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Space systems — Detailed space debris mitigation requirements for spacecraft

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Contents

Page

Foreword ..... **iv**
Introduction ..... **v**
1 Scope **1**
2 Normative references **1**
3 Terms and definitions **1**
4 Symbols and abbreviated terms **2**
5 Avoiding release of space debris into Earth orbit during normal operations **2**
6 Avoiding break-ups in Earth orbit **3**
6.1 General 3
6.2 Accidental break-up caused by an on-board source of energy 3
6.2.1 General measures 3
6.2.2 Subsystem-specific measures 4
6.3 Accidental break-up caused by a collision 5
6.3.1 Collision avoidance 5
6.3.2 Assessment of the probability of structural break-up caused by impacts with debris or meteoroid 6
7 Disposal of spacecraft after the end of mission **6**
7.1 General 6
7.2 Ensuring execution of disposal action 6
7.3 Disposal to minimize interference with the GEO protected region 7
7.3.1 General 7
7.3.2 Developing basic manoeuvre requirements for a stable disposal orbit 7
7.3.3 Developing long-term (100-year) disposal orbit characteristics 7
7.3.4 Determining the manoeuvre sequence 8
7.4 Disposal to minimize interference with the LEO protected region 8
7.4.1 General 8
7.4.2 Re-entry 8
8 Estimating mass of remaining usable propellant **9**
8.1 General 9
8.2 Uncertainty of estimation 9
8.3 Incorporating required function into spacecraft design 9
8.4 Documentation of data 10
9 Space debris mitigation plan **10**
9.1 General 10
9.2 Break-up prevention plan 11
9.3 End of mission disposal plan (EOMDP) 11
9.4 Contingency plan 12
Annex A (informative) **Procedure for estimating probability of accidental break-up** **13**
Annex B (informative) **Examples of estimation methods** **16**
Annex C (informative) **Deployable drag enhancement device** **19**
Bibliography **20**

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.

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 documents 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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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

This first edition cancels and replaces ISO 16127:2014, ISO 16164:2015, ISO 23339:2010 and ISO 26872:2019.

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

This document is developed to incorporate the content of ISO 16127, ISO 16164, ISO 23339, ISO 26872 and other detailed requirements relevant to spacecraft related debris mitigation, corresponding to ISO 24113. The purpose of this document is to enable conformance with those high-level space debris mitigation requirements in ISO 24113 that are relevant to spacecraft.

This document acts as one of the supporting technical standards for space debris mitigation, to provide implementation requirements and details for the top-level requirements in ISO 24113.

Space systems — Detailed space debris mitigation requirements for spacecraft

1 Scope

This document defines detailed space debris mitigation requirements and recommendations for the design and operation of unmanned spacecraft in Earth orbit.

This document defines detailed requirements that are applicable to:

a) avoiding the intentional release of space debris into Earth orbit during normal operations;

b) avoiding break-ups in Earth orbit;

c) disposal of a spacecraft after the end of mission;

d) estimating the mass of the remaining usable propellant;

e) developing and maintaining the space debris mitigation plan.

NOTE This document does not cover nuclear power sources on spacecraft.

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 24113:2019, *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:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
acquiring organization
organization that plans and manages the development and acquisition contracts for the space system

Note 1 to entry: The responsibilities of the acquiring organization include the engineering and technical aspects of the space system's design and operations.

3.2
book-keeping method
method for determining fluid consumption by monitoring flow rates and the duration of propellant expenditure periods

3.3
disposal orbit
orbit in which a spacecraft resides following the completion of its disposal actions

3.4
PVT method
method for determining the remaining fluid quantity by estimating the mass of gas by deriving density in a known volume from pressure and temperature measurements

3.5
remaining usable propellant
propellant that remains in the propellant system and that is effective for attitude and orbit control manoeuvres excluding residuals and uncertainty

4 Symbols and abbreviated terms

ΔV	delta velocity or total velocity change
EOL	end of life
EOMDP	end of mission disposal plan
GEO	geostationary Earth orbit
LEO	low Earth orbit
$\dot{m}$	mass flow rate
MLI	multilayer insulation
PVT	pressure, volume, temperature
SDMP	space debris mitigation plan
t	time

5 Avoiding release of space debris into Earth orbit during normal operations

ISO 24113 specifies that a spacecraft shall be designed so as not to release space debris into Earth orbit during normal operations. To satisfy this requirement, as a minimum, the following measures shall be implemented.

a) Any appendage related to spacecraft normal operations shall be designed not to be released.

NOTE 1 Appendages include items such as apogee kick propulsion devices, fasteners of holding and deployment mechanisms, caps, hoods, heat insulation enclosures, springs, explosive bolts and related fragments.

b) Releasing parts essential for mission objectives should be assured not to pose a risk to the safety of operating spacecraft and deteriorate the space environment.

c) Paint, MLI and surface materials that are exposed to the space environment, should be selected and processes applied properly, to avoid flaking off from the spacecraft.

NOTE 2 Following ISO documents could help to assure compliance:

1) ISO 16691, Thermal control coatings for spacecraft — General requirements.

2) ISO 23129, Space systems — Thermal control coatings for spacecraft — Atomic oxygen protective coating on polyimide film.

3) ISO 23230, Space systems — Paint materials — Processes, procedures, requirements.

d) Programs using tethers shall take extra measures to limit the collision risk with resident space objects, and not to be severed with a single impact of debris or meteoroid.

NOTE 3 Potential measure for tethered system is to apply multi-strand tether, to retract the tether in the disposal phase.

6 Avoiding break-ups in Earth orbit

6.1 General

ISO 24113 specifies requirements to avoid the accidental break-up of a spacecraft in Earth orbit both before and after its end of life. 6.2 and 6.3 provide detailed measures to help satisfy these requirements.

6.2 Accidental break-up caused by an on-board source of energy

6.2.1 General measures

6.2.1.1 Spacecraft design

The spacecraft design measures to prevent accidental break-ups caused by on-board source of energy are as follows.

a) The calculations to determine the probability of accidental break-up while in orbit until its end of life shall be performed and assessed with probability levels defined in ISO 24113:2019, 6.2.2.1.

NOTE 1 Annex A provides an example of an acceptable detailed evaluation approach.

b) Measures shall be designed to ensure that all on-board sources of stored energy can be depleted or made safe and permanently deactivated once they are no longer required for the mission operation.

NOTE 2 Source can be residual propellants, batteries, high-pressure vessels, self-destructive devices, flywheels, and momentum wheels.

c) The design of the on-board sources of stored energy shall take into account the following influences:

— the environmental extremes expected to be encountered during the normal operations;

— mechanical degradation during the normal operations;

— chemical decomposition;

— the effect of potential failure modes of the spacecraft during the mission, and

— what effect they would have on the ability to passivate the spacecraft.

d) The robustness of the design shall be confirmed during the design review process, to ensure that adequate reliability and quality control has been performed to inhibit any failure that can lead to a break-up event with a probability worse than specified in ISO 24113.

e) The first issue of passivation procedures shall be established prior to the end of the design phase.

6.2.1.2 Spacecraft operations

The spacecraft in-orbit operation measures to prevent accidental break-ups caused by on-board source of energy are as follows.

a) For the operations of the spacecraft, procedures shall be defined to allow monitoring of the relevant parameters of each subsystem, which has been identified as a potential source of space debris generation, in order to detect malfunctions.

b) The following items, as a minimum, shall be monitored from the ground, if applicable:

— pressure and temperature in the engines, tanks, pressure vessels;

— parameters (temperature and voltage) of batteries to detect failures;

— parameters to detect failure modes of the orbit and attitude control system.

c) Prior to the disposal phase, the passivation procedures shall be updated to take into account any failures that have occurred during the mission and that affect the ability to passivate the spacecraft.

d) At the time when spacecraft operation is concluded either purposefully or due to malfunction and disposal manoeuvres have been finished, passivation shall be performed.

NOTE If a controlled re-entry is to be performed, then passivation is not necessary.

e) In the event of in-orbit malfunctions which can lead to break-up or the loss of operating function, a contingency plan to prevent debris generation should have been studied and, where appropriate, implemented.

6.2.2 Subsystem-specific measures

6.2.2.1 Electrical systems

The specific measures for electrical systems are as follows.

a) The performance of batteries shall be monitored and assessed in accordance with standardized procedures to assure the safety of the mission and post-mission disposal.

NOTE 1 Standardized procedure for health assessment of lithium-ion batteries can be found in ISO/TR 20891.

b) Batteries and/or electrical systems shall be designed and manufactured, both structurally and electrically, to prevent break-ups during all orbital life.

c) Pressure increase in battery cells and assemblies, potentially leading to a break-up, shall be prevented.

NOTE 2 This can be done by mechanical measures for some types of batteries as far as it doesn't decrease the reliability.

d) At the end of operations, take measures to prevent re-charging to batteries, and discharge the stored electric energy with assuring to keep necessary electric energy for following disposal action.

6.2.2.2 Propulsion systems

The specific measures for propulsion systems are as follows.

a) Pressure vessels, such as tanks and high-pressure gas bottles, shall be designed to avoid accidental break-up caused by stored energy sources.

NOTE 1 ISO 14623 and ISO 24638 contain requirements relating to the design of pressure vessels.

b) For a bipropellant propulsion system, especially with hypergolic propellants, tanks and lines should be designed so that any single-point failure does not cause the unplanned mixture or combustion of the propellants.

c) Before end of life, as part of the disposal phase, the spacecraft shall have consumed or vented residual liquid propellants and pressurized fluids, such as cold gas, liquefied gas, and propellant for the fluid-based electric propulsion systems, which are potential sources of break-ups. Any residual liquid propellants and pressurized fluids can be a source of break-ups also for spacecraft drifting outside protected regions after end of life and should be consumed or vented to the maximum extent as possible before end of life.

d) End of venting shall be monitored (or confirmed), if appropriate, by proper means, such as on-board pressure sensors, fluid gauging systems, thermal sensing, attitude sensing, or any other demonstrable means.

e) If it is not possible to vent, a sufficient safety margin to ensure no break-ups under expected post-disposal environmental conditions shall be adopted.

f) The venting system and process shall be designed not to be prevented by the frozen propellants.

g) The venting process should be defined to take into account any potential effects on the spacecraft's attitude or orbit and any ground visibility issues.

h) Solid rocket motors shall only be actuated in the case that there have been no sensor indications of motor degradation due to mission-induced damage or due to adverse environmental conditions.

i) Solid motor should not be allowed if it generates slags in the GEO and LEO protected regions.

6.2.2.3 Pressurized systems such as heat pipes/fluid loops

All pressurized systems which are typically not designed to be vented, such as heat pipes/fluid loops, shall be designed and qualified with safety margins that prevent break-up of the spacecraft when considering thermal effects in orbit.

NOTE Specific venting operations for this kind of pressurized systems are not required in the disposal phase.

6.2.2.4 Rotating hardware

The specific measures for rotating hardware are as follows.

a) All rotating devices, for example flywheels, reaction wheels, and momentum wheels, shall be designed so that failure of the rotating part does not cause the break-up of the spacecraft under nominal mechanical environmental conditions.

b) All rotating parts shall be allowed to de-spin, or stopped by termination of the power supply, at the end of life.

6.2.2.5 Other devices

The specific measures for other devices are as follows.

a) Any other energy sources, such as pyrotechnically operated devices, shall be designed so that they do not cause unacceptable risk of break-up and generate fragments.

b) Where this is unavoidable, the fragments shall be self-contained within the device which is affected by break-up.

6.3 Accidental break-up caused by a collision

6.3.1 Collision avoidance

The spacecraft shall be designed and operated properly to prevent collision with trackable orbital objects before its end of life.

a) During the mission operation, the conjunction assessment shall be conducted periodically against potentially approaching objects based on the reliable orbit data.

b) Exchange of orbital parameters should be encouraged among spacecraft operators or space agencies, to precisely check the close approach distance, and then determine an optimal avoidance manoeuvre strategy for operators.

c) The probability of collision with approaching trackable orbital objects shall be assessed during operation.

NOTE 2 ISO/TR 16158 can be used to estimate the probability of collision.

d) If the risk of collision is above the threshold set by an approving agent, then the collision avoidance manoeuvre (and/or returning manoeuvre) shall be planned and conducted appropriately, to reduce the collision risk below the corresponding risk threshold.

6.3.2 Assessment of the probability of structural break-up caused by impacts with debris or meteoroid

It is required to assess the probability of structural break-ups of spacecraft caused by impacts with debris or meteoroid before its end of life.

a) The vulnerability of spacecraft against impact of space debris or meteoroid shall be assessed during the design phase.

b) If the risk of structural break-up caused by impacts with debris is above the threshold set by an approving agent, then the special design measures should be considered to minimize this risk.

NOTE 1 ISO 11227 and ISO 16126 provide guidance for analysing the impact risk from small debris impacts and improving the design of spacecraft.

NOTE 2 The probability of successful collision avoidance, induced from the experience and authorized by approving agent, can be incorporated into this assessment.

NOTE 3 The estimated probability of collision with trackable object will provide information of the expected number of collision avoidance during operation and contribute on the planning of propellant allocation for 7.2 c).

7 Disposal of spacecraft after the end of mission

7.1 General

ISO 24113 specifies requirements for the disposal of a spacecraft after the end of mission so as to minimize interference with the protected regions. 7.2 to 7.4 provide detailed measures to help satisfy these requirements.

NOTE Measures to prevent break-up, as a part of disposal action, is written in 6.2.

7.2 Ensuring execution of disposal action

The measures to ensure execution of disposal action are as follows.

a) The probability of successful disposal should be determined during the design phase, and decide to terminate the operation taking into account the events that have occurred during the operating phase.

NOTE 1 In the case of highly eccentric orbits, considering the uncertainty in estimation of orbital lifetime, the amount of propellant for disposal is designed to assure the compliance with 25-year rule with a probability of more than 0,9. This is excluded from the probability of successful disposal of 0,9.

NOTE 2 Where possible, put in place well-organized systematic surveillance procedures, pre-planned emergency actions, adequate procedures for determining the extension of the lifespan taking into account deterioration or decommissioning, etc. The method to assess this probability can be determined by the approving agent.

b) The availability of items concerning to the specific criteria shall be assured throughout the designated (or planned) mission life.

NOTE 3 Examples are estimated amounts of propellant remaining, redundancy remaining, status of electrical power, status of systems critical to successful disposal, and time required to execute each disposal action.

c) In order to reserve enough usable propellant to ensure the success of disposal manoeuvres, the propellant used over the mission life shall be estimated with stated uncertainty; and the remaining usable propellant shall be regularly monitored with quantified uncertainty.

NOTE 4 The remaining usable propellant can consider and include potentially needed collision avoidance manoeuvres during operation.

NOTE 5 Clause 8 gives details for the estimation of remaining usable propellant.

d) A spacecraft should be injected into an intermediate (lower) altitude before transferring the spacecraft to its final orbit for the planned operation, to provide the opportunity to check-out the system, especially all critical systems required for controlling the spacecraft, performing collision avoidance and post mission disposal.

e) The intermediate orbit should be designed preferably in a way that the spacecraft, even with critical failures, naturally decays in accordance with the 25-year limit for the orbit lifetime as defined in ISO 24113.

7.3 Disposal to minimize interference with the GEO protected region

7.3.1 General

ISO 24113 specifies that a spacecraft shall remain outside of, and not interfere with, the protected regions for a period of at least 100 years after the end of its life.

a) Select a stable disposal orbit and conduct relating disposal manoeuvres for spacecraft before end of life according to ISO 24113:2019, 6.3.2.2 or 6.3.2.3.

b) In the case of inclined GEO spacecraft, re-entry option is possible with feasible velocity increase depending on the specific initial combination of inclination, eccentricity and ascending node. If the orbital lifetime and dwell time passing through the protected orbital regions are acceptable considering the contents of ISO 24113, it can be taken as a disposal option.

7.3.2 Developing basic manoeuvre requirements for a stable disposal orbit

A stable disposal orbit shall be established by one of the two options described below.

a) Use the eccentricity constraint as specified in ISO 24113:2019, 6.3.2.2 a) and Formula (1) to determine initial disposal orbit conditions;

b) Perform long-term (100-year) numerical integrations of the selected disposal orbit to confirm that the predicted minimum perigee is above GEO + 200 km (35 986 km) or the predicted maximum apogee is below GEO − 200 km (35 586 km).

7.3.3 Developing long-term (100-year) disposal orbit characteristics

Long-term (100-year) orbit histories are needed only when the second option [see 7.3.2 b)] is chosen to establish as stable disposal orbit.

a) Obtain orbit propagation results by using a reliable orbit propagator of high precision, including as a minimum the perturbing forces of Earth's gravitational harmonics (up to a degree/order of 6 by 6), lunisolar attractions and solar radiation pressure.

NOTE 1 ISO 27852 describes appropriate methods for achieving this.

b) Count the time duration staying out of the protected orbit region from the point at which all the disposal actions are finished, to the first time at which the spacecraft intersects with the bound of the protected region.

c) Improve the altitude stability by:

— pointing the initial disposal perigee toward the sun (perigee is sun-pointing);

— performing the disposal manoeuvres in the most favourable season of the year, such that the same amount of perigee altitude increase gives the largest clearance over 100 years.

NOTE 2 The true optimal direction differs slightly from the actual sun-pointing direction as a result of lunar perturbations.

7.3.4 Determining the manoeuvre sequence

The manoeuvre sequence shall be determined to place the GEO spacecraft in the required disposal orbit, have the optimal near-sun-pointing perigee and exhaust all the propellant on board.

NOTE The disposal orbit is obtained after passivation and the tank depletion, which can have unpredictable effects on orbital parameters and altitude (see 6.2.2.2 g)).

7.4 Disposal to minimize interference with the LEO protected region

7.4.1 General

The following steps shall be followed when planning for disposal.

a) Predict the orbit lifetime of spacecraft to ensure that the requirements in ISO 24113:2019, 6.3.3.1 are met.

NOTE ISO 27852 provides a guidance for the estimation of orbital lifetime.

b) Select which of the disposal options in the order of priority listed in ISO 24113:2019, 6.3.3.2 is to be used.

c) If the orbital decay is augmented through the use of drag enhancement devices, such as balloons or parachutes, then the recommendations in Annex C should be considered.

7.4.2 Re-entry

The requirements for Earth re-entry are as follows.

a) If the spacecraft has been selected for a re-entry, the casualty risk shall be assessed.

NOTE 1 ISO 27875 provides a guidance for the assessment of re-entry casualty risk.

b) If the casualty risk for uncontrolled re-entry exceeds the value specified by approving agent, all disposal options that can reduce the risk to the value specified by approving agent shall be used.

NOTE 2 Retrieval, controlled re-entry by choosing an unpopulated region on Earth, design for demise or other innovative solutions can also reduce the casualty risk.

c) If the spacecraft is to perform an uncontrolled re-entry, any remaining on-board propellant should be used to further reduce the decay duration.

8 Estimating mass of remaining usable propellant

8.1 General

The mass of remaining usable propellant for performing disposal manoeuvres shall be estimated.

a) The amount of fuel, including uncertainties, necessary to perform spacecraft disposal shall be estimated from the design phase.

NOTE 1 Propellant mass and volume determine the spacecraft bus characteristics in size and mass and influence the launch cost. A careful consideration of the estimation error of remaining usable propellant at the design phase can optimize the design and reduce the propellant loading amount.

b) The minimum ΔV need (3-σ) to reach the targeted disposal orbit shall be calculated based on the predicted end of mission orbit of the spacecraft, and the required decay or time duration staying outside of the protected region.

c) The fuel required to provide this ΔV shall be maintained for end-of-life disposal.

d) The estimation method (and allowances for estimation error) that best meets the objectives shall be selected at an early stage of the spacecraft design phase and mission development.

NOTE 2 The use of multiple estimation methods can be helpful for redundancy and higher certainty. Annex B lists estimation methods suitable for applicable spacecraft.

e) During the on-orbit mission phase, the actual mass of remaining usable propellant shall be monitored regularly over the mission life to ensure that a positive margin of usable propellant remains to perform the disposal manoeuvre as planned.

f) The margin shall include a mass equivalent to the assumed estimation error.

8.2 Uncertainty of estimation

Considering the uncertainty of estimation are as follows.

a) The measurement uncertainty estimation shall account for all significant error contributions.

b) The error contributions shall be expressed as equivalent propellant amounts, typically in kilograms.

NOTE 1 Examples of error contributing parameters are given in Annex B.

c) When several methods are available after taking account of cost, mass, performance, etc., the optimal measurement or set of measurements should be used, considering that different kinds of measurements are best for each mission phase (early operation, partially consumed, nearly empty).

NOTE 2 Designers can choose between low-cost, coarse sensors and expensive, very precise sensors. The drawback of low-cost sensors is a higher mass of propellant.

d) Measurement uncertainty estimation shall reflect its estimation error as well as the particular characteristics of the propulsion system, its performance and the planned propellant consumption.

e) The estimate of measurement uncertainty shall reflect the uncertainty associated with the initial loading propellant mass.

8.3 Incorporating required function into spacecraft design

The design requirements for estimation of remaining useful propellant are as follows.

a) After the estimation method or methods have been selected, the hardware and software required to estimate the mass of remaining propellant and to record, store and transmit the associated data shall be incorporated into the system design.

b) The hardware and software design features required to estimate the mass of remaining propellant shall be assessed throughout the spacecraft's development.

c) The functions of hardware and software required to estimate the mass of remaining propellant shall be verified at the test phase.

d) The mass of remaining propellant shall be re-estimated as necessary parameters are determined and their contributions to error become clear, considering degradation of the overall measuring system over the mission life.

e) The amount of propellant estimated as being necessary for the disposal manoeuvre (including the measurement uncertainty) shall be determined before launch and loaded on the spacecraft.

f) The required propellant measurement uncertainty shall be specified; and evidence shall be provided to demonstrate that the design meets this requirement throughout the spacecraft's nominal life.

8.4 Documentation of data

The requirements for documentation of data are as follows.

a) The data necessary for estimating the remaining usable propellant mass, including estimation errors, shall be documented throughout the manufacturing and testing.

NOTE See Annex B for examples of key parameters to be documented for each estimation method.

b) The data acquired through the testing phase shall be described in the spacecraft handbook so that it can be referenced at the operation phase.

c) A measurement of available propellant shall provide the following information:

1) the time at which the measurement applies;

2) the estimated amount of available propellant in units chosen by the user;

3) the uncertainty on this estimate to a confidence level chosen by the user and in the same units as the measurement (e.g. 95 % confidence that the actual amount of propellant is within *x* kg of the reported measurement), evaluated using a technique supported by documented evidence;

4) a note of any significant issues relating to the use of the reported measurement.

d) The measurement uncertainties of all sensors shall be documented at the design phase at the component test level and, finally, at the system test level, in order to evaluate its contribution to the estimated remaining usable propellant value.

9 Space debris mitigation plan

9.1 General

a) All management requirements for the space debris mitigation plan (SDMP) shall be done in accordance with ISO 24113.

b) The spacecraft provider, operator and acquiring organization shall be involved in each review of the SDMP throughout all phases of the mission.

c) Planning for disposal actions at a detailed-level should begin at least six months prior to the date of disposal in order to allow sufficient time for the planning to occur.

d) A specific report for the detailed implementation of the SDMP shall be submitted to the related approving agent after the end of life.

e) Each of the following plans shall be an integral part of the SDMP:

1) break-up prevention plan;

2) end of mission disposal plan;

3) contingency plan.

9.2 Break-up prevention plan

a) The plan shall be developed by considering each item containing stored energy. The following systems are most likely to cause the accidental break-up of a spacecraft:

— electrical systems, especially batteries;

— propulsion systems and associated components;

— pressurized systems;

— rotating mechanisms.

b) When producing the break-up prevention plan, a system level risk assessment approach shall be used.

NOTE Annex A provides further details regarding producing the plan for estimating probability of accidental break-up.

c) The break-up prevention plan shall include the following:

1) each source of stored energy;

2) what potential failure modes can result in an in-orbit break-up of the spacecraft (including post-disposal phase);

3) what can be performed to mitigate the risk in the design, operational, and disposal phases of the mission as well as after the end of life;

4) measures to reduce the risk of malfunction mitigate that causes a break-up.

9.3 End of mission disposal plan (EOMDP)

The EOMDP shall include the following:

a) details of the nominal mission orbit;

b) details of the design that provides the basis for the estimate of the probability of successful disposal;

c) a statement of the chosen disposal method (as specified in ISO 24113), and the basis/justification for selection of that method;

d) details of the targeted disposal orbit;

e) the minimum ΔV capability (3-σ) to reach the targeted disposal orbit;

f) details on the orbit propagator used, assumptions made and analysis results;

g) estimates of the propellant, power, controllability, and communications required for any disposal manoeuvre;

h) identification of systems and capabilities required for successful completion of each disposal action;

i) specific criteria for initiating each disposal manoeuvre;

j) timeline for initiating and executing each disposal manoeuvre;

k) identification of energy sources required to be depleted before end of life;

l) the effects of the depletion action on the final orbit of the spacecraft (e.g. for GEO the goal should be either to increase altitude or at least to limit a possible decrease in altitude);

m) criteria and timeline for depleting the remaining energy sources;

n) individuals and/or entities to be notified of the end of mission and disposal and a timeline for notification;

o) plan and timeline for retracting or furling any large expendable antennas, where this is applicable and possible;

p) a long-term (at least 100-year) orbital perturbation analysis for spacecraft staying outside of the protected region, only for GEO disposal;

q) the estimate and computations verifying that the operations (after placing spacecraft in a disposal orbit) do not compromise the long-term stability of the orbit (i.e. perigee shall remain above the protected region for 100 years), only for GEO disposal;

r) an estimate of the casualty risk posed by the re-entry of the spacecraft, only for Earth re-entry.

9.4 Contingency plan

a) Independent of the success or failure of other aspects of a disposal action, a contingency plan shall be developed to deplete all energy sources before the final disposal of the spacecraft, to ensure that actions necessary to passivate the vehicle are taken before end of life.

NOTE 1 It is not necessary to compile a contingency plan prior to the failure of a critical system as it is infeasible to cover all possible eventualities.

b) In the event that the systems and capabilities required for the successful completion of disposal stop functioning prior to the end of the mission, the contingency plan shall be performed.

NOTE 2 In this situation, best efforts can be taken to lower the orbital perigee altitude as much as possible.

c) The contingency plan shall include the following:

1) criteria and techniques for selecting an alternative option which is the least likely to interfere with the protected area;

2) criteria that define when the passivation actions are to be taken, the rationale for each criterion;

3) steps to remove the spacecraft from the protected region to an alternative orbit and passivate it before any further critical systems are lost.

Annex A
(informative)

Procedure for estimating probability of accidental break-up

A.1 General

This procedure is informative as other methods can be proposed to estimate the probability of break-ups.

This document is required to limit probability of accidental break-up to a level as specified in ISO 24113. This annex provides analytical procedures to verify compliance with this requirement. The analysis covers the period up to the end of life of the spacecraft, i.e. the point at which the spacecraft is permanently turned off.

A.2 Background

Historical reports indicate that accidental break-ups of spacecraft have been caused by batteries and collisions with other space objects. On-board propulsion systems, both solid and bipropellant, have been suspected of causing spacecraft break-up. In addition, the orbital stages of launch vehicles have been broken up by the explosion of hypergolic (homogeneous) sets of propellants and ruptures of tanks due to the vaporization of cryogenic propellant.

A.3 Procedure

The steps in the recommended procedure are outlined below and discussed in more detail in A.4 and A.5.

a) For each failure mode of interest, construct fault trees to identify the components associated with the failure mode and the functional relationship among these components (e.g. identify if components are connected in series, parallel, or using some other kind of functional connection). A failure modes and effects analysis (FMEA) can support this process.

b) For each component associated with the failure mode, the probability of accidental break-up should be inputs to the fault tree analysis to estimate the overall probability of accidental break-up if the failure mode of interest occurs. Probability data can be obtained through in-orbit heritage, design margins, analysis, or test. For example:

   1) for pressure vessels and other mechanical elements whose margins of safety are ensured by structural design, the probability of accidental break-up can be assumed to be zero;

   2) the probability of accidental break-up of a rotating mechanism in a container can be assumed to be zero, if designed to have sufficient margins of safety for the expected mechanical environment imposed during ground and orbital operation;

   3) where the break-up event is at system level, i.e. the break-up is a symptom of one or more failures at system level, the probability of accidental break-up is reviewed indirectly by its system reliability.

c) If the overall probability of accidental break-up is greater than or equal to a threshold defined in ISO 24113, identify corrective actions required to reduce this probability of accidental break-up to an acceptable level.

A.4 Fault tree analysis

A full system review, including historical failure data, should identify potential causes of break-up events. Consider only failure modes involving components having enough stored energy available to cause failures that would produce debris. Performing FMEAs in accordance with ISO 24113 helps ensure that all risk elements having the potential to generate debris are identified.

Examples include:

a) propellant tanks whose capacity is below the loading generated when propellants in the tanks are mixed and ignite;

b) a propulsion system whose capacity is below the loading generated when residual propellant (e.g. hydrazine) trapped in the system experiences a chemical reaction induced by mechanical shock, thermal heating, etc.;

c) a cryogenic propellant tank whose capacity is below the loading generated by the vaporization of cryogenic material in the tank, thus causing the tank to rupture;

d) batteries whose break-up pressure is below the amount that can be generated when pressures inside the batteries are increased by electric failure and inadequate structural design or manufacturing.

The following cases can be excluded:

— hardware whose stored energy is too small to damage its structural element or other components;

— stored energy which does not lead to the ejection of fragments outside the spacecraft.

Construct a fault tree to identify all the elements associated with the failure modes of break-ups as well as the functional relationship among these elements. Resulting fault trees should clearly show the functional relations among elements associated with the failure modes of break-ups (see Figure A.1).

The failure rate for each risk element should be identified and provided in a table with the fault tree for each failure mode.

A.5 Corrective action

If corrective action should be required, the design should be modified, and the risk assessment should be repeated starting at A.4.

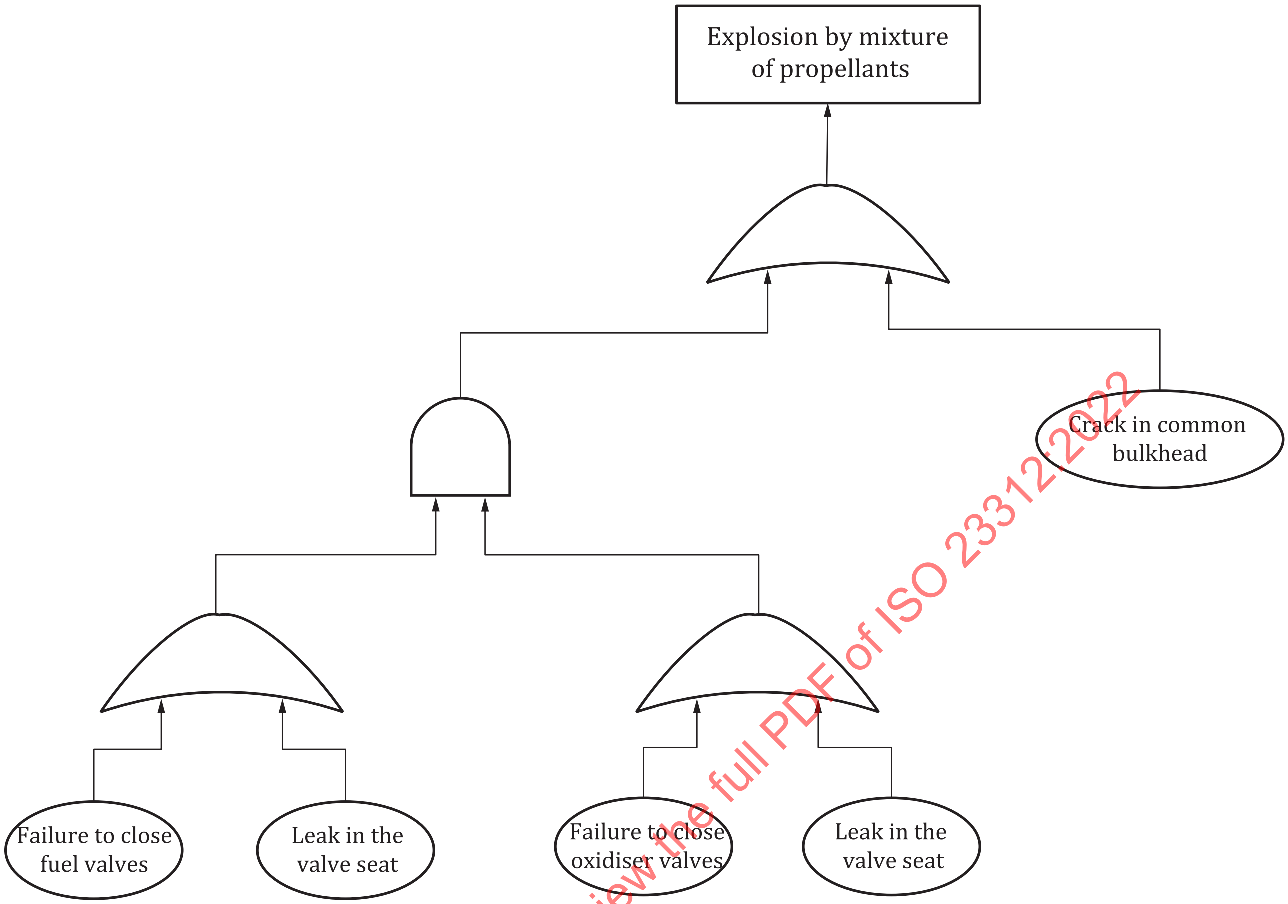

Figure A.1 — Fault tree analysis chart

Annex B
(informative)

Examples of estimation methods

Table B.1 gives examples of estimation methods typically used in propulsion systems using liquid or gaseous chemical propellants.

Table B.1 — Examples of estimation methods (reproduced with permission from Reference [27], © ESA)

a) Methods for propellant gauging between thruster firings

Method	Used for	Measurement Principle	Advantages and Disadvantages
pVT	3 axis + spinner	Measurement of the tank temperature and pressure and calculation of the tank ullage volume and thereby the remaining propellant mass by applying the gas law.	+ no additional equipment and lowest costs - decreasing accuracy towards EOL, low accuracy with conventional pressure transducer
Thermal Knocking	3 axis + spinner	Heating of the propellant tank and measurement of its thermal response which is related to the propellant load.	+ no additional equipment - low accuracy, high calibration efforts and long operational gauging times
Gas Injection	3 axis	Transfer of a known amount of pressurant gas into the propellant tank and measurement of the pressure and temperature increase to determine the ullage volume and thereby the remaining propellant mass	+ good accuracy at EOL - complex system, modification of propulsion system required, needs high accuracy pressure transducer, high calibration effort and high costs
Liquid Leveling	spinner	Measurement of liquid level in tanks of satellites where propellants are settled due to spin acceleration.	+ simple system with very high accuracy - limited to spinning satellites

b) Methods for propellant gauging during thruster operation.

Method	Used for	Measurement Principle	Advantages/ Disadvantages
NOTE "Thermal knocking" is also called "thermal gauging".			