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BSI Standards Publication

Space systems — Space debris mitigation design and operation guidelines for spacecraft

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National foreword

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Space systems — Space debris mitigation design and operation guidelines for spacecraft

Systèmes spatiaux — Conception de mitigation des débris spatiaux et lignes directrices de manoeuvre de la navette

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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 documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2. www.iso.org/directives

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

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

Introduction

Coping with debris is essential to preventing the deterioration of the orbital environment and ensuring the sustainability of space activities. Effective actions must also be taken to ensure the safety of those on the ground from re-entering objects that were disposed of from low-Earth orbit.

Recently, the orbital environment has become so deteriorated by debris that action must be taken to prevent damage due to the impact. Collision avoidance manoeuvres should be taken to avoid large debris (larger than 10 cm, for example), which can be observed from the ground. Spacecraft design should protect against micro-debris (even smaller than 1 mm) that can cause critical damage to vulnerable components.

The following ISO standards and technical reports cover these issues: ISO 24113, *Space systems — Space debris mitigation requirements*; ISO/TR 16158, *Space systems — Avoiding collisions with orbiting objects*; ISO 16126, *Space systems — Assessment of the survivability of unmanned spacecraft against space debris and meteoroid impacts to ensure successful post-mission disposal*. Other ISO documents, introduced in Clause 2, are currently being developed to encourage debris mitigation and protection from debris impact. Table 1 shows those requirements together with the recommendations in the United Nations Space Debris Mitigation Guidelines and the Inter-Agency Space Debris Coordination Committee (IADC) space debris guidelines referred to in the UN guidelines.

Reliability and quality shortfalls have resulted in fragmentation events that generated thousands of fragments. ISO 24113 and other debris-mitigation guidelines make the assumption that space hardware quality and reliability issues have been addressed by other management programs. But for low-cost or low-criticality missions, spacecraft of reduced quality have been developed. The failure of such spacecraft may not pose critical damage to their owners but they may adversely affect the environment and impair the sustainability of space activities. This Technical Report suggests activities that can improve reliability and quality sufficiently to avoid this problem. This aspect of space-debris mitigation is particularly important for micro-satellites developed by universities and newcomers to space activities.

Space systems — Space debris mitigation design and operation guidelines for spacecraft

1 Scope

This Technical Report contains non-normative information on spacecraft design and operational practices for mitigating space debris.

This Technical Report is a supporting document to the family of international standards addressing space debris mitigation (see 2.2). The purpose of these standards is to minimize the creation of additional space debris by ensuring that spacecraft and launch vehicle orbital stages are designed, operated and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime.

This Technical Report can be used to guide spacecraft engineers in the application of these space debris mitigation standards. Table 1 lists the main debris mitigation requirements defined in the standards and compares them to equivalent recommendations published by the United Nations and the Inter-Agency Space Debris Coordination Committee.

In Clause 3, the main space debris mitigation requirements are reported and discussed. Clause 4 provides guidance for life-cycle implementation of space debris mitigation related activities.

In Clause 5, the system level aspects stemming from the space debris mitigation requirements are highlighted, while in Clause 6, the impacts at subsystem and component levels are detailed.

Where it is not directly required by existing ISO standards but considered relevant to spacecraft operations, design and debris mitigation, content in this Technical Report is labelled as such with "[information]".

Table 1 — Comparison of ISO debris-related documents with UN and IADC space debris mitigation Guidelines

	Measures	ISO International Standards (or Technical Reports)	UN Guidelines	IADC Guidelines
Released objects	General measures for avoiding the release of objects	ISO 24113, 6.1.1	Recommendation-1	5.1
	Operational debris	Included in above	Included in above	5.1
	Slag from solid motors	ISO 24113, 6.1.2.2, 6.1.2.3	--	--
	Combustion products from pyrotechnics	ISO 24113, 6.1.2.1 (Combustion Products < 1 mm)	--	--
On-orbital break-ups	Intentional destruction	ISO 24113, 6.2.1	Recommendation-4	5.2.3
	Accident during operation	ISO 24113, 6.2.2 (Probability < 10^{-3})	Recommendation-2	5.2.2 (Monitoring)
	Post-mission break-up (Passivation, etc.)	ISO 24113, 6.2.2.3 **(Detailed in** ISO 16127**)**	Recommendation-5	5.2.1
Disposal at end of operation **GEO**	Reorbit at EOL	ISO 24113, 6.3.2 **(Detailed in** ISO 26872**)** 6.3.2.1: General Requirement. 6.3.2.2: 235 km+ (1000·Cr·A/m), e < 0,003 6.3.1: Success Probability > 0,9	Recommendation-7 (No quantitative requirements) Note: ITU-R S.1003-1 recommends; 235 km + 1000 $Cr*A/M$ Here, A[m^2], M[kg], Cr[-]	5.3.1 235 km+ (1000·Cr·A/m), e < 0,003
Disposal at end of operation **LEO**	Reduction of orbital lifetime	ISO 24113, 6.3.3 **(Detailed in** ISO 16164**)** 6.3.3.1: EOL Lifetime < 25 years 6.3.1: Success Probability > 0,9	Recommendation-6 (No quantitative requirements)	5.3.2 (Recommend 25 years)
	Transfer to graveyard	ISO 24113, 6.3.3.2 **(f)** (guarantee 100 years' non-interference)	Mentioned in recommendation-6	5.3.2
	Other options	ISO 24113, 6.3.3.2 **(a) ~ (e)**	--	5.3.2
Re-entry	Avoidance of ground casualties	ISO 24113, 6.3.4 **(Detailed in** ISO 27875**)**	Included in Recommendation-6	5.3.2
Collision avoidance for large debris		ISO/TR 16158 **(for assessment)**	Recommendation-3	5.4
Protection from the impact of micro-debris		ISO 16126 **(for assessment)**	--	5.4

2 Related documents and abbreviated terms and symbols

2.1 Overview of ISO debris-related standards

The requirements, recommendations, and best practices for mitigating debris generation and preventing other debris related problems are now examined.

Figure 1 shows a general diagram of major ISO documents relevant to debris.

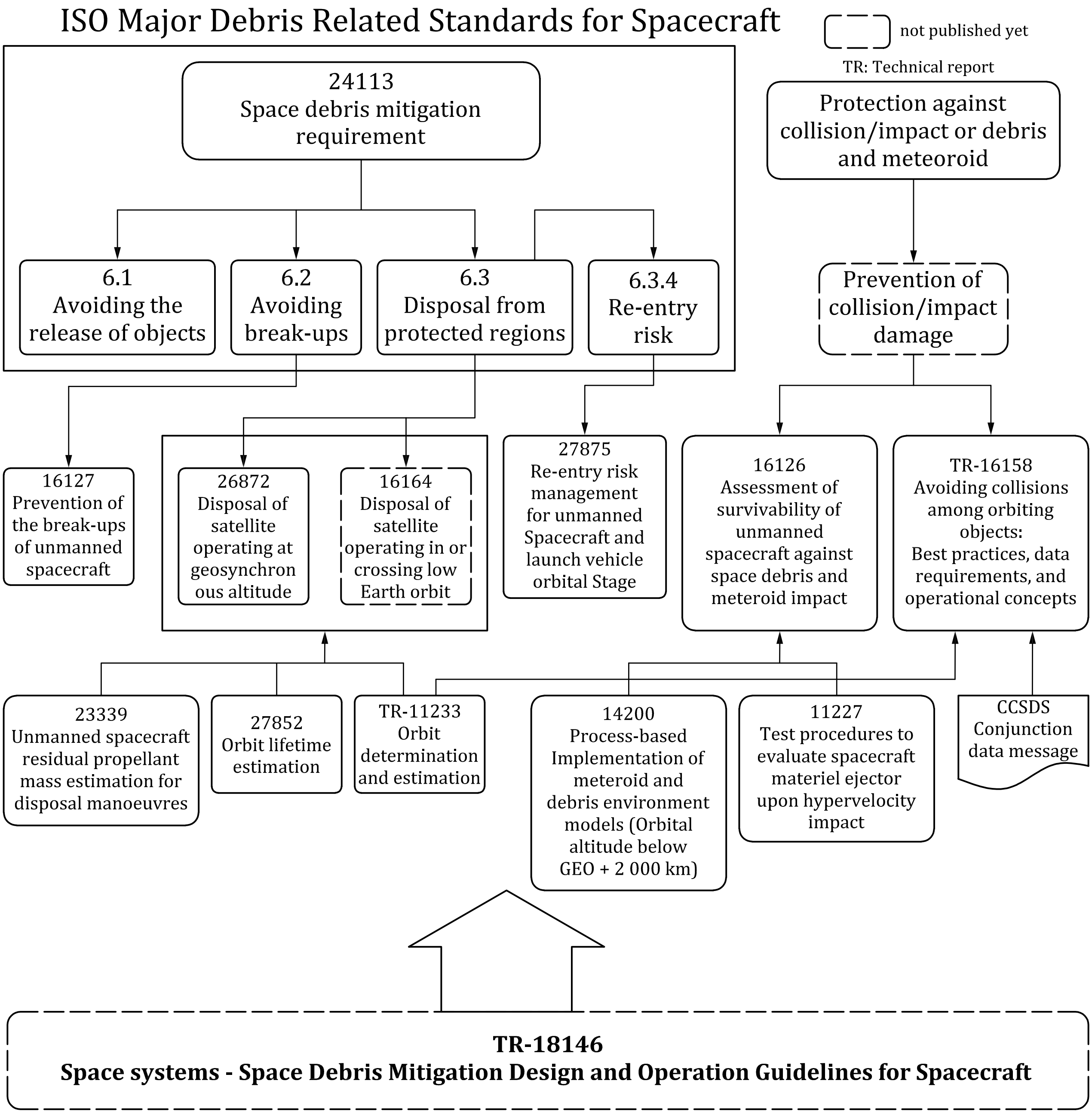

Figure 1 — Structure of major ISO debris-related standards

2.2 ISO debris-related standards as of February 2015

The following ISO standards have been published to address space debris mitigation:

(1) ISO 11227:2012, *Space systems — Test procedures to evaluate spacecraft material ejector upon hypervelocity impact*

(2) ISO 14200:2012, *Space environment (natural and artificial) — Guide to process-based implementation of meteoroid and debris environmental models (orbital altitude below GEO + 200 km)*

(3) ISO 16126:2014, *Space systems — Assessment of survivability of unmanned spacecraft against space debris and meteoroid impacts to ensure successful post-mission disposal*

(4) ISO 16127:2014, *Space systems — Prevention of break-up of unmanned spacecraft*

(5) ISO 16164:2015, *Space systems — Disposal of satellites operating in or crossing Low Earth Orbit*

(6) ISO 23339:2010, *Space systems — Unmanned spacecraft residual propellant mass estimation for disposal manoeuvres*

(7) ISO 24113:2011, *Space systems — Space debris mitigation requirements*

(8) ISO 26872:2010, *Space systems — Disposal of satellites operating at geosynchronous altitude*

(9) ISO 27852:2011, *Space systems — Estimation of orbit lifetime*

(10) ISO 27875:2010, *Space systems — Re-entry safety control for unmanned spacecraft and launch vehicle orbital stages*

2.3 Other relevant ISO standards

The following ISO standards are not specific to space debris mitigation but are considered relevant:

(1) ISO/TR 11225:2012, *Space environment (natural and artificial) — Guide to reference and standard atmosphere models*

(2) ISO/TR 11233:2014, *Space systems — Orbit determination and estimation — Process for describing techniques*

(3) ISO 14300-1:2011, *Space systems — Programme management — Part 1: Structuring of a project*

(4) ISO 14623:2003, *Space systems — Pressure vessels and pressurized structures — Design and operation*

(5) ISO/TR 16158:2013, *Space systems — Avoiding collisions among orbiting objects: Best practices, data requirements, and operational concepts*

(6) ISO 16404:2013, *Space systems — Programme management — Requirements management*

(7) ISO 27025:2010, *Program management — Quality assurance requirements*

2.4 Other documents

The following relevant documents are listed to provide the reader with additional background of the above ISO standards:

(1) UN, *Space Debris Mitigation Guidelines of the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space*, Annex IV of A/AC.105/890, 6 March 2007, endorsed by the United Nations General Assembly under Resolution A/RES/62/217

(2) *IADC Space Debris Mitigation Guidelines*, IADC-02-01, Revision 1, September 2007, available at http://www.iadc-online.org/index.cgi?item=docs_pub

(3) *Support Document to the IADC Space Debris Mitigation Guidelines*, IADC-04-06, Issue 1, 5 October 2004, available at http://www.iadc-online.org/index.cgi?item=docs_pub

(4) *ITU Recommendation on GEO Disposal*, ITU-R S.1003, January 2004

(5) IADC-08-03 Sensor system to detect impact on spacecraft (http://www.iadc-online.org/)

2.5 Abbreviated terms and symbols

A/m:	Area-to-mass
AOCS:	Attitude and Orbit Control System
CDR:	Critical Design Review
CFRP:	Carbon-Fiber-Reinforced Plastic
CNES:	Centre National d'Etudes Spatiales
COPUOS:	Committee on the Peaceful Uses of Outer Space
Cr:	Solar Radiation Pressure Coefficient
DAS:	Debris Assessment Software (NASA)
DIS:	Draft International Standard (drafting phase in the process in ISO for registration of new standard)
DoF:	Degrees-of-Freedom
COTS:	Commercial Off-The-Shelf
DRAMA:	Debris Risk Assessment and Mitigation Analysis (ESA)
e:	eccentricity
EOMDP:	End-of-Mission (Operation) Disposal Plan
EOL:	End of Life
ESA:	European Space Agency
FMEA:	Failure Mode and Effect Analysis
GEO:	Geosynchronous orbit
GPS:	Global Positioning System
GTO:	Geosynchronous transfer orbit
IADC:	Inter-Agency Space Debris Coordination Committee
IRU:	Inertial Reference Unit
ISO:	International Organization for Standardization
JAXA:	Japan Aerospace Exploration Agency
JSpOC:	Joint Space Operations Center (USA)
LEGEND:	LEO-to-GEO Environment Debris model
LEO:	Low Earth orbit
MASTER:	Meteoroid and Space Debris Terrestrial Environment Reference
MEO:	Medium Earth orbit

MMOD:	Micro-Meteoroid Orbital Debris
NOTAM:	Notice To Airmen and Notice to Mariners
NSS:	NASA Safety Standard
ORDEM:	Orbital Debris Engineering Model
ORSAT:	Object Re-entry Survival Analysis Tool
PDR:	Preliminary Design Review
PNF:	Probability of no Failures
QA:	Quality Assurance
QR:	Qualification Review
RAAN:	Right ascension of the ascending node
RCS:	Reaction Control System
S/C:	Spacecraft
SCARAB:	Space Craft Atmospheric Re-entry and Aerothermal Break-up
SDA:	Space Data Association,
SDR:	System Definition Review
SDMP:	Space-Debris-Mitigation Plan
STELA:	Semi-analytic Tool for End of Life Analysis (CNES)
USSTRATCOM:	United States Strategic Command
STS:	Space Transportation System
TLE:	Two-Line Element Set
TR:	Technical Report (a type of ISO document)
TT&C:	Telemetry Tracking and Command
UN:	United Nations
UNCOPUOS:	United Nations Committee on the Peaceful Uses of Outer Space Scientific and Technical Subcommittee

3 Requirements in ISO standards and system-level methodologies for complying with them

3.1 General

To accomplish comprehensive activities for debris mitigation and protection work, the following steps are to be considered:

(1) Identifying debris-related requirements, recommendations and best practices.

(2) Determining how to comply with these requirements, recommendations, and best practices.

(3) Apply those methods early and throughout development and manufacturing to ensure sound debris mitigation capability in the final product.

(4) Apply appropriate quality assurance and qualification program to ensure compliance with debris mitigation requirements

This sub-clause provides methodologies for taking comprehensive action at the system level. More detailed information for action of subsystem and component levels is provided in Clause 6. The following specific subjects are emphasized:

(1) Limiting the release of objects in protected orbital regions.

(2) Preventing fragmentation in orbit.

(3) Proper disposal during the end of operation to preserve the environment in protected orbital regions.

(4) Minimization of hazard on the ground from re-entering debris.

(5) Collision avoidance for trackable known objects.

(6) Protection against the impact of micro-debris and meteoroid.

(7) Quality, safety and reliability assurance.

3.2 Design for limiting the release of objects

3.2.1 Requirements

ISO 24113, 6.1 requires avoiding the intentional release of space debris into Earth orbit during normal operations:

(1) For general objects:

  a) Spacecraft and launch vehicle orbital stages shall be designed so as not to release space debris into Earth orbit during normal operations.

  b) Space debris released into Earth orbit as part of normal operations, other than as covered by next (2), shall remain outside the GEO protected region, and its presence in the LEO protected region shall be limited to a maximum of 25 years after release.

(2) For the combustion-related products:

  a) Pyrotechnic devices shall be designed so as to avoid the release into Earth orbit of products larger than 1 mm in their largest dimension.

  b) Solid rocket motors shall be designed and operated so as to avoid releasing solid combustion products into the GEO protected region.

  c) *In the design and operation of solid rocket motors, methods to avoid the release of solid combustion products that might contaminate the LEO protected region shall be considered.*

The following classes of released objects are of concern from an orbital debris mitigation standpoint:

(1) Objects released as directed by mission requirements (ISO 24113, 6.1.1).

(2) Mission-related objects, such as fasteners, under the responsibility of designers (ISO 24113, 6.1.1).

(3) Combustion products from pyrotechnic devices (ISO 24113, 6.1.2.1).

(4) Combustion products from solid motors (ISO 24113, 6.1.2.2).

ISO 24113, 6.1.1.2 states that if objects must unavoidably be released despite requirements in ISO 24113, 6.1.1.1, orbital lifetime of such objects in Low Earth Orbit (LEO) and interference with Geostationary

Earth Orbit (GEO) is to be limited as described in ISO 24113, 6.1.1.2. A typical example is the support structure utilized in multiple payloads mission.

3.2.2 Work breakdown

Table 2 shows the work breakdown for the actions required to prevent the releasing of debris.

Table 2 — Work breakdown for preventing the release of objects

Process	Subjects	Major work
Preventive measures	Identification of released objects and design measures	(1) Take preventive design to avoid releasing objects turning into space debris. (ISO 24113, 6.1) (2) If objects might be released unintentionally, designers will investigate design problems and take appropriate action during design phase. (Examples: paint flakes, insulators) (3) If release is unavoidable, designers will estimate the orbital lifetime of released objects and check compliance with 6.1.1.2.
Risk detection	Monitoring during operation	(1) Confirm that the orbiting characteristics of released parts are as estimated, if needed. (2) If an unexpected object is detected, the origin of the objects will be confirmed.
Countermeasures	Preventive measures	If an object is released unexpectedly, it will be investigated and appropriate action will be taken to avoid repeating the release in the following missions.

3.2.3 Identification of released objects and design measures

Identify the parts planned to be released, estimate their orbital lifetimes, and determine the propriety of their release.

(1) Mission requirements that require dispersing objects

Assess the effects of proposed mission requirements on the environment. If the proposed mission may deteriorate the environment more than justified by its benefit, system engineering may suggest alternative approaches.

Examples are:

a) The experiment called “WESTFORD NEEDLES,” conducted in *1961 and* 1963, scattered 480 million needles in orbit. More than 100 clumps of needles have been registered and many of them are still in orbit. *The legacy of Project West Ford can still be found in international policies, including the first major United Nations accord on activities in outer space that calls for international consultations before undertaking an experiment which might cause “potentially harmful interference with activities of other State Parties in the peaceful exploration and use of outer space.*[1)]

b) Missions that conduct intentional fragmentation (one of the major causes of deterioration of the orbital environment).

(2) Mission-related objects

Release of the following objects shall be avoided by appropriate mission and spacecraft design (ISO 24113, 6.1.1):

a) fasteners for deploying and holding devices for panels or antennas

b) nozzle closures for propulsion devices and certain types of solid motor igniters

1) *[Ref. NASA, JSC, Orbital Debris Quarterly News, Volume 17, Issue 4 October 2013* http://orbitaldebris.jsc.nasa.gov/]

c) clamp bands that tie spacecraft and launch vehicles (usually as vehicle components)

Remark: The structural elements which support upper spacecraft used in the case of multi-payloads launching are allowed to be released due to their unavoidability. Disposal orbit of these elements should be comply with 6.1.1.2. (Note that these elements usually belong to the launch vehicle, not the spacecraft.)

(3) Combustion products from pyrotechnic devices

Devices should be selected and/or designed to avoid the production and release of combustion by-products. Employing vehicle components that trap all fragments and combustion products inside for segregation (ISO 24113, 6.1.2.1).

(4) Combustion products from solid motors

Solid motors should not generate slag in geosynchronous orbit. (ISO 24113, 6.1.2.2)

In very low Earth orbit, particles smaller than 1 cm will decay quickly. But large-sized slag ejected in LEO at the end of propulsion burns is a concern; generation of this kind of slag can be prevented by either designing the nozzle adequately to avoid a pocket upstream of the nozzle that may trap melting metals or to develop propellant that does not contain metal (i.e. aluminium).

3.2.4 Design measures

In general, only devices that do not release parts into the space environment are to be selected. If parts would be released for unavoidable reasons, the orbital lifetime of the parts and the impact on other spacecraft should be assessed, and a final decision should be made about whether to proceed with the mission. The orbital lifetime can be assessed according to ISO 27852. This Technical Report does not designate a specific analysis tool but rather requires that the user employ specific techniques depending upon orbit regime, so that designers can select any tool(s) which adhere to ISO 27852 approved techniques. Available simplified tools that can be used to estimate the long term orbital lifetime are, for instance: NASA DAS (Debris Assessment Software), ESA DRAMA (Debris Risk Assessment and Mitigation Analysis) [an account at https://sdup.esoc.esa.int must be created to obtain a license before downloading], or CNES STELA (Semi-analytic Tool for End of Life Analysis; https://logiciels.cnes.fr/content/stela?language=en).

3.2.5 Monitoring during operation

[Information] The release of objects should be confirmed by ground-based space tracking facilities to ensure that they released as expected and that their orbital lifetimes are sufficiently short. The Space Situation Report provided by US Joint Space Operations Center (JSpOC) provides a good reference.

3.2.6 Preventing failure

[Information] If objects are released unexpectedly, the origin of the objects should be identified to help prevent recurrence in future missions. Because such phenomena may indicate a malfunction, the situation should be reviewed carefully and appropriate action taken to prevent further abnormal conditions.

3.3 Break-up prevention

3.3.1 Requirements

ISO 24113 requires the prevention of space object break-ups in 6.2 as follows:

(1) Intentional break-ups

a) In Earth orbit, intentional break-up of a spacecraft or launch vehicle orbital stage shall be avoided.

(2) Accidental break-ups

a) The probability of accidental break-up of a spacecraft or launch vehicle orbital stage shall be no greater than 10^{-3} until its end of life.

b) The determination of accidental break-up probability shall quantitatively consider all known failure modes for the release of stored energy, excluding those from external sources such as impacts with space debris and meteoroids.

c) During the disposal phase, a spacecraft or launch vehicle orbital stage shall permanently deplete or make safe all remaining on-board sources of stored energy in a controlled sequence.

ISO 16127 provides more detailed requirements and procedures for complying with them.

3.3.2 Work breakdown

Table 3 shows the work breakdown for preventing orbital break-up.

Table 3 — Work breakdown for preventing orbital break-ups

Process	Subjects	Major work
Preventive measures	Identification of sources of breakup	Identify components that may cause fragmentation during or after operation.
	Design measures	(1) Missions that involve intentional break-ups should not be designed. (2) Take preventive design to limit the probability of accidental break-up. Confirm it in FMEA. (3) Provide functions for to prevent break-ups after disposal.
Risk detection	Monitoring during operation	(1) Provide functions to monitor symptoms of break-up. (2) Monitor the critical parameters periodically. (3) Take immediate actions if the symptom of a malfunction that could lead to a breakup is detected.
Countermeasures	Preventive measures for break-up	Perform the disposal operations to eliminate the risk of break-ups.

3.3.3 Identification of the sources of break-up

For post-operation break-ups, ISO 16127 identifies the following components as the most-likely causes of the break-up of spacecraft:

(1) Batteries in the electrical subsystem,

(2) Propulsion mechanisms and associated components (such as engines, thrusters, etc.)

(3) Pressurized components (such as tanks or bottles in the propulsion subsystems, or pneumatic control system, and heat pipes)

(4) Rotating mechanisms

3.3.4 Design measures

(1) Intentional break-up

Missions that involve intentional break-ups are prohibited if the fragments would be ejected outer space. This includes attacks from the ground or airplane as well as self-destruction in orbit. For the case that there would be justification to conduct intentional destruction to improve ground safety, IADC guidelines state that it should be conducted at sufficiently low altitudes so that orbital fragments are short-lived.

(2) Accidental break-up during operation

According to ISO 24113, t*he probability of accidental break-up shall be no greater than* 10^{-3} *until its end of life.* The causes of break-ups are identified in failure mode and effects analysis (FMEA), and preventive measures should be incorporated in the design. Causes of break-ups are typically controlled by failure detection, isolation, and recovery (FDIR) concept in system-safety management. More detailed assessment procedures are presented in ISO 16127, Annex A, Procedure for Estimating Break-up Probability. For engineers wondering how to cope with rotating mechanism or complicated subsystems such as apogee engines, in ISO 16127, Annex A provides good instruction.

Note that quality and reliability management should be emphasized, as well as design for debris mitigation.

(3) Break-ups that occur after the end of operation

Many break-ups have occurred long after (e.g. 10 years after disposal) the end of operation life. ISO 24113 and ISO 16127 require detailed concepts and procedures for preventing these break-ups. The key-points are to provide venting mechanisms for residual fluids and shut-off functions for charging lines for battery-cells, etc. Historically, for example, propellant tank design combined fuel and oxygen tanks, separating them only by a common bulkhead in a way that caused many explosions[2)].

3.3.5 Monitoring during operations

ISO 16127, 4.3.1 requires monitoring of critical parameters to detect the symptoms that can lead to (1) break-up, (2) loss of mission capability, or (3) the loss of orbit and attitude control function, and requires immediate action to be taken when any symptoms are detected.

To prevent the occurrence of a break-up, a detection mechanism and operation procedures should be designed to monitor and facilitate immediate mitigation once any possible detection of malfunction is observed to prevent break-ups.

3.3.6 Disposal operations

Sources of break-ups listed in 3.3.3 should be mitigated (vented or operated in safe mode) according to ISO 16127, 4.4.

3.4 Disposal at the end of operation

3.4.1 Requirements

ISO 24113 requires removing a spacecraft or launch vehicle in orbital stage from the protected regions after end-of-mission in 6.3 as follows

(1) Probability of successful disposal

a) The probability of successful disposal of a spacecraft or launch vehicle in orbital stage shall be at least 0,9 at the time disposal is executed.

2) NASA Safety Standard (NSS) 1740.14 says in its section 4.1 that "Investigations determined that the cause of the explosion was failure of the common bulkhead separating the two fuel components. This failure allowed residual bipropellants to combine, producing an explosion, the most recent of which occurred after 16 years in orbit".

b) The probability of successful disposal shall be evaluated as conditional probability weighted on the mission success.

c) The start and end of the disposal phase shall be chosen so that all disposal actions are completed within a period of time that ensures compliance with above a).

(2) GEO disposal manoeuvres

a) A spacecraft or launch vehicle orbital stage operating in the GEO protected region (defined in ISO 24113, 5.3), with either a permanent or periodic presence, shall be maneuvered in a controlled manner during the disposal phase to an orbit that lies entirely outside the GEO protected region.

b) A spacecraft operating within the GEO protected region shall, after completion of its GEO disposal manoeuvres, have an orbital state that satisfies at least one of the following two conditions:

· *the orbit has an initial eccentricity less than 0,003, and a minimum perigee altitude, ΔH (in km), above the geostationary altitude in accordance with*

$\Delta H = 235 + 1000 * C_R * A/m$ (Here, A[m²], M[kg], Cr[-])

· *the orbit has a perigee altitude sufficiently above the geostationary altitude that long-term perturbation forces do not cause the spacecraft to enter the GEO protected region within 100 years.*

(3) LEO disposal manoeuvres

a) A spacecraft or launch vehicle orbital stage operating in the LEO protected region (defined in ISO 24113, 5.2), with either a permanent or periodic presence, shall limit its post-mission presence in the LEO protected region to a maximum of 25 years from the end of mission.

b) After the end of mission, the removal of a spacecraft or launch vehicle orbital stage from the LEO protected region shall be accomplished by one of the following means (in order of preference):

1) retrieving it and performing a controlled re-entry to recover it safely on the Earth, or

2) manoeuvring it in a controlled manner into a targeted re-entry with a well-defined impact footprint on the surface of the Earth to limit the possibility of human casualty, or

3) manoeuvring it in a controlled manner to an orbit with a shorter orbital lifetime that is compliant with above a), or

4) augmenting its orbital decay by deploying a device so that the remaining orbital lifetime is compliant with above a), or

5) allowing its orbit to decay naturally so that the remaining orbital lifetime is compliant with above a), or

6) manoeuvring it in a controlled manner to an orbit with a perigee altitude sufficiently above the LEO protected region that long-term perturbation forces do not cause it to re-enter the LEO protected region within 100 years.

ISO 26872 provides more detailed requirements and procedures for the disposal of GEO missions to comply with the high-level requirements stated in ISO 24113.

ISO 16164 provides more detailed requirements and procedures for the disposal of LEO missions to comply with the high-level requirements stated in ISO 24113.

3.4.2 Work breakdown

Table 4 shows the work breakdown for protecting orbital regions:

Table 4 — Work breakdown for preservation of protective orbital regions

Process	Subjects	Major work
Preventive measures	Disposal plan	Estimate orbital lifetime and define a disposal orbit.
	Design measures	(1) Functions to remove spacecraft from the protected orbit region should be provided. (2) Disposal operations need to be ensured. The probability of successful disposal should be larger than 0,9 (ISO 24113, 6.3.1.12). (3) It is recommended that protective design be used to protect against the impact of micro-debris to maintain disposal functions (ISO 16126).
Risk detection	Monitoring critical parameters	(1) Critical parameters should be monitored to detect symptoms that can lead to the loss of the ability to conduct disposal manoeuvres. (ISO 16127, 4.3.1) (2) Residual propellants should be monitored to maintain the required quantity for disposal.
Preventive measures	Decision to end operation	A termination date and time should be chosen that leaves sufficient resources for disposal actions.
	Disposal sequence	Disposal operations should be executed in the proper sequence.
	Registration with the United Nations	Notify the United Nations of the end of operation or removal from orbit as early as possible.

3.4.3 Estimation of the orbital lifetime and definition of a disposal plan

For LEO missions, ISO 16164, 7.3.1 shows the steps for disposal manoeuvres. ISO 27852 shows the steps and tools to estimate the orbital lifetime in detail. The precision of analysis is depending on the algorithm. The high-precision algorithm needs several hours to complete analysis which is not adequate to use in the early phase when the exact operation plan has not been fixed. Tools should be selected during the design phase considering the certainty of planned orbit and disposal timing.

There are a number of tools available to calculate the orbital lifetime, for instance:

(1) ISO 27852 introduces “STELA (Semi-analytic Tool for End of Life Analysis)” available via the CNES freeware server. At the February 2014, the latest version is 2.5.2, and can be downloaded from; https://logiciels.cnes.fr/content/stela?language=en.

(2) NASA freely provides “DAS (Debris Assessment Software)” (since April 2012, latest version is v 2.0.2), which has functions to analyse various aspects of debris comprehensively, including orbital lifetime analysis. (http://orbitaldebris.jsc.nasa.gov/mitigate/das.html)

(3) ESA provides DRAMA (Debris Risk assessment and Mitigation Analysis) tool [an account at https://sdup.esoc.esa.int must be created to obtain a license before downloading],

(4) Other viable Commercial Off-The-Shelf (COTS) tool kits exist to determine orbit lifetime as well.

In ISO 24113, 6.3.3.2, several options are presented for disposal of LEO spacecraft. Current disposal options include:

a) Retrieval and controlled re-entry to recover the satellite safely on the Earth.

   Although this option comes at the top of the list, there are no available systems since the Space Transportation System (STS) was retired.

b) Manoeuvring the spacecraft into a targeted re-entry

This option is discussed in 3.5.

c) Manoeuvring the spacecraft to an orbit with a shorter orbital lifetime

This is currently the most common disposal option.

d) Augmenting its orbital decay by a drag-enhancement device

Drag-enhancement devices are effective for small spacecraft with altitude not higher than roughly 600 km. Drag enhancement is typically ineffective for larger spacecraft operating in high altitudes, and may suffer from impact of small debris and meteoroids. Solar radiation pressure has also been examined for higher orbits (e.g. outside of the drag regime) as a resonance method to accomplish orbit disposal and may be effective above 600 km.

e) Allowing its orbit to decay naturally so that the remaining orbital lifetime is compliant with 25 years

If the estimated orbital lifetime is shorter than 25 years, the spacecraft can be left in its operation orbit at the end of operation. Typically 25 years of orbital lifetime corresponds to 600 km in altitude.

f) Manoeuvring it to an orbit with a perigee altitude sufficiently above the LEO protected region

If the operation altitude is higher than roughly 1400 km, another disposal option is to manoeuvre it to an orbit with a perigee altitude sufficiently above the LEO protected region that long-term perturbation forces do not cause it to re-enter the LEO protected region within 100 years. Needless to say, if there is enough margin of propellant (such as if the operation is terminated before the end of its design life), reducing its orbital lifetime is preferable, as stated in ISO 16164, 6.4.

Among the six options listed above, ISO 16164 provides more detailed requirements mainly for options c), d) and f). An end-of-operation disposal plan (EOMDP) is required by ISO 16164. The process of developing it is described in detail in ISO 16164, Clause 7.

3.4.4 Function to remove spacecraft to disposal orbit.

If the spacecraft has an “Attitude and Orbit Control (AOCS) function”, a simple way to move the spacecraft to a disposal orbit is to include additional propellant to reduce perigee altitude. ISO 16164, 7.3.2 specifies the procedures to lower the altitude by using thrusters. The propulsion system (or actuators of AOCS subsystem) will be confirmed to have enough function and performance to accomplish the procedure and to have enough propellant for disposal manoeuver.

When augmenting decay by deployable device(s), ISO 16164, 7.3.3.2 present the related requirements.

3.4.5 Reliability of accomplishing disposal manoeuvre

[Information] To comply with requirements to ensure a successful disposal, a spacecraft should be designed to have enough reliability to conduct disposal operations within a few years (depending on the reliability of the bus system) after termination of operations. Even if reliability is enough under ordinary circumstances, postponement of disposal actions more than few years may cause the disposal conditional probability to violate requirements. [See 4.7.6]

The impact of micro-debris can’t be ignored for maintaining the disposal function. Consensus in protection design has not yet been reached preventing a quantitative requirement at this time; the unavailability of sufficiently accurate debris environment models, coupled with the burden of mass increase necessary to protect against micro-debris impact, has prevented consensus.

With regard to the ISO standard framework, impact damage is dealt with separately from the conditional probability of a successful disposal. However to ensure a successful mission in the current orbital environment, it is prudent to assess the risk of impact according to ISO 16126 and to adjust protection against micro-debris in response. The issue of impact of micro-debris is described in 3.7.

3.4.6 Function to monitor critical parameters

A monitoring system for the disposal function and for estimating residual propellant should be used, to provide the support required for proper decision-making to terminate operation. It is required in ISO 16164, 7.4 (and also in ISO 16127, 5.3). Calculation of propellant reserves are discussed in ISO 23339.

3.4.7 Decision-making to terminate operations and for execution of disposal operations

The decision to terminate operation will be done by the time that the required propellant and other criteria will be satisfied to guarantee the successful disposal. (ISO 16164, 7.4)

When directed to terminate spacecraft operations, mission users will be notified and the disposal operation will be executed.

3.4.8 Disposal sequence

[Information] Disposal actions should be conducted in the proper sequence introduced in 4.8.

3.4.9 Registration according to the UN treaty

[Information] Operators should be aware of that the UN treaty “Convention on the Registration of Objects Launched into Outer Space” requires that operators provide information about the termination of operations according to the consensus resolution of the General Assembly in 2007. The information should include “any change of status in operations (e.g. when a space object is no longer functional)”. Operators should notify the United Nations at the end of operation of a spacecraft and its removal from orbit as soon as possible. To avoid in-orbital collision, the operation status is important information for mutual coordination and collision avoidance manoeuvres.

3.4.10 Specific subjects for GEO mission

Detailed requirements and procedures are defined in ISO 26872. ISO 26872, Clause 8 requires disposal planning and the development of an EOMDP.

3.5 Ground safety from re-entering objects

3.5.1 Requirements

ISO 24113, 6.3.4 requires ensuring ground safety from the re-entering objects as follows:

> For the re-entry of a spacecraft or launch vehicle orbital stage (or any part thereof), the maximum acceptable casualty risk shall be set in accordance with norms issued by approving agents, and be complied with it.

ISO 27875 provides procedures for assessing, reducing, and controlling the potential risks that spacecraft and launch vehicle orbital stages pose to people and the environment when those space objects re-enter Earth’s atmosphere and impact the Earth’s surface.

ISO 27875 doesn’t specify quantitative criteria for the expected number of casualties; these criteria are defined by appropriate regulatory bodies.

3.5.2 Work breakdown

ISO 27875 specifies the risk assessment procedure.

Table 5 shows the work breakdown for assuring ground safety from re-entry.

Table 5 — Work breakdown relating to ground safety from re-entry

Process	Subjects	Major work
Preventive measures	Identification of requirements	Identify the re-entry safety requirements imposed contractually, voluntarily, or by national or international authorities.
	Hazard analysis to estimate the casualties	Hazard analysis should be conducted to estimate the expected number of casualties, and the pollution on the ground. (Depending on the applicable safety requirements, hazards analysis may include the risks from kinetic energy of fragments, hazardous material which could reach the ground, fragment fall back footprint size and its estimated falling location, etc.)
	Design measures	(1) Design for demise should be incorporated. (see 3.5.4.1) (2) Prevent the environmental pollution on the ground. (3) If the expected number of casualties is larger than requirement, the controlled re-entry are to be planned.
Risk detection	Notification of impact	For controlled re-entry, notifications should be sent to all countries that may be affected or sent through the NOTAM (Notice To Airmen and Notice to Mariners) system.
Countermeasures	Conduct controlled r-entry and Monitoring	(1) Conduct controlled re-entry as planned. (2) Monitor the re-entry procedure and take adequate action in abnormal situations.

3.5.3 Identification of requirements

Re-entry safety requirements imposed contractually, voluntarily, or by national or international authorities need to be determined. ISO 27875 indicates the risk assessment procedures but do not define quantitative requirements as of 2015.

[Information 1] The most typical parameter to assess re-entry risk is the risk of human casualty. Some space agencies and regulatory bodies apply public risk criteria of 10^{-4} / re-entry.

[Information 2] Although there are no clear controlled re-entry guidelines in ISO 24113 or ISO 27875, the fall-back zone associated should not impinge on the area, including the territorial waters, of any State, without permission from the relevant authority prior to its re-entry.

3.5.4 Hazards analysis

According to ISO 27875, 5.2 to 5.5, safety requirements will be identified and the risk will be estimated with approved processes, methods, analysis tools, models (architectural design of spacecraft, atmosphere, human population distribution, etc.), and data (orbital characteristics and detail design data of spacecraft, physical characteristics of materials, etc.). (According to the applicable safety requirements, hazards analysis may include the risks from kinetic energy of fragments, from hazardous material which could reach the ground, the fragment fall-back footprint size and location, etc.) The estimated risk will be assessed to determine the necessity of risk reduction measures.

Despite design improvements, if the expected number of casualties exceeds the criteria, (ISO 27875, 6.3), the impact area will be controlled according to ISO 27875, 6.2. Because the system concept may be affected significantly depending on whether the re-entry is controlled or not, decisions should be made by the Preliminary Design Review when the "System Technical Specifications" will be approved. In either case, hazards analysis should be performed both to uncontrolled and controlled re-entry.

[Information] At present, there is no consensus on the standard analysis tools or algorithms, analysis conditions, thermal properties of materials, distribution model of human population with prediction models for the future, or even equations to calculate casualties from the size of object impacts. The factors depend on the technical judgement or management decision of organizations.

There are several analysis tools available in the world such as:

a) DAS (Debris assessment software) provided by NASA, available at http://orbitaldebris.jsc.nasa.gov/mitigate/das.html,

b) DRAMA (Debris Risk assessment and Mitigation Analysis) tool by ESA, [an account at https://sdup.esoc.esa.int must be created to obtain a license before downloading], and

c) DEBRISK tool by CNES, [Download needs an agreement of CNES.]

3.5.5 Design measures

3.5.5.1 Design for demise

Even in controlled re-entries, where the risk of human casualty on the ground is determined from a combination of the failure rate of related disposal functions and the expected number of casualties for a natural re-entry, it is prudent to strive for demise as soon as possible.

The following methods are recommended for the design phase:

(1) Selection of materials

Whenever possible, materials with a high melting temperature, specific heat, and heat of fusion, such as titanium or beryllium, should be replaced by other materials with thermal characteristics that encourage demise during re-entry. Generally, propellant tanks and high-pressure bottles are made of titanium and have been found on the ground after surviving re-entry.

(2) Different sizes and shapes

Demise is a function of the ratio of surface area to mass. Changing the size or shape of an object to attain a relatively higher ratio of surface area to mass accelerates its demise under certain conditions. Because the size and mass are not in a simple liner relation with demise, accurate assessments will be done case by case. Shape does not significantly affect demise under normal, expected, practical, and feasible conditions.

(3) Multiple materials, changes in wall thickness, etc.

Sometimes a material that does not undergo demise can be replaced by multiple materials that do undergo demise while still maintaining structural integrity. [For example, a titanium propellant tank might be replaced by an aluminium skin overwrapped with composite materials.]

If there is enough structural margin, and wall thickness can be reduced without changing dimensions, the material will undergo demise more readily.

If a dummy mass or balance weight is applied, it should be designed with adequate materials and should be separated into multiple layers, instead of one thick, solid mass.

(4) Selection of a location that is advantageous for exposing material to the ablation environment

Components located in an area that is easily exposed to the ablation environment will undergo demise more readily. If propellant tanks or high-pressure bottles are located such that they are exposed to outer space, they will undergo demise more readily. However exposure to outer space incurs disadvantages, in terms of protection from the thermal effects and debris impact.

3.5.5.2 Prevention of environmental pollution on the ground

Efforts should be made to avoid polluting the environment with toxic substances (including radioactive materials) as required in ISO 27875, 5.4. However few problems are anticipated, unless nuclear reactors are installed on-board.

3.5.6 Specific design for controlled re-entry in subsystem level

Corresponding to the system level requirement to controlled re-entry, subsystem engineers should develop and implement specific controlled re-entry functions, performance requirements, and ground station support. Controlled re-entry also requires that a safe ground area (or ocean area) be defined capable of accepting the footprint of survived fragments. For these reasons, the decision to apply controlled re-entry method should be made in an early phase of planning, prior to defining the system.

(1) Propulsion subsystem

Thrusters only designed for attitude and orbit control functions may be insufficient to conduct efficient controlled re-entry. A propulsion system adequate for the planned re-entry manoeuvre sequence should be designed.

(2) Attitude and orbit control subsystem

To support controlled re-entry (in addition to the functions and performance required for normal space operation), the Attitude and Orbit Control System (AOCS) should include functions to determine and control orbit, attitude, and position in low altitude through the final burn (as stated in 6.4.2.2).

(3) Telemetry Tracking and Command (TT&C) subsystem

To ensure that the link with the ground station is maintained during controlled re-entry, transponder performance shall be enhanced to cope with the increase of velocity relative to the ground station.

(4) Ground station

To keep the command link for all manoeuvres (even if stored commands will be used), and to confirm the re-entry trajectory and impact zone, ground stations will be prepared.

3.5.7 Notification

ISO 27875, 6.4 requires notification in the case of the planned re-entry event.

3.5.8 Conduct controlled re-entry and monitoring

Conduct controlled re-entry as planned. Monitor the re-entry procedure and take adequate action when abnormal situations occur.

3.6 Collision avoidance

3.6.1 Background

There are no definite requirements for collision avoidance in ISO 24113. However, UNCOPUOS space debris mitigation guidelines indicate following practice:

> *Guideline 3: Limit the probability of accidental collision in orbit*
>
> *In developing the design and mission profile of spacecraft and launch vehicle stages, the probability of accidental collision with known objects during the systems' launch phase and orbital lifetime should be estimated and limited. If available orbital data indicate a potential collision, adjustment of the launch time or an orbital avoidance manoeuvre should be considered*

Collision with a large object (observable from the ground; larger than approximately 10 cm) causes catastrophic damage to spacecraft and poses great risk to other intact spacecraft when thousands of fragments are dispersed within a range of a few thousand kilometres. Therefore, the UN Space Debris Mitigation Guidelines recommend collision avoidance. ISO/TR 16158 addresses best practices to evaluate and avoid collisions among orbiting objects.

[Information] To conduct collision avoidance, space operators need a thrusters (as actuators in AOCS), technology for conjunction assessment, and the capability to conduct avoidance and returning manoeuvres. Each operator should define its philosophy, policy, and strategy for collision avoidance. The philosophy for collision avoidance, including the following, should be described in the system specification to avoid the risk of insufficient propellant or manoeuvre function when needed.

(1) A basic concept for collision avoidance (determination of allowable criteria for collision probability, apply functions in design to avoid collision, prepare propellant for avoidance manoeuvre, etc.)

(2) Collision detection measures (including self-analysis, or analysis performed by external collision service providers at present they are, for example JSpOC, the Space Data Association, etc.) http://www.space-data.org/sda/

(3) Criteria for notification (conjunction distance, probability of collision, etc.)

(4) Criteria for conducting avoidance manoeuvres (conjunction distance, features of approaching objects, etc.)

(5) Method of estimating the number of manoeuvres, amount of propellant for avoidance and returning manoeuvres, and how to ensure the propellant,

(6) A sequence for avoidance and returning manoeuvre (methods of avoidance, concepts for avoidance by altitude change or phase shift)

(7) How to access contact points to plan coordinated avoidance manoeuvres, data exchanging rules, etc.

3.6.2 Recommendation

ISO/TR 16158 describes the workflow for perceiving and avoiding collisions among orbiting objects, the data requirements for these tasks, the techniques that can be used to estimate the probability of collision, and guidance for executing avoidance manoeuvres.

3.6.3 Work breakdown

Table 6 shows the work breakdown for avoiding collisions with large objects.

Table 6 — Work breakdown for avoiding collision with large objects

Process	Subjects	Major work
Preventive measures	Estimation of collision probability	Estimate collision probability by debris population models.
	Design measures	(1) If the collision probability cannot be ignored, the function to avoid collision needs to be incorporated in design. (2) Define the criteria of decision-making for avoidance, and estimate the expected number of collision avoidance manoeuvres during mission operations. It will be reflected in the design of the mass of propellant.
	Standardize the procedures for collision avoidance	The criteria of collision avoidance and the standard procedure for collision avoidance should be documented.

Table 6 *(continued)*

Process	Subjects	Major work
Risk detection	Receipt of warning from the collision avoidance services	(1) If warning of close approach comes from US/STRATCOM/JSpOC, check the conjunction risk and identify the approaching object in detail. Reconfirm that the up-to-date, authoritative orbit ephemerides are provided to JSpOC for re-analysis. (2) Operators can also use commercial services (e.g. the Space Data Association's conjunction assessment process) or one provided by other agencies. (3) Determine the necessity of collision avoidance based on the result of re-analysis conducted by collision avoidance service and, if possible, by internal analysis.
	Internal detection of risk	If the operators have their own observation data and conjunction analysis systems, they may be capable of performing their own analysis.
Countermeasures	Avoidance and returning manoeuvres	(1) Decide to conduct avoidance manoeuvres, if necessary. (2) Ahead of time, develop an avoidance manoeuvre plan (include return plan, if needed). (3) Communicate avoidance manoeuver plan to collision avoidance service and if any to the operator of the approaching spacecraft. (4) Develop the avoidance manoeuvre plan (include returning manoeuver, if needed) coordinating with them. (5) Confirm conjunction probability during avoidance and returning manoeuvres. (6) Execute avoidance and returning manoeuvres.

3.6.4 Estimation of collision probability

Collision probability can be roughly estimated using the following databases and models:

(1) Information on in-orbit objects from the "Space-Track" website posted by the United States [https://www.space-track.org/perl/login.pl]

(2) ESA-MASTER (Meteoroid and Space Debris terrestrial Environment Reference) provides statistical debris population. [an account at https://sdup.esoc.esa.int must be created to obtain a license before downloading]

(3) NASA-ORDEM (NASA Orbital Debris Engineering Model) provides statistical debris population. The point of contact can be known from User's Guide available at:

"http://ston.jsc.nasa.gov/collections/trs/_techrep/TP-2014-217370.pdf"

(4) ESA-DRAMA *(Debris Risk assessment and Mitigation Analysis)* has dedicated routines based on MASTER to assess statistically the number of expected collision / avoidance manoeuvres. [an account at https://sdup.esoc.esa.int must be created to obtain a license before downloading]

[Information] The expected number of avoidance manoeuvres during operational life can be estimated from the probability of conjunction with the allowable distance of conjunction or allowable probability of collision.

The procedure to determine the probability is described in ISO/TR 16158, Clause 8.

3.6.5 Design measures

If the probability cannot be ignored, considering mission importance and the impact of collision on orbital environment, the decision should be made to incorporate the function of collision avoidance in design.

The criteria of decision-making for avoidance should be defined, and the expected number of collision avoidance manoeuvres during mission operations should be defined. They will be reflected in the design of the mass of propellant.

If the spacecraft has a sufficient orbit and attitude control function, the practice of collision avoidance manoeuvres would be possible without any design changes. If high-risk conjunction events are identified early enough using actionable data, a timely manoeuvre can be conducted such that propellant required for collision avoidance is minimized, and it would not affect the planned mission operation.

3.6.6 Procedures for collision avoidance

[Information] The criteria of collision avoidance and the standard procedure for collision avoidance should be documented. It will include

(1) criteria of warning for conjunction

(2) criteria to conduct re-analysis with up-to-dated authoritative orbit ephemerides

(3) criteria to decide the collision manoeuvre

(4) standard collision manoeuvre planning

Procedures will facilitate timely avoidance manoeuvres.

3.6.7 Detection of risk

3.6.7.1 Receipt of warning from the collision avoidance services

[Information] Joint Space Operations Centre (JSpOC) provides ready access to a conjunction warning service. When conjunctions involve actively-manoeuvring satellites (particularly in GEO), an approach such as the Space Data Association's (SDA), which incorporates authoritative operator data (planned manoeuvres, momentum dumps, high-fidelity 3 Degree of Freedom (DoF) and 6 DoF attitude and orbit propagation, and active transponder ranging across the orbital arc) is likely to be more actionable and credible. Both JSpOC and SDA sides recommending applying both services in a complementary fashion.

When notified of an upcoming close approach, current orbital characteristics from operational data, including potential avoidance manoeuvre(s), should be submitted for re-analysis.

ISO/TR 16158, Clause 12 specifies the minimum content of warning information.

3.6.7.2 Internal conjunction analysis

To determine the orbital characteristics for an operator's own satellites, follow the procedures defined in ISO/TR 11233.

If the operators have their own observation data and conjunction analysis systems, they may be able to perform their own analysis.

[Information] Orbital data for other satellites and debris can be obtained via public sources (e.g. JSpOC TLEs and Conjunction Data Messages) or by services such as provided by the SDA which aggregates actionable operator ephemerides to provide the most actionable and timely analyses for operator-on-operator spacecraft conjunctions.

3.6.8 Avoidance and return manoeuvres

3.6.8.1 Determine if avoidance manoeuvres are necessary

Operators should specify criteria for conjunction warnings and decide how to conduct avoidance manoeuvres. These criteria will affect the consumption of the propellant for avoidance manoeuvres through its operation life. ISO/TR 16158, Clause 9 lists points to be considered when determining avoidance manoeuvres.

Operators will also estimate the impact of avoidance manoeuvres on mission operations, and if the effect can't be ignored it is better to warn the mission users of the effects.

3.6.8.2 Communication with the collision avoidance service

Operators will communicate with the collision avoidance service, send up-to-dated orbital data (ephemeris data, etc.) obtained through spacecraft operation, and request re-analysis for final decision. Also the risk of collision during avoidance and returning manoeuvre will be assessed on the process to develop avoidance plan.

3.6.8.3 Communication with the operator of the approaching spacecraft

In parallel with developing an avoidance manoeuvre plan, operators should confirm, for the approaching object, the following:

(1) The owner of the approaching object and the owner's contact information.

(2) The operational status (under operation or disposed of) of the objects and the manoeuvrability of the objects

(3) The feasibility of coordinated mutual avoidance manoeuvres

(4) A manoeuvre plan for preventing collision during avoidance manoeuvres due to lack of coordination

NOTE Officially, operation statuses are identified by the UN database (http://www.oosa.unvienna.org/oosa/showSearch.do).

3.6.8.4 Collision-avoidance plan

ISO/TR 16158, Clause 12 recommends the development of an avoidance plan. This avoidance manoeuvre plan should include a return manoeuvre plan. It is recommended to determine conjunction probability during avoidance and returning manoeuvres, the effects of avoidance on mission operation, and a compensation plan for any damage caused to other spacecraft.

[Information] A variety of methods and services exist for detecting and monitoring upcoming conjunction events. But in any case, methods which yield the most timely and actionable reports are most preferable, since significant propellant savings and collision risk mitigation can be achieved using such timely and actionable services.

3.7 Protection against the impact of micro-debris

3.7.1 Background

Impact of micro-debris and meteoroid can be frequent, especially in highly-populated orbital regions. Effects of impacts may be significant (although there is lack of real statistics of MMOD induced damage on S/C). ISO 16126 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.

ISO 24113 does not require designs that protect against debris impact. However the IADC guidelines recommend that spacecraft design should limit the consequences of collision damage from "small debris" (= "micro-debris" in this TR) as indicated by underline in the following column:

> **5.4 Prevention of on-orbit collisions**
>
> *In developing the design and mission profile of a spacecraft or orbital stage, a program or project should estimate and limit the probability of accidental collision with known objects during the spacecraft or*

orbital stage's orbital lifetime. If reliable orbital data is available, avoidance manoeuvres for spacecraft and co-ordination of launch windows may be considered if the collision risk is not considered negligible. Spacecraft design should limit the consequences of collision with small debris which could cause a loss of control, thus preventing post-mission disposal.

3.7.2 Recommendation

ISO 16126 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 for performing post-mission disposal. ISO 16126 also describes two impact risk analysis procedures that may be used.

ISO 14200 engineers with guidance in the selection and use of a debris flux model for the assessment of impact survivability of a spacecraft in its planned operational orbit. Several models for space debris exists, sometimes with different predictions of debris fluxes versus size distributions. Since each model will be revised every several years, the designers are recommended to confirm the latest revision of those models.

3.7.3 Work breakdown

Table 7 shows the work breakdown for protection design against micro-debris and meteoroid.

Table 7 — Work breakdown related to avoidance of damage from collision with micro-objects

Process	Subjects	Major work
Preventive measures	Definition of requirements	Define the requirement for impact survivability, as a form of Probability of no Failures (PNF).
	Assessment of the risk	(1) Identify the vulnerable components that are potentially damaged by impact, with confirming spacecraft orbital parameters and design architecture. (2) Identify existing ballistic limit for the surfaces of vulnerable components (3) Analyse failure probability with adequate impact risk analysis codes, and the environment models. (4) Estimate impact-induced probability of no perforation, and confirm to be greater than requirements.
	Design improvement	For elements that require protective design, apply proper counter-measures, i.e. re-allocation behind the hard elements, adding redundant elements, putting shielding in front of vulnerable components, and other measures.
Risk detection	Detection of impact	No recommendation [Note: Various techniques to detect impact have been discussed, but a matured recommendation has not been released yet. (Reference: IADC-08-03 Sensor system to detect impact on spacecraft (http://www.iadc-online.org/)]
Counter-measures		No recommendation

3.7.4 Preventive measures

Since risk assessment and protection design will be completed in the design phase according to ISO 16126, the specifications for mission operation and hardware design of spacecraft, material data including ballistic limit curves, and applicable analysis codes and models should be prepared.

3.7.4.1 Definition of requirements

Define the impact survivability requirement with minimum probability of no perforation (PNF_{min}). It will be defined to assure the successful post-mission disposal.

3.7.4.2 Assessment of the risk

The risk assessment procedure is defined in ISO 16126 and consists of:

(1) Confirmation of spacecraft orbital parameters and design architecture.

(2) Identification of vulnerable components as critical components, which contribute the post operation disposal, and those could be potentially damaged by impact to lose their functions. (See ISO 16126, 7.3) The IADC Protection Manual (http://www.iadc-online.org/), which is referred to by ISO 16126 in the bibliography provides the information about components to be considered.

(3) Identification of existing ballistic limit for the surfaces of critical components. If there is no adequate data, additional hypervelocity impact testing and modelling will be conducted to obtain new ballistic limit. ISO 16126, Annex C will support it.

(4) Conduct failure probability analysis with selecting impact risk analysis codes, and the space debris and meteoroid environment models. ISO 14200 provides guidance on the selection of space debris and meteoroid environment models.

(5) Estimate "impact-induced probability of no perforation" (PNFs/c), and confirm that PNFs/c is larger than the "required probability of no perforation" (PNF_{min}).

3.7.4.3 Design improvement

If the requirement isn't satisfied, take every possible step that might reduce the impact risk. The IADC Protection Manual provides the example of measures.

3.8 Quality and reliability assurance

It is important to ensure sufficient quality and reliability for the bus subsystem. ISO 16127, 5.1 contains the requirements for reliability and quality control to prevent failures that could lead to a break-up event.

The methodology for assessing break-up probability and the probability of successful disposal are provided in ISO 24113, 6.2.2 and 6.3.1.

Other considerations not defined quantitatively in ISO standards include the expected number of casualties due to re-entry specifically defined in launching state, and the probability of no perforation defined in impact risk assessment conducted for specific mission. It is important to ensure sufficient quality and reliability, at least for the bus subsystem complying with above requirements.

A trade-off between cost reduction and quality/reliability exists in the development of space systems. Levelling quality assurance according to importance of a mission is typically conducted during project management. However it should be noted that spacecraft of low quality may become debris immediately after injection into orbit and can pose a risk to other space operators.

[Information] Balancing quality assurance according to the importance of a mission is typically conducted during project management. For less important spacecraft (i.e. including micro-satellites), where developers are tempted to use lower-grade parts with limited verification testing, such spacecraft may fail soon after orbit injection and pose unacceptable risks to other space operators (even if the spacecraft satisfies the orbital lifetime requirement of less than 25 years). It is essential to develop part-selection criteria and defining adequate classes of parts to ensure the least probability of break-ups and the highest possible probability of successful disposal. Using commercial parts not designed for space use can pose a potential risk, even when validation testing is conducted.

ISO 27025 provides the quality assurance system, and wider scope consists of product assurance, quality assurance, and dependability assurance are defined in ISO 14300-2.

4 Debris-related work in the development cycle

A typical phased planning of development lifecycle can be illustrated, as in Figure 2, according to ISO 14300-1.

From an early phase in the life-cycle, the preservation of the orbital environment should be considered when creating a system concept and to be realized through the spacecraft's lifecycle. To minimize the effect on the environment, the "disposal phase" should be clearly identified as the final phase of the lifecycle.

4.1 Concept of debris-related work in phased planning

The following debris-related activities will be considered in each phase:

(1) The Mission Analysis Phase (phase 0 or pre-phase A) consists of an initial definition of the mission and of a preliminary assessment of the concepts needed for consideration in the feasibility phase, as defined in ISO 14300-1, 8.2.2. The mission requirements are assessed to ensure that they do not pose risk of adverse effects on the orbital environment, and the debris-mitigation requirements should be identified as a part of requirements, such as design requirements and regulatory constraints

(2) The Feasibility Phase (phase A) consists of exploring the various possible concepts so as to meet the defined objectives (performance, cost and schedules), as defined in ISO 14300-1, 8.2.3**.** The major debris related specifications will be determined and reflected in a functional specification and a technical specification which are drafted in this phase. Examples are the re-entry control function and the design reliability, which affect system design and cost.

(3) The Definition Phase (phase B), consists of selecting one proposal for development among those proposed at the end of the feasibility phase and in specifying the necessary requirements, as defined in ISO 14300-1, 8.2.4. All the major debris mitigation and protection concepts that impact functions, performance, allocation of resources, reliability, and so on should be reflected in the System Level Technical Specification.

(4) The Development Phase (phase C) consists of making a detailed study of the proposal selected upon completion of the definition phase, as defined in ISO 14300-1, 8.2.5.3.1. The purpose of this phase is to obtain a qualified design for the mass production of deliverable products required for system operation and support. All the debris mitigation design, protection design and operation procedures will be defined.

(5) The Production Phase (phase D) consists of manufacturing and delivering to the customer. Qualification of the product design marks the end of the production phase.

(6) During the Utilization Phase (phase E) the system and the resources required to fulfil its operational mission are put into service, used and supported. According to the defined process and procedures, the critical parameters will be monitored periodically and conjunction assessment will be conducted. For contingency events, termination of operation or collision avoidance manoeuvre will be determined.

(7) During the Disposal Phase (phase F), disposal manoeuvre and break-up preventing procedures will be conducted.

Through above all phases, debris-related characteristics will be identified and reflected in design, and implemented by the completion of disposal. The output of each phase will be reviewed at the end of each phase.

Debris-related measures that impact on design and options for solution are described in Clause 3, and subsystem and component-level considerations are in Clause 6.

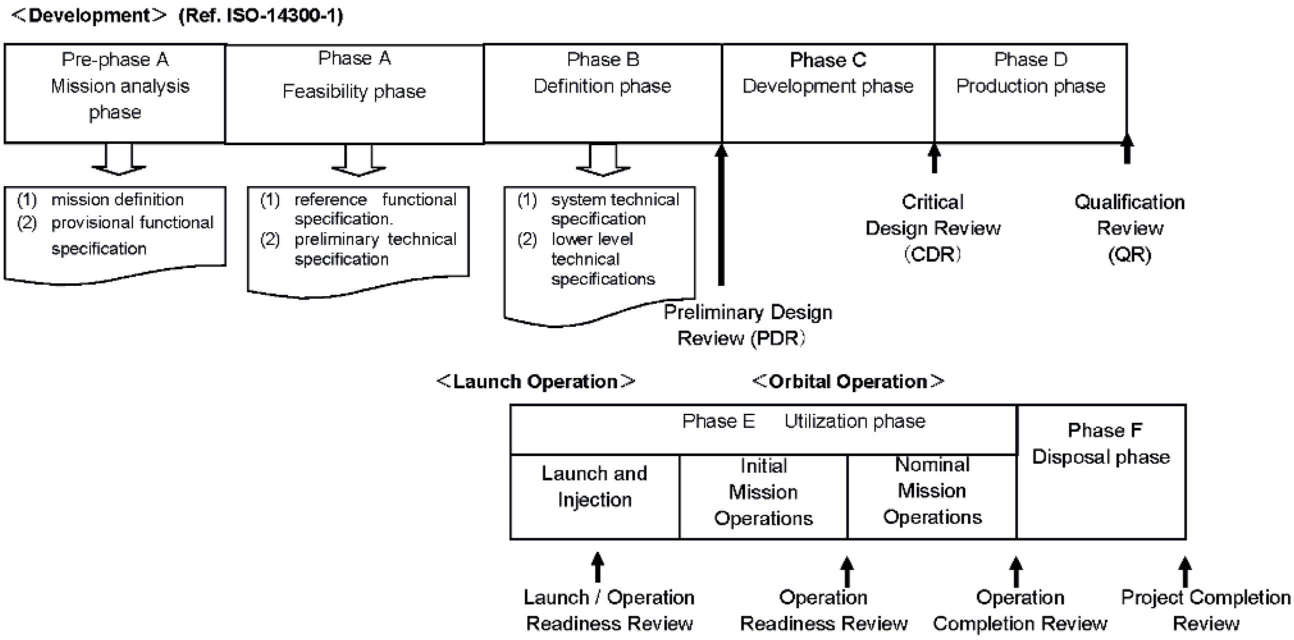

Figure 2 — Typical phased planning of development lifecycle

Table 8 — Major work related to debris in each phase

	Phase			
	Pre-phase A: Mission analysis phase Phase A: Feasibility phase	Phase B: Definition phase Phase C: Development phase Phase D: Production phase	Phase E: Utilization phase	Phase F: Disposal phase
Subjects				
System-level work	1) Input debris related requirements. 2) Clarify debris related design philosophy and input them to the “reference functional specification” & “preliminary system technical specification”.	1) Propellant allocation (including that for disposal manoeuvre, collision avoidance, controlled re-entry, etc.). 2) Mass allocation (including protection shields, propellants for debris issues, etc.).	1) Transfer debris-mitigation plan to operators. 2) Fix the procedure to terminate the operation (with guarantee the propellant for disposal).	1) Final determination for disposal action (including disposal manoeuvre, break-up prevention, controlled re-entry).
Quality assurance	1) Clarify QA design philosophy. 2) Define QA program including parts program.	1) Confirm that the probabilities for successful disposal and non-break-up, and other probability required in launching state, or the mission requirements.	1) Identify a disposal action for use in case of failure.	1) Ensure that the probability of successful disposal is complied with requirement.
Limiting debris generation (ISO 24113/6.1)	1) Clarify debris-mitigation design philosophy.	1) Fix the design to limit releasing objects, limit their orbital lifetime, etc. 2) Identify the energy sources of break-up, and design to prevent them.	1) Monitor critical parameters to check symptoms of critical malfunctions that lead to break-ups or prevent disposal actions.	1) Vent residual energy. 2) Terminate operation in the proper sequence.
Disposal (ISO 24113/6.3)	1) Clarify disposal concept. 2) Estimate propellant for disposal.	1) Design a propulsion subsystem for the planned disposal manoeuvre.	1) Monitor the residual propellant and decide to terminate operation timely.	1) Remove spacecraft to avoid interference with protected regions.
Re-entry safety (ISO 24113/6.3.4)	1) Clarify re-entry safety concept. 2) Define re-entry survivability analysis method. 3) Determine to apply controlled re-entry or not.	1) Design a propulsion subsystem and attitude control system for controlled re-entry, if needed.		1) Conduct controlled re-entry.
Collision avoidance	1) Clarify avoidance procedures. 2) Define debris population model to estimate the frequency of the collision avoidance manoeuvre.	1) Design a propulsion subsystem for collision avoidance. 2) Allocate an amount of propellant for avoidance manoeuvres.	1) Perform periodic conjunction analysis, and determine the avoidance manoeuvres, if needed.	
Impact protection	1) Clarify protection design philosophy. 2) Define the debris population model and ballistic limit equations. 3) Estimate mass for shielding.	1) Protection design for vulnerable components to guarantee disposal function at least.		

4.2 Mission analysis phase (phase 0 or pre-phase A)

4.2.1 General

[Information] The main purpose of this phase is to identify and characterize the mission. From the point of view of debris-related issues, the followings should be done:

(1) Assess mission requirements to ensure that they do not deteriorate the orbital environment unreasonably.

(2) Identify the debris-mitigation requirements in ISO standards, national regulations, etc.

(3) Identify safety, reliability, and quality requirements to avoid loss of ability to conduct debris-mitigation measures, to prevent the fragmentation caused by malfunctions, etc.

The requirement-analysis method is defined in ISO 16404. Traditionally, the following aspects are to be considered in requirement analysis:

a) requirements from mission users

b) constraints of the launching system

c) constraints of the spacecraft bus system

d) constraints of the ground facility

e) legal regulations

Although ISO 16404 doesn't address the issue of debris, this Technical Report recommends to pay attention to the following debris mitigation measures during the work of "definition of mission requirements":

i. reduction of risk caused by the impact of micro-debris and collisions with orbital objects

ii. safety on ground from re-entry

4.2.2 Debris-related work

(1) Identification of debris-related requirements

Debris-mitigation requirements reported in ISO 24113 applicable to the mission should be identified. If there are other applicable debris-related regional and national regulations, they should also be considered, and the final set of requirements should be identified.

ISO 24113 presents requirements only for mitigating the generation of debris. ISO/TR 16158 and ISO 16126 address collision avoidance manoeuvre and protection from the impact of debris.

(2) Assessment of user's requirements considering consequences for the orbital environment

Missions that release excessive numbers of objects or are at high risk of fragmentation will be carefully assessed regarding their potential effects on the orbital environment, and will be reviewed for confirmation of their justification by their inevitable needs for international benefit being worth to sacrifice the long-term sustainability of space activities.

[Information] *If user's requirements include the possibility of releasing an excessive number of objects, causing a hazardous explosion, posing high risk to the ground after re-entry, inviting an unacceptably high probability of debris collisions, introducing unacceptably high vulnerability to debris impact, or posing a threat to other spacecraft careful assessment and consideration will be made. Some recommendations will be provided to the users for preservation of the orbital environment upon demand.*

4.3 Feasibility phase (phase A)

In this phase, the various possible concepts are studied to meet the defined objectives. From the point of debris mitigation aspects, not only the mission requirements but also debris-related requirements and other regulatory rules will be taken into account.

Due to limited required resources (e.g., mass, quantity of propellant, electric power, communication capacity), allocation should be coordinated among the mission equipment and bus elements in the later phases. With regard to the issue of debris, for example, mass allocation will consider the impact of mass increase due to the propellant for disposal, for controlled re-entry, and for collision avoidance, and the protection shields against the impact of debris and meteoroids, etc. should be considered.

Preliminary versions of the following plans related to debris mitigation, risk reduction, and mission assurance will be created in this phase. Detailed specifications will be created in a later phase, however the concepts may impact later system design and operation.

(1) reorganization of debris-mitigation requirements in accordance with ISO 24113 and other debris related documents

(2) preliminary prediction of re-entry risk and risk reduction concepts, if needed

(3) plan for collision avoidance

(4) plan for protection design

(5) Quality assurance to comply with the debris mitigation requirements, and also to contribute on the sustainability of space activities.

The output of this phase are reflected in the reference functional specification and preliminary technical specification.

Those documents are reviewed during the "system requirement definition review (SRR)".

4.4 Definition phase (phase B)

4.4.1 Work in phase B

In this phase, the system requirements are defined in a system technical specification as specified in ISO 14300-1.

[Information] The principal configurations, including physical characteristics, functional and performance characteristics, as well as the operational concept, verification concept, and project resources (development regime, budget, and scheduling) are chosen in this phase. Therefore, the decision to implement a re-entry control function that may impose a heavy burden on the functional and performance characteristics should be fixed during this phase at the latest.

The plan for complying with ISO 24113 should be defined in a "space-debris-mitigation plan (SDMP)" as defined in ISO 24113, Clause 7.

The output of this phase will be reflected in the "system technical specifications" and "subsystem technical specifications". They will be reviewed during the system definition review (SDR).

4.4.2 Work procedure

(1) Basic concept

Excessively low reliability or high vulnerability to debris impact is not only unfavourable on its own, but also undesirable, due to its effects on the orbital environment in case it causes a malfunction or fragmentation. Therefore, a mission assurance philosophy is needed to be developed.

(2) Consideration of debris mitigation measures in system design

a) In the allocation of propellant, the propellant for disposal manoeuvres, controlled re-entry manoeuvres, and collision avoidance manoeuvres will be taken into account.

b) In the allocation of mass, beside the propellant mass mentioned above, the mass increase for protection shields (if any) will be taken into account.

c) In the allocation of reliability, the probability of a successful disposal after the end of the mission and the probability of break-up during operation are considered.

d) Measures for ground safety assurance

i. In planning the controlled re-entry, the manoeuvre sequence will be studied and the function and performance of the propulsion subsystem and attitude control system will be studied in an early phase of development lifecycle. Moreover, as the total system, including the ground control and monitoring system, will be studied in an early phase.

ii. To encourage demise during re-entry, the titanium and beryllium materials should be minimized, and other hard to be demised materials substituted where possible. Composite-material tanks and high-pressure bottles are preferable for facilitating easy demise.

iii. Potential contamination of the ground environment due to radioactive material (if any), such as nuclear batteries, for example, will be assessed and prevented.

4.5 Development phase (phase C)

4.5.1 Work in phase C

In this phase the system specifications are allocated at the component and part levels. In the specifications, the functional and performance requirements are defined to satisfy the “space-debris-mitigation plan (SDMP)”.

During the above procedure, the following are considered:

(1) Quality assurance

Lack of quality may lead directly to break-up or indirectly generate non-functioning spacecraft as a potential source of future fragments due to explosion caused by residual propellant or collision with large debris. Quality assurance for spacecraft is essential not only for the mission completion, but also for the safety of other spacecraft operating in orbit. [ISO 16127, 5.1]

(2) Break-up prevention and safety control

a) Major causes of break-up are the explosion of the propulsion subsystem and the rupture of batteries. To prevent them, appropriate design measures (prevention of the mixture of bi-propellants, robust structural and electric design for batteries, etc.) and reliability and quality control are essential. [ISO 16127]

b) In order to detect malfunctions that may induce break-up, and to conduct disposal actions before the complete loss of operation functions, the spacecraft should be designed to enable monitoring of critical parameters during operation. [ISO 16127, 5.3.1]

(3) Prevention of releasing parts

According to ISO 24113, 6.1, spacecraft is to be designed so as not to release objects (such as fasteners for deployed devices, nozzle closures, lens-cap, combustion-related products etc.) into Earth orbit during normal operations.

(4) Protection from damage caused by the impact of micro-debris

Assess the risk of impact of micro-debris according to ISO 16126. If the risk can't be ignored, protective measures should be implemented, including protection of critical surfaces with shielding while considering the impact angle, allocation of vulnerable components behind strong structural elements, and the use of redundant design.

(5) Collision avoidance manoeuvre

To avoid collision from orbital objects observable from the ground, procedures for conjunction analysis should be developed and criteria for the choice of avoidance manoeuvres should be identified, and avoidance manoeuvre sequences should be designed. The required ground infrastructure, analysis tools, communication lines with relevant organizations, and the decision-making process for conducting avoidance manoeuvres should also be identified. [ISO/TR 16158]

(6) Disposal after the end of operation

During the design phase, enough propellant will be allocated to carry out the disposal manoeuvre. In order to ensure that enough propellant remains by the end of the operation, an accurate measuring system and algorithm for estimating residual propellant as precisely as possible will be prepared. [ISO 23339]

(7) Safety assurance from ground impact after re-entry

a) According to ISO 27875, the expected number of casualties will be estimated, and the safety on the ground should be assured**.**

b) If there is significant risk on the ground, a controlled re-entry will be planned. Such a plan will include the design of a re-entry trajectory with control manoeuvres, error analysis, prediction of the footprint of surviving objects, etc. for controlled re-entry. It will require a propulsion subsystem that can generate a large thrust in a limited period, sufficient propellant, and a control system that ensures the spacecraft's attitude, even at low altitude. These factors may require additional constraints for mass allocation. A total support system is also required, including ground tracking and control systems. [ISO 27875]

4.5.2 Conditions

The following are completed before the design phase initiation:

(1) Identification of technical measures, operation measures, and infrastructure measures that are essential for realizing debris-related plans.

(2) Preparation of related analysis tools and models (debris-mitigation-assessment tool, orbital lifetime analysis tool, impact damage analysis tool, re-entry survivability assessment tool, solar activity model, atmospheric model, etc.)

(3) Technical data for analysis (ballistic limit equation, physical characteristic of materials for re-entry analysis, etc.)

4.6 Production phase (phase D)

4.6.1 Work in phase D

There are no specific debris-related requirements for manufacturing and verification/validation, because the process will be controlled properly under the quality and reliability assurance program.

If the spacecraft system is newly developed, the design and production procedures will be qualified at the end of this phase.

4.6.2 Qualification review

Prior to qualification review, it must be confirmed that the final design and manufacturing procedure meets the requirements specified in the SDMP. The following are reviewed:

(1) List of parts that are designed to separate or to be released

(2) List of sources of break-up energy, and disposal procedures for removing them after the end of operation

(3) A monitoring system for detecting critical malfunctions that may cause break-up or prevent disposal operations

(4) A disposal operation plan and data to be transferred to the operation phase, including procedures for determining when to terminate the mission, the disposal operation plan, etc.

(5) Ground casualty expectations, if the spacecraft will be disposed of by decaying its orbit

(6) Review of the operation plan, if controlled re-entry is planned.

(7) Plan for notifying air traffic and maritime traffic authorities, in the case of controlled re-entry

(8) Protection and collision avoidance measures against the impact of debris

4.7 Utilization phase (phase E)

4.7.1 Launch preparation

It should be confirmed that debris-related design has been reflected in operation procedures.

Before proceeding to the nominal operation phase, the following should be confirmed:

(1) SDMP and the related status

(2) List of parts that will be released into orbit, as designed

(3) A description of a precise propellant-measuring system. An initial propellant mass and its allocation, including compensation for any errors during insertion into orbit, attitude and orbit control during operation, disposal manoeuvres, collision avoidance, etc.

(4) A precise description of a monitoring system for critical parameters, and a monitoring procedure and contingency plan for the case of detecting malfunction.

(5) A decision making process in case a malfunction is detected that could lead to fragmentation, loss of operation function, or a lack of propellant for disposal manoeuvres

(6) A procedure for a conjunction assessment and collision avoidance manoeuvres

(7) Status of the protection of components against the impact of micro-debris

(8) Procedure and criteria for deciding to terminate of operation

   a) coordination process among mission users to agree to the termination of mission operation

   b) procedure for disposal manoeuvres and the sequence of activities involved in the termination of the operations

   c) Re-entry control plan

4.7.2 Lift-off time

Lift-off time may be coordinated to ensure that neither orbital stages nor payloads will threaten collision with existing space objects (or, at least, will not approach manned mission spacecraft or the space-station), under the responsibility of the launch service provider.

4.7.3 Initial operation

This phase covers from the separation of spacecraft to transferring it to the planned operation orbit with adjusting injection error.

Re-allocation of propellant will be done based on the actual consumption for adjustment of injection error, and the operative life will be re-estimated taking into account the propellant required for collision avoidance manoeuvres and disposal manoeuvres.

Design information related to debris mitigation should be transferred to the operation team. In specific, the following should be confirmed:

(1) Criteria for decision making when to terminate operation (in case of a malfunction, consumption of propellant, etc.) and the process for disposal of the spacecraft

(2) Criteria for the choice of collision avoidance manoeuvres, and practical procedures for avoiding collision

(3) Periodical monitoring of critical parameters, and contingency planning for the case of failure detection.

(4) Target disposal orbit

4.7.4 Normal operation

The following will be monitored, and actions will be taken according to the contingency plan:

(1) Critical parameters for detecting symptoms of malfunctions that may lead to fragmentation or loss of mission function, so that immediate action can be taken

(2) The probability of collision with other orbital objects; conjunction assessment will also be conducted in planning collision avoidance and the return to the original orbit

(3) Residual propellant, to ensure that enough propellant remains to complete planned disposal manoeuvres

In addition, it is recommended that the following environmental changes to be monitored, so that action can be taken in regards to attitude control or a change to a safe mode of operation:

a) Meteor showers

b) The generation of debris clouds due to fragmentation

4.7.5 Decision to terminate operations

Procedures should be planned for terminating the operation if any of the following situations is detected, as partly identified in locations such as ISO 16127, 5.3.2:

(1) Detection of fragmentation, loss of disposal function, loss of operation function.

(2) Shortage of propellant to conduct disposal manoeuvres.

(3) Any incidents that may reduce the probability of successful disposal of the spacecraft to less than 0.9.

(4) As a normal process, for the end of design life.

4.7.6 Process for extending mission operations

[Information] Although design life may come to an end, operators sometimes want to extend the operation period. Mission operations may be extended as long as the probability of successful disposal of the spacecraft remains above 0.9, in accordance with ISO 24113, 6.3.1. Housekeeping operation without significant meaning (such as monitoring of bus equipment only to acquire performance data) will not have justification to violate this requirement of the probability of successful disposal.

[Information] Because spacecraft are designed with an adequate reliability level (larger than 0.8 at the end of designed life of 5 years on the condition that the failure rate is 0.04 per year, for example), disposal action is recommended to be conducted within two years after mission termination, in order to comply with the requirement for a probability of successful disposal of more than 0.9.]

4.8 Disposal phase (phase F)

Disposal actions will be conducted as follows in accordance with ISO 16164 or ISO 26872:

(1) At the end of operation, the planned disposal manoeuvres defined in the SDMP should be conducted.

NOTE It is recommended that conjunction analysis to be conducted for the targeted disposal orbit. Although, under the condition that the amount of residual propellant cannot be measured precisely, the disposal orbit may not be estimated precisely, and the conjunction analysis also may not be conducted precisely, the disposal manoeuvres will be done as far as possible.

(2) After completion of disposal manoeuvres, residual energy (propellant, high pressure fluids, etc.) will be removed, and battery charging line will be shut-off to prevent orbital break-up.

(3) If the number of expected casualties is larger than an acceptable value, a planned controlled re-entry will be conducted, with notification given to the relevant nations, air traffic authorities, and maritime authorities.

NOTE The operators should remember that the United Nation’s “Convention on Registration of Objects Launched into Outer Space” also recommends that information about the termination of operations be given.]

Table 9 shows a typical sequence of disposal actions.

Table 9 — Typical sequence of disposal actions

	Event	Actions
1	Turn-off mission equipment	a) Turn-off mission equipment after coordinating with all mission users.
2	Determination of disposal orbit	a) Estimate residual propellant. b) Reconfirm or re-define the disposal orbit.
3	Disposal manoeuvre	a) GEO: Reorbit at a higher orbit. b) LEO: Reduce orbital lifetime below 25 years or take other measures described in ISO 24113. c) Conduct controlled re-entry, if needed.
4	Confirmation of final orbit	a) Confirm the final orbit by communication line, or afterward by space surveillance data.
5	Termination of spacecraft system	a) Shut-off the charging line to the batteries. b) Stop the solar paddle drivers c) Vent propellant, high pressure gas, and other fluids, while maintaining attitude d) Shut off attitude control sensors and actuators e) Shut off every electric device, as far as possible by command from the ground f) Shut off the telemetry transmitter with a monitoring TT&C signal
6	Confirmation of the termination of communication lines	a) Confirm the termination of communications systems using a ground station.

5 System-level considerations

5.1 Mission design

Debris-mitigation measures will be considered in mission design as following:

(1) Mission analysis and definition of mission orbit

The mission orbit is defined, and the configuration and formation method (including constellation) will be defined to reflect the latest state of the debris environment and its predicted future. It is desirable if the operation orbit could be selected to be less affected by debris, and to be lower altitude for shorter orbital lifetime to the extent if the mission could allow it.

(2) Definition of spacecraft configuration

Spacecraft configuration is naturally defined to satisfy mission requirements. However, because the probability of impact is different depending on the direction that the spacecraft is traveling in, the shape of the spacecraft, the structural design for the front plane, and the allocation of critical components may be chosen to reduce the risk of impact from micro-debris.

5.2 Mass allocation

In mass allocation, the following mass increase and other effects of debris-mitigation measures are considered (Table 10):

Table 10 — Factors that affect mass control

Activities	Effects on mass management
1. Debris mitigation a) Limiting the release of objects	— mass of bolt catchers and other devices to hold fragments of fastener, etc.
b) Prevention of fragmentation	— mass of monitoring systems to detect critical failures — mass of the venting mechanism, shut-off relay for battery charging lines, etc.
2. Collision avoidance	— additional propellant for avoidance manoeuvres, although it can be almost negligible usually
3. Protection against impact of micro-debris	— mass of the protection shields or bumpers — additional redundant devices, fuses for short circuits, etc. — shift of the centre of gravity due to re-allocation of critical components behind structures
4. Disposal manoeuvre	— additional propellant for disposal manoeuvres
5. Re-entry safety	— additional propellant for controlled re-entry

5.3 Propellant allocation

[Information] For spacecraft in LEO, the quantity of propellant will be chosen with consideration given to the following:

(1) Compensation for orbit-injection error caused by the launch vehicle (often specified by considering 3 σ)

(2) Orbit and attitude control during mission operations

(3) Disposal operations (shorter orbital lifetime or transfer to outside of the protected orbit regions)

(4) Orbit change manoeuvres and following targeted re-entry for a controlled re-entry

(5) Collision avoidance manoeuvres (estimated based on the expected annual number of avoidance manoeuvres)

(6) Recovery from safe mode (estimated based on the expected annual number of safe mode operations)

(7) Margin

5.4 Power allocation

[Information] Impacts of micro-debris can damage solar cells thereby degrading the power generation capability of a spacecraft. This effect can be compensated for by providing sufficient margin in the design of the power supply.

6 Subsystem/component design and operation

6.1 General

During the design phase, the requirements defined in ISO 24113 and other related standards are converted to design requirements and allocated at the system level, at the subsystem-level, or in the component-level design specifications. In this Clause, those specifications allocated at the subsystem level and at the component-level will be introduced, to comprehensively assist spacecraft engineers.

6.2 Debris-mitigation measures and subsystem-level actions for realizing them

Clause 3 introduced system-level design concepts. This section shows a more detailed allocation of functions and performance for each subsystem. Table 11 shows the relationship between the debris related requirements and the necessary actions at the subsystem level.

6.3 Propulsion subsystem

This sub-clause applies to the apogee engine, and the thrusters for the AOCS (attitude and orbit control subsystem), as listed below.

(1) hydrazine thrusters

(2) bi-propellant engine and thrusters

(3) solid motor

6.3.1 Debris-related design

The items to be considered are shown in Table 12.

6.3.2 Considerations for propulsion subsystems

6.3.2.1 Prevention of the release of objects

Propulsion subsystems should be designed to avoid the release of any objects during normal operations. Typical objects from the propulsion subsystem are:

(1) Slag from solid motors, disposal-type igniters and nozzle closures. (See 6.3.3.1)

(2) Apogee kick engines (or motors), which have been separated, in very rare cases.

6.3.2.2 Break-up prevention

Propulsion subsystems are major source of fragmentation in spacecraft, although there is not so much cases that it actually caused it in history, more often caused by that of launch vehicle orbital stages.

The following are potential threats for break-up in the propulsion subsystem:

(1) Failures of solid motor

(2) An explosion due to malfunctioning of the engine and/or thruster during operation

(3) An explosion due to the mixing of a homogeneous set of fuel and oxidizer

(4) The rupture of a high-pressure vessel, such as the gas reservoir and propellant tank

(5) An explosion caused by cold start of thrusters due to failure of heater for catalyst bed, when the thrusters are not designed to withstand cold start.

The followings are good practices and design measures for preventing break-up. More detail for each component are presented in 6.3.3:

(1) The reliability of components that may cause break-up should be designed to limit the probability to less than 0,001 for the total spacecraft system.

(2) The liquid propulsion subsystem should be designed to be able to vent residual propellant and other fluids when they are no longer needed or, at the end of operation.

(3) Because critical parameters shall be monitored according to ISO 16127, sensors shall be installed to detect and avoid failures by providing data to FDIR (failure detection, isolation, and recovery) systems.

Table 11 — Relationship between debris-related requirements and the actions in subsystem-level

	Debris-related requirements	Necessity of subsystem-level actions *					
		Propulsion RCS	AOCS	Power	TT&C	Structure	Thermal
1	Limit the number of separation/release items						
	a) parts released from fasteners, etc.	Yes		Yes	Yes	Yes	
	b) slag from solid motors	Yes					
2	Prevent break-up in orbit after the end of operation due to:						
	a) chemical explosion	Yes					
	b) rupture of high-pressure vessels	Yes		Yes			Yes
	c) rotating devices		Related				
3	Monitor critical parameters to prevent break-up in orbit during operation	Yes	Related	Yes	Related		Related
4	Remove the spacecraft from protected orbital regions:						
	a) function for disposal manoeuvres	Yes			Related		
	b) measuring system for residual propellant	Yes			Related		
	c) adequate operation terminating sequence		Yes	Yes	Related		
5	Ground safety from re-entering objects						
	a) improvement of survivability	Yes					
	b) prevention of the ground pollution by toxic substance	Yes				Yes	
	c) controlled re-entry	Yes	Yes		Yes	Yes	
6	Collision avoidance against large objects	Yes	Yes		Related		
	a) conjunction assessment, and collision avoidance						
7	Protection against the impact of micro-debris	Yes	Related	Yes	Related	Yes	Related
	a) protection design						

RCS: Reaction Control System
AOCS: Attitude & Orbit Control System
TT&C: Telemetry Tracking & Command

Table 12 — Debris-related measures in the propulsion subsystem, as well as thrusters in the AOCS

Mitigation measures	Propulsion subsystem (and AOCS actuator)	Major components			
		Thrusters	Propellant tank	Valve, piping	Solid motor
Prevention of the release of parts	Yes	Yes			Yes (slag)
Break-up prevention	Yes	Yes	Yes	Yes	Yes
Disposal manoeuvre	Yes	Yes	Yes		
Ground safety*	Yes		Yes		
Re-entry control*	Yes	Yes	Yes		
Collision avoidance	Yes	Yes	Yes		
Protection from the impact of micro-debris	Yes		Yes	Yes	
* Only applicable to LEO spacecraft					

6.3.2.3 Disposal manoeuvres

The propulsion subsystem should be designed to ensure successful disposal manoeuvres. (See 6.3.3.3 and 6.3.3.4)

The required velocity and propellant consumption will be estimated according to ISO 16164, Clause 8, and ISO 23339.

[Information] The required velocity increase for a re-orbit manoeuvre is roughly 11 m/s, which is equivalent to 3 months of typical GEO operation. Detail should be confirmed by ISO 26872.

6.3.2.4 Ground safety from re-entry

6.3.2.4.1 General considerations

Clause 6 in ISO 27875 addresses the typical measures to reduce re-entry risks. Generally, materials with either a high specific heat or a high melting point tend to survive re-entry. However, many elements of the propulsion subsystem (especially, rocket engines, titanium tanks, etc.) are designed to withstand high temperatures, the alternative design will be very limited. An example of possible improvement may be propellant tanks or pressure vessels made of CFRP which will be designed to demise during re-entry. (See 6.3.3.4)

6.3.2.4.2 Controlled re-entry

Consistent with ISO 27875, 6.2, if the expected number of casualties would be larger than requirement, controlled re-entry into a safe area should be planned. Thrusters, which are usually designed for attitude and orbit control functions, may be insufficient to conduct efficient controlled re-entry. Thrust level and tank capacity will be designed to satisfy such requirements. (See 6.3.3.2 and 6.3.3.4)

6.3.2.5 Collision-avoidance manoeuvres

The thrusters for AOSC will be used not only for its primary purpose but also for collision avoidance manoeuvres.

The amount of propellant to conduct the expected number of collision avoidance manoeuvres should be estimated based on the probability of a collision. (See 3.6.4 for estimation of number of collision.)

6.3.2.6 Protection from the impact of micro-debris

The vulnerable points in the propulsion subsystem are tank, high-pressure vessels, and propellant feeding lines.

The probability of collision can be estimated from the debris flux model, surface area, operation period, etc. (See 3.7.4.2 for estimation of number of impact, and see ISO 16126 for risk assessment.)

[Information] Propellant tanks and high-pressure vessels will be vulnerable to the impact of small-debris (millimetre-class debris). The highly pressurized vessels may rupture, and the bipropellant tanks may explode if the event cause mixture of propellants. Shields, bumpers, or other design measures, including setting behind rigid elements, should be used to protect tanks and vessels.

6.3.3 Consideration in component design

6.3.3.1 Selection of engines or motors (liquid, solid, ion, etc.)

The propulsion subsystem is generally selected based on mission requirements, typically a solid motor or a bipropellant engine for an apogee kick motor, as well as hydrazine thrusters, ion engine, or plasma jet for the reaction control system.

This sub-clause is mainly applicable to liquid engines and chemical thrusters.

For solid motors, the following are considered:

(1) Solid motors that generate slag are not recommended for use as the apogee kick propulsion for a GEO mission. (ISO 24113)

(2) Solid motors that eject slag are not recommended for operation in high orbit (for example, higher than 800 km), where the slag does not decay within 25 years. Specific propellants that do not generate slag (such as metal-free propellants) are preferable. (If the nozzle is not designed to be submerged into the combustion chamber, the pocket accumulating slag is not formulated, but such method will not be commonly applied.)

(3) The solid motors should not release disposal-type igniters or nozzle closures, etc. to be left in long lived high altitude orbits.

6.3.3.2 Thrust level

Apogee engines and thrusters are usually designed to satisfy their defined mission requirements.

If the controller re-entry will be planned, thrust level and operational duration should be designed to complete it.

6.3.3.3 Propellant budget and measurement systems

The propellant budget should be developed considering various debris-related activities, adding to for normal mission operations.

A monitoring system that can guarantee the amount of propellant required for disposal manoeuvres shall be designed. (See ISO 23339)

For LEO spacecraft, the following is a typical equation for estimating the necessary amount of propellant:

(Estimated Propellant) = {(compensation for insertion error)

+ (orbit and attitude control in the mission phase)

+ (collision avoidance manouvres) *

+ (disposal manouvres) *

+ (controlled re-entry) *

+ (recovery from safe mode)}

* (estimated margin of error for propellant (6~10 %))

+ (safety margin)

(*: debris-related activities)

6.3.3.4 Propellant-tanks and pressure-vessels

The propellant tanks and pressure-vessels should be designed in a way that takes into consideration the following debris-relating countermeasures:

(1) Volume of propellant tanks will be designed according to the propellant budget. (See 6.3.3.3)

(2) Propellant tanks and pressure-vessels made of titanium do not demise during re-entry. Recently, tanks made of CFRP and aluminium skin have been developed. This type of tanks should be chosen to ensure ground safety. (In this case the compatibility between propellant and tank materials, and the degradation of composite materials should be accounted.)

(3) Propellant tanks, which contain a set of homogeneous propellants, and has a common bulkhead which separate oxidizer and fuel, have caused break-up of launch vehicle orbital stages many times in history. This type of tank should be carefully applied to spacecraft.

(4) Since the tanks and pressure vessels are vulnerable to the impact of debris, they should be located behind the strong elements of the system structure or protected by shielding materials.

(5) Pressure vessels should have the capability to decrease pressure low enough at the end of the operations to prevent a rupture during thermal cycles due to solar heating.

(6) If the pressure vessels can't be vented during the disposal phase, they should be designed with enough safety margin considering the solar heating.

6.3.3.5 Valves and piping

[Information] The valves and piping are designed as follows:

(1) They enable the venting of residual fluids at the end of operation as far as possible.

(2) After the apogee kick engine complete its bi-propellant mode, and oxidizer is thus no longer needed in the following mono-propellant mode, the oxidizer lines will be blocked and be isolated to avoid mixing with fuel.

(3) Shielding or other protective designs against the impact of debris should be provided if the probability of impact can't be ignored. (See 3.6.4 for estimation of impact probability, and ISO 16126 for assessment of risk)

(4) To limit the probability of the accidental break-up to be less than 0.001, the failure rate of valves, whose failures would cause break-up of tanks, should be enough low.

(5) Venting lines should be designed to prevent a blockage due to the freezing of propellant.

(6) Venting lined should be designed for the final disposal actions so as not to disturb the attitude of the spacecraft.

6.4 Attitude and orbit control subsystem

6.4.1 Debris-related designs

In this subsection, the design and orbital operation of the attitude and orbit control system (AOCS) of the spacecraft are described. The AOCS consist of control devices, sensors, and actuators. In this Technical Report, gas-jet device, which is used as actuator for the reaction control function in AOCS, is discussed in 6.3 “the propulsion subsystem”.

The measures to be considered for AOCS are shown in Table 13:

Table 13 — Debris-related measures in the AOCS subsystem

Mitigation measures	AOCS	Major components		
		Attitude monitoring sensor	Actuators (Wheels)	Electronic circuit
Break-up prevention	Yes		Related	
Disposal manoeuvre	Yes (Normal function)			
Ground safety*	Yes		Yes	
Re-entry control*	Yes	Yes		
Collision avoidance	Yes (Normal function)			
Protection from the impact of micro-debris	Yes (Protection design)	Yes	Yes	Yes
*Applies to LEO satellites only				

6.4.2 Considerations for AOCS

6.4.2.1 Break-up prevention

The source of fragmentation in AOSC is the rotating devices, such as wheels. (See 6.4.3.2)

6.4.2.2 Controlled re-entry

[Information] If a controlled re-entry is planned, the AOCS should support it. (See 6.4.3.1)

6.4.2.3 Protection from impact of micro-debris

[Information] To avoid the loss of disposal function due to the impact of micro-debris or a meteoroid during operation, it is preferable to apply protection shield, redundant devices and circuits, keeping enough distance between the main wiring routes and secondary ones, or sheltering the sensor head and lines. (See ISO 16126 for risk assessment)

Keeping stand-off distance between outer panel and AOCS devices may reduce the risk of damage caused by impact of debris and meteoroids or ejectors penetrating panels.

6.4.3 Considerations in component design

6.4.3.1 Attitude sensors

[Information] Sensors that are exposed to outer space, such as the earth sensor, solar sensor, and star sensor should be designed as follows, (if necessary based on the risk assessment for debris impact).

(1) The sensors should be located in a position that reduces the risk of impact, or designed to include appropriate redundancy.

(2) Since an Earth sensor may not be enough to determine the attitude in lower altitude for controlled re-entry. An integrated AOCS that includes GPS, an inertial reference unit (IRU), and a star sensor may be studied. Other specifications for controlled re-entry will be added to a normal space operation.

6.4.3.2 Wheels

[Information] Wheels can be a source of break-up in AOCS due to their kinetic energy. Typical rotating devices are reaction wheels, momentum wheels, and control momentum gyros. However, these rotating devices will stop moving shortly after the termination of electric supply. Also, they will be designed to withstand the expected mechanical environment, including ground transportation, the launch environment, and the in-orbital environment so that they may not cause break-up so easily. Then, further actions such as intentional breaking will not be necessary, rather, intentional breaking may cause sudden disturbance of attitude of spacecraft which may prevent other disposal actions (TT&C termination, etc.).

6.4.3.3 Electronic circuit

Although the electronic circuit will be installed inside the spacecraft and not be exposed to outer space, the impact risk should be assessed according to ISO 16126.

6.5 Power-supply subsystem

6.5.1 Debris-related designs

The power-supply subsystem consists of components that provide function of power generation, power energy storage, power control, and power distribution.

The items to be considered for debris mitigation are shown in Table 14:

Table 14 — Debris-related measures in the power-supply subsystem

Mitigation measures	Power-supply subsystem	Major components			
		Battery	Solar paddle	Cable	Control / distribution device
Refraining from releasing parts	Yes		Yes		
Break-up prevention	Yes	Yes	Yes		
Disposal manoeuvre	Yes (Normal function)	Yes			
Ground safety*	Yes	Yes (Residual)			
Re-entry control*	Yes (Normal function)		Yes		
Collision avoidance	Yes (Normal function)				
Protection from the impact of micro-debris	Yes (Protection design)		Yes	Yes	Yes
*Applies to LEO satellite only					

6.5.2 Considerations for power-supply subsystems

6.5.2.1 Refrain from releasing fasteners during paddle deployment

Deployable solar paddles should be designed not to release fasteners (separation bolts, wire, wire cutters, etc.), or their fragments.

6.5.2.2 Break-up prevention

The sources of fragmentation in the power-supply subsystems will be batteries. (See 6.5.3.1)

Monitoring systems that can detect the symptoms of break-up for batteries are designed, and procedures will be developed to take immediate action when a symptom of a break-up is detected. The monitoring plan and contingency planning will be included in this procedure.

6.5.2.2.1 Disposal actions

At the end of operation, the power-supply subsystem should provide the energy to conduct disposal manoeuvres and break-up preventive measures.

6.5.2.3 Ensuring ground safety

[Information] The battery case is an item that may survive re-entry.

ISO 24113 also requires the limitation of pollution of the ground environmental due to radioactive substances, toxic material, and so on. Nuclear power subsystems should be carefully designed and comply with the UN treaty for the nuclear power system, if applied.

6.5.2.4 Protection from the impact of micro-debris

Following items are vulnerable to the impact of micro-debris. (See ISO 16126)

(1) power cable exposed to outer space

(2) solar panels

(3) primary components such as the shunt device, electrical control device, and battery may not be so vulnerable but essential to guarantee the disposal manoeuvre.

[Information] Because design changes for protective measures and additional redundant elements affect system characteristics such as the mass property, thermal property, and so on. The latest configuration should be coordinated with spacecraft system design and other related subsystem design.

6.5.3 Considerations in component design

6.5.3.1 Batteries

[Information] Because batteries will be high-pressure vessels, it is necessary to take precautions and prevent their break-up.

The battery should be designed properly in all electrical and mechanical aspects to prevent a break-up due to excessive charging / discharging or temperature increase.

Critical parameters of the battery, such as temperature and pressure, should be monitored during operation to detect the cause of a rupture according to ISO 16127**.**

At the end of operation, the charging line should be shut-off. The complete discharging is not necessary to complete RF (radio frequency as meaning that including all electromagnetic frequency) termination, etc. (Without complete discharging, batteries would be discharged gradually through various electric and electronics devices.)

The battery should further incorporate these features:

(1) A rapture disk or relief valve to control the increase of internal pressure of the battery, to the extent that the reliability of the battery can be assured

(2) Protections designed based on assessment of the risk of micro-debris impact is preferable.

(3) The energy required for de-orbit, re-orbit, and controlled re-entry should be guaranteed.

(4) To guarantee the ground safety after the re-entry, design data should be sent to an analyst for survivability analysis.

6.5.3.2 Power control/distributing box

6.5.3.2.1 Control device

[Information] The major components such as the shunt device and electrical control device should be located in an area with low probability of impact. If that is impossible, protection design (shielding) should be studied.

6.5.3.2.2 Wire harness

[Information] When a power cable is exposed to outer space, it is at risk of impact of micro-debris that may cause fail or short circuit. The shielding of cables and connectors, as well as the use of redundant cables and multiple power-supply systems will be studied.

The following are suggested:

(1) Wire harnesses exposed to outer space will be protected with shielding, as far as possible.

(2) To limit the damage of debris impact, the power-supply cables should not be tied-up within one bundle. The multiple wiring routes also should be allocated separated each other as far as possible.

(3) The potential problems such as short circuits should be assessed and applied measures to isolate possible failures.

6.5.3.3 Solar cell panel

[Information] For the solar panel, the risk of debris impact should be assessed and the following measures should be taken:

(1) Assess the risk of an open circuit or short circuit caused by debris impact, and apply design to have redundancy, and a margin of electricity. It is recommended that the system margin at the initiation of operation guarantee the electricity required until the end of operation, with considering the damage caused by the impact of debris.

(2) The ground fault of an array circuit due to debris impact should be prevented by applying the bleeder resistance, or other measures.

(3) Solar panels should be designed not to release objects such as fasteners. Pyrotechnics for deployment mechanism should not release combustion products larger than a maximum length of 1 mm.

6.6 TT&C subsystem

6.6.1 Debris-related designs

Items to be considered for the telemetry tracking and command (TT&C) subsystem are shown in Table 15.

Table 15 — Debris-related measures in the TT&C subsystem

Mitigation measures	TT&C subsystem	Major components		
		Tele-communica-tion	Deployable antenna	Measurement
Refraining from releasing parts	Yes		Yes	
Break-up prevention	Yes (Monitor)	Yes		Yes
Disposal manoeuvre	Yes (Normal function)			
Ground safety*	Yes			
Re-entry control*	Yes	Yes	Yes	
Collision avoidance	Yes (Normal function)			
Protection from the impact of micro-debris	Yes (Protection design)	Yes		Yes
*Applies to LEO satellite only				

6.6.2 Considerations for TT&C subsystems

6.6.2.1 Refrain from releasing parts

Potential source of generating debris is fasteners for deployable antennas. (See 6.6.3.1)

6.6.2.2 Break-up prevention

There will no devices to be potential sources of fragmentation in TT&C subsystems.

Monitoring system according to the requirements of ISO 16127 that can detect the symptoms of a break-up and send warning to operators will be designed as a function of TT&C.

6.6.2.3 Disposal action

This subsystem should secure the measurement, command and communication functions required to vent residual energy and conduct orbital manoeuvring functions at the end of operation (see ISO 23339).

After disposal operations, communication lines (transmitters, receivers, etc.) should be shut-off.

6.6.2.4 Re-entry control

6.6.2.4.1 Keeping the communication link during operation for controlled re-entry

The design and operations are recommended for keeping the communication / command link to enable ground support (trajectory monitoring) during controlled re-entry, taking into account changes in signal level and Doppler bands.

6.6.2.4.2 Lower-limit of altitude for transmission during controlled re-entry

When planning controlled re-entry, the limit of lowest altitude for the communication line will be defined.

6.6.3 Considerations in component design

6.6.3.1 Deployable antenna

ISO 24113 requires the pyro-devices and other fasteners used for deploying mechanism to refrain from the release of objects.

6.6.3.2 Components installed outside the primary structure of spacecraft

When components are installed outside the primary structure of spacecraft, it is considered to be best practice to note that the front plane (X plane, which faces the direction of velocity) has the highest probability of impact of micro-debris comparing the other plane.

If the component must be installed on in the X plane, the impact risk of micro-debris are assessed, and redundant devices or shielding measures may be studied if needed. (See ISO 16126 for risk assessment)

6.6.3.3 Components installed inside the primary structure

Components installed just behind the X plane may be damaged by micro-debris that penetrate the panel and generate clouds of ejectors. Keeping standoff distance from the panel may reduce the risk of damage.

6.7 Structural subsystem

6.7.1 Debris-related design

In this sub-clause, structural element (structural panel, deck, cylinder, truss, etc.) and deployment devices are discussed. Items related to debris issues for these elements are shown in Table 16.

Table 16 — Debris-related measures in the structural subsystem

Mitigation measures	Structural subsystem	Major component			
		Structural panel	Truss	Deployment devices	Dummy mass
Prevention of the release of parts	Yes			Yes	
Ground safety*	Yes	Yes	Yes		Yes
Protection from the impact of micro-debris	Yes (Protection design)	Yes			
*Applies to LEO satellite only					

6.7.2 Considerations for structural subsystems

6.7.2.1 Refrain from releasing parts

Fasteners for deployment mechanism should not release fragments into outer space.

6.7.2.2 Ground safety

The materials that easily demise during re-entry is recommended for structural elements.

Dummy masses and balance weights tend to survive during re-entry.

6.7.2.3 Protection from the impact of micro-debris

The probability of the impact of micro-debris is highest on the front plane perpendicular to the direction of velocity. The shape of the spacecraft, the materials for the panel, the angle between the honeycomb panel and the direction of impact velocity, and the installation of vulnerable components behind strong elements may reduce the risk of damage.

6.7.2.4 Dummy mass and balance weight

Dummy mass and balance weight should be designed for easy demise during re-entry. Selection of adequate materials is one point. Materials with a high melting point and/or high specific heat, such as titanium, beryllium and tungsten, are not recommended, due to their high survivability.

Another option is making it a set of multiple layers, instead of one thick, solid mass.

6.8 Thermal-control subsystem

6.8.1 Debris-related design

Items to be considered for debris-related measures are shown in Table 17:

Table 17 — Debris-related measures in the thermal-control subsystem

Mitigation measures	Thermal-control subsystem	Major components	
		Heat pipes	Heat radiator
Break-up prevention	Yes	Yes	
Ground safety*	Yes		
Protection from the impact of micro-debris	Yes	Yes	Yes
*Applies to LEO satellite only			

6.8.2 Considerations for thermal-control subsystem

6.8.2.1 Break-up prevention

Heat pipes should be designed to prevent a rupture, considering the heat input after the end of operation. Then heat pipes are not required venting at the end of operation.

6.8.2.2 Protection from the impact of micro-debris

6.8.2.2.1 Heater and radiator

Radiators and other components that are exposed to outer space should be assessed the risk of impact of micro-debris and meteoroids. If the risk assessment shows vulnerability, protective measures or redundant elements should be employed. (See ISO 16126 for risk assessment)

6.8.2.2.2 Reconfirmation of thermal design considering the influence of protective design

If any part of spacecraft is shielded against the impact of debris, the adverse effect of the shielding on the thermal design will be assessed and resolved.

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