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

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
- 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

<table>
<thead>
<tr>
<th>Velocity (km/s)</th>
<th>Critical Al Proj. Diameter (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>0.3</td>
</tr>
<tr>
<td>15</td>
<td>0.1</td>
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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

1. If not meeting MMOD requirements, improve PNP by increasing shielding in areas that drive MMOD risk
2. If exceeding MMOD requirements, decrease shielding mass by reducing shielding in areas that do not drive MMOD risk
3. If meeting MMOD requirements with little (<10%) margin: reduce shielding mass by optimization

MMOD assessment results to Integrated PSA/PRA Mission LOC/LOM
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, Fiberglass cloth, Nextel ceramic cloth</td>
<td>5mil beta cloth: 0.03 g/cm²</td>
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<tr>
<td></td>
<td></td>
<td>FG 7781: 0.029 g/cm²</td>
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<tr>
<td></td>
<td></td>
<td>Nextel AF10: 0.0292 g/cm²</td>
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<tr>
<td>Spacing Layer</td>
<td>Open Cell Foam (polyimide foam), Polymer Batting</td>
<td>Polyimide AC 550 foam 1.0” thick: 0.018</td>
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<tr>
<td></td>
<td></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: 0.018</td>
</tr>
<tr>
<td>Stopper Layer</td>
<td>Spectra (Polyethylene), Kevlar (Aramid), Beta Cloth</td>
<td>Spectra 1000 style 955 – 0.0112 g/cm²</td>
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<tr>
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<td></td>
<td>Spectra 1000 style 952 – 0.0237 g/cm²</td>
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<td></td>
<td></td>
<td>Kevlar KM2 style 705 – 0.0244 g/cm²</td>
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<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>
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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
Test Results: Design Equations

- 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

![Graph showing ballistic limits for toughened thermal blanket, config. 3](image)
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
- Blue: Beta cloth
- Green: Disrupter
- Orange: Stopper
- Red: 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

View of MMOD toughened thermal blankets in thermal vacuum test chamber

Mechanical impact tester (“whacker”) built and operated to -175F to verify capability of impact detection film at reduced temperatures
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/metal 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