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Space systems — Test procedure to evaluate spacecraft material ejecta upon hypervelocity impact

National foreword

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Space systems — Test procedure to evaluate spacecraft material ejecta upon hypervelocity impact

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 11227 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

Throughout its orbit lifetime, any spacecraft is exposed to the risk of collision with man-made space debris and natural micrometeoroids. Concentration of natural particles is nearly stable, but the amount of man-made debris is likely to increase over time. Details concerning this space environment can be found in the documents cited in the bibliography (see References [1] and [2]).

Damage caused by meteoroids or debris can result in total or partial mission failure and in a potential generation of small debris. Because of the large collision velocities (hypervelocity domain), even a small object produces upon impact a large amount of small particles, which are called ejecta. Ejecta can damage parts of the spacecraft itself and increase the population of space debris. The orbital lifetime of the ejecta depends on several factors such as size, initial velocity, and orbit altitude of the parent body. This population of space debris is already evaluated at a few percent of the total space debris population and it is likely to increase in the future[3][4][5]. It is therefore necessary, for the mitigation of such particles, to assess the mechanism of their production.

As shown by previous experimental studies[6][7][8], the amount of ejecta depends primarily on the type of material exposed directly to the space environment. It is greater for brittle materials than for ductile materials; it depends also on the size and on the velocity of impacting particles. Consequently, the best approach for assessing the process is to perform laboratory impact simulation using hypervelocity launchers.

The purpose of this International Standard is to describe a standard approach for assessing the behaviour, under orbital debris or meteoroid hypervelocity impacts, of the materials that are used on the external surfaces of spacecraft[9].

Results obtained from the standard tests carried out on as wide a range of materials as possible will be stored in a database created for this purpose, or incorporated into an existing one such as ECSS-Q70-71A (see Annex D and Reference [10]). This database will help designers choose spacecraft outer materials that mitigate the risk of space debris.

Space systems — Test procedure to evaluate spacecraft material ejecta upon hypervelocity impact

1 Scope

This International Standard describes an experimental procedure for assessing the behaviour, under orbital debris or meteoroid impacts, of materials that are intended to be used on the external surfaces of spacecraft and launch vehicle orbital stages. This International Standard provides a unified method by which to rank materials. The ejecta production characteristics of different materials are compared under standardized conditions in which test parameters are fixed to one number. Optional tests with different parameters are also useful for the proper selection of materials in other conditions, and they could be performed as research items.

This International Standard establishes the requirements to be satisfied for the test methods in order to characterize the amount of ejecta produced when a surface material is impacted by a hypervelocity projectile. Its purpose is to evaluate the ratio of ejecta total mass to projectile mass, and the size distribution of the fragments. These are the necessary inputs for modelling the amount of impact ejecta that a surface material might release during its orbital lifetime, thereby helping to assess its suitability for space use while mitigating the production of small space debris.

The purpose of this International Standard is to provide data that need to be taken into account in the selection of outer spacecraft materials, though the selection is not based on these criteria alone.

The experimental procedure defines

— the type of facility to be used,

— the size, velocity and type of projectile to be used,

— the evaluation of impact ejecta released,

— the reporting of test results, and

— the quality requirements to be used.

It is anticipated that this International Standard will be the first of several test procedure standards aimed at characterizing the release of small debris from the external surfaces of spacecraft and launch vehicle orbital stages as the result of interaction with the space environment. It is applicable to spacecraft and launch vehicles operating in all types of Earth orbits.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 24113, *Space systems — Space debris mitigation requirements*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 24113 and the following apply.

3.1.1
brittle material
material that breaks due to a propagation defect under the action of a stress

3.1.2
ductile material
material that can be plastically deformed without breaking under the action of a stress

3.1.3
ejecta cone
shaped spray of fine particles, comprising fragments and spalls that are released during a high-velocity impact.

3.1.4
fragmentation
process by which an orbiting space object dissociates and produces debris, such as break-up, exposure to space environment, and ageing

3.1.5
hypervelocity impact
impact occurring with a velocity greater than the velocity of sound in any given material

3.1.6
impact crater
damage left on a material, generally hemispherical in shape, after a projectile has hit its surface without going throughout the material

3.1.7
light gas gun
LGG
experimental device consisting of a powder gun that compresses a low-density gas to accelerate a projectile up to hypervelocities

3.1.8
meteoroid
particles of natural origin, resulting from the disintegration and fragmentation of comets and asteroids, which orbit the sun

3.1.9
perforation
hole created by an impact on a thin material in which there is no formation of a crater

3.1.10
plasma gun
experimental device that produces an accelerated plasma flow, which is compressed in a coil and then drags a projectile up to hypervelocities

3.1.11
silica aerogel
low-density solid material, made with a porous, silica-based structure, used for the retrieval of ejecta fragments in impact experiments

3.1.12
spall
piece of material broken and ejected upon high-velocity impact, usually by stress waves, mainly on brittle material

NOTE If the resulting tensile stress caused by the reflection of the compression wave on the surface (front or back) exceeds the tensile strength of the material, a thin sheet of material separates from the target and is ejected.

3.1.13
specimen
target
representative sample of a spacecraft material that is used in impact experiments

3.1.14
stress
force exerted on a body that tends to strain or to deform its shape.

3.1.15
tensile strength
power to resist tensile stress

NOTE The tensile strength of brittle materials is about two orders of magnitude less than the tensile strength of metals.

3.1.16
tensile stress
stress on a material produced by pulling forces along an axis, which tends to extend or break the material

3.1.17
witness plate
flat sheet of ductile material used in impact experiments to capture ejecta and characterize the resulting damage

3.2 Abbreviated terms

CFRP	carbon-fibre-reinforced polymer
HVI	hypervelocity impact
LGG	light gas gun
MLI	multilayer insulation
PVDF	polyvinidylene fluoride

3.3 Symbols

M_{e}	total ejecta mass
K	material-type-dependent coefficient (ductile or brittle)
β	ratio of the mass ejected from the cone to the total ejected mass from the impact crater
t	thickness of test sample
d	diameter of projectile

4 General requirements

4.1 If this International Standard is applied during the design of a spacecraft or launch vehicle orbital stage, then the test procedure and results shall be approved by approving agents and documented in accordance with the space debris mitigation plan specified by ISO 24113.

4.2 Tests shall be performed at a hypervelocity impact facility that can fully satisfy the experimental procedure.

4.3 Before performing the experimental procedure, a calibration of the hypervelocity impact facility shall be carried out to provide a reference data point for the subsequent tests at the facility.

4.4 The calibration tests will be used to confirm the facility independencies of the test procedure.

5 Calibration

5.1 General

Subclauses 5.2 to 5.5 describe each step of a procedure for calibrating a hypervelocity impact test facility prior to it performing the experimental procedure described in Clause 6. The use of light gas guns or plasma guns to perform the tests is acceptable.

5.2 Impact parameters

5.2.1 Perform a test shot using the following projectile parameters:

a) material: aluminium alloy Al 2017 or Al 2024; the choice is based on ISO 209-1:1989[11] or JIS H 4040:2006[12];

b) size and shape: 1 mm ± 0,1 mm diameter sphere;

c) impact velocity: 5 000 m/s ± 100 m/s is recommended;

d) impact angle of incidence relative to target normal: 0°.

5.2.2 Use a target with the following characteristics:

a) size: 50 mm (± 1,5 mm) × 50 mm (± 1,5 mm);

b) material: synthetic fused silica glass (see Annex E for details);

c) thickness: 20 mm (± 1,5 mm);

d) attachment: fixed at the edges to a mounting plate.

NOTE The target material is fragile and it is recommended the target be placed in a small box with a window (hole) to prevent mass measurement error of the target after the impact test.

5.2.3 Use a witness plate with the following characteristics to collect ejecta particles released from the front side of the target during impact:

a) size: 250 mm × 150 mm, with a circular hole (diameter not greater than 30 mm) cut in the centre in order to allow the projectile to go through;

b) material: copper; the choice is based on ISO 197-1:1983[13] or JIS H 3100:2006[14] (purity: 99,90);

c) chemical polishing is recommended[15];

d) thickness: 2 mm;

e) distance and position (angle) to the target: 100 mm in front of the target, parallel to the target;

f) attachment: by threaded rods and bolts, fixed on the target holding plate

NOTE See Annex C for details.

5.3 General environment

The general environment shall satisfy the following parameters:

a) operating temperature: room temperature (measurement accuracy: ±5 °C);

b) operating pressure: < 0,1 Pa (recommended).

5.4 Ejecta characterization

At a minimum, the following parameters shall be measured:

a) size distribution of diameter of craters created by front-side ejecta particles within the following ranges:
   1) between 0,025 mm and 0,05 mm (mainly from the ejecta cone);
   2) between 0,05 mm and 0,1 mm (mainly from the ejecta cone);
   3) between 0,1 mm and 1 mm (mainly from spall);
   4) $>$ 1 mm (from spall).

NOTE More details for the ejecta characterization are given in 6.4 and in Annex C.

5.5 Report of calibration tests

The results shall be summarized in tabular form as shown in Table 1.

Table 1 — Calibration tests

Date of test	Location	Type of facility	Reference of test	Projectile parameters: velocity, size	Target material	Total mass ejected g	Size of crater on target cm
xxx	xxx	xxx	xxx	xx, xx	xx	xx	xx

6 Experimental procedure

6.1 General

This clause defines an experimental procedure for conducting tests in order to characterize the behaviour of materials upon hypervelocity impact and in particular to evaluate the amount of ejecta. The use of light gas guns or plasma guns to perform the tests is acceptable.

6.2 Impact parameters

6.2.1 Perform the shots using the following projectile parameters

a) material: aluminium alloy Al 2017 or Al 2024; the choice is based on ISO 209-1:1989[11] or JIS H 4040:2006[12];

b) size and shape: 1 mm ± 0,1 mm diameter sphere;

c) impact velocity: 5 000 m/s ± 100 m/s;

d) impact angle of incidence relative to target normal: 0°.

6.2.2 Use a target with the following characteristics:

a) size: at least 50 mm × 50 mm, in order to avoid edge effects upon impact;

b) material: representative of the material to be used on the spacecraft;

c) thickness: representative of the material to be flown;

NOTE The ejecta process depends on the ratio of target thickness to projectile diameter (t/d); in the case that there is a perforation of the sample under test, it is necessary to evaluate the amount of ejecta from the front side and from the rear side.

d) attachment: held in place by fixing at the edges only;

e) rear side left free to allow collection of ejecta if perforation or rear-side spall occurs.

6.2.3 Use a witness plate with the following characteristics to collect ejecta particles released from the front side and from the rear side of the target during impact:

a) size: 250 mm × 150 mm, with a circular hole (diameter not greater than 30 mm) cut in the centre of the front witness plate in order to let the projectile go through;

b) material: copper; the choice is based on ISO 197-1:1983[13] or JIS H 3100:2006[14] (purity: 99,90);

c) chemical polishing is recommended[15];

d) thickness: 2 mm;

e) distance and position (angle) to the target: 100 mm in front of and parallel to the target plane;

f) similarly, a witness plate shall be placed behind the target;

g) attachment: by threaded rods and bolts, fixed on the target holding plate.

NOTE More details are given in Annex C.

6.3 General environment

The general environment shall satisfy the following parameters:

a) operating temperature: room temperature or defined by user (measurement accuracy: ± 5 °C);

b) operating pressure: $<$ 0,1 Pa (recommended).

6.4 Ejecta characterization and evaluation

6.4.1 To characterize and model the production of ejecta, it is appropriate to choose relevant parameters that are based on the physics of the impact process (more details are given in Annexes A and B).

6.4.2 At a minimum, the following parameters shall be measured:

a) The total amount of ejecta, M_e, which is obtained by measuring the target mass before and after the test. Of course, part of the material ejecta comes from the projectile itself. This contribution is, however, small in comparison with material coming from the target (less than 1 %).

b) The size distribution of craters. On the witness plate used to characterize the ejecta, the size distribution of the diameter of craters formed by the front-side and rear-side ejected particles is determined within the following ranges:

    1) between 0,025 mm and 005 mm (mainly from the ejecta cone);

    2) between 0,05 mm and 0,1 mm (mainly from the ejecta cone);

    3) between 0,1 mm and 1 mm (mainly from spall);

    4) $>$1 mm (from spall).

NOTE 1 As an option, the average velocity of the ejecta can also be measured. At present, it is not possible to measure the ejecta velocity within each crater diameter range specified. Only the bulk velocity (of cone and spall fragments) can be measured using active velocity sensors or high-speed video recording.

NOTE 2 Annex C describes in more details measurement methods that can be employed in the determination of ejecta parameters.

6.4.3 The fundamental analysis of test results shall be documented in tabular form as shown in Table 2.

Table 2 — Fundamental analysis of test results

<table>
<tr><td colspan="2">Total amount of ejecta (mg): M_e xxx</td><td colspan="1">Target mass before impact (mg) xxx</td><td colspan="2">Target mass after impact (mg) xxx</td></tr>
<tr><td>Size distribution of crater diameter, D</td><td>0,025 mm to 0,05 mm</td><td>0,05 mm to 0,1 mm</td><td>0,1 mm to 1 mm</td><td>$>$ 1 mm</td></tr>
<tr><td>Front side, number of craters</td><td>xxx</td><td>xxx</td><td>xxx</td><td>xxx</td></tr>
<tr><td>Rear side, number of craters</td><td>xxx</td><td>xxx</td><td>xxx</td><td>xxx</td></tr>
<tr><td>Projectile mass (mg)</td><td>xxx</td><td></td><td></td><td></td></tr>
<tr><td colspan="5">xxx values to be filled in after the tests</td></tr>
</table>

When using copper witness plates to record the impact craters produced by the ejecta, the size of the fragments (d) can be derived from the size of the impact craters (D). However, the ratio of crater diameter to projectile diameter (D/d) depends on the impact velocity (v). A commonly used conversion equation is the following:

$$D/d = 1{,}28v^{0{,}68} \text{ } (v \text{ in km/s})$$

NOTE 1 Since the determination of the velocity of ejecta fragments is currently difficult, the determination of particle diameter is therefore still imprecise. The next edition of this International Standard will be amended as more accurate velocity measurements become available.

When crater diameters are converted into particle diameters, the results shall be given in a table similar to Table 2. Details and rationale are given in Annex C, Table 2, and in References [16] to [18].

NOTE 2 As an option, soft or low-density material such as foam or silica aerogel can be used to ensure intact recovery of ejecta fragments. In this case, fragment sizes can be sieved and measured and their size will be the average of the maximum and minimum length or diameter for near-spherical fragments.

6.5 Additional tests

In order to investigate the ejecta process in more detail, if the facility is able to perform such tests, it is recommended that the following additional tests be performed:

a) incidence angle varying from 0° to 75°, in 15° steps;

b) velocity varying from 1 km/s to 16 km/s.

6.6 Analysis of test results

The applicability of statistical methods to the evaluation of numerical results usually depends on the number of tests performed on a specific material for a specific set of test conditions; this should be large enough to constitute a statistically significant sample. Due to the complexity and cost of hypervelocity impact testing, only a limited number of tests need be performed on each sample.

A minimum of three shots shall be performed at normal incidence.

7 Reporting of test results

7.1 General

The report shall provide all information relevant to the understanding and correct interpretation of the test activity and test results. It shall contain the following:

a) an abstract summarizing the test procedure and findings;

b) an introduction providing the background information to the test (i.e. reason for testing, use and applicability of results);

c) the objective of the test activity;

d) information on the tested material;

e) a description of the test procedure and test conditions;

f) the calibration report;

g) a presentation of the results, as shown in Table 2;

h) a discussion of the results;

i) conclusions and recommendations;

j) numerical data in a format agreed by the customer;

k) the customer's authorization for the tests.

7.2 Report of testing of materials

7.2.1 Information on test sample

The report should include the following information on the test material and on the witness plate, as provided by the supplier:

a) supplier's name and code;

b) material standard designation;

c) date of batch manufacturing;

d) specified chemical composition;

e) material and heat treatment specifications:

    1) surface treatment, if any;

    2) description of other manufacturing processes (e.g. welding, cutting and milling);

    3) non-destructive inspection before the tests;

    4) safety information and handling notice.

7.2.2 Description of test procedures

The report shall provide a description of specimen preparation, test equipment and test procedure. The information provided shall be in accordance with the requirements specified in the relevant subclauses of this International Standard.

Estimated values of precision and bias for the test results shall be included.

Anomalies and deviations from test procedures shall be reported.

7.2.3 Presentation of test results

The test results shall be presented in the report in an appropriate format (e.g. tables, drawings, plots, diagrams and photos), together with a written description.

Units of measure and scales shall be consistent and in accordance with the SI system of units, which should be consistent and in accordance with customer specifications.

7.3 Database

The test results should be provided to standards organizations that maintain databases on spacecraft materials such as ECSS-Q-70-71A[10] and made publicly available.

The test results should be provided in an electronic format that can be incorporated into such databases. Annex D gives an example of a material data sheet from the standard ECSS-Q-70-71A[10].

8 Quality assurance

8.1 General

The test facility shall implement the quality assurance, inspection and quality control procedures specified herein before conducting any test activity. The implementation of these procedures shall be maintained for the entire duration of the test activity.

The test facility shall establish and implement adequate quality control actions and inspections to provide evidence of conformity to the test requirements.

Quality control actions and inspections for test activities carried out by sub-contractors to the test facility are under the direct responsibility of the test facility.

8.2 Quality requirements

8.2.1 Request for HVI testing of materials

The customer shall request a hypervelocity impact facility to test the materials. The request for testing shall specify:

a) objective of the test activity;

b) background and justification to the test activity;

c) material to be investigated;

d) description of the test activity;

e) deliverables.

8.2.2 Work proposal for HVI testing of materials

The test facility shall issue a work proposal for the testing of materials. The work proposal shall specify:

a) test objective;

b) test method and reference to test standards;

c) material;

d) description of proposed test procedure;

e) deliverables;

f) work breakdown structure;

g) planning and time schedule;

h) itemized cost list and payment.

8.2.3 Calibration

In addition to the calibration test specified in Clause 4, the test facility shall carry out and maintain the calibration of test equipment throughout the duration of the test activity. Calibration records shall be readily accessible and retrievable for the entire duration of the test activity on customer request.

8.2.4 Testing, evaluation and reporting

The test facility shall provide evidence that the test activity, evaluation and reporting is carried out in accordance with the requirements listed in Clauses 4, 5 and 6, respectively.

8.2.5 Traceability and records

Traceability of testing shall be ensured as follows:

a) Materials shall be durably marked to unequivocally identify manufacturer's code, batch number and material standard designation.

b) Specimens shall be durably marked to unequivocally identify individual specimens.

c) The test facility shall maintain test records for the entire duration of the contract.

d) Test records shall be accessible and retrievable on customer request.

e) Storage of materials and specimens by the test facility shall be agreed with the customer.

f) Disposal of materials and specimens shall be authorized by the customer.

Annex A
(informative)

Characterization of material ejected upon impact (ejecta)

Upon hypervelocity impact, a large amount of small debris (ejecta) is produced, especially in the case of impacts on brittle materials. The material coming from the impact crater is usually ejected as small, high-velocity fragments (cone) or as large, low-velocity fragments (spall); a very small amount is ejected in a process called “jetting” and this can be neglected (see Figure A.1). The relative amount of each category depends primarily on the ductile or brittle behaviour of the target. Metals (aluminium, copper) are usually ductile (see Figure A.2); glass, ceramics and solar cells are brittle (see Figure A.3); other materials, such as CFRPs, polymers, complex materials, thermal control paint and MLI, have an intermediate behaviour.

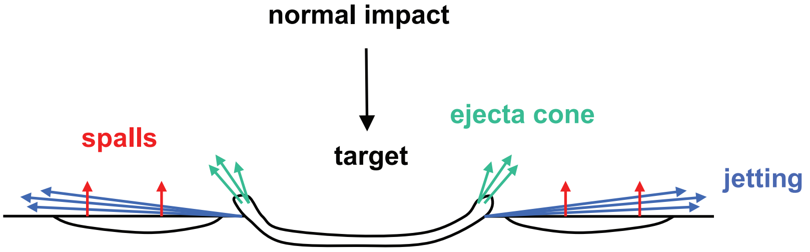

Figure A.1 — The three types of HVI ejecta: ejecta cone, ejecta spalls, jetting

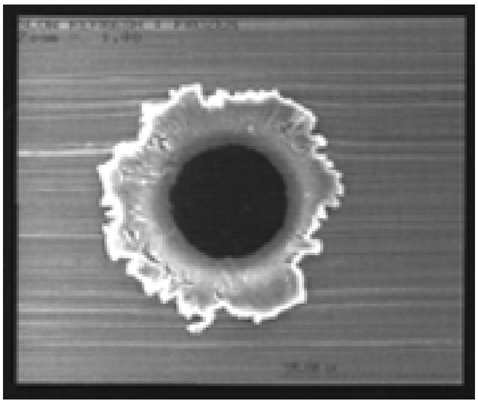

Figure A.2 — Typical HVI onto ductile material (aluminium)

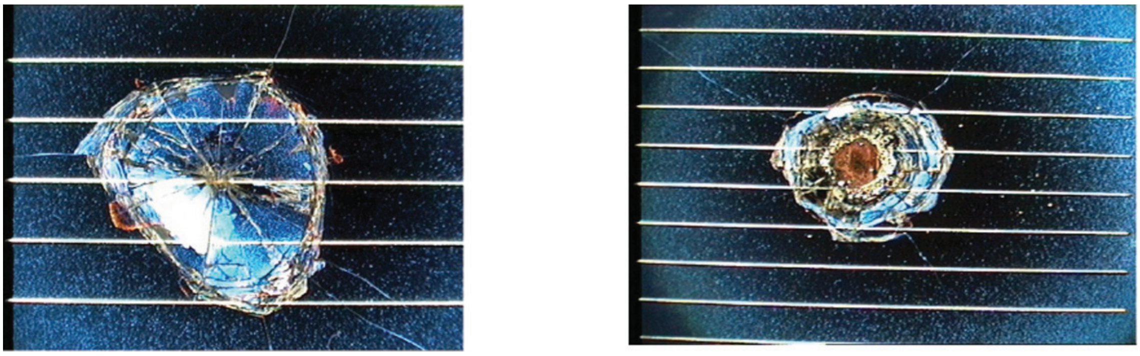

Figure A.3 — Typical HVI onto brittle material (Hubble Space Telescope solar cell)

The smaller ejecta (< 100 μm for a 1 mm diameter projectile) are from the cone and come from melted or finely fragmented projectile and target material. The ejection velocity ranges from about 100 m/s up to the projectile velocity. The cone ejection angle (aperture and width) depends slightly on the target material.

Spalls are the biggest fragments (> 100 μm for a 1 mm diameter projectile); they are normally emitted at the surface with a velocity range between 10 m/s and 100 m/s.

Ductile targets have no or few spall fragments.

For brittle targets, the spalls represent between 60 % and 90 % of the total ejected mass.

Previous studies have shown that it is possible to model the ejecta process (production and evolution) for a small set of materials[6][7]. It is expected that the implementation of the present test method will greatly extend the original database.

An ejecta model such as that described in Reference [8] is summarized in Annex B. This model can be used to compute the amount of ejecta produced upon HVI on a specific material. It will be updated according to results obtained in any new tests.

The total amount of ejecta present in orbit at a given time can be computed using the approach described in References [3] and [7].

Annex B
(informative)

Example of an ejecta model

B.1 General

When orbital debris or a micrometeoroid impacts a spacecraft surface, a large number of particles, called ejecta, are produced. These particles can contribute to a modification of the debris environment, either locally by the occurrence of secondary impacts on the components of complex and large space structures, or at great distance by the formation of a population of small orbital debris.

B.2 Approach

B.2.1 General

In order to determine the ejecta population, the following sub-tasks are necessary:

a) determine the primary impact flux;

b) target modelling;

c) use an ejecta model;

d) propagate ejecta orbits.

An ejecta model has been developed by ONERA/DESP within the framework of ESA contract 11540/95/NL/JG, updated and documented in the subsequent ESA contract 1887/96/NL/JG. The model is described in detail in several publications (see References [7] and [8]). The main features of the model are summarized below.

B.2.2 Ejecta types

Material ejection under normal and oblique hypervelocity impact is divided in three different processes:

a) cone ejecta:

    1) 0,1 µm up to impactor size within a cone of 60°;

    2) from 100 m/s to impact velocity;

b) jetting:

    1) liquid jet within a 10° cone;

    2) up to three times the impact velocity;

    3) less than 1 % of the ejecta mass involved;

c) spallation:

    1) brittle fracture near free surfaces;

    2) about 10 to 20 spall fragments ≥ projectile size;

    3) between 10 m/s and 50 m/s perpendicular to target surface.

In general, no spalls are observed on ductile targets.

B.2.3 Model inputs

Models inputs are as follows:

a) target characteristics: ductile or brittle, density;

b) projectile characteristics: mass, density;

c) impact characteristics: relative impact velocity and directions.

B.2.4 Model outputs

The model provides a function $n(\phi,\theta,\delta,v)$ that gives the number of fragments of size δ ejected at velocity v in the spatial direction (ϕ,θ) per solid angle unit. The model is currently applicable under the following conditions:

a) projectile diameters between 5 µm and 1 cm;

b) impact velocities between 1 km/s and 20 km/s;

c) thick targets;

d) ductile and brittle homogeneous targets, solar cells, painted surfaces.

B.3 Total mass ejected

Materials that produce the greatest amount of ejecta after a hypervelocity impact are brittle surfaces, especially multi-layer targets (such as solar cells) and painted surfaces (thermal-control coating on satellites and anti-static paint used on upper stages).

The total mass of ejecta, M_e, is computed in SI units according to the formula given by Gault[19]:

$$M_\mathrm{e} = K \times 7{,}41 \times 10^{-6} \left(\frac{\rho_\mathrm{p}}{\rho_\mathrm{t}} \right)^{1/2} E_\mathrm{i}^{1{,}133} \left(\cos\theta_\mathrm{i} \right)^2 \quad (1)$$

where:

K is the material-type-dependent coefficient (ductile/brittle);

ρ_p is the projectile density (kg/m^3);

ρ_t is the target density (kg/m^3);

E_i is the projectile kinetic energy (J);

θ_i is the impact incidence angle (°).

The coefficient K depends on the target material. It can be determined experimentally by HVI data processing, following Formula (1), with knowledge of target and projectile characteristics. The range for values of K is presented in Table B.1.

The coefficient K has been determined for some materials[3][6] and could serve as the basis for a classification of the target behaviour under hypervelocity impact as suggested in this International Standard.

Table B.1 — Sample values of coefficient K for different projectile parameters (d_p)

Projectile diameter	$d_\mathrm{p} < 10$ µm	$d_\mathrm{p} \geq 10$ µm
Ductile target	$K = 10^{-2}$ to 10^{-3}	$K = 10^{-1}$
Brittle target	$K = d_\mathrm{p}/10^{-5}$ (d_p in m)	$K = 1$

B.4 Ejected mass partitioning

The total ejected mass, M_e, consists of three components:

$$M_\mathrm{e} = M_\mathrm{jet} + M_\mathrm{cone} + M_\mathrm{spalls} \tag{2}$$

$$M_\mathrm{jet} \approx 0 \tag{3}$$

$$M_\mathrm{cone} = \beta\, M_\mathrm{e} \tag{4}$$

$$M_\mathrm{spalls} = (1 - \beta)\, M_\mathrm{e} \tag{5}$$

Table B.2 — Value of coefficient β (ratio of mass ejected from the cone to total ejected mass)

Projectile diameter	$d_\mathrm{p} \leq 1$ µm	1 µm $< d_\mathrm{p} \leq$ 10 µm	10 µm $< d_\mathrm{p} \leq$ 100 µm	$d_\mathrm{p} >$ 100 µm
Ductile target	$\beta = 1$	$\beta = 0{,}95$		$\beta = 0{,}90$
Brittle target	$\beta = 1$	$\beta = -0{,}3\log d_\mathrm{p} - 0{,}8$		$\beta = 0{,}4$
Solar cell	$\beta = 1$	$\beta = -0{,}3\log d_\mathrm{p} - 0{,}8$	$\beta = -0{,}6\log d_\mathrm{p} - 2{,}3$	$\beta = 0{,}1$

Annex C
(informative)

Ejecta measurement methods

At least two parameters shall be measured during hypervelocity impact tests in order to characterize the ejecta:

— total mass ejected;

— size distribution of fragments (as an option, the velocity of fragments, in magnitude and in direction).

The choice of method is left to the discretion of the user on the premise that there is no absolute measurement method and that it will depend on the instrumentation available at the facility performing the tests. Some guidelines are given in this annex. More details are available in Reference [6]. Recent experimental set-up and preliminary results are described by K. Sugahara *et al.*[15] and by A. Francesconi *et al.*[20].

a) The total mass ejected is obtained by measuring the weight of the target before and after the test. It can also be derived from measuring the volume of the impact crater.

b) The size and spatial distribution of the fragments can be obtained with a metal witness plate and adequate conversion equations. A copper plate is preferred (composition different from projectile and target). For a normal impact, it will be located up-range of the target (with a hole in the centre in order to let the projectile go through), at a distance of 50 mm to 100 mm; oblique impacts will require a slightly different set-up (a similar witness plate can also be used behind the target in order to study the down-range ejecta, if perforation occurs). The plate size will typically be 250 mm × 150 mm, with a thickness of 2 mm. The sample holder plate will be a similar aluminium plate, out of which a 60 mm × 60 mm square is cut in the centre in order to study the rear-side ejecta, if any. A possible set-up, such as the one used at the Kyushu Institute of Technology[9] is shown in Figure C.1 and Figure C.2.

   The analysis of impacts on the witness plate will provide data on the geometry of the ejecta cloud. Scanning of the witness plate will be made with a medium-power optical microscope and can benefit from automated pattern recognition techniques. As evidenced by Sugahara[15], it is difficult and time-consuming to identify impact features smaller than 25 µm in diameter.

c) The size of the fragments (d) can be derived from the size of the secondary craters (D) formed on the plate, using a conversion equation such as:

$$\frac{D}{d} = C \cdot v^{0{,}68}$$

where:

D is the crater diameter;

d is the ejecta particle diameter;

v is the impact velocity (km/s);

C is a parameter depending on target material.

The value given by Cour-Palais, $C = 1{,}28$ (see References [16] and [17]) can be chosen for use in this International Standard. As an example, the D/d ratio for an ejecta velocity of 1 km/s is close to 1,3, whereas it is close to 3,9 for an ejecta velocity of 5 km/s.

Table C.1 — Detailed analysis for test results

Size distribution of particle diameter, d (mm)		<0,010	0,01 to 0,1	0,1 to 1	>1
Front side	**Number of particles**	xxx	xxx	xxx	xxx
	Velocity (optional)	xxx	xxx	xxx	xxx
Rear side	**Number of particles**	xxx	xxx	xxx	xxx
	Velocity (optional)	xxx	xxx	xxx	xxx
xxx values to be filled in after the tests					

Since the determination of the velocity of ejecta fragments is currently still difficult, the determination of particle diameter is therefore still imprecise. The next edition of this Interntional Standard will be amended as more accurate velocity measurements become available.

The size of the ejecta can also be derived from the size of perforations obtained on a thin witness foil. In this case, the size of the holes is the same as the size of the particles, when the foil is thin compared to the size of the ejecta (see Reference [18]).

d) Recovery of intact fragments is possible using, instead of metal witness plates, a low density material such as silica aerogel (see Figure C.3), or a soft material such as foam or cardboard. Fragments are extracted mechanically or chemically and sieved. The determination of the size distribution of the ejecta fragments by this technique will be more precise than the previous one, but it is more time-consuming and requires the use of solvents.

e) The velocity (and also the spatial distribution) of the ejecta can be measured with a high-speed video camera, as shown on Figure C.4. Analysis of the pictures can be automated in order to derive the velocity/size distribution of the fragments. Velocity can also be measured with the use of impact sensors, made with piezoelectric material or PVDF foils. Sensors must be located on the witness plates and must be triggered upon impact of the projectile on the main target, in order to obtain a time of flight measurement.

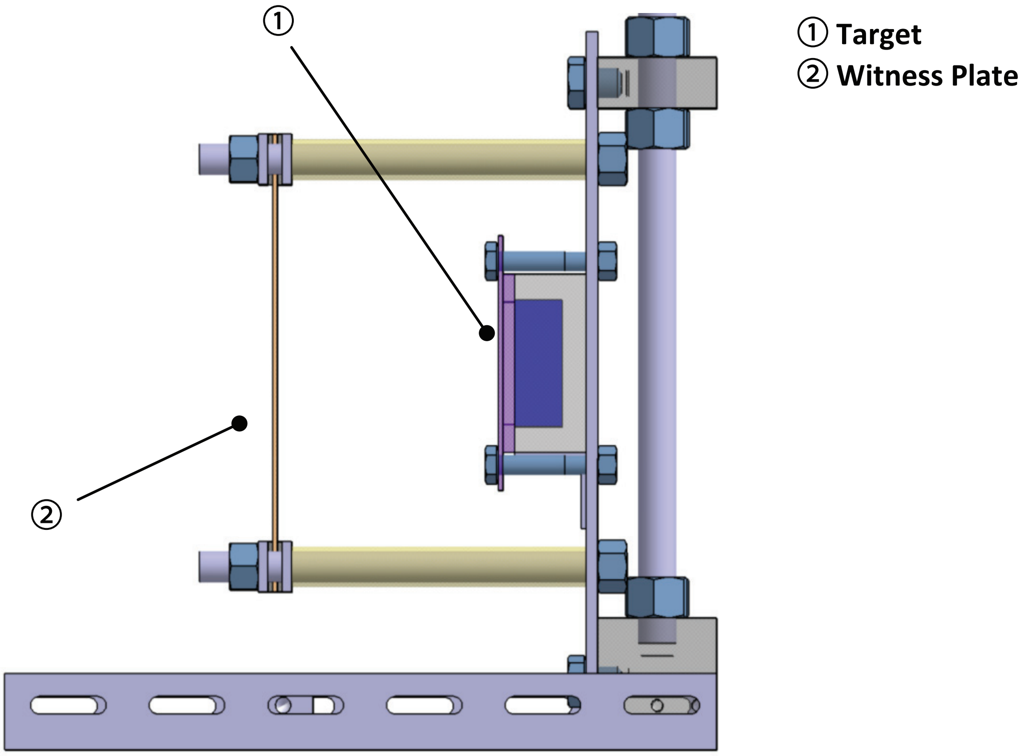

Figure C.1 — Sketch of target and witness plate assembly

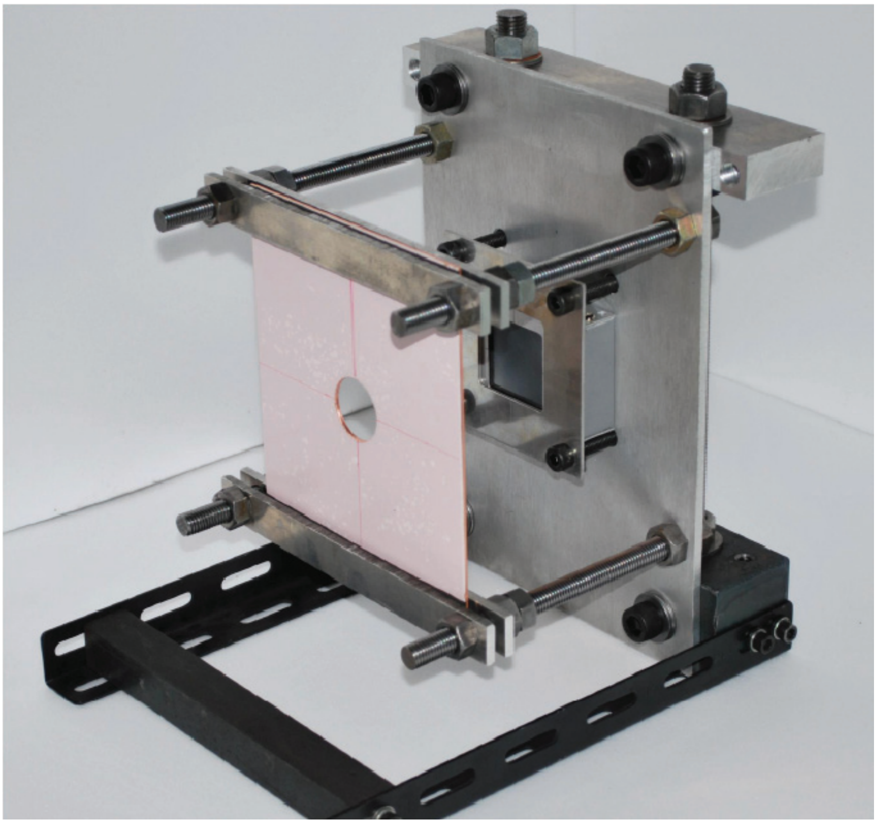

Figure C.2 — Picture of target and witness plate set-up

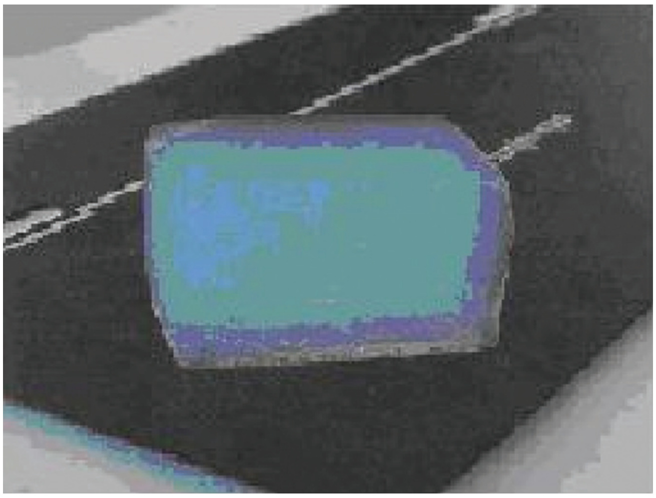

Figure C.3 — Sample of silica aerogel material

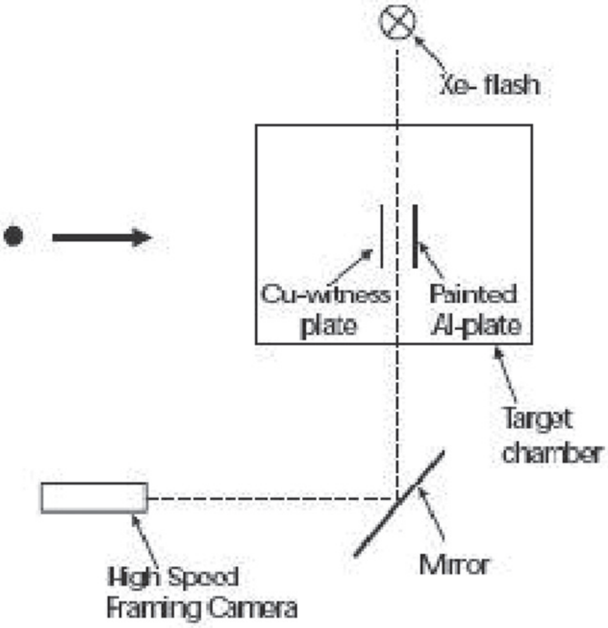

Figure C.4 — Typical set-up for high-speed video (shadowgraph technique)

Annex D
(informative)

Example of a data sheet

This annex shows an example of a suitable data sheet (from ECSS-Q-70-71A[10]). The last section, “Meteoroid and debris: Material ejecta upon hypervelocity impact”, summarizes the main parameters relating to ejecta, as derived from the impact tests performed on the material described in the data sheet.

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Aluminium (ISO Al 99,5)

Aluminium and Al alloys

Type: metal alloy

Chemical composition: 99,5 % Al

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Fax: —

E-mail: customer-services@corusgroup.com

Website: www.corusgroup.com

Aluminium Pechiney

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Fax: +33 (0)5 61 02 42 01

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Corus Metallversteib Deutschland

Kennedydamm 17, D–40476 Düsseldorf, Germany

Tel: +49 211 4926–0

Fax: +49 211 4926–282

E-mail: —

EXPERIENCE AND AVAILABILITY

Development status: commercial product

Cost range: very low

Lot reproducibility: AA 1050, BS 1B, AFNOR A5, DIN Al 99,5

Space experience: good

GENERAL PROPERTIES (physical, mechanical, thermal, electrical, optical)

Nature and typical value

Specific gravity: 2,71 at room temperature

Ultimate tensile strength: 75 MPa to 146 MPa at room temperature

Proof stress (0,2 %): 55 MPa to 133 MPa at room temperature

Elongation at break: 25 % at room temperature

Thermal expansion coefficient: 24×10^{-6} $°C^{-1}$ at room temperature

Thermal conductivity: 230 W m^{-1} $°C^{-1}$ at room temperature

Electrical resistivity $0{,}028 \times 10^{-6}$ $\Omega\cdot$m at room temperature

PROPERTIES RELEVANT TO SPACE USE

Nature and typical value

Corrosion: excellent resistance to atmospheric corrosion

For more severe environments, part can be either

- chromated
- chromated and painted
- sulphuric anodized, or
- chromic anodized

Stress corrosion: high resistance

METEOROIDS AND DEBRIS: MATERIAL EJECTA UPON HYPERVELOCITY IMPACT

- Physical behaviour of material under hypervelocity impact (coefficient K, see Annex B): ductile or brittle material type behaviour.
- Total mass of ejecta (using a 1 mm diameter, 5 km/s velocity, spherical Al projectile): M_e
- Mass partitioning (ratio: mass from the cone to total mass ejected, M_e): coefficient β

Annex E
(informative)

Technical data

No standards on the physical properties of synthetic fused silica have been identified. In order to make a consistent comparison of the calibration shots made at different facilities, the use of synthetic fused silica "LITHOSIL[1)]", manufactured by SCHOTT AG is recommended.

Contact: SCHOTT AG
Hattenbergstrasse 10
55122 Mainz
Germany

[1)] Lithosil is an example of a suitable product available commercially. This information is given for the convenience of users and consistency of calibration tests and does not constitute an endorsement by ISO of this product.

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2) European Cooperation for Space Standardization: www.ecss.nl.

3) Japanese Industrial Standards, available from the Japanese Standards Association: www.jsa.or.jp.

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