OVERVIEW OF THE INTER AGENCY DEBRIS COMMITTEE PROTECTION MANUAL

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ABSTRACT

Man's enthusiasm for exploring space has resulted in the launch of many payloads over the years, leading to the creation of a man-made orbital blanket of debris around the Earth in addition to the meteoroid hazard. Risk analysis studies have indicated space debris or meteoroids impact damages can have a wide range of effects on spacecraft. The primary objective of the Protection Manual (PM) is to capture results of interchange and cooperative activities among members of the Protection Working Group of the Interagency Space Debris Coordination Committee (IADC). The PM provides the framework that allows comparable meteoroid/orbital debris (M/OD) risk assessments between member agencies. In particular, the PM provides a standard methodology for meteoroid/debris risk assessments, a mean to cross-calibrate risk assessment tools, documentation of reliable ballistic limit equations, procedures and results used to calibrate member hypervelocity impact test facilities, and description of validation activities for hypervelocity impact simulation codes.

1. INTRODUCTION

The naturally occurring meteoroid environment, both in the neighbourhood of the Earth and further afield, was considered for space programmes like NASA's Apollo missions in the nineteen sixties, Soviet Salut and Mir space stations in the seventies and later, and ESA's Giotto mission to Comet Halley in the eighties. Man's enthusiasm for exploring space has resulted in the launch of many payloads over the years, leading to the creation of a man-made orbital blanket of debris around the Earth in addition to the meteoroid hazard. Since the beginning of the space age and the launch of Sputnik-1 on 4 October 1957, there have been more than 3000 launches, leading to some 3600 satellites being placed in orbit. For each satellite launched, several other objects are also injected into orbit, including rocket upper stages, instrument covers, etc. Accidental, and sometimes deliberate, collisions between or explosions of such objects have created a very large number of fragments of varying sizes over the years.

Risk analysis studies have indicated space debris or meteoroids impact damages can have a wide range of effects on spacecraft. A simple impact on an electronics box cover can generate internal fragments (i.e., spall particles) which can fatally degrade a sensitive electronic equipment. Pressure vessels can leak or burst and lead to the premature termination of the mission with possible creation of more debris. Designers need data to build spacecraft able to cope with the space debris threat. It is thus imperative to define a coherent set of damage laws addressing the various effects of hypervelocity impacts.

However, it has to be recognized there is a huge number of spacecraft configurations, each one with various and peculiar exposed surfaces. In addition, the penetration of an external wall does not necessarily mean the loss of the mission.

Considering the above constraints, the content of the Protection Manual [1] is focused on the most critical topics related to spacecraft protection : impact risk assessment, damage laws for most common material and configurations, system aspects of impact damage, performances and limitations of available test

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techniques, verification of the damage laws in the high velocity regime (above 10 km/s) by numerical simulation.

The aim of this document is to provide a synthesis of the knowledge and experience available among the contributors with respect to spacecraft protection against orbital debris and micro-meteoroids. The primary objective of the Protection Manual (PM) is to capture results of interchange and cooperative activities among members of the Protection Working Group (PWG) of the Interagency Space Debris Coordination Committee (IADC). The PM provides the framework that allows comparable meteoroid/orbital debris (M/OD) risk assessments across the spectrum of member agencies. In particular, the PM provides a standard methodology for meteoroid/debris risk assessments, a means to cross-calibrate risk assessment tools, documentation of reliable ballistic limit equations, procedures and results used to calibrate member hypervelocity impact test facilities, and description of validation activities for hypervelocity impact simulation codes.

The contents of the PM reflect the activities carried out by the meteoroid/debris Protection Working Group of the IADC. Activities of the PWG are illustrated in Figure 1.

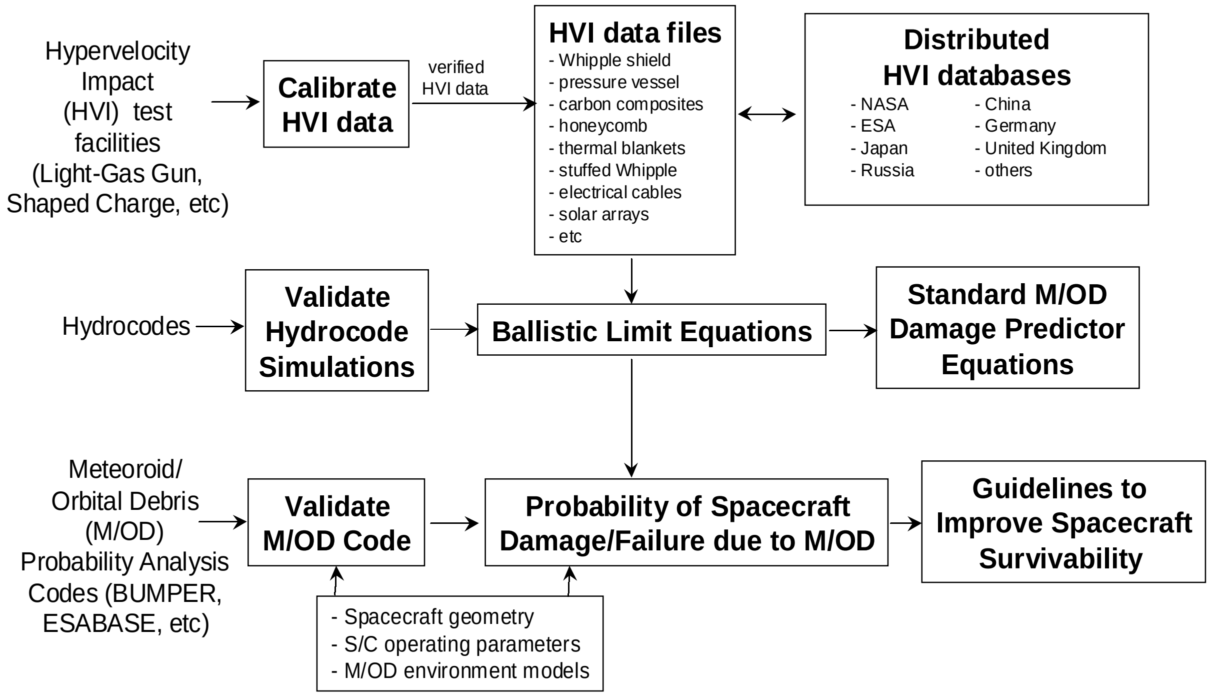

Fig. 1. IADC Protection Working Group Activities: Calibrated Databases and Analysis Codes

2. RISK ASSESSMENT

The standard M/OD risk assessment methodology for spacecraft is illustrated in Fig. 2.

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

1. Identify vulnerable spacecraft components/subsystems. The M/OD analyst must know many details of spacecraft design, operation, failure modes and effects, to properly perform a spacecraft M/OD risk assessment. The systems and components that are exposed to M/OD are identified.

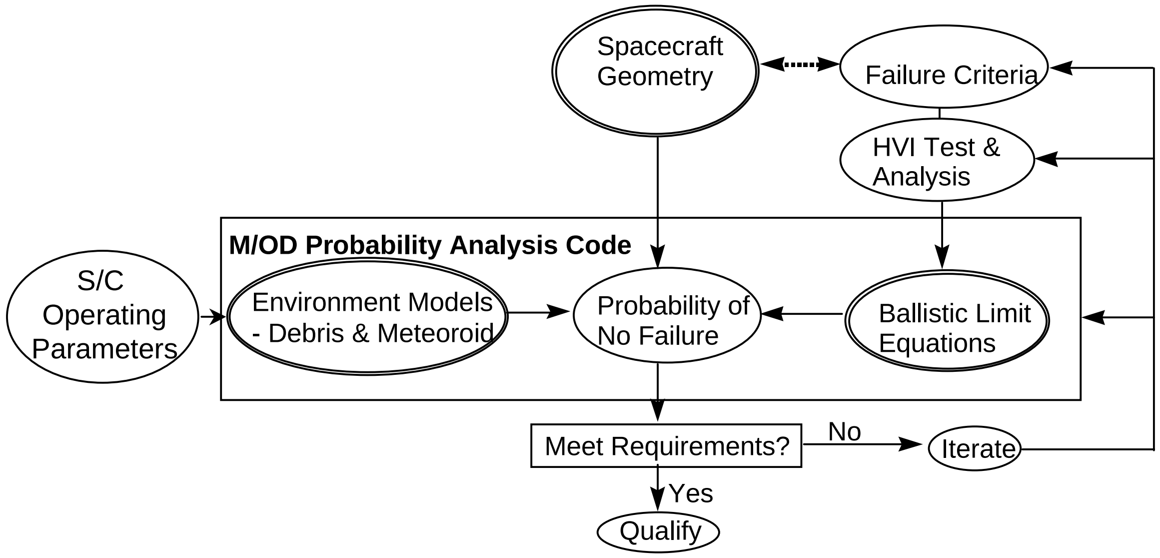

Fig. 2. Standard Process for Assessing Spacecraft Meteoroid/Orbital Risks

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

3. Determine failure criteria. A very clear failure criteria is defined from the many potential hypervelocity impact damage modes for each spacecraft system. The PM defines many potential damage modes for different spacecraft systems. The failure mode is explicitly defined for each ballistic limit equation.

4. Perform HVI test/analysis to define "ballistic limits". Ballistic limit equations (BLE) are analytical equations that define the particle on the threshold of "failure" of the spacecraft system/component. Failure is defined by the failure criteria selected in step 3. BLEs relate projectile diameter to the impact speed, angle, projectile density and target parameters. BLEs must span the impact velocity range of on-orbit impacts (1-14.5 km/s for debris and 11-72 km/s for meteoroids). These equations are needed in the M/OD risk/probability codes which assess the probability of impact from particles that are of the ballistic limit particle size and greater.
   Hypervelocity impact (HVI) tests are necessary to anchor and verify the ballistic limit equations within the testable range. Two-stage light-gas guns (LGG) typically achieve velocities from 2 km/s to 7 km/s using hydrogen driver gas in the second stage. Higher velocities are necessary to verify BLEs at higher velocities which are possible on-orbit from M/OD impacts. As such, ultra-high speed launchers are being developed and used by the various agencies to assess spacecraft protection performance. These launchers include explosively launched projectiles, 3-stage launchers, and other techniques.
   Hydrocodes, analytical models, semi-empirical approaches and other analysis techniques are used to formulate and/or verify the BLEs.

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. Typically, computer codes are used to perform the probability calculations for complex spacecraft. They have been developed to conduct this analysis in a reliable manner, including the effects of shadowing and/or semi-shadowing from other spacecraft components.

3. BALLISTIC LIMIT EQUATIONS

Ballistic limit equations (BLEs) are developed to define impact conditions (particle size, particle density, impact velocity, impact angle) that results in threshold failure of specific spacecraft components or subsystems. The Protection Working Group uses a combination of hypervelocity impact test results and analyses to determine the BLEs. Hypervelocity impact test techniques are described in paragraph 4. Analyses can include hydrocode and engineering models.

Components and subsystems submitted to evaluation cover a wide range of materials and configurations. Structures made of aluminium or composites, thermal protections, windows and glass, pressure vessels, tethers are considered. Planned work will address propulsion, thermal control, power subsystem, communication and data management subsystem and Attitude and Orbit Control System.

The Protection Manual includes several examples of ballistic limit equations. NASA Ballistic limit equations for Whipple Shields are given below [2], [3]. The notations are as follows: A experimental constant, d_c critical diameter for penetration[cm], t_w thickness of back-up wall [cm], t_b thickness of bumper/shield [cm],ρ_p particle density [g/cm^3], ρ_w back-up wall density [g/cm^3], ρ_b bumper density [g/cm^3], V impact Velocity [km/s], S spacing between 1st bumper and back-up wall [cm], θ impact angle [deg], V_n normal component of impact velocity ($V_n = V \cdot \cos\theta$), σ Yield Strengh of back-up wall [ksi].

For $V_n \leq 3$ km/s

$$d_c = \left[\frac{t_w(\sigma/40)^{1/2} + t_b}{0.6(\cos\theta)^{5/3} \cdot \rho_p^{1/2} \cdot V^{2/3}}\right]^{\frac{18}{19}} \quad (1)$$

For $V_n \geq 7$ km/s.

$$d_c = \left[\frac{A \cdot t_w^{2/3}(\sigma/70)^{1/3}}{(\cos\theta)^{2/3} \cdot \rho_p^{1/3} \cdot \rho_b^{1/9} \cdot V^{2/3} \cdot S^{-1/3}}\right] \quad (2)$$

where *A* depends on the details of the shield: Whipple Shield without MLI (A = 3.919),Whipple Shield with MLI on top of the bumper (A = 2.9754). Linear interpolation is used between low and high velocity regions. These formulas are within the ranges of conditions for which they have established [2]. More formulas are presented in the Protection Manual.

4. TEST METHODS AND FACILITIES CALIBRATION

HVI tests are necessary to obtain the reference points of BLEs within the testable range and to provide data for evaluating numerical simulation computer codes including modeling of materials behaviour under HVI conditions. Various acceleration techniques are available

- one-stage powder guns;
- two-stage light-gas guns (LGG);
- electromagnetic launchers;
- electrostatic launchers;
- explosive launchers.

Instrumentation is of prime importance to get a maximum of information from the tests. The most frequently used measurement techniques are: high speed optical camera, multiple X-ray photography, pressure gauges embedded in the targets and post-test characterization of the damage.

Two-stage light-gas guns (LGG) typically achieve velocities from 2 km/s to 7 km/s using hydrogen driver gas in the second stage. Higher velocities are necessary to verify BLEs at impact velocities representative of in orbit environment. As such, ultra-high speed launchers are being developed and used by the various agencies to assess spacecraft protection performance. These launchers include explosively launched projectiles, 3-stage launchers, and coupled techniques.

4.1 Light Gas Guns Calibration Procedures

The purpose of the calibration is to ensure test results are reliable. A good shot can be defined as : a test with a complete record of the test conditions (mass and size of the projectile, dimension and mass of the target, impact incidence), good diagnostics (impact velocity, projectile integrity prior to impact, pressure in the test chamber) , impact velocity within 0.1 km/s of the desired velocity and no degradation of the target by objects which are not the projectile(i.e., a clean test). The procedure to be used is:

1. Hypervelocity impact test series are conducted by one agency (A) on multi-layer shields (usually 4 to 5 tests). All tests are to be near perforation/detached spall ballistic limit of the shields.
2. Exact same test articles are prepared by the first agency (A) and shipped to the second agency (B) with projectiles and test instructions.
3. Agency B completes the tests and sends targets back to Agency A.
4. Agency A may have to repeat some tests to obtain close agreement in impact conditions such as impact velocity obtained at Agency B.
5. Comparison of results are made by both Agencies A & B. Results are presented at IADC PWG meetings and documented in the PM.

4.2 ESA-NASA Calibration

ESA and NASA JSC-Houston test facilities exchanged test articles in 1992. ESA has performed calibration shots on NASA Multi-Shock Shields and Mesh Double Bumper Shields at Ernst Mach Institut [4]. The target size is 15cmx15cm for the 0.32cm projectile tests, it is 30cmx30cm for the 0.64cm projectile tests, all projectiles are Al2017T4 spheres (Fig. 3). All tests (at NASA & ESA) resulted in bulge but no perforation of the rear wall for the 4 different configurations . Results of the tests indicated similar results are obtained in both test facilities.

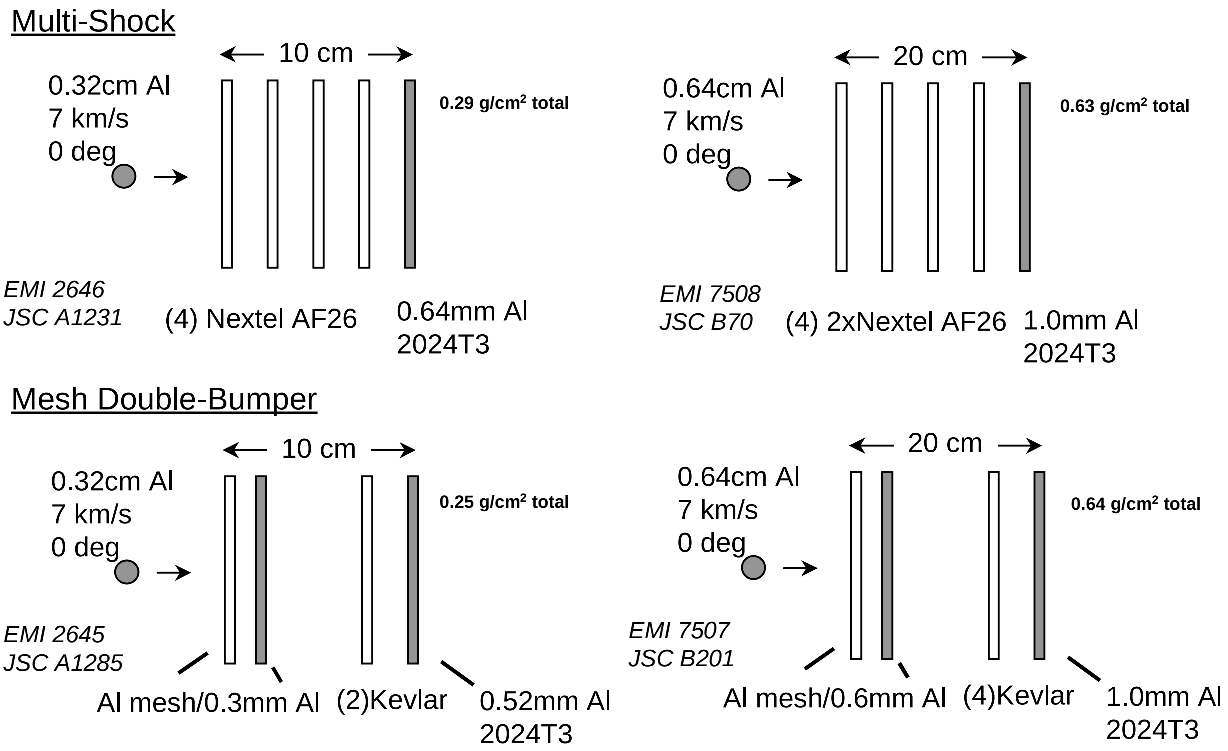

Fig. 3 1992 ESA-NASA Calibration Tests

5. NUMERICAL SIMULATIONS

In order to perform numerical simulation of fast transient events a specific type of code was developed since the early 50s. The so called Hydrocodes or Wave propagation codes allow to study the time resolved development of acoustic and shock wave propagation due to impact, penetration or detonation in fluids and solids.

The nature of this kind of codes is that, based on a spatial and time discretization the conservation equations for mass, momentum and energy are solved. Together with an equation of state (EOS) providing the relationships between pressure, density and internal energy a complete set of equations for hydrodynamic behaviour was given. Since the first applications on atomic detonations involved very high pressures, the material strength was negligible; hence the name "Hydrocodes". Later material strength was added as the sum of the hydrostatic pressure given in the EOS and the deviatoric stress expressed by a stress tensor.

Up to recently, the formulation for modeling particular configurations was either Eulerian or Lagrangian. Eulerian codes require a complete modeling of the volume considered in the problem. The large spacing generally used in Whipple Shields require models with a huge number of elements. Lagrangian codes are not fully adequate for problems with very large material distortions as they require work intensive remeshing. New codes based on the Smoothed Particle Hydrodynamics have emerged to provide an answer to the drawback of the previous formulations. As any numerical simulation, they require in depth comparisons with experimental results to provide a certain level of confidence in the predictions of the codes.

5.1 Validation of Numerical Simulations

Four benchmark test cases are defined hereafter. All the cases cover aluminium shields only. Two cases address Whipple shields at two velocities typical of Light Gas Guns experiments. The two last cases address the more complex configuration of Double Bumper Shields. One test was performed with Light Gas Gun while the last case was an oblique impact test performed with Shaped Charges.

Whipple shield 6.5 km/s

Projectile : 1100 aluminium sphere 5 mm diameter, 6.5 km/s, normal impact (shot line perpendicular to target surface)
Bumper : 2024-T3 aluminium 1.5 mm thick
Spacing : 200 mm
Backwall : 2024-T3 aluminium 1.5 mm thick

Whipple shield 3.1 km/s

Projectile : 1100 aluminium sphere 10 mm diameter, 3.1 km/s, normal impact (shot line perpendicular to target surface)
Bumper : 2024-T3 aluminium 2 mm thick
Spacing : 200 mm
Backwall : 2024-T3 aluminium 10 mm thick

Double Bumper Shield 8 km/s

Projectile : 1100 aluminium sphere 4 mm diameter, 8.0 km/s, normal impact (shot line perpendicular to target surface)
First bumper: 2024-T3 aluminium 0.8 mm thick
Spacing: 60 mm
Second bumper: 2024-T3 aluminium 0.5 mm thick
Spacing: 60 mm
Backwall: aluminium 3.2 mm thick made of 0.8 mm 2024-T3 + 0.15 mm adhesive + 3.10 mm AlMg3

Double Bumper Shield 11 km/s Oblique Impact

Projectile : 99.9% pure aluminium 1.1 gram, length / diameter ratio 4.3 , 11.2 km/s, oblique impact : 45 degrees
First bumper : 6061T4 aluminium 2.5 mm thick
Spacing : 60 mm
Second bumper : 6061-T4 aluminium 2.5 mm thick
Spacing : 60 mm
Backwall : 2219-T851 aluminium 5 mm thick

6. STRUCTURES AND SHIELDS DESIGN

Based on the experience gained with technological work and support to programmes, several recommendations have been made for designing the structure, and thermal control of unmanned spacecraft:
-Use an integrated approach to protection.
-A balance must be struck between the level of structural shielding and the internal arrangement of units.
-Identify the areas of the satellite most vulnerable to debris impact.
-Identify mission-critical and sensitive equipment.
-Consideration of items such as batteries, propulsion tanks and pipes, reaction and momentum wheels and gyros is especially important.
-Use redundant equipments.
-Use redundant wiring and make sure they follow different routes.
-Avoid unprotected wire bundles.
-For internal equipment, move sensitive and critical units away from vulnerable surfaces and/or place them behind (relative to the vulnerable face) less critical units or internal structure.
- Protect internal equipment by enhancing the structure, thermal control, etc., especially in the most vulnerable areas.

7. ONGOING AND FUTURE WORK

Cross calibration of test facilities is still in progress between some agencies. Impact data on various subsystems is added regularly. New hybrid codes are evaluated. Pending availability of funding, it is envisaged to explore new test techniques like pyrotechnic accelerators. More benchmark cases for validation of numerical simulations will be introduced as computer codes mature and as adequate material models are made available.

8. CONCLUSIONS

The aim of this document is to provide a synthesis of the knowledge and experience available among the contributors with respect to spacecraft protection against orbital debris and micro-meteoroids. The primary objective of the Protection Manual (PM) is to capture results of interchange and cooperative activities among members of the Protection Working Group (PWG) of the Interagency Space Debris Coordination Committee (IADC). The PM provides the framework that allows comparable meteoroid/orbital debris (M/OD) risk assessments across the spectrum of member agencies. In particular, the PM provides a standard methodology for meteoroid/debris risk assessments, a mean to cross-calibrate risk assessment tools, documentation of reliable ballistic limit equations, procedures and results used to calibrate member hypervelocity impact test facilities, and description of validation activities for hypervelocity impact simulation codes.

This document is regularly updated to reflect the evolution of the acquired experience. It is intended to provide, in the frame of the IADC activities, guidelines and eventually standards related to spacecraft meteoroid/orbital debris protection design, testing, characterization and verification. It is planned to make the Protection Manual publicly available as it matures.

Acknowledgement : The Protection Manual is the result of a collective work. The authors want to thank all the participants of the Protection Working Group of the Inter-Agency Space Debris Committee.

9. REFERENCES

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