Hypervelocity Impact Testing and MMOD Risk Reduction

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Hypervelocity Impact Testing

• **Purpose:**
  – Provide data to develop, update, and/or verify ballistic limit equations used in the MMOD risk assessment
  – Provide data used to compare two or more shielding options to reduce MMOD risk
  – Determine failure modes and failure criteria for hardware
    • **Failure modes:** how hardware fails (pressure vessels, pressurized lines, electronic hardware, power cables)
    • **Failure criteria:** quantify damage level that results in hardware failure (for example: depth of penetration into pressure vessel that results in leak or burst)
ISS Lithium-Ion Battery Tests

Test: HITF-12143, 1cm diameter Al @ 6.86 km/s

Figure 1.2-1. HITF12143 visible video frames at 1s-2s intervals after impact.
ISS Lithium-Ion Battery Tests

- **Energetic response to hypervelocity impact**

  Post-test photos from HITF-12143, 1cm diameter Al @ 6.86 km/s

*Figure 1.2-2. After test imagery of HITF12143 a) shield with 9.5cm diameter through-hole, and b) cell close-up with impacted cell on right showing molten material from cell interior that was ejected and deposited on exterior of cell.*
ISS Lithium-Ion Battery Tests

- Hundreds of centimeter size metallic fragments ejected from the battery cell

Post-test photos of test chamber floor after test HITF-12143, 1cm diameter Al @ 6.86 km/s

Each of the blocks (white/black checker board) in this ruler are 1cm long
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
Impact into fused silica glass

- Test HITF-14079: 3.6mm diameter Nylon spherical projectile at 7.16 km/s, 0 deg impact angle; target: 12.7mm thick fused-silica glass
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, 0°

MLI
0.1cm Aluminum AMG6 bumper

MLI
0.4cm Aluminum AMG6 pressure shell

DC-1 Ballistic Limit Equations and HVI Test Data

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

Velocity (km/s)
MMOD Protection

- Iteration of spacecraft MMOD protection design and operations is key to meeting MMOD requirements with minimum mass
  - Hypervelocity impact tests needed to verify ballistic limit equations used in the risk assessment
Methods to Reduce MMOD Risk

• Iterate analysis & test
  – focus on risk drivers
  – Include MLI (in BLEs), include shadowing hardware (in FEM), include thicker/more robust structures (in FEM)
  – Perform impact tests on risk drivers, evaluate risk reduction alternatives

• Operations
  – if possible, assess attitudes to reduce MMOD risk while meeting mission objectives
  – Monitor impact damage (sensors), and/or inspect to locate critical MMOD damage, followed by repair

• Design
  – Increase standoff (30x desired average projectile diameter want to stop to meet requirements)
  – Toughened thermal blankets
  – Improve rear wall: add or substitute high-strength materials
  – Adequate bumper thickness (mass per unit area): all bumpers should have 20% of critical projectile mass per unit area
Toughened thermal blankets

• Impact tests demonstrated methods to toughen thermal blankets against MMOD impacts:
  – Beta cloth and fiberglass cloth for disrupter layer
  – Open cell polyimide foam for spacer layer
  – Spectra 1000-952 for stopper layer

• References:
Protection concept

- Obtain significant improvements in MMOD protection by adding a full-MMOD shield within thermal blanket; i.e., disrupter (bumper), spacer (standoff) and stopper (rear wall)

<table>
<thead>
<tr>
<th>Element</th>
<th>Material Candidates Evaluated</th>
<th>Mass / Area (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disrupter Layer</td>
<td>Beta cloth</td>
<td>5mil beta cloth: 0.03 g/cm²</td>
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<tr>
<td></td>
<td>Fiberglass cloth</td>
<td>FG 7781: 0.029 g/cm²</td>
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<tr>
<td></td>
<td>Nextel ceramic cloth</td>
<td>Nextel AF10: 0.0292 g/cm²</td>
</tr>
<tr>
<td>Spacing Layer</td>
<td>Open Cell Foam (polyimide foam)</td>
<td>Polymide AC 550 foam 1.0” thick: 0.018</td>
</tr>
<tr>
<td></td>
<td>Polymer Batting</td>
<td>AC 530 foam, 1” thick: 0.014 g/cm²</td>
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<tr>
<td></td>
<td></td>
<td>Polyester 1.0” thick foam</td>
</tr>
<tr>
<td>Stopper Layer</td>
<td>Spectra (Polyethylene)</td>
<td>Spectra 1000 style 955 – 0.0112 g/cm²</td>
</tr>
<tr>
<td></td>
<td>Kevlar (Aramid)</td>
<td>Spectra 1000 style 952 – 0.0237 g/cm²</td>
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<tr>
<td></td>
<td>Beta Cloth</td>
<td>Kevlar KM2 style 705 – 0.0244 g/cm²</td>
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<td></td>
<td></td>
<td>Kevlar 159 style 779 – 0.0132 g/cm²</td>
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<tr>
<td></td>
<td></td>
<td>5mil Beta Cloth – 0.03 g/cm²</td>
</tr>
</tbody>
</table>
Test results

- 36 hypervelocity impact tests performed on 21 different thermal blanket configurations
  - Test velocities: 6.89 km/s – 7.16 km/s, and 9.63 km/s
  - Impact angle: 0 deg (normal to target)
  - Projectiles: 0.4mm – 6.0mm diameter Al 2017-T4 spheres
- Example result on 0.212 g/cm² blanket with fiberglass cloth disrupter, 1” thick foam, Spectra-952 stopper
  - HTIF-11270: No failure from 1.4mm diameter Al projectile @ 7.16 km/s
Test results: Scale-Up

- **2x scale-up**: 0.359 g/cm² blanket with fiberglass cloth disrupter, 2” thick foam, Spectra-952 stopper
  - HTIF-11360: No failure from 2.6mm diameter Al projectile @ 7.10 km/s

- **6x scale-up (0.805 g/cm²) blanket** stops a 6.0mm diameter Al projectile at 6.91 km/s

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**Materials Key**
- Beta cloth
- Fiberglass cloth
- Scrim
- Aluminized Mylar
- Open-cell foam
- Spectra-952
- Back cover

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Front
• Best disrupter materials: beta-cloth and fiberglass fabric
• Light-weight open cell foam used as spacer effective at increasing performance
• Best stopper materials: Spectra 1000-952 and Kevlar KM2-705
• Equations developed to predict performance of several versions of the toughened blanket
Impact sensor

- Integrate thin-film piezoelectric sensor into thermal blanket to detect and locate MMOD impact damage
  - Sensor panels are low mass (0.13 kg/m²), highly flexible, divided into 48-96 pixels, internal connections made by printed circuitry

Materials Key
- Beta cloth
- Disrupter
- Stopper
- Sensor film

Piezoelectric impact sensor film (18" x 16", with 48 pixels)

Several strike detector panels linked into system at lab

The linked strike detector panels display “hit” information on a spacecraft schematic (hundreds of pixels resolve impact location & damage extent)
Thermal testing

- Thermal-vacuum tests were conducted on several versions of the toughened thermal blanket to determine effective emittance of each blanket
  - Only slight increase in effective emittance measured (relative to baseline) and considered acceptable
  - Data confirmed thermal math models
  - Mechanical impact tests performed on piezoelectric film indicated no significant degradation of signal output down to -175F
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
Summarizing MMOD shielding configuration and materials considerations

• 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

  – 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