermal protection system (TPS) for atmospheric entry vehicles
    - Coatings
  - Windows
  - Solar arrays
  - Solar array masts
  - EVA Handrails
  - Thermal Blankets

MMOD Environment Models

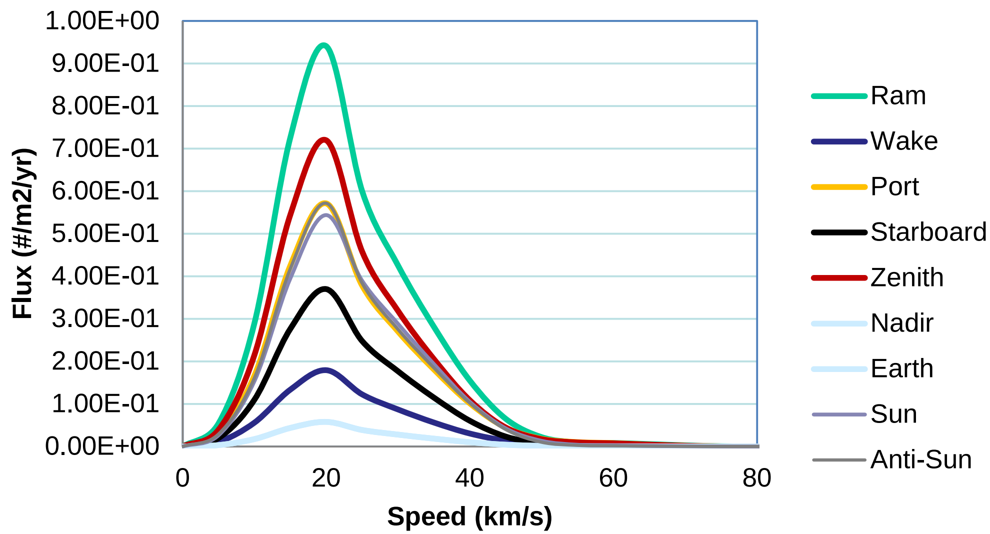
- **Orbital Debris provided by JSC & is the predominate threat in low Earth orbit**
  - ORDEM 3.0 is latest model (released December 2013)
  - http://orbitaldebris.jsc.nasa.gov/
  - Man-made objects in orbit about Earth impacting up to 16 km/s
    - average 9-10 km/s for ISS orbit
  - High-density debris (steel) is major issue

- **Meteoroid model provided by MSFC**
  - MEM-R2 is latest release
  - http://www.nasa.gov/offices/meo/home/index.html
  - Natural particles in orbit about sun
    - Mg-silicates, Ni-Fe, others
  - Meteoroid environment (MEM): 11-72 km/s
    - Average 22-23 km/s

MEM Environment for ISS



Speed Distributions by Surface, one month average, ISS



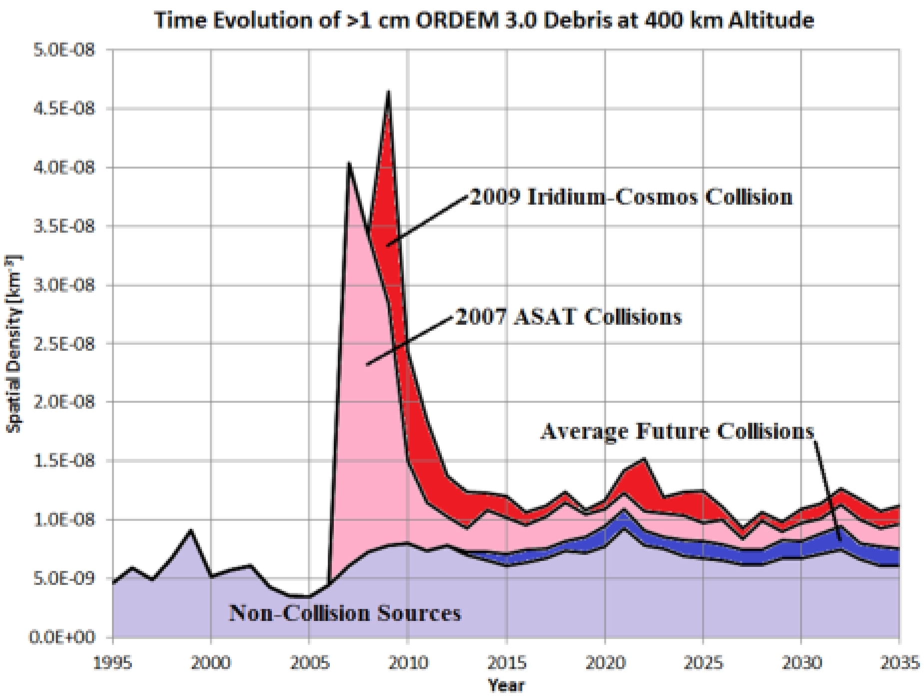
Total Flux on Spacecraft
Average of All States
Cross Sectional Flux 7.258269e+000 /m^2/yr

	Ram	Wake	Port	Starboard	Zenith	Nadir	Earth	Sun	Anti-Sun
Average Speed (km/s)	22.8	23.3	23.5	22.7	22.8	23.2	23.2	23.2	23.4
Total Flux (#/m2/yr)	3.586e+000	7.037e-001	2.211e+000	1.408e+000	2.694e+000	2.250e-001	2.251e-001	2.160e+000	2.181e+000

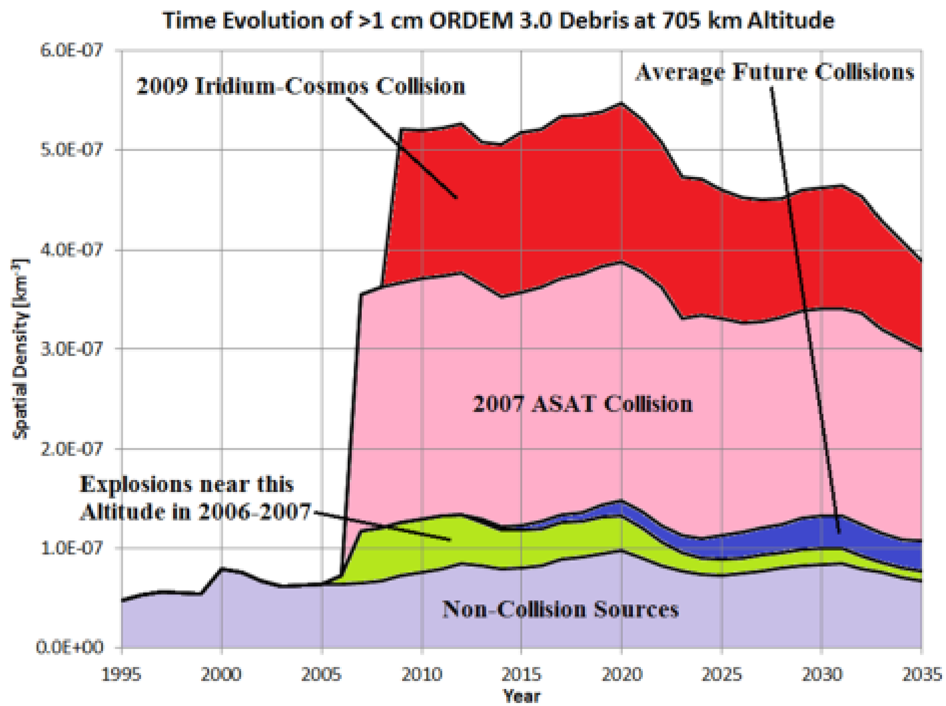
MMOD Environment Dynamics

- **Meteoroids consist of background sporadic flux (static), and streams from meteor showers (variable)**
  - Occasionally, showers can turn into storms
- **Orbital Debris changes as function of orbital altitude, the rate of on-orbit explosions & collisions, launch rate, atmospheric drag/solar activity and other factors**

400km altitude

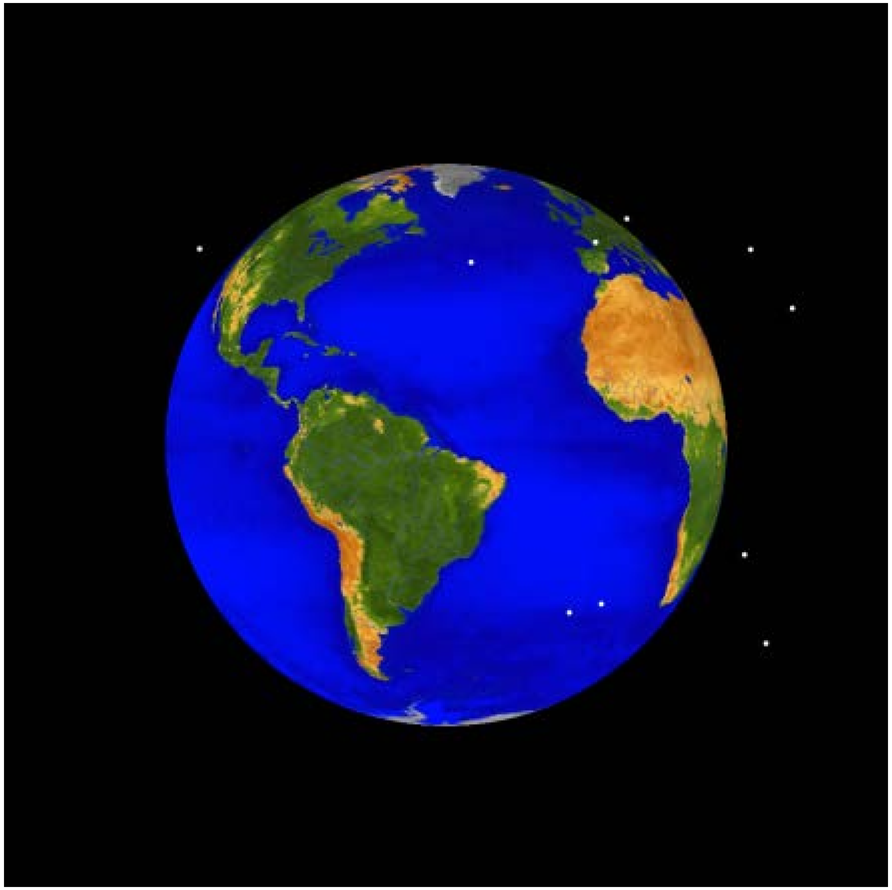


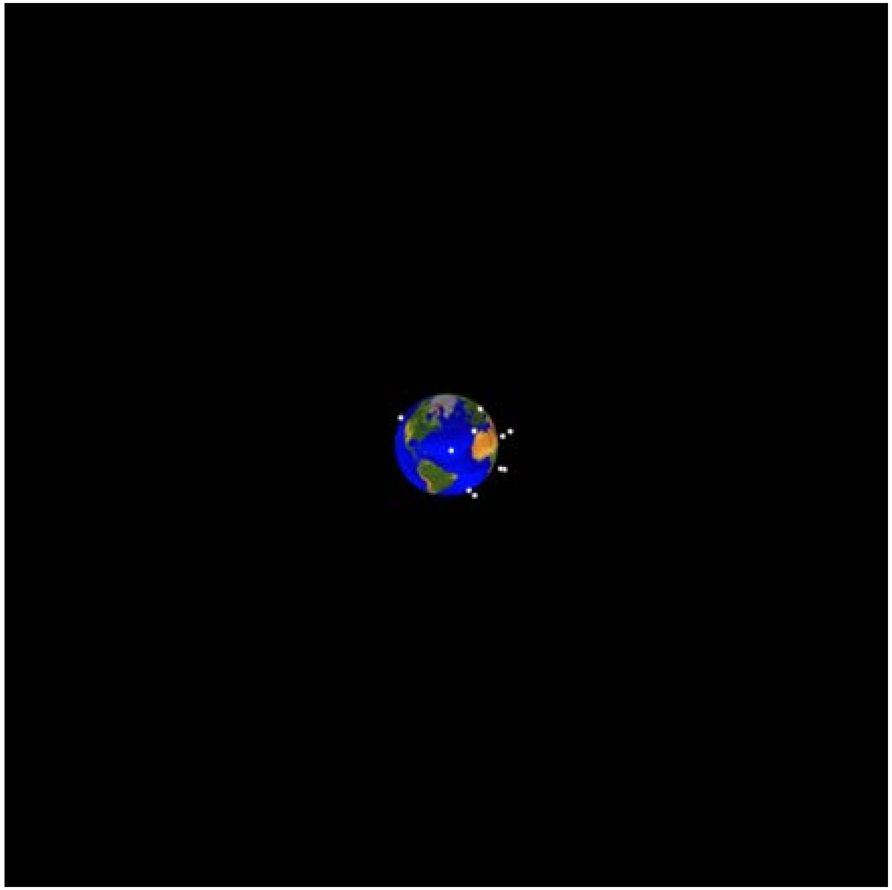
705km altitude



Note, Spatial Density is proportional to impact risk

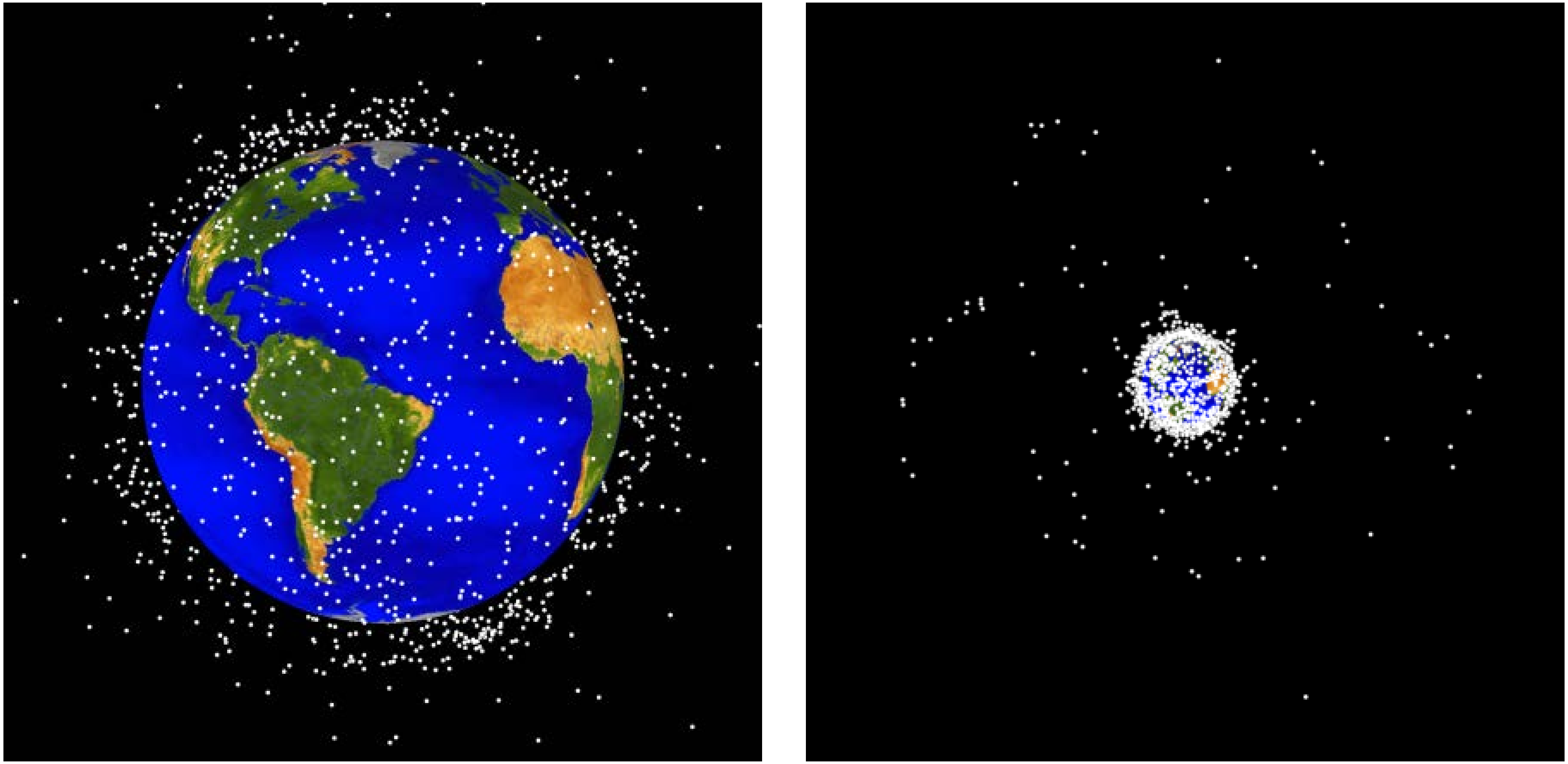
1960





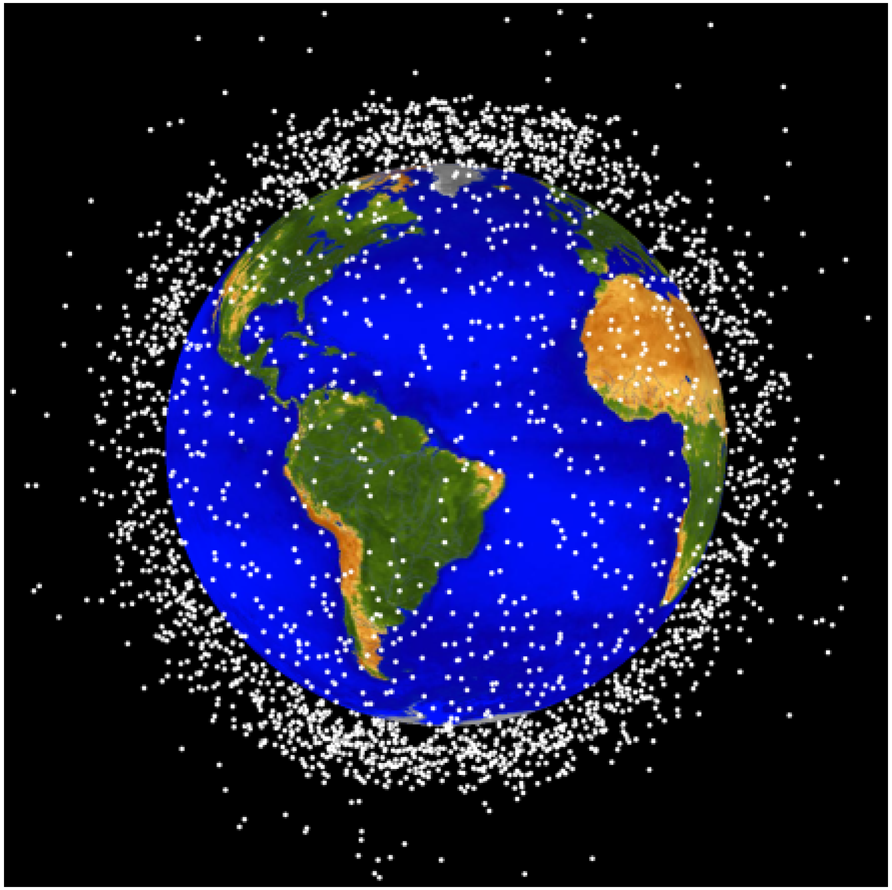
Cataloged objects >10 cm diameter

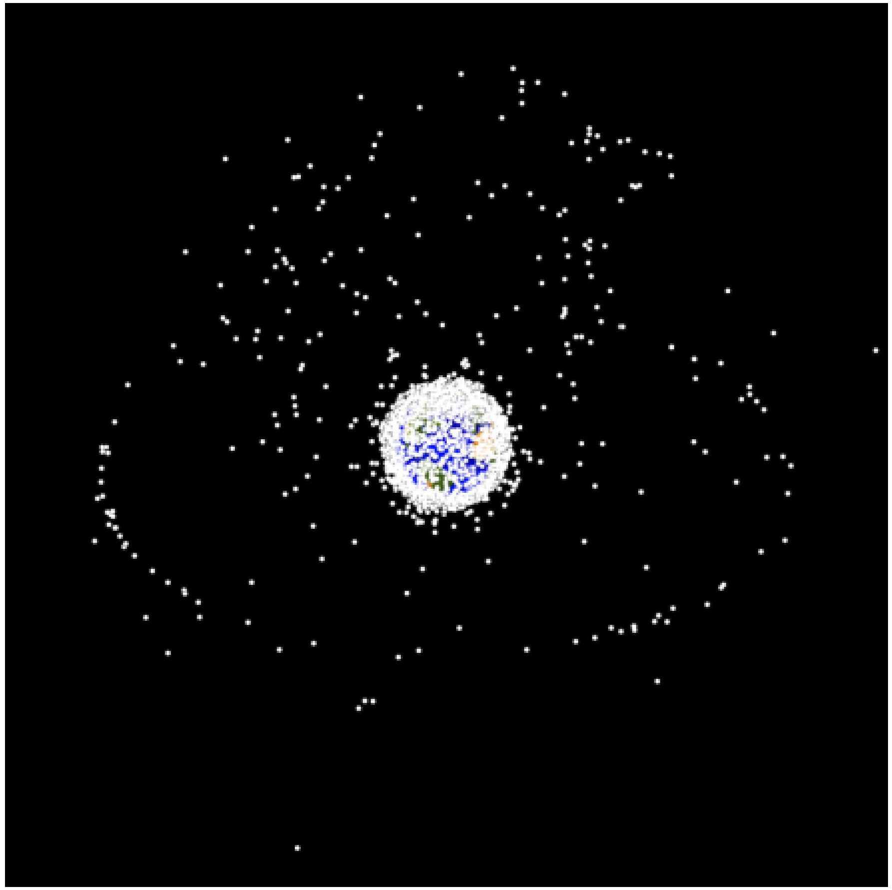
1970



Cataloged objects >10 cm diameter

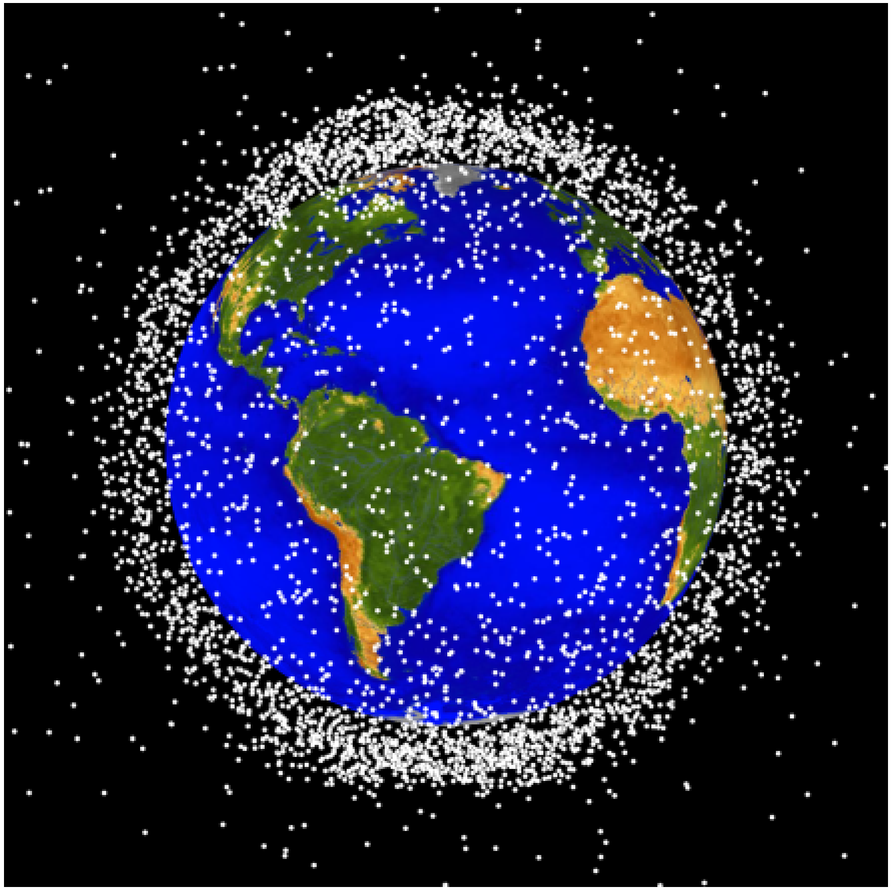
1980

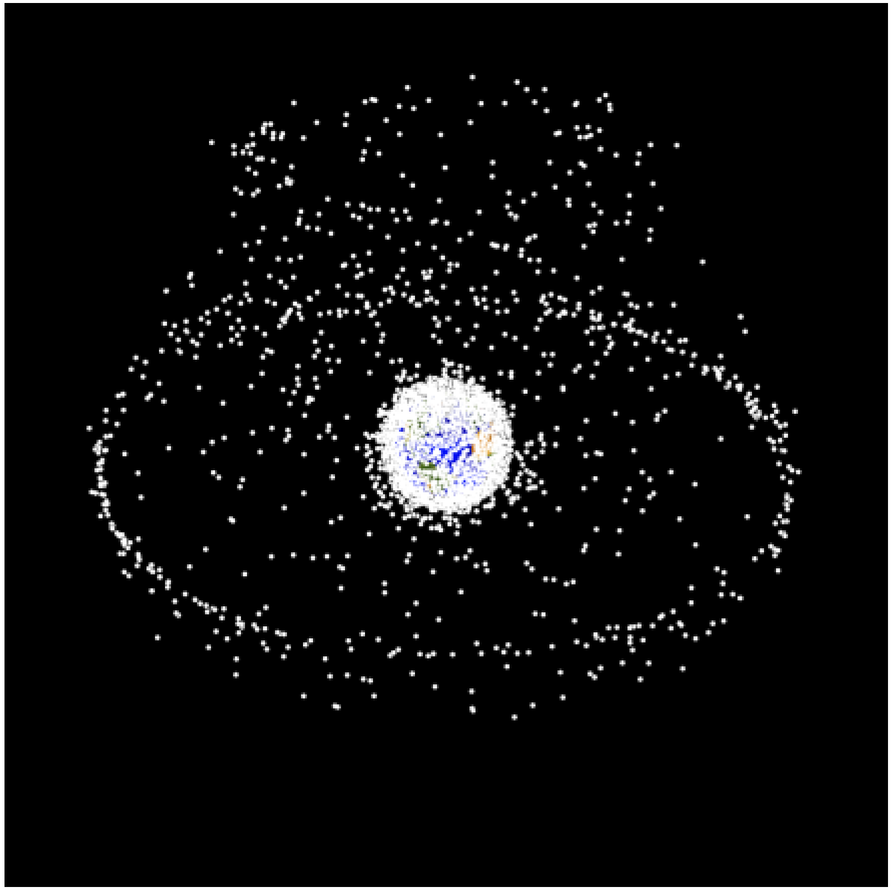




Cataloged objects >10 cm diameter

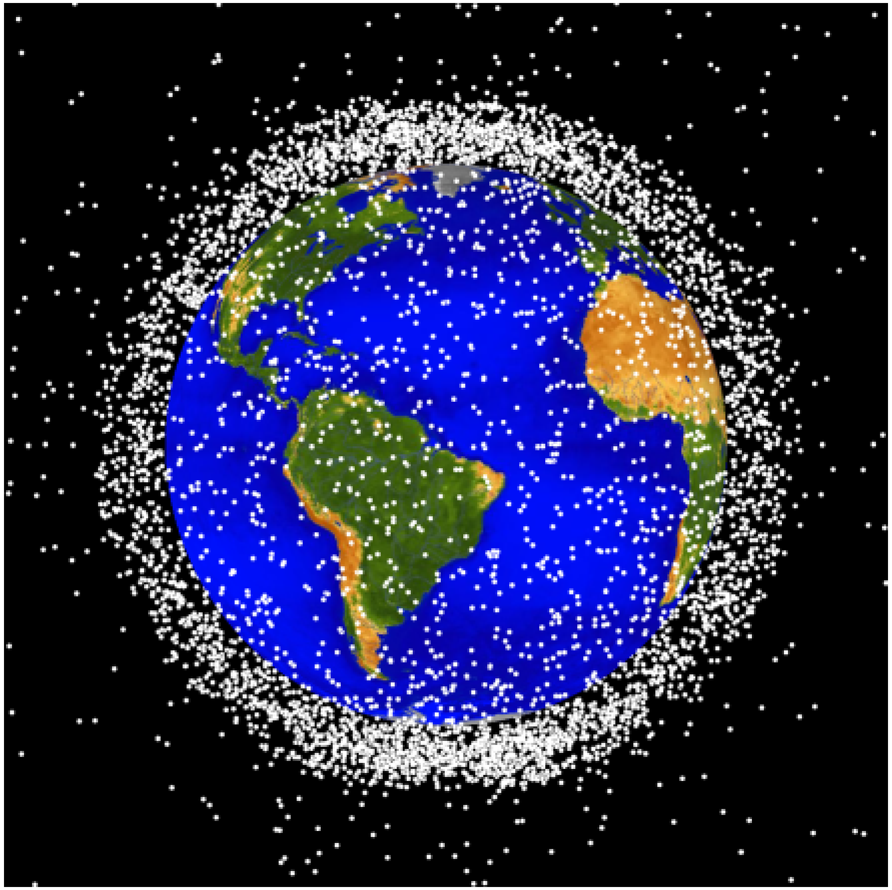
1990

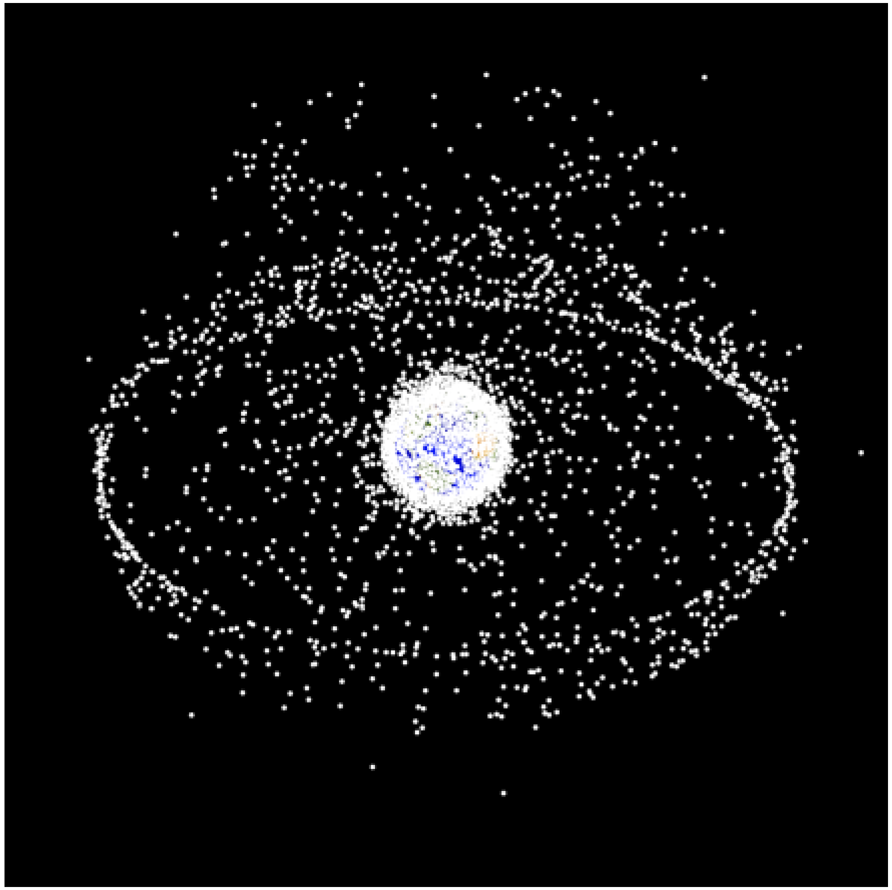




Cataloged objects >10 cm diameter

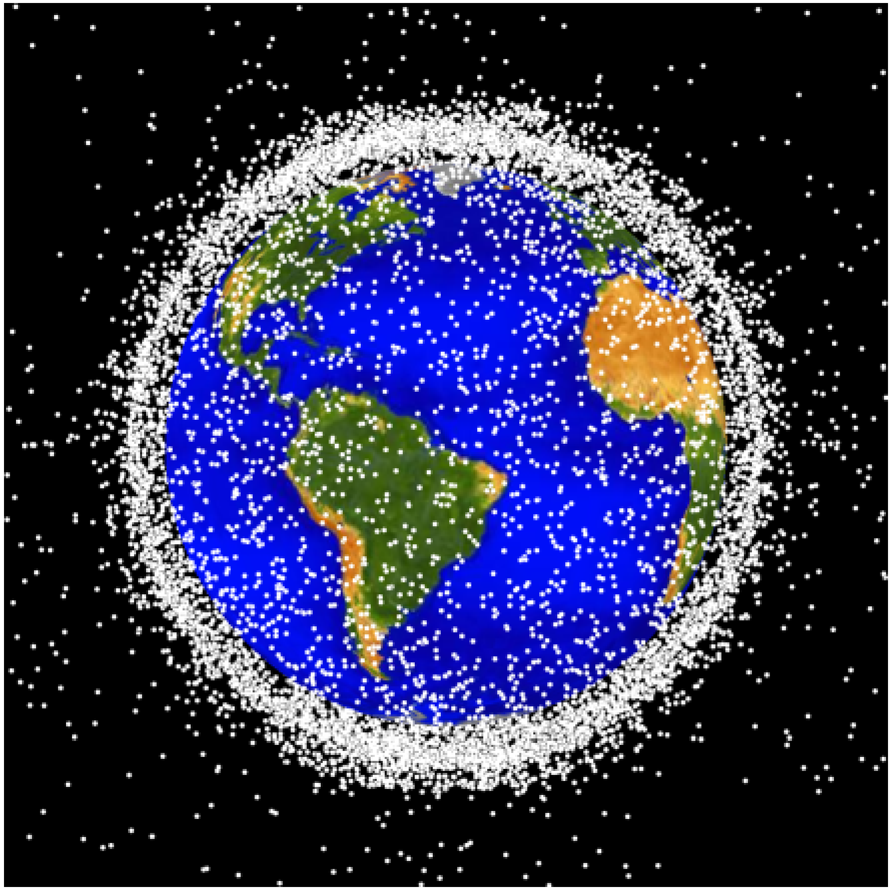
2000

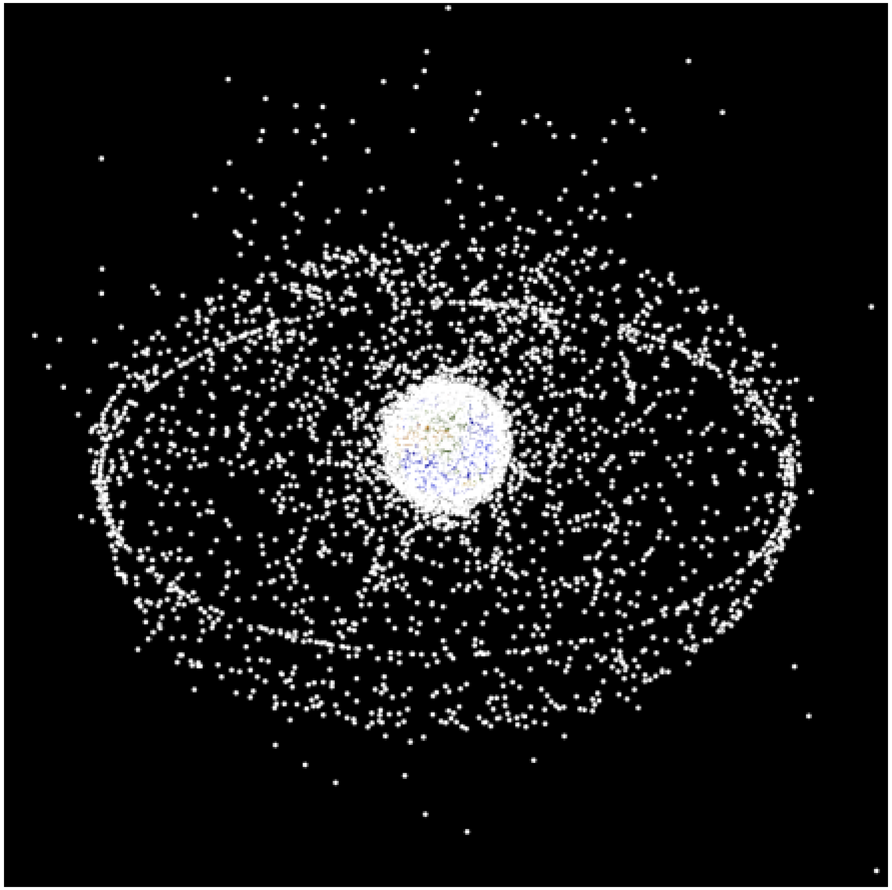




Cataloged objects >10 cm diameter

2010

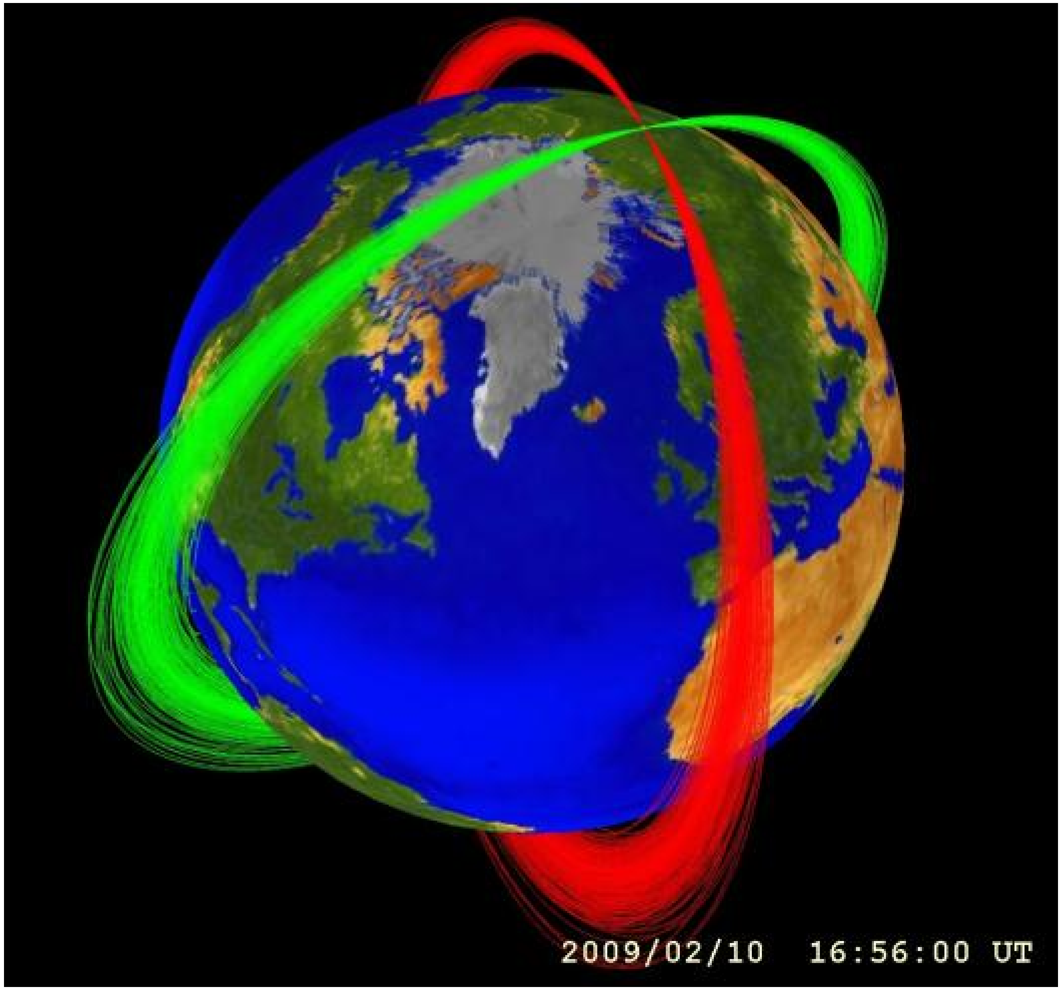




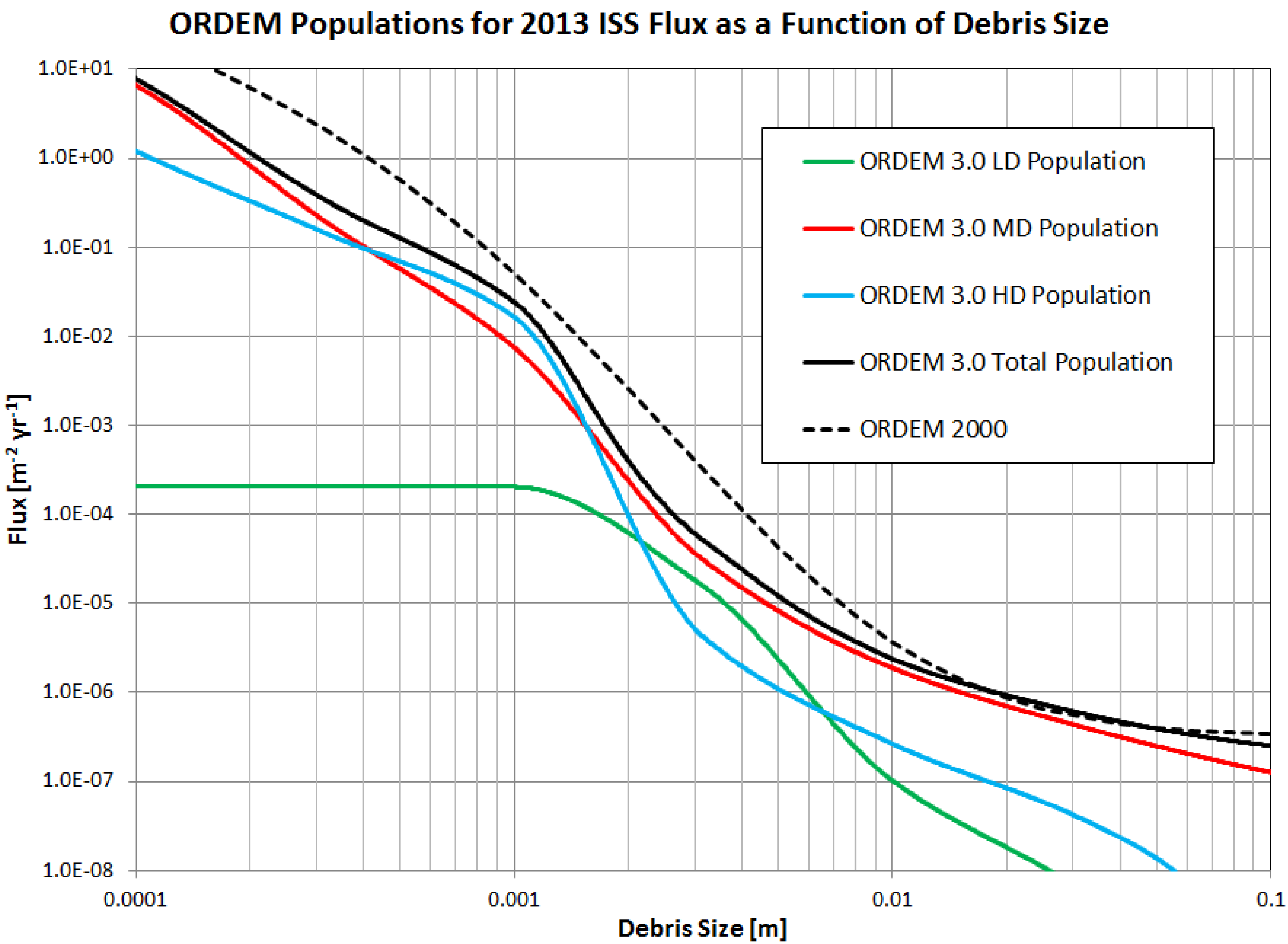
Cataloged objects >10 cm diameter

Debris movies

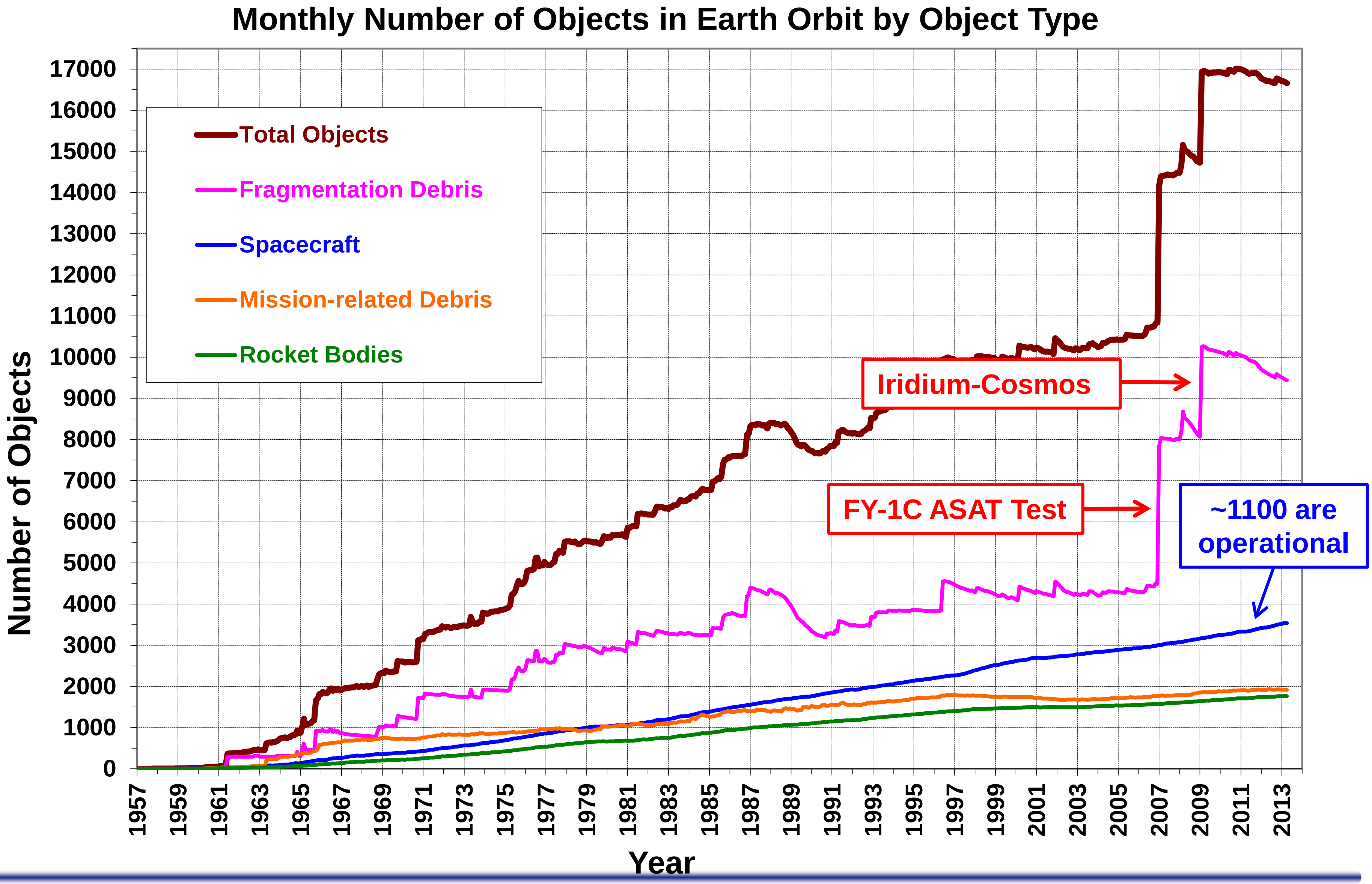
- **Debris fly-through**
- **Iridium-Cosmos collision**



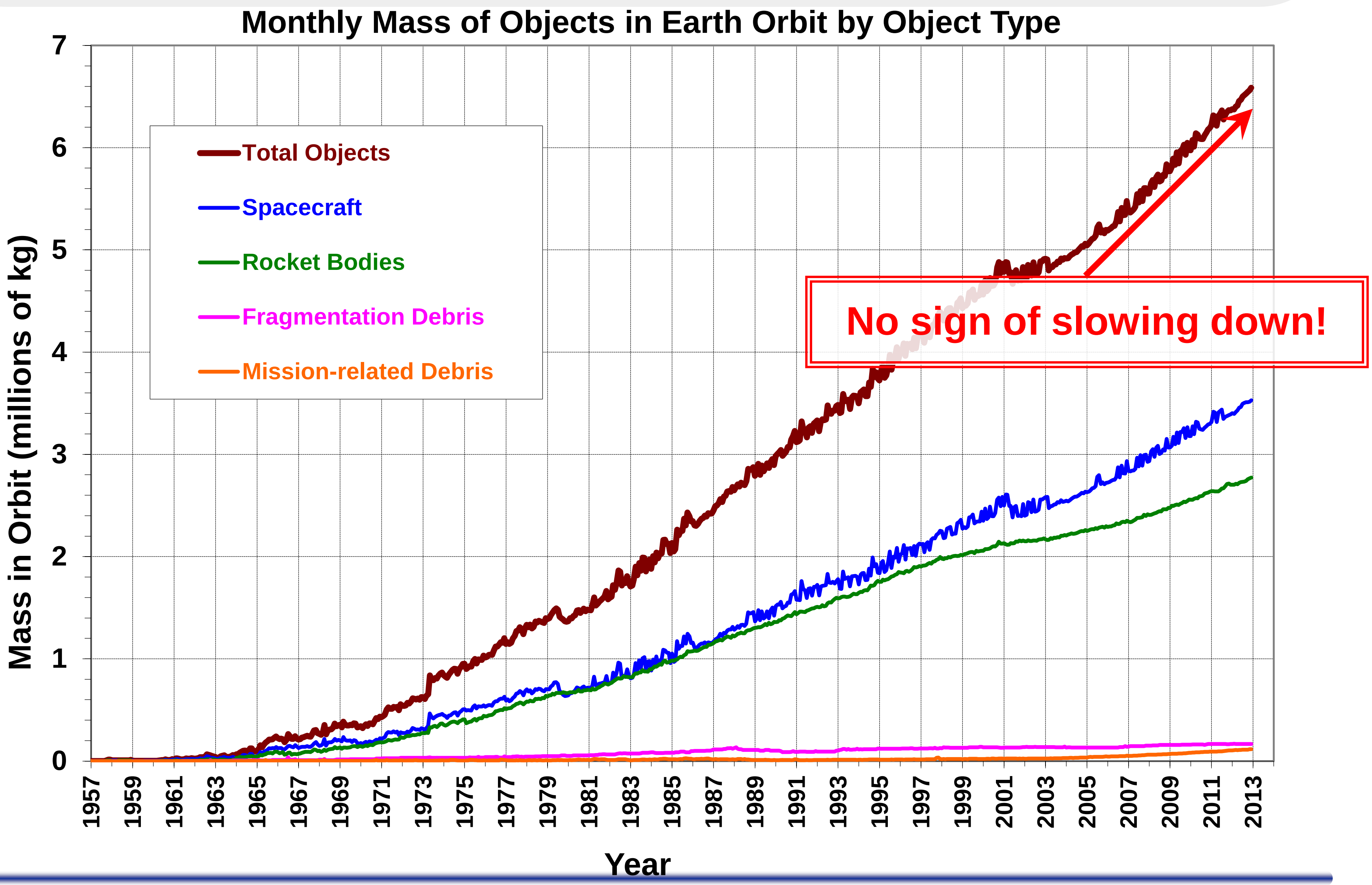
Orbital Debris Material Distributions - ISS



Growth of the Cataloged Populations



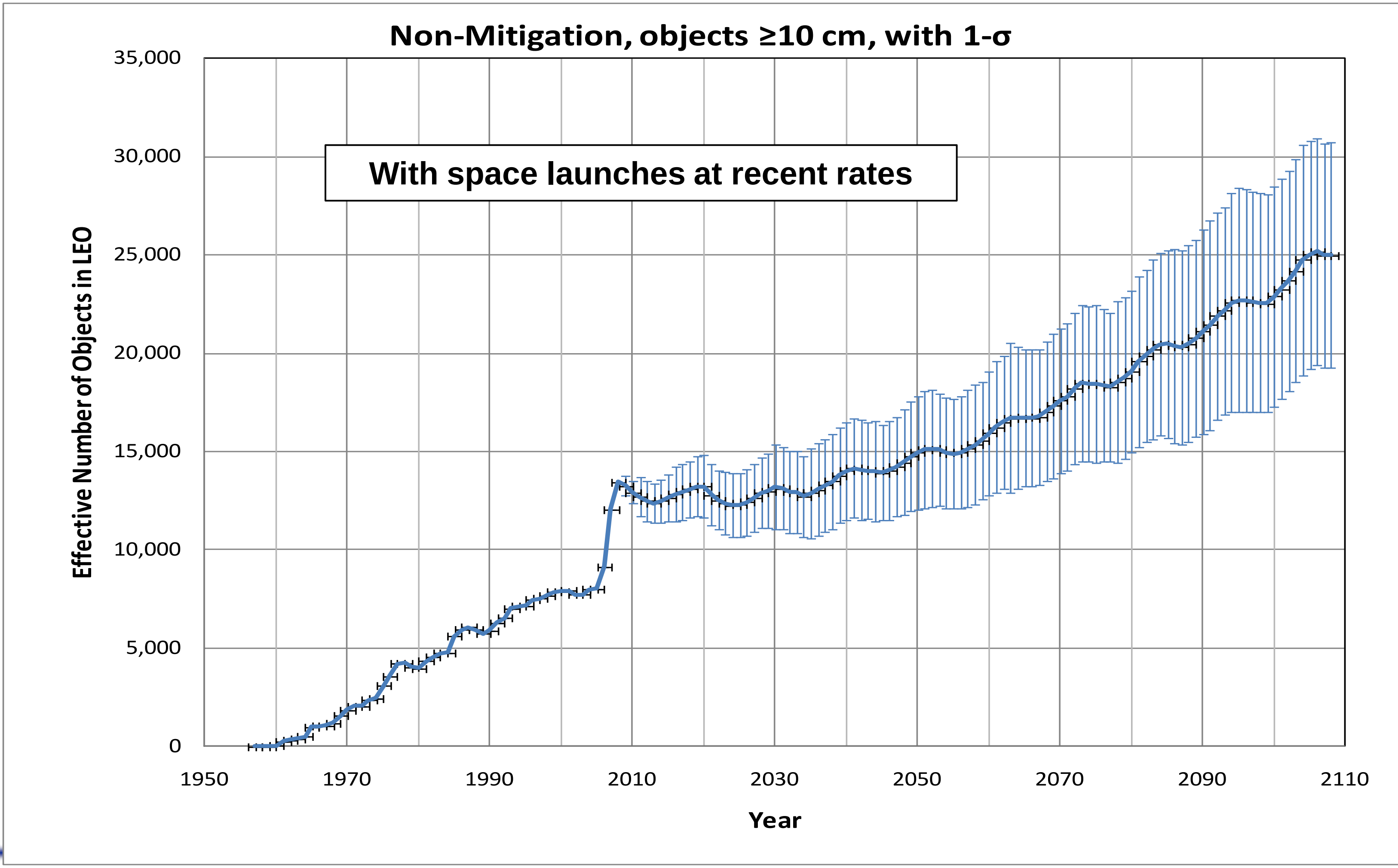
Mass in Space



Long-Term Projection & the Kessler Syndrome

"The current debris population in the LEO region has reached the point where the environment is unstable and collisions will become the most dominant debris-generating mechanism in the future"

– Liou and Johnson, Science, 20 January 2006



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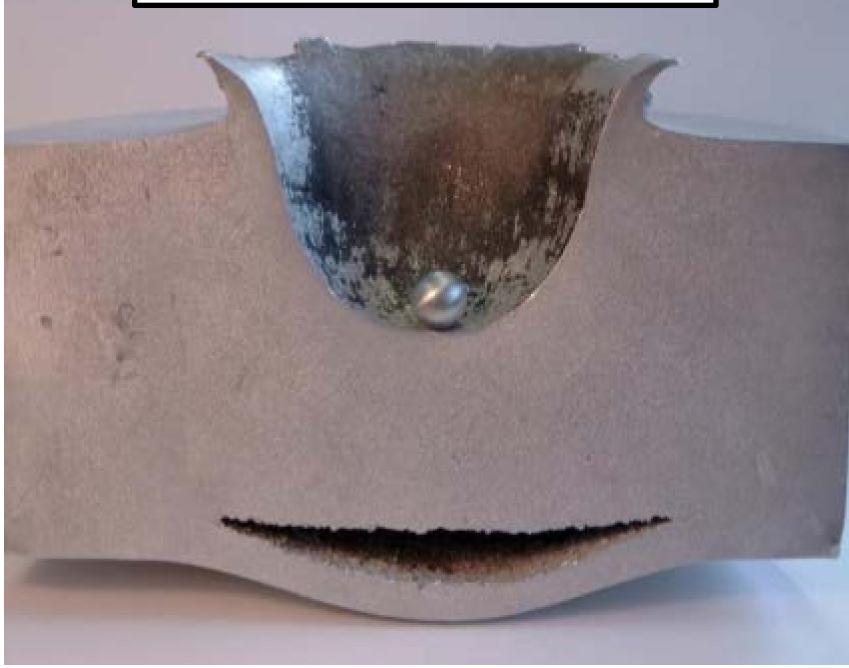
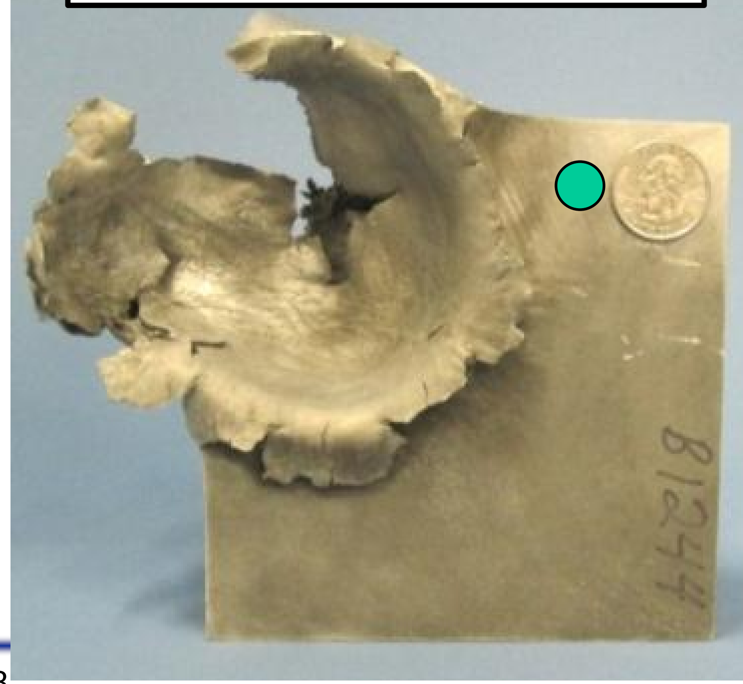
Hypervelocity impact effects

- **Even small MMOD impacts can cause a lot of damage**
  - Hypervelocity MMOD impacts represent a substantial threat to spacecraft
  - Rule of thumb: at 7km/s, aluminum sphere can penetrate completely through an aluminum plate 4x the sphere's diameter
  - A multi-layer spaced shield provides more effective protection from hypervelocity impact than single layer

Comparison of size of projectile to size of impact crater

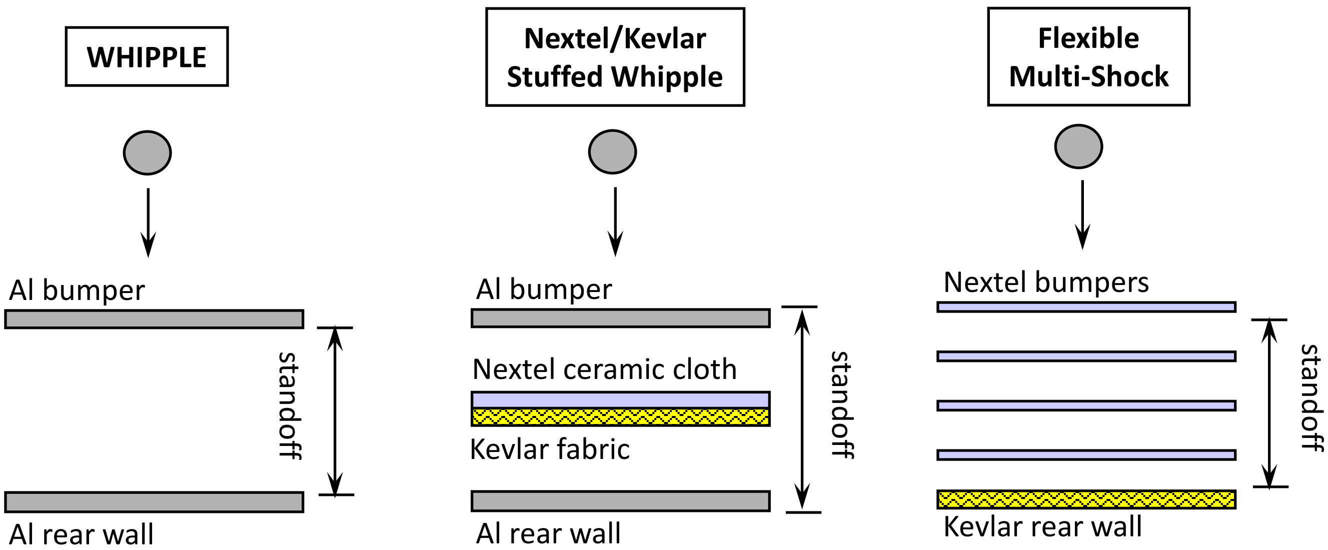


Damage from a 1.3cm diameter sphere at 7km/s



MMOD Shielding

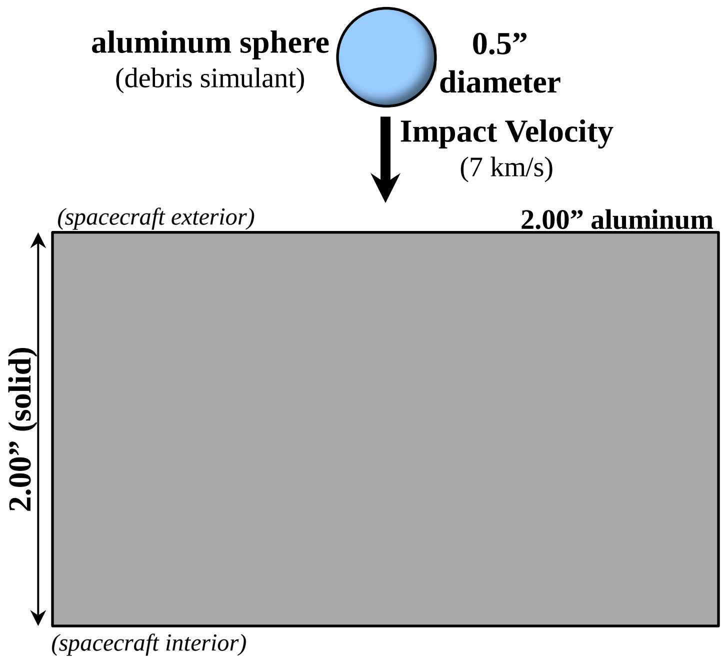
- **Several types of shielding applied to spacecraft MMOD protection**
  - Whipple shields
  - Nextel/Kevlar "Stuffed Whipple" shields
  - Multi-Shock shields
- **Protection performance characterized by impact tests, simulations**
  - Defined by "ballistic limit" equations (BLEs)



Monolithic versus Stuffed Whipple Shield
Weight Comparison of Equal-Performance Shielding

Aluminum "Monolith" Shield

29.1 pounds per square foot



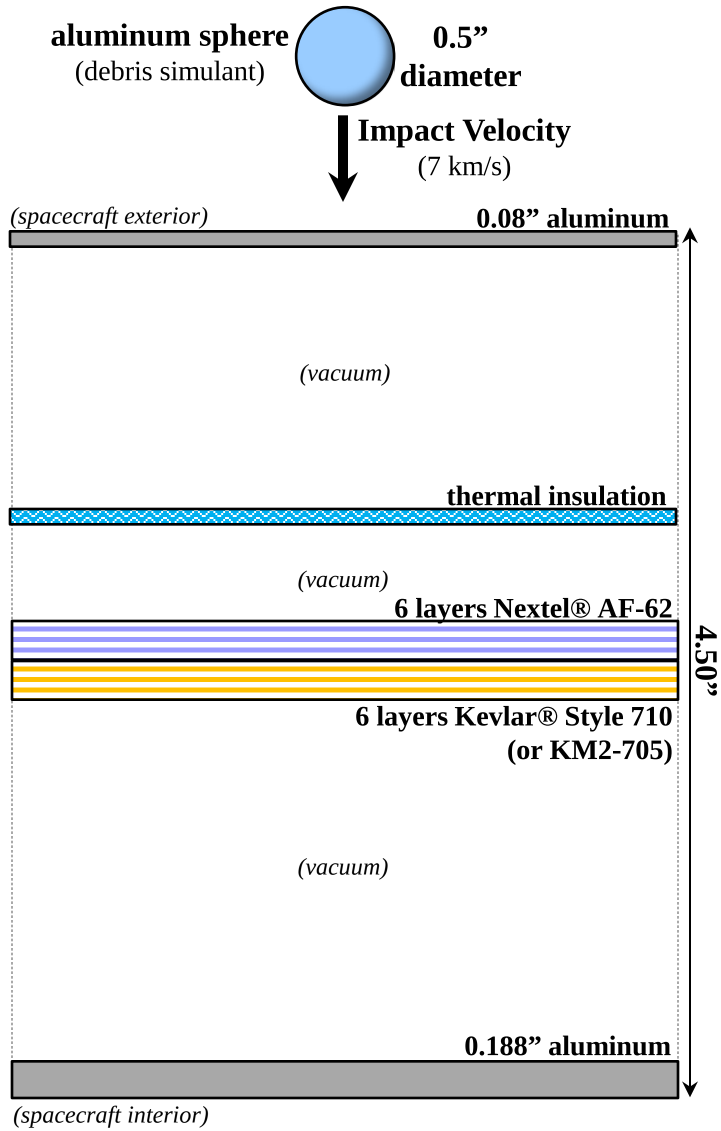
Scale: 1" = 1"

equal performance

84% weight reduction

Stuffed Whipple Shield

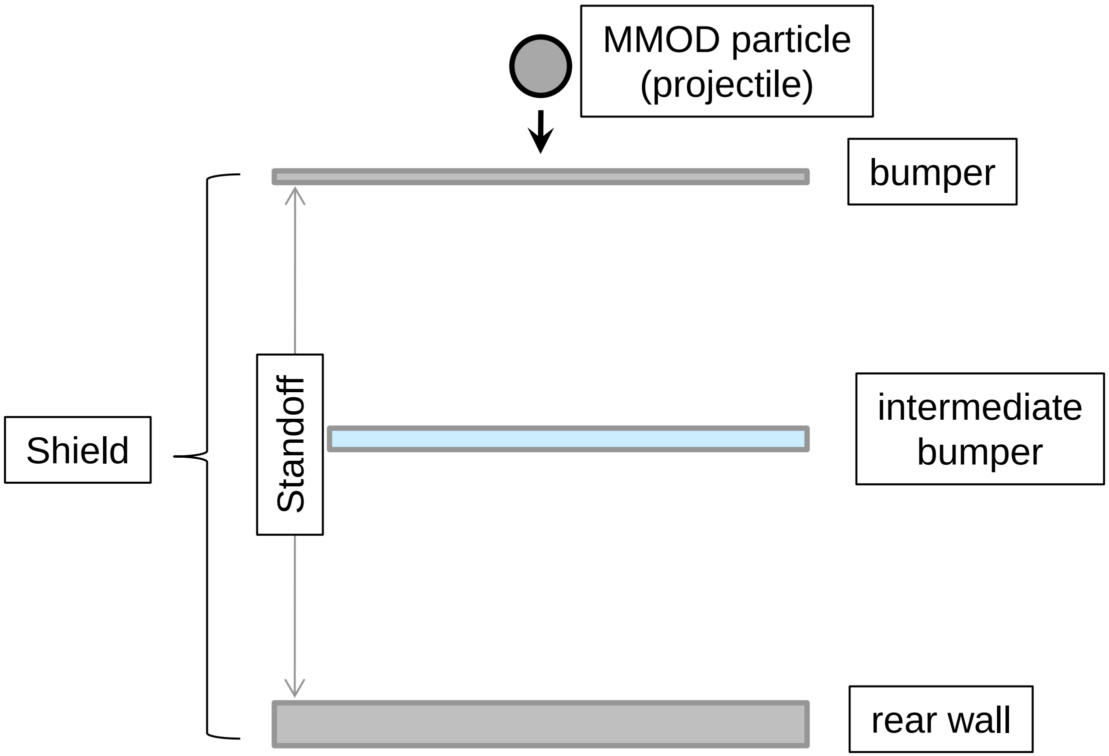
4.5 pounds per square foot



These shields can stop a 0.5" diameter aluminum debris projectile impacting at 7km/s, but the Stuffed Whipple shield weighs 84% less (94% if rear wall is excluded) and costs much less to launch to orbit

MMOD shielding background

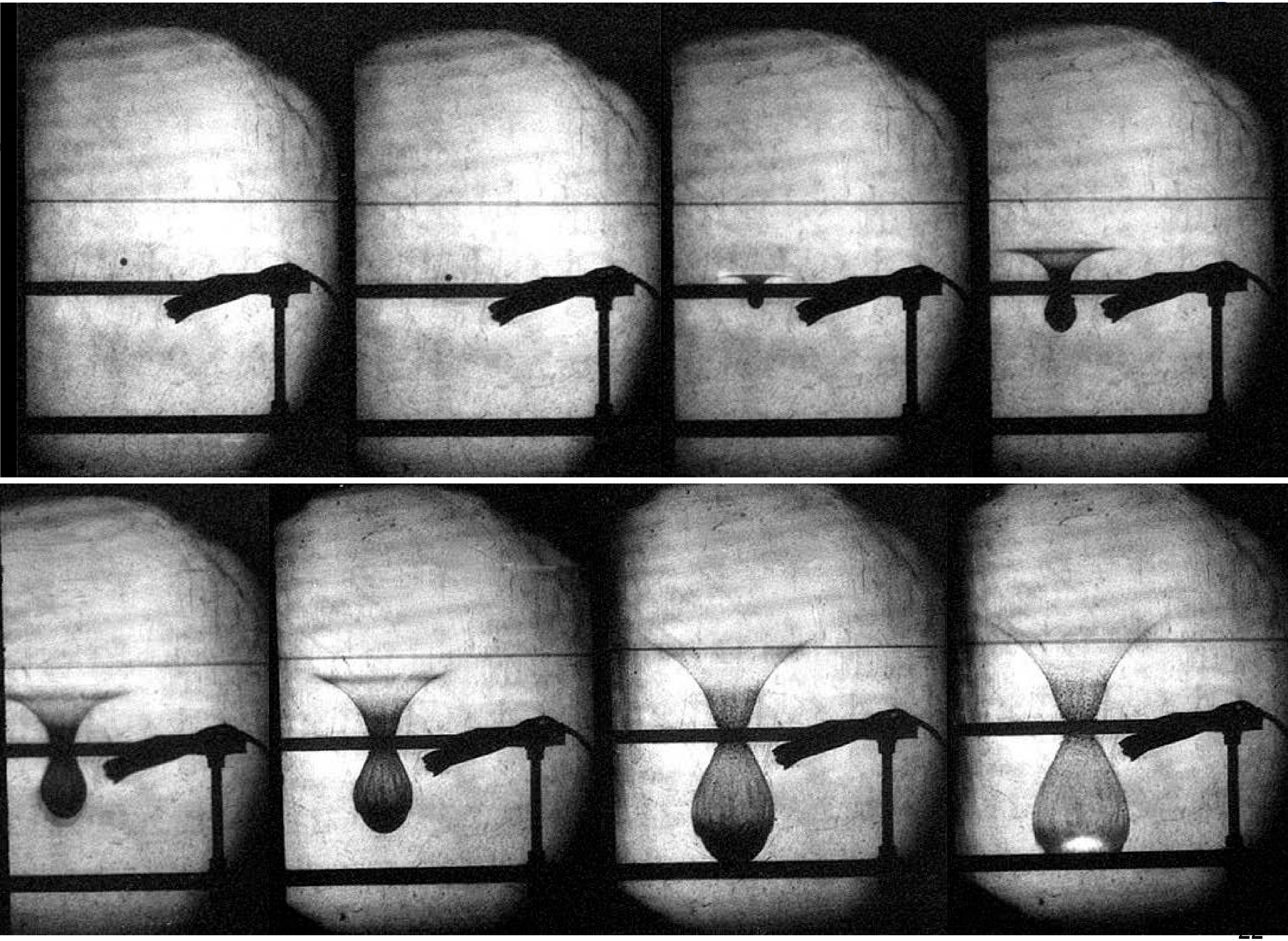
- **MMOD shields typical composed of bumper(s), standoff, and rear wall (final protection layer)**
  - Exclude multi-layer insulation (MLI) thermal blanket



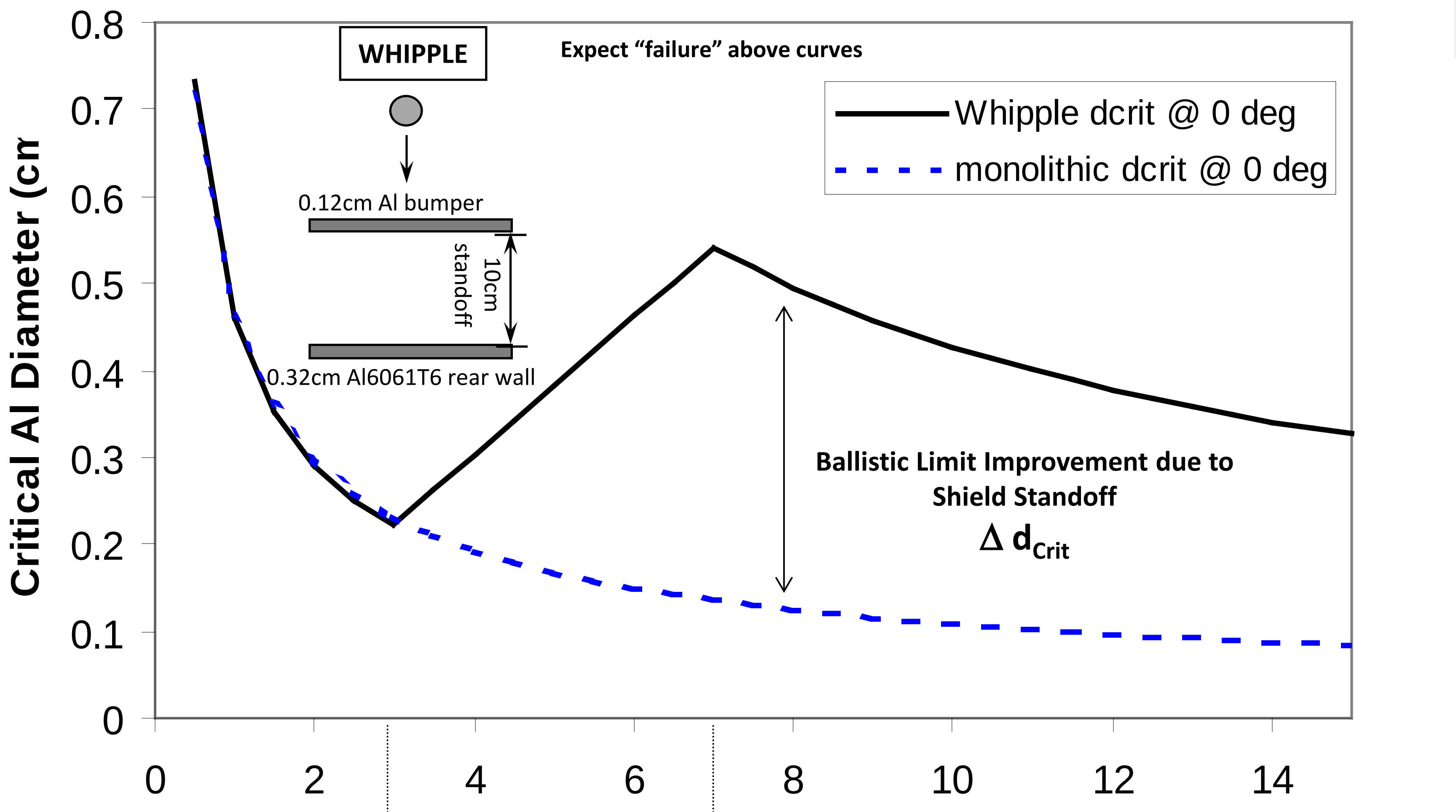
Purpose: Breakup MMOD particle, laterally disperse resulting debris
Key material & physical parameters (V ≥ 7 km/s): density, thickness to projectile diameter ratio, thermal properties

Purpose: Further breakup debris from first impact, slow expansion of debris cloud
Key material & physical parameters (V ≥ 7 km/s): combination of first bumper and rear wall properties

Purpose: Stop debris from MMOD & bumper(s)
Key material & physical parameters (V ≥ 7 km/s): strength, toughness, thickness



Ballistic Limits for Whipple Shield & equal mass Monolithic

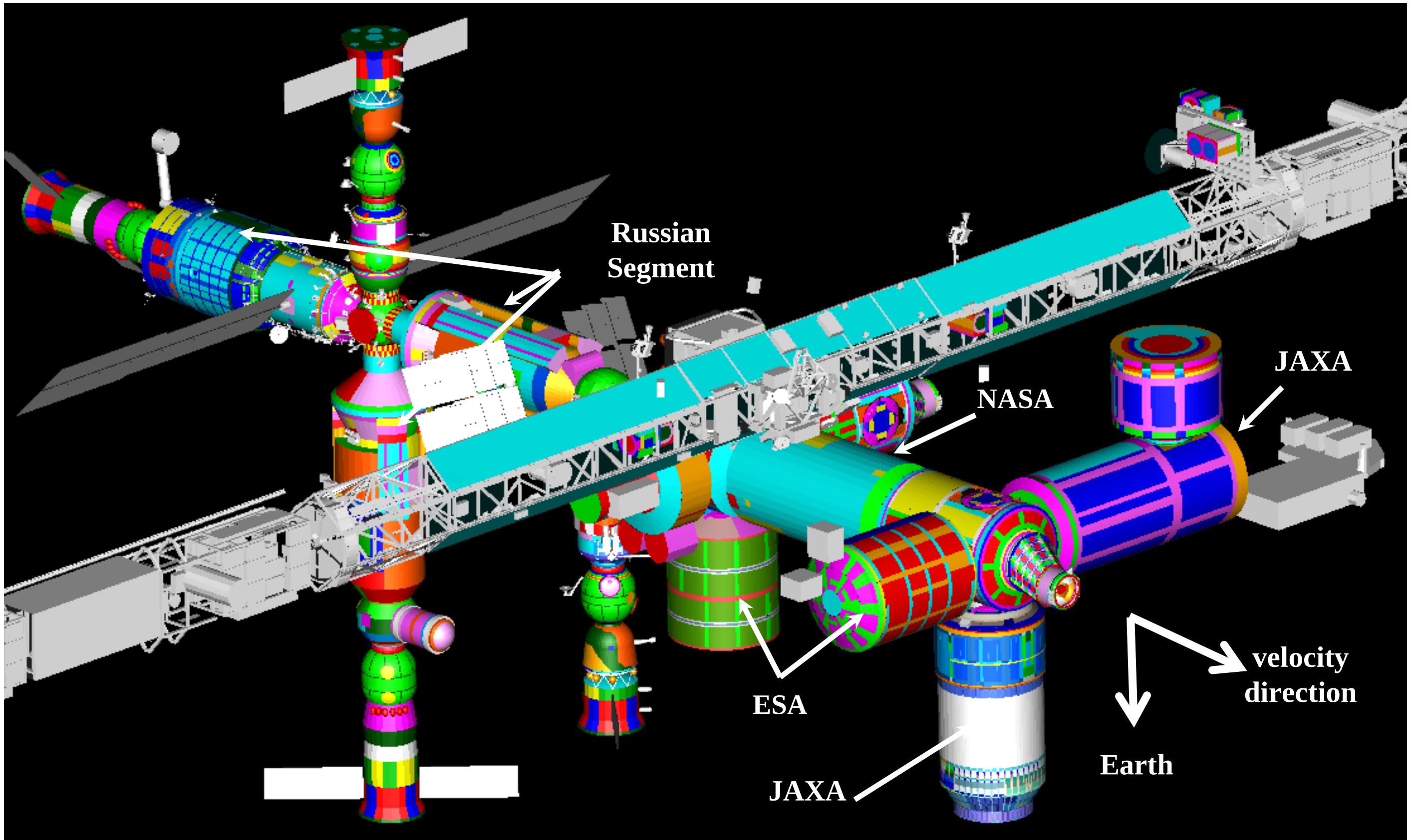


Velocity Range:	**Ballistic Regime**	**Fragmentation & Partial Melt Regime**	**Complete Melt Regime**
State of Debris Cloud: *(for Al on Al impacts)*	Few solid fragments	Many (increasing with velocity) solid fragments & liquid droplets	Fine droplets, few solid fragments, some vapor

ISS shielding overview

- **Several hundred MMOD shields protect ISS, differing by materials, standoff distance, and capability**
- **Heavier shields on front & sides (where we expect most MMOD impacts), less capable shielding on aft, nadir and visiting vehicles**

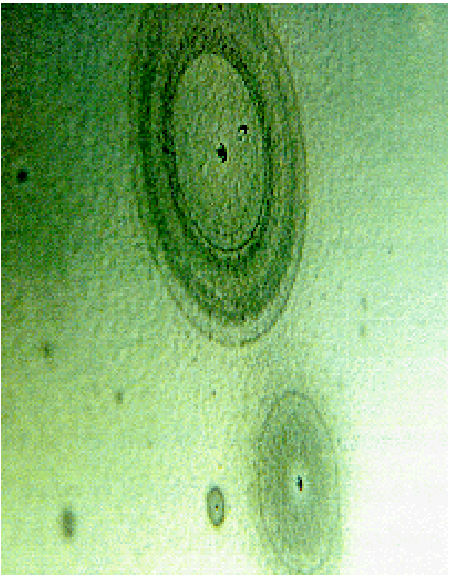
Finite Element model (FEM) used in ISS MMOD risk assessments

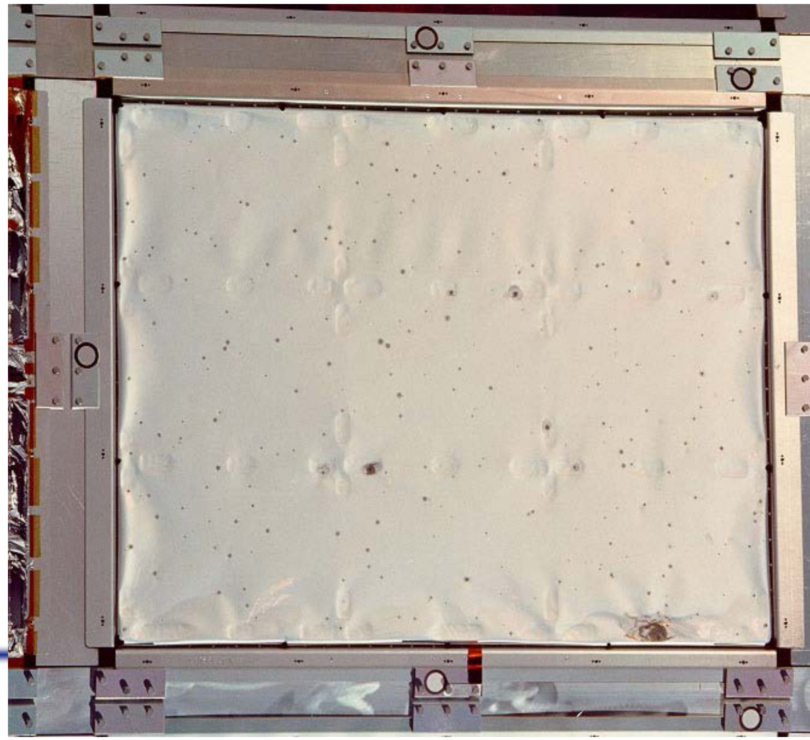


colors represent different MMOD shield configurations

MMOD directionality

- **The Long-Duration Exposure Facility (LDEF) [1984-1990] provided the first detailed assessment of small particle debris in low Earth orbit**
  - LDEF maintained its orientation relative to the velocity vector, Earth/Space for its entire mission
- **Over 30,000 observable MMOD strikes were identified on the exterior of LDEF (damage diameter ≥ 0.3mm)**
- **Of these MMOD impacts, approximately 20x more impacts were found on the forward face relative to the aft face, and 200x more on the forward than Earth**

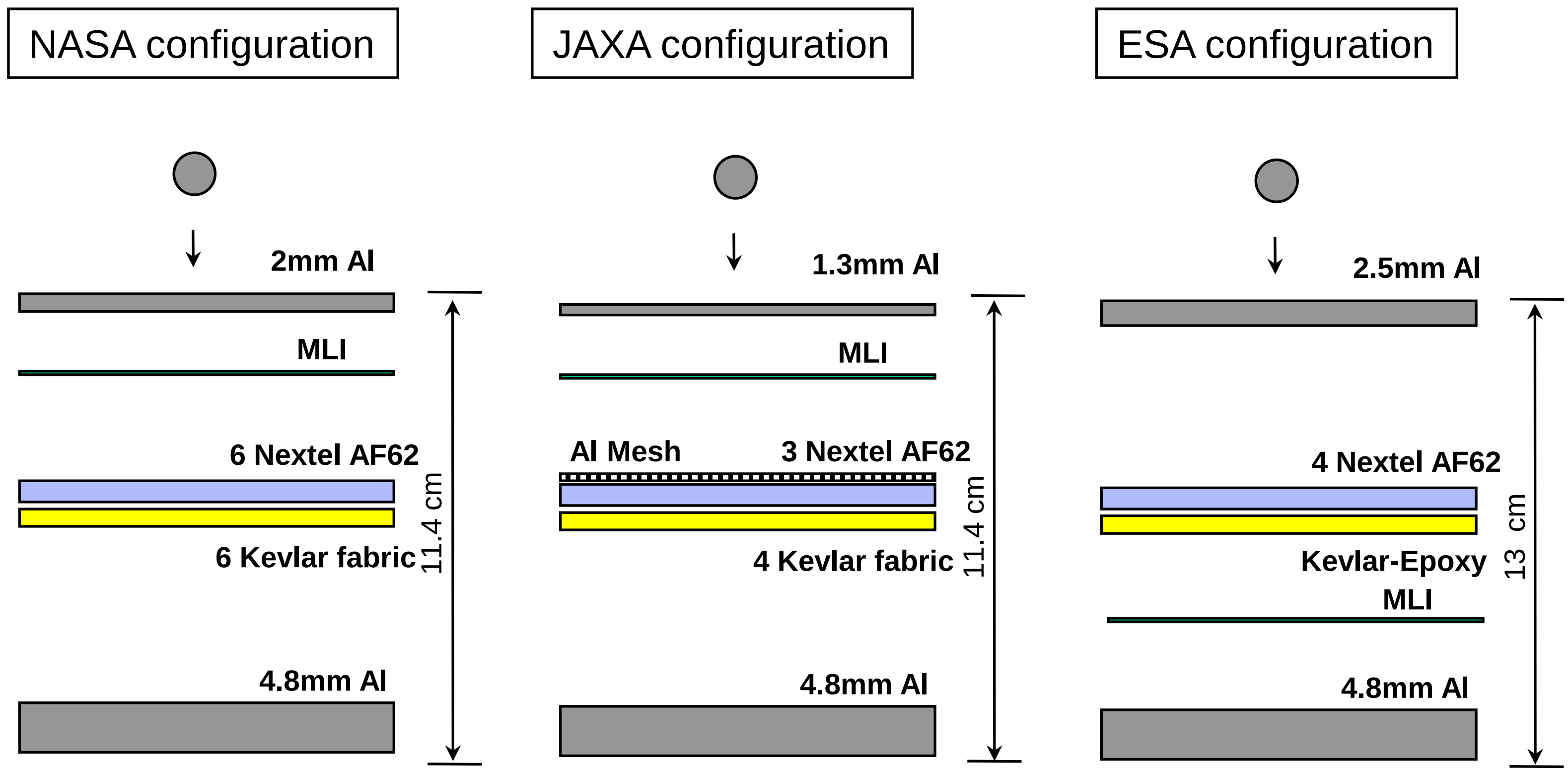




ISS “Stuffed Whipple” Shielding

(Typical Configurations Illustrated)

- US, JAXA and ESA employ “Stuffed Whipple” shielding on the areas of their modules exposed to greatest amount of orbital debris & meteoroids impacts
  - Nextel and Kevlar materials used in the intermediate bumper
  - shielding capable of defeating 1.3cm diameter aluminum sphere at 7 km/s, normal impact



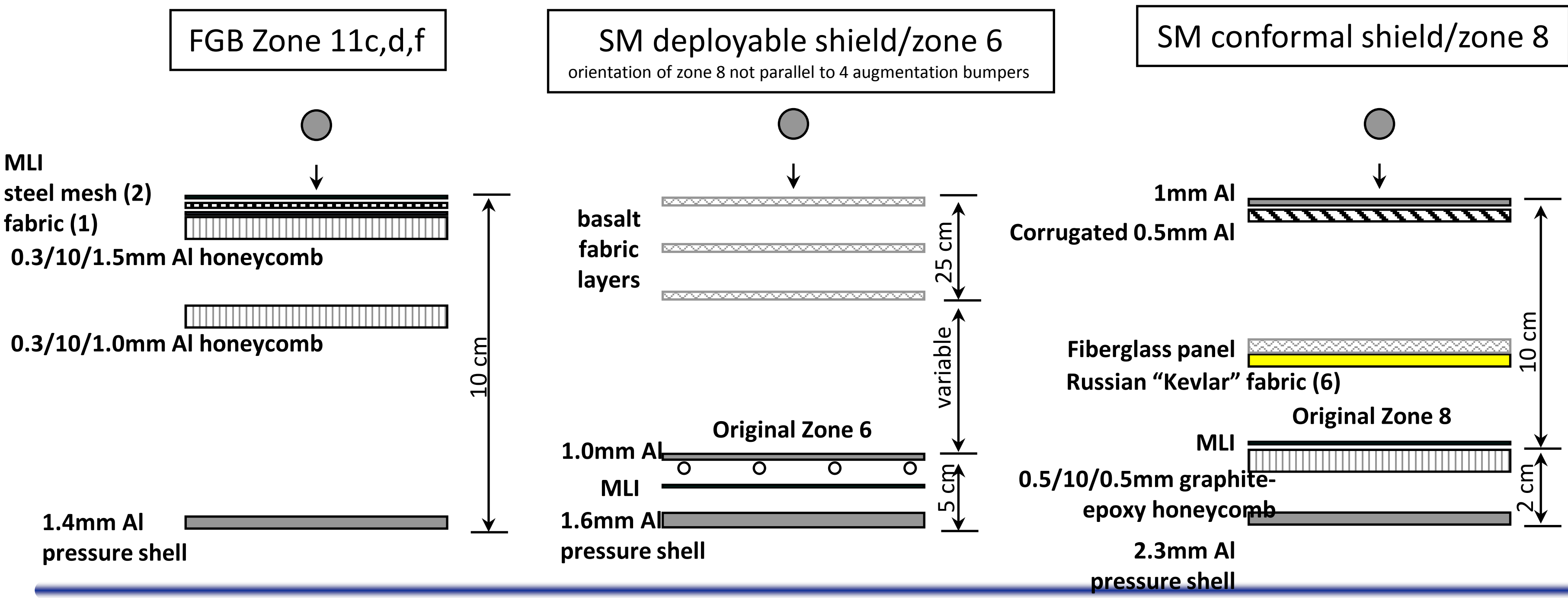
Typically, bumpers are Al 6061-T6, rear walls are Al 2219-T87 or Al 2219-T851
Kevlar 29 style 710 or Kevlar KM2 style 705 fabric are typically used

Shielding materials

- **Nextel (3M Inc. trade mark): fabric consisting of alumina-boria-silica ceramic fibers**
  - Other ceramic and glass fabrics tested, and will provide adequate MMOD protection (substitute equal mass for Nextel)
- **Kevlar aramid fabric: highest hypervelocity protection performance found using Kevlar KM2 fabrics**
  - Other high-strength to weight materials incorporated in MMOD shields include Spectra, Vectran, carbon fabric and carbon-composites

FGB and Service Module (SM) Mesh & Multi-Shock MMOD Shields

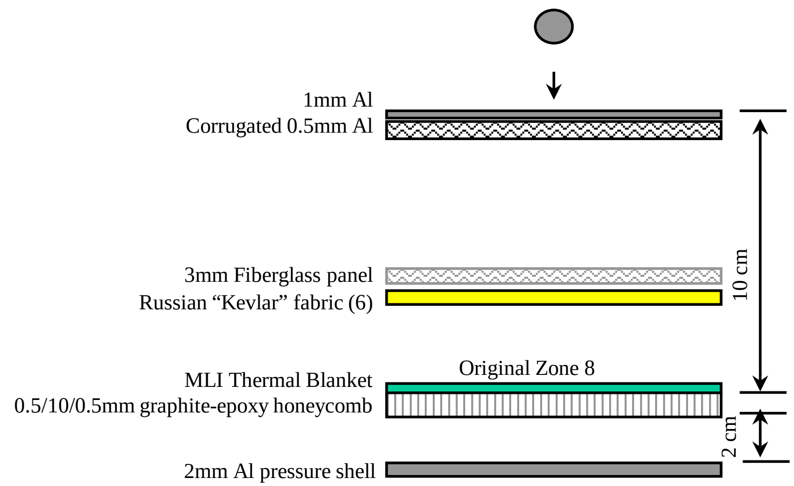
- Majority of FGB shields include 2 or more bumpers spaced in front of the module pressure shell or propellant tank wall (superior to single bumper shields)
  - Metal mesh layers provide additional protection in many FGB shields (a mesh causes greater spread to the debris cloud resulting from high velocity collision)
  - SM augmentation shields rely on multi-shock ceramic fabric layers
- FGB shields & SM augmentation shields provide protection from 1-1.5cm diameter aluminum projectiles (typical).
  - Unaugmented SM shields protect from ~0.3cm aluminum projectiles (typical)



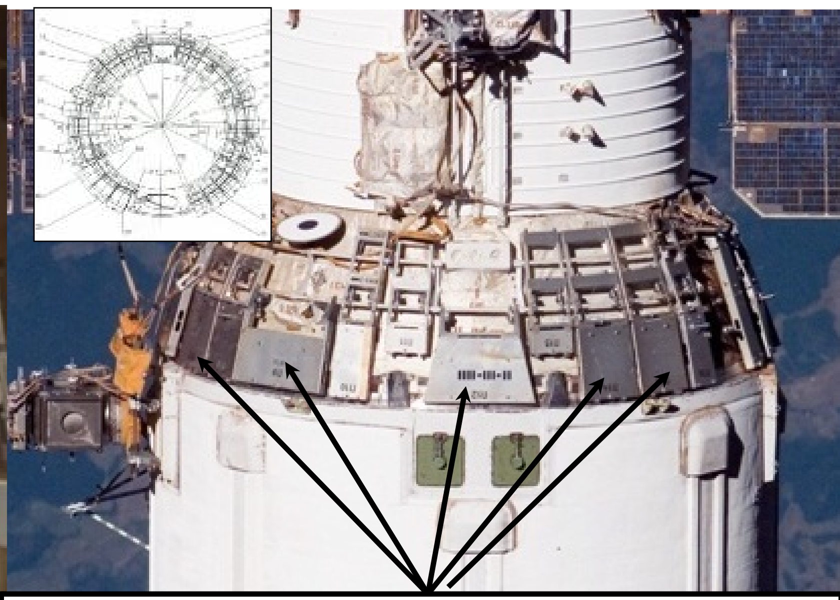
ISS Service Module Shielding

- **Service Module (SM) identified as high penetration risk using Bumper risk analysis**
  - large cone region
  - forward sides of small diameter cylinder
- **Shields designed and tested, EVA installed**
  - 23 augmentation shields for the cone region
  - 5 augmentation shields for the cylinder region
- **28 shields reduced SM MMOD risk by 30%**

SM "conformal" augmentation shield



EVA Installation

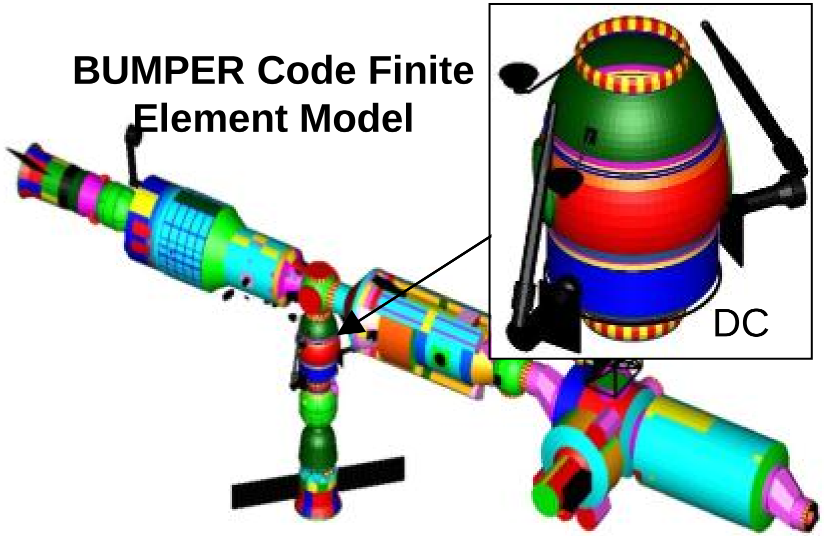


23 "conformal" panels on cone region

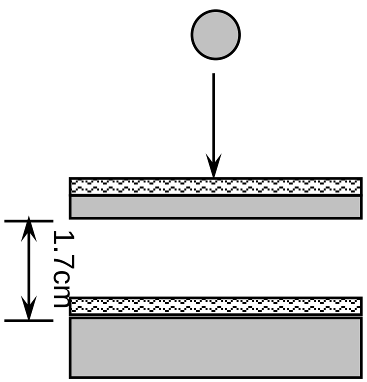
5 panels on small diameter cylinder

Docking Compartment (DC) MMOD Shield & Performance Capability

BUMPER Code Finite Element Model



Typical DC Shield
(Whipple shield with MLI thermal blankets)

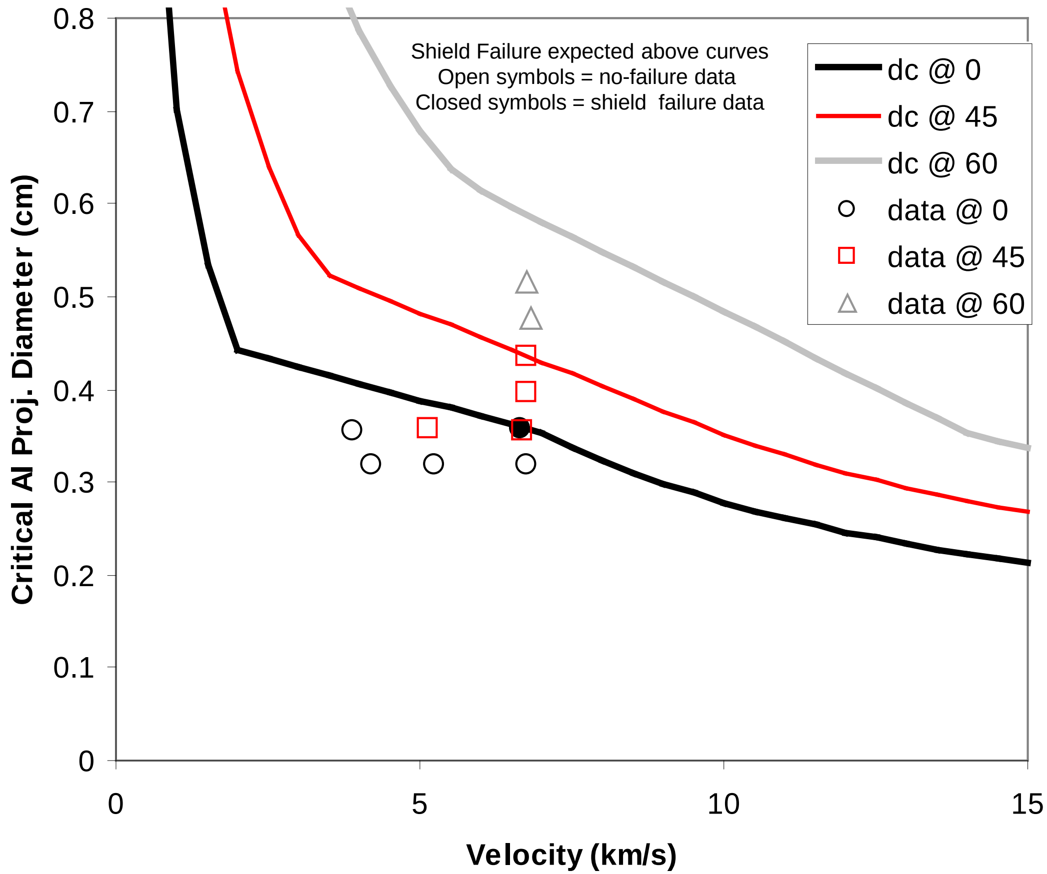


Ballistic Limit of shield (typical):
0.35cm Al projectile @ 7km/s, 0º

MLI
0.1cm Aluminum AMG6 bumper

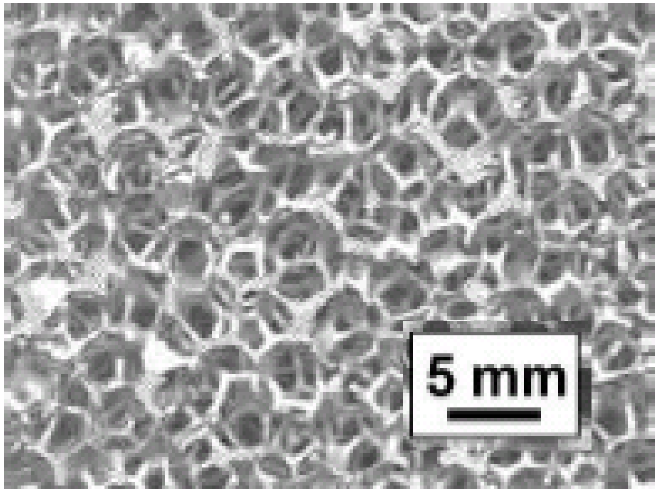
MLI
0.4cm Aluminum AMG6 pressure shell

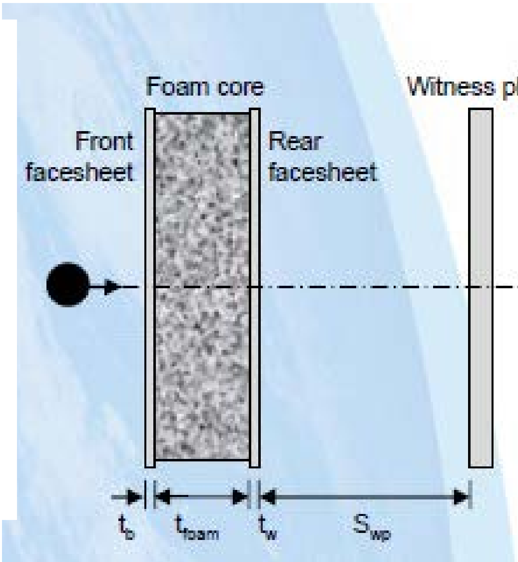
DC-1 Ballistic Limit Equations (BLEs) and HVI Test Data

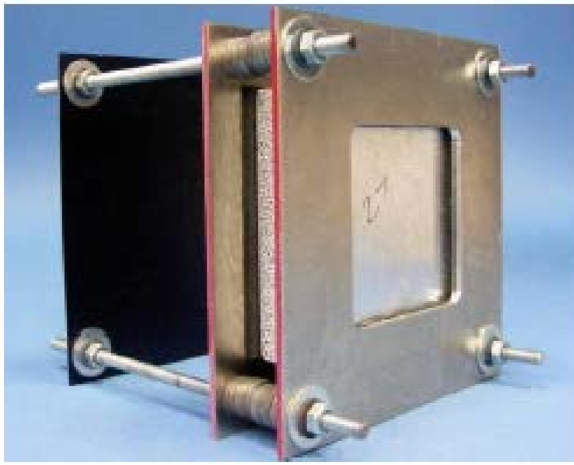


Foam sandwich MMOD shielding

- **Honeycomb core sandwich structures are used extensively on spacecraft**
- **Honeycomb core tends to “channel” debris cloud and results in a relatively poor MMOD shield**
- **Replacing the honeycomb core with a metallic or ceramic foam provides improved MMOD protection**

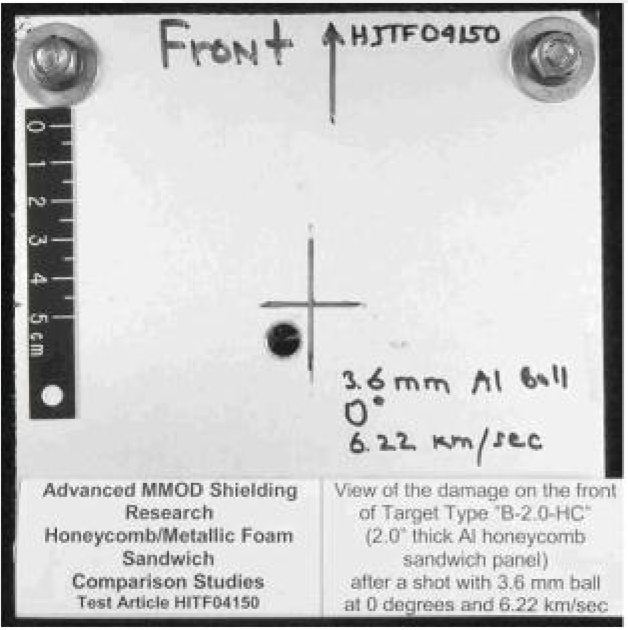


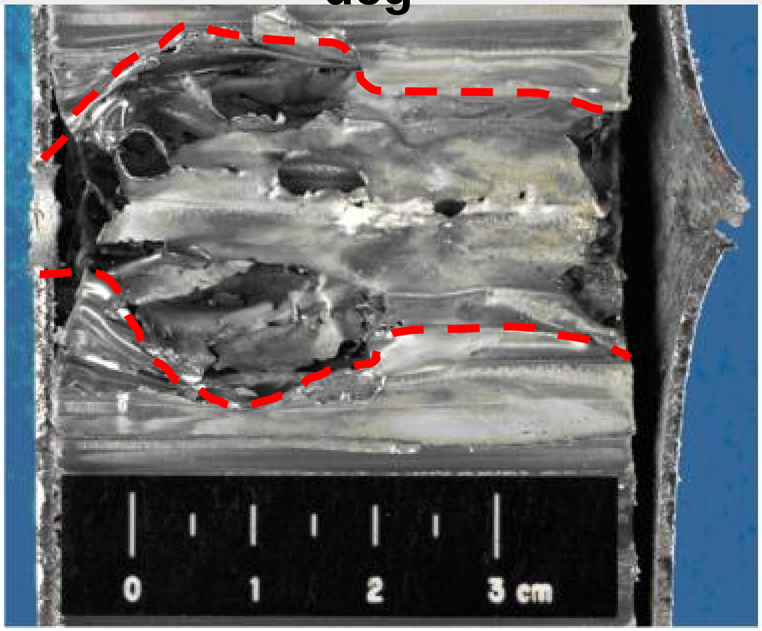


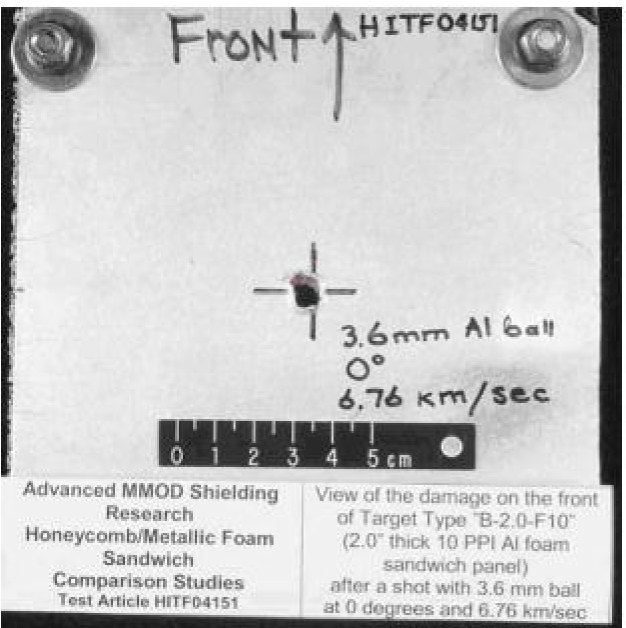


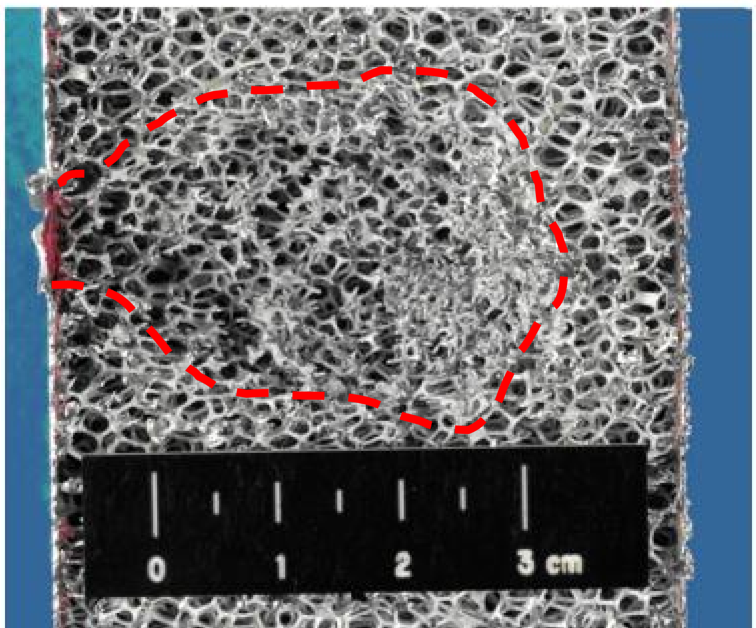
Foam sandwich hypervelocity test

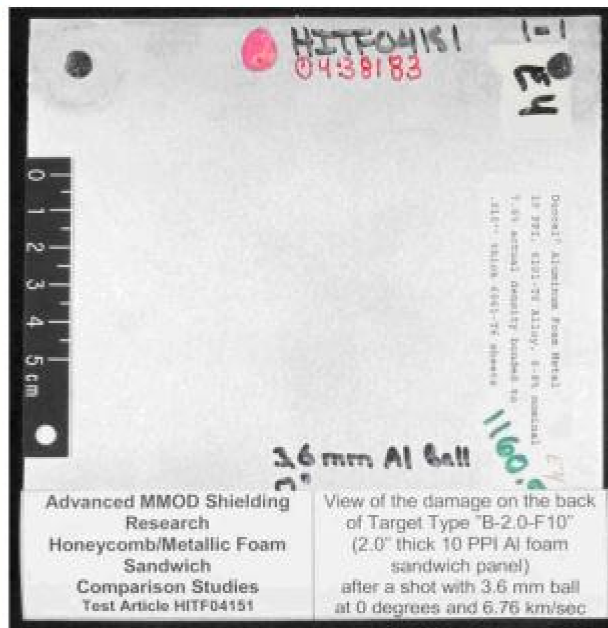
3.6mm diameter Al2017T4 sphere at 6.2-6.8 km/s, 0-deg







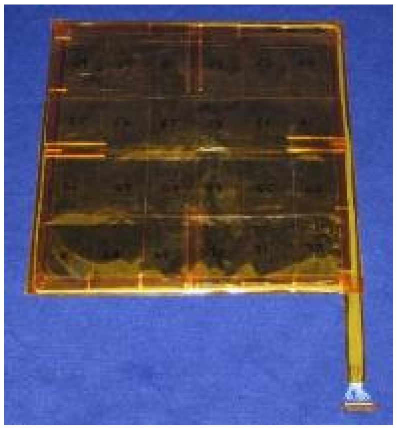




Smart MMOD shields

- **Implementing impact damage detection/location sensors is a high-priority**
  - Successfully added wireless accelerometer sensor detection system to Shuttle to monitor ascent and MMOD impacts on wing leading edge
  - Other methods to detect/locate impact damage available based on sensors to detect: acoustic emissions, fiber-optic & electrical grids, piezoelectric PVDF film, impact flash, radiofrequency emissions
  - Working to implement/integrate impact sensors into MMOD protection shields on next generation spacecraft

Test article (2'x2') with integrated sensors & piezoelectric sensor array



Distributed impact detection system (DIDS)

Shielding Summary

- **MMOD shielding capability influenced by both:**
  1. Configuration – “standoff” (more is better), number of bumper shield layers
  2. Material selection – ceramics/metals on exterior of shield, high-strength to weight ratio (fabrics & composites) on interior of shield

- **More information available (including many BLEs):**
  - NASA TP-2003-210788, Meteoroid/Debris Shielding
  - NASA TM-2009-214785, Handbook for Designing MMOD Protection
  - NASA TM-2003-212065, Integration of MMOD Impact Protection Strategies into Conceptual Spacecraft Design
  - NASA TM-2009-214789, MMOD Shield Ballistic Limit Analysis Program
  - NASA/TM-2014-218268, Volume I & II, Micrometeoroid and Orbital Debris (MMOD) Design and Analysis Improvements, NASA Engineering and Safety Center Report NESC-RP-12-00780
  - E.L. Christiansen and J.H. Kerr, Ballistic Limit Equations for Spacecraft Shielding, *International Journal of Impact Engineering*, Vol. 26, pp. 93-104, 2001

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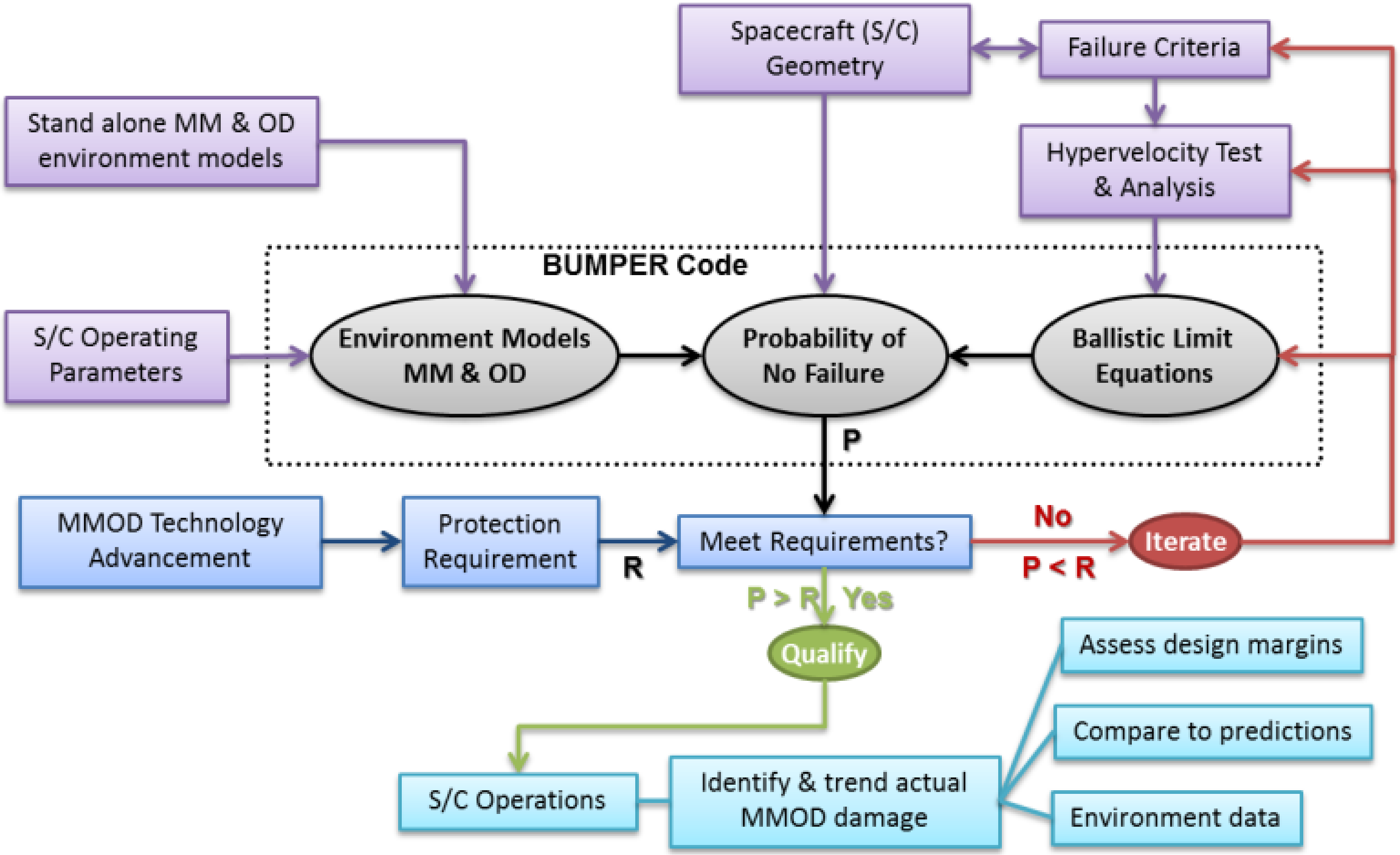
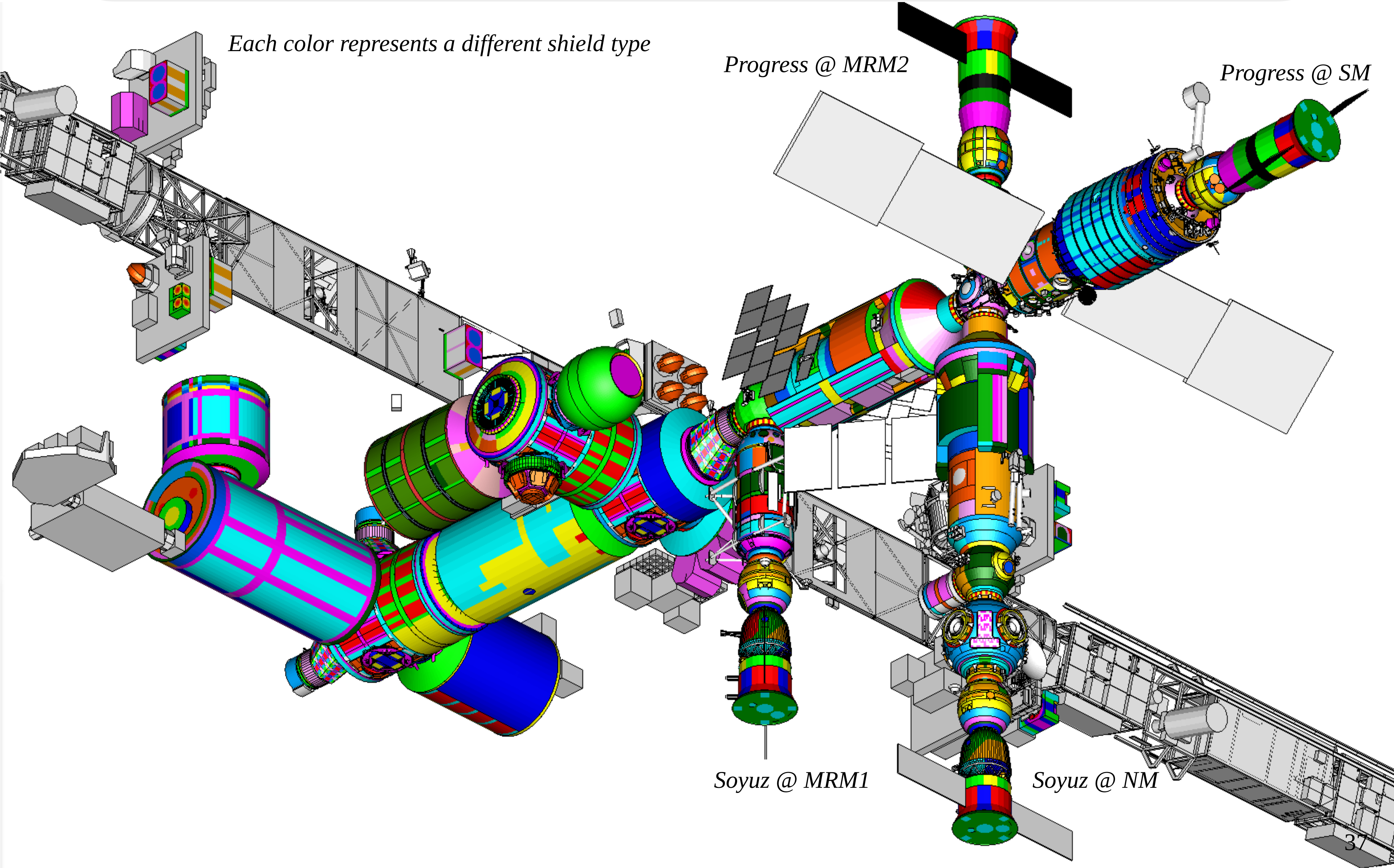
MMOD Risk Assessment Process

- **Process used to identify MMOD risk drivers, evaluate risk mitigation options & optimization, verify compliance with protection requirements**



ISS Finite Element Model for MMOD risk assessment
Block 7 (2017-2028)

PMM relocated to N3f, add BEAM, IDA-1 & IDA2



Failure criteria

- **Failure criteria required for each zone of spacecraft that clearly defines the limits of allowable damage (or failure threshold)**
  – Basis of impact tests/analysis, ballistic limit equations, risk assessments
- **Typically defined by Engineering & Program/Project (not by MMOD)**
- **ISS crew module pressure shell**
  – Typically failure is defined as detached spall or through-hole of pressure shell

Damage Class C3: Detached spall

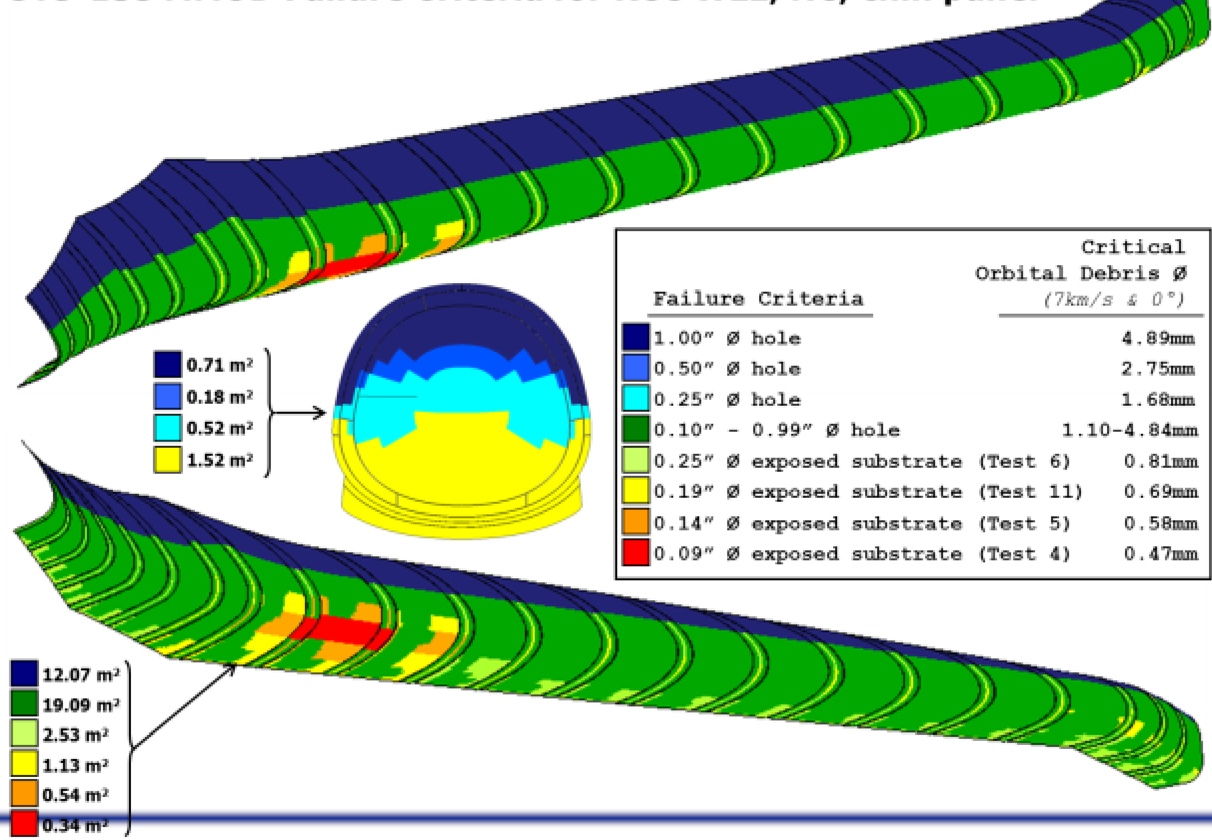
Damage Class C4: Perforation

  – Loss-of-crew (LOC) assessments for ISS include analysis of internal effects of penetrations, with criteria established for LOC due to fatal crew injury, hypoxia, fragmentation/explosion of pressure vessels (internal and external), and several other failure modes

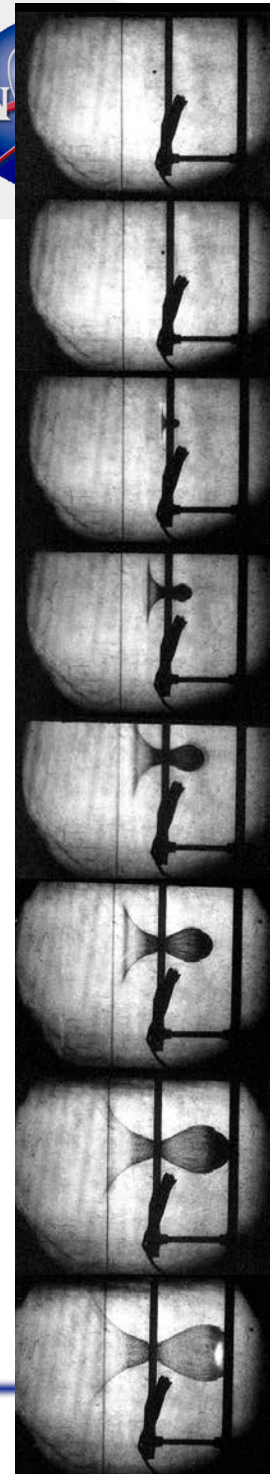
Failure criteria (cont.)

- **Reentry vehicles, crew return vehicles**
  - Loss-of-crew (LOC) failure include: (a) pressure vessel puncture and/or rupture leading to immediate on-orbit loss-of-vehicle/crew, (b) damage to thermal protection system (TPS) leading to loss-of-vehicle during reentry
  - Loss-of-mission (LOM) failure includes: (a) radiator/coolant leaks, (b) others

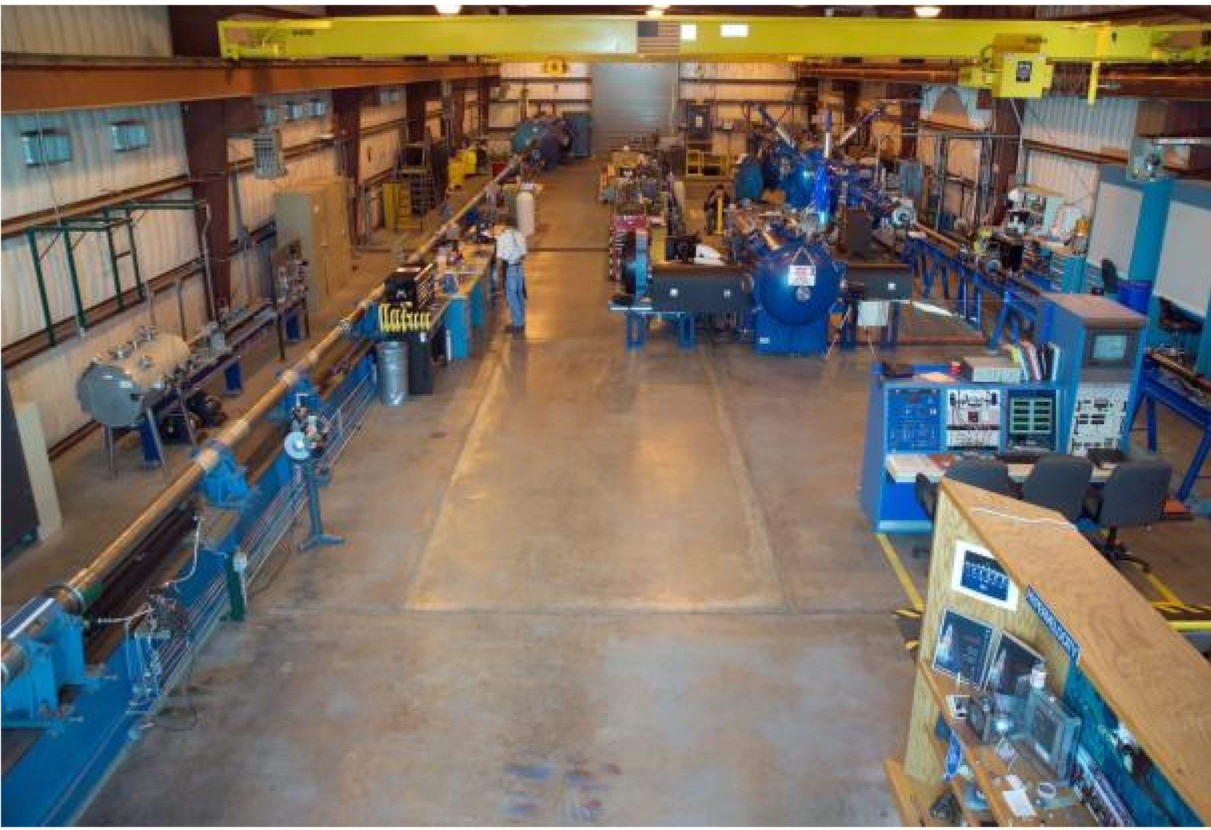
STS-135 MMOD Failure Criteria for RCC WLE, NC, chin panel



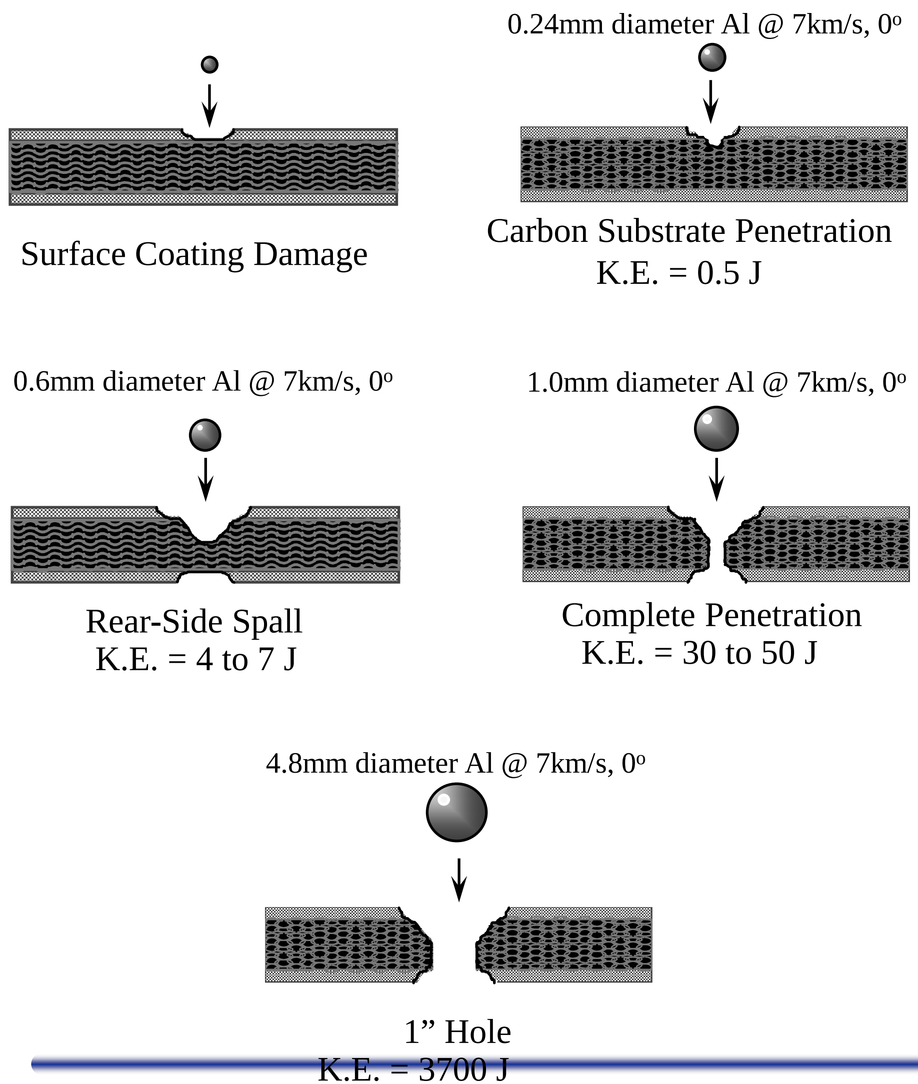
Hypervelocity Impact Test Results Anchor Analysis

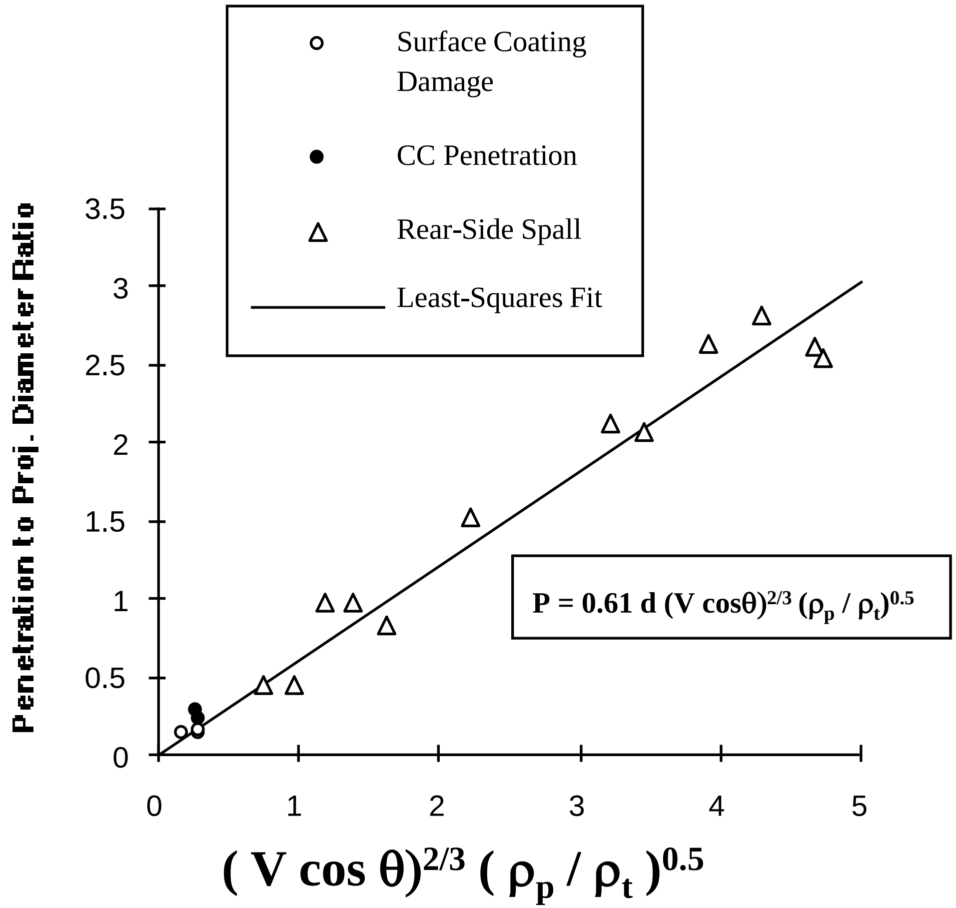


- **JSC-KX plans and performs over 400 impact tests per year**
  - Primarily WSTF two-stage light gas-guns up to 8 km/s
  - University of Dayton Research Institute 3-stage launcher to 10 km/s
  - Southwest Research Institute shaped-charge launcher to 11 km/s
- **Data used to develop and verify ballistic limit equations used in Bumper code on range of different spacecraft components and subsystems**



Hypervelocity Impact Results: Reinforced Carbon-Carbon (RCC) Example





RCC Penetration depth $P = 0.61\ d\ (V \cos\theta)^{2/3} (\rho_p/\rho_t)^{0.5}$

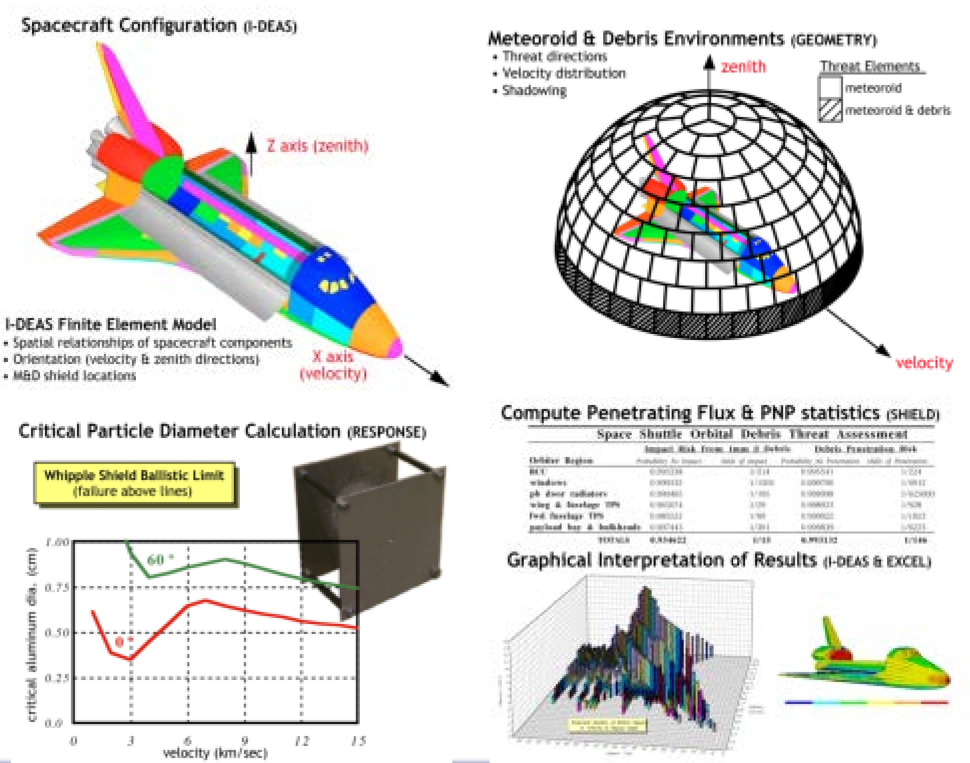
Thickness to Prevent Complete Penetration $t_p = 2.3 * P$

Thickness to Prevent Rear-Side Spall $t_s = 4.5 * P$

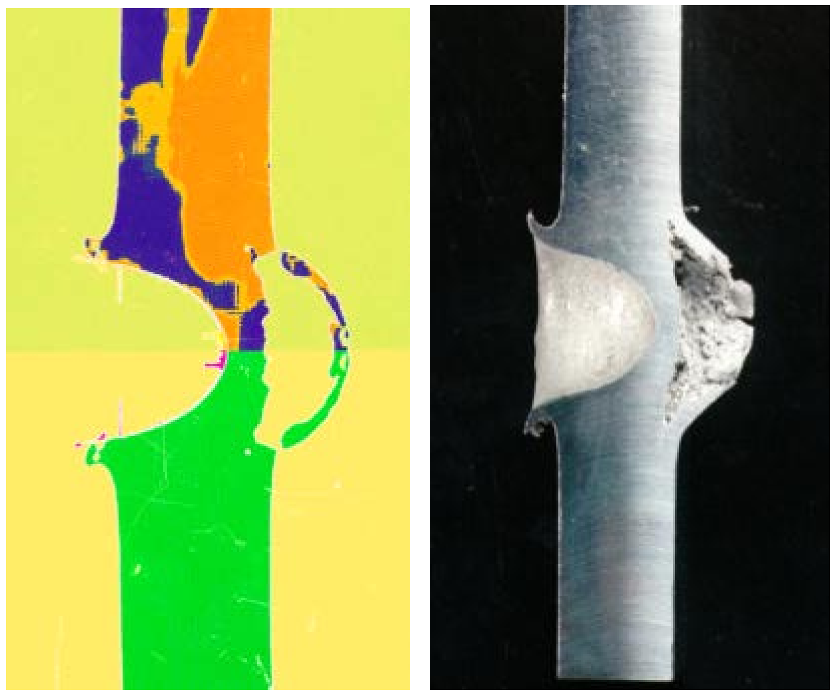
MMOD Risk Assessment Tools

- **Bumper Code – Perform penetration & damage risk assessments**
- **MSC-Surv – Assess consequences of penetration for ISS: loss-of-crew, evacuation risk**
- **Hydrocodes (CTH, Exos, others) – Numerical simulation of hypervelocity impact (virtual test shots)**

Bumper Code



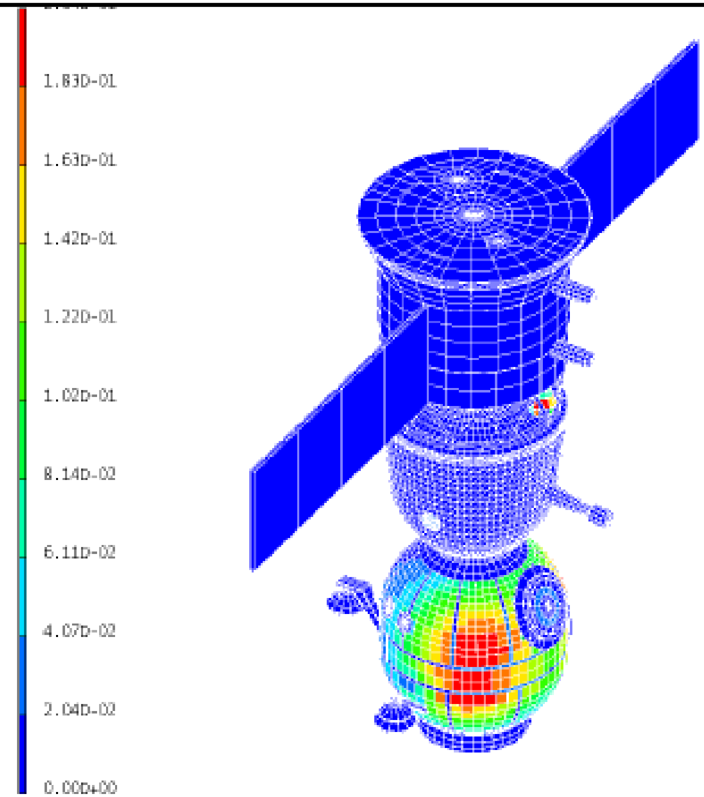
CTH Code



Analysis Products

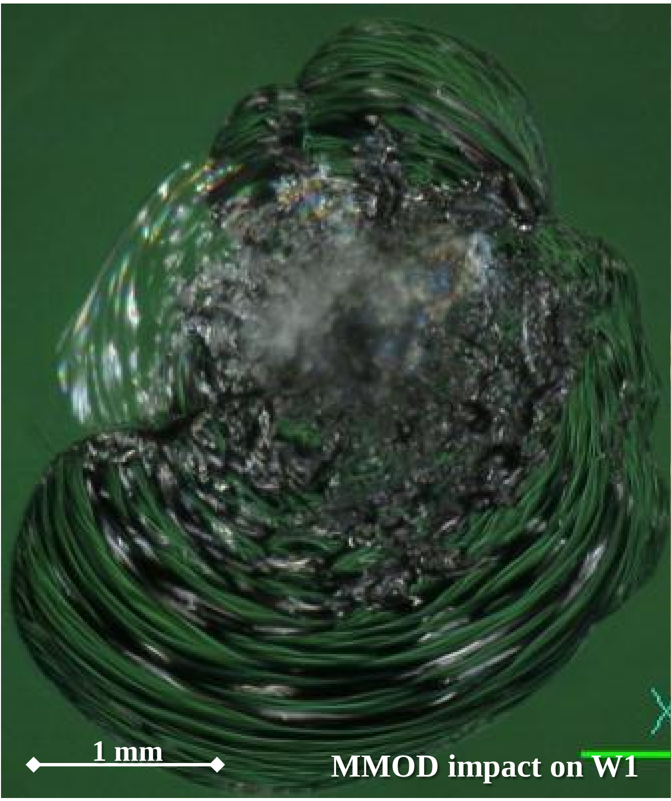
- **Ballistic limit equations, damage equations**
- **Risk quantification:**
  - Spacecraft damage and/or loss
  - Penetration of pressure shell – air leak
  - Crew evacuation
  - Loss of crew
  - Uncertainties
- **Requirements verification**
- **Risk drivers – what area of vehicle controls risk, focus of more analysis and/or shielding modifications**
- **Assess operational methods to control risk:**
  - Flight attitude, altitude
  - Dock location, orientation
  - Thermal protection system (TPS) inspection/damage mitigation

ISS Soyuz Penetration Risk Color Contour
Red=high risk, Blue=low risk



Post Flight MMOD Inspection: STS-130

	Number of MMOD impacts	Largest MMOD impacts
Windows	15 craters	W1, 4.2 x 3.6 mm 6 R&R's (W1,2,6,7,8 & 11)
Radiators	25 MMOD damages reported	1 face sheet perforation
Wing leading edge & nose cap	9 MMOD indications (reviewed by LESS PRT)	Panel 18R, 3.2 x 2.8 mm, max depth = 0.46 mm no exposed substrate



MMOD impact on W1

MMOD impact on Panel LH3

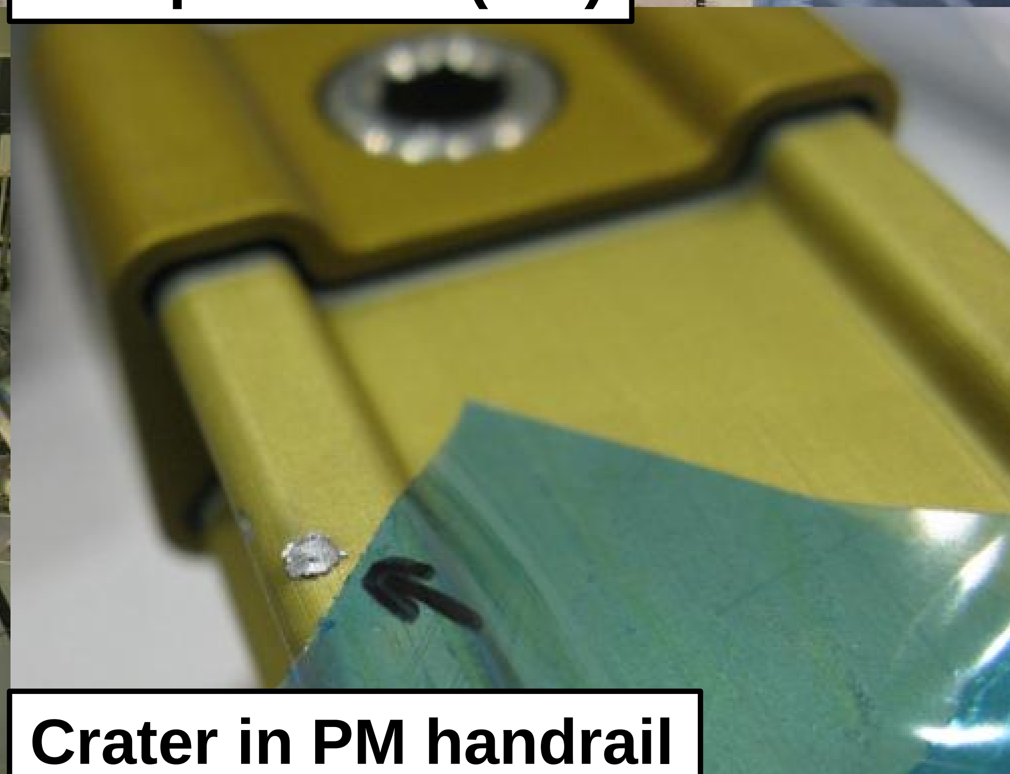
MMOD impact on Panel 18R

Post Flight MMOD Inspection: ISS

MPLM

Pump Module (PM)

PM Adapter Plate



Crater in PM handrail

Agenda

- Micrometeoroid and orbital debris (MMOD) environment overview
- Hypervelocity impact effects & MMOD shielding
- MMOD risk assessment process
- **Requirements & protection techniques**
  - ISS
  - Shuttle
  - Orion/Commercial Crew Vehicles
- MMOD effects on spacecraft systems & improving MMOD protection
  - Radiators
    - Coatings
  - Thermal protection system (TPS) for atmospheric entry vehicles
    - Coatings
  - Windows
  - Solar arrays
  - Solar array masts
  - EVA Handrails
  - Thermal Blankets

International Space Station (ISS) MMOD Requirements

- **MMOD requirements are key aspect of providing adequate MMOD protection**
- **ISS MMOD requirement (SSP 41000): 0.76 probability of no penetration (PNP) or better over 10 years**
  - No more than 24% penetration risk allowed over 10years for all MMOD critical items which include crew modules and external stored energy devices (pressure vessels & control moment gyros)
- **No more than 0.8% penetration risk allowed on average over 10years per MMOD critical item**
- **Loss-of-crew and crew evacuation risk assessments performed for input into ISS Probabilistic Risk Assessment (PRA)**
  - Risk informed decisions based on PRA
- **Requirements for functional equipment set on case-by-case basis (functional = failure does not lead to loss-of-crew)**

ISS MMOD protection approach

- **Multi-faceted approach to mitigating MMOD Risk on ISS**

1. Robust shielding

– ISS has best shielding ever flown: US/ESA/Japan Nextel/Kevlar "stuffed" Whipple shields effective for 1.3cm diameter debris impacting at typical impact conditions

– Augmentation shields added by extravehicular activity (EVA) to Russian Service Module

– Upgrades to Soyuz and Progress MMOD protection

– Redundant & hardened external systems; e.g. US Radiators

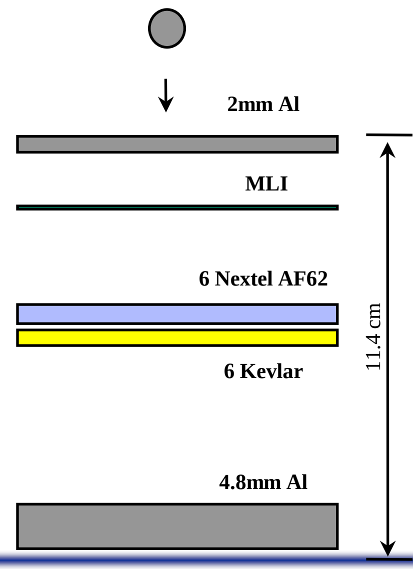
2. Collision avoidance

– Maneuver to avoid ground-trackable orbital debris (typically ≥ 10cm diameter)

3. Sensors & crew response to leak if needed

– Leak detection, isolation, repair

0.5" diameter hypervelocity projectile penetrates nearly 2" thick aluminum block, but is stopped by NASA stuffed Whipple shields which weigh far less (same as 3/8" thick aluminum)



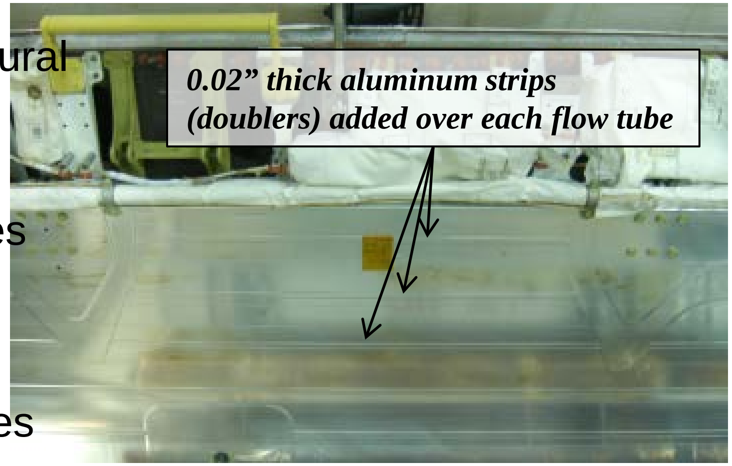
Visiting Vehicle Requirements

- **Shuttle MMOD requirements were two fold:**
  - Loss-of-crew (LOC) risk should not exceed 1 in 200 per mission
    - Driving loss-mode for LOC was MMOD damage to thermal protection system (TPS) materials leading to loss-of-vehicle during reentry
  - Loss-of-mission (LOM) due to radiator tube leaks should not exceed 1 in 61 per mission

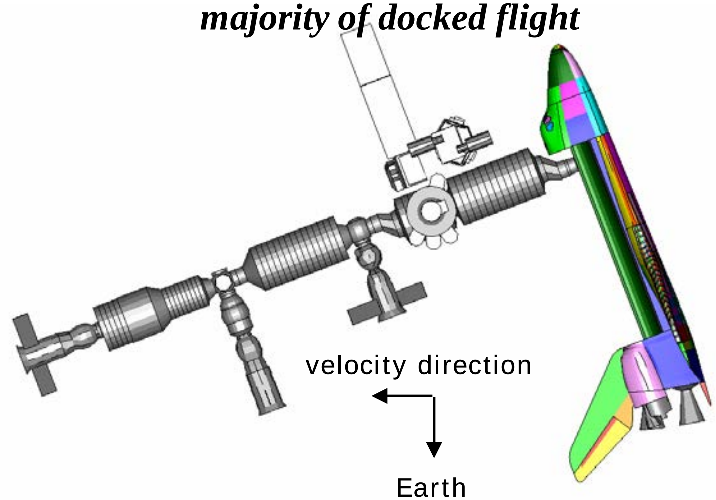
- **ISS commercial crew transport vehicle MMOD requirements:**
  - Penetration risk causing crew-module leak &/or tank failure while docked to ISS should not exceed 1-0.99999^(surface area_m^2 * duration_years)
  - MMOD LOC/LOM requirements are derived from overall vehicle LOC/LOM requirements, and cover the risk to TPS & loss of vehicle during reentry

Shuttle MMOD protection strategy

- **Design improvements:**
  - Added thermal protection to wing leading edge structural attach fittings
  - Added doublers to radiator flow tubes
  - Added protective sleeves to radiator interconnect lines
  - Added automatic isolation valves to thermal loops
- **Attitude/orientation selection:**
  - Implemented flight rules to fly low-risk MMOD attitudes during free-flight
  - Flew ISS-Shuttle stack backwards after dock, to reduce MMOD risk to Shuttle TPS
- **Inspection/sensors in high MMOD risk areas:**
  - Implemented late mission inspection of wing leading edge and nose cap for critical MMOD damage
  - Added sensors to wing leading edge to monitor for impact damage (ascent & MMOD)
- **Collision avoidance:**
  - Collision avoidance from ground-trackable debris (10 and larger)



Shuttle-ISS orientation during majority of docked flight



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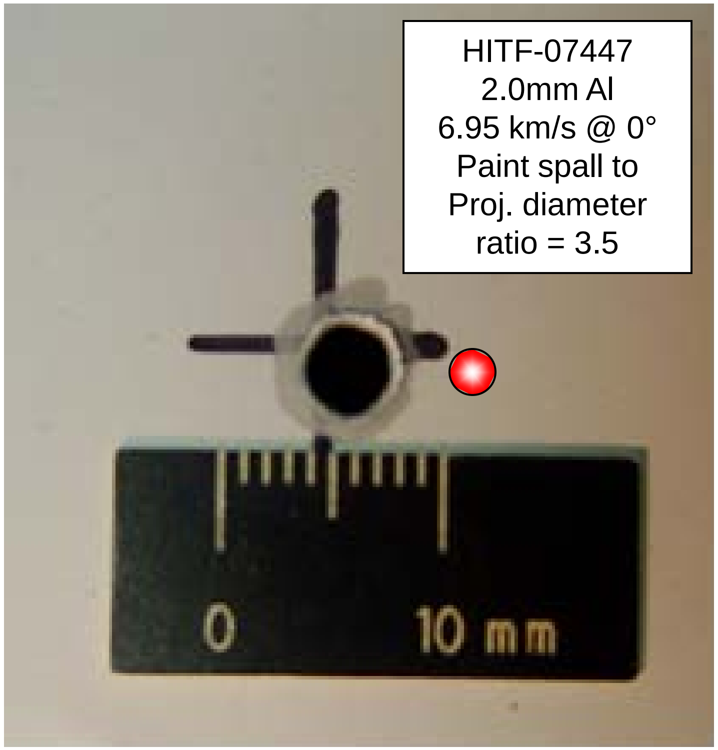
  - Thermal Blankets

MMOD Considerations for Radiators

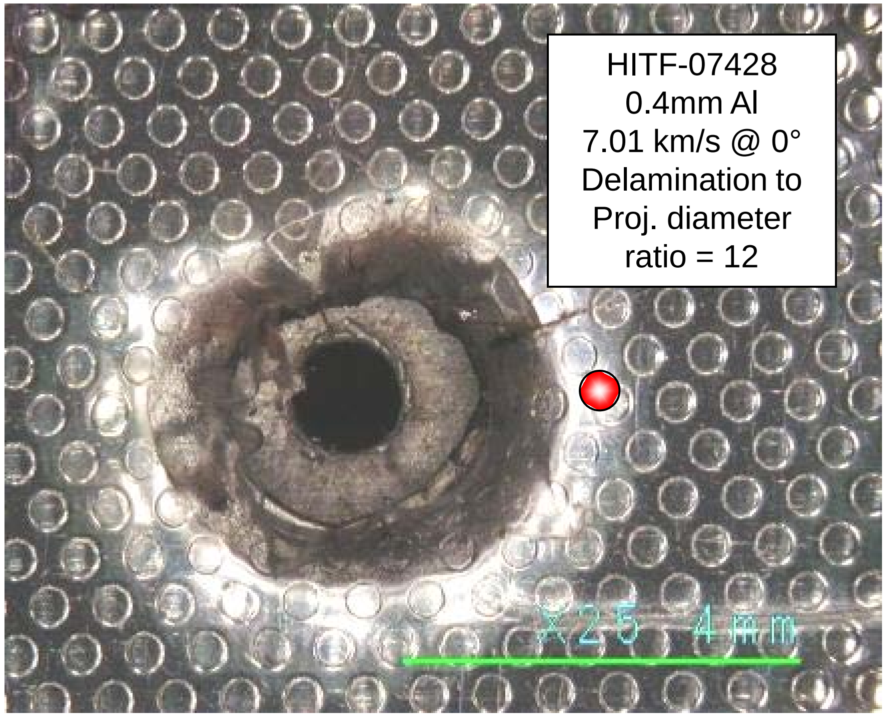
- **Radiator flow loops are subject to penetration by MMOD**
  - Radiators are large and will be impacted by MMOD during each flight
  - Radiator flow tube area is smaller, but still experiences MMOD damage
  - Leaks can result in degraded spacecraft function and early mission termination
  - Radiator flow paths can be hardened to reduce the risk of leaks from MMOD damage
  - Radiator interconnect lines also subject to MMOD failure, and can be hardened from damage by increasing thermal insulation, adding beta-cloth sleeves, thicker walls, increasing flexible braiding, or wrapping with Nextel/Kevlar
- **Radiator coatings typically either spall or delaminate around impact site**
  - Silver-teflon (Shuttle radiator panels) delaminate
  - Z93 paint (ISS radiator panels) spall
  - Diameter of spall/delamination typically large compared to impactor diameter (4-15x), but area covered by spall/delamination small relative to radiator area, even for long-duration missions (a few percent of coating is damaged over 10-30year ISS missions), therefore not likely to result in major thermal issue

Radiator coating damage
typical hypervelocity impact test results

Z-93 paint

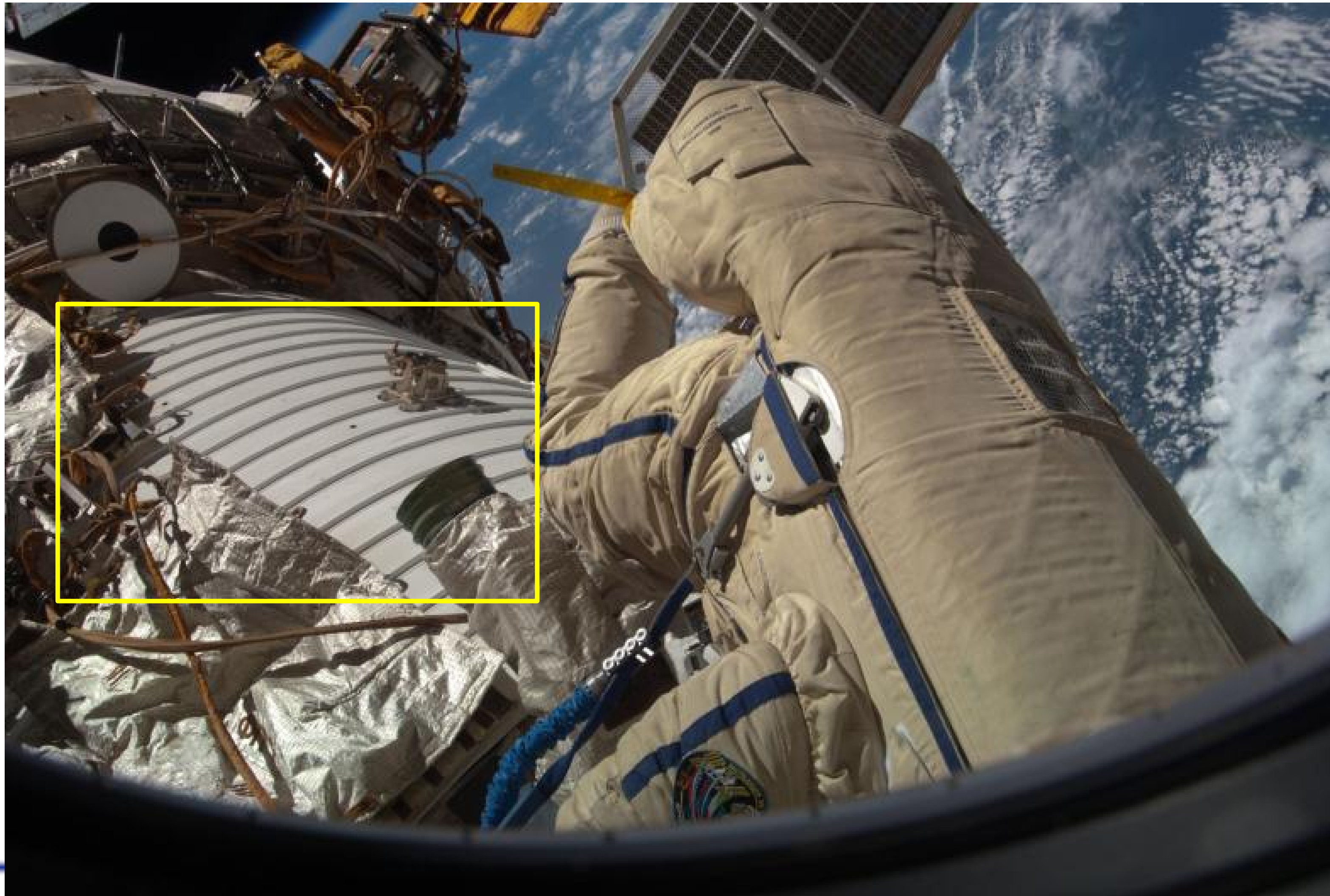


Silver-Teflon tape



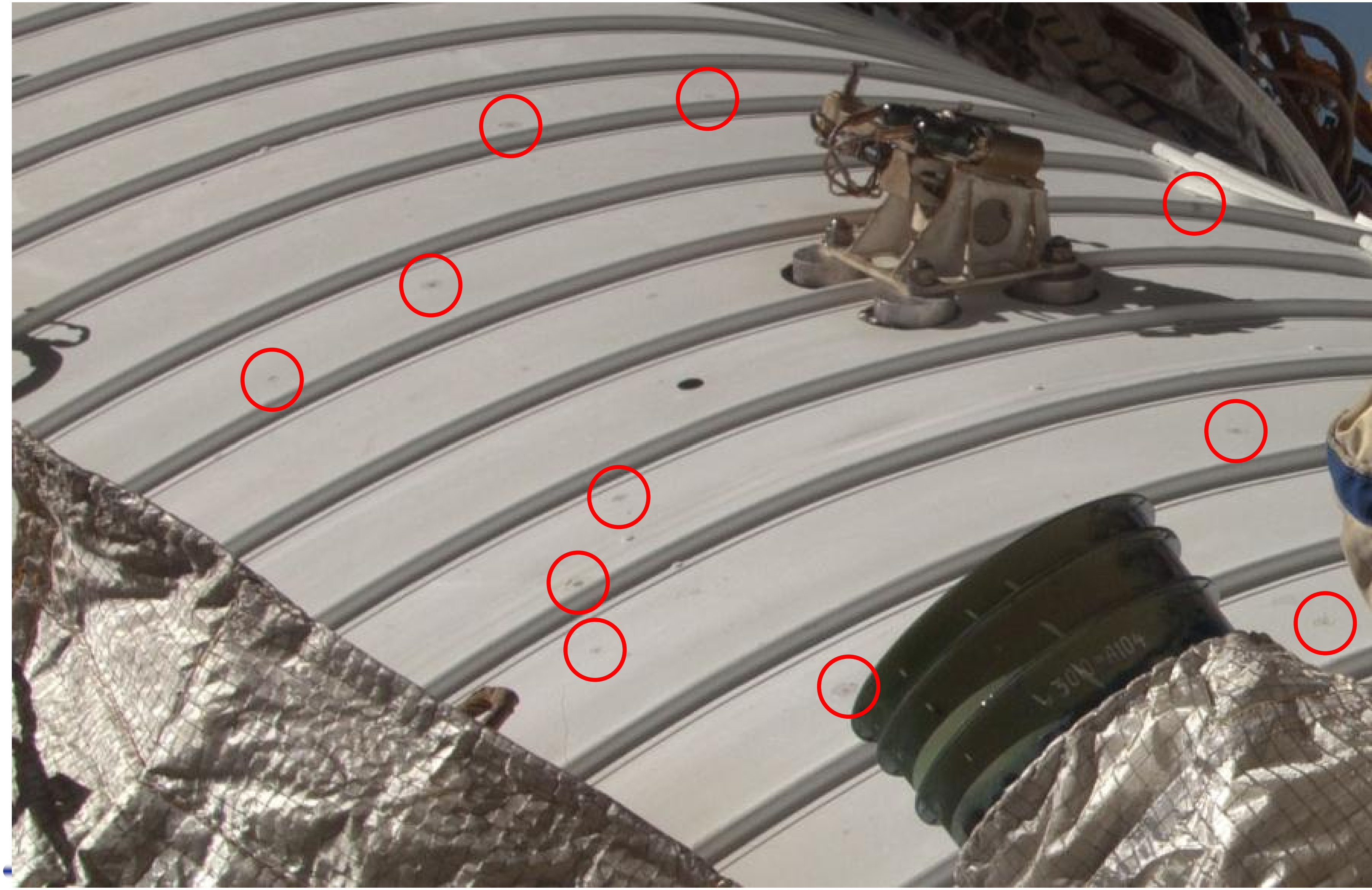
Issues: MMOD Damage to ISS Radiators

- **MMOD impact damages observed to ISS radiator panels during Russian EVA (June 2013)**



ISS036e011356

MMOD Damage to ISS Radiators



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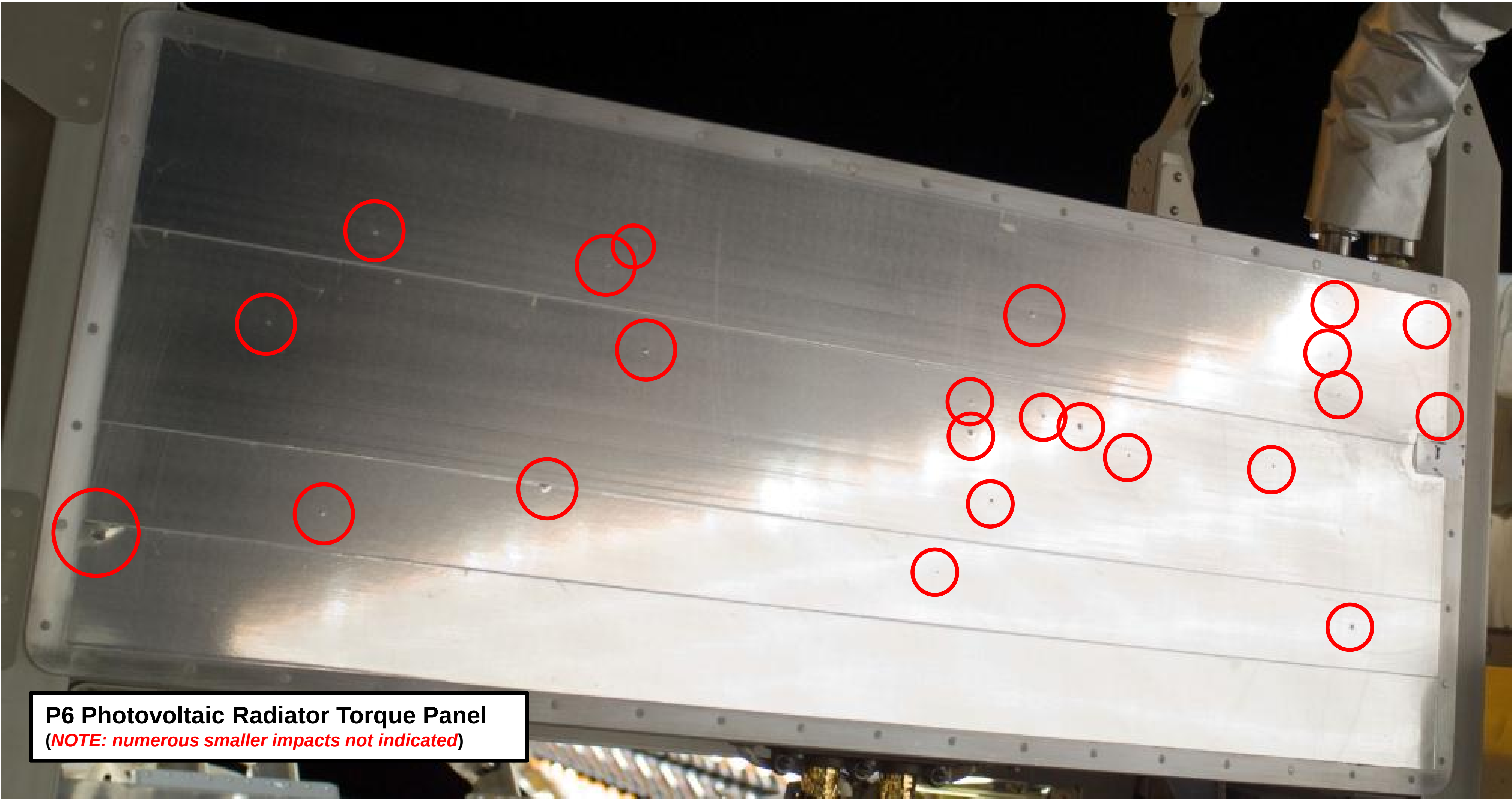
MMOD Damage to ISS

- **MMOD impact damages observed to radiator panel during EVA-20 (Nov. 2012)**

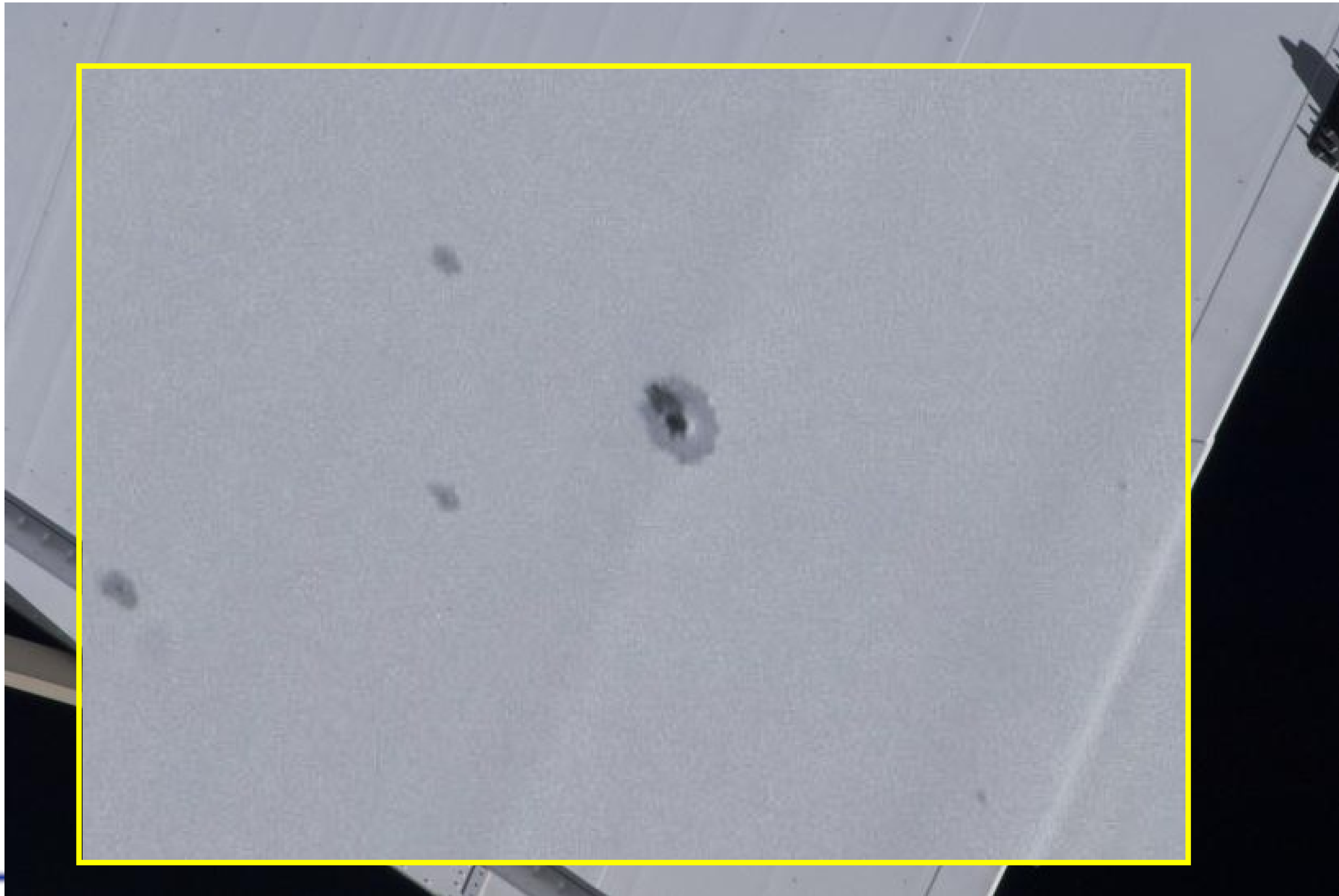


P6 Photovoltaic Radiator Torque Panel
(*NOTE: numerous smaller impacts not indicated*)

ISS033e017859

MMOD Damage to ISS Radiators (US)

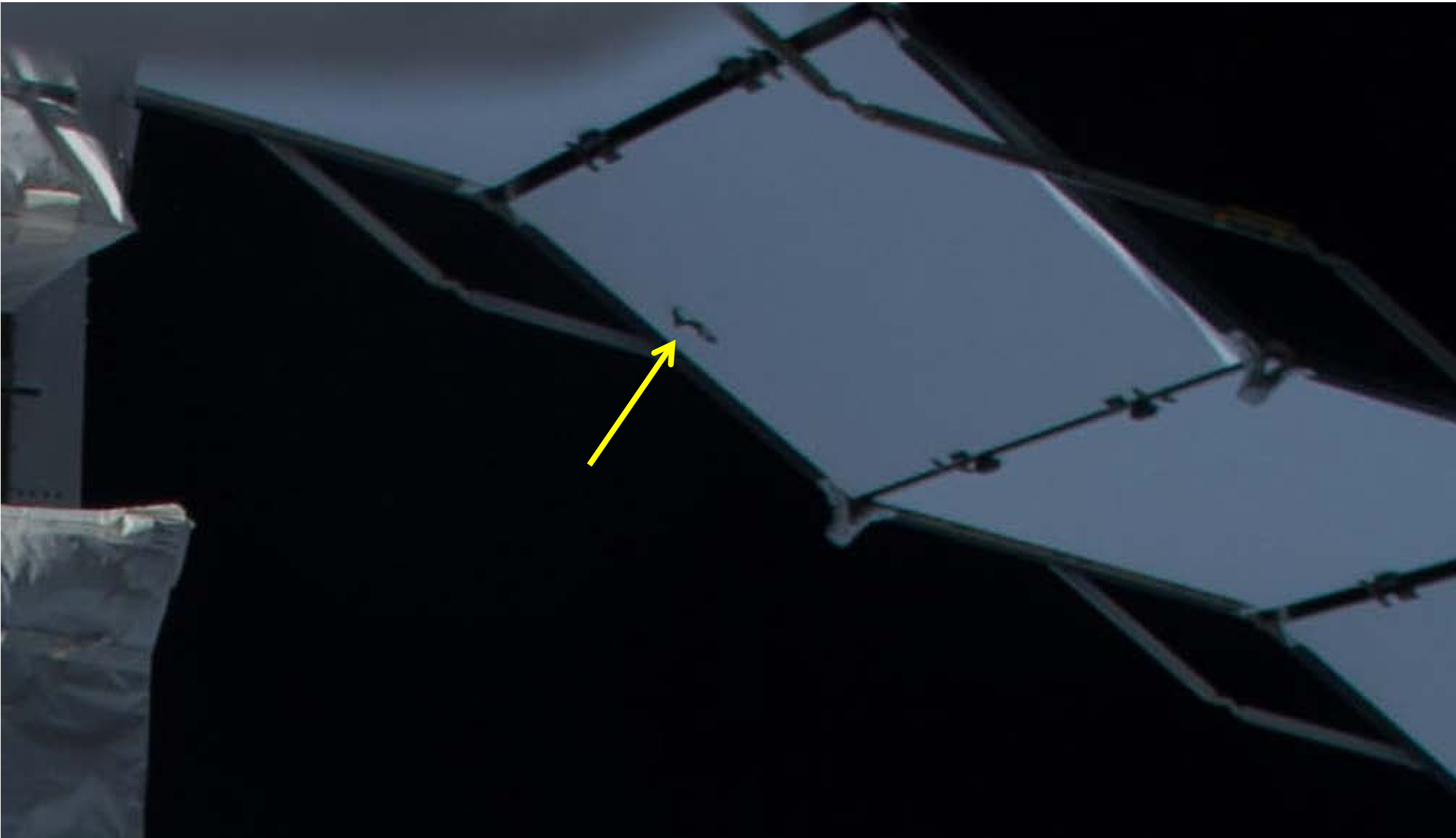
- **MMOD impact damages observed to ISS radiator panels (Aug. 2013)**



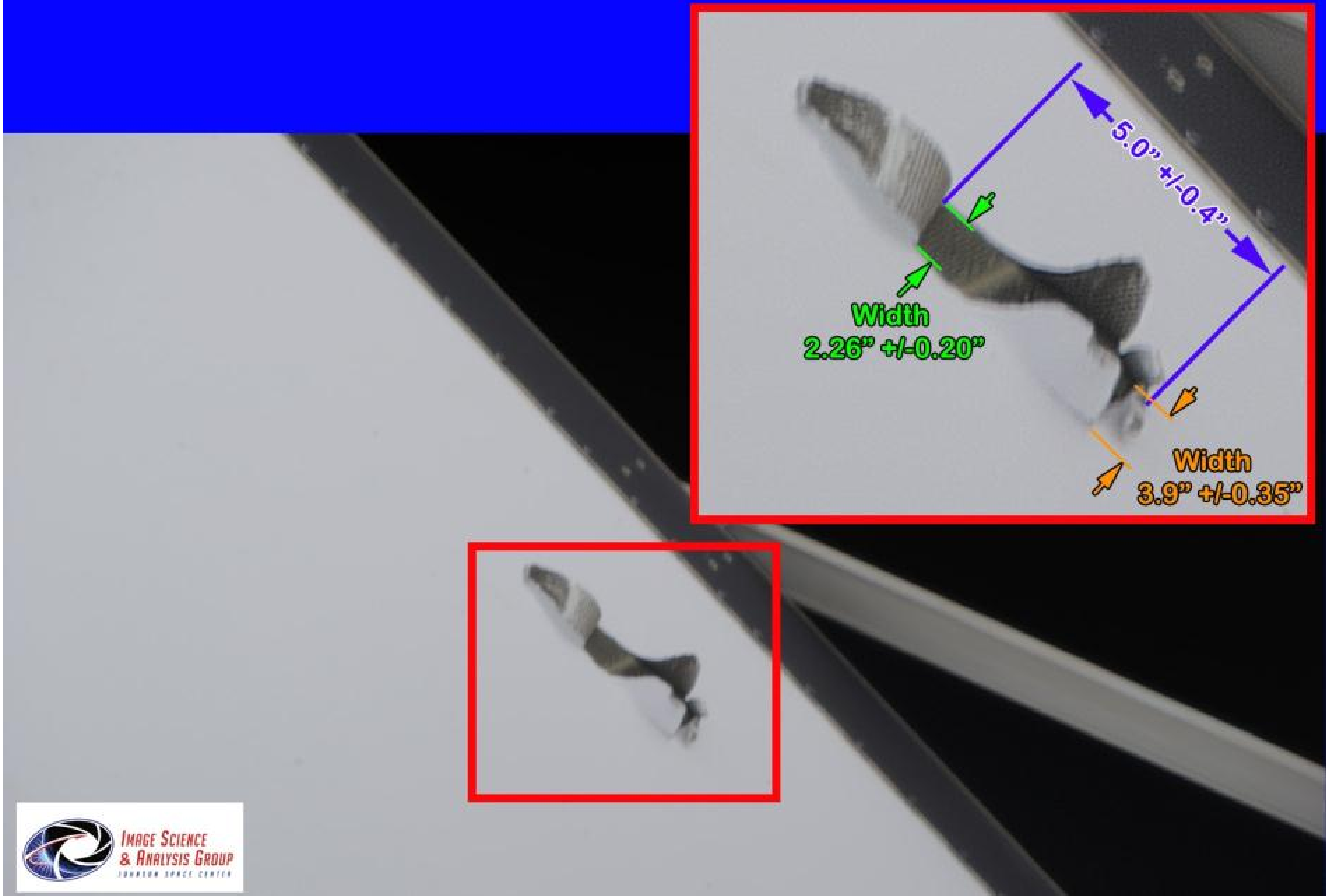
ISS036e037365

P4 photovoltaic radiator

- **Initial indication found on 6/30/2014**

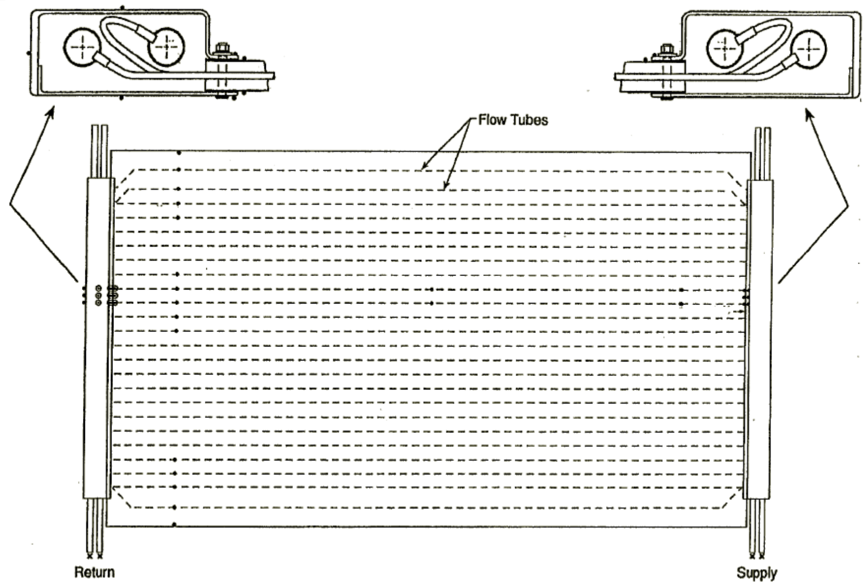


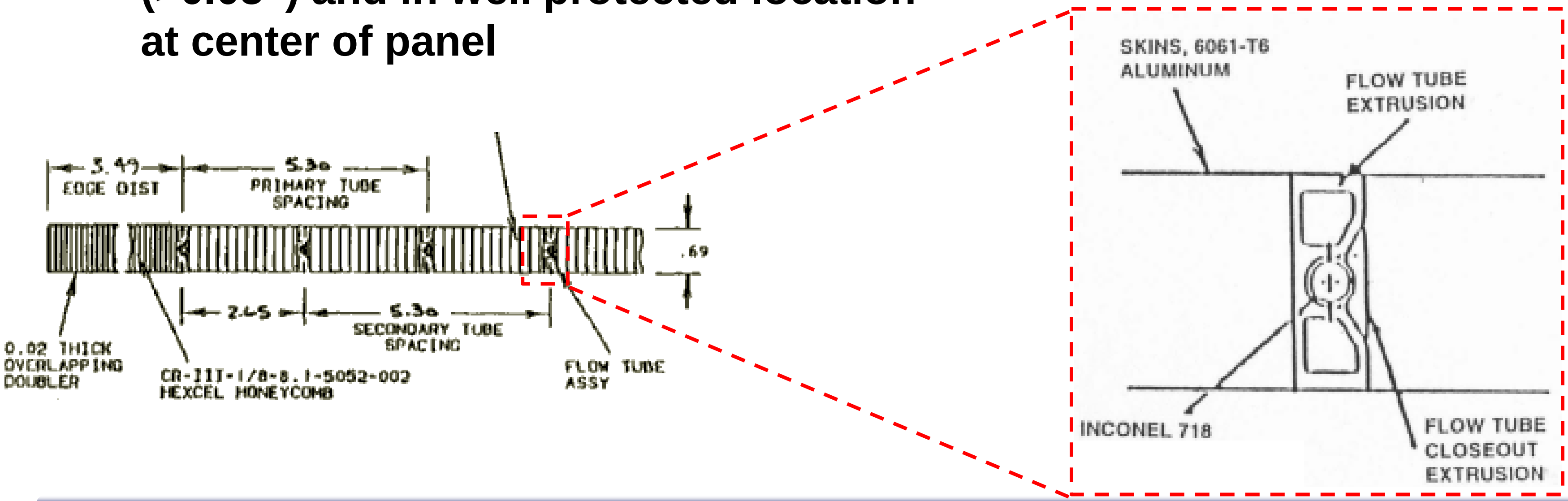
Measurement of P4-PVR Radiator Damage
"2A" Side of Panel 3



ISS PVR Panel Construction

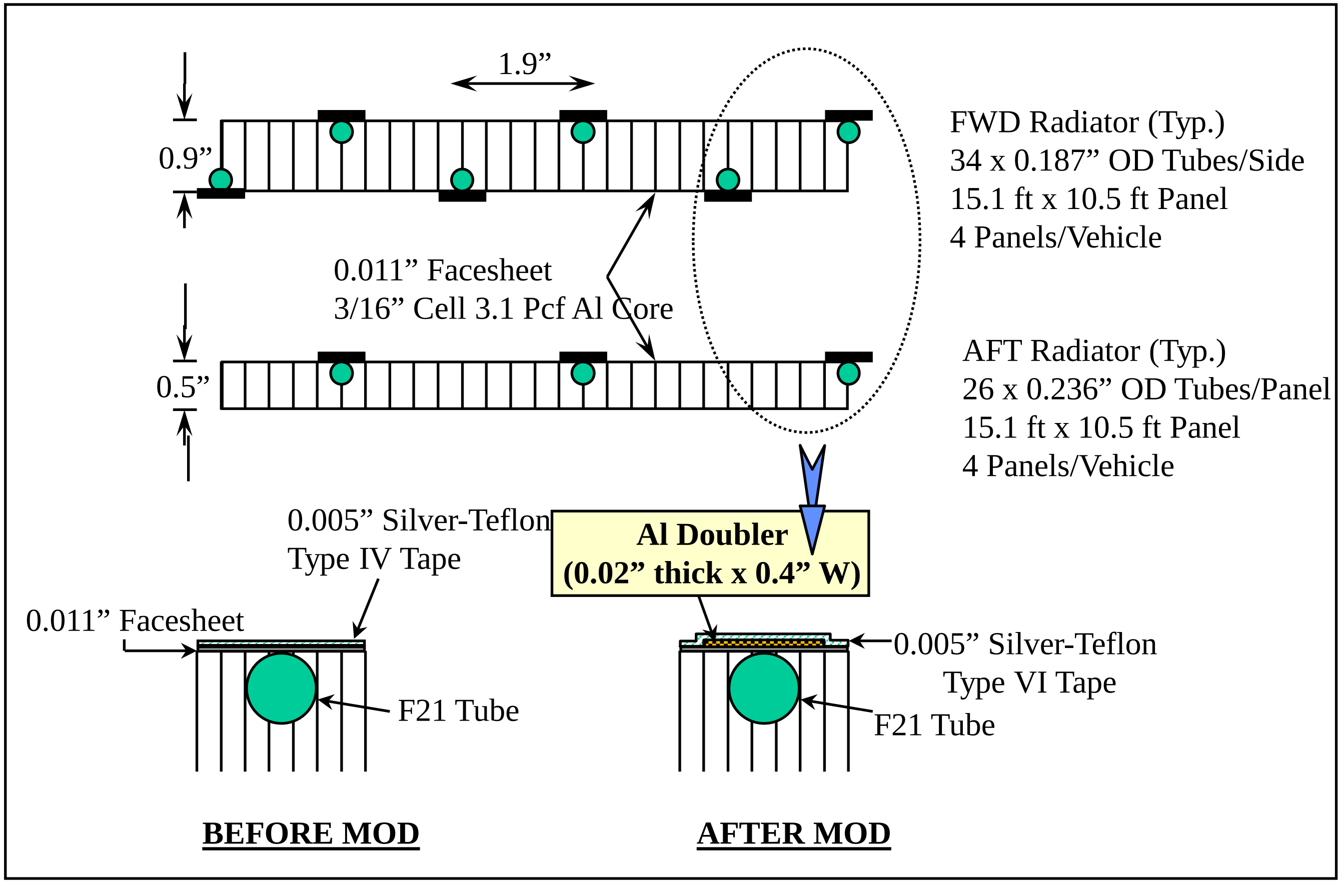
- **124” x 70” x 0.69” thick panel**
- **Aluminum face sheet**
  - Z93 white paint
- **Aluminum flow tube housing extrusion with Inconel flow tube**
  - Evenly spaced 2.6 inches except outermost tube spaced 3.5 inches
- **Note, flow tube relatively thick wall (>0.05”) and in well protected location at center of panel**





Shuttle Radiator Panels

- Shuttle radiator flow tubes are located directly below facesheet and are relatively thin-walled (0.02” thick)
- Shuttle flow tubes are more vulnerable than ISS radiators to MMOD failure
- Aluminum doublers adhesively bonded to Shuttle radiator facesheets over each flow tube to improve MMOD penetration resistance & decrease leak risk
- Completed modification in 1999-2000 across Orbiter fleet

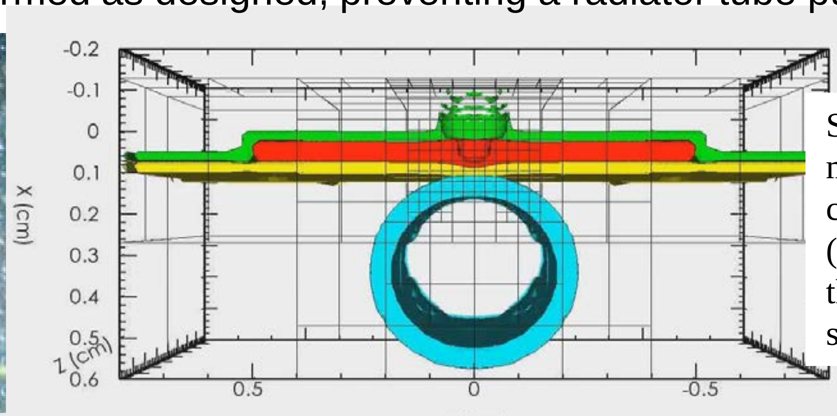


STS-128 Shuttle Radiator Impact

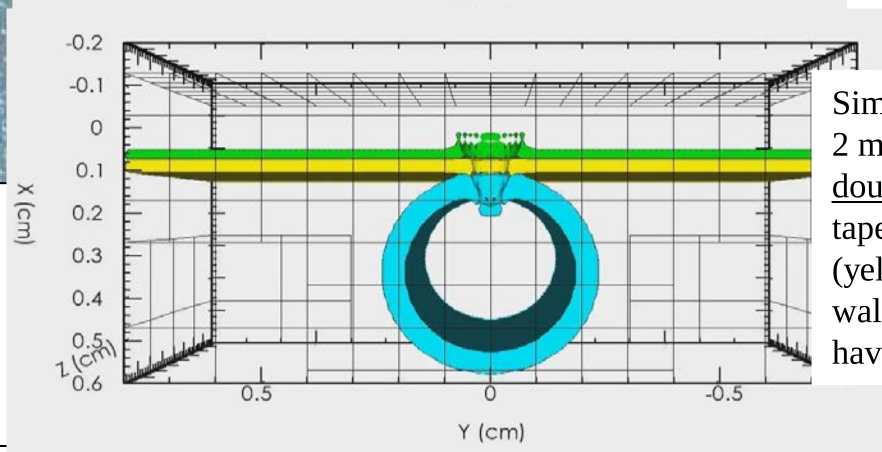
shows why adding protection to vulnerable areas of spacecraft is a good thing

- **During STS-128, an impact occurred on center-line of a radiator doubler, which protects the Shuttle radiator flow tubes from MMOD**
  - Impact crater penetrated through the thermal tape, completely through the 0.02” thick doubler, and damaged the facesheet below the doubler
  - Analysis indicates this impact would have penetrated the flow tube if the doublers were not present
  - Doublers added in 1997-1999 time period, to provide additional protection for ISS missions
  - Conclusion: Doublers performed as designed, preventing a radiator tube puncture

Image of MMOD impact into LH1 Radiator doubler protecting flow-tubes
Crater diameter in Al doubler = 0.8 mm
Crater depth = 0.58 mm
Doubler thickness = 0.51 mm



Simulation of impact after 2 micro-seconds with doubler: crater through thermal tape (green) and penetration nearly through doubler (red)…i.e., similar to actual damage.



Simulation of same impact after 2 micro-seconds without doubler: crater through thermal tape (green), through facesheet (yellow) and through flow tube wall (blue)…i.e., leak would have occurred without doubler.

Radiator Hypervelocity Impact References

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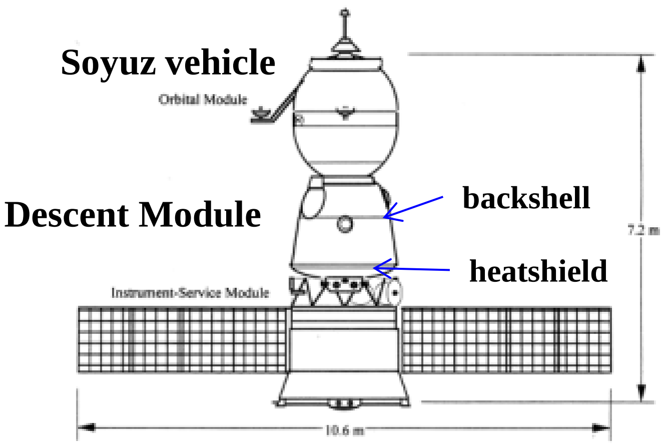
- J.L. Rhatigan, E.L. Christiansen, and M.L. Fleming, On Protection of Freedom's Solar Dynamic Radiator From the Orbital Debris Environment: Part I - Preliminary Analysis and Testing, Journal of Solar Energy Engineering, Vol.114, p.135, August 1992
- J.L. Rhatigan, E.L.Christiansen, and M.L. Fleming, On Protection of Freedom's Solar Dynamic Radiator From the Orbital Debris Environment: Part II - Further Testing and Analysis, Journal of Solar Energy Engineering, Vol.114, p.142, August 1992
- J.L. Rhatigan, E.L. Christiansen, and M.L. Fleming, On Protection of Freedom Solar Dynamic Radiator from the Orbital Debris Environment: Part 2 – Further Testing and Analyses, NASA TM-104514, April 1992
- J.L. Rhatigan, E.L. Christiansen, and M.L. Fleming, On Protection of Freedom Solar Dynamic Radiator from the Orbital Debris Environment: Part I - Preliminary Analysis and Testing, NASA TM-102458, April 1990

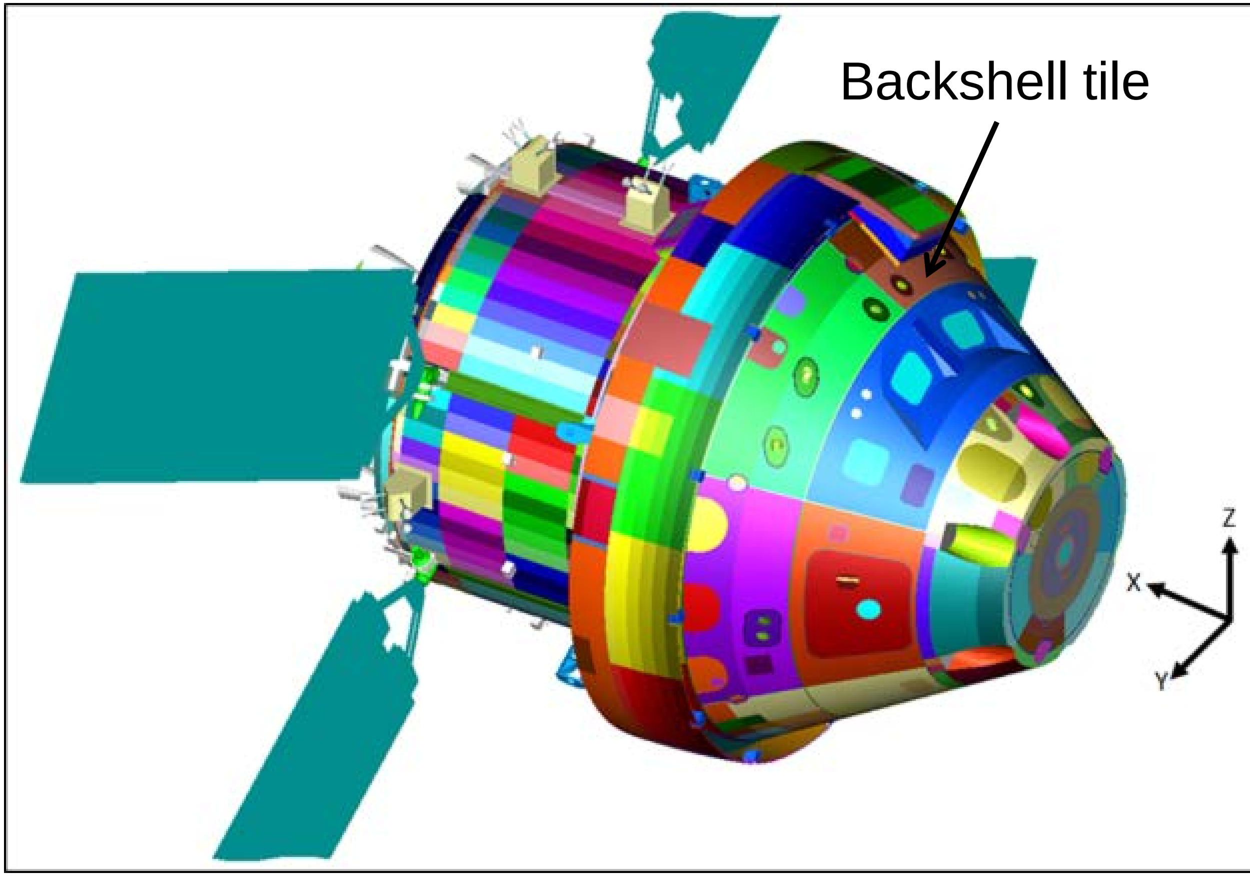
Thermal protection systems (TPS) for crew return vehicles

- **MMOD risk to thermal protection system (TPS) of ISS crew return vehicles (Soyuz, Commercial vehicles) is high**
  - Concern is TPS damage that can lead to loss-of-vehicle during reentry
  - Issue can be mitigated by inspection and repair or safe-haven (not Program baseline)



Thermal protection systems (TPS) for crew return vehicles (cont.)

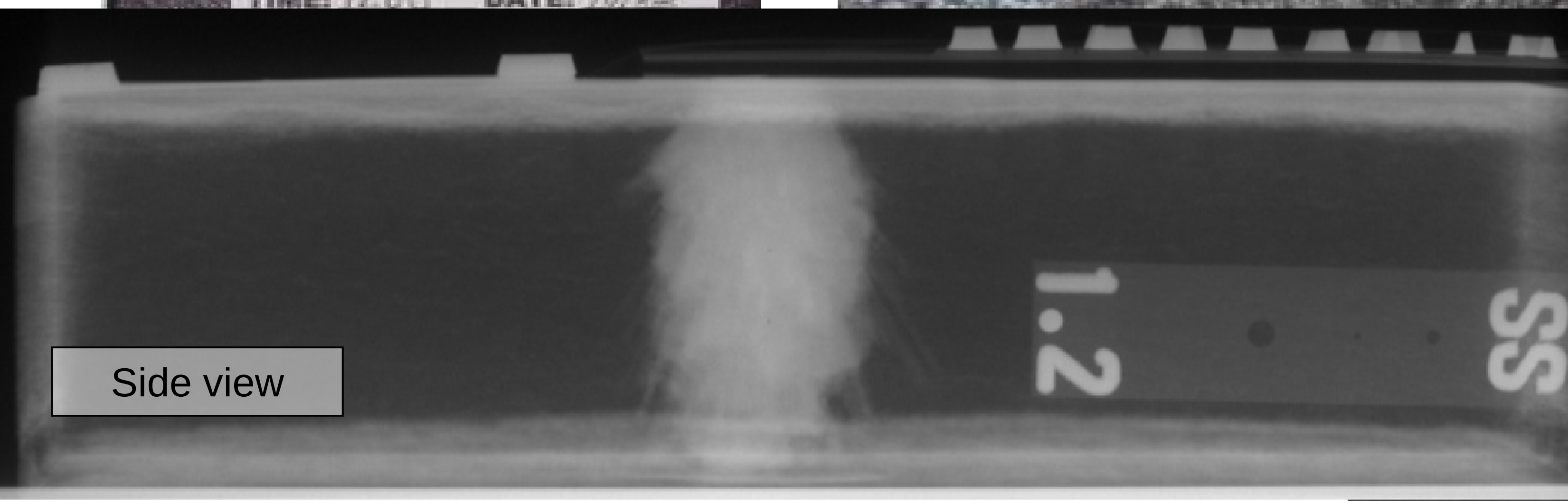
- **TPS example: Low-density ceramic tiles cover backshell of Orion crew module**
- **Impact penetrations into TPS that extend to bondline with substrate are limits of allowable damage**
- **Typical hypervelocity damage: craters with “fingers” of higher density debris that extend beyond crater boundary**
- **Inspection and or sensors could be used to find critical damage before reentry**
- **TPS repair or rescue flight needed if critical damage found in inspection**

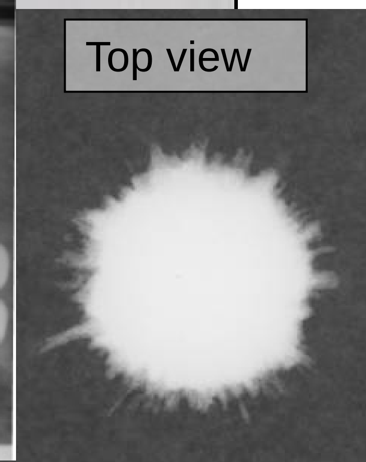


Typical Thermal Protection System (TPS) Tile Impact Damage

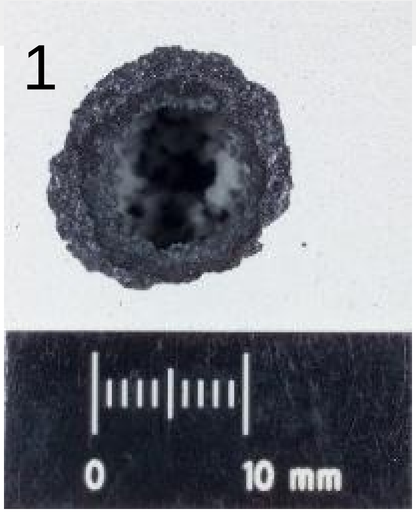
Tile Test HITF-7469

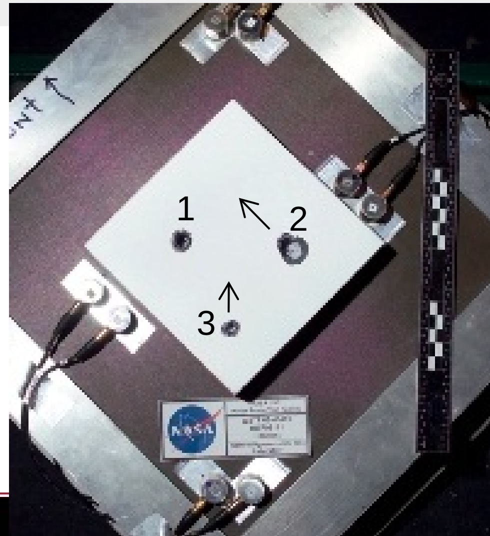
projectile: 2.4mm (3/32”) diameter Al 2017T4, 7.00 km/s, 0^{o} impact angle

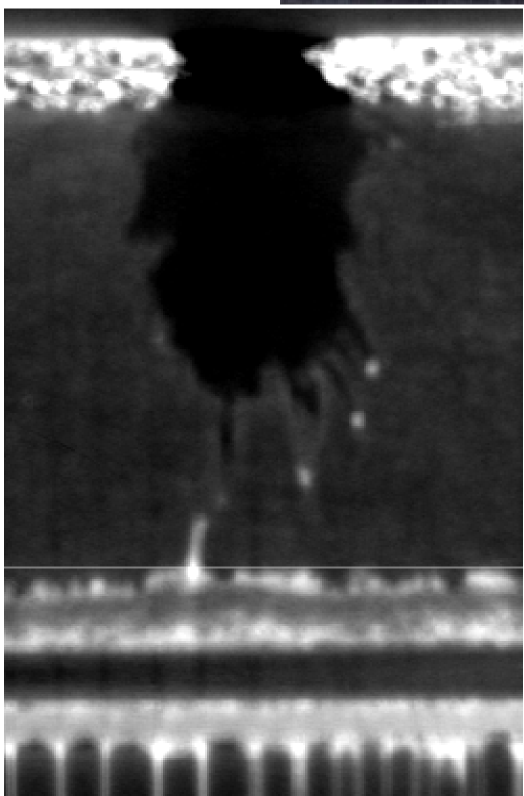


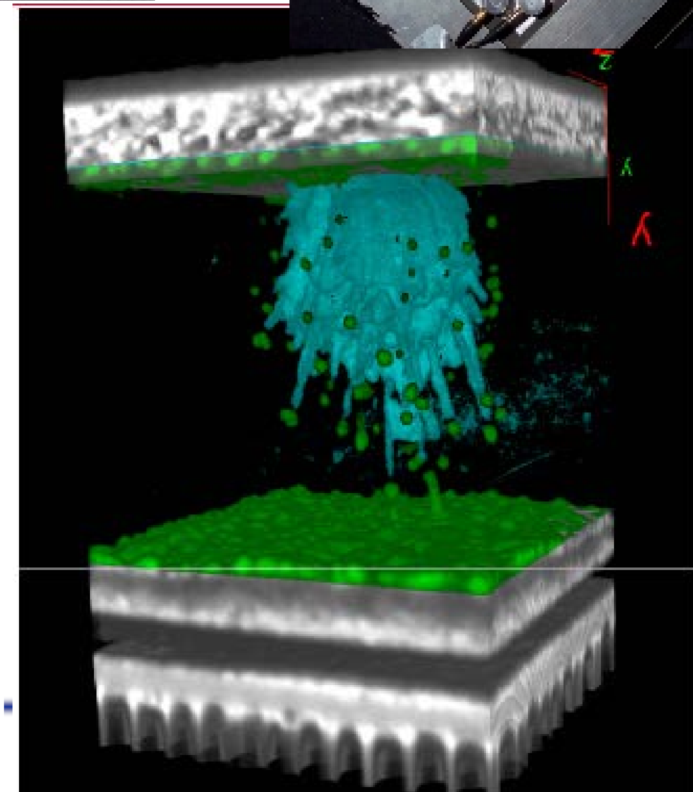


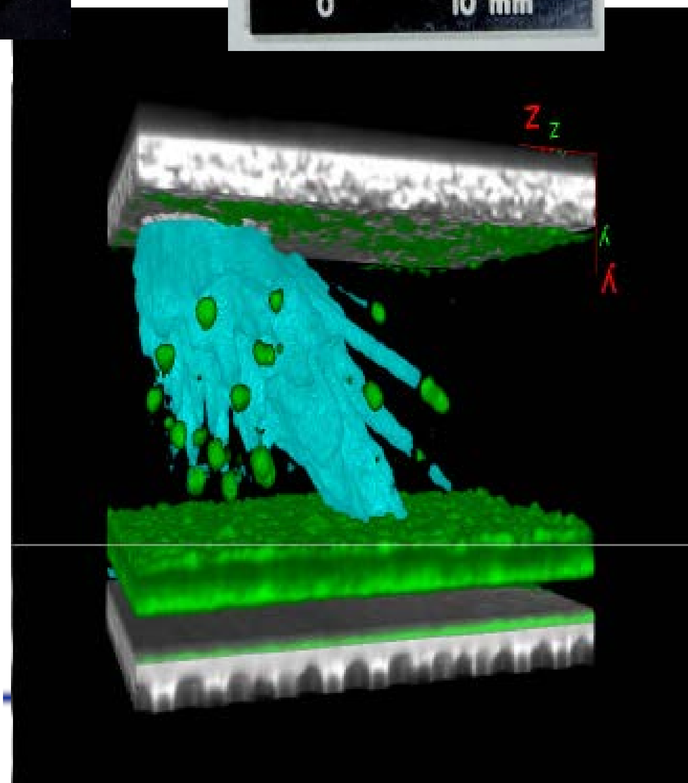
CT Scans of Tile Damage







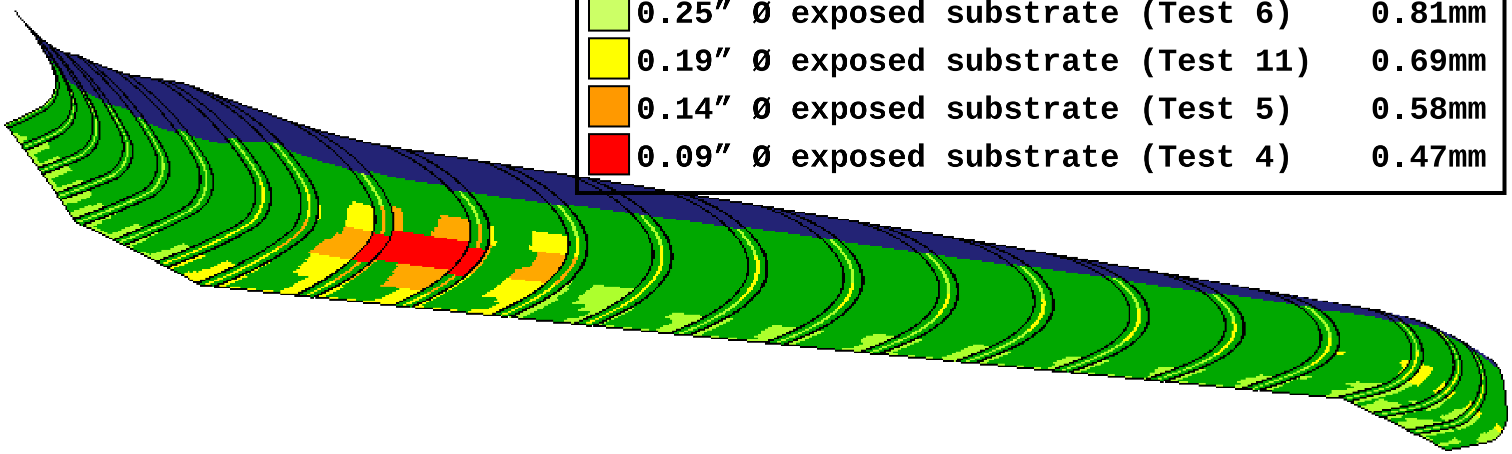




TPS Coating Damage

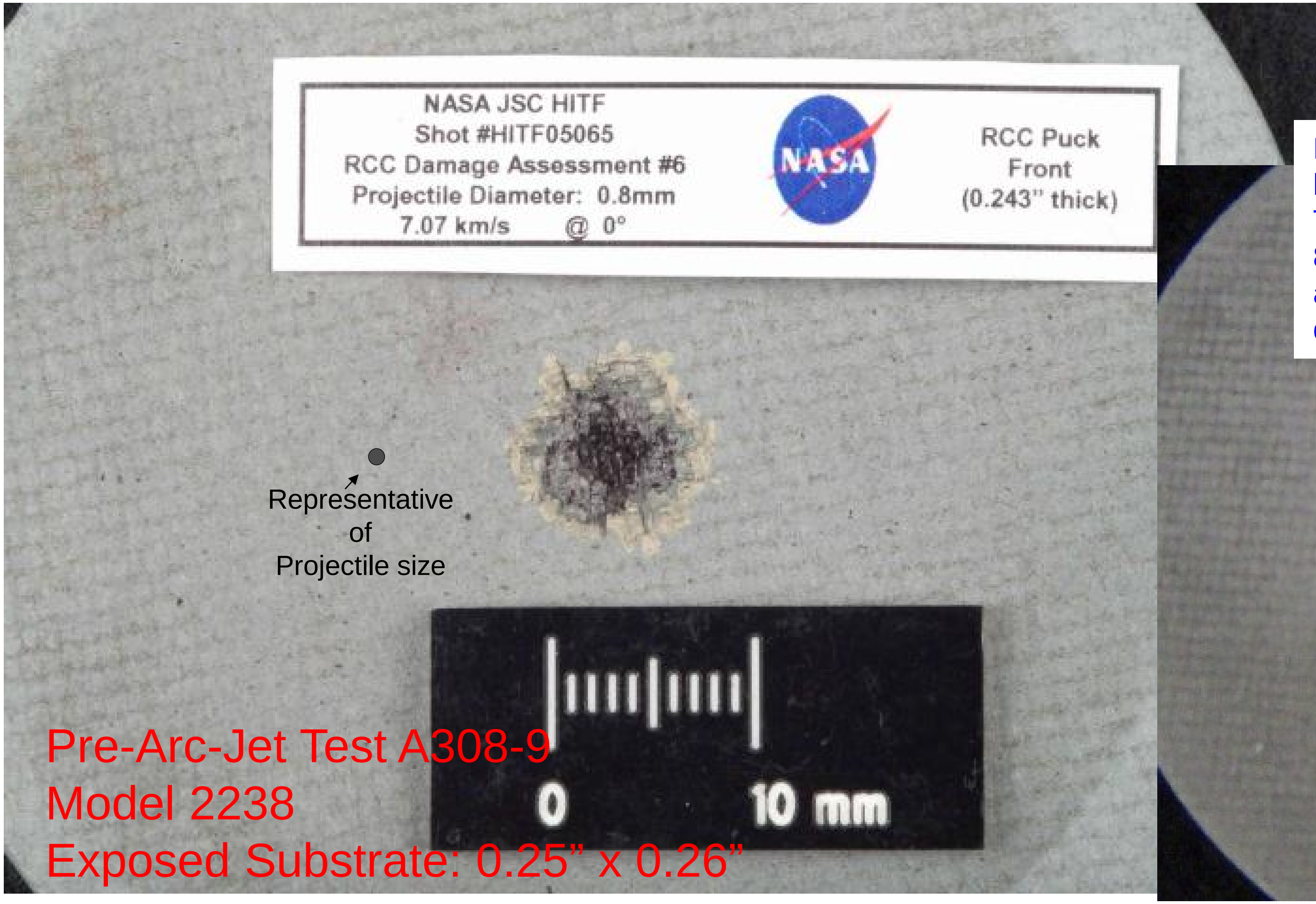
- Coatings on TPS can be important in reentry survivability
- Example: Si-C coating on Reinforced Carbon-Carbon of Shuttle wing-leading edge and nose cap
- Coating damage was considered limits of acceptable damage for “hot” areas of wing leading edge and nose cap based on results of hypervelocity impact tests and arc-jet tests, as well as thermal analysis

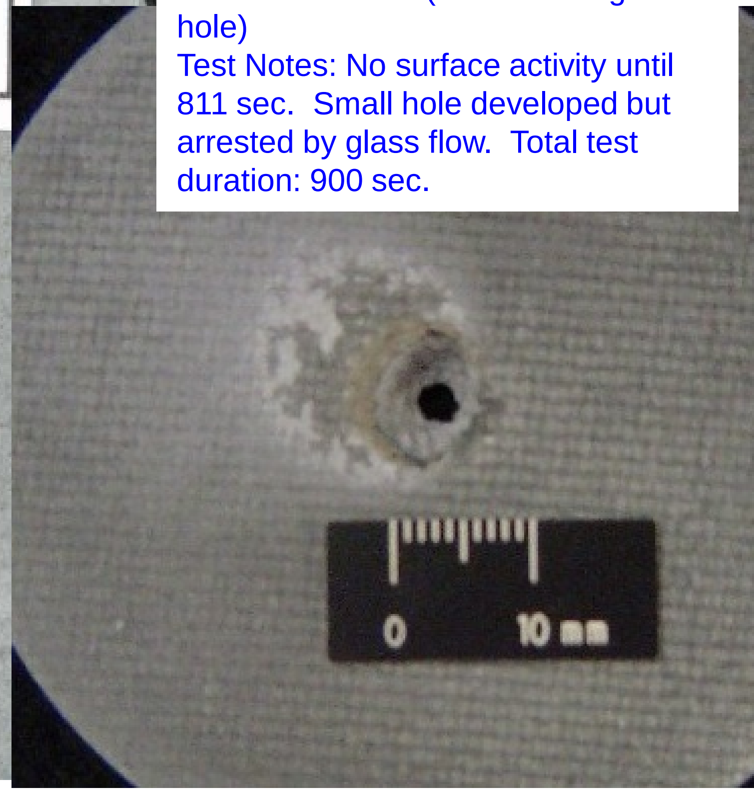
Failure Criteria	Critical Orbital Debris Ø *(7km/s & 0°)*
1.00” Ø hole	4.89mm
0.50” Ø hole	2.75mm
0.25” Ø hole	1.68mm
0.12” - 0.99” Ø hole	1.10-4.84mm
0.25” Ø exposed substrate (Test 6)	0.81mm
0.19” Ø exposed substrate (Test 11)	0.69mm
0.14” Ø exposed substrate (Test 5)	0.58mm
0.09” Ø exposed substrate (Test 4)	0.47mm



RCC Failure Criteria "Test 6"
Model 2238 (Front)

Test Condition: 2700F/100 psf **FAILED WITH SMALL BREACH (0.125")**





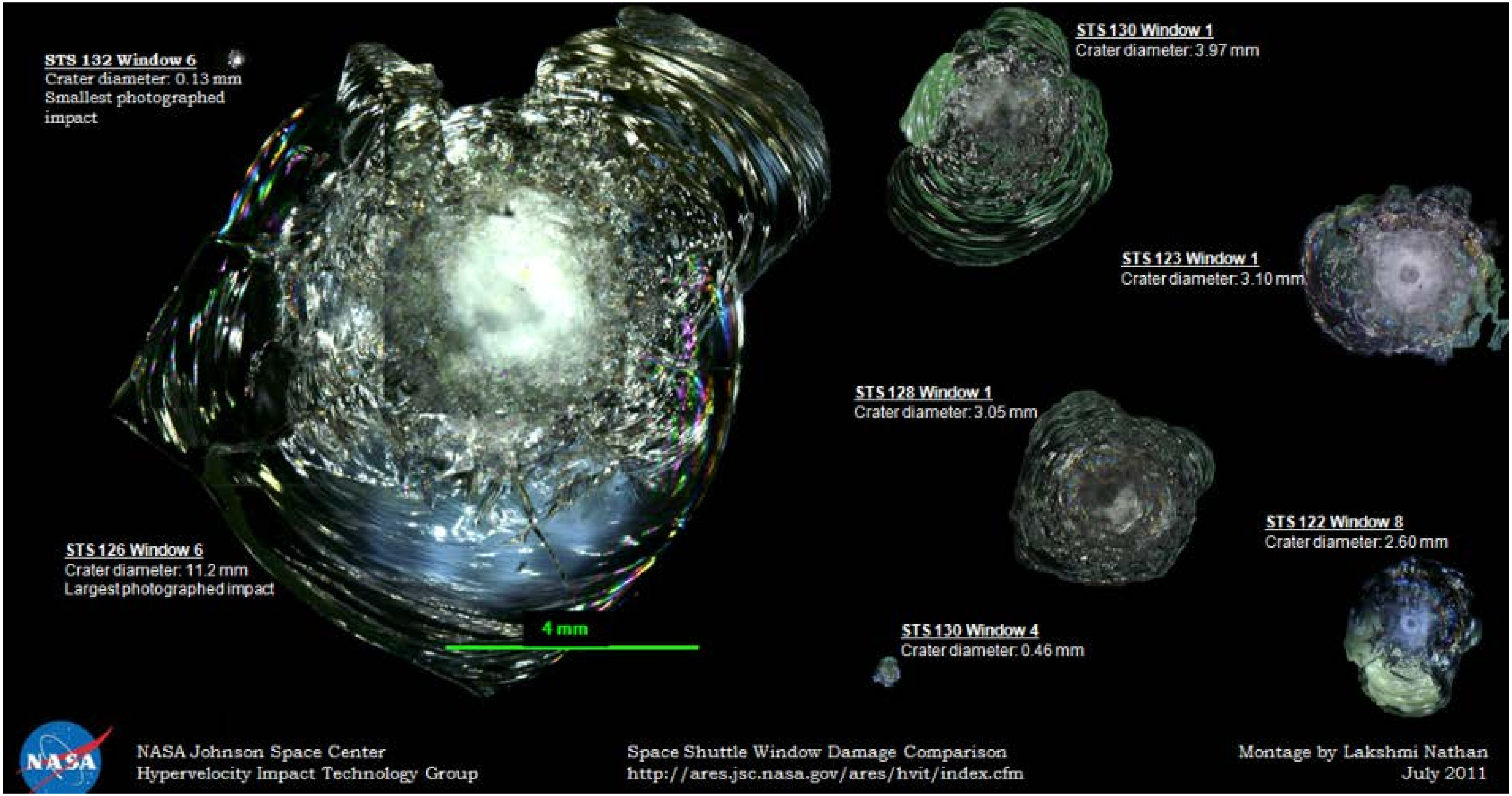
Post Arc-Jet Test (0.125" through-hole)
Test Notes: No surface activity until 811 sec. Small hole developed but arrested by glass flow. Total test duration: 900 sec.

Window Damage & MMOD Protection

- **Spacecraft windows typically are multiple panes of glass/transparent materials**
  - Thermal pane or debris pane
  - Redundant pressure panes (typical)
- **MMOD impacts on fused-silica glass creates large diameter craters relative to impactor size**
  - Typical crater diameters 30-50x impactor diameter in HVI tests
  - Issue for pressure panes and for re-use of thermal panes (e.g. Shuttle)
- **Window protection:**
  - Thermal panes for reentry vehicles, debris panes for spacecraft, exterior of pressure pane(s)
  - Shutters (ISS): US Lab window has single wall shutter, Cupola has multiwall shutters
  - Window materials
    - Fused-silica: conventional window material for both thermal/debris panes and pressure panes, brittle, good optical qualities
    - Polycarbonate (Hyzod): hatch window external cover
    - Acrylic: pressure pane alternative
    - Tempered glass (Chemcor): high-strength but very-low MMOD damage tolerance

Observed Spacecraft MMOD Impacts

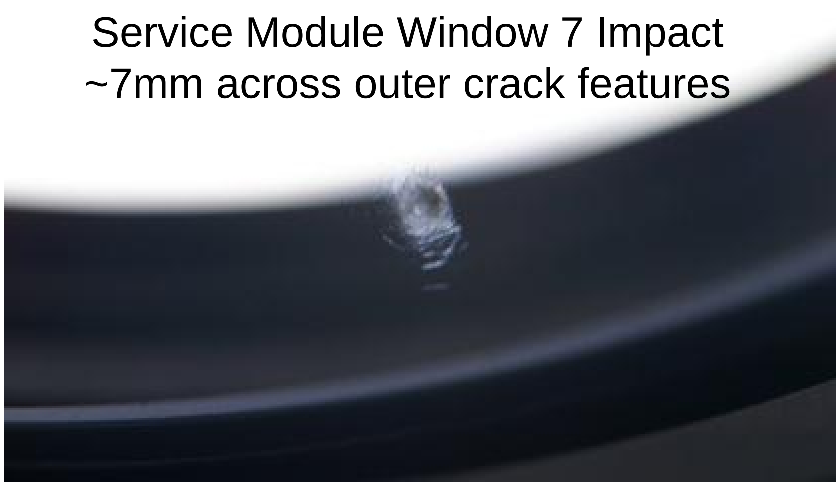
Shuttle Windows



Sampling of Shuttle Window MMOD Impact Craters
(all displayed on same dimensional scale)

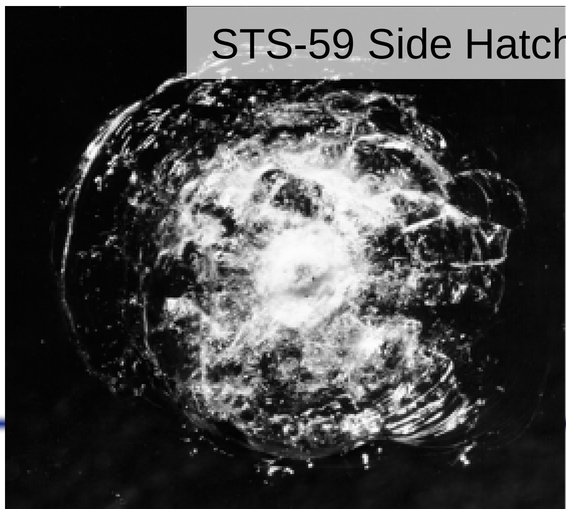
MMOD Impacts on Windows

- **Window ports are exposed to meteoroid/orbital debris impact**
  - Over 1500 hypervelocity pits identified on Shuttle windows and ~130 of these large enough to caused window replacement

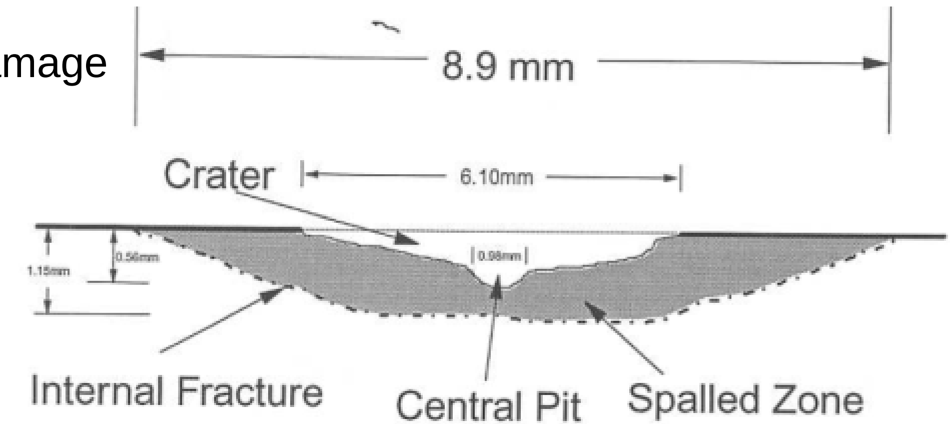


Service Module Window 7 Impact
~7mm across outer crack features

STS-94 Window damage observed on-orbit
0.6mm deep, Al impactor

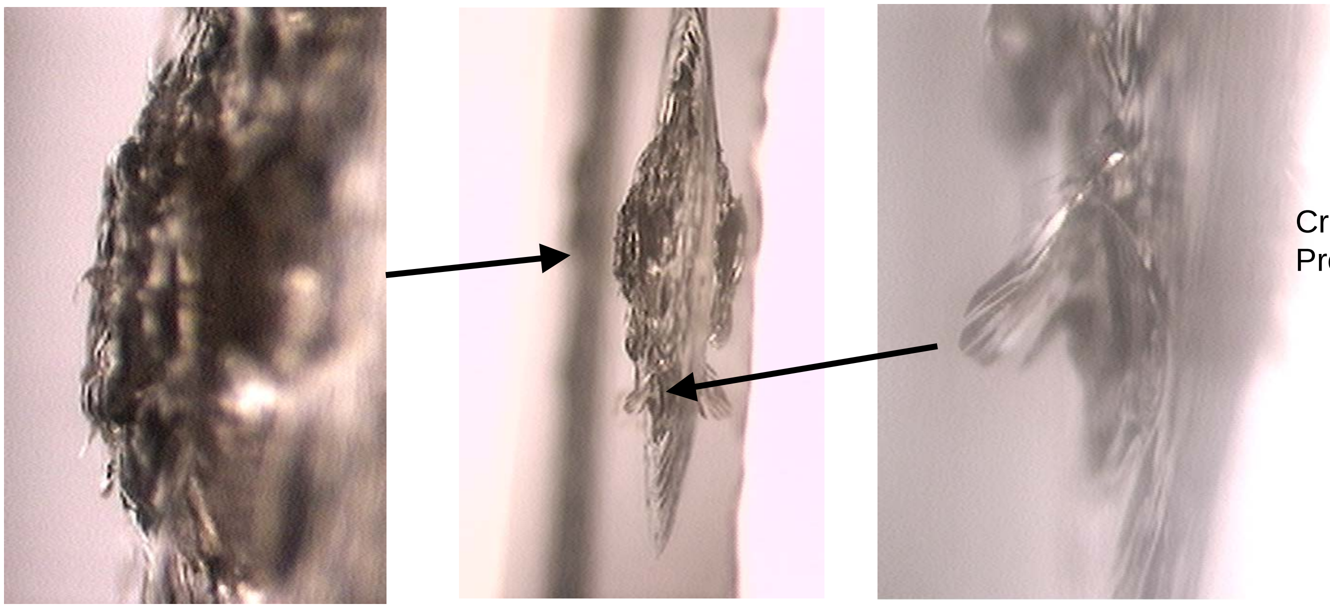


STS-59 Side Hatch Window Damage

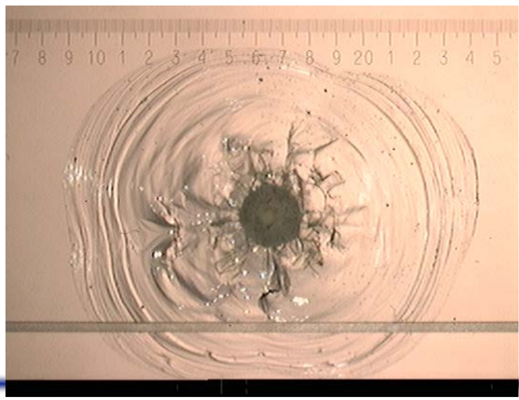


Fused-Silica Internal Glass Damage

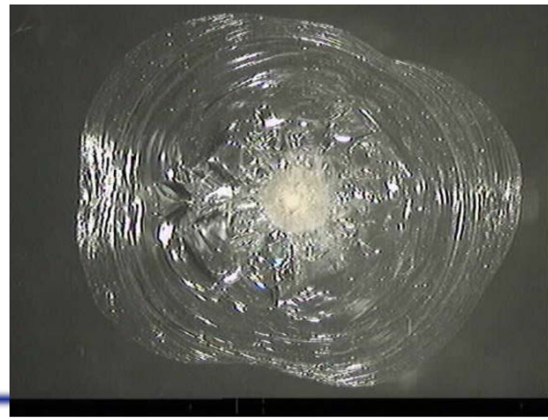
- **Internal crack studies performed by polishing the sides of impacted samples and measuring internal damage**



Test: JSC-120069
Crater: 15.8mm dia. by 0.9mm deep
Projectile: 0.4mm dia. Al, 5.24km/s, 0º



Back-lit

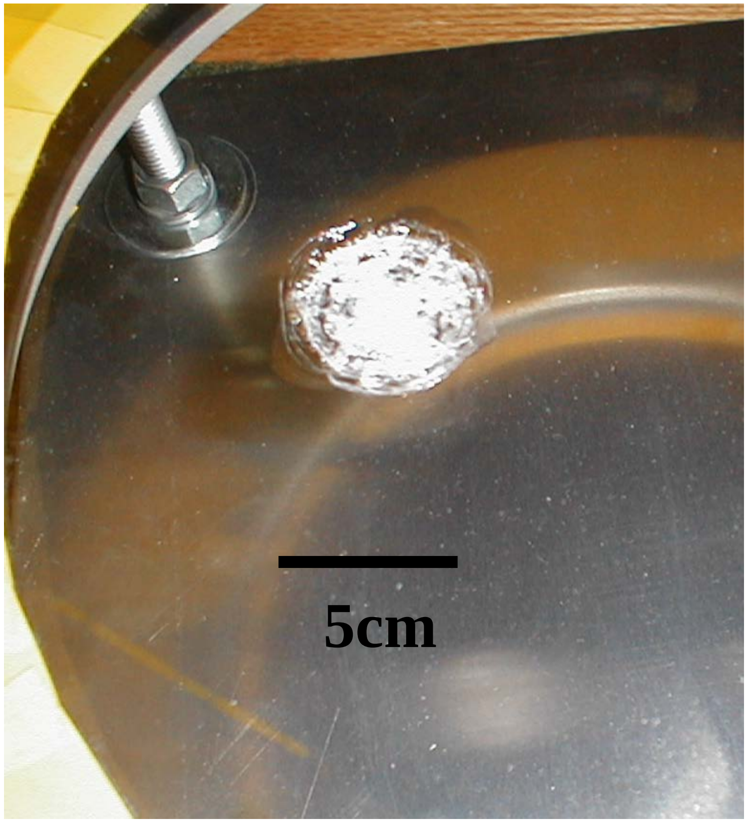


Front-lit

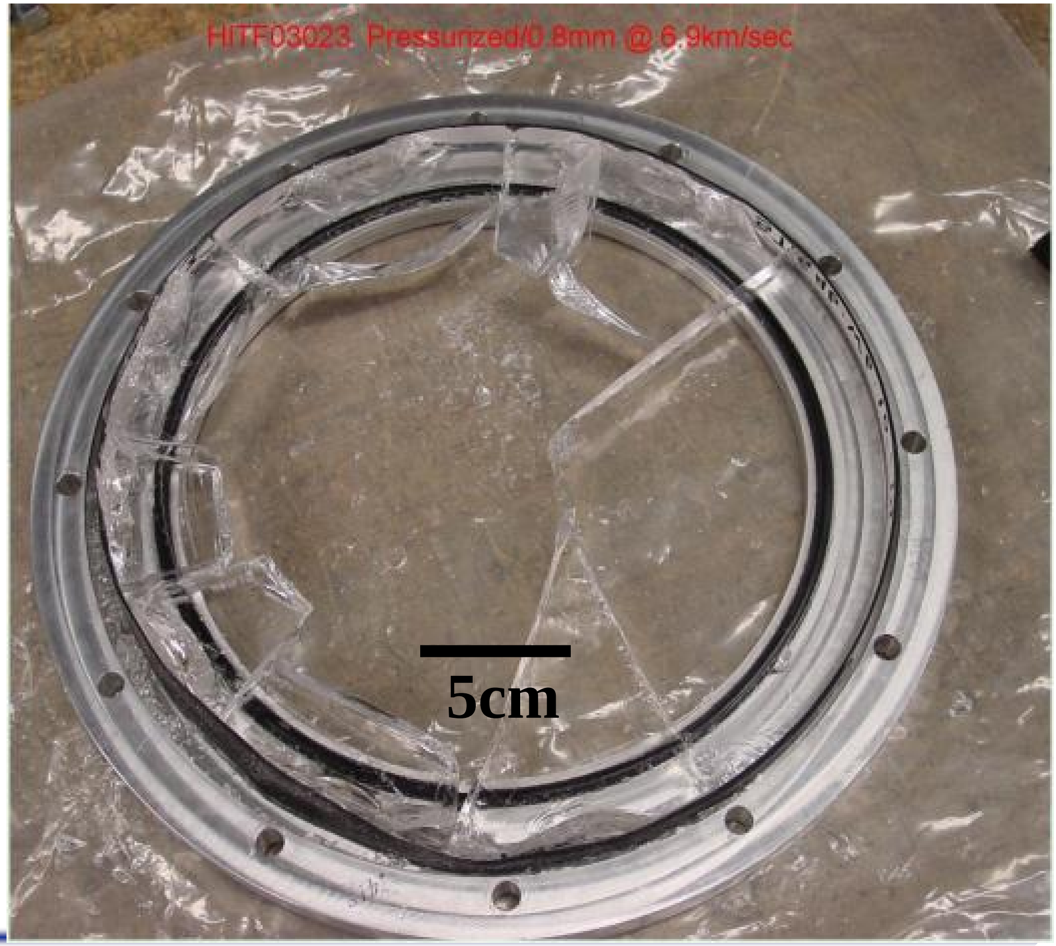
Test Results (Unpressurized vs. Pressurized)

- **Projectile Conditions: 0.8 mm diameter Al 2017T4, 6.9 km/s, 0º**

Unpressurized – Glass Unstressed

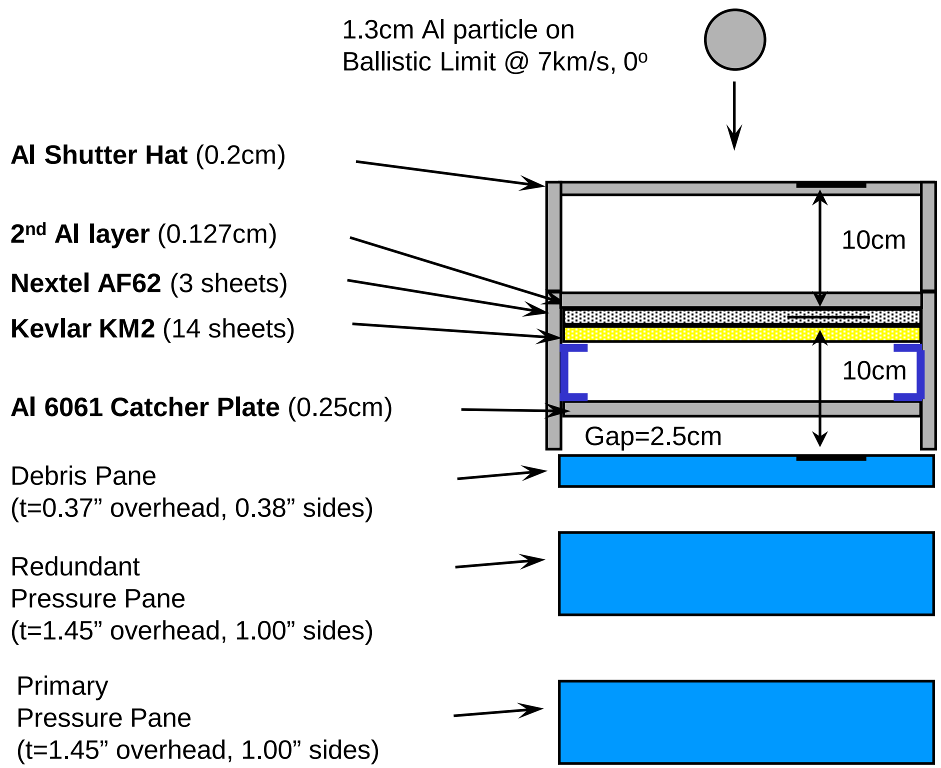


Pressurized – Glass Stressed

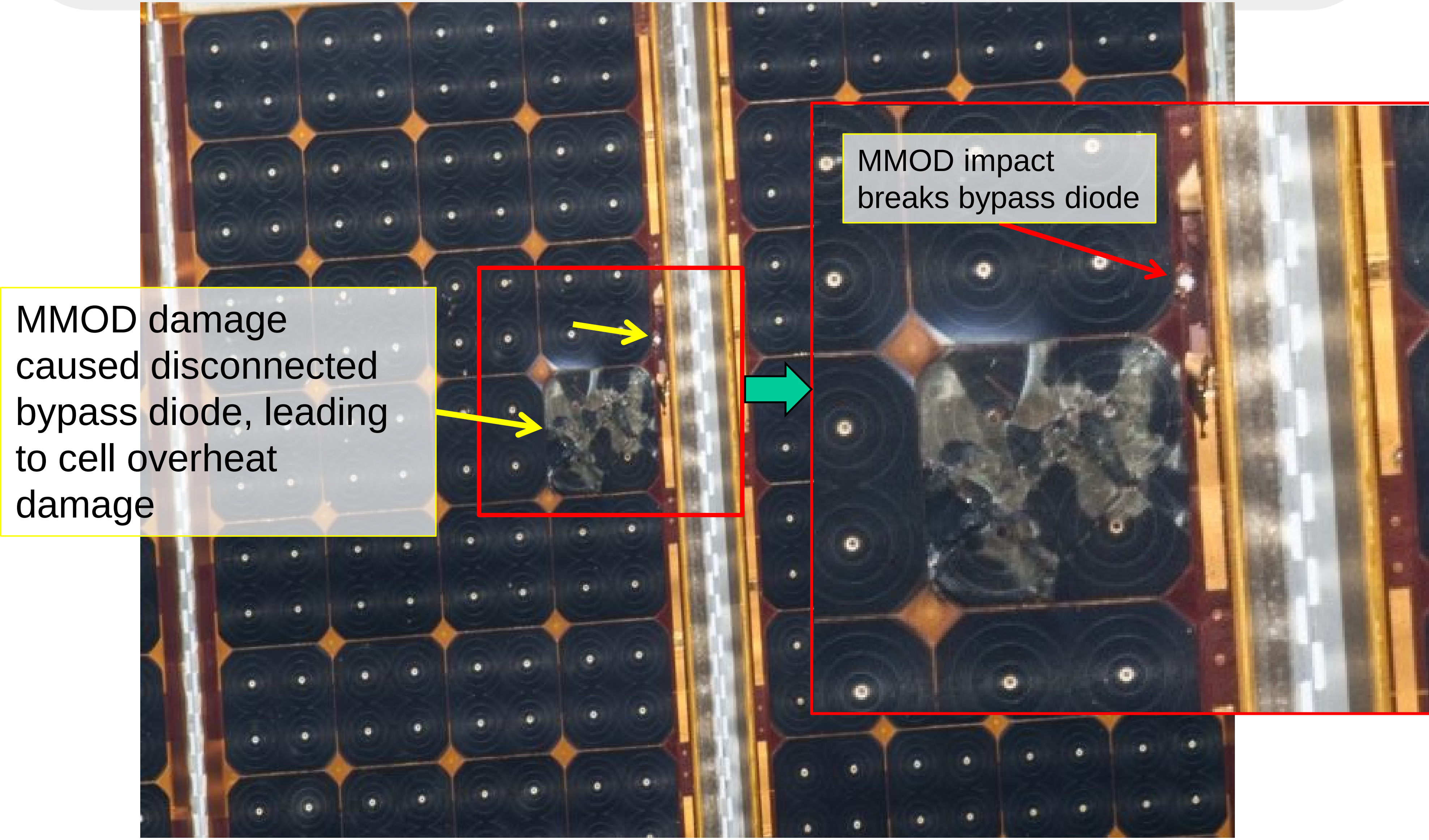


Cupola Shutters

- **ISS Cupola have multi-layer Shutters that provide MMOD protection of the windows, when the shutters are closed**

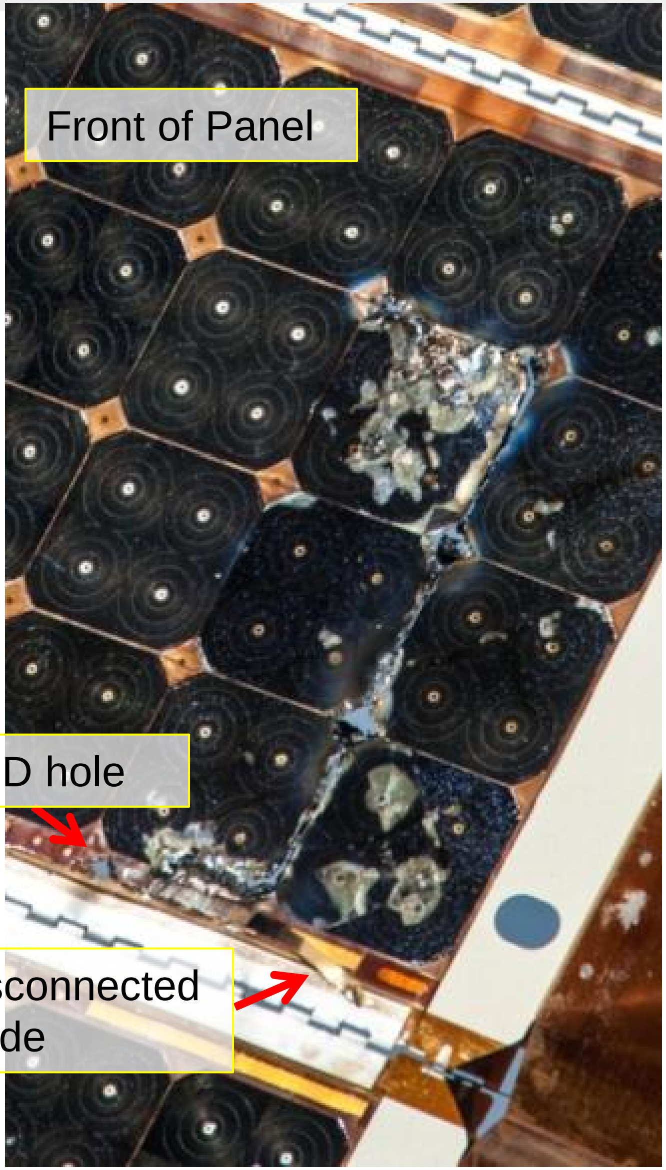


ISS Solar Array Damage

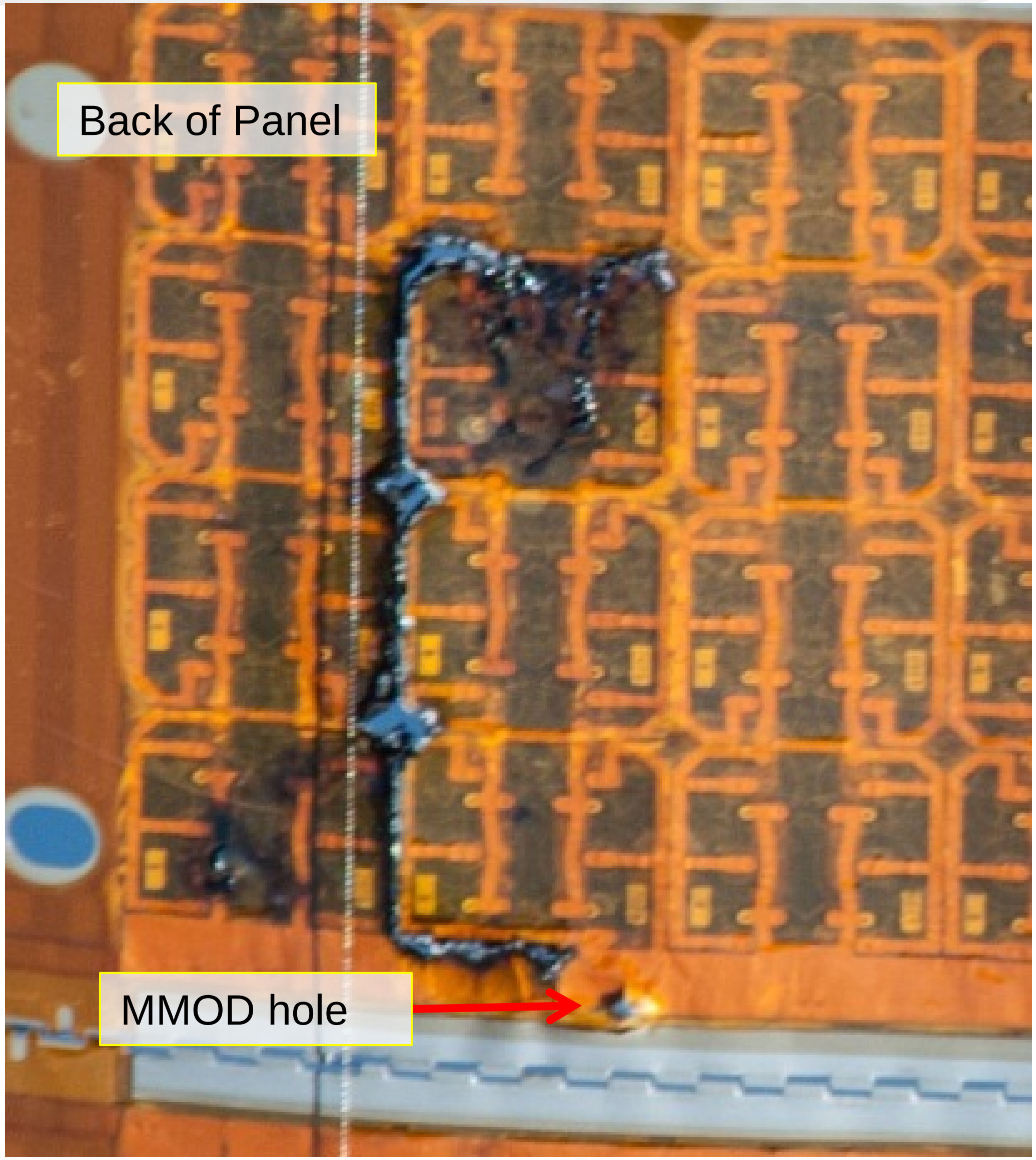


Solar Array Damage

MMOD impact breaks bypass diode causing overheat



iss040e064550



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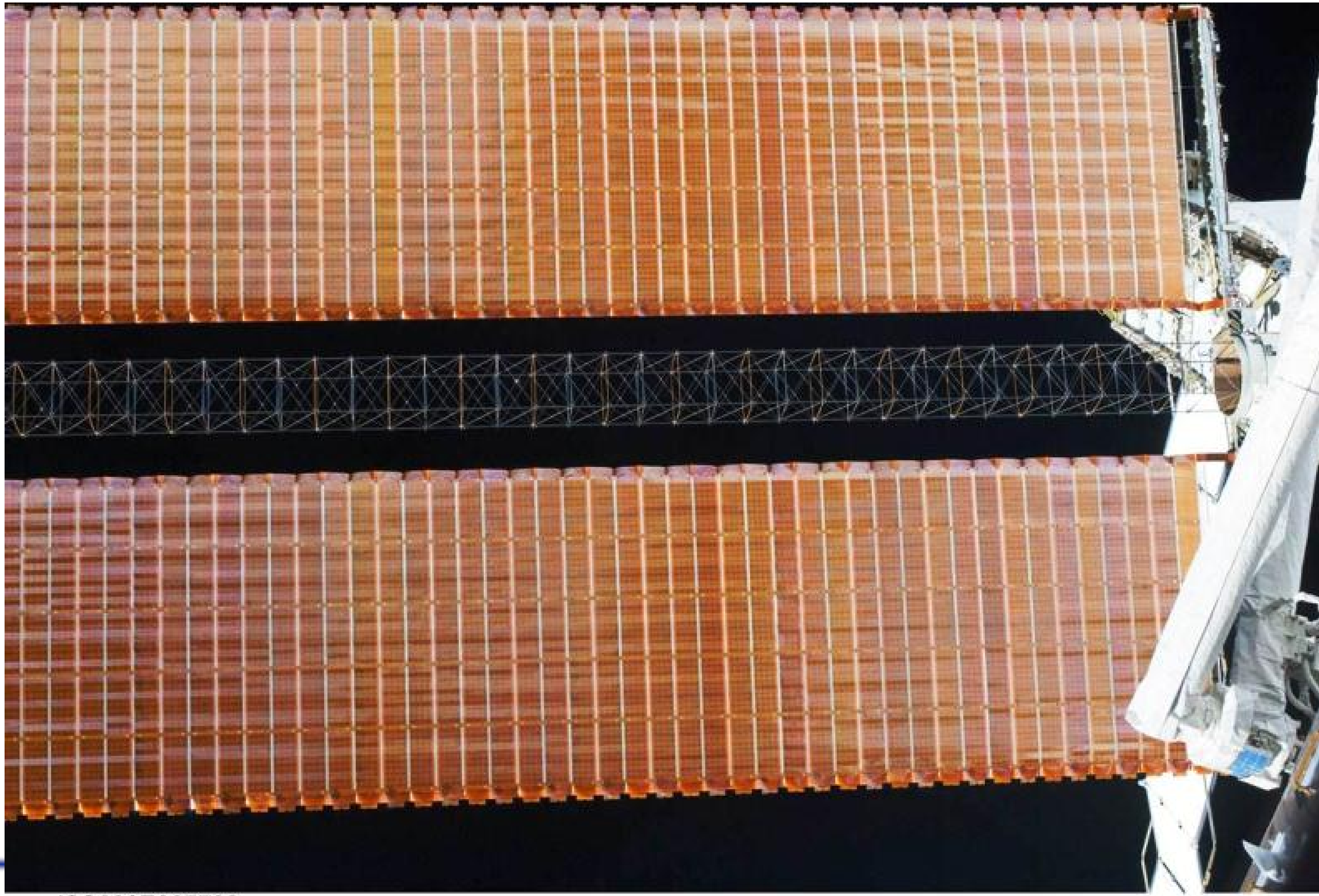
ISS Solar Array Mast

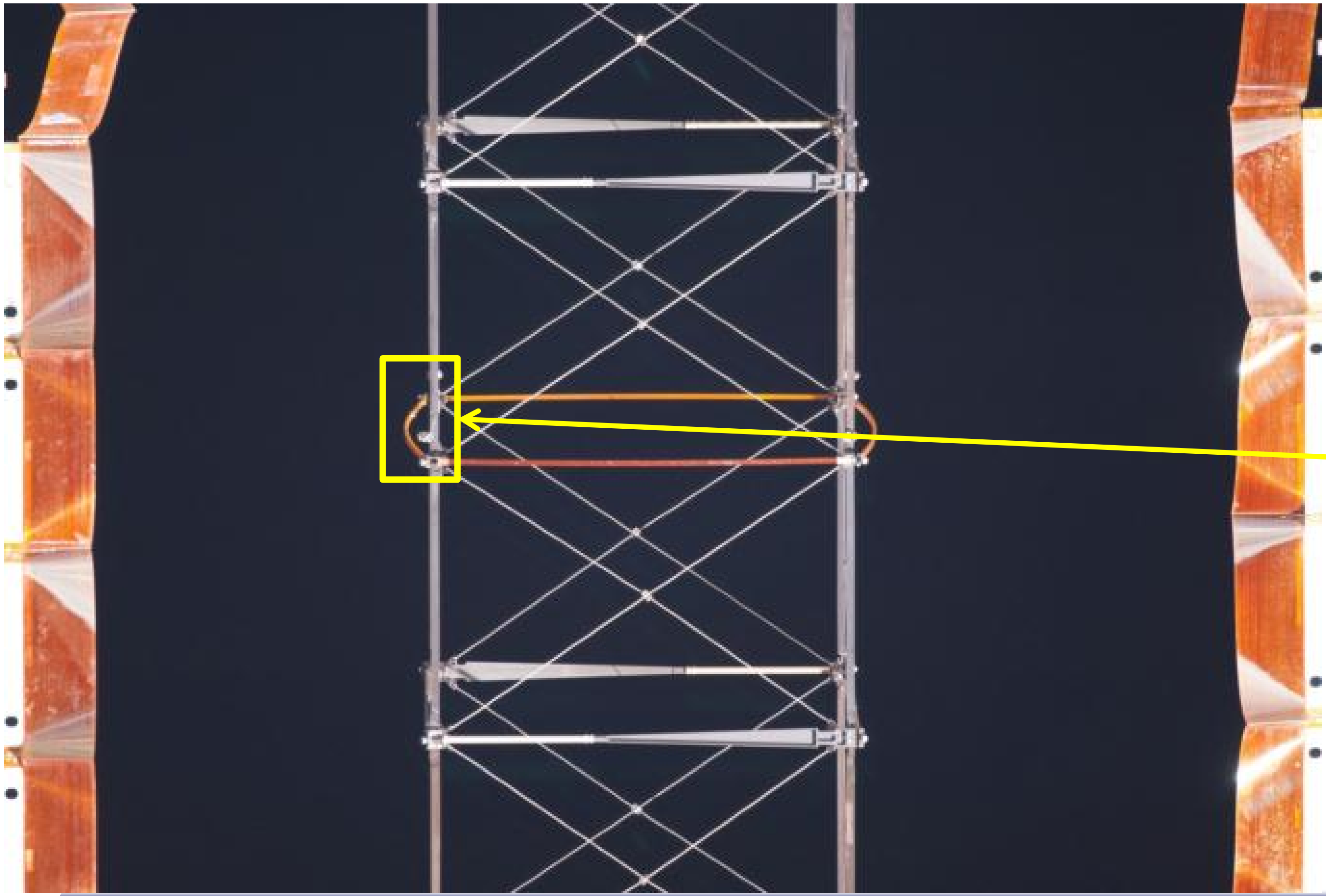
- **Deployable structural booms or masts used to support ISS solar arrays**



ISS022E067792

MMOD Damage to ISS Solar Array Masts

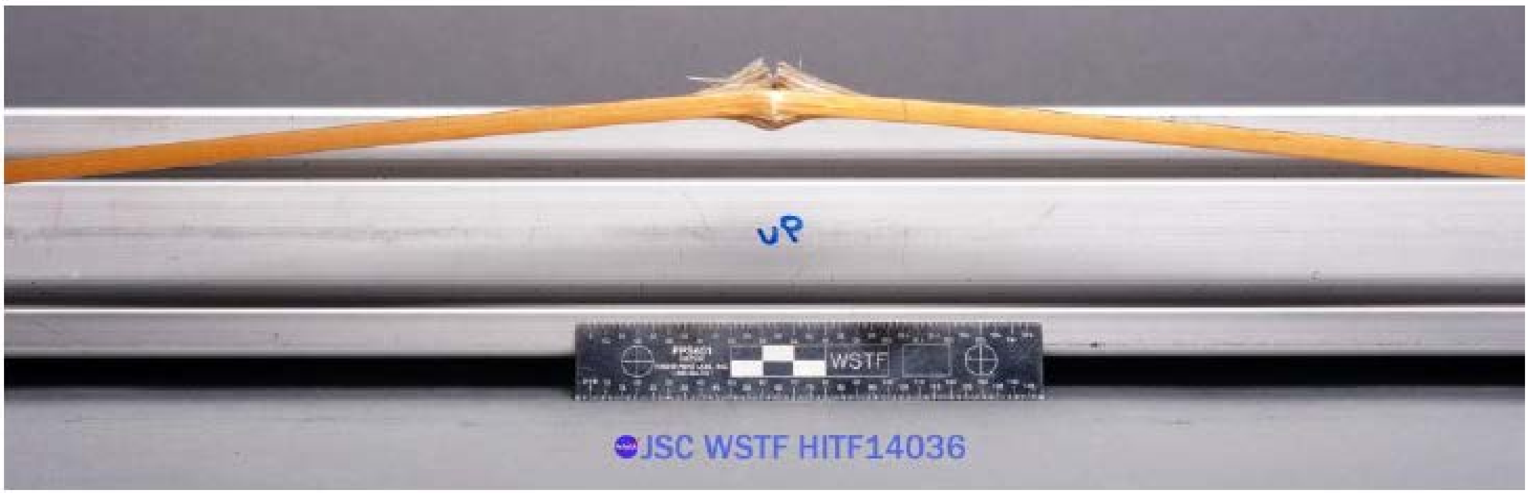
- **Elements of the solar array masts have been damaged from MMOD impacts**
- **If critical damage to mast elements found during inspection, solar array will need to be operated under restricted/protect flight rules**



ISS038e006032, Nov. 2013

Hypervelocity impact tests

- **Mast elements have been hypervelocity impact tested and structurally tested to assess residual strength for ISS life extension**

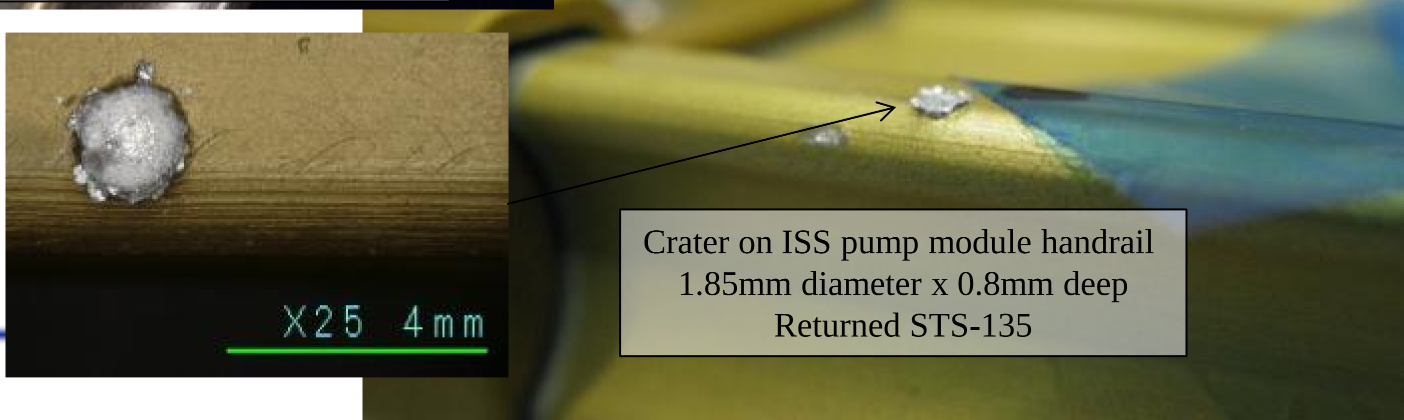


Handrail and EVA tool MMOD damage

- Many craters noted to ISS handrails and EVA tools
- Sharp crater lips have lead to cuts on EVA gloves
- EVA terminated early on STS-118 due to glove cuts
- Modifications to EVA suit and ISS EVA procedures necessary to reduce cut glove risk from MMOD damage

Crater on D-handle tool
5mm diameter
Repaired on-orbit during STS-123

Tear in EVA glove
(STS-118 EVA#3)

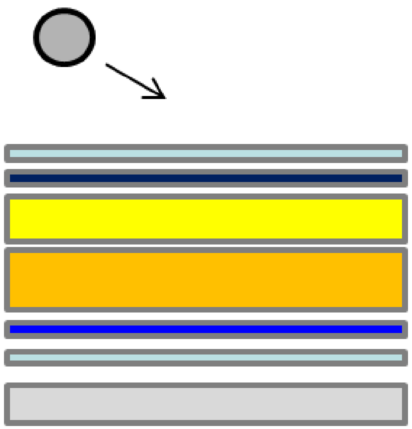


Crater on ISS pump module handrail
1.85mm diameter x 0.8mm deep
Returned STS-135

Thermal Blankets

- **Thermal blankets are typically light-weight and easily penetrated by MMOD impacts**
- **Toughened thermal blankets incorporate additional MMOD layers to improve projectile breakup and stopping capability**
  - Additional data available in NASA/TM-2014-218268, Volume I & II, Micrometeoroid and Orbital Debris (MMOD) Design and Analysis Improvements, NASA Engineering and Safety Center Report NESC-RP-12-00780

Toughened thermal blankets with integrated impact sensor film



(1) Outer cover (standard/typical)
(2) **Disrupter** layer(s) (added)
(3) Standard MLI (multiple metallized Kapton or Mylar layers with scrim separators)
(4) **Spacer** layer (added)
(5) **Stopper** layer(s) (added)
(6) Back cover (standard/typical)
(7) Spacecraft/hardware surface

Impact tests

Impact Sensor Film

Concluding Remarks

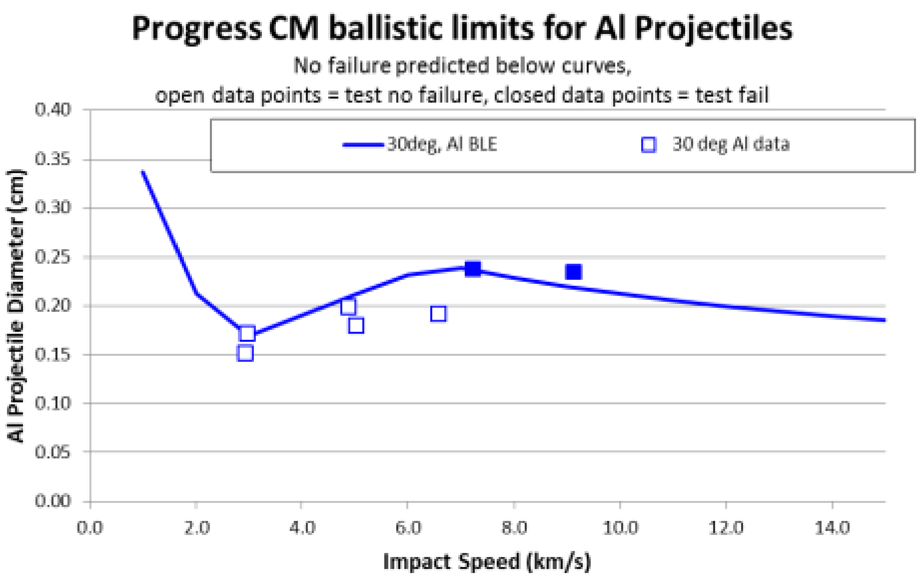
- **Highly effective MMOD shields have been developed & implemented on ISS and commercial vehicles**
- **Toughened radiator systems have been developed & implemented**
- **Reentry vehicles are sensitive to MMOD damage and require combination of improved design as well as operations (low-risk attitudes, on-orbit inspection) to reduce MMOD risk:**
  - Thermal protection systems
  - Windows
  - Radiators

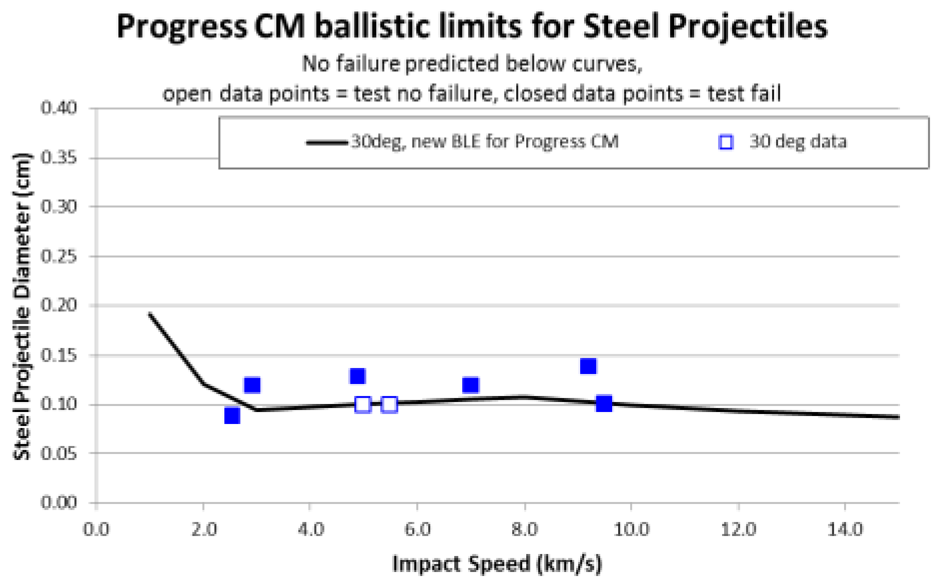
BACKUP CHARTS

Progress CM Shielding

30deg impact data for Aluminum and Steel Projectiles

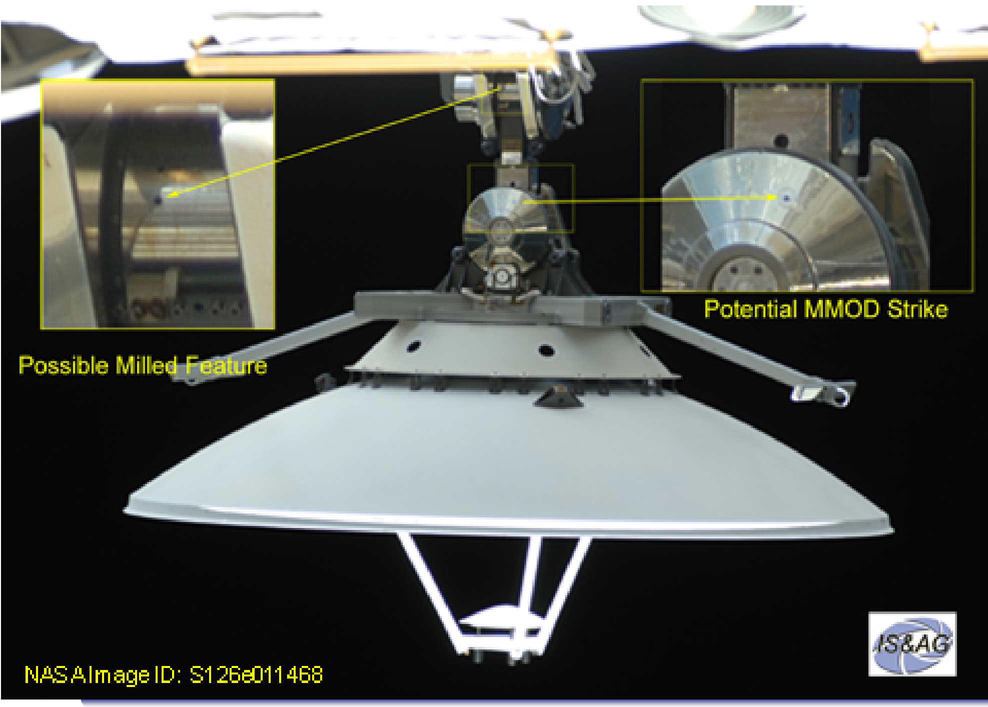
- **Tests indicate approximately 2mm diameter aluminum projectile penetrates Progress CM shielding (creating hole in pressure shell), whereas 1mm diameter steel projectile penetrates Progress CM**
  - Aluminum used with ORDEM 2000, steel with ORDEM 3.0
  - Risk increases substantially as MMOD penetration size decreases

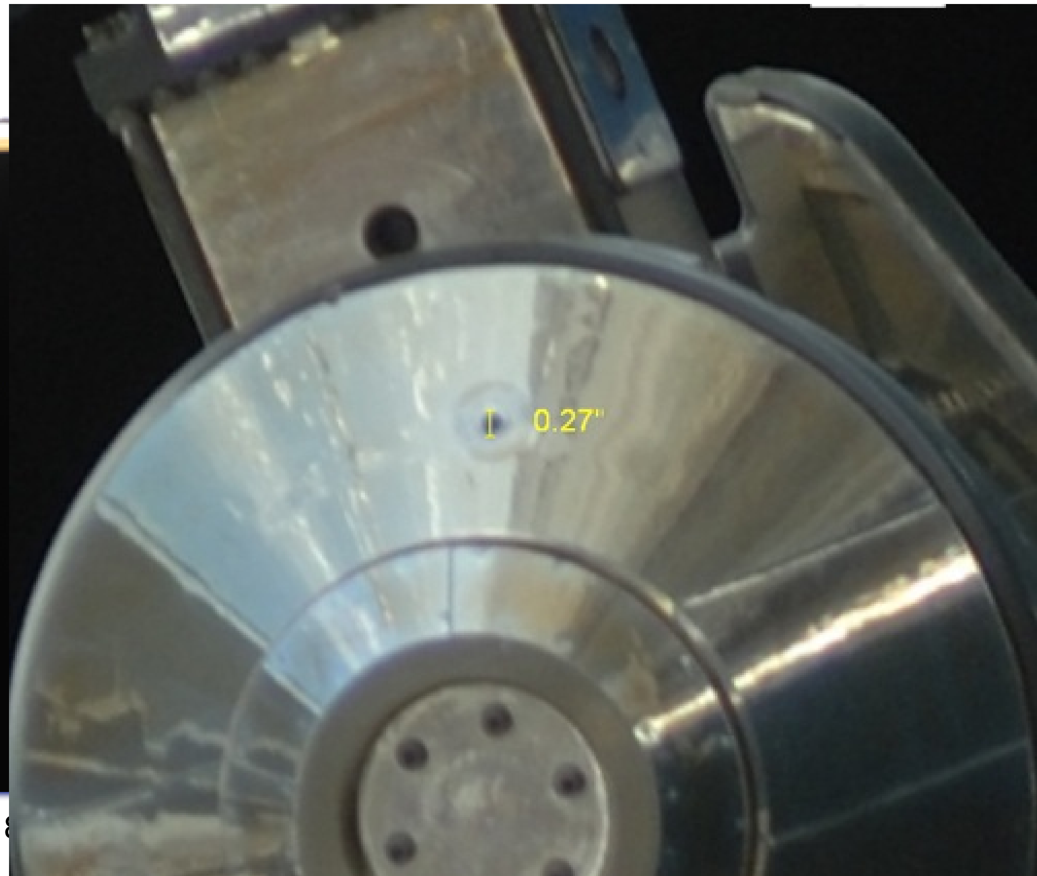




Ku-band antenna

- **An MMOD Strike was seen on the ISS Ku Antenna Gimbal Gear Cover. The image was captured during Mission ULF2 / STS-126.**
- **Interior damage?**

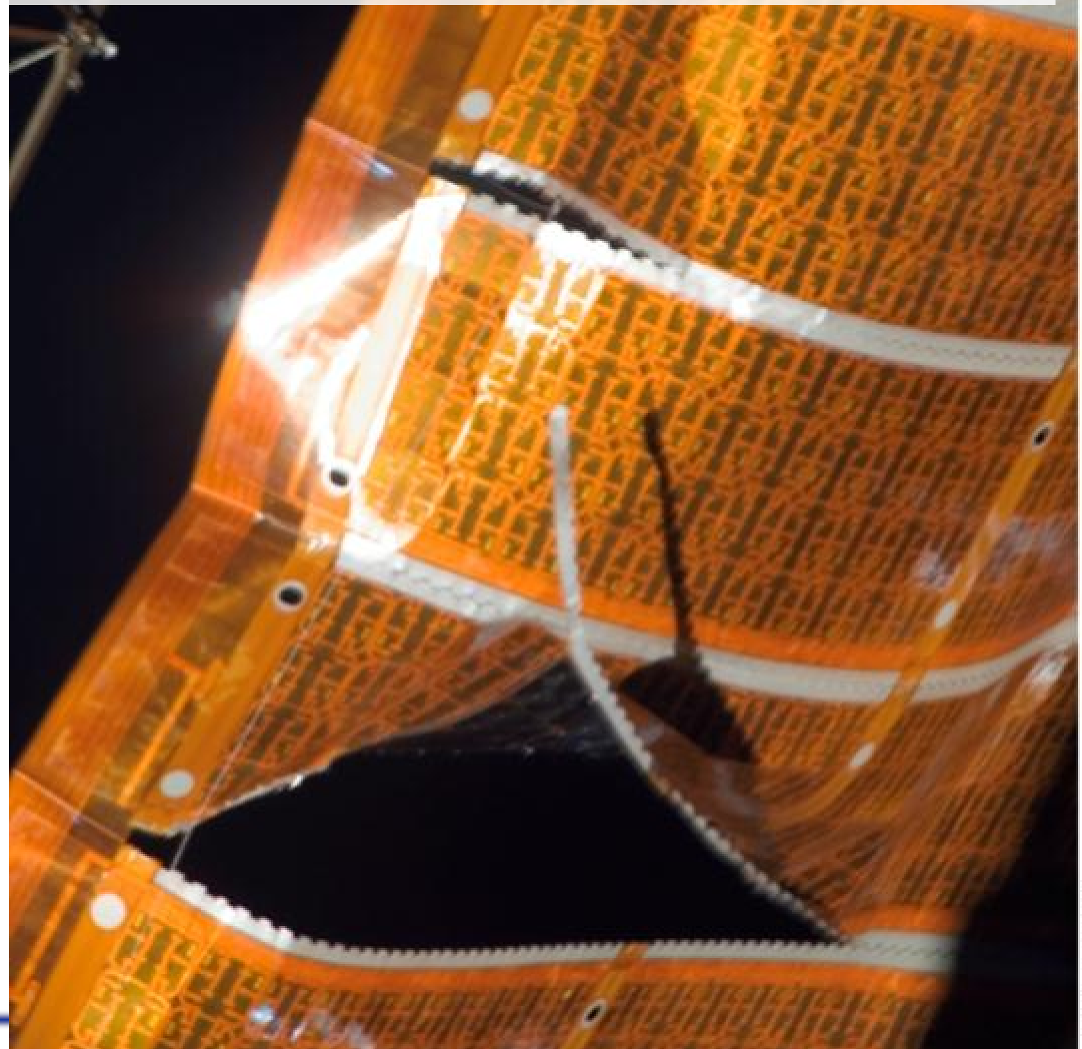




STS-120 Solar Array Wing (SAW) EVA repair was caused by MMOD impact damage

During STS-120 two solar array wings were removed from Z1 truss and relocated to P6 location. During re-deployment, the 4B solar array wing was torn in two places, due to a snagged guide wire. The guide wire was removed and "cuff-links" added to stabilize the array.

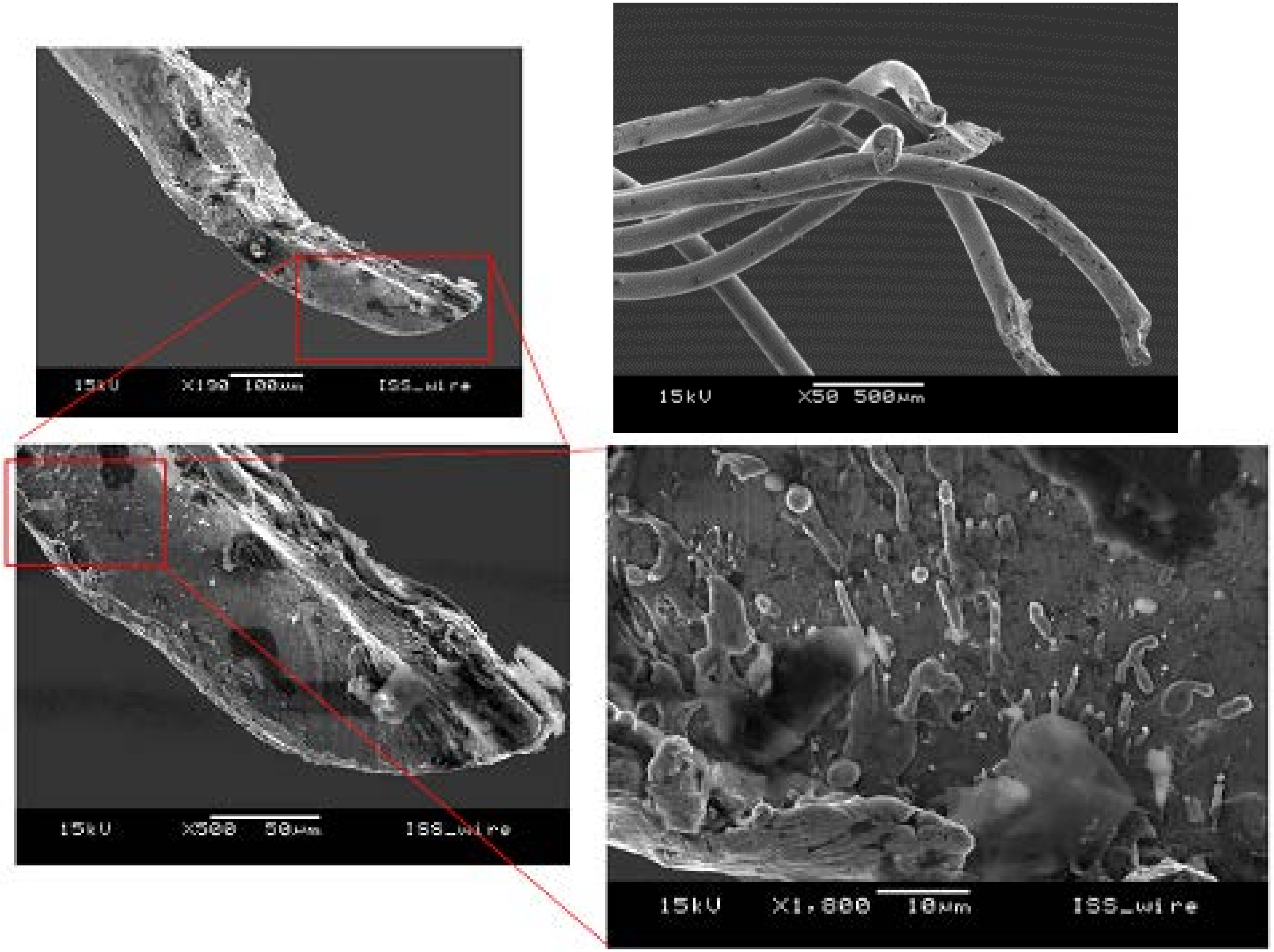
ISS016E009184



S120E008247

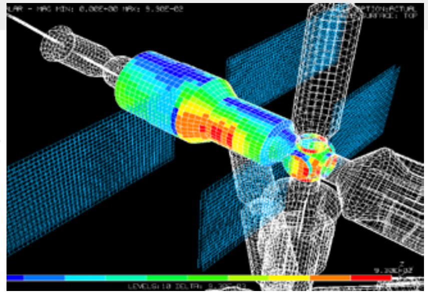
Scanning Electron Microscope EDXA Evaluation of retrieved guide wire

7 of 21 wires in the guide wire cable were broken, causing the guide wire to hang-up in a solar array grommet.
3 of the 7 cut wires exhibited evidence of extensive melt at broken ends, indicative of MMOD impact.



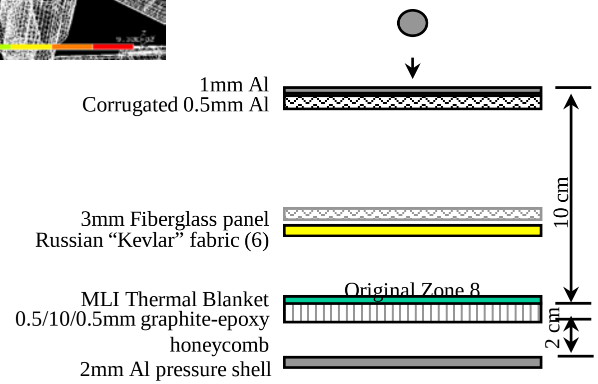
ISS Service Module Shielding

- **Service Module (SM) identified as high penetration risk using Bumper risk analysis**
  - large cone region
  - forward sides of small diameter cylinder
- **Shields designed and tested, EVA installed**
  - 23 augmentation shields for the cone region
  - 5 augmentation shields for the cylinder region
- **28 shields reduced SM MMOD risk by 30%**

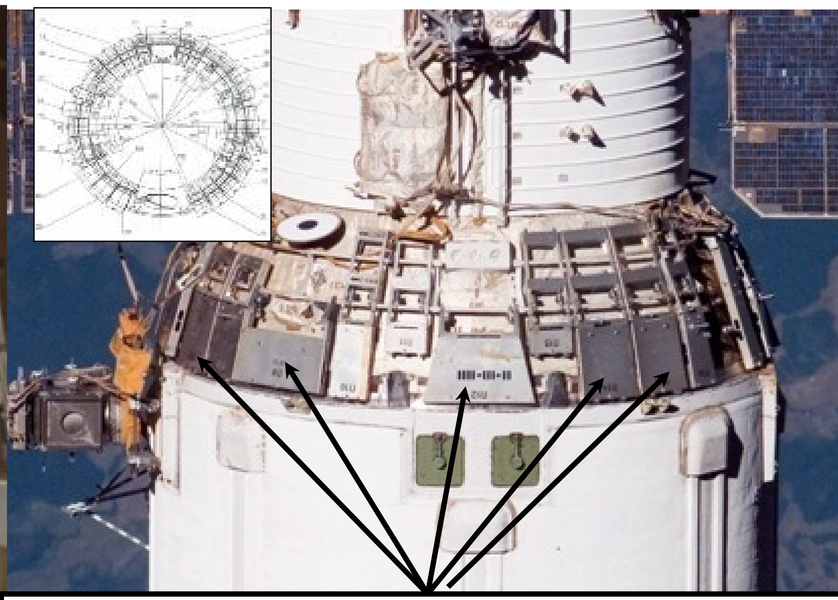


High-risk (red)
Low-risk (blue)

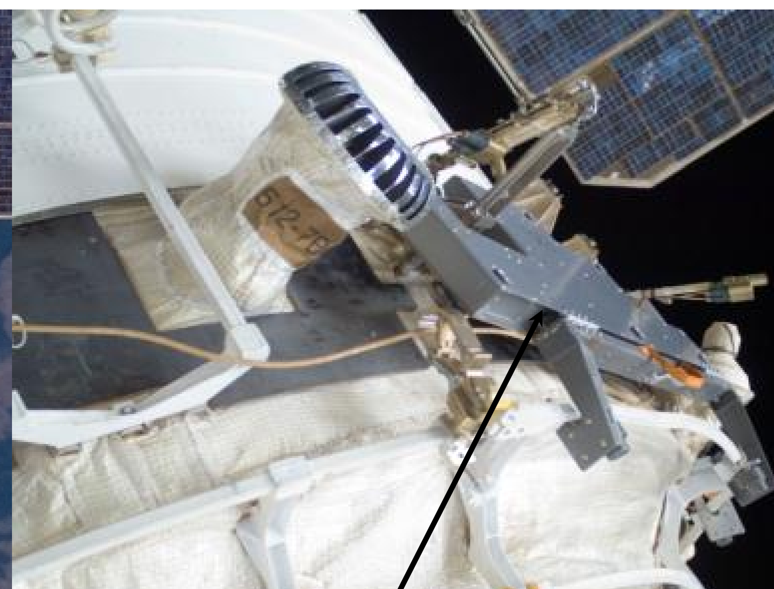
SM "conformal" augmentation shield



EVA Installation



23 "conformal" panels on cone region



5 panels on small diameter cylinder

HVIT Team: HVI Testing and MMOD Risk Assessments

Hypervelocity Impact Testing:

- Objective: understand how a spacecraft surface and underlying structure “shield” responds to impact from an orbital debris or micrometeoroid

- Inputs: impact velocity (mostly 3-8 km/s), impact angle (usually 0º, 30º, 45º, 60º), projectile diameter (aluminum, nylon, ruby, steel)

- Product: a ballistic limit equation (BLE) that calculates a critical particle diameter that will fail the shield as defined by the specific failure criteria

MMOD Risk Assessments:

- Objective: use the Bumper risk assessment code to estimate the micrometeoroid and orbital debris (MMOD) risk to a spacecraft for a given set conditions.

- Bumper inputs:
  - spacecraft geometry
  - altitude, inclination, orientation
  - start year, exposure duration
  - debris or meteoroid
  - BLE and failure criteria

- Product:
  - MMOD risk results
  - Impact (NI, PNI, odds)
  - Penetration (NP, PNP, odds)
  - Color risk contours & VBETA

Hypervelocity Impact Testing

Testing at WSTF:

- 3,500 HVI tests completed 2004-2011
- average 440 tests per year
- testing performed on WSTF two-stage light gas guns (2SLGG)
  - range selection driven by projectile size, test sample size, and budget
  - .17-cal, .50-cal, 1" ranges
  - turnaround times vary

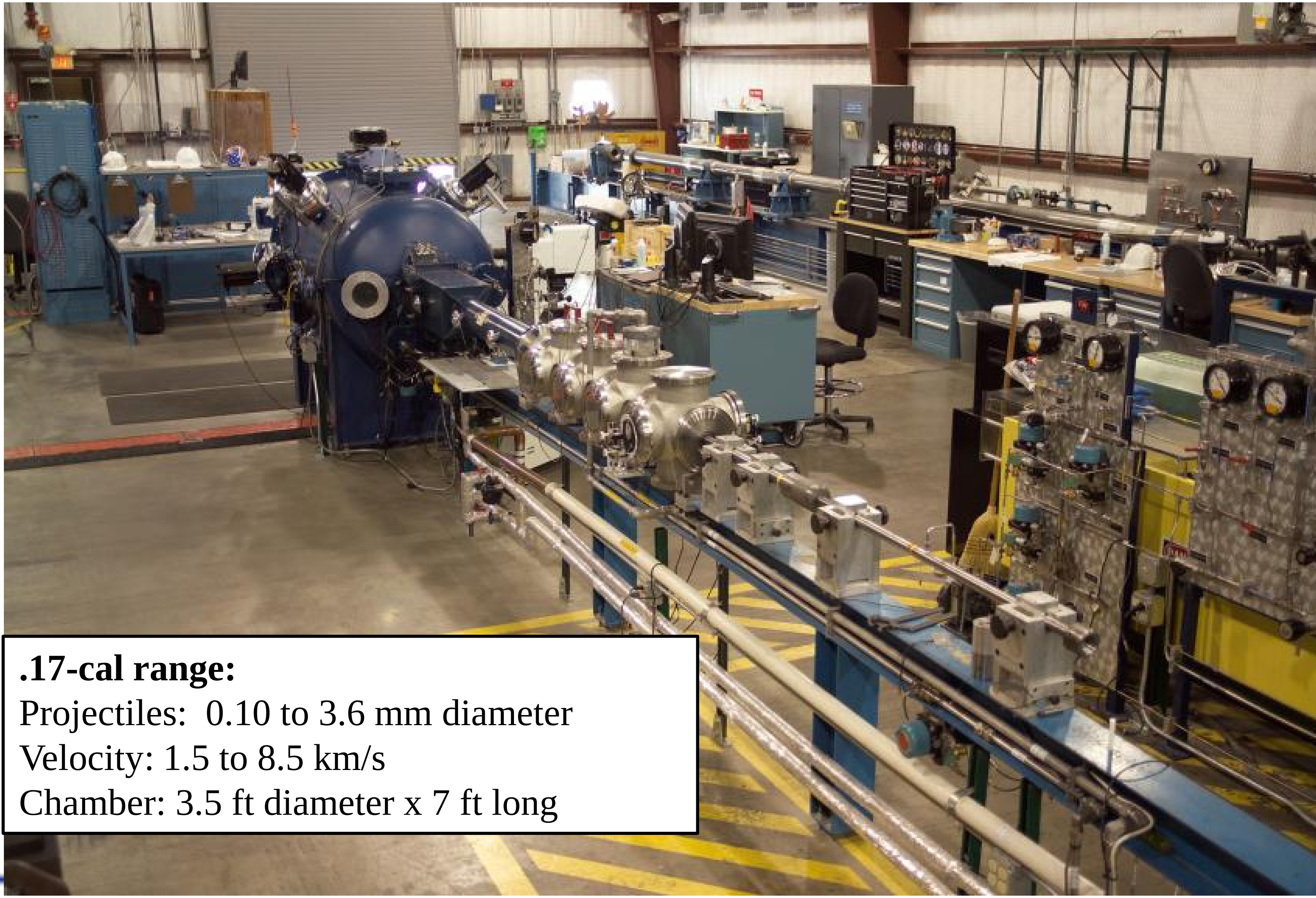
JSC-KX Hypervelocity Impact Technology (HVIT) Team:

- develops test matrix
- completes test readiness review
- prepares (builds up) test samples
- ships samples and projectiles to WSTF
- daily coordination with WSTF
- performs post test sample analysis
- documents test series in report
- develops ballistic limit equations

WSTF Remote Hypervelocity Test Laboratory (RHTL)

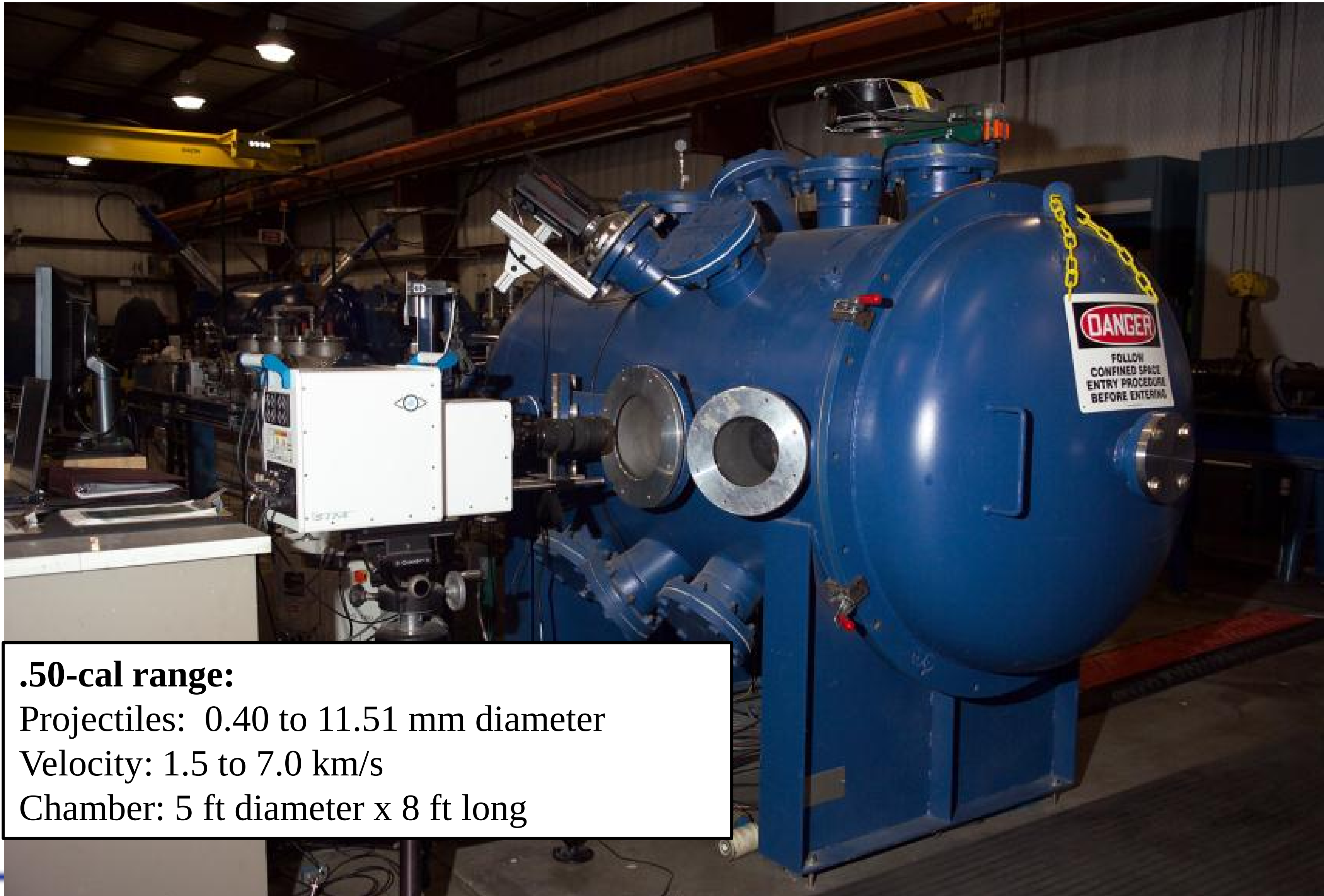
WSTF Remote Hypervelocity Test Laboratory (RHTL)

WSTF .17-cal range



.17-cal range:
Projectiles: 0.10 to 3.6 mm diameter
Velocity: 1.5 to 8.5 km/s
Chamber: 3.5 ft diameter x 7 ft long

WSTF .50-cal range



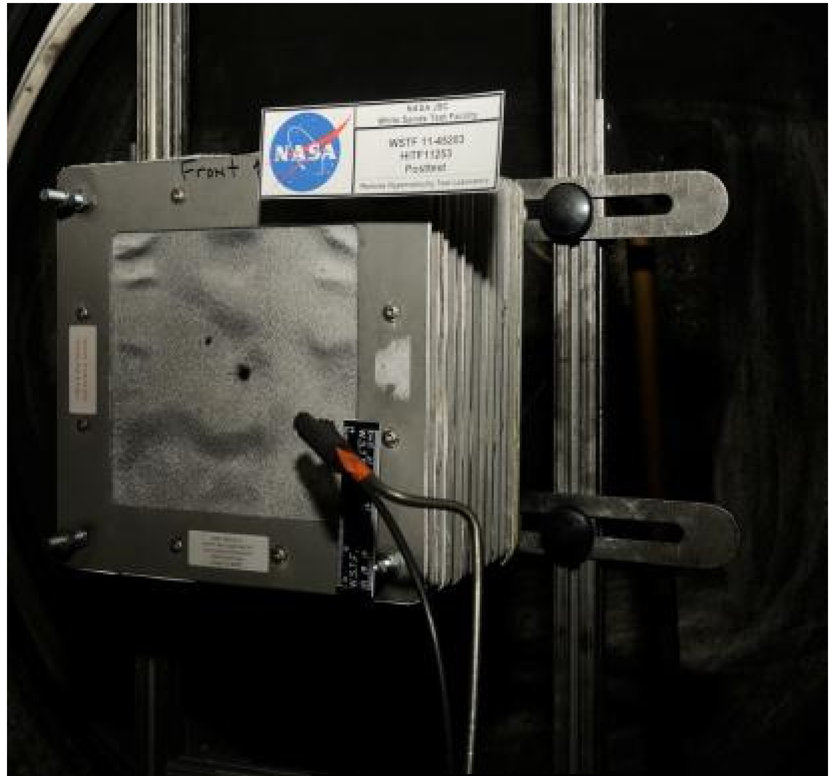
.50-cal range:
Projectiles: 0.40 to 11.51 mm diameter
Velocity: 1.5 to 7.0 km/s
Chamber: 5 ft diameter x 8 ft long

WSTF 1” range

1”range:
Projectiles: 0.40 to 22 mm diameter
Velocity: 1.5 to 7.0 km/s
Chamber: 9 ft diameter x 30 ft long

.50-cal Test

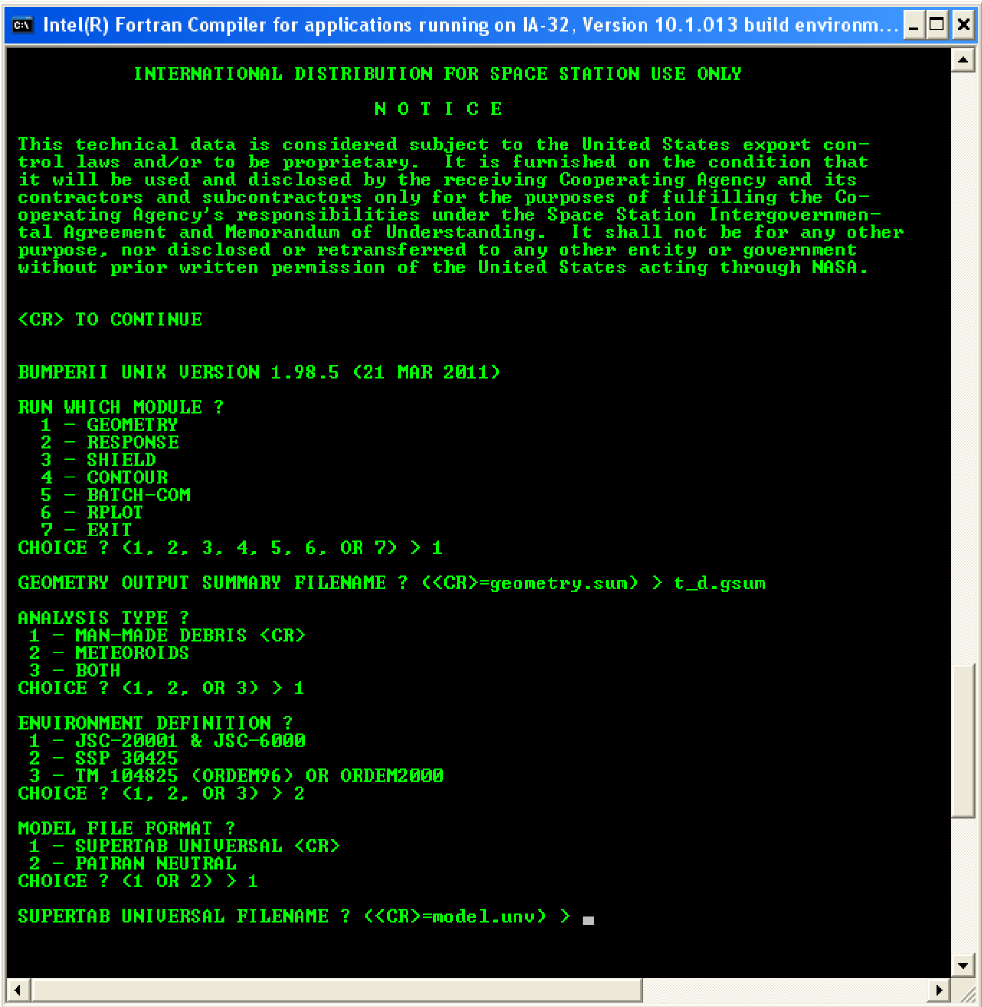
Pretest photo



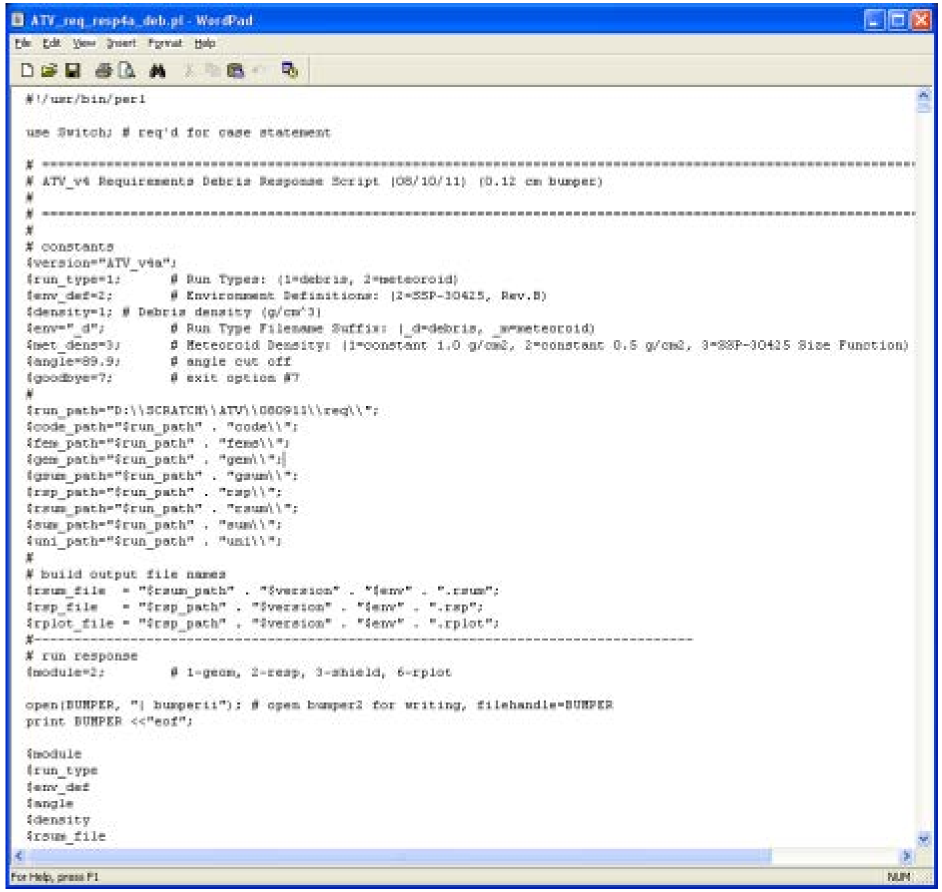
Post Test Photo

Phantom camera impact video (67 kfps)

HVIT Team: MMOD Risk Assessments
Bumper Code

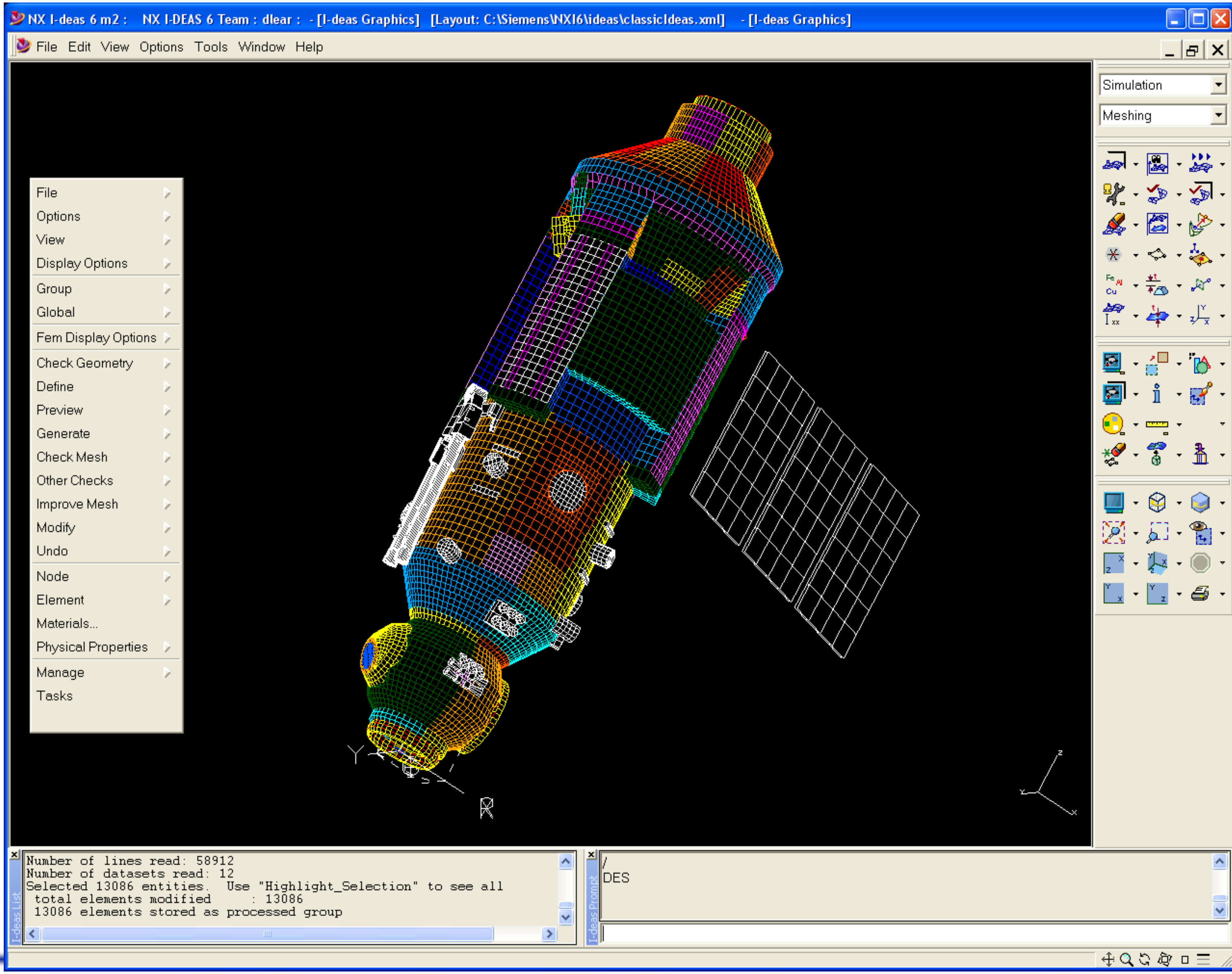


Running Bumper interactively (single run)



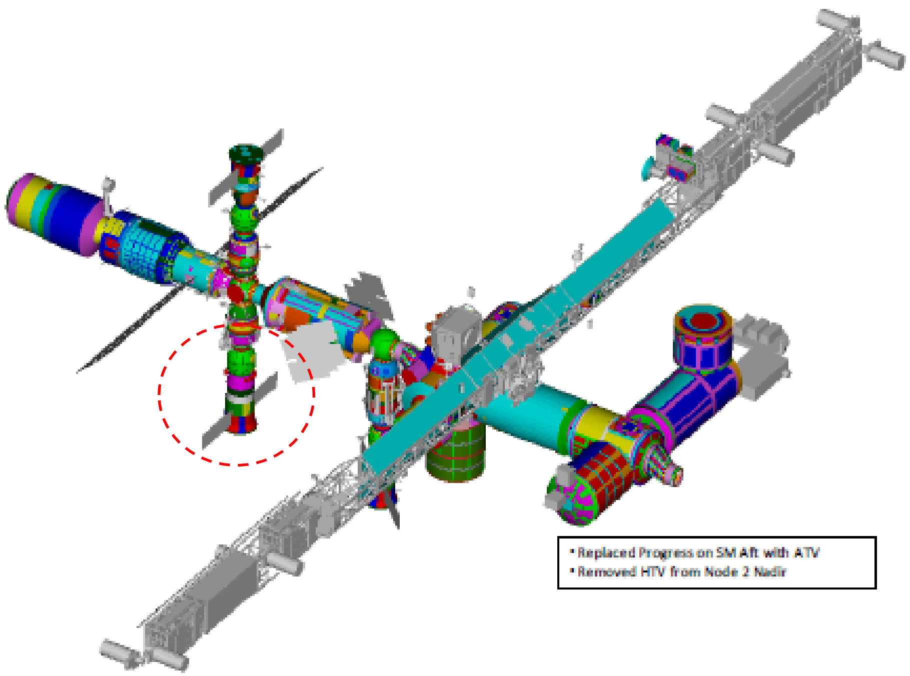
Running Bumper automatically with scripts (multiple runs)

HVIT Team: I-DEAS Modeling Software

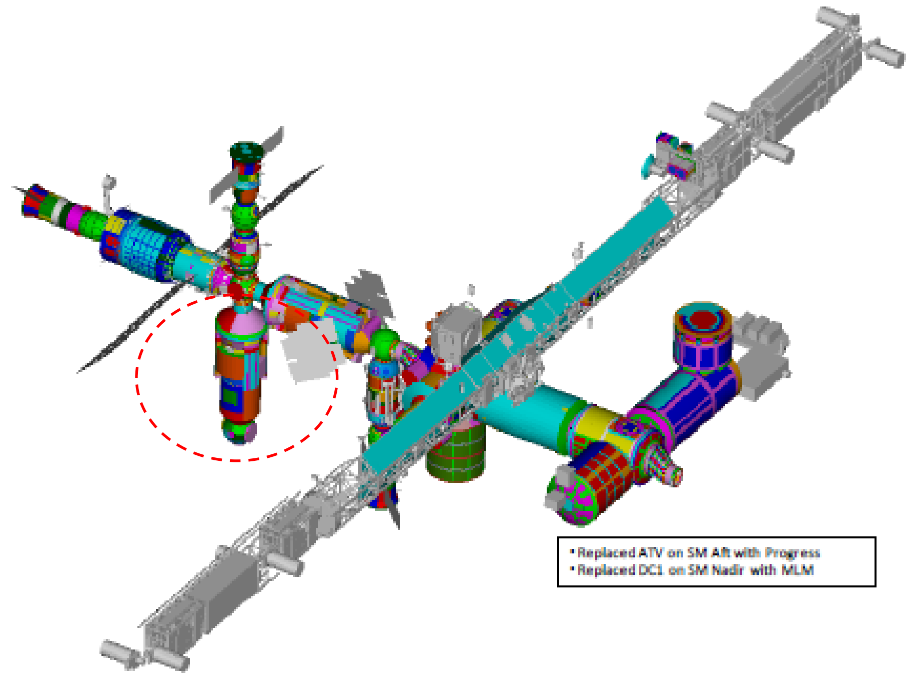


I-DEAS Graphical User Interface

HVIT Team: Finite Element Model (FEM)

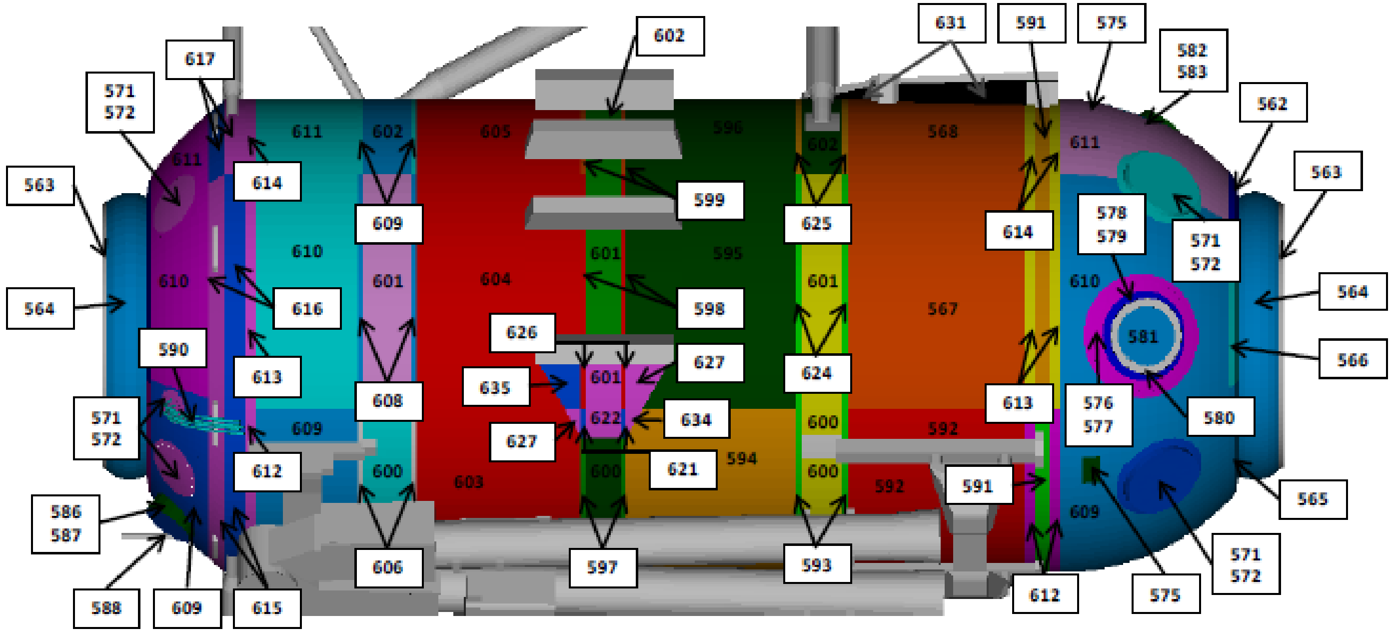


ISS MMOD Risk Assessment FEM
(representing current configuration)



ISS MMOD Risk Assessment FEM
(representing configuration after MLM launch)

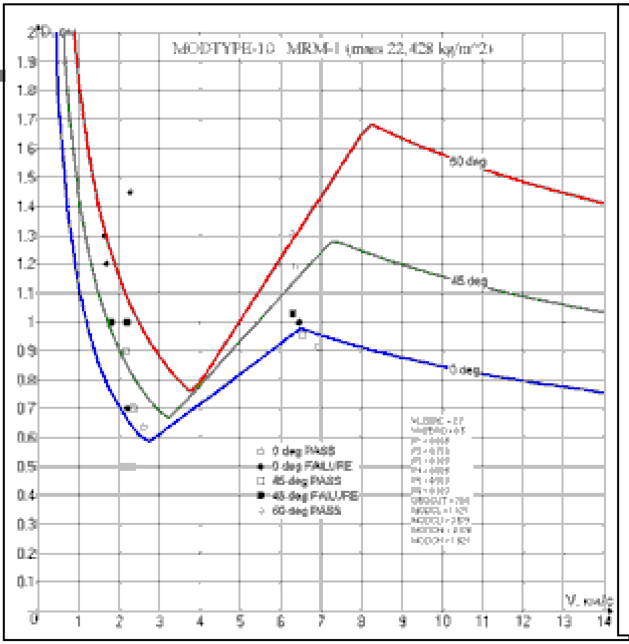
HVIT Team: Finite Element Model (FEM)



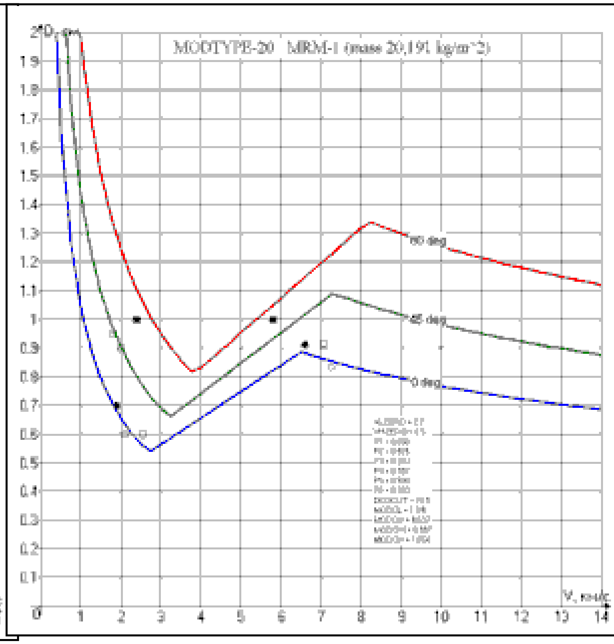
PID 1 - SHADOWING
PID 562 - ZEN RING LOW FIRM
PID 563 - SHPANGOUT I
PID 563 - SHPANGOUT IV
PID 564 - DOCKING MECHANIZM
PID 565 - ZEN RING HIGH FIRM
PID 566 - ZEN RING MIDDLE FIRM
PID 567 - ZEN CYLINDER MIDDLE FIRM
PID 568 - ZEN CYLINDER LOW FIRM
PID 569,570 - ZEN SPHERE
PID 571,572 - ZEN/NAD SPHERE
PID 573,574 - ZEN SPHERE
PID PID 575 - ZEN/NAD SPHERE
PID 576 - ROUND PLATE RING 1
PID 577 - ROUND PLATE RING 2
PID 578 - ROUND PLATE RING 3
PID 579,580 - ROUND PLATE RING 4
PID 581 - ROUND PLATE
PID 582-585 - ZEN SPHERE
PID 586 - ZEN/NAD SPHERE
PID 587 - ZEN SPHERE
PID 588 - ZEN/NAD SPHERE
PID 588 - NAD SPHERE
PID 589 - ZEN SPHERE
PID 590 - NAD SPHERE STEEL TUBES
PID 591 - RING 2A THICK
PID 592 - ZEN CYLINDER
PID 593 - RING 3A THIN
PID 594-596 - CENTRAL-ZEN CYL
PID 597 - RING 4A THIN (FWD)
PID 598 - RING 4A THIN (STBD/PORT)
PID 599 - RING 4A THIN (AFT)
PID 600 - RING 3A,4A,5A THICK (FWD)
PID 601 - RING 3A,4A,5A THICK (STBD/PORT)
PID 602 - RING 3A,4A,5A THICK (AFT)
PID 603 - CENTRAL-NAD CYL (FWD)
PID 604 - CENTRAL-NAD CYL (STBD/PORT)
PID 605 - CENTRAL-NAD CYL (AFT)
PID 606 - RING 5A THIN (FWD)
PID 607 - RING 5A THIN (STBD/PORT)
PID 608 - RING 5A THIN (AFT)
PID 609 - ZEN/NAD SPHERE/CYL (FWD)
PID 610 - ZEN/NAD SPHERE/CYL (STBD/PORT)
PID 611 - ZEN/NAD SPHERE/CYL (AFT)
PID 612 - RING 2A,6A THIN (FWD)
PID 613 - RING 2A,6A THIN (STBD/PORT)
PID 614 - RING 2A,6A THIN (AFT)
PID 615 - RING 6A/NAD CONE,RING (FWD)
PID 616 - RING 6A/NAD CONE,RING (PORT/STBD)
PID 617 - RING 6A/NAD CONE,RING (AFT)
PID 618 - RING 2A THIN (PORT)
PID 619 - RING 3A THICK (PORT)
PID 619 - RING 5A THICK (PORT)
PID 620 - RING 3A THIN (PORT)
PID 621 - RING 4A THIN (FWD)
PID 622 - RING 4A THICK (FWD)
PID 623 - RING 5A THIN (PORT)
PID 624 - RING 3A THIN (STBD/PORT)
PID 625 - RING 3A THIN (AFT)
PID 626 - RING 4A THIN (STBD)
PID 627 - CENTRAL-ZEN CYL (STBD)
PID 628 - CENTRAL-NAD CYL (FWD)
PID 629 - PRM LONG STANDOFF
PID 630 - PRM SHORT STANDOFF
PID 631 - PRM SIDE
PID 632 - ZEN CYLINDER (PORT)
PID 633 - CENTRAL-NAD CYL (PORT)
PID 634 - CENTRAL-ZEN CYL (FWD)
PID 635 - CENTRAL-NAD CYL (STBD)

ISS Mini-Research Module #1 (MRM-1) FEM Property Identification (PID) Map (partial)

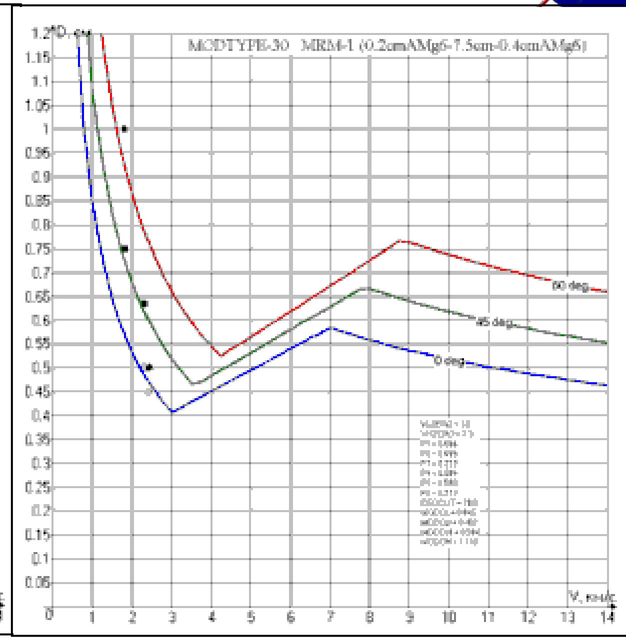
Mini-Research Module (MRM-1) MMOD Shield Type Map



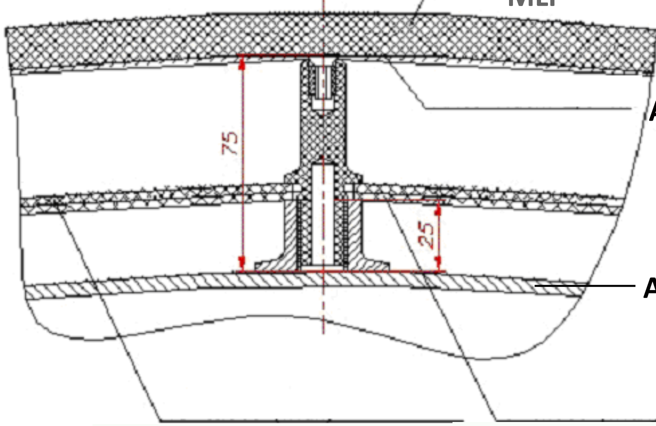
MODTYPE10
Basalt Fabric БТ-13Н (18
Industrial Fabric 8353/11 (6 layers)
4-mm AMr6 rear wall (scaling factor=1.0)



MODTYPE20
Basalt Fabric БТ-13Н (9 layers)
Industrial Fabric 8353/11 (6 layers)
4-mm AMr6 rear wall (scaling factor=1.0)

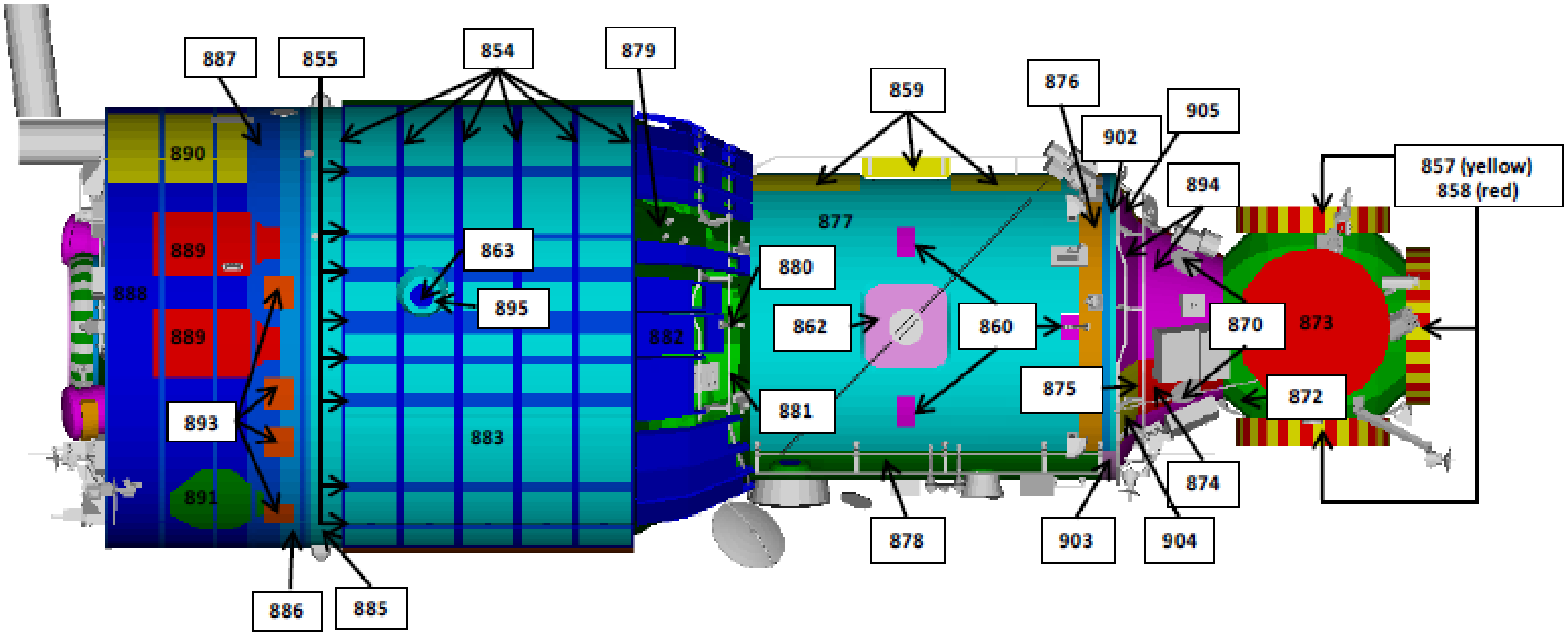


MODTYPE30
Basalt Fabric БТ-13Н (NONE)
Industrial Fabric 8353/11 (NONE)
4-mm AMr6 rear wall (scaling factor=1.0)



Ref: A. Gorbenko, RSC-E MRM-1 MMOD PNP Assessment Report P41491, April 2010.

HVIT Team: Finite Element Model (FEM)



PID 1 - SHADOWING
PID 854 - WORKING MODULE PANEL EDGES (6.0 MM)
PID 855 - WORKING MODULE PANEL CROSS MEMBERS (3.5 MM)
PID 856 - WORKING MODULE "ZENITH CYL"
PID 857 - DOCKING MECH PID
PID 858 - DOCKING MECH PID
PID 859 - WORKING MODULE ZENITH
PID 860 - WORKING MODULE RECTANGULAR EQUIPMENT PLATES
PID 861 - WORKING MODULE CIRCULAR EQUIPMENT PLATES
PID 862 - PV ARRAY BASES
PID 863 - WINDOW #1 AND 2
PID 864 - WINDOW #3 AND 5
PID 865 - WINDOW #4
PID 866 - WINDOW #6
PID 867 - WINDOW #26
PID 868 - WINDOW #7
PID 869 - WINDOW #8
PID 870 - WINDOW #12, 13 AND 14
PID 871 - WINDOW #9
PID 872 - TRANSFER MODULE "SPHERE"
PID 873 - PORT COVER
PID 874 - TRANSFER MODULE "CONE"
PID 875 - WORKING MODULE "BOTTOM"
PID 876 - WORKING MODULE "FWD CYL"
PID 877 - WORKING MODULE "RADIATOR CYL"
PID 878 - WORKING MODULE "NADIR CYL"
PID 879 - WORKING MODULE "CONE" PANELS - 4.5 MM
PID 880 - WORKING MODULE "CONE" PANELS - 4.0 MM
PID 881 - WORKING MODULE "CONE" PANELS - 2.3 MM
PID 882 - CONFORMAL SHIELD
PID 883 - WORKING MOD "RADIATOR CYL"
PID 884 - WORKING MODULE "NADIR CYL"
PID 885 - POWER MODULE "VERY SHORT S.O. CYL"
PID 886 - POWER MODULE "SHORT S.O. CYL"
PID 887 - POWER MODULE "LONG S.O. CYL"
PID 888 - POWER MODULE "VERY LONG S.O. CYL"
PID 888 - POWER MODULE AFT (16) PID675
PID 889 - PROPELLANT TANKS
PID 890 - COMPRESSOR UNITS
PID 891 - WATER TANKS
PID 892 - TRANSVERSE CHAMBER "COVER"
PID 893 - SPHERICAL TANKS
PID 894 - THICK PLATE@TRANSFER MOD. CONE
PID 895 - WINDOWS #1 AND 2 UNSHIELDED REGION
PID 896 - SM POWER MODULE - CONE
PID 897 - SM POWER MODULE - DOCKING MECH FRAME
PID 898 - SM POWER MODULE - DOCKING MECH (THICK WALL)
PID 899 - SM POWER MODULE - DOCKING MECH (THIN WALL)
PID 900 - SM POWER MODULE - DOCKING MECH FRAME
PID 901 - POWER MODULE "VERY LONG S.O. CYL"
PID 902 - SM WORKING MODULE FWD CYL - THK RING WALL
PID 903 - SM WORKING MODULE NADIR CYL - THK RING WALL
PID 904 - SM WORKING MODULE BOTTOM RING
PID 905 - SM THICK PLATE TRANSFER MODULE CONE RING

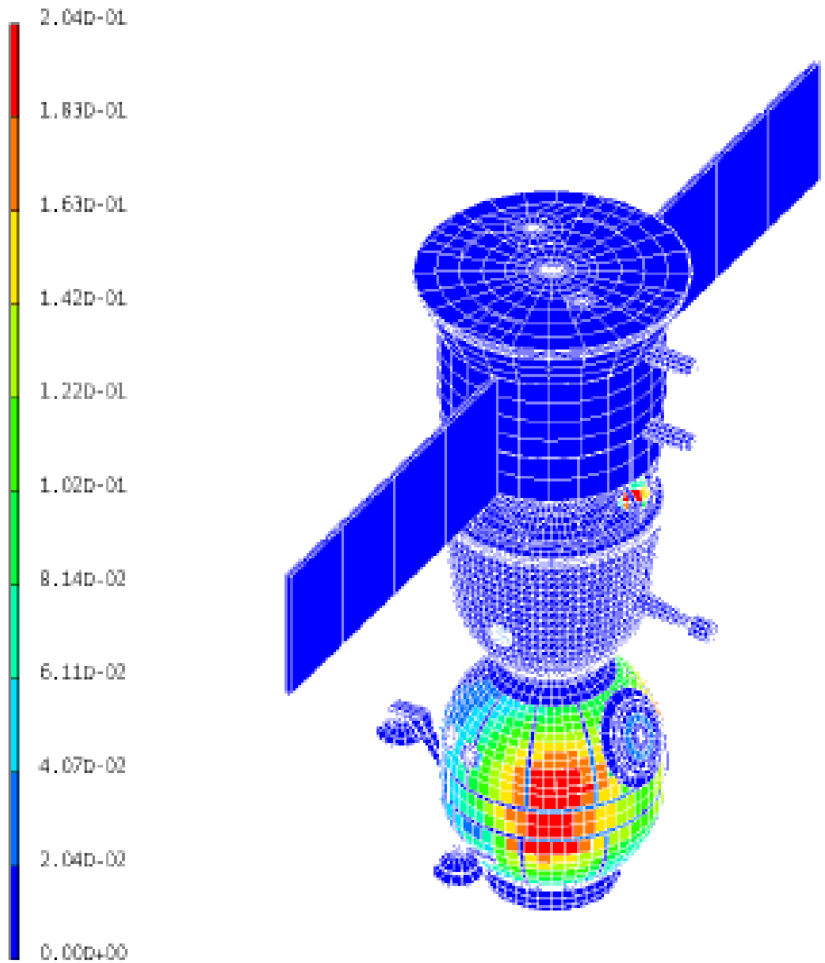
ISS Service Module FEM Property Identification (PID) Map (partial)

HVIT Team: PID Table

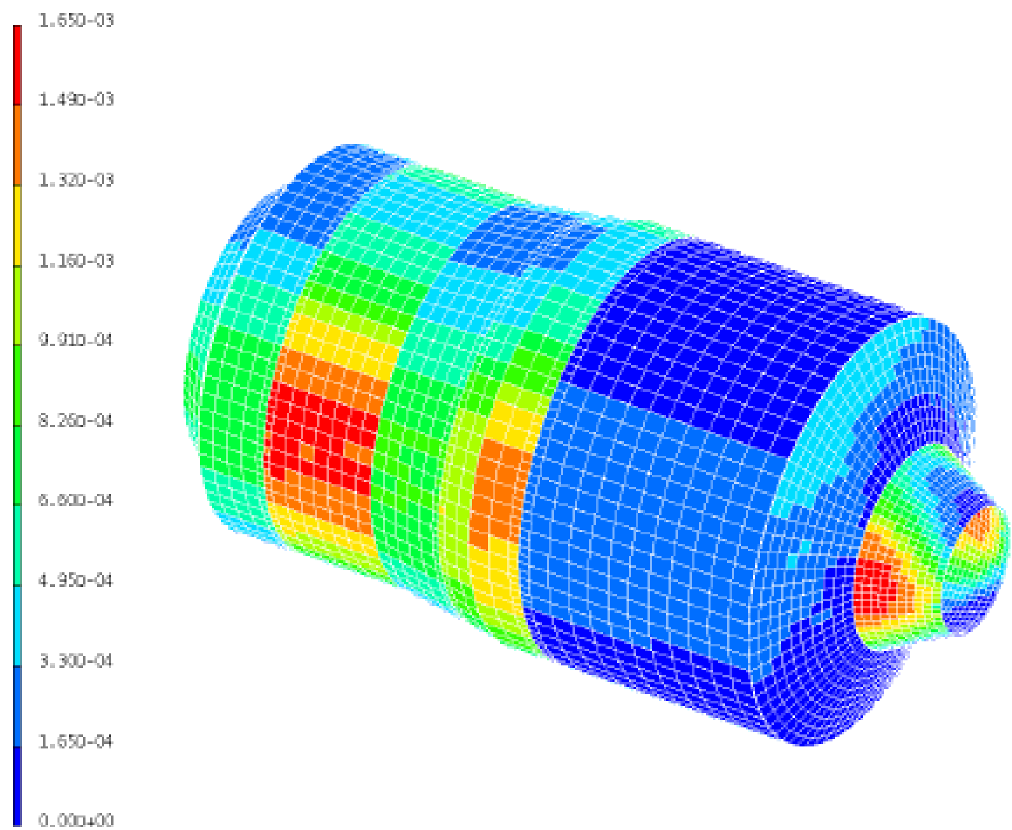
Region	Start ID	End ID	# of Elements	PID #	Area (m2)	Shield Type	Bumper (cm)	Bumper Mat'l	Standoff (cm)	Rear Wall (cm)	Rear Wall mat'l	MOD Type	Curve Adj	Dcrit (cm)
Service Module	**30,001**	**56,196**	**127,228**	-	**506.98**	-	-	-	-	-	-	-	-	-
transfer module "sphere" (1)	30,001	30,080	80	872	6.48	NNO	0.20	AMg6	2.0	0.60	AMg6	-	-	0.485
transfer module "cover" (2)	30,081	30,160	80	873	5.57	NNO	0.10	AMg6	10.0	0.50	AMg6	-	-	0.735
transfer module "cone" (3a)	30,161	30,368	208	874	1.44	NNO	0.10	AMg6	2.0	0.40	AMg6	-	-	0.370
working module "bottom" (4)	30,369	30,464	96	875	0.94	NNO	0.10	AMg6	2.0	0.35	AMg6	-	-	0.339
working module "fwd cyl" (5)	30,465	30,580	116	876	1.39	NNO	0.10	AMg6	2.0	0.16	AMg6	-	-	0.201
working module "radiator cyl" (6)	30,581	31,730	1,150	877	19.66	SM NASA	-	-	-	-	-	60	-	0.364
working module zenith plate aft (6)	31,731	31,754	24	859	0.52	NNO	0.15	AMg6	9.0	0.16	AMg6	-	-	0.332
working module zenith plate fore (6)	31,755	31,778	24	859	0.52	NNO	0.15	AMg6	9.0	0.16	AMg6	-	-	0.332
working module zenith box (6)	31,779	31,792	14	859	0.61	NNO	0.15	AMg6	9.0	0.16	AMg6	-	-	0.332
working module rectangular equipment plates	31,793	31,808	16	860	0.32	NNO	0.30	AMg6	2.0	0.16	AMg6	-	-	0.201
working module circular equipment plates (port)	31,809	31,816	8	861	0.20	NNO	0.30	AMg6	2.0	0.16	AMg6	-	-	0.201
working module "nadir cyl" (7)	31,817	32,465	649	878	5.97	NNO	0.10	AMg6	5.0	0.16	AMg6	-	-	0.273
working module "cone" panel 1 (8) - 4.5 mm	32,466	32,604	139	879	0.58	NNO	0.10	AMg6	2.0	0.45	AMg6	-	-	0.401
working module "cone" panel 1 (8) - 4.0 mm	32,605	32,616	12	880	0.06	NNO	0.10	AMg6	2.0	0.40	AMg6	-	-	0.370
working module "cone" panel 1 (8) - 2.3 mm	32,617	32,800	184	881	0.84	NNO	0.10	AMg6	2.0	0.23	AMg6	-	-	0.256
working module "cone" panel 2 (8) - 4.5 mm	32,801	32,969	169	879	0.72	NNO	0.10	AMg6	2.0	0.45	AMg6	-	-	0.401
working module "cone" panel 2 (8) - 4.0 mm	32,970	33,019	50	880	0.24	NNO	0.10	AMg6	2.0	0.40	AMg6	-	-	0.370
working module "cone" panel 2 (8) - 2.3 mm	33,020	33,139	120	881	0.52	NNO	0.10	AMg6	2.0	0.23	AMg6	-	-	0.256
working module "cone" panel 3 (8) - 4.5 mm	33,140	33,278	139	879	0.57	NNO	0.10	AMg6	2.0	0.45	AMg6	-	-	0.401
working module "cone" panel 3 (8) - 4.0 mm	33,279	33,329	51	880	0.24	NNO	0.10	AMg6	2.0	0.40	AMg6	-	-	0.370
working module "cone" panel 3 (8) - 2.3 mm	33,330	33,474	145	881	0.65	NNO	0.10	AMg6	2.0	0.23	AMg6	-	-	0.256
working module "cone" panel 4 (8) - 4.5 mm	33,475	33,612	138	879	0.59	NNO	0.10	AMg6	2.0	0.45	AMg6	-	-	0.401
working module "cone" panel 4 (8) - 4.0 mm	33,613	33,658	46	880	0.22	NNO	0.10	AMg6	2.0	0.40	AMg6	-	-	0.370
working module "cone" panel 4 (8) - 2.3 mm	33,659	33,804	146	881	0.66	NNO	0.10	AMg6	2.0	0.23	AMg6	-	-	0.256
working module "cone" panel 5 (8) - 4.5 mm	33,805	33,978	174	879	0.72	NNO	0.10	AMg6	2.0	0.45	AMg6	-	-	0.401
working module "cone" panel 5 (8) - 4.0 mm	33,979	34,003	25	880	0.12	NNO	0.10	AMg6	2.0	0.40	AMg6	-	-	0.370
working module "cone" panel 5 (8) - 2.3 mm	34,004	34,104	101	881	0.49	NNO	0.10	AMg6	2.0	0.23	AMg6	-	-	0.256
working module "cone" window area (8) - 4.5 mm	34,105	34,462	358	879	1.46	NNO	0.10	AMg6	2.0	0.45	AMg6	-	-	0.401
working module "cone" panel 6 (8) - 4.5 mm	34,463	34,587	125	879	0.53	NNO	0.10	AMg6	2.0	0.45	AMg6	-	-	0.401
working module "cone" panel 6 (8) - 4.0 mm	34,588	34,602	15	880	0.07	NNO	0.10	AMg6	2.0	0.40	AMg6	-	-	0.370
working module "cone" panel 6 (8) - 2.3 mm	34,603	34,721	119	881	0.55	NNO	0.10	AMg6	2.0	0.23	AMg6	-	-	0.256
working module "cone" panel 7 (8) - 4.5 mm	34,722	34,860	139	879	0.60	NNO	0.10	AMg6	2.0	0.45	AMg6	-	-	0.401
working module "cone" panel 7 (8) - 4.0 mm	34,861	34,897	37	880	0.18	NNO	0.10	AMg6	2.0	0.40	AMg6	-	-	0.370
working module "cone" panel 7 (8) - 2.3 mm	34,898	35,050	153	881	0.70	NNO	0.10	AMg6	2.0	0.23	AMg6	-	-	0.256
working module "cone" panel 8 (8) - 4.5 mm	35,051	35,188	138	879	0.57	NNO	0.10	AMg6	2.0	0.45	AMg6	-	-	0.401

ISS Service Module FEM Property Identification (PID) Table (partial)

HVIT Team: Graphical Risk Maps "color contour"

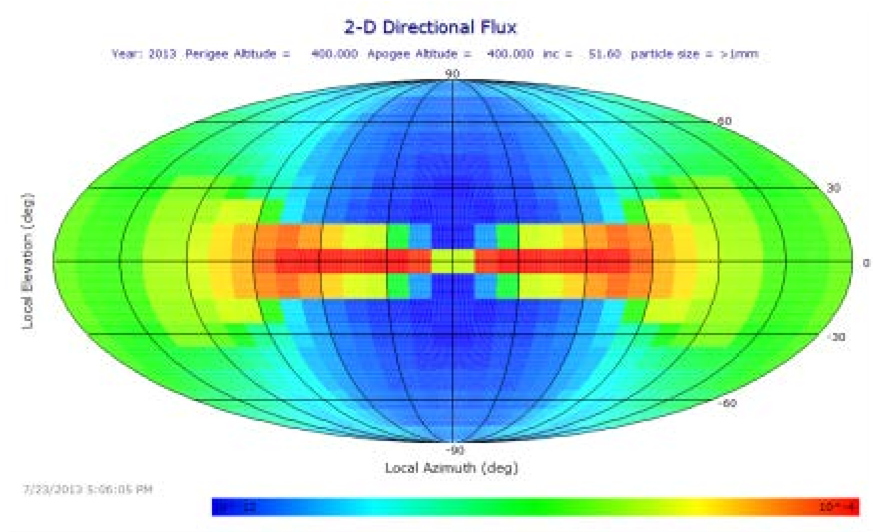


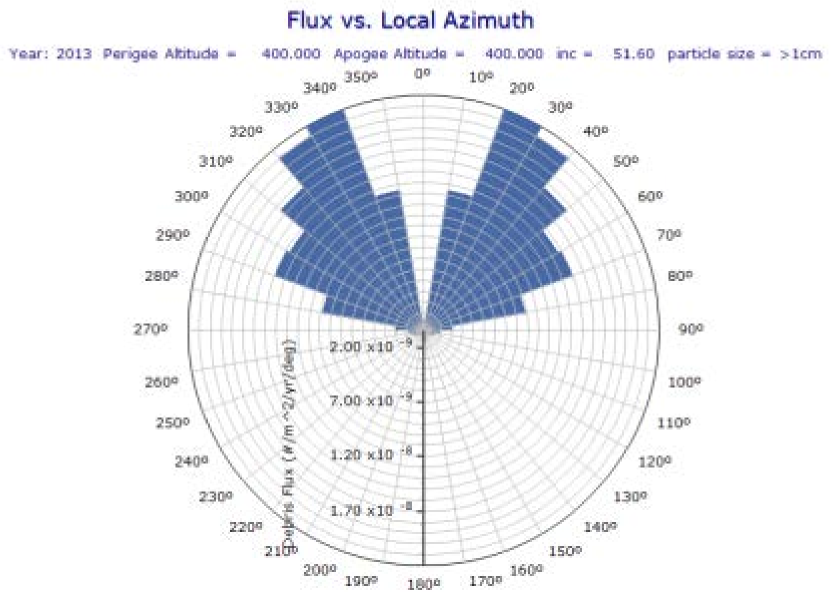
ISS Soyuz Penetration Risk Color Contour

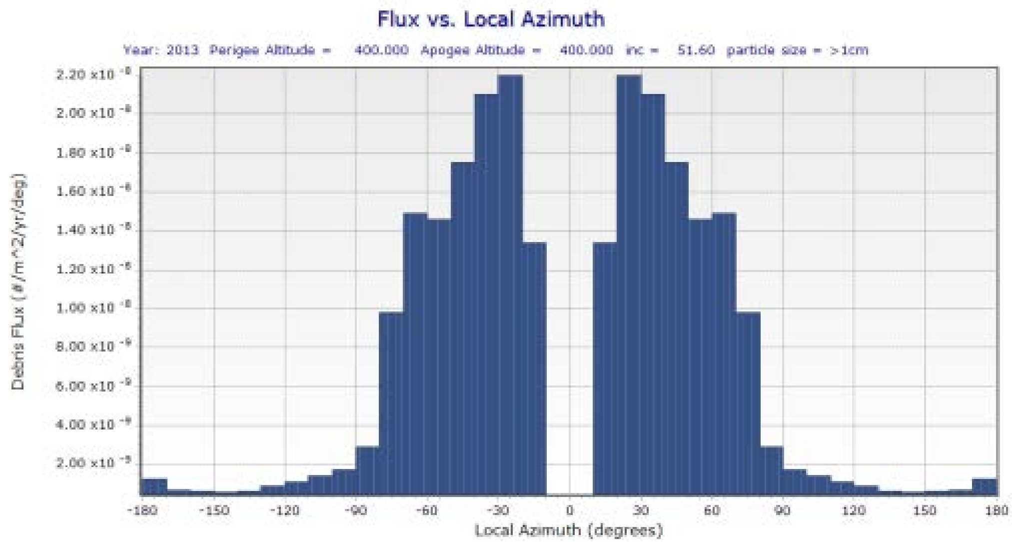


ISS ATV Penetration Risk Color Contour

ORDEM 3.0 Debris Model Graphics







Hypervelocity Impact Test Parameters for Orion Tiles, Phase 3

[redacted]

Test Number / HITF Number / Tile ID	Shot Sequence	Projectile Type	Projectile Diameter (cm)	Projectile Mass (g)	Actual Velocity (km/s)	Impact Angle (deg)	Damage Measurements (mm)
#1 HITF09189	1	Al 2017-T4	0.16	0.00597	7.13	0º	Paint damage diameter = 15 x 16, RCG surface damage = 13 x 12 Entry hole diameter = 9 x 8 (0.35” x 0.31”) Primary cavity depth = TBD Max. penetration depth = 24.1 Max cavity diameter = 20 (estimated)
#2 HITF09190	2	Al 2017-T4	0.318	0.04704	3.64	45º	Paint damage diameter = 24 x 20.5 RCG surface damage = 21 x 15 Entry hole diameter = 17 x 14 (0.67” x 0.55”) Primary cavity depth = 38.1 (tile perforated) Max. penetration depth = 38.1 (tile perforated) Max cavity diameter = 35 (estimated)
#3 HITF09191	3	440C SS	0.1	0.00405	4.19	45º	Paint damage diameter = 12 x 13 RCG surface damage = 8 x 9 Entry hole diameter = 6 x 5 (0.24” x 0.20”) Primary cavity depth = TBD Max. penetration depth = 20.5 (calculated) Max cavity diameter = 12 (estimated)

ISS MPLM and ATA MMOD Impact Damage

Inspected after STS-131 mission	Duration exposed to MMOD	Number of MMOD impacts	Largest MMOD impacts
Multi-Purpose Logistics Module (MPLM)	8 days attached to ISS, 7 days in payload bay	75 impact craters from 0.1mm to 1.5mm diameter	1.5mm diameter through-hole in outer 0.8mm thick Al bumper
Ammonia Tank Assembly (ATA)	7 years attached to ISS	49 impact craters from 0.1mm to 1.0mm diameter	1.0mm diameter crater (elliptical) in an aluminum label

MPLM perforation A3 corner panel (exterior)

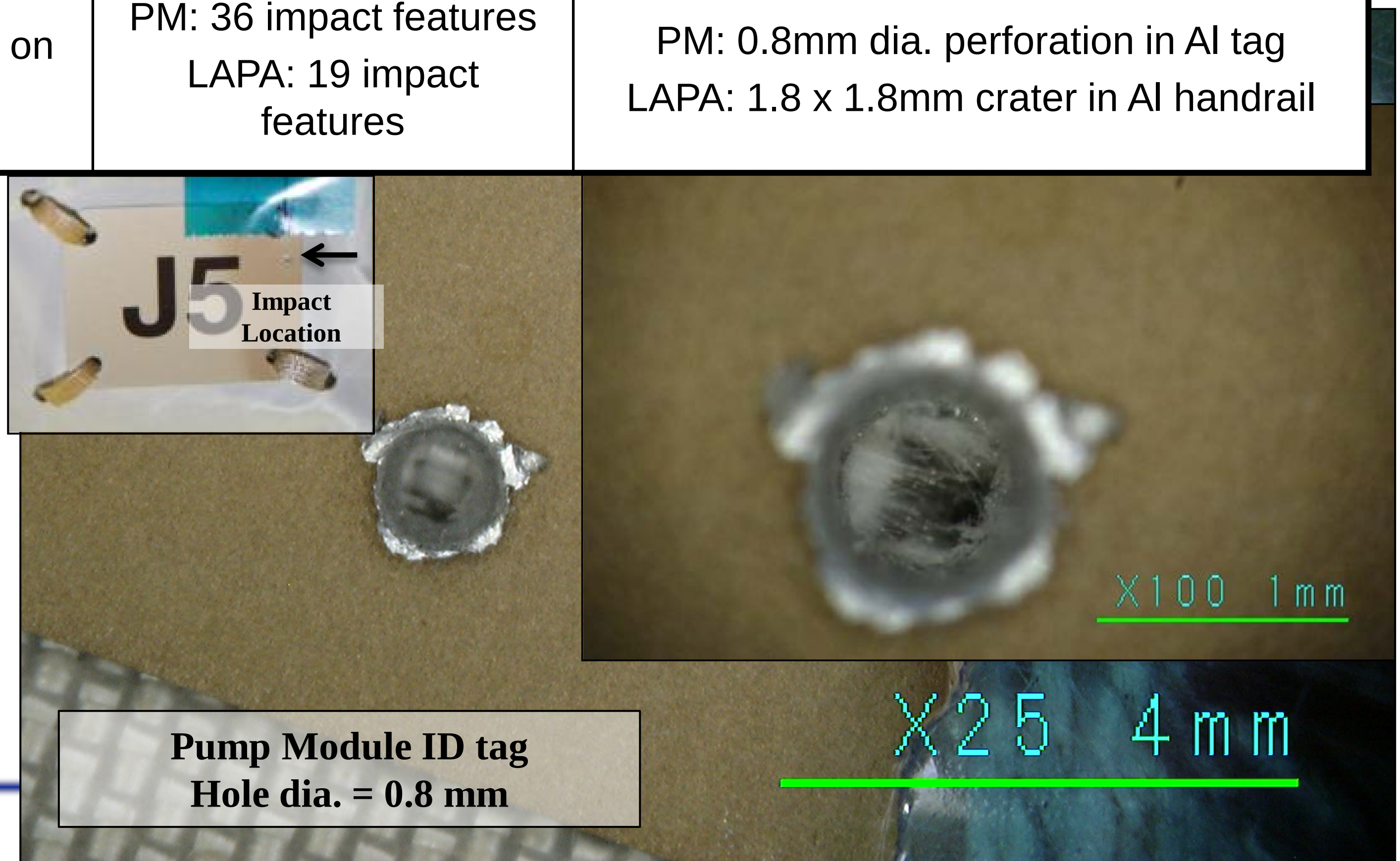
MPLM perforation (side view)

ATA impact

ISS MPLM and PMIA MMOD Impact Damage

Inspected after STS-135	MMOD Exposure	Number of MMOD Impacts	Largest MMOD Impacts
Multi-Purpose Logistics Module (MPLM)	7.0 days on ISS, 5.7 days in payload bay	64 craters between 0.1mm and 0.7mm diameter	0.7mm dia. crater in 0.8mm thick Al bumper
Pump Module Integrated Assembly (PMIA)	8.7 years on ISS	PM: 36 impact features LAPA: 19 impact features	PM: 0.8mm dia. perforation in Al tag LAPA: 1.8 x 1.8mm crater in Al handrail

MPLM grapple fixture coating spall dia. = 0.6 mm



Pump Module ID tag Hole dia. = 0.8 mm