THE INTER-AGENCY SPACE DEBRIS COORDINATION COMMITTEE (IADC) PROTECTION MANUAL

F. Schäfer [1], M. Lambert [2], E. Christiansen [3], S. Kibe [4], H. Stokes [5], H.-G. Reimerdes[6], S. A. Meshcheryakov [7], F. Angrilli [8], Han Zengyao [9]

[1] *Fraunhofer EMI (Ernst-Mach-Institut), Eckerstr. 4, D-79104 Freiburg, Germany, Email: schaefer@emi.fhg.de*
[2] *European Space Agency ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, Email: Michel.Lambert@esa.int*
[3] *NASA Johnson Space Center, Mail Code SX2, Houston, TX, 77058, USA, Email: eric.l.christiansen@nasa.gov*
[4] *Japan Aerospace Exploration Agency (JAXA), 2-4-1 Hamamatsu-cho, Minatu-ku, Tokyo 105-8060, Japan, Email: kibe.seishiro@jaxa.jp*
[5] *Space Department, QinetiQ, Farnborough, GU14 0LX, UK, Email: hstokes@space.qinetiq.com*
[6] *RWTH Aachen, Institut für Leichtbau, Wullnerstr. 7, 52062 Aachen, Email: hg_reim@ifl.rwth-aachen.de*
[7] *Central Institute of Machine Building, TSNIIMASH, 4, Pionerskaya Str., Korolev, Moscow Region, 141070 Russia, Email: Smeshcheryakov@mtu-net.ru*
[8] *University of Padua, CISAS, Via Venezia 1, 35131 Padova, Italy, Email: francesco.angrilli@unipd.it*
[9] *Chinese Academy of Space Technology (CAST), P.O. Box 5142-92, Beijing 100094, China, Email: hanzengyao@hotmail.com*

ABSTRACT

This paper gives an overview of the contents of the of the Protection Manual (PM) ver. 3.3 of April 4, 2004, which was prepared by the Protection Working Group (PWG) of the Inter-Agency Space Debris Coordination Committee (IADC). The objective of the PWG is to exchange results of national and cooperative activities among its member space agencies related to meteoroid/orbital debris (M/OD) risk assessments, design and technology of spacecraft shielding against meteoroids and space debris impacts, and the associated test methods. The PM summarizes all significant results of the member agencies in that area.

1. INTRODUCTION

Since the beginning of the space age and the launch of Sputnik-1 on 4 October 1957, there have been more than 4000 launches, leading to over 9000 satellites and ground-trackable debris currently in Earth orbit (ODQN, 2005). 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.

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 (NASA, 1969), Soviet Salyut and Mir space stations in the seventies and later (Nazarenko *et al.*, 1996), and ESA's Giotto mission to Comet Halley in the eighties (Lainé and Felici, 1982). Risk analysis studies have indicated space debris or meteoroids impact damages can have a wide range of effects (e. g. Lambert, 1990; Christiansen, 2003) ranging from perturbations of mission operations to complete mission failure. For example, an impact on an electronics box cover can generate internal fragments (i.e., spall particles) which can fatally degrade sensitive electronic equipment; pressure vessels can leak or burst and lead to the premature termination of the mission with possible creation of more debris.

There has been clear evidence of hypervelocity impacts on spacecraft in various missions, e. g. on surfaces of EURECA (Drolshagen, 1994), LDEF (Love et al., 1995), the Hubble Space Telescope HST (Drolshagen et al., 2003), and the Space Shuttle (Hyde et al., 2001a). The ISS has weathered reasonably well through 6.4 years of exposure to the meteoroid/orbital debris (M/OD) environments (FGB launch on 20.11.98, through March 2005), with no hardware failures reported due to M/OD impact. However, “thumbnail-sized” impacts on a DC-DC Converter Unit (DDCU) heat pipe have been observed by the crew. Fig. 1 shows an impact crater (3-5mm diameter) on a Service Module window transmitted to the ground in January 2002 (NASA JSC ISAG, 2002). Other direct evidence of M/OD impacts have been found on Multi-Purpose Logistics Module (MPLM) surfaces: During 5 MPLM missions to ISS, 26 hypervelocity impacts have been observed on MPLM exterior surfaces; 2 of these penetrated completely the outer 0.8 mm thick Al-bumper of the module, see Fig. 2 (Hyde et al., 2001b).

Designers need data to build spacecraft able to cope with the space debris threat. It is thus imperative to

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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.

2. THE IADC PROTECTION WORKING GROUP AND THE PROTECTION MANUAL

The primary objective of the Protection Working Group (PWG) of the IADC is to exchange results of national and cooperative activities among its member space agencies on the most critical topics related to spacecraft protection from hypervelocity impacts:

- impact risk assessment
- damage laws for most common materials and configurations
- system aspects of impact damage
- performances and limitations of available hypervelocity impact test techniques, and
- verification of the damage laws in the velocity regime > 10 km/s by numerical simulation.

The PWG presently consists of representatives of the following space agencies:

- ASI (Agenzia Spaziale Italiana)
- BNSC (British National Space Centre)
- CNES (Centre National d'Etudes Spatiales)
- CNSA (China National Space Administration)
- DLR (German Aerospace Center)
- ESA (European Space Agency)
- ISRO (Indian Space Research Organisation)
- JAXA (Japan Aerospace Exploration Agency)
- NASA-JSC (Johnson Space Center)
- NSAU (National Space Agency of Ukraine)
- ROSCOSMOS (Russian Federal Space Agency)

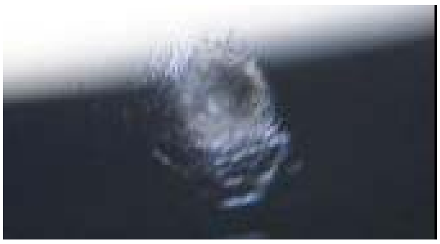

Figure 1. Meteoroid/Debris impact damage on Service Module Window #7

Figure 2. Perforation of MPLM aluminium bumper after Flight STS-102/ISS-5A.1. Hole inside diameter is 1.4 mm, outside diameter is 2.5 mm

The aim of the Protection Manual (PWG, 2004) is to provide a synthesis of the knowledge and experience available among the members of the Protection Working Group (PWG). 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 current version of the protection manual is ver. 3.3 (PWG, 2004). It consists of 5 major chapters and is 227 pages long. The following paragraphs summarize the main contents of the PM chapters and concentrate on selected aspects.

3. METEOROID/ORBITAL DEBRIS RISK ASSESSMENT

To ensure that appropriate protection measures are implemented in spacecraft, it is necessary to assess the meteoroid and debris impact risks. The chapter on Risk Assessment in the PM (PWG, 2004) describes the standard methodology and the principal software codes that are currently available to quantify these risks. Validation of the codes is an important activity of the PWG which is documented in some detail. Typical applications of the codes are also presented, including an assessment of the Automated Transfer Vehicle (ATV).

3.1. Standard M/OD Risk Assessment Methodology

The standard M/OD risk assessment methodology for spacecraft is illustrated in Fig. 3: Based on spacecraft design and orbit parameters, the Probability of No Failure (PNF) of a spacecraft is calculated using environmental flux models for meteoroids/debris (IADC web page, 2005) in combination with suitable ballistic limit equations (BLE) that provide the limit conditions for failure for the structure (concerning BLE see par. 4 of this paper). The Probability of No Failure (PNF) is sometimes referred to as the Probability of No Penetration (PNP). These probabilities are determined using Poisson statistics, which are used for statistical assessment of random events, hence suited to M/OD assessments. The PNF is assessed by the following equation:

$$PNF = \exp(-N) = \exp(-\text{Flux} * \text{Area} * \text{Time}) \qquad (1)$$

Where N is the average number of expected component failures from M/OD impacts over a given time period. N is assessed from the flux (number per unit area per unit time) of M/OD particles that result in failure of the component/subsystem, the exposed area, and the exposure time. The Risk (in percent) of M/OD failure in this case is assessed simply as:

$$Risk = (1 - PNP) * 100 \quad (2)$$

The different steps of the iterative procedure for assessing and reducing spacecraft risks from M/OD impact are described below:

(1) **Identify vulnerable components**. Identify M/OD exposed spacecraft components/subsystems vulnerable to hypervelocity impacts.

(2) **Assess damage modes**. Assess HVI damage modes for each vulnerable and exposed component/subsystem.

(3) **Determine failure criteria**. A clear failure criterion has to be defined from the various potential hypervelocity impact damage modes for each component/subsystem.

(4) **Define Ballistic limit Equations**. Perform Hypervelocity Impact (HVI) tests to define the "ballistic limits" of the relevant structures, from which the Ballistic Limit Equations (BLE) are derived. HVI tests are required to anchor and verify the BLE within the testable range. 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, BLE and M/OD environment models. Typically, computer codes are used to perform the probability calculations for complex spacecraft, including the effects of shadowing and/or semi-shadowing from other spacecraft components.

(6) **Compare M/OD analysis results with goal or requirement**: The analysis results (PNP or PNF) are compared to the 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, the analysis can be considered complete, otherwise continue with step 7.

(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 BLEs. It is often possible to remove engineering conservatism in the BLEs after additional testing is conducted. Other options include changes to the spacecraft design or orientation of the spacecraft in ways to minimize M/OD hazards.

(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.

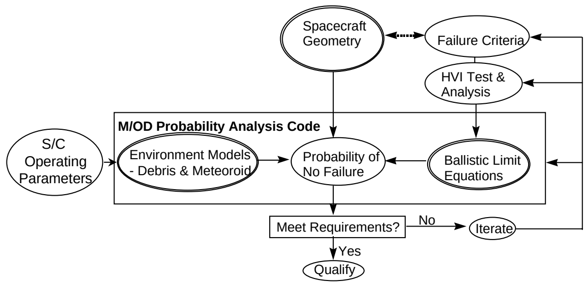

Figure 3. Standard Process for Assessing Spacecraft Meteoroid/Orbital Risks

3.2. M/OD Risk Assessment Tools and Cross-Calibration Procedures

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. Typical user specified input parameters for these tools are:

- the orbit and mission parameters,
- spacecraft attitude, geometry and shielding,
- the particle type, size, mass density and velocity range to be analyzed, and
- the damage equations and related parameters to be applied.

The computed output typically includes:

- the number of impacts for the specified particle range,
- the resulting number of damaging impacts (failures) taking into account the spacecraft shielding and damage assessment equations,
- the mean particle impact velocity vector,
- the numbers of craters of specified size, and
- the probability of no failure.

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

- BUMPER: NASA, JAXA
- ESABASE/DEBRIS: ESA
- COLLO, BUFFER, PSC: ROSCOSMOS
- MDPANTO: DLR
- SHIELD: BNSC

The impact risk assessment tools can be validated to some extend by comparing the results of different codes for well-defined test cases. The results from the "benchmark" test cases performed in the PWG have proven to be useful to calibrate the results obtained and reported by different agencies using different codes. Three generic spacecraft geometries were defined for the validation of the M/OD risk assessment tools:

- a simple box with edge length of 1m
- a simple space station (see Fig. 4)
- a sphere with 1 square meter cross section

4. BALLISTIC LIMIT EQUATIONS

The chapter on Ballistic Limit Equations in the PM (PWG, 2004) provides a description of specific characteristics for each BLE such as: the relevant spacecraft system, subsystem or component (name, use, materials, thickness, gaps, etc); the impact related damage modes or - failure modes of the component/ subsystem; the specific ballistic limit equations with appropriate nomenclature defined; and the limits of applicability and references. Also, for most components/subsystems recommendations on how to improve the protection performance are provided.

Ballistic limit equations (BLEs) are developed to define impact conditions (particle size, particle density, impact velocity, impact angle) that result in threshold failure of specific spacecraft components or subsystems. 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). For each ballistic limit equation the failure criterion is explicitly defined by one of the failure criteria selected in step 3 of par. 3.1. 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. The PWG uses a combination of hypervelocity impact test results and analyses to determine the BLEs. Analyses can include hydrocode- and engineering models.

Components and subsystems for which damage prediction and ballistic limit equations are available in the PM cover a wide range of materials and configurations i.e., structures made of aluminium or composites; single-bumper-, stuffed-, multi-shock-, and special shields; thermal protection systems; windows and glass, pressure vessels, Propulsion Subsystems, Thermal Control Subsystems, Power Subsystems, Tethers, Communication and Data Management Subsystems, and Attitude Control Subsystems. For several configurations more than one BLE is provided. No ranking is provided; the user of the data has to make a selection of a suitable BLE for his/her problem e. g. based on the level of detail the experimental validation of the equation has been described in the PM.

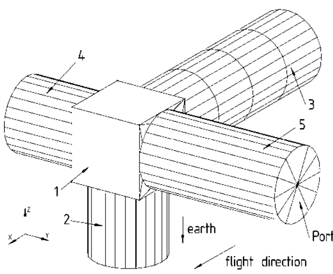

Figure 4. Geometry of the simple Space-Station Model for calibration benchmark test cases

5. TEST METHODS AND FACILITIES CALIBRATION

The chapter on Test Methods and Facilities Calibration in the PM (PWG, 2004) provides a description of test facilities, the PWG calibration procedures for hypervelocity impact launcher facilities, and the status of cross-calibration among PWG representative's launchers.

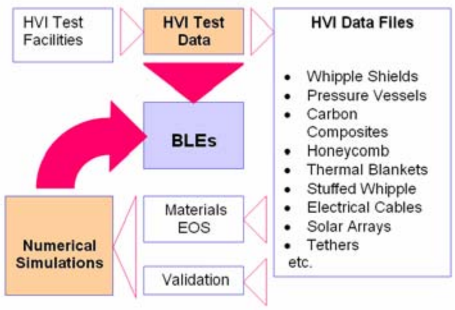

Figure 5. The role of HVI experiments

5.1 Experimental determination of BLE

The most straightforward method of deriving Ballistic Limit Equations (BLE) is to run a series of hypervelocity impact experiments and to analyse and relate the damage data collected. Since the velocity ranges BLEs must span are far away from the capabilities of laboratory hypervelocity launchers, BLEs must be obtained from a combination of laboratory experiments, analytical considerations and numerical simulations. Numerical simulations represent the only means to analysing impact phenomena in the velocity ranges not easily accessible to launch facilities. Numerical Simulations require suitable Equations of State (EOS) and Material Models which are itself a topic of experimental research.

Therefore, HVI tests are necessary to obtain the reference points of BLEs within the testable range and their verification and to provide data for testing of the numerical codes including material models under HVI conditions. The set-up of a test (both launching facility and registration methodology) depends on its aim. It could be either a simple low-cost series of tests, or a detailed set of tests to thoroughly assess the impact process. The facilities typically used for Hypervelocity impact are one-stage powder guns; two-stage light-gas guns (LGG); electromagnetic launchers; electrostatic launchers; explosive launchers.

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.

The following types of measurement technique could be involved:

- high frame-rate optical photography;
- single or multi-flash X-ray photography;
- registration of dynamic pressures, stresses and impulse by gages placed into target;
- registration of time of arrival by contact gages;
- post-test study of damage (craters, holes, etc.)

5.2 Light Gas Guns Calibration Procedures

In order to ensure that hypervelocity impact tests performed at various facilities provide comparable results, the PWG agreed that calibration of the test facilities is important. The availability of cross-calibrated facilities allows to mutually using impact test data e. g. for BLE validation.

The procedure for the facility calibration is:

- Hypervelocity impact test series is 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.
- Exact same test articles are prepared by the first agency (A) and shipped to the second agency (B) with projectiles and test instructions.
- Agency B completes the tests and sends targets back to Agency A.
- Agency A may have to repeat some tests to obtain close agreement in impact conditions such as impact velocity obtained at Agency B.
- Comparison of results is made by both Agencies A & B. Results are presented at IADC PWG meetings and documented in the PM.

Cross calibration campaigns have been performed between the impact facilities of the following agencies:

- ESA - NASA/JSC (1992)
- NASA/JSC - NASDA (1999)
- NASA/JSC - Khrunichev Space Center (2000)
- NASA/JSC - CNES (2001)
- NASA/JSC - CNSA - ESA (2005/ongoing)

All test facilities have provided similar test results so far i.e., have passed successfully the calibration campaign.

As an example, the ESA-NASA Cross-Calibration campaign is described: 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 (Fig. 8) at Fraunhofer EMI (Ernst Mach Institut), Freiburg, Germany. The target size was 15cmx15cm for the 0.32cm projectile tests, it is 30cmx30cm for the 0.64cm projectile tests, and all projectiles were Al2017 T4 spheres (Fig. 8). All tests (at NASA & ESA) resulted in bulge but no perforation of the rear wall for the 4 different configurations. The results of the tests indicated similar results are obtained in both test facilities.

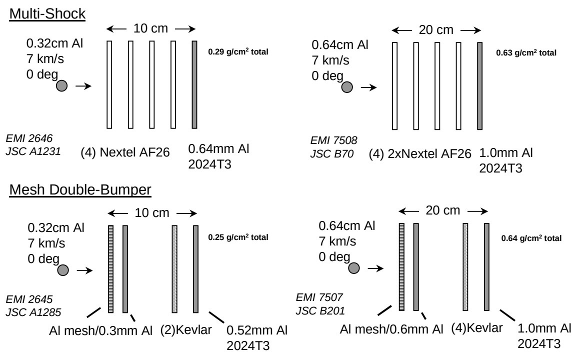

Figure 6. 1992 ESA-NASA Calibration Tests

6. NUMERICAL MODELLING

The chapter on Numerical Modelling in the PM (PWG, 2004) describes the development and application of numerical models to simulate hypervelocity impacts on spacecraft structures and materials. Following an introduction to the modelling approach, this chapter describes the models currently in use by the PWG, and the benchmark scenarios defined to validate them. Other activities covered in the chapter include the development of material models, and numerical simulation examples.

6.1 Overview of Numerical Modelling and Codes

Hydrocodes are used for performing numerical simulation of 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. Material strength is 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 requires models with a huge number of elements. In order to solve the problem of very large deformations, "meshless" methods are applied, where continuum bodies are represented through an array of Lagrangian nodes that are not physically connected by a grid, but whose relative motion is controlled by interpolating functions. Smoothed Particle Hydrodynamics (SPH) has shown to be, up to now, the most promising meshless method for application to hypervelocity impact simulation. Currently the following hydrocodes, based on meshless methods, are widely used within the hypervelocity analysis community:

- AUTODYN, Century Dynamics Ltd.
- EPIC, Alliant Techsystems
- EXOS, University of Texas
- MAGI, Air Force Research Laboratory
- PAMSHOCK, Engineering Systems International
- SOPHIA, Ernst-Mach-Institute
- SPHINX, Los Alamos National Laboratory

6.2 Validation of Numerical Simulations

In order to validate hydrocodes for application to hypervelocity impact, several reference cases of HVI are currently being discussed by the PWG. Codes are validated if they are able to predict the known hole sizes in bumpers, fragment cloud shapes and velocities, and crater sizes or perforation of backwalls to a reasonable accuracy. Four benchmark test cases have been defined for validating hydrocodes, covering aluminium shields only. Two cases address Whipple shields at two velocities typical of Light Gas Guns experiments. The last two cases address the more complex configuration of Double Bumper Shields. The status of the validation campaign is still ongoing.

7. PROTECTION DESIGN RECOMMENDATIONS

This chapter summarises the recommendations that have been produced to help designers in the implementation of debris protection in spacecraft described in the following. The list is not intended to be exhaustive or prescriptive, but is meant to be a useful guide when considering these design issues.

7.1. General Recommendations

Most space debris standards concentrate on the mitigation issue and include only some general recommendations concerning spacecraft protection. In this section the rules published by various space agencies and containing high level guidance on protection are described.

NASA: General guidelines for spacecraft meteoroid and orbital debris protection system design are documented in NASA SP-8042, 1970, National Research Council, 1995, and The Office of Science and Technology Policy, 1995. Program specific meteoroid/debris protection guidelines have been developed for the Shuttle and the Space Station (Loftus *et al.*, 1997; National Research Council, 1997). Implementation of these guidelines for NASA spacecraft follows the techniques described in (Christiansen *et al.*, 1992 and 1999).

ESA: The European Space Debris Mitigation & Safety Standard (EDMS, 2000), has been prepared as part of the series of ECSS Standards intended to be applied in European space projects and applications. The EDMS presents fundamental safety and mitigation requirements and recommendations related to space debris. As part of this, the Standard proposes measures to protect a space vehicle from the debris collision hazard. The following design recommendations are stated:

- Measures should be investigated and applied in order to insure the survivability of space vehicles to debris impacts (for example, shielding) and to decrease the probability of such impacts to occur (for example, avoidance manoeuvres).
- Practices related to the connection and positioning of nominal and redundant devices (for example, an equipment and related system routing) should be optimised to maximise survivability from particle impacts.
- If the risk due to a collision between a space vehicle and space debris exceeds project criteria, the space project should implement appropriate protection measures (for example, shields, redundancies, location, relative positioning) to reduce this risk.

The need for debris protection has also been considered at the highest international levels. For example, the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS, 1999) recommends the following: "Spacecraft designers should consider incorporating implicit and explicit protection concepts into their space vehicles"

7.2. Recommendations for Structure, Thermal Control and Shield Design

The following general set of recommendations has been prepared for designing the structure, shielding and thermal control on an unmanned spacecraft: These have been adapted from (Cour-Palais and Crews, 1990), and subsequently expanded upon by (Turner *et al*., 2000). The following list is an excerpt from the PM:

- Provide the means for melting and/or vaporising particles over a large range of size and velocity.
- Cover the structure with MLI (except for placement on outer bumpers of Whipple Shields, where MLI was found to have a deteriorating effect on protection capability under some circumstances). MLI can be offset from the structure and/or enhanced with materials such as Betacloth, Nextel, and Kevlar for extra resistance.
- Be amenable to simple design and construction, e.g. by using standard processes.
- Any resulting debris, spall or dust from a perforated structure should minimise the risk of subsequent failure or deterioration of spacecraft equipment.
- Avoid adding debris to the orbital environment following an impact, e.g. by trapping it, using exterior materials that do not generate significant secondary ejecta, and using thin outer layers.
- Be resistive to the effects of atomic oxygen (for low earth orbits only).
- Fit within launch shroud and be capable of surviving the normal launch and in-orbit vibration environments.
- Satisfy system requirements.

7.3. Recommendations for Equipment Design and Placement

Unlike for manned spacecraft, it may be possible for an unmanned spacecraft to tolerate a degree of penetrative impact damage. Depending on the internal configuration of equipment and its redundancy, shielding and the internal arrangement of units are options to be considered (Stokes *et al*., 2000; Turner *et al*., 2000):

- Identify the areas of the satellite most vulnerable to debris impact. These are mostly surfaces facing the velocity vector (RAM) direction.
- Identify mission-critical and sensitive equipment by performing a Failure Modes Effects and Criticality Analysis (FMECA) analysis. Consideration of items such as batteries, propulsion tanks / pipes, reaction / momentum wheels and gyros is especially important.
- For internal equipment, move sensitive and critical units away from vulnerable (e.g. RAM-facing) surfaces and/or place them behind less critical units. Any reconfigurations do of course need to take account of various system constraints, such as mass and thermal balance.
- Protect internal equipment by enhancing the shielding offered by the structure.
- For vulnerable units consider thickening the unit casings. Incremental protection can be provided by covering units with (enhanced) MLI.
- Avoid mounting critical external equipment on vulnerable surfaces, and prevent external instruments such as attitude sensors viewing in the directions of greatest debris flux.

8. ONGOING AND FUTURE WORK

Cross calibration of test facilities is still in progress between some agencies. Impact data on various subsystems is added regularly. More benchmark cases for validation of numerical simulations will be introduced. Other topics of interest will be added in the future e. g. Impact Sensor Networks.

9. CONCLUSIONS

The aim of the Protection Manual is to provide a synthesis of the knowledge and experience available among the member agencies of the IADC Protection Working Group 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 member agencies. This document is regularly updated to reflect the evolution of the acquired experience.

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.

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