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Space systems — Survivability of unmanned spacecraft against space debris and meteoroid impacts for the purpose of space debris mitigation

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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

This second edition cancels and replaces the first edition (ISO 16126:2014), which has been technically revised.

The main changes are as follows:

- the provision of new impact risk analysis requirements and procedures aimed specifically at satisfying the high-level impact risk requirements defined in the top-level International Standard on space debris mitigation, ISO 24113;
- the provision of new informative annexes to assist in the implementation of the impact risk analysis procedures.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The purpose of this document is to help satisfy two of the high-level requirements defined in the top-level International Standard on space debris mitigation, ISO 24113. Specifically, this document aims to maximise the survival of critical equipment required to perform post-mission disposal of an unmanned spacecraft, and to limit the possibility of an impact-induced break-up of the spacecraft. The analysis procedures in this document are consistent with those defined in References [1] and [2].

In principle, this document can also be used to assess the impact survivability of an unmanned spacecraft in support of other mission objectives. However, careful adaptation of the document can be necessary if put to such use.

This document 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 space debris throughout their orbital lifetime. All of the primary space debris mitigation requirements are contained in ISO 24113. The remaining International Standards, of which this is one, provide supporting methods and procedures to enable compliance with the primary requirements.

Space systems — Survivability of unmanned spacecraft against space debris and meteoroid impacts for the purpose of space debris mitigation

1 Scope

This document defines requirements and procedures for analysing the risk that an unmanned spacecraft fails as a result of a space debris or meteoroid impact.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1
ballistic limit
threshold of impact-induced 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 thresholds other than perforation are also possible.

3.2
catastrophic break-up
event that completely destroys an object and generates space debris

3.3
critical equipment
item(s) on a spacecraft whose failure would prevent the completion of one or more essential functions, such as post-mission disposal

3.4
high-energy SD/M
space debris or meteoroid object whose impact kinetic energy exceeds the threshold necessary to cause the *catastrophic break-up* (3.2) of a spacecraft

Note 1 to entry: The threshold is usually expressed in terms of the kinetic energy of an SD/M impact relative to the mass of the spacecraft, i.e. an energy-to-mass ratio (EMR). A typical value for the EMR threshold is 40 J/g.

3.5

project lifecycle

phases of a project from mission analysis through to disposal

Note 1 to entry: The phases of a project are summarised in Table 1. A more detailed description can be found in ISO 14300-1[3].

Table 1 — Summary of the phases of a project

Phase	Description
Pre-phase A	Mission analysis
Phase A	Feasibility
Phase B	Definition
Phase C	Development
Phase D	Production
Phase E	Utilization
Phase F	Disposal

3.6

small SD/M

space debris or meteoroid object whose size does not exceed one centimetre in its largest dimension

Note 1 to entry: This threshold is defined for two reasons. First, in impact risk analysis models it is difficult to characterise accurately the penetrative damage inside a spacecraft from an SD/M impactor larger than one centimetre in size. Second, it is difficult for current shielding technology to protect a spacecraft against an SD/M impactor larger than one centimetre in size.

4 Symbols and abbreviated terms

4.1 Symbols

A	power law term
B	power law term
C	speed of sound of the material in a target wall (km/s)
D	constant value
d_c	critical diameter of an impactor at the threshold of failure of a wall, panel or shield (cm)
d_{LF}	diameter of largest fragment in an in-line cloud ejection cone (cm)
d_p	diameter of impacting particle or projectile (cm)
G	constant value
H	Brinell hardness of the material in a target wall
K	factor that combines the material properties of a target
K_{CFRP}	factor that combines the material properties of a CFRP target
K_f	factor that distinguishes between different types of impact damage failure
K_1	factor that combines the material properties of a target
K_2	factor that combines the material properties of a target

K_3	factor that combines the material properties of a target
K_{3D}	factor that combines the material properties of a target
K_{3S}	factor that combines the material properties of a target
K_4	factor that combines the material properties of a target
k	factor that distinguishes between different types of impact damage failure
L_1	adjustable coefficient to separate the ruptured and non-ruptured data points in an RLE
L_2	adjustable coefficient to separate the ruptured and non-ruptured data points in an RLE
L_3	adjustable coefficient to separate the ruptured and non-ruptured data points in an RLE
m_p	mass of impacting particle or projectile (g)
p_{int}	internal pressure in a pressurised tank (ksi)[1]
p_0	constant value
r_o	outer radius of a pressurised tank (cm)
S	stand-off distance between the outer bumper of a shield and a back wall (cm)
t_{al}	thickness of aluminium wall (cm)
t_b	thickness of bumper shield (cm)
t_{CFRP}	thickness of CFRP wall (cm)
t_{comp}	thickness of composite material in a COPV (cm)
t_f	thickness of foam core in sandwich panel (cm)
t_{hc}	total thickness of honeycomb cell walls perforated by a projectile impacting at angle θ (cm)
t_{lin}	thickness of liner material in a COPV (cm)
t_{tot}	total thickness of cylindrical portion of COPV material overwrap, i.e. $t_{comp} + t_{liner}$ (cm)
t_w	thickness of a single wall, or thickness of back wall in a multiple wall configuration (cm)
v	impact velocity (km/s)
v_h	high velocity limit for transition from fragmentation to hypervelocity regime (km/s)
v_l	low velocity limit for transition from ballistic to fragmentation regime (km/s)
v_{LF}	velocity of largest fragment in an in-line cloud ejection cone (km/s)
v_n	normal component of impact velocity, i.e. $v \cos\theta$ (km/s)
α	weighting coefficient
β	weighting coefficient
γ	weighting coefficient

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[1] 1 ksi = 6,895 MPa.

δ	weighting coefficient
ζ_1	weighting coefficient
ζ_2	weighting coefficient
η	weighting coefficient
θ	impact angle with respect to surface normal (degrees)
κ	weighting coefficient
λ	weighting coefficient
μ	weighting coefficient
ξ	weighting coefficient
ρ_A	areal density of one or more layers of material (g/cm^2)
$\rho_\mathrm{A,f}$	areal density of foam core in sandwich panel (g/cm^2)
ρ_al	density of aluminium wall (g/cm^3)
ρ_b	density of bumper shield (g/cm^3)
ρ_CFRP	density of CFRP wall (g/cm^3)
ρ_comp	density of the composite material in a COPV (g/cm^3)
ρ_f	density of foam core in sandwich panel (g/cm^3)
ρ_hc	density of honeycomb core in a sandwich panel (g/cm^3)
ρ_p	density of impacting particle or projectile (g/cm^3)
ρ_w	density of a single wall, or density of back wall in a multiple wall configuration (g/cm^3)
σ_h	hoop stress of a pressurised tank, i.e. $p_\mathrm{int}\, r_\mathrm{o} / t_\mathrm{tot}$ (ksi)
σ_u	ultimate tensile stress of the material in a pressurised tank (ksi)
$\sigma_\mathrm{u,\,comp}$	unidirectional ultimate stress of the composite material in a COPV (ksi)
$\sigma_\mathrm{u,\,lin}$	ultimate stress of the liner material in a COPV (MPa)
$\sigma_\mathrm{y,\,lin}$	yield stress of the liner material in a COPV (MPa)
$\sigma_\mathrm{y,\,w}$	yield stress of material in a single wall or the back wall in a multiple wall configuration (ksi)
ϕ	angle between central axis of in-line cloud ejection cone and surface normal (degrees)
ψ	spread angle of in-line cloud ejection cone (degrees)

4.2 Abbreviated terms

AIT	assembly integration and test
BLE	ballistic limit equation
CFRP	carbon fibre reinforced plastic
COPV	composite overwrapped pressure vessel
CVCM	collected volatile condensable material
EMR	energy-to-mass ratio
FTA	fault tree analysis
GEO	geostationary orbit
GVF	geometric view factor
HVI	hypervelocity impact
IADC	Inter-Agency Space Debris Coordination Committee
LEO	low Earth orbit
MLI	multi-layer insulation
MVF	modified view factor
REACH	registration, evaluation, authorisation and restriction of chemicals
RLE	rupture limit equation
RML	recovery mass loss
SD/M	space debris/meteoroid(s)
STENVI	standard environment interface
TT&C	telemetry, tracking, and command

5 Requirements for impact risk analysis

5.1 General

5.1.1 The top-level International Standard on space debris mitigation, ISO 24113, specifies two high-level SD/M impact risk assessment requirements that aim to:

a) ensure the post-mission disposal of a spacecraft;

b) limit the probability that a spacecraft experiences an SD/M impact-induced break-up before its end of life.

5.1.2 To satisfy these high-level requirements, the following two distinct analysis cases can be defined:

a) case 1: an analysis of the probability of SD/M impact-induced failure of the spacecraft, where failure is defined by an inability to perform successful disposal;

b) case 2: an analysis of the probability of SD/M impact-induced failure of the spacecraft, where failure is defined by a catastrophic break-up.

5.1.3 The analysis in case 2 can be subdivided by analysing the following two types of catastrophic break-up separately:

a) case 2a: a catastrophic break-up caused by the impact of a small SD/M on an equipment item containing a large amount of stored energy, such as a pressurised vessel;

b) case 2b: a catastrophic break-up caused by the impact of a high-energy SD/M on the spacecraft.

5.1.4 Detailed requirements to support the implementation of these analyses are provided in 5.2 and 5.3.

5.2 Failure probability thresholds

5.2.1 For case 1, during the design of a spacecraft for which a disposal manoeuvre has been planned, a threshold shall be specified for the probability that an SD/M impact prevents the disposal from being successful.

5.2.2 For case 2a, during the definition of a mission and the design of a spacecraft, a threshold shall be specified for the probability that the spacecraft experiences a catastrophic break-up before its end of life as a result of a small SD/M impacting an equipment item containing a large amount of stored energy.

5.2.3 For case 2b, during the definition of a mission and the design of a spacecraft, a threshold shall be specified for the probability that the spacecraft experiences a catastrophic break-up before its end of life as a result of a high-energy SD/M impacting the spacecraft.

NOTE The threshold in case 2b can be specified taking into account the significance of the mission, the mission requirements, and the expected severity of adverse effects on the orbital environment if a break-up occurs.

5.2.4 The failure probability thresholds shall be set by the approving agent responsible for requirements in the space debris mitigation plan.

NOTE Each of the probability thresholds can be expressed as a maximum value for the probability of failure, $P_{\text{F max}}$.

5.3 Failure probability analysis

5.3.1 To satisfy each of the failure probability thresholds in 5.2, an analysis shall be performed in which the corresponding probability of failure, P_F, is calculated and compared with the specified maximum value, $P_{\text{F max}}$.

5.3.2 If $P_F > P_{\text{F max}}$, then measures shall be taken to reduce P_F so that it is below the maximum value.

5.3.3 The analysis and reduction of P_F for each of the analysis cases shall follow a clearly defined procedure.

NOTE An example procedure for analysis case 1 is described in Clause 6. Example procedures for analysis cases 2a and 2b are described in Clause 7. For some types of spacecraft, such as small ones or those operating in GEO, simplified procedures for analysis cases 2a and 2b can be considered if the impact risks are sufficiently low.

5.3.4 The results of the impact risk analysis, the methodology used, and any assumptions made shall be approved by the approving agent of the spacecraft.

6 Impact risk analysis procedure for case 1

6.1 The consideration of SD/M at sub-centimetre sizes is particularly important when analysing the impact risks that can prevent the successful disposal of a spacecraft. An analysis of such impactors:

a) enables the probability of impact-induced failure of the spacecraft to be calculated, where failure is defined by not being able to perform a successful disposal;

b) allows any impact vulnerabilities in the spacecraft design to be identified;

c) guides the implementation of appropriate levels of impact protection in the spacecraft.

6.2 A procedure for performing a detailed analysis of the probability that a spacecraft cannot complete a successful post-mission disposal, as a result of impacts from small SD/M, is shown in Figure 1. The procedure is designed to be followed in phases B and C of the spacecraft project lifecycle.

NOTE It is also possible to perform a simple impact risk analysis during phase A for the purpose of defining key aspects of the proposed design of the spacecraft, such as its geometric characteristics. A procedure for such an analysis is described in Annex A.

6.3 During the preliminary design in phase B, the aim of an impact risk analysis is to be sufficiently detailed that it can suggest and enable efficient protection solutions which can otherwise be impossible during the final stages of development.

6.4 By contrast, in the late development stages a redesign of the general spacecraft architecture is not usually possible due to the complex subsystem interrelationships that are characteristic of spacecraft. Thus, during phase C, the main goal is to refine the impact risk analysis of the spacecraft and identify areas of its design where additional shielding is necessary.

Figure 1 illustrates the key steps in the procedure and the flow of information between the steps.

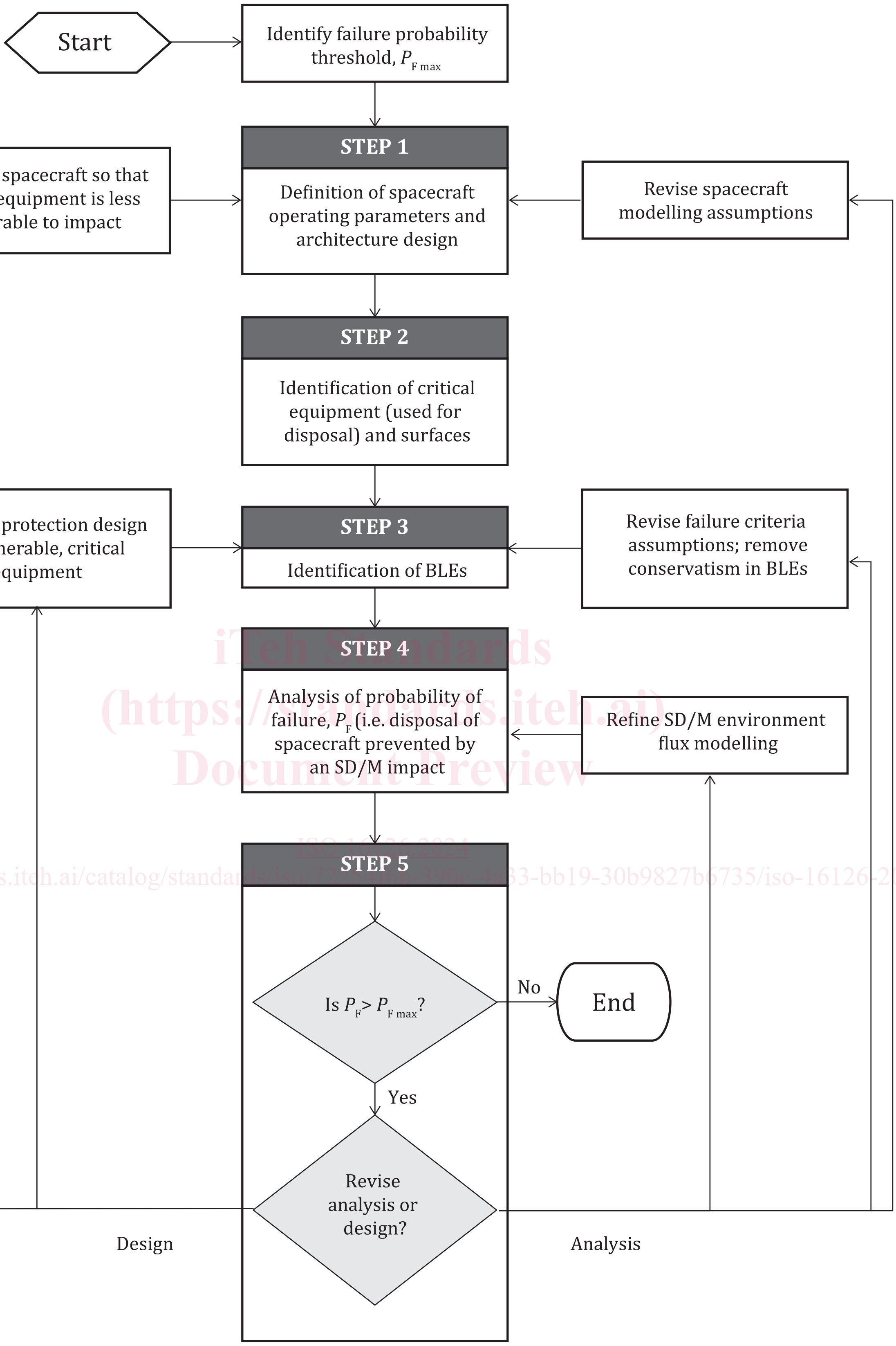

Figure 1 — Impact risk analysis procedure for case 1