M/OD Hypervelocity Impacts and Protection Research in CAST

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Leading Scientist of hypervelocity impact research

Beijing Institute of Spacecraft Environment Engineering,
China Academy of Space Technology (CAST), China
• Founded in February 20, 1968;
• The first president: Chien Hsuch-Sen;
• The largest space technology research center in China
• The largest Spacecraft development, production base in China.
• April 24, 1970: Chinese first artificial Earth satellite – DFH-1;
• October 2003: manned spacecraft – Shenzhou-5;
• October 24, 2007: Chinese first lunar detector – Chang'E-1;
• October 1 2010 the second lunar detector Chang'E-2.

• Beijing Institute of Spacecraft Environment Engineering
• The Spacecraft Environment Engineering department of CAST.
Outline

§ 1  Space Debris Environment and Its Risks
§ 2  Space Debris Modeling
§ 3  Orbital Debris impact Risk Assessment in CAST
§ 4  HVI Testing and M/OD Protection in CAST
§ 5  Orbital Debris Mitigation in CAST
§ 1

Space Debris Environment and Its Risks
Orbital debris : Humankind digs his own grave!

Space debris are all man made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional.

Orbital debris is the only man-made Space environment.

The past 50 years of space exploration has unfortunately generated a lot of junk that threatens the reliability of spacecraft.
The Space Debris Environment in 2010

- More than 5000 satellite launches since 1957 till the end of October 2010;
- 245 on-orbit break-ups led to 12,500 objects in the US Space Surveillance catalog;
- catalog size threshold ⇒ 10cm;
- mass on orbit ⇒ 6,000 tons;
- catalog orbit distributions:
  - low Earth orbits ⇒ 73%;
  - near-geostationary orbits ⇒ 8%;
  - highly eccentric orbits ⇒ 10%;
  - other orbits (incl. GNSS) ⇒ 9%
- catalog composition ⇒ 7% operational satellites,
  - About 800 operational satellites;
  - 380 active spacecraft on the GEO;
- catalog composition ⇒ 40% non-operational but intact objects, and 53% fragments.
LEO stands for low Earth orbit and is the region of space within 2,000 km of the Earth's surface. It is the most concentrated area for orbital debris.
The GEO images are images generated from a distant oblique vantage point to provide a good view of the object population in the geosynchronous region (around 35,785 km altitude). Note the larger population of objects over the northern hemisphere is due mostly to Russian objects in high-inclination, high-eccentricity orbits.
The GEO Polar images are generated from a vantage point above the north pole, showing the concentrations of objects in LEO and in the geosynchronous region.
<table>
<thead>
<tr>
<th>Country/Organization</th>
<th>Payloads</th>
<th>Rocket Bodies &amp; Debris</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHINA</td>
<td>98</td>
<td>3395</td>
<td>3493</td>
</tr>
<tr>
<td>CIS</td>
<td>1406</td>
<td>4600</td>
<td>6006</td>
</tr>
<tr>
<td>ESA</td>
<td>39</td>
<td>44</td>
<td>83</td>
</tr>
<tr>
<td>FRANCE</td>
<td>49</td>
<td>426</td>
<td>475</td>
</tr>
<tr>
<td>INDIA</td>
<td>41</td>
<td>133</td>
<td>174</td>
</tr>
<tr>
<td>JAPAN</td>
<td>113</td>
<td>76</td>
<td>189</td>
</tr>
<tr>
<td>USA</td>
<td>1124</td>
<td>3701</td>
<td>4825</td>
</tr>
<tr>
<td>OTHER</td>
<td>479</td>
<td>115</td>
<td>594</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>3349</strong></td>
<td><strong>12490</strong></td>
<td><strong>15839</strong></td>
</tr>
<tr>
<td>Common Name</td>
<td>Year of Breakup</td>
<td>Altitude of Breakup</td>
<td>Cataloged Debris*</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-----------------</td>
<td>---------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Cosmos 2251</td>
<td>2009</td>
<td>790 km</td>
<td>1267</td>
</tr>
<tr>
<td>STEP 2 Rocket Body</td>
<td>1996</td>
<td>625 km</td>
<td>713</td>
</tr>
<tr>
<td>Iridium 33</td>
<td>2009</td>
<td>790 km</td>
<td>521</td>
</tr>
<tr>
<td>Cosmos 2421</td>
<td>2008</td>
<td>410 km</td>
<td>509</td>
</tr>
<tr>
<td>SPOT 1 Rocket Body</td>
<td>1986</td>
<td>805 km</td>
<td>492</td>
</tr>
<tr>
<td>OV 2-1 / LCS 2 Rocket Body</td>
<td>1965</td>
<td>740 km</td>
<td>473</td>
</tr>
<tr>
<td>Nimbus 4 Rocket Body</td>
<td>1970</td>
<td>1075 km</td>
<td>374</td>
</tr>
<tr>
<td>TES Rocket Body</td>
<td>2001</td>
<td>670 km</td>
<td>370</td>
</tr>
<tr>
<td>CBERS 1 Rocket Body</td>
<td>2000</td>
<td>740 km</td>
<td>343</td>
</tr>
</tbody>
</table>

Total: 7903  Total: 5172

* As of May 2010
42 debris which had been identified by 9 July, 2010 for Russian Launched Breeze-M tank.
The Space Debris Environment in 2010

- Large debris size diameter $\geq 10\text{cm}$
  - can be tracked using ground-based radars and optical telescopes
  - It can not be defended
  - the probability of collision is very low,
  - It would cause catastrophic failure of spacecraft,
  - spacecraft must maneuverable avoidance Collision
  - up to September 30, 2010, $\sim 12,490$
The Space Debris Environment in 2010

- Hazardous debris: size diameter 1cm - 10cm, called "hazardous orbital debris"
  - Can not be tracked using ground-based radars and optical telescopes
  - It can not be defended
  - The probability of collision is low,
  - It would cause significant damage.
  - Spacecraft must maneuverable avoidance
    Collision
  - More than ~500,000
The Space Debris Environment in 2010

- Small debris size diameter <1cm
  - size >1mm, ~180 million, > 0.1mm 20,000 million
  - can not be tracked ground based
  - The probability of collision is high
  - it would cause significant damage. The damage could functionally compromise the vehicle, or worse, result in catastrophic failure.
  - Spacecraft must be designed to withstand hypervelocity impacts by these small, untraceable particles
Collision Number per year of operational spacecraft with space debris large than 1cm
Space objects larger than 10cm in the coming 200 years

Figure 1. Updated (includes Fengyun-1C ASAT and Iridium/Cosmos collisions) projection of the runaway growth of >10 cm resident space objects if postmission disposal measures are not implemented. Figure includes 1σ uncertainties.
Typical Orbital Debris Impact Distribution
Versus Velocity and Obliquity

SSF WP-1 Lab Module - 1 cm diameter Orbital Debris Risk Assessment
# of impacts vs. velocity & impact angle @ 10° pitch down

Number of impacts

Velocity (km/sec)

Impact Angle
Table 1. Collision Avoidance Maneuvers in 2009

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Maneuver Date</th>
<th>Object Avoided</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDRS 3</td>
<td>27 January</td>
<td>Proton rocket body</td>
</tr>
<tr>
<td>ISS</td>
<td>22 March</td>
<td>CZ-4 rocket body debris</td>
</tr>
<tr>
<td>Cloudsat</td>
<td>23 April</td>
<td>Cosmos 2251 debris</td>
</tr>
<tr>
<td>EO-1</td>
<td>11 May</td>
<td>Zenit rocket body debris</td>
</tr>
<tr>
<td>ISS</td>
<td>17 July</td>
<td>Proton rocket body debris</td>
</tr>
<tr>
<td>Space Shuttle</td>
<td>10 September</td>
<td>ISS debris</td>
</tr>
<tr>
<td>PARASOL (France)*</td>
<td>29 September</td>
<td>Fengyun-1C debris</td>
</tr>
<tr>
<td>Aqua</td>
<td>25 November</td>
<td>Fengyun-1C debris</td>
</tr>
<tr>
<td>Landsat 7</td>
<td>11 December</td>
<td>Formosat 3D</td>
</tr>
</tbody>
</table>

* Operating in NASA-led Earth observation network
ISS Performs First Collision Avoidance Maneuver

The International Space Station (ISS) conducted its first collision avoidance maneuver on October 26, 1999, to ensure no possible contact with a derelict Pegasus upper stage (1998-046K, U.S. Satellite Number 25422).

ISS started the Zarya module’s propulsion system 18 hours before the conjunction would occur. Instead of a miss distance of less than one kilometer, ISS and the Pegasus stage passed at a safe separation of more than 140 km.

So far, 10 times of maneuver...
2008 Debris Impacts on ISS

- During the STS-122 mission to ISS in February 2008, a crew member discovered a small impact crater (~2 mm diameter) on the US airlock hand rail. This ragged feature might have been the source for cuts found on some EVA suit gloves.

- During the STS-123 mission to ISS in March 2008, a larger 5 mm diameter impact crater was observed on an EVA tool which had been externally stored.
Damage to International Space Station

Based on ground test results, it is believed that the likely particle size causing the damage was:

- Projectile: 0.2 cm to 0.3 cm;
- Impact angle: 75°

Damage area □ 6.7cm×3.3cm
Crater □ 1.0cm×0.85cm

Damage to thermal blanket of FGB (Zarya Control Module)
Damage to Space Station

Thermal blanket (MIR)
Damage to Space Station

Detail of MMOD impact on airlock hand rail (ISS)
Damage to Space Station

Detail of MMOD impact on EVA D-Handle (ISS)
# Table Damage to porthole of space shuttle

<table>
<thead>
<tr>
<th>Mission</th>
<th>Time</th>
<th>Altitude (km)</th>
<th>Days</th>
<th>Impact number</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS-87</td>
<td>1997.11</td>
<td>285</td>
<td>16</td>
<td>176</td>
<td>Two glass replaced</td>
</tr>
<tr>
<td>STS-89</td>
<td>1998.1</td>
<td>280-390</td>
<td>16</td>
<td>115</td>
<td>Four glass replaced</td>
</tr>
<tr>
<td>STS-95</td>
<td>1998.10</td>
<td>574</td>
<td>9</td>
<td>73</td>
<td>Five glass replaced</td>
</tr>
<tr>
<td>STS-88</td>
<td>1998.12</td>
<td>390</td>
<td>12</td>
<td>40</td>
<td>Three glass replaced</td>
</tr>
<tr>
<td>STS-92</td>
<td>2000.10</td>
<td>335-446</td>
<td>13</td>
<td>38</td>
<td>Three thermal plate replaced</td>
</tr>
<tr>
<td>STS-97</td>
<td>2000.12</td>
<td>335-446</td>
<td>11</td>
<td>30</td>
<td>Two glass replaced</td>
</tr>
<tr>
<td>STS-114</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>14</td>
<td>One glass replaced</td>
</tr>
</tbody>
</table>
Our ability to safely use outer space in the long term is not guaranteed:

Multiplication of government and private space operators:

- 9 nations operate launch systems (over 60 launches in 2010);
- More than 50 states and regional organizations operate satellites in Earth orbit.
- An increasing number of very large and small private companies operate commercial satellite systems.
- Increased crowding in low earth orbit as well as in the geostationary orbit creates new challenges.
- Managing the orbital and spectral resources will require a new discipline and possibly new international mechanisms to ensure a sustainable use of outer space.
The key question is therefore:
Are space activities in Earth orbit sustainable over the long term?

- Space Security is fragile.

- Ensuring secured and sustainable access to, and use of outer space is a major issue for all, national governments and commercial operators.

- Recent events have shown that the issue is not a theoretical one.
The Inter-Agency Space Debris Coordination Committee (IADC) is an international forum of governmental bodies for the coordination of activities related to the issues of man-made and natural debris in space.

IADC cannot stay for ever with recommendations but should prepare space laws and stronger solutions
Orbital Debris research is divided into the following broad research efforts:

3 projects
§ 2
Space Debris Modeling
2.1 Orbital Debris Measurements

• 1 Ground-based observations
  • (1) Orbital Debris Radar Measurements
  • (2) Orbital Debris Optical Measurements

• 2 Space-based observations
  • In-Situ Measurements And Retrieved Surfaces
2.2 Orbital Debris Modeling

- NASA scientists continue to develop and upgrade orbital debris models to describe and characterize the current and future debris environment. Engineering models, such as ORDEM2000, can be used for debris impact risk assessments for spacecraft and satellites, including the International Space Station and the Space Shuttle. Whereas, evolutionary models, such as LEGEND, are designed to predict the future debris environment. They are reliable tools to study how the future debris environment reacts to various mitigation practices.
The NASA Orbital Debris Program Office at JSC has developed a computer-based orbital debris engineering model, ORDEM2000. The model describes the orbital debris environment in the low Earth orbit region between 200 and 2,000 km altitude. The model is appropriate for those engineering solutions requiring knowledge and estimates of the orbital debris environment (debris spatial density, flux, etc.). ORDEM2000 can also be used as a benchmark for ground-based debris measurements and observations.
Incorporated in the model is a large set of observational data (both in-situ and ground-based), covering the object size range from 10 µm to 10 m and employing a new analytical technique utilizing a maximum likelihood estimator to convert observations into debris population probability distribution functions. These functions then form the basis of debris populations. ORDEM2000 uses a finite element model to process the debris populations to form the debris environment. A more capable input and output structure and a user-friendly graphical user interface are also implemented in the model. ORDEM2000 has been subjected to a significant verification and validation effort. Currently, ORDEM2000 runs on Windows 95/98/2000/NT/XP computers.
The multi-year development of the NASA Orbital Debris Engineering Model 2010 (ORDEM2010) has passed a significant milestone with the release of the Beta version for testing. Like its predecessors in the ORDEM series of engineering models, ORDEM2010 is an empirically derived model that includes assessments of the orbital debris environment as a function of altitude, latitude, and debris size. It provides a state-of-the-art description of the environment, in terms of debris flux onto spacecraft surfaces or the debris detection rate observed by ground-based sensors. The ORDEM2010 model represents a major improvement over the existing ORDEM2000, with significant advances in several fundamental areas.
• The resulting debris population in the 10 μm to 10 cm size range serves as an input to the ORDEM2010 model. The GEO debris population, included in an ORDEM model for the first time, also is derived from NASA debris environment models and by slight extrapolation of GEO measurement data to smaller sizes with the NASA Standard Breakup Model.

• Other quantities for the first time in an ORDEM model. The first is material density for debris smaller than 10 cm. These objects include non-breakup debris for which the compounds are known (e.g., sodium potassium droplets), and breakup fragments, for which low-, medium-, or high-density (i.e., plastics, aluminum, steel) are assigned based on noted ground collision test results. The second, newly included quantity is the population error, which includes measurement, future projection, and modeling uncertainties. Population errors are converted to flux errors in the final calculations of the spacecraft mode.
MASTER series

- MASTER series
- MASTER 2006
- development of MASTER-2009
LEGEND is a full-scale, three-dimensional, debris evolutionary model that is the NASA Orbital Debris Program Office developed primary model for study of the long-term debris environment. It covers the near-Earth space between 200 and 50,000 km altitude, including low Earth orbit (LEO), medium Earth orbit (MEO), and geosynchronous orbit (GEO) regions. The model provides debris characteristics (number, type, size distribution, spatial density distribution, velocity distribution, flux, etc.) as functions of time, altitude, longitude, and latitude. In addition, LEGEND includes both historical simulation and future projection components. Populations included in the model are active and spent satellites, rocket bodies, breakup fragments, mission-related debris, and Sodium-Potassium (NaK) droplets, making it possible for the minimum size (diameter) threshold in the model to be as small as 1 mm.
The main function of the LEGEND future projection component is to provide an understanding of how the orbital debris environment evolves in the future. It is also a reliable tool to examine how various mitigation practices may help protect the environment. A key element in the LEGEND future projection component is a three-dimensional evaluation model that provides a fast and accurate way to estimate future on-orbit collisions from LEO to GEO. Since no assumptions regarding the right ascensions of the ascending node and arguments of perigee of objects involved are required, this probability model captures the collision characteristics in real three-dimensional physical space. It is a critical component of a true three-dimensional debris evolutionary model.
The typical projection period in LEGEND is 100 years. Due to uncertainties involved in the process (e.g., future launch traffic, solar activity, explosions, collisions), conclusions are usually drawn based on averaged results from 100 Monte Carlo simulations.
§ 3

Orbital Debris impact Risk Assessment in CAST
§ 3 Orbital Debris impact Risk Assessment in CAST

3.1 Methodology

3.2 Impact Risk Assessment Codes:

3.2.1 BUMPER: NASA, JAXA
3.2.2 ESABASE/DEBRIS: ESA
3.2.3 COLLO, BUFFER, PSC: ROSCOSMOS
3.2.4 MDPANTO: DLR
3.2.5 SHIELD: BNSC
3.2.6 MODAOST: CAST
3.1 Methodology

The standard M/OD risk assessment methodology for spacecraft is illustrated in Fig 1.

Figure 1 Standard Process for Assessing Spacecraft Meteoroid/Orbital Debris Risks
3.1 Methodology

The procedure for assessing and reducing spacecraft risks from M/OD impact is an iterative one. Specific steps in the procedure are listed below:

Step 1:
Identify spacecraft components/subsystems:
The M/OD analyst must know many details of the spacecraft design, operation, failure modes and effects, to properly perform a spacecraft M/OD risk assessment. The Spacecraft geometry should be well known, including materials and allocation of critical subsystems. The systems and components that are exposed to M/OD are identified and their criticality for the mission is assessed.
3.1 Methodology

Step 2 Assess HVI damage modes
Hazards to be assessed in the M/OD risk assessment are defined for each exposed system and component.

Step 3 Determine failure criteria:
A very clear failure criterion is defined from the many potential hypervelocity impact damage modes for each spacecraft system. The Protection Manual (PM) defines many potential damage modes for different spacecraft systems. The failure mode is explicitly defined for each ballistic limit equation.
3.1 Methodology

Step 4 Perform HVI test/analysis to anchor and verify the ballistic limit equations and to define “ballistic limits”:

Step 5 Conduct probability analysis of failure due to meteoroid/orbital debris:
The probability of M/OD failure is assessed using the spacecraft geometry, ballistic limit equations and M/OD environment models.
3.1 Methodology

Step 6 - Compare M/OD analysis results with goal or requirement:

The analysis results (PNP or PNF) are compared to the goal or requirement for the spacecraft system or component, which is defined by the reliability and/or safety community. If PNF is greater than the required survival probability, than the analysis can be considered complete, otherwise the analysis continues with step 7.
Step 7 Consider updates to design, operations, analysis, test, or failure criteria: If the analysis results do not meet the requirements, iteration of the analysis is necessary. Revising analysis assumptions in terms of failure criteria and/or improved spacecraft modelling is typically the least expensive option, as it has the least effect on the spacecraft design. Additional testing may be necessary to validate the ballistic limit equations. It is often possible to remove engineering conservatism in the BLEs after additional testing is conducted. Other options include changes to the spacecraft design.
3.1 Methodology

Step 8: Update/Iterate as necessary to meet requirement:

Typically, many updates to a spacecraft’s M/OD risk assessment are necessary to reflect changes in the spacecraft, BLEs, and M/OD environment models. These updates are achieved after each iteration of the previous steps.
3.2 Impact Risk Assessment Codes:

Several statistical impact analysis tools have been developed for a detailed impact risk assessment of non-trackable particles. These tools allow a fully three-dimensional numerical analysis, including directional and geometrical effects and spacecraft shielding considerations. They normally support the application of different environment and particle/wall interaction models. The tools allow a 3-D display of the results.
3.2 Impact Risk Assessment Codes:

Typical user specified input parameters for these tools are:

1. the orbit and mission parameters,
2. spacecraft attitude, geometry and shielding,
3. the particle type, size, mass density and velocity range to be analysed,
4. the damage equations and related parameters to be applied.
3.2 Impact Risk Assessment Codes:

the number of impacts for the specified particle range,
1. the resulting number of damaging impacts (failures) taking into account the spacecraft shielding and damage assessment equations,
2. the mean particle impact velocity (amplitude and direction),
3. the numbers of craters of specified size,
4. the probability of no failure.
3.2 Impact Risk Assessment Codes:

Computer codes used by the PWG members to assess the risk from M/OD impacts include:

1. BUMPER: NASA, JAXA
2. ESABASE/DEBRIS: ESA
3. COLLO, BUFFER, PSC: ROSCOSMOS
4. MDPANTO: DLR
5. SHIELD: BNSC
6. MODAOST: CAST
3.2 Impact Risk Assessment Codes:

MODAOST: CAST

Procedure:
Both of the space debris environment models and the meteoroid model have been integrated in MODAOST. The M/OD environment results should be given by filling the mission parameters and finite element model could be defined by the user or provided by older FE model samplings. [Zheng et al., 2005; Sun et al., 2007]
3.2 Impact Risk Assessment Codes:

MODAOST: CAST

Flux Models Implemented

*Meteoroids:*
• Model from [Gruen et al., 1985; Anderson (ed.), 1994]

*Space Debris:*
• NASA 91 [Anderson (ed.), 1994]
• ORDEM 96  [Kessler et al., 1996]
• ORDEM 2000 [Liou et al., 2002]
3.2 Impact Risk Assessment Codes:

MODAOST: CAST

Damage Equations Implemented

Presently, damage equations for the following configurations are implemented:
• single wall [Cour-Palais]
• single bumper [Christiansen]
• stuffed whipple[Christiansen]
• multi-shock shield[Christiansen]
3.2 Impact Risk Assessment Codes:

**MODAOST: CAST**

Special Features/Comments:

- Powerful ability of modelling complex spacecraft
- Easy achievement of the traditional FE model
- High-accuracy of handling complex structures (partly shadowing is considered)
- User-friendly interface
3.2 Impact Risk Assessment Codes:

Calibration Results

Calibration runs were performed by different agencies, using their codes. A summary of available results are presented in Table 1 for the cube. More detailed results for each face of the cube case, for each element of the space station case (cylinders and cube) are generally available. Detailed results for some of the codes are presented in [Version 4.0 of the IADC Protection Manual. Germany: 2009]
### 3.2 Impact Risk Assessment Codes: Calibration Results

Table 1  Calibration results for the cube

<table>
<thead>
<tr>
<th></th>
<th>BUMPER</th>
<th>ESAB./Debris</th>
<th>MDPANTO</th>
<th>COLLO</th>
<th>SHIELD</th>
<th>MODAOST</th>
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<tbody>
<tr>
<td><strong>Type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NASA 2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d &gt; 0.1 mm</td>
<td>2.131E+01</td>
<td>n.a.</td>
<td>2.139E+01</td>
<td></td>
<td>2.143E+01</td>
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<tr>
<td>d &gt; 1.0 cm</td>
<td>2.876E-06</td>
<td>n.a.</td>
<td>2.872E-06</td>
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<td>2.873E-06</td>
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<tr>
<td>p &gt; 1.0 mm</td>
<td>3.528E-01</td>
<td>n.a.</td>
<td>3.360E-01</td>
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<td>3.368E-01</td>
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<tr>
<td>single</td>
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<td>1.639E+00</td>
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<td>double</td>
<td>2.373E-05</td>
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<td>2.257E-05</td>
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<td>2.303E-05</td>
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<tr>
<td>Meteoroid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d &gt; 0.1 mm</td>
<td>2.221E+01</td>
<td>2.12E+01</td>
<td>2.164E+01</td>
<td></td>
<td>2.164E+01</td>
<td></td>
</tr>
<tr>
<td>d &gt; 1.0 cm</td>
<td>1.398E-06</td>
<td>1.30E-06</td>
<td>1.360E-06</td>
<td></td>
<td>1.362E-06</td>
<td></td>
</tr>
<tr>
<td>p &gt; 1.0 mm</td>
<td>1.013E-01</td>
<td>8.30E-02</td>
<td>9.064E-02</td>
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<td>8.812E-02</td>
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<td>6.204E-01</td>
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<td>1.142E-05</td>
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</tr>
</tbody>
</table>
3.2 Impact Risk Assessment Codes:

Applications of Impact Risk Assessment Codes

Protection structures manned spacecraft. During preliminary design phase, MODAOST was used to assess the impact risk and the result was used to guide the protection design. PNP risk has been calculated many times in order to meet the requirement and two specific ballistic limited curves achieved by HVI tests have been integrated into MODASOT system.
3.2 Impact Risk Assessment Codes: Applications of Impact Risk Assessment Codes

Protection structures manned spacecraft. During preliminary design phase, MODAOST was used to assess the impact risk and the result was used to guide the protection design. PNP risk has been calculated many times in order to meet the requirement and two specific ballistic limited curves achieved by HVI tests have been integrated into MODASOT system.
§ 4
HVI Testing and M/OD Protection in CAST
Why Hypervelocity Impact tests?

- To design effective shielding for spacecraft and to evaluate the risk posed by debris and meteoroids, we must be able to perform tests in the laboratory. Hypervelocity Impact testing has some extreme requirements.

- HVI tests are necessary to:
  - obtain the reference points of BLEs within the testable range and their verification;
  - provide data for testing (verification, calibration) of the numerical codes (including models of materials behaviour under HVI conditions).
The role of HVI experiments

HVI Test Facilities

HVI Test Data

BLEs

Materials EOS

Validation

Numerical Simulations

HVI Data Files
- Whipple Shields
- Pressure Vessels
- Carbon Composites
- Honeycomb
- Thermal Blankets
- Stuffed Whipple
- Electrical Cables
- Solar Arrays
- Tethers
- etc.
4.1 Hypervelocity Impact Testing Facilities in CAST

Two stage Light-Gas Gun

- Caliber $\Phi18$
- Launch Speed $2-7\text{km/s}$
- Projectile: aluminium alloy spheres and cylinders, 1-15mm in diameter, 0.0015-5g.
Laser-drive flyer system

- Laser energy: 20J, pulse
- Launch Speed: 1-10km/s
- Projectile: metal foil, 0.5-3mm in diameter, 3-25μs in thickness.

Staff include 1 Professor, 5 doctors, and graduated students.
4.2 Hypervelocity impact (HVI) Research in CAST

1. Development of new shield with high protection performance
2. HVI characteristics of MLI
3. Ballistic limit Curve of porthole glass
4. Development of Debris cloud model
5. Ballistic limit Equations of protection shields
7. Hypervelocity launch technique (V>7km/s)
8. Shape effects of projectile in HVI
9. Development of Laser-driven flyer techniques
10. Velocity Measuring technique for micro-flyer
11. the hypervelocity impact cumulative effects of micro M/OD on the outer surfaces functional of materials of spacecraft
1. Develop new concept shield with high performance

Characters of previous study/research:

- More than two bumpers;
- New composite;
- Complex structure;
- High performance.

Application in our spacecraft:

- Can not get these new materials;
- Can not reduce its weight;
- Linkage is complicated.

Question:

Is there a kind of simple shield with high performance?
Shock wave propagation in bumper:

(a) A point in bumper material.  (b) History of shock wave intensity of the point.
How to increase the shadow area?

Three methods to increase the shadow area:

(a) Promote the initial impact pressure.
(b) Promote / expand the middle region.
(c) Prolong the duration of shock wave.
Fig. 1 The sketch of Whipple Shield and Gong-Hou Shield
Comparison with other enhanced shields:

Characters of Gong-Hou Shield

- Simple construction
- Higher performance
- Routine materials
- Easy to be used and fixed.
The performance of Gong-Hou shield increases more than 50% at 6.4 km/s compared to Whipple shield. While at 4.5 km/s, the BL of Gong-Hou Shield increases 64%.
Image of specimens of Gong-Hou shield

Penetration hole comparison between Gong-Hou Shield and Whipple shield

V=6.38km/s  d=6.5mm
Shot 1-1#  V=6.37 m/s  D=6.0mm
2. HVI characteristics of MLI

Multilayer Insulation Thermal Blanket (MLI) are widely used on spacecraft, which directly exposes to space environment. If it is impacted by space debris, part of its thermal protection will be lost. So it is urgent to study the HVI characteristics of MLI and promote its protection capacity against space debris.

Specimen before experiment

Front: Φ4.8mm hole

Back: Φ16.5mm hole

MLI (installed on honeycomb)
BLCs of honeycomb with enhanced MLI and routine MLI:

CAST

NASA

20 MIL + 5 Kevlar
Conclusion of HVI research on MLI:

1. The experiments show that the performance of honeycomb covered with enhanced MLI increases 200% compared to the routine one.

2. The BLE of honeycomb with enhanced MLI is obtained.

3. This kind of design is of important use in protection against space debris.
3. BLC of porthole glass

The sketch of porthole in spacecraft:
In-situ impact morphology on glass

Ground experiment result
Depth of crater versus momentum

\[ P_C = 0.688 (mV)^0 \]

Diameter of spallation versus momentum

\[ D_1 = 11.64(mV)^{0.338} \]
Failed
Passed

Critical diameter (mm)

Velocit
y (km/s)

BLC of porthole glass
Conclusion:

(1) The ballistic limit (BL) of fused quartz is 12mm when exposed to space debris. That is why the porthole glass of ISS and Space Shuttle was chosen to be 12mm.

(2) The BL shows that when the diameter of projectile is larger than 2.5mm, the 12mm glass can be penetrated, otherwise, it can’t. That mean the BL of 12mm glass is 2.5mm.

(3) The risk assessment show that, the impact possibility of space station by debris larger than 2.5mm is less than 1. So 12mm glass can enable to protect spacecraft.
4. Debris cloud model

Classical morphology of debris cloud:

Debris cloud model is need to founded to analyze the characters of debris cloud and predict the damage of rear wall, so as to help to found ballistic limit equation of shield.
The existed models:

Piekutowski model

First-principle model

Schäfer model
Swift model

Schonberg model
Our work:

X-ray image of debris cloud

The new debris cloud model
Verification:

The results of new model show that $\frac{V_{ap}}{V_0}$ and $\frac{V_{cp}}{V_0}$ are identical with Schonberg after 4.5km/s
77. Hypervelocity launch technique (V>7km/s)

- Complex structure, high cost
- \( V_{\text{limit}} < 7\text{km/s}, \text{tremendous damage to LGG when } V>7\text{km/s} \)

Mass versus velocity of several launch instruments
Configuration of pillow:

Add an extra device on LGG, in which pillow will impact flier-plate. The flier-plate can reach ~16km/s.
Quasi-isentropic compress:

\[ Z(x) = Z_0 + A \left( \frac{x}{d} \right)^p \]
Pillow technique progress

- 2006: Thornhill, Chhabildas
- 1995: Chhabildas
- 1992: Chhabildas
- 1983: Chhabildas, Barke

Pressure: 72 GPa

- 0.5 mm AL – Ti flier plate: 12.2 km/s
- 0.5 mm AL – Ti flier plate: 15.8 km/s
- 0.5 mm AL – Ti flier plate: 18.9 km/s
- 0.5 mm AL – Ti flier plate: 18.9 km/s
- 0.5 mm AL – Ti flier plate: 18.9 km/s
Design of Pillow:

\[ Z(x) = Z_0 + A(x/d)^P \]

\( P=2: \) Best

Different \( P \) and their impact pressure
Our work:

<table>
<thead>
<tr>
<th>Material</th>
<th>Thick (mm)</th>
<th>Density (g/cm³)</th>
<th>$C_0$ [km/s]</th>
<th>Impedance ($\times 10^9$g/m²s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>93W</td>
<td>1.3</td>
<td>17.64</td>
<td>4.005</td>
<td>70.648</td>
</tr>
<tr>
<td>OFC</td>
<td>0.4</td>
<td>8.93</td>
<td>3.96</td>
<td>35.363</td>
</tr>
<tr>
<td>TC₄</td>
<td>0.4</td>
<td>4.45</td>
<td>4.695</td>
<td>20.893</td>
</tr>
<tr>
<td>Al</td>
<td>0.6</td>
<td>2.70</td>
<td>5.328</td>
<td>14.386</td>
</tr>
<tr>
<td>MB₂</td>
<td>1.2</td>
<td>1.77</td>
<td>4.500</td>
<td>7.965</td>
</tr>
</tbody>
</table>
Simulation model:

1—Pillow
2—bumper
3—Flier plate
4—inner tube
5—Launch tube

Bumper material effect:

- **Lexan**
  - 9.909 km/s

- **TPX**
  - 11.45 km/s
Cushion thickness effect:

Vp=5km/s:

- $t_{\text{bumper}} \leq 1.1\text{mm}$ or $t_{\text{bumper}} \geq 2.3\text{mm}$, flier plate breaks up.
- $1.8\text{mm} \leq t_{TPX} \leq 2.2\text{mm}$, flier plate bends.

Velocity of flier plate versus bumper thickness
Influence of flier plate diameter to its velocity:

$V_p = 5\text{km/s}$:

- $D_f \leq 4\text{mm}$, flier plate breaks up;
- Velocity decreases when the diameter of flier plate increases.
Velocity of Pillow and $V_f/V_p$:

- $V_f/V_p$ decreases as a function of velocity of Pillow;
- The quasi-isentropic compress effect decrease as the pillow velocity increases.
Conclution

1. TPX is a better bumper material compared to lexan. (best thickness: 1.5mm)

2. Ti flier palte Φ 4mm × 1mm

3. Maximum velocity: 13.01km/s
8. Shape effects of projectile during HVI

Debris shape:

Table: Distribution of fragment shapes from satellite orbital characterization impact test (SOCIT) experiment.

<table>
<thead>
<tr>
<th>Shape</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fragments</td>
<td>36</td>
<td>60</td>
<td>15</td>
<td>1</td>
<td>628</td>
<td>96</td>
<td>12</td>
<td>2</td>
<td>1112</td>
<td>2799</td>
</tr>
<tr>
<td>Among the 112 largest fragments</td>
<td>9</td>
<td>33</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>56</td>
<td>0</td>
</tr>
<tr>
<td>Among the rest of smaller fragments</td>
<td>27</td>
<td>27</td>
<td>5</td>
<td>1</td>
<td>628</td>
<td>96</td>
<td>10</td>
<td>0</td>
<td>1056</td>
<td>2799</td>
</tr>
</tbody>
</table>

Shapes: 1=Flat plate; 2=Curled plate; 3=Box; 4=Sphere; 5=Flake; 6=Rod; 7=Cylinder; 8=Box and plate; 9=Other; 10=Nugget (cube).

Sphere: 0.02%  Flake: 13.19%  Other: 23.43%  Cube: 58.79%
The chosen shape:
sphere (standard shape), cube, and flake

Characteristic length (based on Radar Cross Section):

<table>
<thead>
<tr>
<th>Shape</th>
<th>Calculation function for $L_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>$L_C = D$</td>
</tr>
<tr>
<td>Cube</td>
<td>$L_C = \frac{L}{3} \left(\sqrt{3} + \frac{2\sqrt{6}}{3} + \sqrt{2}\right)$</td>
</tr>
<tr>
<td>Flake</td>
<td>$L_C = \frac{1}{3} \left(\sqrt{2L^2 + T^2} + \frac{2L\sqrt{L^2 + T^2}}{\sqrt{2L^2 + T^2}} + \frac{2LT}{\sqrt{L^2 + T^2}}\right)$</td>
</tr>
</tbody>
</table>
Orientations considered using the 26-view methodology

### Normal Target Impacts

<table>
<thead>
<tr>
<th>Cube Case</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face On</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>6/26</td>
</tr>
<tr>
<td>Edge On</td>
<td>0</td>
<td>45</td>
<td>0</td>
<td>12/26</td>
</tr>
<tr>
<td>Point On</td>
<td>0</td>
<td>45</td>
<td>45</td>
<td>8/26</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flake Case</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Face (C)</td>
<td>0</td>
<td>90</td>
<td>0</td>
<td>2/26</td>
</tr>
<tr>
<td>Edge (A or B)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4/26</td>
</tr>
<tr>
<td>Point (A-B)</td>
<td>0</td>
<td>0</td>
<td>45</td>
<td>4/26</td>
</tr>
<tr>
<td>Edge A-C</td>
<td>0</td>
<td>45</td>
<td>0</td>
<td>8/26</td>
</tr>
<tr>
<td>Point A-B-C</td>
<td>0</td>
<td>45</td>
<td>45</td>
<td>8/26</td>
</tr>
</tbody>
</table>
Image of debris cloud

Orientation effect of Cube projectile during hypervelocity impact.

Debris cloud takes on different shapes.
Orientation effect of Flake projectile during hypervelocity impact.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Face B or C</th>
<th>Edge B-C</th>
<th>Edge A-B or A-C</th>
<th>Point A-B-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Y view</td>
<td><img src="image1" alt="Debris Cloud" /></td>
<td><img src="image2" alt="Debris Cloud" /></td>
<td><img src="image3" alt="Debris Cloud" /></td>
<td><img src="image4" alt="Debris Cloud" /></td>
</tr>
<tr>
<td>X-Z view</td>
<td><img src="image5" alt="Debris Cloud" /></td>
<td><img src="image6" alt="Debris Cloud" /></td>
<td><img src="image7" alt="Debris Cloud" /></td>
<td><img src="image8" alt="Debris Cloud" /></td>
</tr>
</tbody>
</table>

Debris cloud takes on different shapes
Characteristic parameters of debris cloud:

$D_W$: radical wideness;
$L_E$: expanding length;
$L_I$: interface of projectile and bumper fragment.
Penetration in bumper:

V=5km/s; Cube projectile

V=5km/s; Flake projectile
Diameter of penetration in bumper:

Sphere and Cube

Flake
Front-end velocity and expanding velocity when impacted by cube projectile:

- Front-end velocity
- Expanding velocity

Graphs showing the relationship between impact velocity and front-end velocity, as well as expanding velocity, for different orientations (face on, edge on, point on).
Characteristic parameters of maximum fragment in debris cloud:

<table>
<thead>
<tr>
<th>Shape</th>
<th>coordinate (mm)</th>
<th>Kinetic energy (mJ)</th>
<th>Momentum in x-axis (mg·m·s⁻¹)</th>
<th>Momentum in y-axis (mg·m·s⁻¹)</th>
<th>Momentum in y-axis (mg·m·s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>(3.13,1.85,5.66)</td>
<td>79</td>
<td>445</td>
<td>179</td>
<td>594</td>
</tr>
<tr>
<td>Cube</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>face</td>
<td>(8.54,9.62,1.66)</td>
<td>199</td>
<td>263</td>
<td>243</td>
<td>44</td>
</tr>
<tr>
<td>edge</td>
<td>(2.91,4.84,0.50)</td>
<td>21</td>
<td>110</td>
<td>148</td>
<td>69</td>
</tr>
<tr>
<td>point</td>
<td>(2.88,-2.33,-5.75)</td>
<td>45</td>
<td>222</td>
<td>-132</td>
<td>-270</td>
</tr>
<tr>
<td>Face (A)</td>
<td>(5.42,0.625,8.8)</td>
<td>25</td>
<td>69</td>
<td>2</td>
<td>96</td>
</tr>
<tr>
<td>Flake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Face B or C</td>
<td>(35.9,-0.19,-2.47)</td>
<td>13400</td>
<td>6720</td>
<td>-26</td>
<td>-421</td>
</tr>
<tr>
<td>Edge (B-C)</td>
<td>(38.9,0.57,-2.96)</td>
<td>38600</td>
<td>18300</td>
<td>-12</td>
<td>-1410</td>
</tr>
<tr>
<td>Edge A-B</td>
<td>(3.66,1.7,-6.54)</td>
<td>95</td>
<td>380</td>
<td>95</td>
<td>-370</td>
</tr>
<tr>
<td>A-C point</td>
<td>(31.3,4.76,7.27)</td>
<td>36500</td>
<td>19700</td>
<td>2690</td>
<td>4660</td>
</tr>
<tr>
<td>A-B-C point</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Conclusion:

1. Space debris has many kinds of shapes, little of which are sphere. While cube and flake are the most common shape;

2. The penetration and debris cloud of cube and flake are totally different from that of sphere;

3. Cube and flake are more harmful than sphere to spacecraft.
9. LDF (Laser-Driven Flyer) system in CAST

- Schematic diagram of LDFT in CAST
  - To simulate micro space debris (diameter<1mm)
• Laser parameters
  – Nd:YAG laser
  – Wavelength: 1064nm
  – Pulse duration (FWHM) 10ns
  – Energy range: 0.1\(\text{J}\) – 2\(\text{J}\)
  – Spot diameter > 700\(\mu\text{m}\)
  – Frequency: 1Hz
  – Beam shaping ” top-hat”
  – Lens \(f=200\text{mm}\) – 400\(\text{mm}\)
• Vacuum chamber
  – 10\(^{-3}\)\(\text{Pa}\)
• Flyer target
  – Substrate materials: K9 glass and fused silica
  – Single layer: AL, Ti and Ta
  – Multi-layer: Cr/AL, Cr/AL/SiO2
  – Thick of metal film: 3–10μm, AL foil: 13 μm and 26 μm
  – Deposit method: magnetron sputtering, electron beam evaporation, ion beam sputtering, field-assisted diffusion and Al foil.

Appearance after launching on a Al flyer target deposited by ion beam sputtering
• Velocity measurement system
  – PVDF piezoelectricity sensor
  – Non-touched laser profile velocity measurement system
    • Measurement error: <10 (if v<5km/s, the error is no more than 4 , and v~10km/s error ~9 )
    • Real time measurement in HVI experiments

Oscillograph
  – Time resolution: 2.5GHz

Microscope
  – × 50
10. Research on LDFT
• Analysis of factors in determining flyer velocity
Flyer velocity is not sensitive to pulse duration

Higher flyer velocity is easy to achieve using thin film
• Influence of film structure

- Single layer
- Multi-layer

- Glass/Cr/Al—(Glass:50nm:3μm)
• Deposit techniques

- E-beam evaporation
- Magnetron sputtering
- Ion beam sputtering
- Field-assisted diffusion
• Binding intensity
  - The velocity of flyer is increased significantly with the inclusion of Cr layer which can improve the binding intensity between the substrate and the metal film.
Flyer velocity exceeding 10km/s

- K9/Cr/Al—(K9/50nm/5μm) flyer target prepared using ion beam sputtering
  - A flyer plate with diameter about 1mm and 5 μm thick was accelerated to 10.4km/s at 853mJ laser energy.

Fused silica/Cr/Al/SiO2—
(glass/50nm/3 μm/100nm) flyer target prepared using E-beam evaporation.
Flyer velocity ranges from 9 km/s to 11 km/s with the laser energy no more than 1J.
Velocity Measurement method:

Schematic diagram of Non-touched laser profile velocity measurement method for LDFT system

\[ \sigma_v = \sqrt{\left( \frac{\partial v}{\partial d} \right)^2 \sigma_d^2 + \left( \frac{\partial v}{\partial t} \right)^2 \sigma_T^2} = \sqrt{\left( \frac{1}{\Delta t} \right)^2 \sigma_d^2 + \left( -\frac{d}{\Delta t^2} \right)^2 \sigma_T^2} \]

Error analysis: error can be controlled by changing the value of d.


- **2006**: PVDF
- **2007**: Al foil
- **2008**: Magnetic sputtering
- **2009**: E-beam evaporation
- **2010**: Laser profile velocity measurement

- *Exceeding 8km/s*:
  - Beam shaping
  - Ion sputtering
  - Field-assisted

- *Exceeding 10km/s*:
  - E-beam evaporation
  - Ion sputtering
  - Laser profile velocity measurement
11. HVI experiments

- Fused silica
• K9 glass
• Optic Solar Reflector
§ 5

Orbital Debris Mitigation in CAST
### Orbital Debris Mitigation Standards in CAST & China

1. **QJ3221-2005** Orbital Debris Mitigation Requirements *(promulgated)*
2. **KJSP-T-1-01** rules of Spacecraft passivation design *(under promulgated)*
3. **KJSP-T-1-02** Requirements of GEO Spacecraft treatment and implement after task *(under promulgated)*
4. **KJSP-T-1-03** Requirements of LEO Spacecraft treatment and implement after task *(under promulgated)*
5. **KJSP-T-1-04** Control Requirements and design rules for operational Debris of Spacecraft *(under promulgated)*
6. **KJSP-T-1-05** residual propellant measuring and estimating of Spacecraft *(under promulgated)*
7. **KJSP-T-1-06** procedure Requirements and risk assessment of reentry of Spacecraft *(under promulgated)*
8. **KJSP-M-1-01** Management Requirements for Orbital Debris Mitigation of Spacecraft *(under promulgated)*
Thank you!