Hypervelocity Impact Testing and MMOD Risk Reduction

NASA Hypervelocity Impact Technology (HVIT) Group

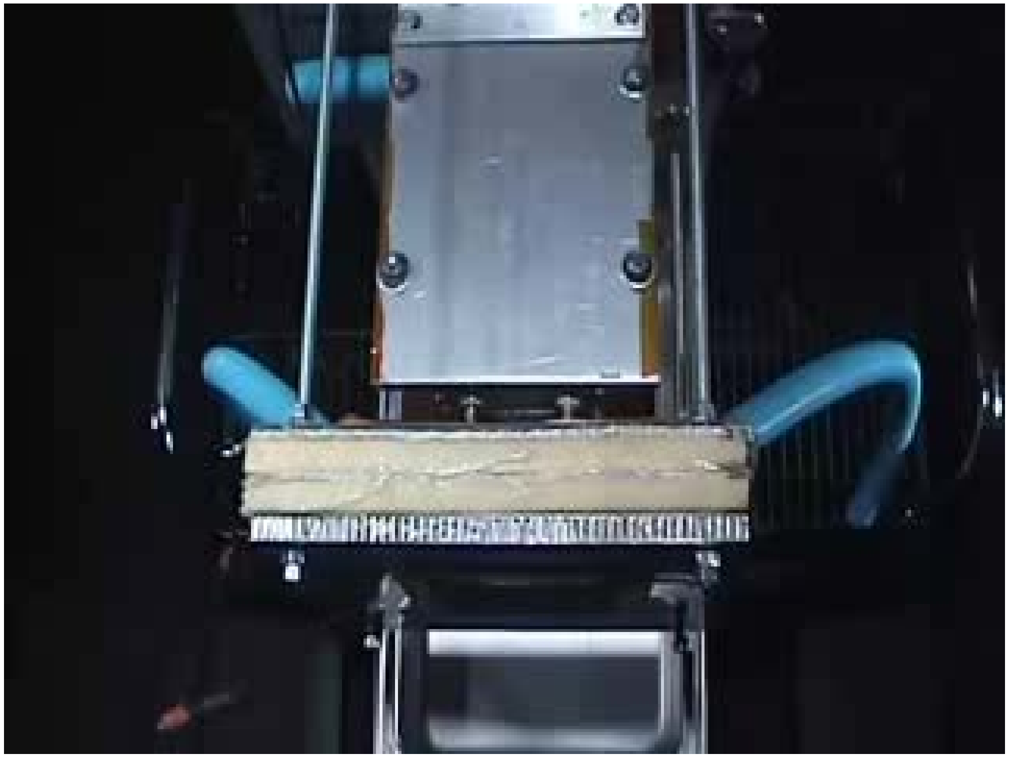
Eric Christiansen/JSC-XI4
Dana Lear/JSC-XI4
Jim Hyde/JSC-XI4 (JETS)

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



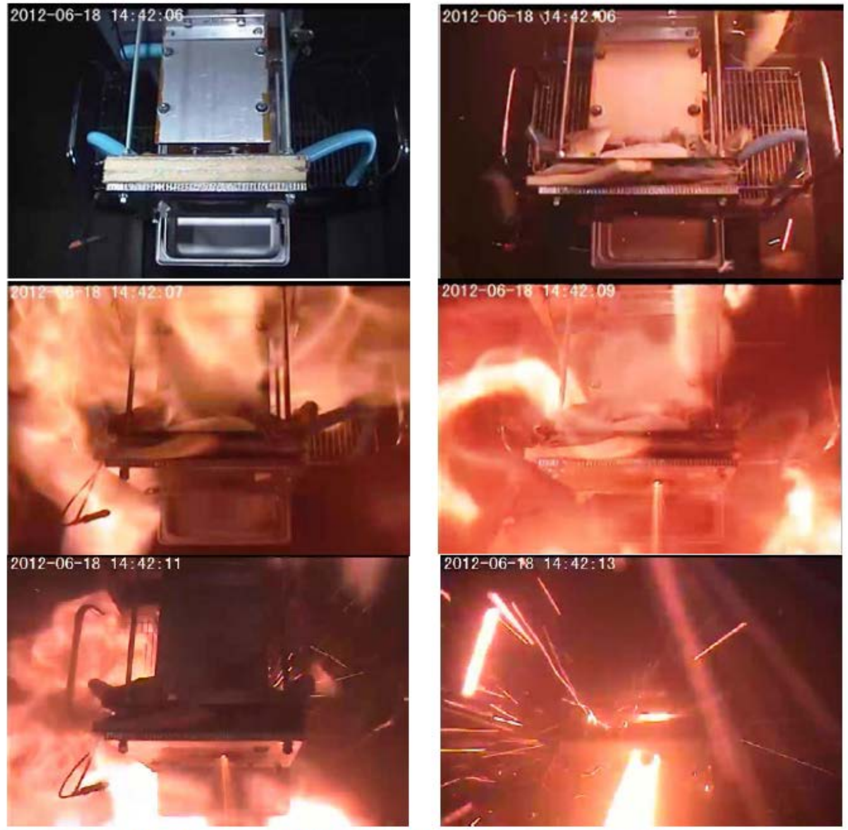


Figure 1.2-1. HITF12143 visible video frames at 1s-2s intervals after impact.

ISS Lithium-Ion Battery Tests

- **Energetic response to hypervelocity impact**

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

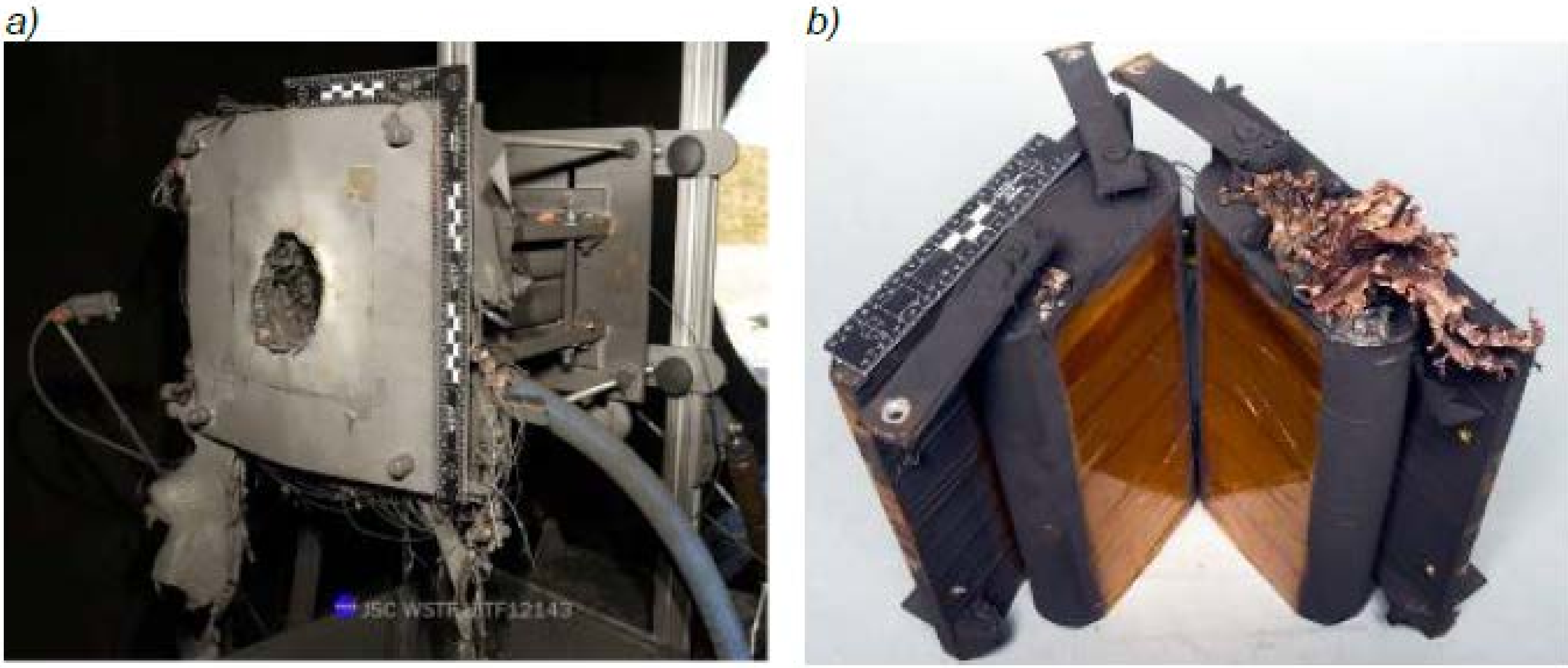


Figure 1.2-2. After test imagery of HITF12143 a) shield with 9.5cm diameter through-hole, and b) cell close-up with impacted cell on right showing molten material from cell interior that was ejected and deposited on exterior of cell.

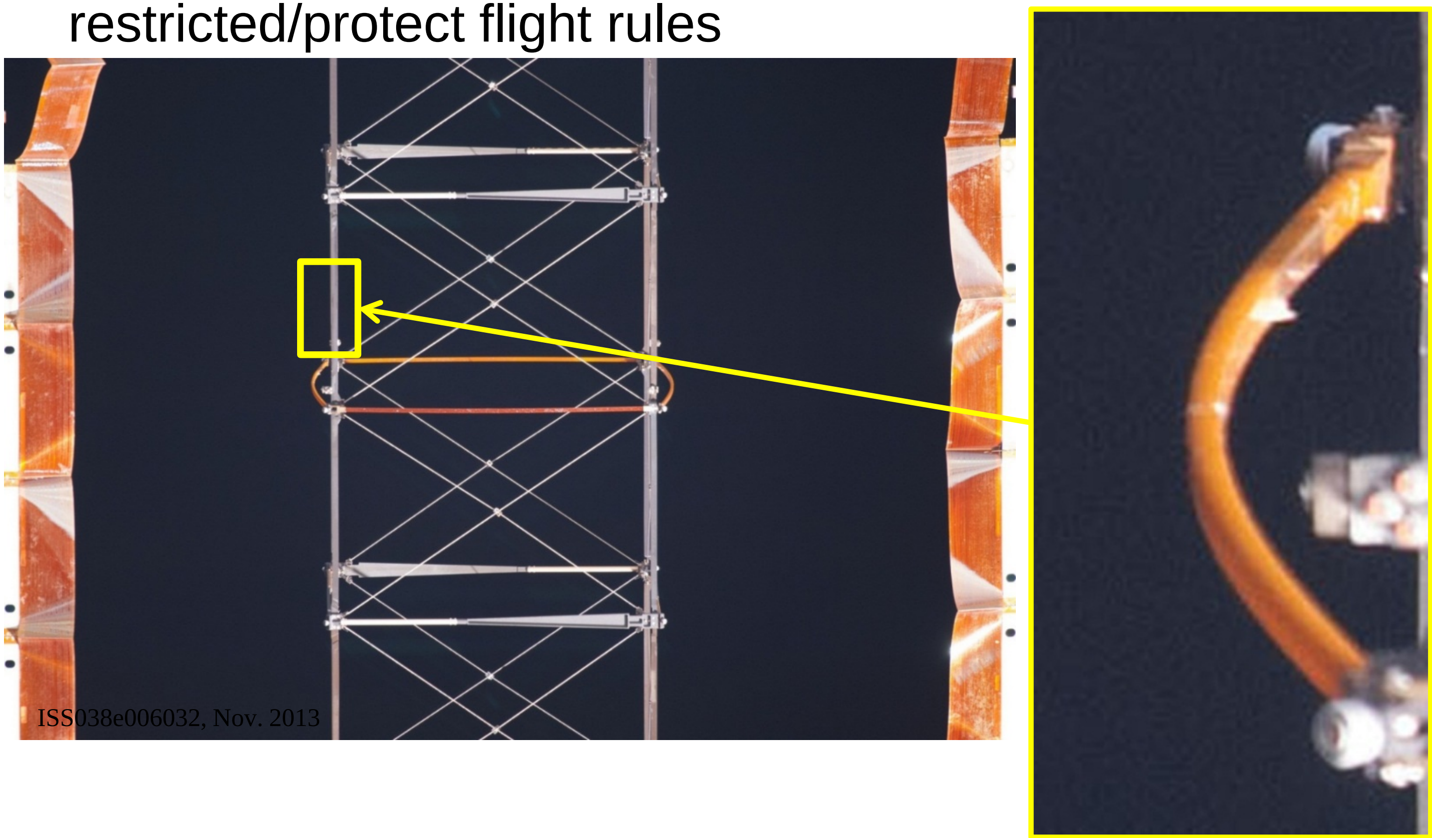
ISS Lithium-Ion Battery Tests

- **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

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



Test #1, HITF14030

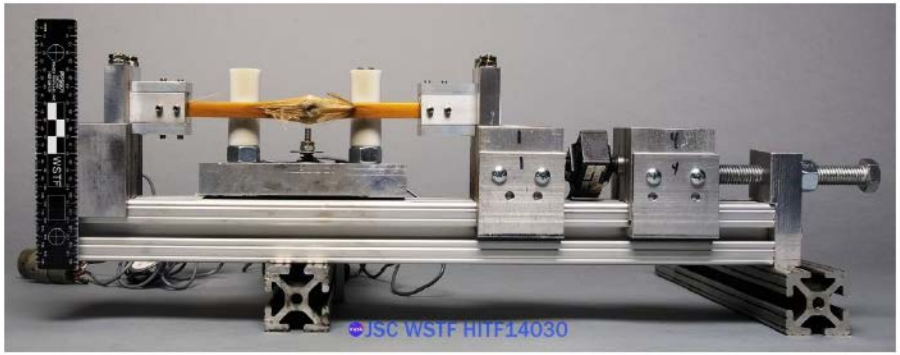


Figure 31: Test Article Front View of ISS SAW Flex Batten Test #1

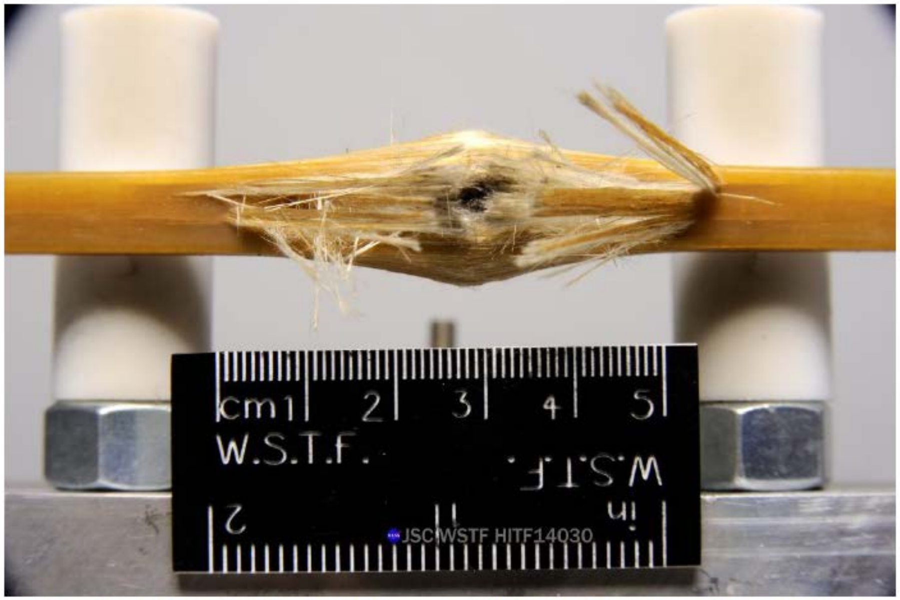
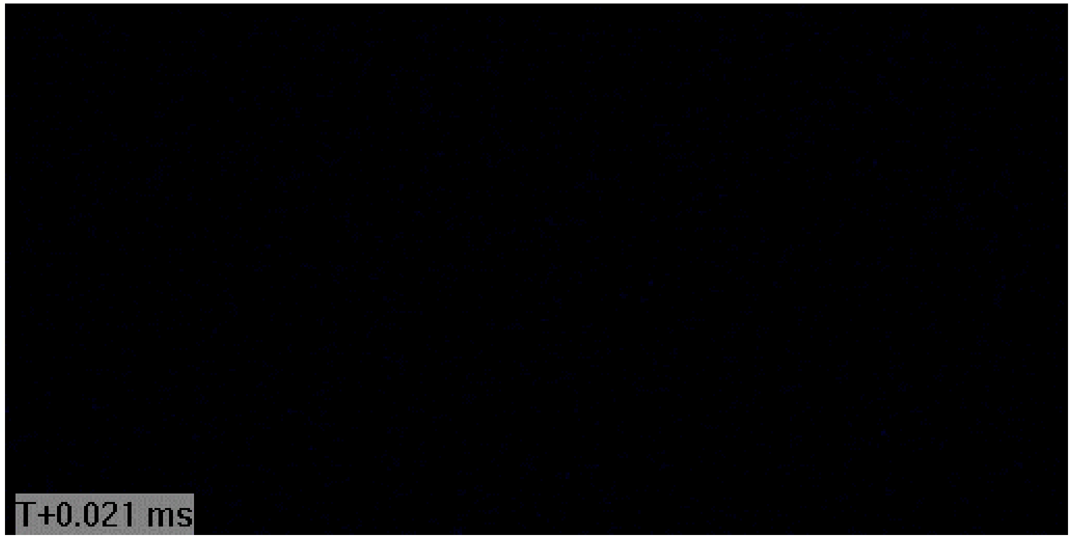
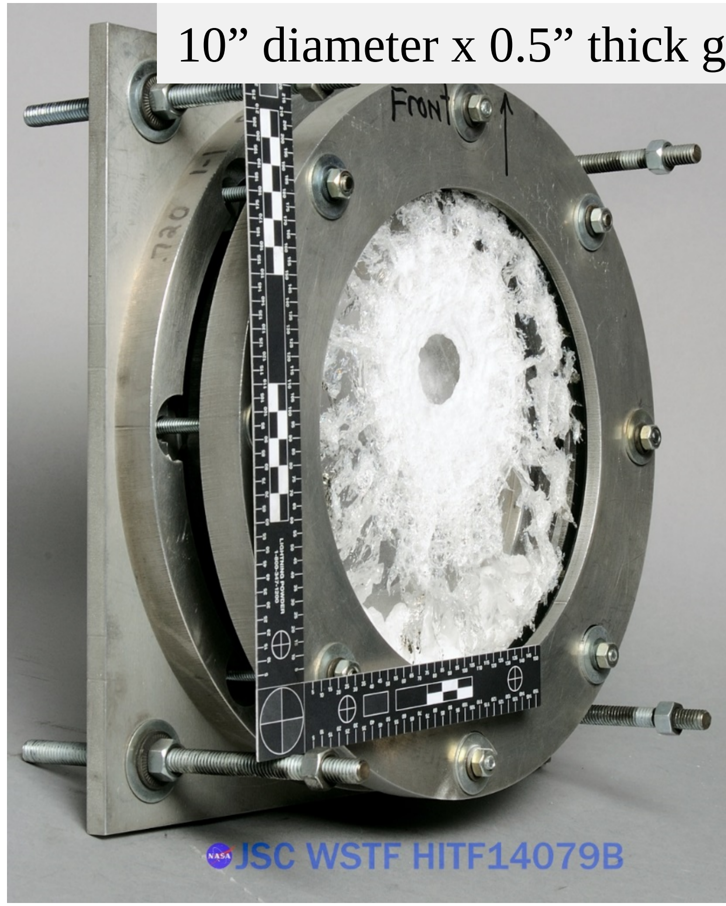


Figure 32: Front Close-up View of ISS SAW Mast Degradation Flex Batten Test #1



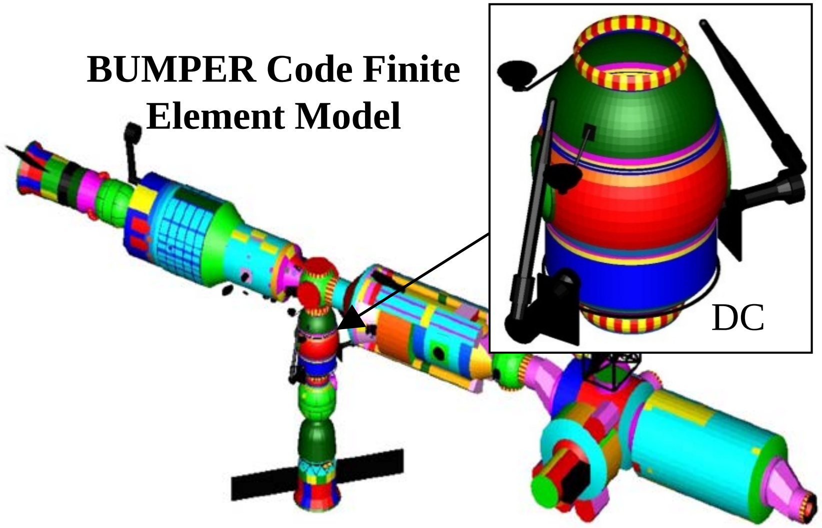
Impact into fused silica glass

- **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**

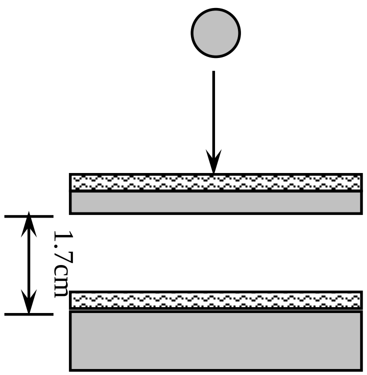


Docking Compartment (DC) MMOD Shield & Performance Capability

BUMPER Code Finite Element Model



Typical DC Shield (Whipple shield with MLI thermal blankets)

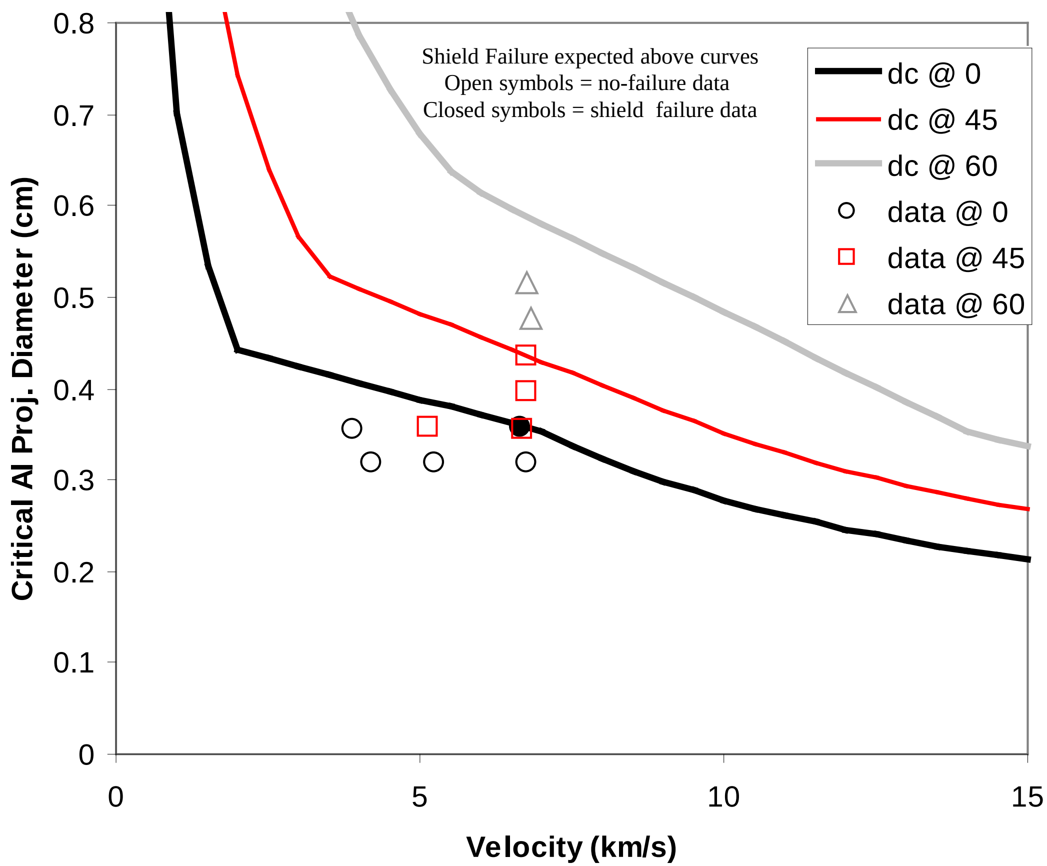


Ballistic Limit of shield (typical): 0.35cm Al projectile @ 7km/s, 0º

MLI
0.1cm Aluminum AMG6 bumper

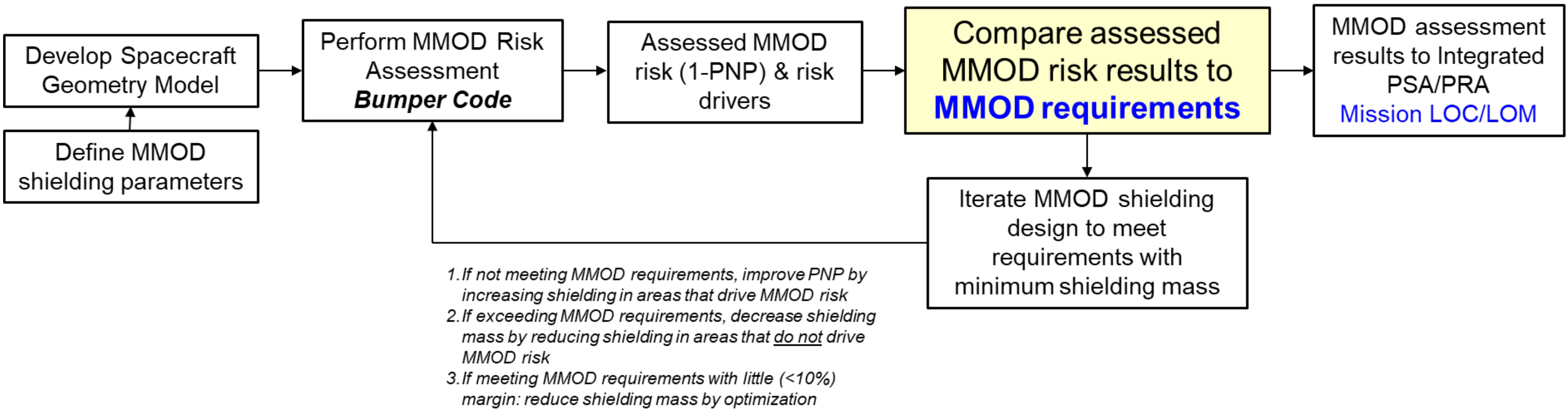
MLI
0.4cm Aluminum AMG6 pressure shell

DC-1 Ballistic Limit Equations and HVI Test Data



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

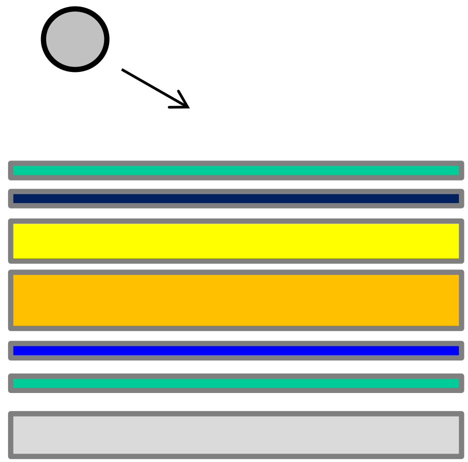
- Iterate analysis & test
  - focus on risk drivers
  - Include MLI (in BLEs), include shadowing hardware (in FEM), include thicker/more robust structures (in FEM)
  - Perform impact tests on risk drivers, evaluate risk reduction alternatives
- Operations
  - if possible, assess attitudes to reduce MMOD 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:**
  - E.L. Christiansen and D.M. Lear: “Toughened thermal blanket for micrometeoroid and orbital debris protection”, 2015 Hypervelocity Impact Symposium.

Protection concept

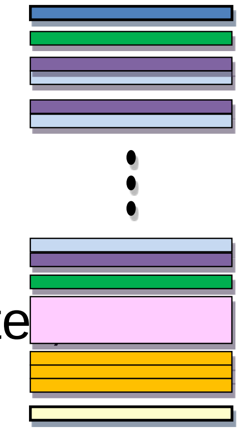
- Obtain significant improvements in MMOD protection by adding a full-MMOD shield within thermal blanket; i.e., disrupter (bumper), spacer (standoff) and stopper (rear wall)

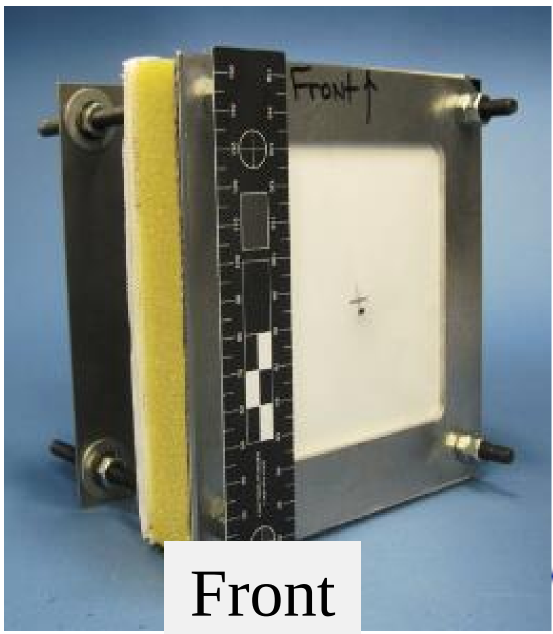


Element	Material Candidates Evaluated	Mass / Area (g/cm²)
Disrupter Layer	Beta cloth Fiberglass cloth Nextel ceramic cloth	5mil beta cloth: 0.03 g/cm^2 FG 7781: 0.029 g/cm^2 Nextel AF10: 0.0292 g/cm^2
Spacing Layer	Open Cell Foam (polyimide foam) Polymer Batting	Polyimide AC 550 foam 1.0” thick: 0.018 AC 530 foam, 1” thick: 0.014 g/cm^2 Polyester 1.0” thick foam
Stopper Layer	Spectra (Polyethylene) Kevlar (Aramid) Beta Cloth	Spectra 1000 style 955 – 0.0112 g/cm^2 Spectra 1000 style 952 – 0.0237 g/cm^2 Kevlar KM2 style 705 – 0.0244 g/cm^2 Kevlar 159 style 779 – 0.0132 g/cm^2 5mil Beta Cloth – 0.03 g/cm^2

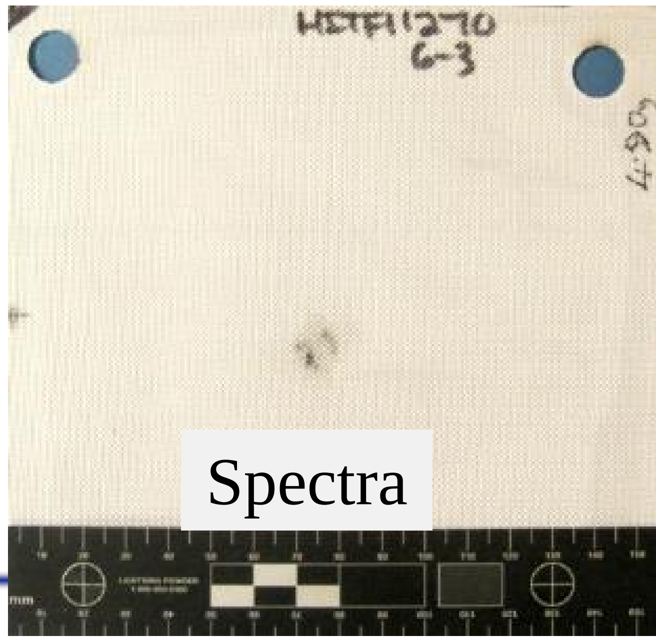
Test results

- 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/cm^2 blanket with fiberglass cloth disrupte thick foam, Spectra-952 stopper
  - HTIF-11270: No failure from 1.4mm diameter Al projectile @ 7.16 km/s





Front

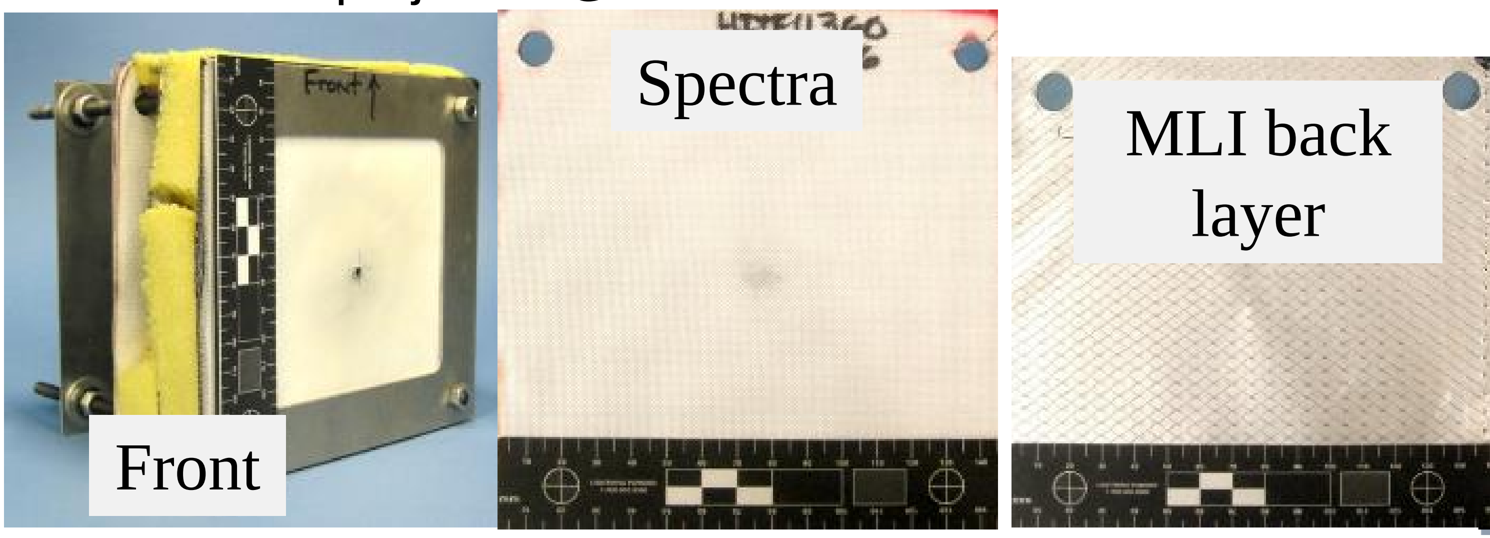


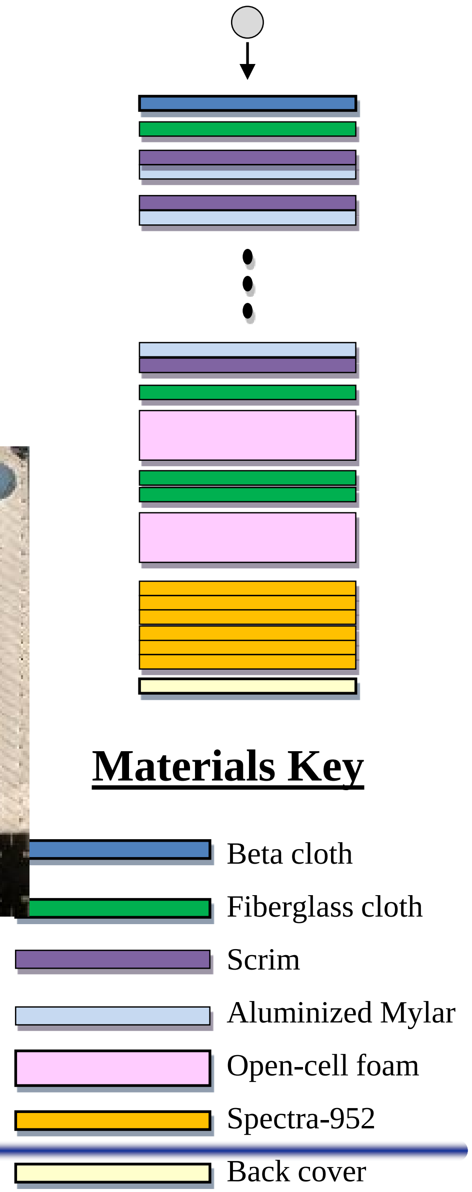
Spectra

MLI back layer

Test results: Scale-Up

- **2x scale-up: 0.359 g/cm^2 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

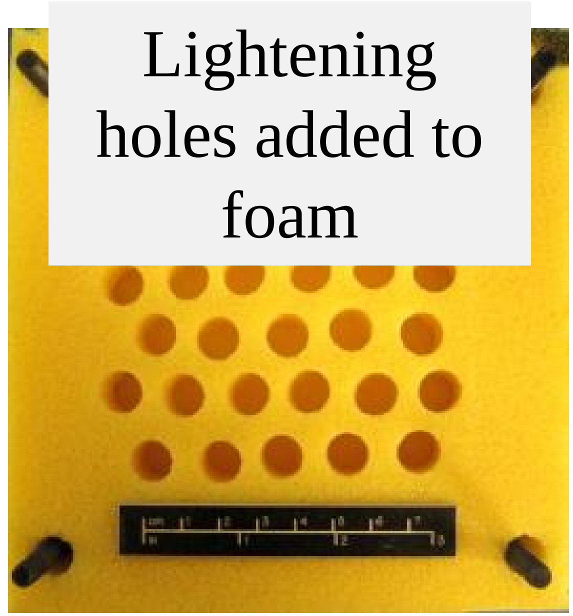


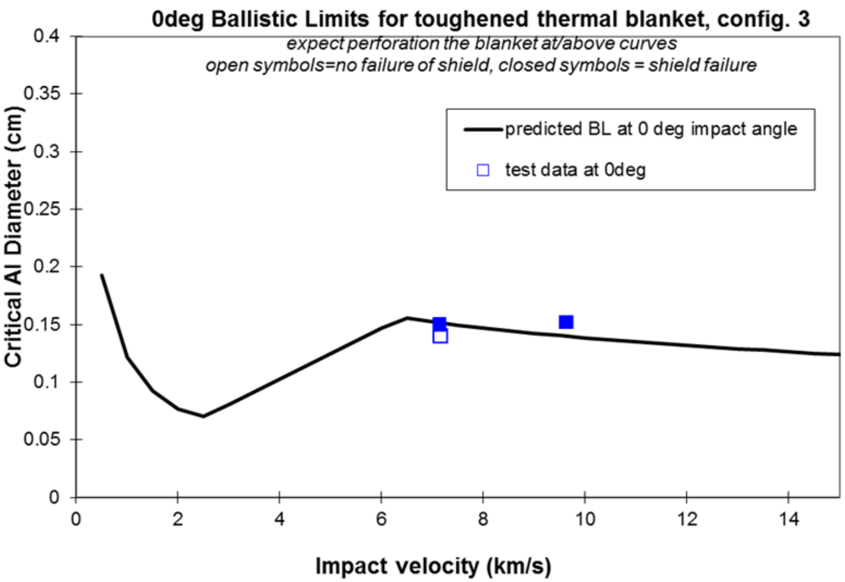


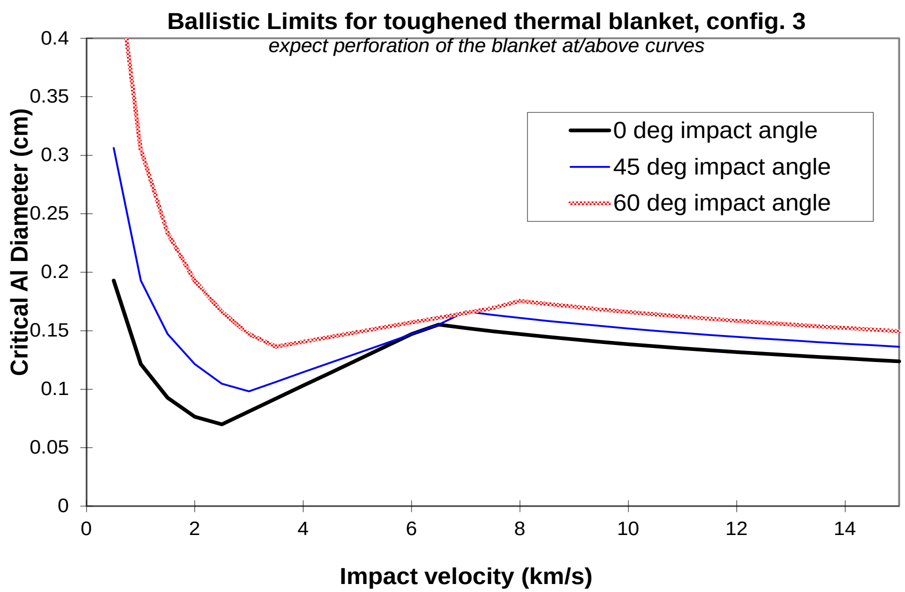
- **6x scale-up (0.805 g/cm^2) blanket stops a 6.0mm diameter Al projectile at 6.91 km/s**

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

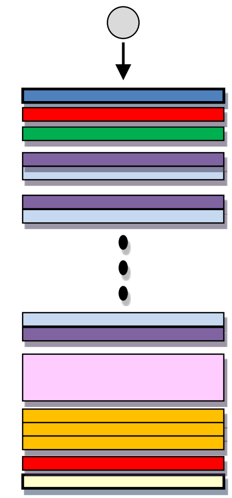






Impact sensor

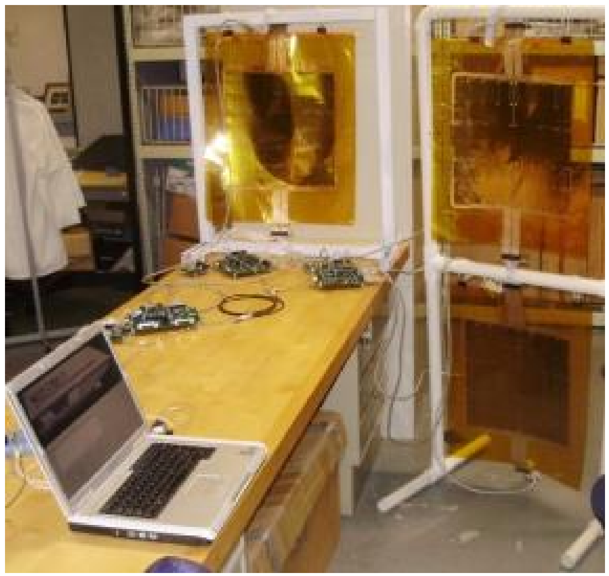
- **Integrate thin-film piezoelectric sensor into thermal blanket to detect and locate MMOD impact damage**
  - Sensor panels are low mass (0.13 kg/m^2), highly flexible, divided into 48-96 pixels, internal connections made by printed circuitry



Materials Key

- Beta cloth
- Disrupter
- Stopper
- Sensor film

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

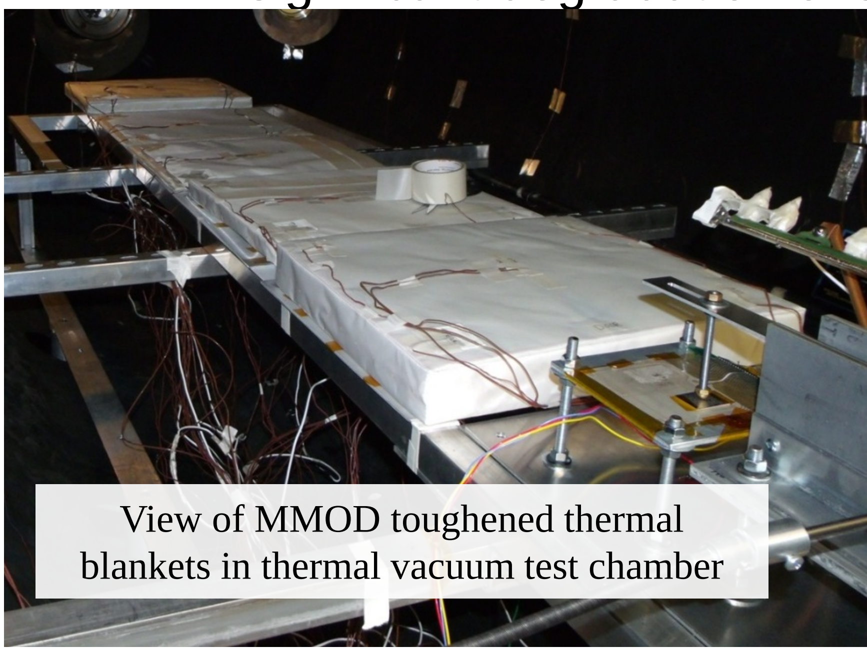


Several strike detector panels linked into system at lab

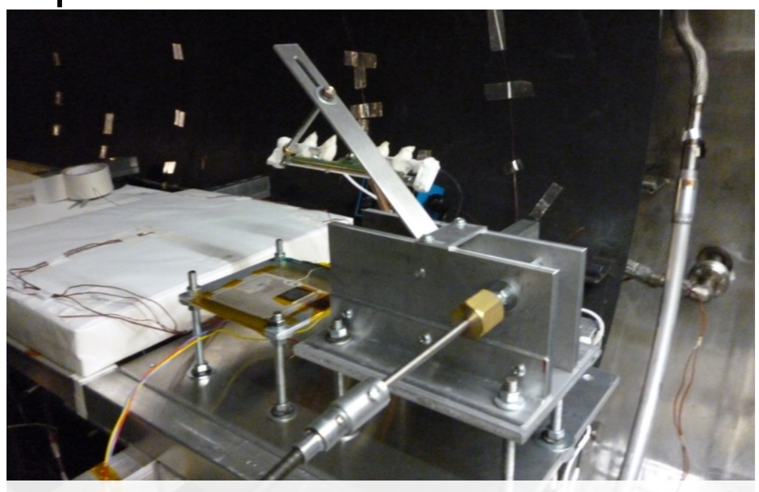
The linked strike detector panels display “hit” information on a spacecraft schematic (hundreds of pixels resolve impact location & damage extent)

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



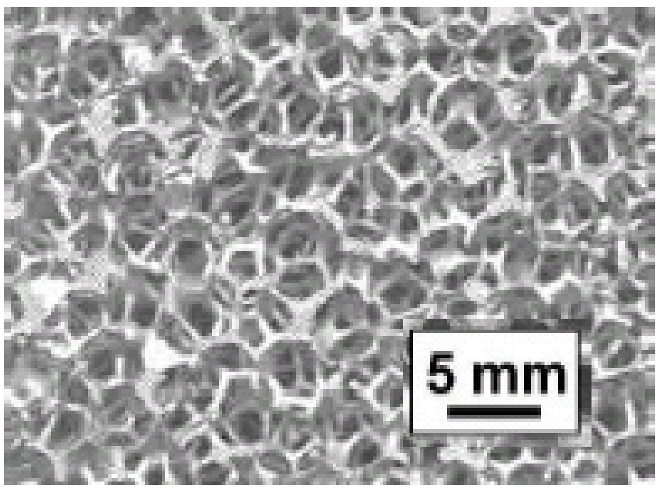
View of MMOD toughened thermal blankets in thermal vacuum test chamber

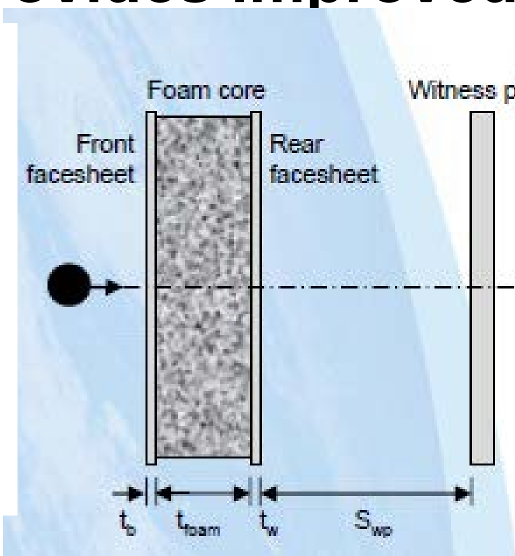


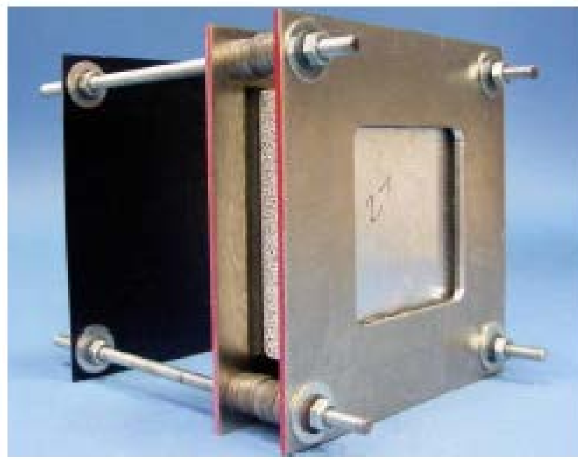
Mechanical impact tester ("whacker") built and operated to -175F to verify capability of impact detection film at reduced temperatures

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



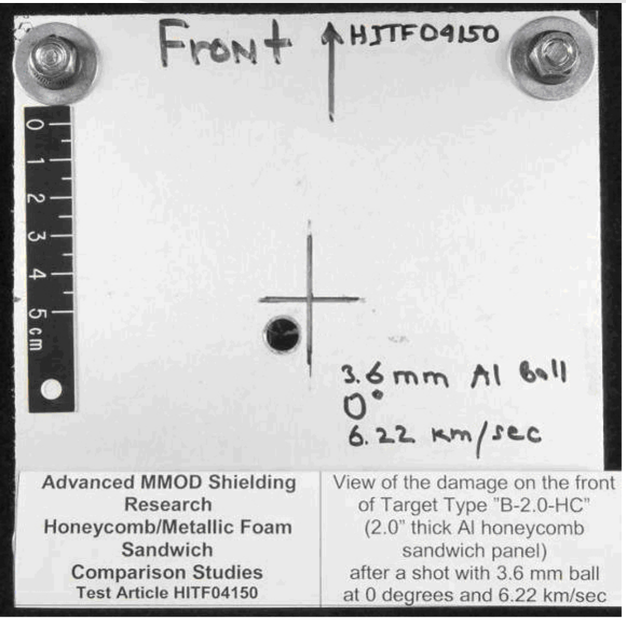


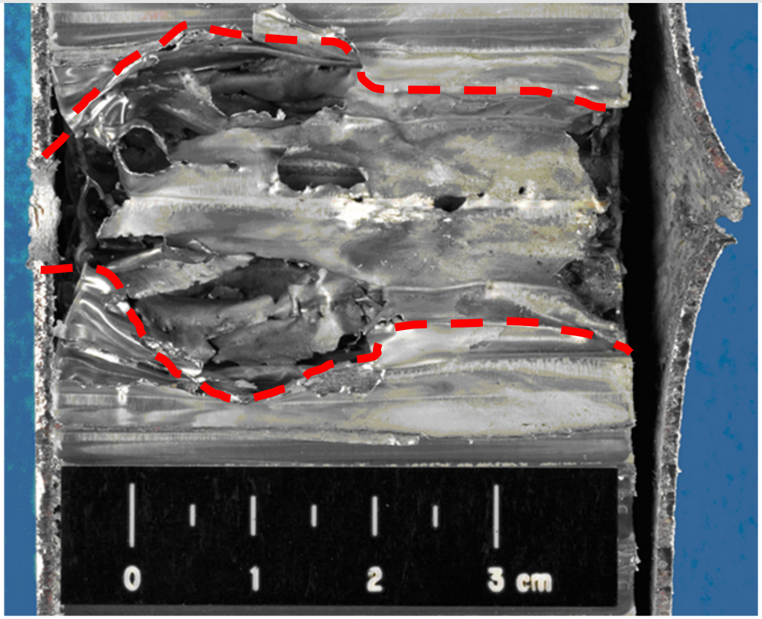


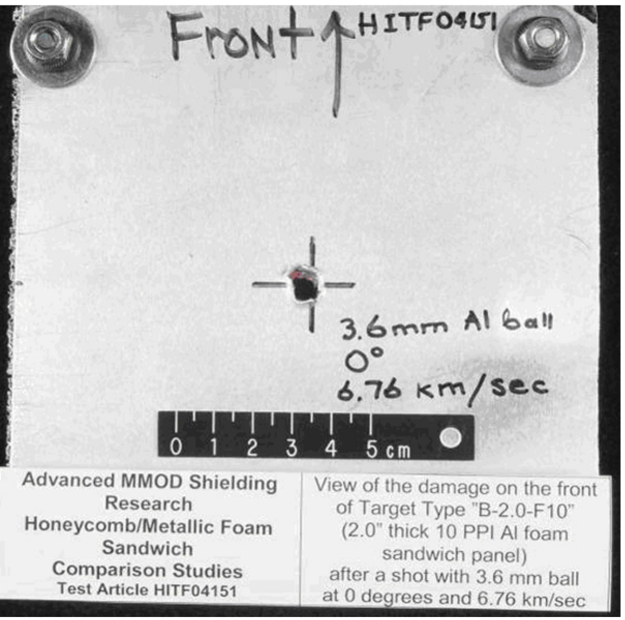
National Aeronautics and Space Administration

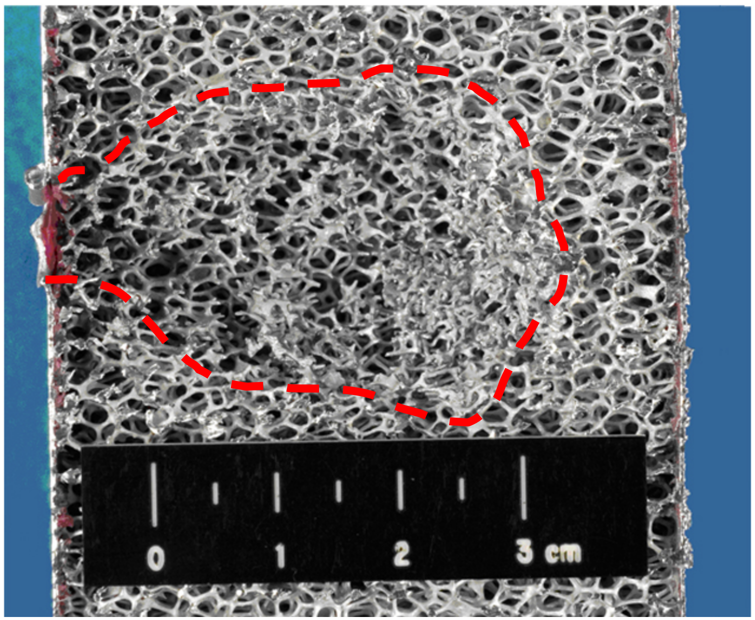
Foam sandwich hypervelocity test

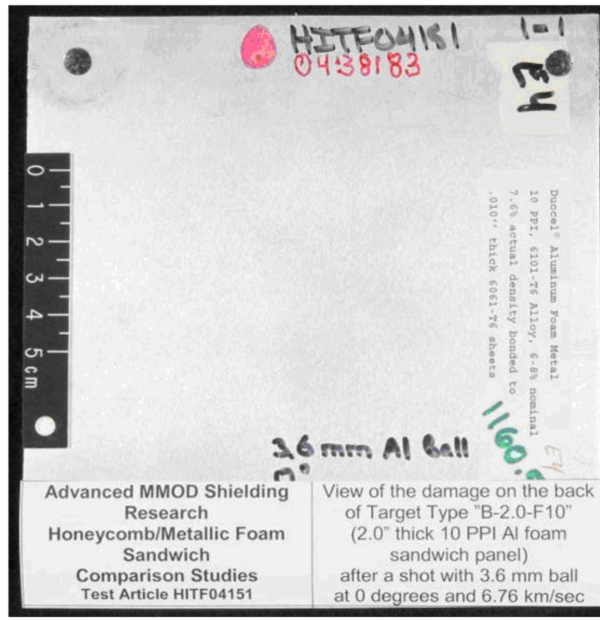
3.6mm diameter Al2017T4 sphere at 6.2-6.8 km/s, 0-deg







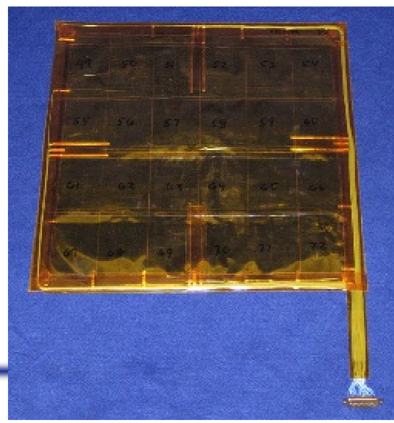




Smart MMOD shields

- **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)

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**