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)

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
• 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 $\frac{2}{3}$ 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)

FGB damage (1” x 2”) likely due to 2mm-3mm diameter MMOD particle

P6 radiator damage noted during STS-118 (0.75” diameter) likely due to 3-5mm diameter x 1mm thick MMOD particle
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
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

**BUMP**

- S/C Operating Parameters
- Environment Models - Debris & Meteoroid
- Probability of No Failure
- Ballistic Limit Equations
- MMOD Probability Analysis Code
- Failure Criteria
- HVI Test & Analysis
- Protection Requirement
- Meet Requirements?
  - Yes: Qualify
  - No: Iterate

\[ P > R \]
\[ P < R \]
ISS MMOD shielding
finite element model for Bumper code MMOD risk assessments

Each color represents a different MMOD shield configuration
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

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**Purpose:** Breakup MMOD particle, laterally disperse resulting debris

**Key material & physical parameters** ($V \geq 7$ km/s):
- density, thickness to projectile diameter ratio, thermal properties

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**Purpose:** Further breakup debris from first impact, slow expansion of debris cloud

**Key material & physical parameters** ($V \geq 7$ km/s):
- combination of first bumper and rear wall properties

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**Purpose:** Stop debris from MMOD & bumper(s)

**Key material & physical parameters** ($V \geq 7$ km/s):
- strength, toughness, thickness
Shielding assessments for inflatables

- 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
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
1960

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

1970
Cataloged objects >10 cm diameter
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**
  - Expect “failure” above curves

- **Whipple dcrit @ 0 deg**
- **monolithic dcrit @ 0 deg**

**Velocity Range:**
- **Ballistic Regime**
  - Few solid fragments
- **Fragmentation & Partial Melt Regime**
  - Many (increasing with velocity) solid fragments & liquid droplets
- **Complete Melt Regime**
  - Fine droplets, few solid fragments, some vapor

**State of Debris Cloud:** Few solid fragments (for Al on Al impacts)

**Ballistic Limit Improvement due to Shield Standoff**
- $\Delta d_{\text{Crit}}$

**Critical Al Diameter (cm)**
- 0.12cm Al bumper
- 0.32cm Al6061T6 rear wall
- 10cm standoff
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)

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**FGB Zone 11c,d,f**
- 1.4mm Al pressure shell
- 0.3/10/1.5mm Al honeycomb
- MLI
- Steel mesh (2)
- Fabric (1)

**SM deployable shield/zone 6**
- Orientation of zone 8 not parallel to 4 augmentation bumpers
- Basalt fabric layers
- 1.0mm Al pressure shell
- Original Zone 6
- 0.3/10/1.0mm Al honeycomb
- 1.0mm Al MLI
- 0.5mm Al Corrugated

**SM conformal shield/zone 8**
- 2.3mm Al pressure shell
- Russian “Kevlar” fabric (6)
- 0.5/10/0.5mm graphite-epoxy honeycomb
- 1mm Al Corrugated
- Fiberglass panel
- 10 cm
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)