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/](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](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

**Total Flux on Spacecraft**
- Average of All States
- Cross Sectional Flux: \(7.258269 \times 10^0 \text{ m}^2/\text{yr}\)

<table>
<thead>
<tr>
<th>Surface</th>
<th>Flux (#/m^2/yr)</th>
<th>Average Speed (km/s)</th>
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<tbody>
<tr>
<td>Ram</td>
<td>3.586e+000</td>
<td>22.8</td>
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<tr>
<td>Wake</td>
<td>7.037e-001</td>
<td>23.3</td>
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<tr>
<td>Port</td>
<td>2.211e+000</td>
<td>23.5</td>
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<tr>
<td>Starboard</td>
<td>1.408e+000</td>
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<td>Zenith</td>
<td>2.694e+000</td>
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<tr>
<td>Nadir</td>
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<tr>
<td>Earth</td>
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</tr>
<tr>
<td>Anti-Sun</td>
<td>2.181e+000</td>
<td>23.4</td>
</tr>
</tbody>
</table>

**Speed Distributions by Surface, one month average, ISS**

- **Flux by Direction (in local spacecraft coordinates)**
- **Degrees Elevation**
- **Degrees Azimuth from Ram(V)**

- **Flux (#/m^2/yr)**
  - Ram: \(1.00 \times 10^0\)
  - Wake: \(9.00 \times 10^{-1}\)
  - Port: \(8.00 \times 10^{-1}\)
  - Starboard: \(7.00 \times 10^{-1}\)
  - Zenith: \(6.00 \times 10^{-1}\)
  - Nadir: \(5.00 \times 10^{-1}\)
  - Earth: \(4.00 \times 10^{-1}\)
  - Sun: \(3.00 \times 10^{-1}\)
  - Anti-Sun: \(2.00 \times 10^{-1}\)

**Speed (km/s)**
- 0 20 40 60 80

**Graphical Elements**
- Color bar indicating flux range from -8 to 0
- Graph of speed distributions for different surfaces.
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

Note, Spatial Density is proportional to impact risk
1970

Cataloged objects >10 cm diameter
Cataloged objects >10 cm diameter
Cataloged objects >10 cm diameter
Cataloged objects >10 cm diameter
Cataloged objects >10 cm diameter
Debris movies

- Debris fly-through
- Iridium-Cosmos collision
Growth of the Cataloged Populations

Monthly Number of Objects in Earth Orbit by Object Type

- **Total Objects**
- **Fragmentation Debris**
- **Spacecraft**
- **Mission-related Debris**
- **Rocket Bodies**

**FY-1C ASAT Test**

**Iridium-Cosmos**

~1100 are operational
Mass in Space

Monthly Mass of Objects in Earth Orbit by Object Type

- Total Objects
- Spacecraft
- Rocket Bodies
- Fragmentation Debris
- Mission-related Debris

No sign of slowing down!
“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](image1.png)

![Damage from a 1.3cm diameter sphere at 7km/s](image2.png)
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

- 2.00” (solid) aluminum sphere (debris simulant)
- Impact Velocity (7 km/s)
- 0.5” diameter
- (spacecraft exterior)
- 2.00” aluminum
- (spacecraft interior)

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.

**Stuffed Whipple Shield**

4.5 pounds per square foot

- 0.5” diameter aluminum sphere (debris simulant)
- Impact Velocity (7 km/s)
- (spacecraft exterior)
- 0.08” aluminum
- (vacuum)
- 0.188” aluminum
- (vacuum)
- 6 layers Nextel® AF-62
- (vacuum)
- 6 layers Kevlar® Style 710 (or KM2-705)
- (spacecraft interior)

84% weight reduction

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 typically 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** \((V \geq 7 \text{ km/s})\): density, thickness to projectile diameter ratio, thermal properties

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

**Purpose**: Stop debris from MMOD & bumper(s)
**Key material & physical parameters** \((V \geq 7 \text{ km/s})\): 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:**
- **Few solid fragments** (for Al on Al impacts)
- **Many (increasing with velocity) solid fragments & liquid droplets**
- **Fine droplets, few solid fragments, some vapor**

**Critical Al Diameter (\(d_{crit}\))**

- **WHIPPLE**
  - 0.12cm Al bumper
  - 0.32cm Al6061T6 rear wall
  - 10cm standoff

**Ballistic Limit Improvement due to Shield Standoff**

- \(\Delta d_{crit}\)

**Expected “failure” above curves**

- **Whipple dcrit @ 0 deg**
- **monolithic dcrit @ 0 deg**
• 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 \( \geq 0.3\text{mm} \))
- 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
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
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%
Docking Compartment (DC) MMOD Shield & Performance Capability

Typical DC Shield
(Whipple shield with MLI thermal blankets)

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

MLI
0.1 cm Aluminum AMG6 bumper

MLI
0.4 cm Aluminum AMG6 pressure shell

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

Shield Failure expected above curves
Open symbols = no-failure data
Closed symbols = shield failure data

- 0.1 cm Aluminum AMG6 bumper
- MLI
- 1.7 cm
- 0.4 cm Aluminum AMG6 pressure shell
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

4 channel DIDS
1.7” x 1.7” x 0.8”

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-2003-212065, Integration of MMOD Impact Protection Strategies into Conceptual Spacecraft Design
  - NASA TM-2009-214789, MMOD Shield Ballistic Limit Analysis Program
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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
National Aeronautics and Space Administration

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

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

Each color represents a different shield type

Progress @ MRM2
Progress @ SM
Soyuz @ MRM1
Soyuz @ NM
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
  - 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
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

0.24mm diameter Al @ 7km/s, 0°
Surface Coating Damage

Carbon Substrate Penetration
K.E. = 0.5 J

0.6mm diameter Al @ 7km/s, 0°
Rear-Side Spall
K.E. = 4 to 7 J

1.0mm diameter Al @ 7km/s, 0°
Complete Penetration
K.E. = 30 to 50 J

4.8mm diameter Al @ 7km/s, 0°

1” Hole
K.E. = 3700 J

\[ P = 0.61 \ d \ (V \cos \theta)^{2/3} \left( \frac{\rho_p}{\rho_t} \right)^{0.5} \]

RCC Penetration depth \( P \) = 0.61 \( d \) (\( V \cos \theta \))\(^{2/3} \) (\( \rho_p/\rho_t \))\(^{0.5} \)
Thickness to Prevent Complete Penetration \( t_p = 2.3 \times P \)
Thickness to Prevent Rear-Side Spall \( t_s = 4.5 \times P \)
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

<table>
<thead>
<tr>
<th></th>
<th>Number of MMOD impacts</th>
<th>Largest MMOD impacts</th>
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</thead>
<tbody>
<tr>
<td>Windows</td>
<td>15 craters</td>
<td>W1, 4.2 x 3.6 mm</td>
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<tr>
<td></td>
<td></td>
<td>6 R&amp;R’s (W1,2,6,7,8 &amp; 11)</td>
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<tr>
<td>Radiators</td>
<td>25 MMOD damages reported</td>
<td>1 face sheet perforation</td>
</tr>
<tr>
<td>Wing leading edge &amp; nose cap</td>
<td>9 MMOD indications</td>
<td>Panel 18R, 3.2 x 2.8 mm, max depth = 0.46 mm, no exposed substrate</td>
</tr>
<tr>
<td></td>
<td>(reviewed by LESS PRT)</td>
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Post Flight MMOD Inspection: ISS

MPLM

Pump Module (PM)

PM Adapter Plate

Crater in PM handrail
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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 10 years 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 10 years 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 $1 - 0.99999^{(surface\ area_{m^2} \times duration\ years)}$
  - 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 cm and larger)
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**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

HITF-07447
2.0mm Al
6.95 km/s @ 0°
Paint spall to
Proj. diameter
ratio = 3.5

HITF-07428
0.4mm Al
7.01 km/s @ 0°
Delamination to
Proj. diameter
ratio = 12
Issues: MMOD Damage to ISS Radiators

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

- MMOD impact damages observed to radiator panel during EVA-20 (Nov. 2012)
MMOD Damage to ISS Radiators (US)

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

- J. Hyde, E. Christiansen, D. Lear, J. Herrin, Recent Shuttle Post-Flight MMOD Inspection Highlights, IAC-10.A6.3.1, presented at the 61st International Astronautical Congress, Prague, CZ, 2010
- NASA JSC-28524, Hypervelocity impact testing of betacloth covers on Orbiter radiator external lines, 2001
- J.P. Loftus, E. Christiansen, W.C. Schneider, and M. Hasselbeck, Shuttle Modifications for Station Support, IAF-97-IAF.I.3.08, 48th International Astronautical Congress, October 6-10, 1997
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)
• 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° impact angle
CT Scans of Tile 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.

<table>
<thead>
<tr>
<th>Failure Criteria</th>
<th>Critical Orbital Debris Ø (7km/s &amp; 0°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00” Ø hole</td>
<td>4.89mm</td>
</tr>
<tr>
<td>0.50” Ø hole</td>
<td>2.75mm</td>
</tr>
<tr>
<td>0.25” Ø hole</td>
<td>1.68mm</td>
</tr>
<tr>
<td>0.12” – 0.99” Ø hole</td>
<td>1.10–4.84mm</td>
</tr>
<tr>
<td>0.25” Ø exposed substrate (Test 6)</td>
<td>0.81mm</td>
</tr>
<tr>
<td>0.19” Ø exposed substrate (Test 11)</td>
<td>0.69mm</td>
</tr>
<tr>
<td>0.14” Ø exposed substrate (Test 5)</td>
<td>0.58mm</td>
</tr>
<tr>
<td>0.09” Ø exposed substrate (Test 4)</td>
<td>0.47mm</td>
</tr>
</tbody>
</table>
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.

Pre-Arc-Jet Test A308-9
Model 2238
Exposed Substrate: 0.25” x 0.26”
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, 0°
Test Results
(Unpressurized vs. Pressurized)

- Projectile Conditions: 0.8 mm diameter Al 2017T4, 6.9 km/s, 0°
• ISS Cupola have multi-layer Shutters that provide MMOD protection of the windows, when the shutters are closed.
ISS Solar Array Damage

MMOD damage caused disconnected bypass diode, leading to cell overheat damage

MMOD impact breaks bypass diode
Solar Array Damage

MMOD impact breaks bypass diode causing overheat
ISS Solar Array Mast

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

- Thermal blankets are typically lightweight and easily penetrated by MMOD impacts
- Toughened thermal blankets incorporate additional MMOD layers to improve projectile breakup and stopping capability

- 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
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?
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.
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%

EVA Installation
- 23 “conformal” panels on cone region
- 5 panels on small diameter cylinder
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 0°, 30°, 45°, 60°), 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)
National Aeronautics and Space Administration

WSTF Remote Hypervelocity Test Laboratory (RHTL)
.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)
Running Bumper interactively (single run)

Running Bumper automatically with scripts (multiple runs)
HVIT Team: I-DEAS Modeling Software

I-DEAS Graphical User Interface
ISS MMOD Risk Assessment FEM (representing current configuration)

ISS MMOD Risk Assessment FEM (representing configuration after MLM launch)
Mini-Research Module (MRM-1) MMOD Shield Type Map

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

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

MODTYPE30
Basalt Fabric 6T-13H (NONE)
Industrial Fabric 8353/11 (NONE)
4-mm AMr6 rear wall (scaling factor=1.0)

| Region                               | Start ID | End ID | # of Elements | PID | Area (m²) | Shield Type | Bumper (cm) | Bumper Mat'1 | Standoff (cm) | Rear Wall (cm) | Rear Wall mat'1 | MOD Type | Curve Adj | Dirt (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 - 0.48
- transfer module "cover" (2) 30,081 30,160 80 873 5.57 NNO 0.10 AMg6 10.0 0.50 AMg6 - 0.73
- transfer module "cone" (3a) 30,161 30,368 208 874 1.44 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.37
- working module "bottom" (4) 30,369 30,464 96 875 0.94 NNO 0.10 AMg6 2.0 0.35 AMg6 - 0.39
- working module "fwd cyl" (5) 30,465 30,580 116 876 1.39 NNO 0.10 AMg6 2.0 0.16 AMg6 - 0.20
- working module "radiator cyl" (6) 30,581 31,730 1,150 877 19.66 SM NASA - - - - 60 0.36
- working module "zenith plate aft" (6) 31,731 31,754 24 859 0.52 NNO 0.15 AMg6 9.0 0.16 AMg6 - 0.33
- working module "zenith plate fore" (6) 31,755 31,778 24 859 0.52 NNO 0.15 AMg6 9.0 0.16 AMg6 - 0.33
- working module "zenith box" (6) 31,779 31,792 14 859 0.61 NNO 0.15 AMg6 9.0 0.16 AMg6 - 0.33
- working module rectangular equipment plates 31,793 31,808 16 860 0.32 NNO 0.15 AMg6 9.0 0.16 AMg6 - 0.33
- working module circular equipment plates (port) 31,809 31,816 8 861 0.20 NNO 0.15 AMg6 9.0 0.16 AMg6 - 0.33
- working module "nadir cyl" (7) 31,817 32,465 649 878 5.97 NNO 0.20 AMg6 5.0 0.16 AMg6 - 0.37
- working module "cone" panel 1 (6) -4.5 mm 32,466 32,604 139 879 0.58 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.40
- working module "cone" panel 1 (6) -4.0 mm 32,605 32,616 12 880 0.06 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.39
- working module "cone" panel 2 (6) -2.3 mm 32,617 32,800 184 881 0.84 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26
- working module "cone" panel 2 (6) -4.5 mm 32,801 32,969 169 879 0.72 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 2 (6) -4.0 mm 32,970 33,019 50 880 0.24 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.30
- working module "cone" panel 2 (6) -2.3 mm 33,020 33,139 120 881 0.52 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 3 (6) -4.5 mm 33,140 33,278 139 879 0.57 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26
- working module "cone" panel 3 (6) -4.0 mm 33,279 33,329 51 880 0.24 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 3 (6) -2.3 mm 33,330 33,474 145 881 0.65 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26
- working module "cone" panel 4 (6) -4.5 mm 33,475 33,612 138 879 0.59 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26
- working module "cone" panel 4 (6) -4.0 mm 33,613 33,658 46 880 0.22 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 4 (6) -2.3 mm 33,659 33,804 146 881 0.66 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26
- working module "cone" panel 5 (6) -4.5 mm 33,805 33,978 174 879 0.72 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 5 (6) -4.0 mm 33,979 34,003 25 880 0.12 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 5 (6) -2.3 mm 34,004 34,104 101 881 0.49 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26
- working module "cone" window area (6) -4.5 mm 34,105 34,463 358 879 1.46 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26
- working module "cone" panel 6 (6) -4.5 mm 34,463 34,587 125 879 0.53 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 6 (6) -4.0 mm 34,588 34,602 15 880 0.07 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26
- working module "cone" panel 6 (6) -2.3 mm 34,603 34,721 119 881 0.55 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 7 (6) -4.5 mm 34,722 34,860 139 879 0.60 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26
- working module "cone" panel 7 (6) -4.0 mm 34,861 34,897 37 880 0.18 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 7 (6) -2.3 mm 34,898 35,050 153 881 0.70 NNO 0.10 AMg6 2.0 0.40 AMg6 - 0.26
- working module "cone" panel 8 (6) -4.5 mm 35,051 35,188 138 879 0.57 NNO 0.10 AMg6 2.0 0.45 AMg6 - 0.26

ISS Service Module FEM Property Identification (PID) Table (partial)
National Aeronautics and Space Administration

HVIT Team: Graphical Risk Maps
“color contour”

ISS Soyuz Penetration Risk Color Contour
ISS ATV Penetration Risk Color Contour
## Hypervelocity Impact Test Parameters for Orion Tiles, Phase 3

<table>
<thead>
<tr>
<th>Test Number / HITF Number / Tile ID</th>
<th>Shot Sequence</th>
<th>Projectile Type</th>
<th>Projectile Diameter (cm)</th>
<th>Projectile Mass (g)</th>
<th>Actual Velocity (km/s)</th>
<th>Impact Angle (deg)</th>
<th>Damage Measurements (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 HITF09189</td>
<td>1</td>
<td>Al 2017-T4</td>
<td>0.16</td>
<td>0.00597</td>
<td>7.13</td>
<td>0º</td>
<td>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)</td>
</tr>
<tr>
<td>#2 HITF09190</td>
<td>2</td>
<td>Al 2017-T4</td>
<td>0.318</td>
<td>0.04704</td>
<td>3.64</td>
<td>45º</td>
<td>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)</td>
</tr>
<tr>
<td>#3 HITF09191</td>
<td>3</td>
<td>440C SS</td>
<td>0.1</td>
<td>0.00405</td>
<td>4.19</td>
<td>45º</td>
<td>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)</td>
</tr>
<tr>
<td>Inspected after STS-131 mission</td>
<td>Duration exposed to MMOD</td>
<td>Number of MMOD impacts</td>
<td>Largest MMOD impacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>--------------------------</td>
<td>------------------------</td>
<td>---------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-Purpose Logistics Module (MPLM)</td>
<td>8 days attached to ISS, 7 days in payload bay</td>
<td>75 impact craters from 0.1mm to 1.5mm diameter</td>
<td>1.5mm diameter through-hole in outer 0.8mm thick Al bumper</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonia Tank Assembly (ATA)</td>
<td>7 years attached to ISS</td>
<td>49 impact craters from 0.1mm to 1.0mm diameter</td>
<td>1.0mm diameter crater (elliptical) in an aluminum label</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MPLM perforation A3 corner panel (exterior)

MPLM perforation (side view)

ATA impact
# ISS MPLM and PMIA MMOD Impact Damage

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

- **MPLM grapple fixture coating spall dia. = 0.6 mm**
- **Pump Module ID tag Hole dia. = 0.8 mm**