Micrometeoroid and Orbital Debris Environment & Hypervelocity Shields

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Purpose of this presentation

• Provide background on micro-meteoroid & orbital debris (MMOD) shielding protection
  • MMOD environment
  • MMOD protection requirements
  • Shielding approaches
MMOD Environment Models

- Orbital Debris (OD) environment models
  - Orbital Debris environment (ORDEM2000): 1-17 km/s
    - Debris flux increases with increasing altitude up to about 1500km altitude
    - Debris is not a major factor above GEO altitude (35786km)
  - Debris environment subject to change (ORDEM 3.0 release pending)

Orbital Debris in Earth Orbit

Normalized Orbital Debris Flux by Year at ISS Altitude
For Threat Particle Sizes > 0.3cm
(Normalized to 2006 flux)
Note OD Risk is proportional to Flux
MMOD Environment Models (cont.)

- Meteoroid model (MEM) provided by MSFC
  - [http://www.nasa.gov/offices/meo/home/index.html](http://www.nasa.gov/offices/meo/home/index.html)
  - Meteoroid environment (MEM): 11-72 km/s
    - Average 22-23 km/s
  - MM environment model is subject to change (new release of MEM is pending)
- Orbital Debris is the predominate threat in low Earth orbit
  - For ISS, debris represents approximately 2/3rd of the MMOD risk
  - For missions to the Moon, L1, or elsewhere, OD risk will need to be assessed for time period spacecraft resides in LEO
- Meteoroid risk is influenced by Earth focusing (gravitational) factor and Earth shadowing while in Earth orbit
  - Meteoroid risk far from Earth is typically less compared to meteoroid risk in LEO
MMOD Damage to spacecraft

- Several ISS and Shuttle MMOD damages appear to have been caused by >1mm diameter MMOD particles
  - FGB compressor damage due to 2mm-3mm diameter particle
  - P6 radiator damage due to 3mm-5mm particle
  - SM solar array damage due to >2mm particle
  - STS-118 radiator damage due to high density 1mm particle

- Good agreement between actual damage to predictions for ISS Pressurized Logistics Module and Shuttle (damage identified after return to ground)
MMOD Shielding
MMOD Protection Requirements

• MMOD risk is a function of vehicle size, mission duration (time exposed to MMOD), failure criteria, shielding, flight trajectory

• MMOD requirements are key aspect of providing adequate MMOD protection, crew safety and vehicle survivability

• Typically MMOD protection requirements expressed in terms of maximum allowable failure risk over a time period, or a reliability level (probability of no failure)
  • For instance, Orion Lunar sortie (24 day mission) maximum allowable MMOD loss-of-crew (LOC) risk is 1 in 1000 (0.1% risk), and Lunar outpost (210 day mission) maximum allowable MMOD risk is 1 in 500 (0.2% risk)
    • Note, that over many missions, the cumulative MMOD risk increases with the total duration of all missions
Hypervelocity impact effects

- At hypervelocity, small particles can cause a lot of damage
  - High velocity MMOD particles represent a substantial threat to spacecraft which typically are constructed with light-weight materials to save mass
  - Rule of thumb: at 7km/s, aluminum sphere can penetrate completely through an aluminum plate with thickness 4 times the sphere’s diameter
  - A multi-layer spaced shield provides more effective protection from hypervelocity impact than single layer (total shield thickness < projectile diameter)
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
     • 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)
Shielding Design and Verification Methodology

- Identify vulnerable spacecraft components/subsystems
- Assess HVI damage modes
- Determine failure criteria
- Perform HVI test/analysis to define “ballistic limits”
- Conduct meteoroid/debris probability analysis
- Compare MMOD analysis results with requirement
- Updates to design, operations, analysis, test, or failure criteria
- Update/Iterate as necessary to meet requirement

**BUMPER**

- **S/C Operating Parameters**
- **MMOD Probability Analysis Code**
  - Environment Models - Debris & Meteoroid
  - Probability of No Failure
    - $P$
    - $P > R$ → **Yes**
    - $P < R$ → **No**
  - Ballistic Limit Equations
- **Protection Requirement**
  - Meet Requirements?
    - **Yes** → Qualify
    - **No** → Iterate
ISS MMOD shielding
finite element model for Bumper code MMOD risk assessments

Each color represents a different MMOD shield configuration
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
MMOD shielding background

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Purpose</th>
<th>Key Material &amp; Physical Parameters (V ≥ 7 km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMOD particle</td>
<td>Breakup MMOD particle, laterally disperse resulting debris</td>
<td>density, thickness to projectile diameter ratio, thermal properties</td>
</tr>
<tr>
<td>bumper</td>
<td></td>
<td></td>
</tr>
<tr>
<td>intermediate bumper</td>
<td>Further breakup debris from first impact, slow expansion of debris cloud</td>
<td>combination of first bumper and rear wall properties</td>
</tr>
<tr>
<td>rear wall</td>
<td></td>
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</tbody>
</table>

Purpose: Stop debris from MMOD & bumper(s)
Key material & physical parameters (V ≥ 7 km/s): strength, toughness, thickness
• Hypervelocity impact tests have been performed for MMOD shielding of potential inflatable modules, for two damage modes:
  
  1. Failure of shield protecting restraint layer
  2. Failure of shield, restraint and bladder

BEAM inflatable on Node 3 aft

Deep Space Habitat inflatable demonstrator on Node 2 nadir
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:
  • 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
Backup Charts
Cataloged objects >10 cm diameter

1960
1970

Cataloged objects >10 cm diameter
Cataloged objects >10 cm diameter

1980
Cataloged objects >10 cm diameter
Cataloged objects >10 cm diameter
August 2009

Cataloged objects >10 cm diameter
Ballistic Limits for Whipple Shield & equal mass Monolithic

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

**Expect “failure” above curves**

- **Whipple d_{crit} @ 0 deg**
- **monolithic d_{crit} @ 0 deg**

**Ballistic Limit Improvement due to Shield Standoff**
\[ \Delta d_{Crit} \]

**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 (cm)**

**Velocity (km/s)**

- 0.0
- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0
- 2
- 4
- 6
- 8
- 10
- 12
- 14

National Aeronautics and Space Administration
ISS MMOD shielding

- Many different shield configurations protect ISS modules, external pressure vessels, gyros, and visiting vehicles from MMOD
  - High risk areas found by analysis
  - More capable shielding (i.e., stopping larger particles) placed where expect greatest amount of MMOD hits
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)
MMOD shields added to Service Module by extravehicular activity (EVA)

Additional MMOD shield panels added by EVA (each consist of layers of aluminum, corrugated aluminum, fiberglass and Russian Kevlar)