Surveys of Returned ISS Hardware for MMOD Impacts

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Introduction

- Comparison of observed hypervelocity impact features with Bumper 3 results using ORDEM 3.0 and MEM-R2
- Post flight MMOD inspection – damage site measurements
- Sampling of impact sites
- SEM analysis – projectile characterization
- Bumper 3 calculations
Airlock Shield Panels

- Airlock launched July 2001
- Installed on ISS Node 1 starboard
- Originally equipped with 4 high pressure gas tanks (HPGT)
- Airlock shield panels 01-04B & 02-04B removed November 2009 to allow for the installation of a 5th HPGT
- Panels returned April 2010
- Exposure time = 8.75 years
Airlock Shield Panels

- Airlock pressure walls are protected by aluminum panels (Whipple Shield)
- Shield panel is 2 mm thick aluminum, with overall dimensions of 1.30 x 0.84 m
Post Flight Inspection Results

- 58 impact feature observed
- Max crater diameter = 1.78 mm
- Average crater diam. = 0.57 mm
Sampling at Impact Sites

- Intact extraction of craters was not permitted
- Portions of the raised lips at 9 craters were removed for analysis

Log #33-8, L x W = 2.4 x 0.9 mm
Log #33-1, diameter = 1.78 mm
SEM/EDS Results

- SEM analysis revealed many areas with silica melted into the aluminum
- Instances of Fluorine and Carbon were also common

<table>
<thead>
<tr>
<th>Impact Site</th>
<th>Crater Size (mm)</th>
<th># of Samples</th>
<th>Impactor Type: Major Constituents</th>
<th>Possible Impactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>33-1</td>
<td>1.78</td>
<td>3</td>
<td>OD: SiO</td>
<td>Silica</td>
</tr>
<tr>
<td>33-2</td>
<td>1.06</td>
<td>1</td>
<td>OD: CF, Si, SiO</td>
<td>PTFE, Silica</td>
</tr>
<tr>
<td>33-8</td>
<td>1.48</td>
<td>1</td>
<td>OD: Fe, SiO, Pb, Cr, Ni, Co</td>
<td>Silica, paint, metal alloys</td>
</tr>
<tr>
<td>33-21</td>
<td>0.73</td>
<td>1</td>
<td>unknown</td>
<td>--</td>
</tr>
<tr>
<td>34-2</td>
<td>1.17</td>
<td>4</td>
<td>OD: CF, Fe</td>
<td>PTFE</td>
</tr>
<tr>
<td>34-8</td>
<td>0.42</td>
<td>4</td>
<td>OD: CF, K, Ca, Ti, SiO</td>
<td>PTFE, Silica</td>
</tr>
<tr>
<td>34-10</td>
<td>0.81</td>
<td>3</td>
<td>OD: SiO, Fe, Cu, Zn</td>
<td>Silica</td>
</tr>
<tr>
<td>34-11</td>
<td>0.91</td>
<td>1</td>
<td>OD: SiO, BaS, Cu, Zn</td>
<td>Silica, paint</td>
</tr>
<tr>
<td>34-14</td>
<td>0.85</td>
<td>3</td>
<td>OD: CF</td>
<td>PTFE</td>
</tr>
</tbody>
</table>
Comparison with Bumper 3

- Bumper 3 was used to calculate the expected number of craters on a 2 m² patch of the equipment lock region of the airlock.
- Years = 2001 through 2010
- Time averaged altitudes
- Damage equation = Cour-Palais crater depth

<table>
<thead>
<tr>
<th>Year</th>
<th>Altitude (km)</th>
<th>Time (year)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>382.68</td>
<td>0.466</td>
<td>07/14/01: Airlock install</td>
</tr>
<tr>
<td>2002</td>
<td>390.04</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>384.61</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>361.66</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>352.54</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>342.20</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>337.55</td>
<td>1.0</td>
<td>10/27/07: P6 moved from Z1 to P5</td>
</tr>
<tr>
<td>2008</td>
<td>345.41</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>348.55</td>
<td>1.0</td>
<td>11/23/09: airlock shields to ESP-2</td>
</tr>
<tr>
<td>2010</td>
<td>349.40</td>
<td>0.282</td>
<td>04/13/10: shields retrieved from ESP-2</td>
</tr>
</tbody>
</table>

Crater Depth (cm) | Crater Diameter (cm) | MEM R2 | ORDEM 3.0 | MMOD TOTAL
0.02 | 0.04 | 26.955 | 0.026 | 26.980
0.04 | 0.08 | 4.726 | 0.006 | 4.732
0.06 | 0.12 | 1.467 | 0.003 | 1.470
0.08 | 0.16 | 0.605 | 0.002 | 0.607
0.10 | 0.20 | 0.297 | 0.001 | 0.298

Crater Depth (cm) | Crater Diameter (cm) | MEM R2 | ORDEM 3.0 | MMOD TOTAL
8.753
Comparison with Bumper 3

- Micrometeoroids are expected to account for nearly all of the craters.
- Shield panels are oriented on the zenith/trailing side of the airlock.
- The abundance of orbital debris impacts can be explained by the proximity of the ISS solar arrays wings and radiator.
- Secondary debris (ejecta) from MMOD impacts on solar arrays and radiators is the suspected source.
- SEM evidence supports the hypothesis, with an abundance of silica detected.
PMA-2 Cover

- Installed July 9, 2013 during US EVA 22
- Removed February 25, 2015 US EVA 30
- Returned on SpaceX CRS-6 May 2015
- Exposure time = 1.633 years
- Beta Cloth outer layer (t = 0.2 mm) with internal layers of ballistic fabric
- Overall diameter of cover = 2.0 m
- Tie down strap length = 0.6 m
Post Flight Inspection Results

- 26 impact feature observed
- Max hole diameter = 1.01 mm
- Average crater diam. = 0.45 mm
Sampling at Impact Sites

- Six samples were extracted intact using a “hole punch” technique
- Relative orientation of internal layers was preserved
SEM/EDS Results

- Textural and compositional indications of high density orbital debris as the source in 4 of 6 samples

<table>
<thead>
<tr>
<th>Impact Site</th>
<th>Hole Size (mm)</th>
<th>Impactor Type: Major Constituents</th>
<th>Possible Impactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.60</td>
<td>OD: Steel, ZnS, FeO, Ti</td>
<td>Steel</td>
</tr>
<tr>
<td>2</td>
<td>1.01</td>
<td>OD: Steel, Nickel-Oxide</td>
<td>Steel</td>
</tr>
<tr>
<td>10</td>
<td>0.80</td>
<td>OD: Steel, Iron-oxide</td>
<td>Steel</td>
</tr>
<tr>
<td>12</td>
<td>0.57</td>
<td>MM: Ca, Mg, Fe, S, O</td>
<td>Chondrite</td>
</tr>
<tr>
<td>13</td>
<td>0.73</td>
<td>MM: Fe, Ni, S</td>
<td>metal/sulfide-rich MM</td>
</tr>
<tr>
<td>24</td>
<td>0.36</td>
<td>OD: Steel, Iron-oxide, Ti</td>
<td>Steel</td>
</tr>
</tbody>
</table>
Comparison with Bumper 3

- Bumper 3 was used to calculate the expected number of holes on a stand alone model of the PMA-2 cover
- Years = 2013 through 2015
- Time averaged altitudes
- Damage equation = beta cloth hole size

<table>
<thead>
<tr>
<th>Hole Diameter (cm)</th>
<th>Particle Diameter (cm)</th>
<th>MEM R2</th>
<th>ORDEM 3.0</th>
<th>MMOD</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0288</td>
<td>0.0125</td>
<td>16.89</td>
<td>14.60</td>
<td>31.49</td>
<td></td>
</tr>
<tr>
<td>0.0460</td>
<td>0.020</td>
<td>4.40</td>
<td>3.87</td>
<td>8.27</td>
<td></td>
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<tr>
<td>0.0920</td>
<td>0.040</td>
<td>0.46</td>
<td>0.68</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>0.1380</td>
<td>0.060</td>
<td>0.11</td>
<td>0.30</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>0.1840</td>
<td>0.080</td>
<td>0.04</td>
<td>0.15</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>0.2300</td>
<td>0.100</td>
<td>0.02</td>
<td>0.08</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>

Start Date | End Date | Days  | Years  | Altitude (km) |
-----------|----------|-------|--------|---------------|
7/9/13     | 1/1/14   | 176   | 0.482  | 413.6         |
1/1/14     | 1/1/15   | 365   | 1.000  | 414.5         |
1/1/15     | 2/25/15  | 55    | 0.151  | 402.1         |
Total      |          | 596   | 1.633  |               |
Comparison with Bumper 3

- Bumper predictions for MM and OD are much closer to observations
Conclusions

- Damage found in post-flight inspection of the PMA-2 cover and the returned airlock bumper panels was generally consistent with Bumper code predictions using the ORDEM 3.0 debris model and MEM-R2 meteoroid model.

- Excess orbital debris damage was observed on the airlock bumper panels compared to predictions, although this discrepancy is likely the result of secondary debris impacts.