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Space systems — Assessment of survivability of unmanned spacecraft against space debris and meteoroid impacts to ensure successful post-mission disposal

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National foreword

This British Standard is the UK implementation of ISO 16126:2014.

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Systèmes spatiaux — Évaluation de la capacité de survie des véhicules spatiaux non habités face aux débris spatiaux et aux impacts de météoroïdes pour garantir une élimination efficace d'après-mission

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Foreword

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The committee responsible for this document is ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Space systems — Assessment of survivability of unmanned spacecraft against space debris and meteoroid impacts to ensure successful post-mission disposal

1 Scope

This International Standard defines requirements and a procedure for assessing the survivability of an unmanned spacecraft against space debris and meteoroid impacts to ensure the survival of critical components required to perform post-mission disposal. This International Standard also describes two impact risk analysis procedures that can be used to satisfy the requirements. The procedures are consistent with those defined in References [1] and [2].

This International Standard is part of a set of International Standards that collectively aim to reduce the growth of space debris by ensuring that spacecraft are designed, operated, and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime. All of the primary debris mitigation requirements are contained in a top-level International Standard.[3] The remaining International Standards, of which this is one, provide methods and processes to enable compliance with the primary requirements.

2 Normative references

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

ISO 10795:2011, *Space systems — Programme management and quality — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10795:2011 and the following apply.

3.1
at-risk area
area of those parts of a surface on a component that are most vulnerable to impacts from space debris or meteoroids

Note 1 to entry: See A.1 for a more detailed explanation of at-risk area.

3.2
ballistic limit
impact-induced threshold of failure of a structure

Note 1 to entry: A common failure threshold is the critical size of an impacting particle at which perforation occurs. However, depending on the characteristics of the item being hit, failure modes other than perforation are also possible.

3.3
catastrophic collision
collision leading to the destruction by fragmentation of a spacecraft

3.4
critical component
component whose failure would prevent the completion of an essential function on a spacecraft, such as post-mission disposal

3.5
critical surface
<impact survivability> surface of a component which, when damaged by impact, will cause the component to fail

3.6
disposal
actions performed by a spacecraft to permanently reduce its chance of accidental break-up, and to achieve its required long-term clearance of the protected regions

[SOURCE: ISO 24113:2011, 3.4, modified]

3.7
impact survivability
ability of a spacecraft to function after being exposed to the space debris or meteoroid environment

Note 1 to entry: A measure of impact survivability is the Probability of No Failure (PNF).

3.8
lethal collision
collision leading to the loss of a critical component on a spacecraft

3.9
orbital lifetime
period of time from when a spacecraft achieves Earth orbit to when it commences re-entry

[SOURCE: ISO 24113:2011, 3.12, modified]

3.10
protected region
region in space that is protected with regard to the generation of space debris to ensure its safe and sustainable use in the future

[SOURCE: ISO 24113:2011, 3.14]

3.11
re-entry
process in which atmospheric drag cascades deceleration of a spacecraft (or any part thereof), leading to its destruction or return to Earth

[SOURCE: ISO 24113:2011, 3.15, modified]

3.12
space debris
orbital debris
man-made objects, including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional

[SOURCE: ISO 24113:2011, 3.17]

3.13
spacecraft
system designed to perform specific tasks or functions in space

[SOURCE: ISO 24113:2011, 3.18]

4 Abbreviated terms

BLE	ballistic limit equation
HVI	hypervelocity impact
IADC	Inter-Agency Space Debris Coordination Committee
ISO	International Organization for Standardization
M/OD	meteoroid/orbital debris
PNF	Probability of No Failure
PNP	Probability of No Perforation
S/C	spacecraft

5 Impact survivability assessment requirements

5.1 During the design of a spacecraft, if an assessment is required to determine the survivability of the spacecraft against space debris and meteoroid impacts for the purpose of achieving successful post-mission disposal, then the procedure in Clause 6 shall be followed.

5.2 The results of an impact survivability assessment, the methodology used, and any assumptions made shall be approved by the customer of the spacecraft.

6 Impact survivability assessment procedure

6.1 General

6.2 and 6.3 describe a procedure for assessing the space debris and meteoroid impact survivability of a spacecraft.

6.2 Definition of survivability requirement

6.2.1 Specify a requirement for the survivability of the spacecraft against space debris and meteoroid impacts for the purpose of achieving successful post-mission disposal.

6.2.2 Express the survivability requirement in terms of a minimum allowable value of impact-induced Probability of No Failure, PNF_{min}, over the operational phase of the spacecraft.

NOTE The operational phase of a spacecraft can be understood by referring to Annex B in Reference [3].

6.3 Impact risk analysis

6.3.1 Perform an impact risk analysis to determine and compare the impact-induced Probability of No Failure of the spacecraft, $PNF_{\text{s/c}}$, with the minimum allowable value, PNF_{min}.

6.3.2 If $PNF_{\text{s/c}} < PNF_{\text{min}}$, then take appropriate steps to reduce the impact risk.

NOTE Clauses 7 and 8 describe two procedures for analysing and reducing the impact risk.

7 Procedure for performing a simple impact risk analysis

7.1 General

7.1.1 A procedure for performing a simple analysis of the risk that a spacecraft will not be able to complete a successful post-mission disposal, as a result of impacts from space debris and meteoroids, is illustrated in Figure 1. The procedure, which is based on that recommended in Reference [1], is used to determine whether impacts from small-size space debris and meteoroids could cause the failure of components that are critical for post-mission disposal. That is, the procedure is concerned with evaluating lethal collisions rather than catastrophic collisions. If the risk analysis shows that there is a significant probability of failure, then this indicates the need for a more rigorous analysis to determine and validate possible protection enhancements to the spacecraft, including the design of shielding. Clause 8 provides such an approach.

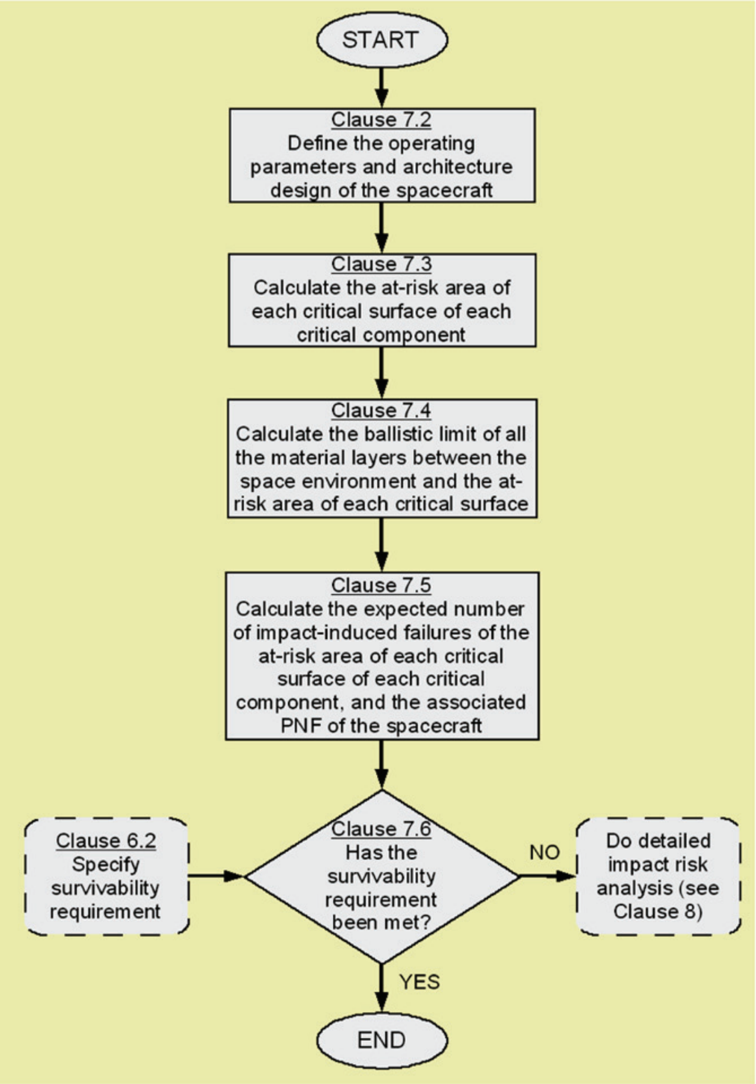

Figure 1 — Procedure for performing a simple analysis of the risk to a spacecraft from space debris and meteoroid impacts

7.1.2 7.2 to 7.6 describe each step in the procedure.

7.2 Spacecraft operating parameters and architecture design

7.2.1 Define the operating parameters of the spacecraft, such as its orbit and attitude orientation relative to the direction of motion.

7.2.2 Define the architecture design of the spacecraft, such as its configuration and dimensions, and the material properties of each of its surfaces, including any shielding.

7.3 Identification of critical components and surfaces

7.3.1 Identify every component on the spacecraft that contributes to post-mission disposal.

7.3.2 For each component identified in 7.3.1, determine its redundancy, impact damage modes, and failure criteria.

7.3.3 Use a reliability analysis technique, such as Fault Tree Analysis or Failure Modes and Effects Analysis, to identify the system-level consequences that might result when each of the components in 7.3.2 is damaged by impact.

7.3.4 Identify the critical components, i.e. those components which, when damaged by impact, would prevent post-mission disposal.

7.3.5 For each critical component, identify its most critical surface.

7.3.6 For each critical component, calculate the at-risk area of its most critical surface.

NOTE A.1 provides additional information on the calculation of at-risk area of a critical surface.

7.4 Ballistic limits

For each critical surface, do the following:

a) identify other elements of the spacecraft, e.g. components and structures that lie between the at-risk area of the critical surface and the space environment;

b) in the direction that has the least intervening material protecting the at-risk area of the critical surface from the space environment, identify the thickness and density of each layer of the material and hence its areal density;

c) in the direction that has the least intervening material protecting the at-risk area of the critical surface from the space environment, sum the areal densities of the material layers to obtain the total areal density between the at-risk area of the critical surface and the environment;

d) calculate the minimum diameter of space debris or meteoroid impactor that will penetrate the total areal density of material between the at-risk area of the critical surface and the environment.

NOTE A.2 provides additional information on the calculation of areal density and the minimum diameter of impactor that will penetrate a given areal density.

7.5 Failure probability analysis

7.5.1 For each critical surface, determine the expected number of impact-induced failures of the at-risk area of the critical surface.

7.5.2 Sum the expected number of impact-induced failures of the at-risk areas of all the critical surfaces to obtain the expected number of impact-induced failures of all the critical components.

7.5.3 Calculate the probability that one or more of the critical components will fail during the operational phase of the spacecraft as a result of impact with space debris or meteoroids, i.e. determine the impact-induced Probability of No Failure of the spacecraft, $PNF_{s/c}$, to achieve its post-mission disposal.

NOTE A.3 provides additional information on the calculation of the expected number of impact-induced failures and the probability of failure.

7.6 Completion of analysis

7.6.1 If $PNF_{s/c} \geq PNF_{min}$, then end the analysis.

7.6.2 If $PNF_{s/c} < PNF_{min}$, then perform a detailed impact risk analysis.

NOTE Clause 8 describes a procedure for performing a detailed impact risk analysis.

8 Procedure for performing a detailed impact risk analysis

8.1 General

8.1.1 A procedure for performing a detailed analysis of the risk that a spacecraft will not be able to complete a successful post-mission disposal, as a result of impacts from small-size space debris and meteoroids, is shown in Figure 2. Thus, the procedure is concerned with evaluating lethal collisions rather than catastrophic collisions. The procedure, which is based on that recommended in Reference [2], is used to provide a more accurate determination of the Probability of No Failure of the spacecraft, $PNF_{s/c}$, than that obtained in Clause 7. This is important when making decisions concerning the need for additional protection on the spacecraft and the design of that protection.

8.1.2 Figure 2 provides a simple illustration of the key steps in the procedure and the flow of information required between these steps. It is possible that the implementation of such a procedure in practice can be more complicated than that depicted in the figure.

8.1.3 8.2 to 8.6 describe each step in the procedure.

8.2 Spacecraft operating parameters and architecture design

8.2.1 Define the operating parameters of the spacecraft, such as its orbit and attitude orientation relative to the direction of motion.

8.2.2 Define the architecture design of the spacecraft, such as its configuration and dimensions, and the material properties of each of its surfaces, including any shielding.

8.3 Identification of critical components

8.3.1 Identify every component on the spacecraft that contributes to post-mission disposal.

8.3.2 For each component identified in 8.3.1, determine its redundancy, impact damage modes, and failure criteria.

8.3.3 Use a reliability analysis technique, such as Fault Tree Analysis or Failure Modes and Effects Analysis, to identify the system-level consequences that might result when each of the components in 8.3.2 is damaged by impact.

8.3.4 Identify the critical components, i.e. those components which, when damaged by impact, would prevent post-mission disposal.

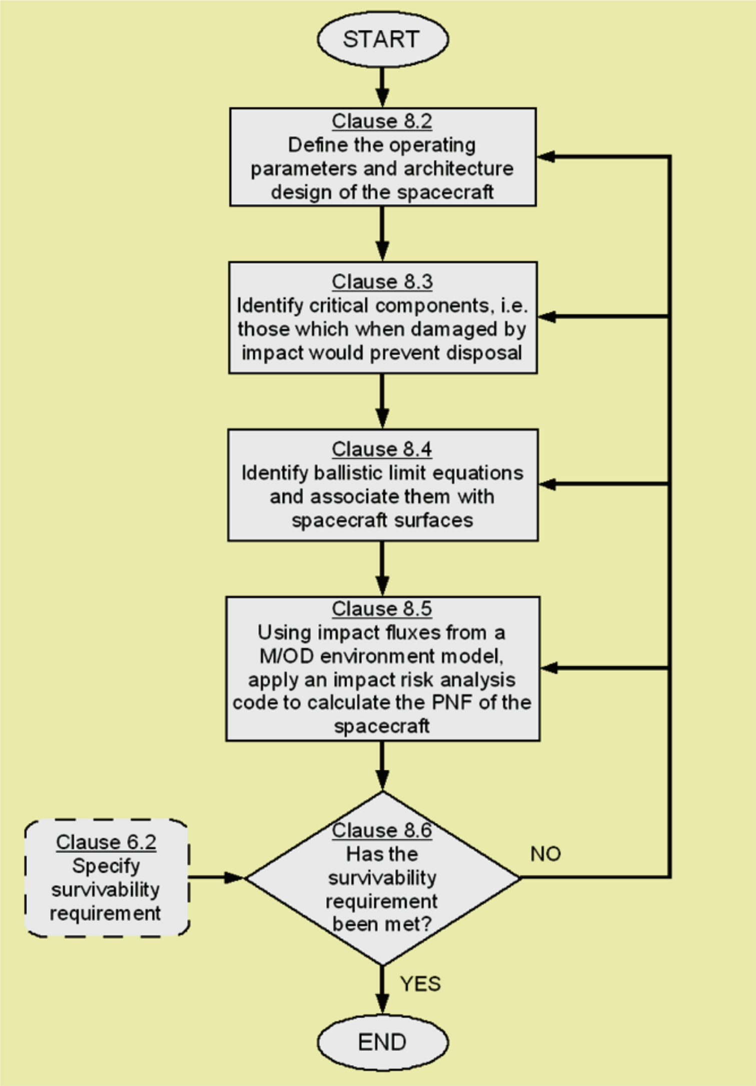

Figure 2 — Procedure for performing a detailed analysis of the risk to a spacecraft from space debris and meteoroid impacts

8.4 Ballistic limits

8.4.1 Identify existing ballistic limit equations (BLEs) that might be suitable for determining the ballistic limit of each surface or combination of surfaces on the spacecraft (including components).

NOTE Annex B identifies some commonly used BLEs.

8.4.2 If a suitable BLE cannot be identified for a particular surface or combination of surfaces, then adapt an existing formula or derive a new formula.

8.4.3 In satisfying 8.4.2, perform a set of hypervelocity impact (HVI) tests to derive a new BLE or verify the validity of an adapted BLE. Although the exact nature of the tests will depend on a range of factors, such as the configuration to be investigated, the following might be suitable for a variety of circumstances:

a) impact shots in each of the following three velocity ranges: the ballistic range (typically below ~3 km·s^{-1}), the transition range (typically between ~3 km·s^{-1} and ~7 km·s^{-1}), and the hypervelocity range (typically above ~7 km·s^{-1});

b) impact shots at each of the following two angles: the angle perpendicular to the outermost surface and the average angle of impact on the outermost surface as determined from the flux analysis in 8.5.3.

NOTE 1 C.1 provides background information on HVI testing.

NOTE 2 Hydrocode analyses are sometimes performed to complement HVI tests, particularly for investigating ballistic limits at impact velocities that are beyond the capability of impact test facilities. Annex C.2 provides background information on hydrocode modelling and its applicability.

8.4.4 For each surface or combination of surfaces on the spacecraft (including components), associate a BLE.

8.4.5 For those surfaces that have failure criteria besides penetration, such as a maximum area of impact crater damage, associate the appropriate crater/hole damage formulae.

NOTE Reference [2] identifies some commonly used crater/hole damage formulae.

8.5 Failure probability analysis

8.5.1 Select a space debris and meteoroid impact risk analysis code.

NOTE C.3 provides background information on space debris and meteoroid impact risk modelling.

8.5.2 Select space debris and meteoroid environment models that are suitable for use with the impact risk analysis code chosen in 8.5.1.

NOTE ISO 14200 provides guidance on the selection and use of space debris and meteoroid environment models.

8.5.3 Apply the chosen space debris and meteoroid environment models, with the information arising from 8.2, to produce a data set of impact fluxes on the spacecraft.

8.5.4 Apply the chosen impact risk analysis code, with the data set of impact fluxes and the information arising from 8.2 to 8.4, to calculate the probability that one or more of the selected critical components will fail during the operational phase of the spacecraft as a result of impact with space debris or meteoroids, i.e. determine the impact-induced Probability of No Failure of the spacecraft, $PNF_{s/c}$, to achieve its post-mission disposal.

NOTE Annex D describes a method for calculating the Probability of No Failure that is commonly used in impact risk analysis codes.

8.6 Iteration of analysis

8.6.1 If $PNF_{s/c} \geq PNF_{min}$, then end the analysis.

8.6.2 If $PNF_{s/c} < PNF_{min}$, then iterate the analysis by considering the following (in order of preference):

a) revise the analysis assumptions in terms of failure criteria or spacecraft modelling; or

b) compare the flux values obtained from the selected space debris and meteoroid environment models with those from other models, e.g. as discussed in Reference [4] to characterize the differences due to inherent uncertainties in the models and, if appropriate, select alternative models for the analysis; or

c) perform additional impact testing and, if necessary, hydrocode modelling to remove engineering conservatism in the BLEs; or

d) identify those areas of the spacecraft design which are the greatest contributors to the spacecraft impact failure probability, and systematically apply one or more modifications, such as those listed in Annex E; or

e) examine alternatives for designing the spacecraft so that it can be orientated in such a way that its most vulnerable, critical components do not face the direction of greatest impact flux.

Annex A
(informative)

Supplementary information on the simple impact risk analysis procedure

A.1 Critical components

On a typical unmanned spacecraft, many of the components will contribute to its post-mission disposal, such as elements of the attitude and orbit control subsystem, the communication subsystem, and the power subsystem. However, to determine whether a component is critical, consideration also has to be given to how it might respond under impact (i.e. its damage modes), whether there is any redundancy, and the criteria for failure.

The identification of the critical surface on a critical component depends on the failure criterion for that component. For example, an unpressurized tank might only fail as a result of full penetration of the tank wall, whereas a pressurized tank can fail because of the pressure shock on the external surface of the tank wall. In the former case, the critical surface would be the interior surface of the tank wall, and the tank wall itself can be treated as part of the material protecting the surface from the space environment. In the latter case, the critical surface would be the external surface.

To calculate the at-risk area of a critical surface it is necessary to do the following:

a) determine the area of those parts of the critical surface that are most exposed to space (and therefore vulnerable to impact failure). If the critical surface is equally protected by other parts of the spacecraft, then the at-risk area is simply the total area of the critical surface.

b) adjust the at-risk area to take account of the orientation of the spacecraft. This gives the average cross-sectional area at risk. For spacecraft that maintain their orientation relative to the velocity vector, the average cross-sectional area at risk is the area projected in the impact threat direction. For spacecraft that tumble randomly, the area is one-quarter of the projected area with the greatest exposure to space.

A.2 Ballistic limit

The areal density of a layer of material, σ, is its mass density, ρ, multiplied by its thickness, T. The minimum diameter, d, of M/OD impactor that will penetrate an areal density, σ, is given by Formula (A.1):[1]

$$d = K \times \sigma \tag{A.1}$$

where K has a value of 0,07 for a typical material such as aluminium alloy 6061-T6, assuming that the units for d and σ are cm and g·cm^{-2}, respectively. Higher K values can be achieved for specially designed shields such as the Whipple shield (K = 0,35) and the multi-shock shield (K = 0,70). Note that these K values are only intended to give an estimate of the shielding effectiveness of a material. The calculation of the minimum diameter, d, provides a lower bound on the size of impactor that might be expected to penetrate the material, i.e. it is a conservative value for the ballistic limit.

It should be noted that Formula (A.1) does not require any information on the properties of a typical M/OD impactor, such as mean impact speed or mean angle of impact, since these are embedded within the K term. For a more precise determination of ballistic limit, in which particle characteristics are explicitly considered, it is necessary to use the formulae in Annex B.

It should also be noted that the ballistic limit is dependent on the criterion for failure. Although, in this case, the failure criterion is assumed to be perforation, other criteria can also be applied depending on the characteristics of the component being hit. For example, a titanium propellant tank has three notable impact-related failure modes: rupture caused by perforation; leak and loss of function; and fatigue cracking which, over time, causes a leak and loss of function. One or more of these criteria might be examined in an analysis.

A.3 probability analysis

The expected number of failures, h_i, for the at-risk area of a critical surface, i, is calculated from Formula (A.2):[1]

$$h_i = \left[L_{\text{deb}} \times F_{\text{deb}}\left(d_i, H\right) + L_{\text{met}} \times F_{\text{met}}\left(d_i, H\right) \right] \times A_i \times t_m \tag{A.2}$$

where $F(d_i, H)$ is the cross-sectional area flux at orbital altitude H for the M/OD diameter calculated in Formula (A.1); A_i is the at-risk area of the critical surface, as determined in A.1; t_m, in years, is the planned mission duration; and L is a correction factor for the attitude profile of the spacecraft, as defined in Table A.1. It should be noted that the value of the cross-sectional area flux is not constant in time. Therefore, for large values of t_m (e.g. more than two years), an averaged value of the cross-sectional area flux should be used. Space debris and meteoroid environment models, such as those listed in Reference [4], can be used to obtain averaged values of $F(d_i, H)$ flux for the spacecraft mission life.

Table A.1 — *L* factors for critical surfaces on spacecraft stabilized relative to the velocity vector [1]

	Surface[a]				
	Front	**Side**	**Top**	**Bottom**	**Rear**
Debris (L_{deb})	3	3	0,01	0,01	0,02
Meteoroid (L_{met})	2	1	2	1	0,2

[a] Front = facing direction of motion; side = perpendicular to the direction of motion and the surface of the Earth; top = facing the zenith; bottom = facing the centre of the Earth; rear = facing opposite to the direction of motion.

For a spacecraft that has a fixed orientation relative to its velocity vector, the *L* factor for a critical surface depends on the orientation of the surface relative to the direction of motion, as shown in Table A.1. If the surface does not face one of the orthogonal directions exactly, then the *L* factor has to be approximated. This is done either by using the *L* factor for the closest orthogonal surface, or by averaging the *L* factors of the bounding orthogonal surfaces. For a spacecraft that does not have a fixed orientation relative to its velocity vector, an *L* factor of 1 should be used.

The expected number of impact-induced failures of all the critical components, F_c, is given by:

$$F_c = \sum h_i \tag{A.3}$$

Therefore, the impact-induced probability of failure of one or more critical components, P_c, is given by:

$$P_c = 1 - \exp\left(\text{-}F_c\right) \tag{A.4}$$

Thus, the Probability of No Failure of the spacecraft ($PNF_{s/c}$) to achieve its post-mission disposal is:

$$PNF_{s/c} = 1 - P_c = \exp\left(\text{-}F_c\right) \tag{A.5}$$

Note that the presence of any redundancy is not specifically considered in Formulae (A.3) to (A.5), and so the use of these formulae is likely to produce a conservative result. Upon using this simple impact risk analysis procedure, if the value of $PNF_{s/c}$ is too low, then the more detailed analysis in Clause 8 can be performed.

Annex B
(informative)

Ballistic limit equations

B.1 General

A ballistic limit equation (BLE) is a type of damage formula which defines the characteristics of an impacting particle on the threshold of failure of a wall, panel, or shield, where failure is defined by a user-specified criterion (e.g. perforation/no perforation). That is, a BLE yields the critical size of an impacting particle at which the user-defined damage criterion for a structure is exceeded.

Note that BLEs are empirical in nature, i.e. generally derived from impact test programmes, and so they tend to have a limited range of application. Such limitations might include the range of impact velocities and angles, and the types of material in the target and projectile. Therefore, care is needed when using these formulae, especially in situations where the limits are exceeded.

B.2 BLE terms

BLEs comprise terms that describe the properties of a particle and the target that it impacts, as shown in Table B.1.

Table B.1 — BLE terms [5]

Symbol	Description
d_p	Diameter of impacting particle
T_t, T_B, T_s	Thickness of target, back wall, total shield
v	Impact velocity
K_f	Failure factor
K_1, K_2	Formula-specific factors
S	Space between shielding and back wall
α	Impact angle with respect to surface normal
ρ_t, ρ_p, ρ_s, ρ_B	Density of target, particle, shield, back wall
$\beta, \gamma, \delta, \kappa, \lambda, \mu, \xi, \upsilon 1, \upsilon 2$	Weighting coefficients

B.3 Single wall BLE

The single wall BLE defines the critical size of particle on the threshold of failure of a homogeneous structure such as an aluminium wall. It can be written in the following parametric form:[5]

$$d_{p,\lim} = \left[\frac{T_t}{K_f K_1 \rho_p^{\beta} v^{\gamma} (\cos\alpha)^{\xi} \rho_t^{\kappa}} \right]^{\frac{1}{\lambda}} \quad \text{(B.1)}$$

References [2] and [6] provide comprehensive collections of BLEs including several that are specific to single walls. The limitations of the formulae are also clearly identified.

B.4 Multiple wall BLE

To determine the critical size of a particle penetrating a multiple wall configuration, the BLE can be written in the following parametric form:[5]

$$d_{p,\lim} = \left[\frac{T_B + K_2 T_s^{\mu} \rho_s^{\upsilon 2}}{K_1 \rho_p^{\beta} v^{\gamma} (\cos\alpha)^{\xi} \rho_B^{\kappa} S^{\delta} \rho_s^{\upsilon 1}} \right]^{\frac{1}{\lambda}} \tag{B.2}$$

In using Formula (B.2), three velocity regions have to be considered. At low velocities (typically below ~3 km·s^{-1}), the ballistic region, an impactor is poorly fragmented by a bumper, and a very small number of solid particles are released. Between approximately 3 km·s^{-1} and 7 km·s^{-1}, an impactor is broken into several pieces, which can be solid or vaporous. This is the transition region. Above ~7 km·s^{-1}, the hypervelocity region, an impactor is broken up into a dense cloud of numerous fine vaporous particles. The three velocity regions are denoted by $v < v_l$, $v_l \le v \le v_u$, and $v > v_u$; where v_l, and v_u are the lower and upper transition velocities between the three regions, respectively.

For impacts whose velocities are either in the ballistic region or the hypervelocity region, Formula (B.2) is used. However, for impact velocities in the transition region, i.e. between v_l and v_u, linear interpolation is used to calculate the critical particle diameter, as follows:

$$d_{p,\lim} = \left(\frac{v_u - v}{v_u - v_l} \right) d_{p,\lim}(v_l) + \left(\frac{v - v_l}{v_u - v_l} \right) d_{p,\lim}(v_u) \tag{B.3}$$

References [2] and [6] provide comprehensive collections of BLEs including several that are specific to multiple walls. The limitations of the formulae are also clearly identified.

Annex C
(informative)

Background information on hypervelocity impact testing and modelling

C.1 Hypervelocity impact testing

The most straightforward method of deriving ballistic limit equations (BLEs) is to run a series of hypervelocity impact (HVI) experiments and to analyse and relate the damage data collected. BLEs shall span the impact velocity ranges of on-orbit impacts, which is approximately 1 $km \cdot s^{-1}$ to 16 $km \cdot s^{-1}$ for debris and 11 $km \cdot s^{-1}$ to 17 $km \cdot s^{-1}$ for meteoroids. Since laboratory hypervelocity launchers generally cannot accelerate projectiles above 10 km s^{-1}, it is sometimes necessary to combine the laboratory experiments with numerical simulations (e.g. using hydrocodes) to characterize BLEs over the full velocity range. Therefore, HVI tests are necessary to (a) obtain the reference points of BLEs within the testable range and their verification, and (b) provide data for testing (i.e. verification, calibration) of the numerical codes (including models of material behaviour under HVI conditions).

The hypervelocity launchers normally used for impact testing are the following:

— one-stage powder guns;

— two-stage light-gas guns;

— electromagnetic launchers;

— electrostatic launchers;

— blast (explosive) launchers.

The following types of measurement technique can be employed:

— process' optical registration (high frame-rate photography);

— process' X-ray registration (if possible, multi-flash and multi-aspect X-ray);

— registration of dynamic pressures, stresses, and impulse by gauges placed into target;

— registration of time of arrival by contact gages;

— post-test study of damage (craters, holes, etc.).

Reference [2] provides information on several HVI launchers that are capable of simulating space debris and meteoroid impacts on targets. These have been put through a series of calibration tests, defined by the IADC, the purpose of which is to provide confidence in the results obtained.

C.2 Hydrocode modelling

In order to perform numerical simulation of fast transient events, innovative numerical methods have been under development since the early 1950s. These so-called hydrocodes or wavepropagation codes allow the study of the time-resolved progression of acoustic and shock wave propagation due to impact, penetration, or detonation in fluids and solids. This class of codes is fundamentally based on a spatial and time discretization of the impacting bodies into small elements to which the first principles or conservation formulae for mass, momentum and energy are applied over small time steps. In hydrocodes, the first principles of physics are applied together with a formula of state to give the relationships between pressure, density, and internal energy. This provides a complete set of formulae governing hydrodynamic behaviour.

Hydrocode modelling complements impact testing as a means of determining ballistic limit equations, particularly at the very high velocities that are characteristic of space debris and meteoroid impacts. Before applying a hydrocode for this purpose, its applicability needs to be verified by comparison with experimental results. Reference [2] provides information on several hydrocode models which might be suitable. These have been undergoing a series of benchmark simulations defined by the IADC for the purpose of demonstrating that results obtained are comparable to those from impact tests.

C.3 Space debris and meteoroid impact risk modelling

A number of statistically-based computer codes have been developed to perform detailed impact risk analyses of non-trackable space debris and meteoroid particles. These 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 codes provide 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 analysed, and
- the damage formulae 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 formulae,
- the mean particle impact velocity (amplitude and direction),
- the numbers of craters of specified size, and
- the probability of no failure (as described in Annex D).

Reference [2] provides information on several codes that are capable of analysing the risk to a spacecraft from space debris and meteoroid impacts. These codes have been validated in different ways. For simple test cases, such as a flat plate and fixed impact velocity, the results have been compared to calculations done by hand. However, for more complex test cases, such as when the full directional and velocity distribution of the impacting particles is included, the codes have been validated by comparing results against a set of benchmark test cases defined by the IADC.

Annex D
(informative)

Method to calculate impact-induced Probability of No Failure

For spacecraft that fly with a fixed orientation, the meteoroid and orbital debris fluxes have to be treated as vector quantities and the effects of directionality shall be carefully evaluated. Most impacts from meteoroids and space debris will occur on forward-facing, side-facing, and space-facing surfaces with the forward-surface defined as the leading surface in the direction of motion of the spacecraft, i.e. the velocity direction or "ram" direction.

The number of impacts, N, from debris and meteoroid particles larger than a given diameter, increases linearly with exposed area (A), flux (F), and exposure time (Δt):

$$N = FA\Delta t \tag{D.1}$$

It should be noted that the value of flux, F, is not constant in time. Therefore, for large values of Δt (e.g. more than two years) it is customary to use an averaged value of F or, alternatively, to sum N over smaller time steps. Flux data are usually obtained from debris and meteoroid environment models, principal examples of which are discussed in Reference [4]. For a spacecraft in a given orbit, these models typically provide the number of impacts per unit area per unit time as a function of particle size, speed, and impact angle.

The probability of exactly n impacts occurring in the corresponding time interval can be determined using Poisson statistics, provided N is sufficiently small (<~10):

$$P_{i=n} = \left(\frac{N^n}{n!}\right) \mathrm{e}^{-N} \tag{D.2}$$

Thus, the probability of no impacts, $P_{i=0}$, is given by:

$$P_{i=0} = \mathrm{e}^{-N} \tag{D.3}$$

The same formulae apply if one wants to determine the number of impacts, N, that cause failure of the walls, panels, or shields on the spacecraft. In this case, however, an extra calculation step is needed which involves the definition of a failure criterion and the use of damage formulae such as ballistic limit equations. A widely used failure criterion is for there to be no perforation. However, other criteria are also possible, e.g. a crater is not to exceed a certain penetration depth or a hole shall be smaller than a given diameter. If the failure criterion is "perforation/no perforation", then the Probability of No Failure (PNF) is the same as the Probability of No Perforation (PNP), i.e.

$$PNF = PNP = \mathrm{e}^{-N} = \mathrm{e}^{-FA\Delta t} \tag{D.4}$$

where N is the number of debris and meteoroid impact perforations, i.e. failures, that can be expected over a given time period. N is calculated from: the flux (number per unit area per unit time) of impacting particles that exceed the ballistic limit; the exposed area; and the exposure time.

Annex E
(informative)

Options for improving impact survivability

E.1 Spacecraft design

An impact risk analysis of a spacecraft may have to be iterated several times before the survivability requirement is satisfied. This process can necessitate making various changes to the design of the spacecraft. In particular, the following modifications merit consideration:[2]

- enhance the protection of those surfaces that are most vulnerable to impact, e.g. by altering properties such as thickness, or changing materials, or adding shielding;
- reduce the area of the most vulnerable surfaces;
- relocate critical items away from the most vulnerable parts of the spacecraft;
- protect sensitive external equipment through the use of shadowing;
- compartmentalize the interior;
- increase redundancy of vulnerable items;
- determine if “redundancy within an item” is better than “redundancy of an item”;
- determine if redundant items should be collocated or distributed;
- include automatic systems to isolate damage (e.g. automatic isolation valves, self-sealing bladders);
- include an impact sensor network to detect impacts and guide operators in resolving any anomalies that might result;
- include the capability to perform safe-mode operations.

E.2 Vulnerable spacecraft surfaces

As noted in E.1, the impact protection of vulnerable spacecraft surfaces can be improved either by enhancing the design of existing panels, walls, etc. or by adding layers of shielding. In the event that shielding is added, it is recommended that the shields should satisfy the following design criteria:[2]

- affordable;
- impose minimum weight penalty;
- amenable to simple design and construction;
- after being impacted, continue to provide protection against further impacts;
- produce non-damaging secondary ejecta and spall;
- provide a means of melting and/or vaporizing meteoroid and debris particles over a large range of projectile mass, size, and velocity;
- provide a degree of thermal and radiation protection;
- resistive to the effects of atomic oxygen (a requirement for low-Earth orbits only);

- ideally, when impacted, prevent the creation of more debris (e.g. by trapping any resulting ejecta or spall);
- capable of surviving the normal launch and in-orbit vibration environments;
- meet spacecraft system requirements such as having a conductive external surface, electrically grounded to the spacecraft structure and acceptable thermo-optical properties;
- when impacted, any resulting debris, spall or dust from the shield should not cause subsequent failures of spacecraft equipment or unacceptable deterioration in performance (jamming of mechanisms, coating of optics, etc.);
- avoid interfering with the normal operation of the spacecraft such as deployment sequences, observation and taking measurements, communication and telecommand, etc.

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